AN INVESTIGATION OF ENERGETIC
PARTICLE INJECTIONS ASSOCIATED
WITH MAGNETOSPHERIC SUBSTORMS

NICHOLAS JAMES FLOWERS

MULLARD SPACE SCIENCE LABORATORY
DEPARTMENT OF SPACE AND CLIMATE PHYSICS
UNIVERSITY COLLEGE LONDON

SPACECRAFT ENVIRONMENT & PROTECTION
DEFENCE EVALUATION AND RESEARCH AGENCY
FARNBOROUGH, HAMPSHIRE

THESIS SUBMITTED FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY
TO THE UNIVERSITY OF LONDON
SEPTEMBER 1998
ABSTRACT

Periods of southward interplanetary magnetic field load the magnetotail with energy that is subsequently unloaded into the magnetosphere by a sequence of processes collectively termed a magnetospheric substorm. The mechanism responsible for the unloading of energy and the process of particle injection into the inner magnetosphere is a source of ongoing controversy. The work presented determines boundaries for the particle injection region using drift tracing and studies the solar wind-substorm relationship.

Selection of events during the CRRES epoch is based on dipolarisations seen in magnetometer data and further qualified by retaining only those with accompanying particle injections. Solar wind interaction with the magnetosphere immediately prior to onset is statistically described using superimposed epoch analyses and correlations are sought with injection attributes. Substorm rate is shown to be related to solar wind power, however only a limited connection between event magnitude and solar wind is seen. Work on the substorm trigger process indicates that northward-turning IMF is associated with many onsets although is not mandatory, and the onset mechanism is probably internal although susceptible to external factors.

The morphology of substorm injections is investigated by tracing particle signatures to convergence. A relativistic guiding centre drift particle tracing methodology is developed preserving adiabatic invariants, using realistic magnetic fields fitted to magnetometer data and electric field representations. A subset of ten events is traced back to give boundaries to the eastward electron injection region. Leading edge particle tracing is found to be closely dependent on pitch angle, and hence subject to the effects of shell splitting. Pitch angles are inferred from inter-spacecraft leading edge travel times, and found to be below 70°, probably due to removal of higher pitch angles by shell splitting. Particle tracing indicates the electron injection region eastern extent varies between 0300 and 0600 LT with a mean position of 0400 LT.
CONTENTS

ABSTRACT 2

LIST OF FIGURES 6

LIST OF TABLES 10

CHAPTER 1 – BACKGROUND 11
  1.1 HISTORICAL FOUNDATIONS OF MODERN SUBSTORM RESEARCH 11
  1.2 SUBSTORMS 14
  1.3 THESIS OBJECTIVE AND OVERVIEW 15

CHAPTER 2 – SPACECRAFT AND INSTRUMENTATION 17
  2.1 USAF COMBINED RELEASE AND RADIATION EFFECTS SATELLITE 17
    2.1.1 MISSION 17
    2.1.2 SCIENCE PAYLOAD 18
    2.1.3 ORBIT 19
    2.1.4 LEPA INSTRUMENT 19
    2.1.5 EPAS INSTRUMENT 21
    2.1.6 FLUXGATE MAGNETOMETER 22
  2.2 LOS ALAMOS NATIONAL LABORATORY DETECTORS 23
    2.2.1 CPA INSTRUMENT 23
    2.2.2 SOPA INSTRUMENT 24
  2.3 GOES 6 AND 7 24
    2.3.1 MAGNETOMETER 25
  2.4 INTERPLANETARY MONITORING PLATFORM (IMP) 8 25

CHAPTER 3 – SUBSTORMS AND PARTICLE INJECTIONS 26
  3.1 CHAPTER OBJECTIVE 26
  3.2 DYNAMICS OF THE MAGNETOSPHERE 26
    3.2.1 GEOMAGNETIC STORMS 29
    3.2.2 SUBSTORMS 31
    3.2.3 EFFECTS 36
  3.3 SUBSTORM THEORY 36
    3.3.1 THE SUBSTORM CURRENT WEDGE 36
    3.3.2 PROPOSED MODELS 38
    3.3.3 RESOLUTION OF SUBSTORM ISSUES BY PARTICLE TRACING 42
  3.4 CHARACTERISATION OF THE SUBSTORM ENVIRONMENT 42
    3.4.1 EVOLUTION OF FIELD CONFIGURATIONS 43
    3.4.2 SUBSTORM PLASMA PARTICLE ENVIRONMENT 44
    3.4.3 EVENT FREQUENCY 50
    3.4.4 AE, AU AND AL INDICES 52

CHAPTER 4 – IDENTIFICATION OF SUBSTORM EVENTS 54
  4.1 CHAPTER OBJECTIVE 54
  4.2 CRITERIA FOR SUBSTORM IDENTIFICATION IN DATA 54
    4.2.1 CRRES MAGNETOMETER DATA 55
    4.2.2 GOES 6 AND 7 MAGNETOMETER DATA 56
    4.2.3 CRRES LEPA PARTICLE DATA 57
    4.2.4 CRRES EPAS PARTICLE DATA 60
    4.2.5 LANL SOPA/CPA PARTICLE DATA 61
    4.2.6 METEOSAT SEM-II PARTICLE DATA 62
    4.2.7 GROUND MAGNETOMETER DATA 62
    4.2.8 AE, KP AND DST INDICES 62
  4.3 SUBSTORM IDENTIFICATION BY CONSENSUS 64
    4.3.1 METHOD 65
**Chapter 5 – Substorm Relationship to Solar Wind**

- **5.1 Substorm Energy**
- **5.2 IMP-8 Solar Wind Data**
- **5.3 Solar Wind Superimposed Epoch Analysis**
  - 5.3.1 Literature Review
  - 5.3.2 Method
  - 5.3.3 Results
  - 5.3.4 Discussion & Conclusions
- **5.4 Triggering**
  - 5.4.1 The Triggering Debate
  - 5.4.2 Solar Wind Triggering of the 187 Event Collection
  - 5.4.3 Conclusions on Solar Wind Triggering of Substorms
- **5.5 Correlation of Solar Wind Attributes with Onsets**
  - 5.5.1 Introduction
  - 5.5.2 Correlation Method
  - 5.5.3 Anticipated Results
  - 5.5.4 Results
  - 5.5.5 Discussion of Tilt Angle Effects
  - 5.5.6 Progression of Study

**Chapter 6 – Particle Tracing**

- **6.1 Particle Drift Theory**
  - 6.1.1 Guiding Centre Approximation
  - 6.1.2 Adiabatic Invariants
  - 6.1.3 Guiding Centre Drifts
  - 6.1.4 Bounce Averaging
- **6.2 Tracing Algorithm**
  - 6.2.1 Runge-Kutta Technique
  - 6.2.2 Adaptive Step-Size Timing Mechanism
  - 6.2.3 Co-ordinate System
  - 6.2.4 Transformations
  - 6.2.5 Algorithm
  - 6.2.6 Handling of Special Case Situations
- **6.3 Magnetospheric Magnetic Field Models**
  - 6.3.1 Internal Field Model
  - 6.3.2 External Field Models
  - 6.3.3 Growth/Expansion/Recovery Phase Adaptations
  - 6.3.4 Comparison with Spacecraft Data
  - 6.3.5 Discussion
- **6.4 Magnetospheric Electric Field Models**
  - 6.4.1 Corotation Field Model
  - 6.4.2 Convection Field Models
  - 6.4.3 Inductive Component Due to Magnetic Field Evolution
  - 6.4.4 Elimination of Parallel Electric Field Components
  - 6.4.5 Comparison with CRRES Electric Field Data
  - 6.4.6 Conclusions
- **6.5 Testing**
  - 6.5.1 Echo Trace to Injection Observations
- **6.6 Error Analysis**
  - 6.6.1 Model Inaccuracies
  - 6.6.2 Instrument Data Errors
  - 6.6.3 Program Errors
- **6.7 Selection of Trace Particles**
  - 6.7.1 Preferential Use of Electrons as Trace Particles
  - 6.7.2 Selection from Typical Pulse Signatures

**Chapter 7 – Tracing of Substorm Events**

- **7.1 Prior Particle Tracing Work**
An investigation of energetic particle injections associated with magnetospheric substorms

7.2 SHELL SPLITTING

7.3 RESULTANT PITCH ANGLE DISTRIBUTION SEEN AT GEO

7.4 DETERMINATION OF LEADING EDGE PITCH ANGLES

7.5 METHODOLOGY & RESULTS PRESENTATION

7.5.1 EVENT 6 (ONSET AT 0805, 6.9.90)

7.6 IDENTIFIED EVENT INJECTION TRACINGS

7.6.1 EVENT 13 (ONSET AT 0537/0545, 6.10.90)

7.6.2 EVENT 18 (ONSET AT 0930, 15.10.90)

7.6.3 EVENT 21 (ONSET AT 0858, 25.10.90)

7.6.4 EVENT 28 (ONSET AT 0725, 5.12.90)

7.6.5 EVENT 32 (ONSET AT 0814, 23.12.90)

7.6.6 EVENT 33 (ONSET AT 1033, 31.12.90)

7.6.7 EVENT 41 (ONSET AT 0815, 24.1.91)

7.6.8 EVENT 51 (ONSET AT 1022, 27.2.91)

7.6.9 EVENT 61 (ONSET AT 1021, 08.3.91)

7.6.10 EVENT 67 (ONSET AT 0653, 13.03.91)

7.6.11 EVENT 88 (ONSET AT 1011, 2.4.90)

7.6.12 EVENT 181 (ONSET AT 0639, 5.10.91)

7.7 COMPOSITE RESULTS AND CONCLUSIONS

CHAPTER 8 – CONCLUSIONS

8.1 SUBSTORM CHARACTERISATION

8.2 THE SOLAR WIND – SUBSTORM RELATIONSHIP

8.3 MORPHOLOGY AND VARIATION OF PARTICLE INJECTIONS AND REGIONS

8.4 PARTICLE TRACING

8.5 SUMMARY OF CONTRIBUTIONS OF THIS WORK

8.6 POSTSCRIPT

ACKNOWLEDGEMENTS

REFERENCES

APPENDIX A – 187 EVENTS IDENTIFIED AS SUBSTORMS
LIST OF FIGURES

Figure 1.1-1 An artist’s impression (not to scale) of the Sun’s influence on what would otherwise be the Earth’s dipolar magnetic field [NASA, Goddard]. 12

Figure 1.1-2 The spatial distribution of trapped particles in the Van Allen radiation belts. Population a/ Protons $E_p > 30$ MeV b/ Electrons $E_e > 1.6$ MeV c/ Protons $0.1 < E_p < 5$ MeV d/ $E_e > 40$ keV [Parks, 1991]. Fluxes from 2.5 Re onwards exhibit volatility on the timescale of days to hours due to geomagnetic activity. 13

Figure 2.1-1 CRRES releasing a canister of tracer elements 17

Figure 2.1-2 Schematic of local time precession of CRRES’s orbit [Johnson, 1992]. 19

Figure 3.2-1 Topology of the magnetosphere for northward and southward interplanetary fields. In the steady state, the plasma flows as indicated by the short arrows (From Dungey [1963]). 27

Figure 3.2-2 The convection of flux in the magnetosphere during a period of southward interplanetary magnetic field [Kivelson et al., page 243, 1995]. 28

Figure 3.2-3 The storm-induced magnetic disturbance at the Earth’s surface. 30

Figure 3.2-4 The flow of energy from the solar wind into and through the magnetosphere-ionosphere system. [Baker et al., J. Geophys. Res., June 1996]. 33

Figure 3.3-1 Schematic of the substorm current wedge (SCW) [McPherron et al., 1973]. 37

Figure 3.3-2 Events leading to a substorm under the NENL model [Kivelson et al., 1995]. 39

Figure 3.3-3 Diagram [Kivelson et al., 1995] showing plasmoid formation between the NENL and DNL. 40

Figure 3.4-1 Maximum projected energies injected during substorms 47

Figure 3.4-2 The longitudinal extents of the three injections seen in Reeves et al. [1992]. The radial extents are arbitrary. 50

Figure 3.4-3 Histogram of number of 15-hour periods versus number of events seen in that period (for the 187 events identified in this work). 51

Figure 3.4-4 Average AE index development [Koskinen, 1994]. 53

Figure 4.2-1 Plotting graphs of $B_z$-Measured $- B_z$-Model show the effects of field loading (stretching) during the growth phase, followed by dipolarisation during expansion [after Yeoman et al., 1994]. 57

Figure 4.2-2 The background count channel for the CRRES/LEPA instrument over the entire duration of the mission. 59

Figure 4.2-3 EPAS data plot showing a substorm injection signature at ~2140 (courtesy of Reiner Freidel). 60

Figure 4.2-4 An injection as seen in the CPA/SOPA data set (protons blue, electrons red, z-axis UT, y log flux with ions and electrons artificially separated by an offset). 61

Figure 4.3-1 Selected plots of Measured $B_z$ – Tsyganenko 1989 Model $B_z$. 66

Figure 4.3-2 The distribution of dipolarisation signatures seen in GOES-06, GOES-07 and CRRES data. The dash line represents the averaged maximum changes in $B_z$ Meas $- B_z$ Mod for each local time hour (i.e. average over events (max (Bz-Meas $- B_z$-Mod)) $- min (B_z$-Meas $- B_z$-Mod)). This measure indicates the noon events differ in nature to their midnight counterparts. 68

Figure 4.3-3 Distribution and average intensity of dipolarisations as seen by GOES-6, GOES-7 and CRRES in Solar-Magnetic co-ordinate local time (LT markers shown). 69

Figure 4.3-4 An example of how the minima and maxima of a substorm injection were indicated in two LANL spacecraft CPA data set traces. 73

Figure 4.3-5 An instantaneous magnetosphere-wide increase in fluxes at SOPA/CPA energies probably caused by a change in the solar wind dynamic pressure. Several spacecraft see the flux increase at once. 73

Figure 4.4-1 An equatorial projection (SM co-ordinate system, XY plane) of spacecraft positioning for event number 32. The Sun is to the left, Earth is the central sphere, and concentric rings indicate 2 Re markers. Spacecraft are labelled, except for CRRES (which has a trail). 77

Figure 4.5-1 Szita et al. [1996] graph showing the relationship between peak flux seen by Meteosat’s SEM-2 instrument (a modified LANL instrument) and local time. 80

Figure 5.3-1 As per inset caption. From Foster et al. [1971]. 83
An investigation of energetic particle injections associated with magnetospheric substorms

Figure 5.3-2 Superimposed epoch analysis of AE data centred on substorm onsets. From Caan et al. [1978].

Figure 5.3-3 Superimposed epoch analysis of Bz data centred on substorm onsets. From Caan et al. [1978].

Figure 5.3-4 The results of a superimposed epoch analysis, centred on substorm onsets, of solar wind parameters from IMP-8 (tilts < -8°).

Figure 5.3-5 As per Figure 5.3-4, although for data points when the dipole tilt was more than +8°.

Figure 5.3-6 As per Figure 5.3-4, although no tilt discrimination was made for data used.

Figure 5.3-7 The evolution of the Dst index over the lifetime of the CRRES mission.

Figure 5.5-1 Correlation of various solar wind parameters and AE Arnoldy [1971].

Figure 5.5-2 Correlations of solar wind power, integrated over a variable duration period with variable lags, with substorm dipolarisation ΔBz. The colour of the grid points represent the correlation of solar wind data (r) with lag (x) integrated over period (y) with the event ΔBz.

Figure 6.1-1 Cyclotron motion (from Roederer, 1970)

Figure 6.1-2 Cycloid motion of a particle subject to a perpendicular force, resulting in a guiding centre force drift (Roederer, 1970).

Figure 6.1-3 The effect of a perpendicular gradient in the magnetic field on the cycloidal motion of a particle (Roederer, 1970).

Figure 6.1-4 A diagram showing a guiding centre's motion on a curved field line. Rc is the radius of curvature, e is the unit magnetic field vector and n its normal [Roederer, 1970].

Figure 6.1-5 A diagram showing a particle trapped in a magnetic bottle between two magnetic mirror points [Roederer, 1970].

Figure 6.1-6 Numerical bounce averaging scheme.

Figure 6.2-1 Top panel: Euler method of solving a differential equation: iterative evaluation of the function incrementing the position in steps of length h. Bottom panel: Runge-Kutta method where a 'trial step' of ½h is first tried to get to (2) and the function re-evaluated there to give a result used to get from (1) to (3). [Numerical Recipes, Press, 1986].

Figure 6.2-2 Particle tracing algorithm – the particle movement algorithm is executed for each particle in an incrementing time-loop.

Figure 6.3-1 Magnetospheric current systems. Tsyganenko's models are a composite of the effects of a number of current terms, including the ring current, tail current, magnetopause current above.

Figure 6.3-2 Schematic showing the duration of individual modifications to the magnetospheric current systems in T96 and SCW modules.

Figure 6.3-3 Event 32 magnetic model fit.

Figure 6.3-4 A cartoon showing the modelled magnetic development of event 32 according to the magnetic fit.

Figure 6.3-5 Cartoon (see last figure).

Figure 6.3-6 Event 185 magnetic model fit.

Figure 6.4-1 Equatorial projection in SM co-ordinate system of corotational field model (dominant near Earth, directed radially inwards) with superimposed Volland-Stern convection model. Dots indicate pointing direction of vectors.

Figure 6.4-2 Equatorial projection in SM co-ordinate system of corotational field model with superimposed Weimer 96 convection model.

Figure 6.4-3 Equatorial projection in SM co-ordinate system of corotational field model with superimposed HMR model 1.

Figure 6.4-4 Equatorial projection in SM co-ordinate system of spatially averaged CRRES/EFI data.

Figure 6.4-5 The convection field models values, with corotational component included, along Y = 0/Z = 0 at a substorm onset.

Figure 6.4-6 The convection field models values, with corotational component included, along X = 0/Z = 0 at a substorm onset.

Figure 6.4-7 Resulting E cross B drift speeds.

Figure 6.5-1 Event #35 particle trace testing environment.
An investigation of energetic particle injections associated with magnetospheric substorms

Figure 6.5-2 Comparison of modelled and actual arrival times of particles at spacecraft for event 35. 155

Figure 6.5-3 Comparative schematic showing the modelled and actual arrival times of particles at sensors for event 13. 156

Figure 6.7-1 Differential drift of electrons of differing energies from different parts of the injection region. 160

Figure 7.2-1 The three panels show the increasing effects of shell splitting on 200 keV particles as a function of radial distance from the Earth. 163

Figure 7.2-2 The two panels show the effect of energy on shell splitting, with 200 keV particles in the topmost panel, and 45 keV particles below. The 200 keV particles are dispersed more readily than lower energy particles. 164

Figure 7.2-3 The two panels show the effect of magnetospheric field condition on shell splitting. 165

Figure 7.3-1 The three panels above show plots of the observed pitch angle distribution against time (minutes:seconds) for the particles within the injection pulse of event 3, for three energy bands. The pitch angles are those of the particles at the spacecraft rather than at the magnetic minima. 167

Figure 7.5-1 Equatorial projection of spacecraft positioning close to onset. The figure is a SM system XY plane, with the Sun to the left. 169

Figure 7.5-2 Measured minus modelled magnetic field vectors for event 6, pre (light) and post (dark) model fitting. 170

Figure 7.5-3 Particle injection as seen by the LANL instruments for event 6, and particles selected for tracing. 171

Figure 7.5-4 Particle tracing for event 6, y-axis position in local time against UT. Time decreases left (post onset) to right (near onset). 173

Figure 7.6-1 Equatorial projection of spacecraft positioning at onset. 174

Figure 7.6-2 Measured minus modelled magnetic field vectors, pre (light) and post (dark) model fitting. 174

Figure 7.6-3 Particle injection as seen by LANL satellites. Explanation as per equivalent plot for event 6. 175

Figure 7.6-4 CRRES/EPAS 85 < \alpha < 90 data (panel explanations same as for CPA/SOPA data). 176

Figure 7.6-5 Particle tracing for event 13 (X axis non-linear). 177

Figure 7.6-6 Equatorial projection of spacecraft positioning at onset. 177

Figure 7.6-7 Measured minus modelled magnetic field vectors for event 18, pre (light) and post (dark) model fitting. 178

Figure 7.6-8 Solar wind density, velocity, dynamic pressure and Bz conditions for event 18. 178

Figure 7.6-9 Particle injection as seen by the LANL instruments. Explanation as per last event. 179

Figure 7.6-10 Particle tracing for event 18, both leading edge (right) and trail edge (left) signatures. 180

Figure 7.6-11 Equatorial projection of spacecraft positioning at onset. 181

Figure 7.6-12 Measured minus modelled magnetic field vectors for event 21, pre (light) and post (dark) model fitting. GOES-06 shows the small disturbance identified. 181

Figure 7.6-13 Particle injection as seen by LANL satellites. 182

Figure 7.6-14 Trailing edge particle tracing for event 21. The right hand side cut-off is the onset as determined from the magnetic disturbance. The western edge of the electron injection was at approximately 2118LT. 183

Figure 7.6-15 Leading edge particle tracing for event 21 (X axis non-linear). 183

Figure 7.6-16 Equatorial projection of spacecraft positioning at onset. 184

Figure 7.6-17 Measured minus modelled magnetic field vectors for event 28, pre (light) and post (dark) model fitting. 185

Figure 7.6-18 Solar wind density, velocity, dynamic pressure and Bz conditions for event 28. 185

Figure 7.6-19 Event 28's particle injection as seen by LANL satellites, and particles selected for tracing. 186

Figure 7.6-20 CRRES/EPAS fluxes for event 28. 187

Figure 7.6-21 Modelled magnetic reconfiguration during event 28, side (SM co-ordinate system X-Z plane) view. 188

Figure 7.6-22 Particle tracing for event 28, y-axis position in local time against UT. 189

Figure 7.6-23 Equatorial projection of spacecraft positioning at onset. 190
An investigation of energetic particle injections associated with magnetospheric substorms

Figure 7.6-24 Measured minus modelled magnetic field vectors pre (light) and post (dark) model fitting.

Figure 7.6-25 Particle injection as seen by LANL satellites.

Figure 7.6-26 Leading edge particle tracing for event 32 (X axis non-linear).

Figure 7.6-27 Equatorial projection of spacecraft positioning at onset.

Figure 7.6-28 Measured minus modelled magnetic field vectors for event 33, pre (light) and post (dark) model fitting.

Figure 7.6-29 Particle injection as seen by LANL instruments.

Figure 7.6-30 Leading edge particle tracing (X axis non-linear).

Figure 7.6-31 Equatorial projection of spacecraft positioning at onset.

Figure 7.6-32 Measured minus modelled magnetic field vectors for event 41, pre (light) and post (dark) model fitting.

Figure 7.6-33 Solar wind density, velocity, dynamic pressure and Bz conditions for event 41.

Figure 7.6-34 Event 41’s particle injection as seen by LANL satellites, and particles selected for tracing.

Figure 7.6-35 CRRES/EPAS fluxes for event 41.

Figure 7.6-36 Particle tracing for event 41, y-axis position in local time against UT.

Figure 7.6-37 Guiding centre drift velocities for particles with various pitch angles and energies, over local time.

Figure 7.6-38 Equatorial projection of spacecraft positioning a little after onset.

Figure 7.6-39 Measured minus modelled magnetic field vectors for event 51, pre (light) and post (dark) model fitting.

Figure 7.6-40 Solar wind conditions for event 51.

Figure 7.6-41 Event 51’s particle injection as seen by LANL instruments. This graph shows ion traces overlaid in yellow.

Figure 7.6-42 CRRES/EPAS fluxes for event 51. Both species show non-dispersed signatures at 1021.

Figure 7.6-43 Proton tracing for event 51, y-axis position in local time against UT.

Figure 7.6-44 Electron tracing for event 51. Convergence occurs at 2800LT.

Figure 7.6-45 Equatorial projection of spacecraft positioning at onset.

Figure 7.6-52 Measured minus modelled magnetic field vectors, pre (light) and post (dark) model fitting.

Figure 7.6-53 Solar wind data for event 67.

Figure 7.6-54 Particle injection as seen by LANL satellites (only one saw a signature).

Figure 7.6-55 Leading edge particle tracing for event 67.

Figure 7.6-56 Equatorial projection of spacecraft positioning at onset.

Figure 7.6-57 Measured minus modelled magnetic field vectors for event 181, pre (light) and post (dark) model fitting (growth/expansion: 102/20 minutes).

Figure 7.6-58 Solar wind conditions for event 181.

Figure 7.6-59 Event 181’s particle injection as seen by LANL satellites.

Figure 7.7-1 Distribution of results from particle tracing with overlaid distribution seen for dipolarisations in Chapter 4.

Figure 8.4-1 An example of the difficulties posed in identifying the leading edges of injection pulses.
LIST OF TABLES

Table 2.1-1 LEPA energy channels 20
Table 2.1-2 EPAS differential energy channel ranges. 21
Table 2.2-1 LANL/CPA electron channels [Reeves, 1994]. 24
Table 2.2-2 LANL/SOPA electron channels [Reeves, 1994]. 24
Table 3.2-1 Typical storm categories. 30
Table 3.4-1 Magnitude of superimposed electron flux enhancements over energy, Szita et al. [1993]. 46
Table 5.4-1 IMF conditions at time of onset for the 187-event collection. 96
Table 5.5-1 r-values for auto-correlation of substorm measures, divided by dipole tilt. 104
Table 5.5-2 Significant correlation values for solar wind attributes and substorm dipolarisation $\Delta B_z$. 105
Table 5.5-3 Significant correlation values for solar wind attributes and substorm $E_{\text{int}}$. 106
Table 5.5-4 Significant correlation values for solar wind attributes and substorm 40 keV flux increase. 106
Table 5.5-5 Significant correlation values for solar wind attributes and substorm rate. 107
Gating solar wind data on $B_z < 0$ was suspended for these correlations. 107
Table 6.2-1 The SM co-ordinate system. 124
Table 6.3-1 Scope of the parameter search for T96 model fitting. 135
Table 6.3-2 Magnetic field fitting coefficients. 136
Table 6.3-3 Comparison of magnetic field models against CRRES/GOES magnetometer data and relative execution times. 137
Table 6.4-1 Table of HMR model modes. 148
Table 6.4-2 Model accuracy and computation time comparison. 151
Table 7.6-1 Illustration of variable local time of convergence obtainable with different pitch angles for event 181. 212
Table 7.7-1 Particle convergence points from event tracing. 212
CHAPTER 1 – BACKGROUND

1.1 HISTORICAL FOUNDATIONS OF MODERN SUBSTORM RESEARCH

Awestriking and beautiful though the stars and planets may be they are arguably upstaged by rarer lights of the sky – the *aurora borealis*. Science struggled to explain these curtains of pulsating light for centuries. Galileo proposed that air rising out of the Earth’s shadow being illuminated by the Sun caused the aurora, and Descartes believed them to be the reflections from high altitude ice crystals. The foundations of the modern explanation of the aurora, involving substorm activity, were laid in 1722 when George Graham, a famous London instrument maker, noticed that his most accurate compasses were in constant motion, with small perturbations continually disturbing them. A Swedish team confirmed his observations in 1740 and noticed that the magnetic disturbances were most violent during large auroral displays – the lights in the sky were linked to the Earth’s magnetic field. Why the field was so disturbed and how it lit the sky was unknown until observers in British colonies during the early 19th century began to measure disturbances at the same time as counting the Sunspots. The intensity of the perturbations varied in concert with the Sunspot numbers – somehow the Sun was disturbing the Earth’s field and lighting the sky at night.

The evidence implicating the Sun became irrefutable with a chance observation by Richard Carrington on September 1st 1859. Carrington was sketching a number of Sunspots when a transient flare of light from the Sun startled him – by the time he fetched a witness the event was all but faded away. Fortunately another observer had seen the event, and furthermore Kew Observatory in London had made simultaneous measurements showing the magnetic field had been affected almost instantaneously. Within 18 hours, one of the strongest recorded magnetic storms broke out, with auroras stretching as far south as Puerto Rico. Whatever was coming from the Sun to cause the aurora had travelled at nearly 2,300 km/s.

It was not until 1918 that nature of the solar-terrestrial link was correctly determined. Sydney Chapman had postulated that a singly-charged beam of electrons might be streaming out of the Sun, in a ‘solar wind’, towards the Earth to disrupt its magnetic field and channel into its atmosphere, exciting the molecules of the air to fluoresce the greens and blues of the aurora. Chapman’s idea did not survive – surely, said the critics, such a beam would destroy itself with electrostatic repulsion? A modification to the idea proved to be the breakthrough – why just have electrons streaming out, why not instead electrically neutral plasma composed of negative electrons and positive ions? A particle stream of plasma would not destroy itself. The problem was solved, and the plasma idea carried an implication that was proven by spacecraft years.
later. Plasmas carry frozen-in magnetic fields along as they move, such that the plasma and field are fixed relative to one another, and the solar wind plasma would therefore effect the shape of the Earth’s magnetic field. The solar wind streaming by would compress the front of the magnetic field and stretch it out behind the Earth to form a tail, forming a magnetic-cavity around the Earth that the solar wind would rarely penetrate – the magnetosphere.

Soon observations of comets with streaming tails were providing clues as to the density of the solar wind and its speed [Beirmann, 1951]. As comets stream around the Sun they deposit gas and ice in their orbit, but the solar wind deflects the trails so that they point away from the Sun, rather than lie on the comet’s orbit. To deflect the comet tails as seen the wind had to be moving phenomenally fast, at an average of around 450 km/s, and be incredibly rarefied, less than 30 particles per cubic centimetre. Rockets soon confirmed this scientific detective work. A year after Sputnik 1, the space race exploded our knowledge of the near-Earth environment and the solar wind, starting with the US Explorer 1 spacecraft. It carried a Geiger counter from James Van Allen, a physicist from the University of Iowa. The instrument discovered that the Earth’s magnetic field not only protects the planet from the worst of the onslaught of solar radiation, but also marshals some particles in belts of radiation about the planet. These doughnut-shaped regions in near-Earth space can disable spacecraft not designed to withstand such radiation doses.
The process by which solar wind energy is transferred to the magnetosphere to form the radiation belts was explained in 1961 by James Dungey [Dungey, 1961]. The magnetic field of the solar wind and the Earth intermix at the bow of the magnetopause during periods of southward Interplanetary Magnetic Field (IMF). The solar wind drags the magnetic field lines anchored on the Earth back over the magnetosphere to the tail where the field lines reconnect, transferring some of the energy from the solar wind to the magnetosphere in the process. The energy built-up is sporadically dumped into the Earth’s atmosphere and inner magnetosphere.
Chapter 1 – Background

by phenomenon called substorms. These convulsions of the magnetosphere are contractions of the swollen magnetic field, which fling particles into the radiation belts and towards the atmosphere to cause auroras by exciting the molecules of the air to fluoresce as Chapman had suggested.

Since then a flotilla of spacecraft have investigated the effects of this space-weather on Earth and its surrounding geostationary space. Occasionally huge explosions of matter are seen from the Sun, called Coronal Mass Ejections which hit the shielding magnetosphere – the reverberations causing vast magnetic storms involving particles accelerated to tens of MeV and auroras that last for days. Sometimes the solar wind speed can double without warning and the interplanetary magnetic field can chaotically spin and twist. The onslaught and variability of the solar wind can disable terrestrial electrical networks such as power systems and telecommunications networks. Induced currents from the resultant motion of the Earth’s magnetic field trip circuit breakers on long lines at northern latitudes, and have been known to set up eddy currents in equipment that can lead to transformer meltdowns. During magnetic storms and substorms a number of incidences attributed to particle interaction have led to the loss of spacecraft capacity such as the Telstar 401, and the Canadian Aniks. With an increasing reliance upon satellite infrastructure it becomes more important to be able to understand the nature of magnetospheric phenomenon and quantify the risks to spacecraft associated with these events.

1.2 SUBSTORMS

Substorms are a sequence of processes that unload energy from the magnetotail and occur after a period of southward IMF to recycle magnetic flux back to the front of the magnetosphere, closing with the process of solar wind reconnection. Magnetospheric physics progress in understanding substorms is incomplete, with the exact ordering and interdependence of the individual component processes or phenomena unknown. Substorms are known to comprise of disruptions and reconfigurations of the magnetospheric and polar ionospheric current systems, dipolarisations in the Earth’s magnetic field, injections of particles into and below geostationary orbit, Pi2 oscillations in the magnetic field, flows of plasma towards and away from the Earth at various distances, and neutral lines where magnetic field lines reconnect, possibly initiating the entire sequence of events. The probability of their occurrence increases with higher energy levels within the magnetotail, and appears to be the result of an internal instability in the magnetosphere although some argue a direct trigger, such as the reduction of solar wind electric field is responsible.
The details of substorm phenomenology are still lacking, including an explanation for the overall causal mechanism. The catastrophic event occurring in the tail to cause these observations has yet to be explained. There is no physical process to attribute as the mechanism for tail reconnection. No confirmed explanation exists for why substorms often occur with northward IMF turnings and the role current disruption plays is ill defined. Where the near-Earth neutral line forms is a point of debate and varying estimation (although this has narrowed thanks to recent Geotail results). The location of the acceleration of injected particles, and the acceleration process itself, are both unknowns.

This study is an attempt to assist in the many problems substorms pose. By observing the response of the magnetosphere to solar wind changes and the characteristics of injected particle pulses, results are derived that constrain the possible mechanisms that cause substorms to occur, narrow the injection region and similarly constrain the injection process.

1.3 THESIS OBJECTIVE AND OVERVIEW

This thesis aims to contribute to several areas of substorm study and debate. Its primary objective is to contribute to knowledge of substorm injection morphology and subsequently the mechanisms surrounding the injection of energetic particles into the tailward magnetosphere. This is explored by first investigating the field of substorm theory and deriving a characterisation of substorm injections (Chapter 3 – Substorms and particle injections) and using this to identify 187 injections seen during the lifetime of the CRRES missions (Chapter 4 – Identification of substorm events), by looking for a consensus between in-situ magnetometer and particle data for substorm occurrence. This list is used with IMP-8 data to investigate how the solar wind interacts with the magnetosphere to produce substorms, and correlative studies are used in an attempt to constrain the substorm mechanism that stores and unloads solar wind energy (Chapter 5 – Substorm relationship to solar wind).

To realistically trace injected particles and simulate their behaviour, a relativistic guiding centre particle tracing methodology is formulated (Chapter 6 – Particle tracing). This treatment attempts to maximise the effectiveness of tracing by individually fitting Tsyganenko’s 1996 model to each event’s magnetometer data. The resulting particle tracing software is applied to a subset of the 187 candidate injections, tracing a handful of particles from each injection signature as observed by spacecraft instrumentation, to convergence in the tail (Chapter 7 – Tracing of substorm events). This convergence point is interpreted as the easternmost edge of the electron injection boundary. Inconsistencies in some traces during periods of high dynamic pressure lead to an investigation of the difficulties posed by the removal of high-pitch angle, high-energy particles from the leading edges of injection pulses by shell spitting. This
Chapter 1 - Background

has implications for the local time development of injection signatures. The work starts with a survey of instrumentation used in subsequent chapters (Chapter 2 - Spacecraft and instrumentation).
CHAPTER 2 - SPACECRAFT AND INSTRUMENTATION

2.1 USAF COMBINED RELEASE AND RADIATION EFFECTS SATELLITE

A motivation in this substorm study was the use of data from the MSSL instrumentation onboard the USAF Combined Release and Radiation Effects Satellite (CRRES). As the work matured it became apparent that the data was not pertinent in directly diagnosing the early stages of substorm injections due to an instrumental upper energy cut-off of less than 30 keV (an energy with a long geostationary drift time). However, data from other instrumentation onboard the spacecraft was used and the epoch studied remained the lifetime of the CRRES mission: July 1990 to October 1991.

2.1.1 MISSION

The CRRES mission was a joint NASA and U.S. Department of Defense undertaking to study the near-Earth space environment and the effects of the Earth's radiation environment on microelectronic components. CRRES was originally built for STS launch. After the Challenger disaster it was modified for launch on an Atlas Centaur, and placed in orbit on July 25th 1990. Due to battery ageing subsequent to the delay, the spacecraft suffered a premature power system failure in October 1991, having traversed a substantial fraction of near Earth local time, performing valuable studies of Earth bound radiation belts up to geostationary orbit.

![CRRES releasing a canister of tracer elements](image)

Figure 2.1-1 CRRES releasing a canister of tracer elements

Operations supported three major objectives:

- NASA performance of active chemical release experiments in the ionosphere and magnetosphere,
Chapter 2 – Spacecraft and instrumentation

- US DOD studies of the natural radiation environment and studies of the effects of this radiation environment upon microelectronic components as CRRES travelled through the inner and outer radiation belts of the Earth,

- US DOD low-altitude studies of ionospheric irregularities near orbit perigee.

One of the principle objectives of the mission was to study the effect of radiation on spacecraft instrumentation. Electronics subjected to the effects of high-energy particles and radiation typically suffers severe degradation. The primary focus of this study was on the natural radiation environment and the effects of this environment on microelectronic components. CRRES was travelling through the inner and outer radiation belts of the Earth, exposing microelectronic components to this radiation environment to establish their capabilities for use in future space missions. A science payload concurrently mapped the particle environment so that a direct correlation could be made between the exposure and microelectronics performance [Johnson, 1992; Ball Space Systems Division, 1990].

2.1.2 SCIENCE PAYLOAD

The mission carried a number of instruments used in this study:

- The Low Energy Plasma Analyser (LEPA) from the Mullard Space Science Laboratory (MSSL). This investigated thermal plasma in the electronvolt to 28 keV range, gathering data on electron and ion distributions in energy, over azimuthal and polar angle [Hardy et al., 1993],

- The Electron and Proton Wide Angle Spectrometer (EPAS) instrument from Max-Planck-Institut für Aeronomie, Lindau. EPAS observed electrons in the range 21 to 300 keV and protons from 32 to 3200 keV, over a number of detectors giving a 110° fan which swept around as the spacecraft spun, and was used in this study to support observation of injection pulses and regions [Korth et al., 1992],

- The CRRES Electric Field/Langmuir Probe Instrument from the University of California, Berkley provided data for comparison with electric field models used in tracing [Wygant et al., 1992],

- The Fluxgate Magnetometer Instrument from the Air Force Geophysics Lab (AFGL) used to diagnose dipolarisations and adapt field models [Singer et al., 1992].
2.1.3 ORBIT

The initial CRRES orbit was 350 x 33,584 km with an inclination of 18.1°. Following orbit insertion prior to separation from the Centaur, CRRES was oriented with its spin axis lying in the ecliptic plane and pointed 12° ahead of the Sun’s apparent motion, and spun up by the Centaur to its nominal initial spin rate of 2.2 ± 0.2 rpm. The orbital period of the spacecraft was 10.5 hours, decreasing to 9.5 hours by October 1991, with a geomagnetic latitude range of +/-30° degrees. The spacecraft was thus able to sample a range of L shells out to L = 8 Re. Apogee was at 0830 MLT shortly after launch, moving westwards with respect to the Earth. Apogee had reached 0330 MLT by the end of the mission in late 1991.

Figure 2.1-2 Schematic of local time precession of CRRES’s orbit [Johnson, 1992].

2.1.4 LEPA INSTRUMENT

The Low Energy Plasma Analyser (LEPA) was an AFGL / MSSL contribution to the CRRES Mission.

2.1.4.1 DESIGN

The LEPA design allowed the detection of particles in the energy range 10 eV through to 28 keV using two 270° Johnstone Plasma Analysers, one each for ions and electrons. CRRES’s spin axis pointed towards the Sun, and LEPA measured particles in a 128° by 5.6° fan that lay in the plane containing the satellite spin axis. The fan was symmetric about the spin equator so that LEPA sampled from 26° to 154° with respect to the spin axis. The fan was divided into
sixteen $8^\circ$ zones which are numbered from 0 to 15. Each zone simultaneously measured data, and zone 15 was covered in order to form a background channel. LEPA used on board instruments to determine the length of the satellite half spin so that it could divide each half spin into 32 equal sectors. Each sector covers $5.625^\circ$ of a spin. CRRES rotated at approximately 2 rpm so that a half spin period is about 15 seconds, with each sector’s acquisition lasting a little less than a second. In modes 0 and 10 (the predominantly used modes) each sector is divided into 32 steps in which 30 different energies are sampled, while the two remaining steps in each sector were used to reset the voltage source from low to high voltage, [Hardy et al., 1993].

**ENERGY RANGE**

<table>
<thead>
<tr>
<th>Channel Number</th>
<th>Low energy bound (keV)</th>
<th>High energy bound (keV)</th>
<th>Channel Number</th>
<th>Low energy bound (keV)</th>
<th>High energy bound (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>28.46</td>
<td>21.69</td>
<td>15</td>
<td>0.48</td>
<td>0.36</td>
</tr>
<tr>
<td>01</td>
<td>21.69</td>
<td>16.52</td>
<td>16</td>
<td>0.36</td>
<td>0.28</td>
</tr>
<tr>
<td>02</td>
<td>16.52</td>
<td>12.59</td>
<td>17</td>
<td>0.28</td>
<td>0.21</td>
</tr>
<tr>
<td>03</td>
<td>12.59</td>
<td>9.59</td>
<td>18</td>
<td>0.21</td>
<td>0.16</td>
</tr>
<tr>
<td>04</td>
<td>9.59</td>
<td>7.31</td>
<td>19</td>
<td>0.162</td>
<td>0.123</td>
</tr>
<tr>
<td>05</td>
<td>7.31</td>
<td>5.57</td>
<td>20</td>
<td>0.123</td>
<td>0.094</td>
</tr>
<tr>
<td>06</td>
<td>5.57</td>
<td>4.24</td>
<td>21</td>
<td>0.094</td>
<td>0.071</td>
</tr>
<tr>
<td>07</td>
<td>4.24</td>
<td>3.23</td>
<td>22</td>
<td>0.071</td>
<td>0.054</td>
</tr>
<tr>
<td>08</td>
<td>3.23</td>
<td>2.46</td>
<td>23</td>
<td>0.054</td>
<td>0.041</td>
</tr>
<tr>
<td>09</td>
<td>2.46</td>
<td>1.87</td>
<td>24</td>
<td>0.041</td>
<td>0.031</td>
</tr>
<tr>
<td>10</td>
<td>1.87</td>
<td>1.43</td>
<td>25</td>
<td>0.031</td>
<td>0.024</td>
</tr>
<tr>
<td>11</td>
<td>1.43</td>
<td>1.09</td>
<td>26</td>
<td>0.024</td>
<td>0.018</td>
</tr>
<tr>
<td>12</td>
<td>1.09</td>
<td>0.83</td>
<td>27</td>
<td>0.018</td>
<td>0.014</td>
</tr>
<tr>
<td>13</td>
<td>0.83</td>
<td>0.63</td>
<td>28</td>
<td>0.014</td>
<td>0.010</td>
</tr>
<tr>
<td>14</td>
<td>0.63</td>
<td>0.48</td>
<td>29</td>
<td>0.010</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Table 2.1-1 LEPA energy channels

**2.1.4.2 DATA**

LEPA summary data contains a subset of the zones for each 15-second half spin. On board processing determined the spin sectors aligned with the magnetic field and ninety degrees to the magnetic field. The data element corresponding to the zone containing the magnetic field was telemetered down, along with the background channel for the sector (termed the ‘earthward’ or ‘equatorward’ sector). This contained field-aligned particles. Also, the data element for the zone coincident with the vector at right angles to both the spin axis and magnetic vector was sent down (the 90° sector). This contained particles locally mirroring with pitch angles of around 90°. Each data element comprised 20 to 30 energy channels. Excepting data dropouts due to power shortages in eclipses and immediately after the first battery failure, LEPA data is available from July 1990 through October 1991.
2.1.5 EPAS INSTRUMENT

The Electron and Proton Wide-Angle Spectrometer (EPAS) instrument was a Max-Planck-Institut für Aeronomie contribution to the CRRES mission. It consisted of two identical units measuring electrons over ten directions and ions over four, with a total angular range perpendicular to the spin axis of 110°. Observations of electrons (21 to 300 keV) and ions (32 to 3200 keV) were made within the 110° fan as it swept around with the spacecraft spin [Korth et al., 1992].

<table>
<thead>
<tr>
<th>Channel</th>
<th>Electrons, keV</th>
<th>Ions, keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21.0-31.5</td>
<td>37-54</td>
</tr>
<tr>
<td>2</td>
<td>31.5-40.0</td>
<td>54-69</td>
</tr>
<tr>
<td>3</td>
<td>40.0-49.5</td>
<td>69-85</td>
</tr>
<tr>
<td>4</td>
<td>49.5-59.0</td>
<td>85-113</td>
</tr>
<tr>
<td>5</td>
<td>59.0-69.0</td>
<td>113-147</td>
</tr>
<tr>
<td>6</td>
<td>69.0-81.0</td>
<td>147-193</td>
</tr>
<tr>
<td>7</td>
<td>81.0-94.5</td>
<td>193-254</td>
</tr>
<tr>
<td>8</td>
<td>94.5-112.0</td>
<td>254-335</td>
</tr>
<tr>
<td>9</td>
<td>112.0-129.5</td>
<td>335-447</td>
</tr>
<tr>
<td>10</td>
<td>129.5-151.0</td>
<td>447-602</td>
</tr>
<tr>
<td>11</td>
<td>151.0-177.5</td>
<td>602-805</td>
</tr>
<tr>
<td>12</td>
<td>177.5-208.0</td>
<td>805-3200</td>
</tr>
<tr>
<td>13</td>
<td>208.0-242.5</td>
<td>-</td>
</tr>
<tr>
<td>14</td>
<td>242.5-285.0</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2.1-2 EPAS differential energy channel ranges.

The instrument units contained a magnetic deflection system and an array of solid state detectors. Particles entering the spectrometer encountered a homogenous magnetic field that discriminated between protons and electrons. The field's geometry was such that a collection of electrons of differing energies (between 15 and 300 keV) entering the aperture at the same angle would all be deflected to the same detector regardless of energy. Five electron detectors existed within each unit, giving ten angular fields of view over the two units. Pulse-height analysis of the signals from each detector gave energy information for each particle. Each unit had two ion telescopes, giving four angular fields of view over the two units. The ion telescopes also have back detectors that were used to eliminate high-energy particle counts by coincidence counting. Reiner Friedel (at the time, of Max Planck) kindly provided EPAS electron data for a number of orbits that had been identified as containing dipolarisation signatures. These were time-series of pitch-angle energy-channel matrices (at one-minute resolution).
2.1.6 FLUXGATE MAGNETOMETER

Part of the CRRES payload was a three-axis fluxgate magnetometer built by the Phillips Laboratory/Air Force Geophysics Lab. The magnetometer was active throughout the CRRES mission and gave high-resolution data products in a +/- 45,000 nT range [Singer et al., 1992]. Data from the fluxgate magnetometer instrument was used to diagnose dipolarisation events and calibrate/adjust magnetic field models used in particle tracing. The CRRES triaxial fluxgate magnetometer sensors were mounted on a deployable boom, 7.5m from the centre of the spacecraft. The boom however did not deploy correctly and had a 15° offset in the Zsc/Xsc plane. All subsequent data was adjusted for this minor malfunction, and the spacecraft was magnetically clean except for a few nanoteslas offset during the operation of a power amplifier for the transmitter. Data from the instrument is conventionally represented in the VDH system where H (Z) is antiparallel to magnetic dipole axis and positive pointing northward, D (Y) is perpendicular to radius vector R and Z, positive pointing eastwards, and V (X) completes the right handed Cartesian system.

Some complicating factors can cause the magnetometer data to be difficult to interpret. Spacecraft manoeuvres changed the orientation of the satellite spin axis and resulted in distortions of data. Following the manoeuvres there can be apparent variations in the field that last for several days and have an approximate 19-minute period, making data unusable for some orbits. Reiner Friedel (at the time, of MPAe) kindly provided CRRES magnetometer data in the form of one VDH triple per minute for the entire mission. This data was originally from Howard Singer of NOAA, PI of the magnetometer instrument, who provided support in data interpretation.

2.1.6.1 LANGMUIR PROBE

The University of California, Berkley flew a Langmuir probe analyser on the CRRES mission [Wygant et al., 1992] and the resulting data products are used in this work for comparison with electric field models. The data had been processed to remove the effects of spacecraft velocity and the Earth’s dipole field to give corotation field data in the SM co-ordinate system and were provided by Doug Rowlands, University of Minnesota.

The electric field instrument on CRRES (and on almost all spacecraft) was a double probe design that measured the field by taking the potential difference between two widely separated probes, with the resultant signal being sinusoidal due to spacecraft spin through the quasi-static electric field. There are a variety of error sources, including asymmetric illumination and non-identical probe work functions, some of which appear as a DC offset to the sinusoidal electric field signal. The CRRES probes were in the spin plane of the spacecraft with no measurement
along the spin axis (Sunward) and so only provided two vector components of the electric field for each data point, with the third being reconstructed from \( \mathbf{E} \cdot \mathbf{B} = 0 \). The data thus has a dependency on magnetic field fluctuations. CRRES was equipped with two pairs of probes, one of which consisted of a pair of bare wires, and the other which had two small spherical probes at the ends of its wire booms. Originally the spherical probes were designed to give a more accurate measurement. In practice though, one of the spherical probes had a short to a nearby boom element which contaminated measurement [Rowlands, 1998]. Cylindrical probe data has been used here.

### 2.2 LOS ALAMOS NATIONAL LABORATORY DETECTORS

LANL has flown a series of particle detectors on over twelve military/Department of Energy spacecraft spatially distributed around geostationary space for more than 20 years. Los Alamos Charged Particle Analyzers (CPA) have been flown since 1976 and the Synchronous Orbit Particle Analyzers have been flown by LANL since 1989, replacing the CPA instruments. During the CRRES epoch between three and five LANL spacecraft were available at any one time in various longitudes, giving good geostationary coverage. These spacecraft are conventionally designated by their international satellite designator numbers (year + launch number that year). The instrument platforms had a spin period of 10.24 seconds with the spin axis pointed towards Earth, and the spin-synchronised instrumentation had a synchronised temporal resolution of 10 seconds.

CPA/SOPA data is freely available in the form of quick look plots available on the LANL Energetic Particle web page and detailed data files may be ordered from the same site. Geoff Reeves of LANL made CPA/SOPA ASCII data available to this investigation and provided much support in interpreting data. [Reeves, 1997].

#### 2.2.1 CPA INSTRUMENT

Charged Particle Analyzers measure high-energy electrons in the spacecraft equatorial plane using a HiE detector with six channels in the 0.2 to 1.5 MeV energy range. Low energy electrons in the range 30 to 300 keV are measured in six energy channels using the LoE instrument, with detectors mounted at five angles to the spacecraft spin plane. The instrument also measures positive ions (nominally protons) on two sets of energy channels, LoP and HiP, which range from approximately 75 keV to approximately 200 MeV. The nominal energy channels for electrons are the same for all CPA instruments. However, the nominal proton energy channels are different for each satellite.
Chapter 2 – Spacecraft and instrumentation

2.2.2 SOPA INSTRUMENT

The Synchronous Orbit Particle Analyzers detector measures electrons from 50 keV to approximately 26 MeV, ions from 50 keV up, and heavier ions in various channels in the MeV range. The nominal energy levels for electrons, protons, and heavy ions are the same for all SOPA detectors.

Table 2.2-1 LANL/CPA electron channels [Reeves, 1994].

<table>
<thead>
<tr>
<th>CPA Electron Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Channel Name</strong></td>
</tr>
<tr>
<td>LoE1</td>
</tr>
<tr>
<td>LoE2</td>
</tr>
<tr>
<td>LoE3</td>
</tr>
<tr>
<td>LoE4</td>
</tr>
<tr>
<td>LoE5</td>
</tr>
<tr>
<td>LoE6</td>
</tr>
<tr>
<td>HiE1</td>
</tr>
<tr>
<td>HiE2</td>
</tr>
<tr>
<td>HiE3</td>
</tr>
<tr>
<td>HiE4</td>
</tr>
<tr>
<td>HiE5</td>
</tr>
<tr>
<td>HiE6</td>
</tr>
</tbody>
</table>

Table 2.2-2 LANL/SOPA electron channels [Reeves, 1994].

<table>
<thead>
<tr>
<th>SOPA Electron Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Channel Name</strong></td>
</tr>
<tr>
<td>E1</td>
</tr>
<tr>
<td>E2</td>
</tr>
<tr>
<td>E3</td>
</tr>
<tr>
<td>E4</td>
</tr>
<tr>
<td>E5</td>
</tr>
<tr>
<td>E6</td>
</tr>
<tr>
<td>E7</td>
</tr>
<tr>
<td>E8</td>
</tr>
<tr>
<td>E9</td>
</tr>
<tr>
<td>E10</td>
</tr>
<tr>
<td>ESP1</td>
</tr>
<tr>
<td>ESP2+3+4</td>
</tr>
<tr>
<td>ESP5+6</td>
</tr>
<tr>
<td>ESP7</td>
</tr>
<tr>
<td>ESP8</td>
</tr>
<tr>
<td>ESP9</td>
</tr>
</tbody>
</table>

2.3 GOES 6 AND 7

The Geostationary Operational Environmental Satellites each carry a Space Environment Monitor (SEM) instrument package. The SEM package provides magnetometer, energetic
particle, and soft X-ray data for GOES environment. Two GOES usually operate simultaneously in Earth’s equatorial plane in geosynchronous orbit and are generally located at or between 75° and 135° West longitude. There have been nine GOES satellites launched to date, up to five were active in orbit during the CRRES epoch, and continuous data from two were available to this study [Wilkinson, 1994].

2.3.1 MAGNETOMETER

The GOES magnetometer instruments (PI: Howard Singer of NOAA) provided three-dimensional measurements of the magnetic field in geostationary space. A twin-fluxgate spinning sensor allowed the Earth’s magnetic field to be described by three mutually perpendicular components: \( H_p \), \( H_e \) and \( H_n \). \( H_p \) is parallel to the satellite spin axis, which is itself perpendicular to the satellite’s orbital plane. \( H_e \) is parallel to the satellite-Earth centre line and points Earthward. \( H_n \) is perpendicular to both \( H_p \) and \( H_e \), and points westward for GOES-1 through 4, and eastward for later spacecraft including 6 and 7. \( H_e \) and \( H_n \) are deconvoluted from the transverse component \( H_t \). Field strength changes as small as 0.2 nT can be measured. The magnetometer samples the field every 0.75 seconds and this is averaged over one minute periods to provide the data used in this study (from Dan Wilkinson at the Solar-Terrestrial Physics Division of the National Geophysical Data Centre, World Data Centre A for Solar-Terrestrial Physics) [Wilkinson, 1994].

2.4 INTERPLANETARY MONITORING PLATFORM (IMP) 8

To study the correlative relationship between solar wind and substorm parameters, as well as the triggering of onsets by changes in the IMF, IMP-8 was used as a solar wind monitor. IMP-8 (IMP-J) was launched by NASA on October 26, 1973 to measure the magnetic fields, plasmas, and energetic charged particles of the Earth’s magnetotail, magnetosheath and the near-Earth solar wind. IMP-8, the last of ten IMP (Interplanetary Monitoring Platform) spacecraft launched in 10 years, continues to operate (as of August 1998) in its near-circular, 38 Earth Radii, 12-day orbit. IMP-8 included in its payload a LANL plasma package and a magnetometer giving all required solar wind diagnostic measurements for this study. IMP-8 spent 7 to 8 days in the solar wind during each of its orbits, and telemetry coverage for the period of CRRES’s lifetime was ~70%. Solar wind data for the period 010890 to 011191 was obtained from NASA Goddard’s web sites [Papitashvili, 1998].
CHAPTER 3 – SUBSTORMS AND PARTICLE INJECTIONS

3.1 CHAPTER OBJECTIVE

To obtain consistent results regarding the morphology of substorm injections it is necessary to unambiguously identify and characterise substorm events from a large amount of in-situ magnetometer and particle data. However, as our model of substorms is incomplete, the physical link and precise order binding substorm onset signatures is unknown. As a result work does not always agree on what common features definitively constitute a substorm, which are subsidiary and what features define its stages of development. A collection of substorm papers can often favour a number of different identifiers and a number differing definitions for onset using measurements ranging from indices, ground magnetometer data, Pi2’s, polar images through to in-situ spacecraft data. It is possible this may have hindered the comparison of results and communication of work, or led to results about different classes of event, substorm or otherwise, being confused. A better method of identifying substorms or the identification of different classes of substorms may well have bearings on the ongoing discussion regarding the proportion of substorms triggered by northward IMF turnings. Few attempts have been made to measure the relative strengths of individual substorm events, which may clarify results further [Russell, 1998] or help in the identification of substorm mechanism(s), as may a more universally used method of identifying events.

This chapter reviews the definition and differentiation of magnetospheric storms and substorms, substorm phenomenology, current theories and the classification criteria used in other research. From this and work with available data sets, criteria are developed (presented in the next chapter) against which to judge events in the CRRES epoch – depending on both magnetic and particle signatures, concluding with a list of substorms and an ordering for further work.

3.2 DYNAMICS OF THE MAGNETOSPHERE

The dipolar terrestrial magnetic field is immersed in and affected by the flow of the solar wind past the Earth. The terrestrial magnetosphere is subject to variations within that wind and it is these variations cause the complex dynamism of the magnetospheric system. At one AU the solar wind is an electrically neutral plasma with a varying mean bulk velocity in the region of 350 km/s to 800 km/s. The plasma also has a changing density and composition, as well as an embedded magnetic field – the Interplanetary Magnetic Field (IMF) – whose magnitude and orientation continually vary. The changes in IMF strength and direction lead to a variable
geometry in the solar-terrestrial magnetic system, allowing the solar wind direct access to polar magnetospheric regions some of the time, and blocking it during others.

The state of direct access of the IMF to magnetospheric regions, or direct coupling, was postulated by Dungey [1961] and is caused by a process termed reconnection. When southward-orientated IMF lines meet the oppositely orientated terrestrial magnetic field the two fields cancel at the magnetopause. At this 'X-line' the IMF line in the north and the northern component of the dipole field line may merge to form one line (this is mirrored for the southern components so in profile the magnetic field lines appear to form an X). This is anchored at one end in the north magnetic pole and at the other in the solar wind. The motion of the end within the solar wind drags the earthward remainder over the polar cap and into the magnetotail, where it reconnects with its southern conjugate mirror-image.

This interaction leads to the entrance of magnetic flux, solar wind particles and energy to the magnetosphere and is the principle energy input that drives magnetospheric dynamics. When the IMF is northward although the fields may couple in different ways, no similar input of flux and energy occurs and no substantial energy source exists for substorms other than that stored in the tail from prior southward periods. Conditions for geomagnetic storms occur when magnetic field line merging leads to sustained, enhanced energy transfer or when the
Chapter 3 – Substorms and particle injections

The magnetosphere is subject to a disturbance such as a pressure pulse from a Coronal Mass Ejection.

Figure 3.2-2 The convection of flux in the magnetosphere during a period of southward interplanetary magnetic field [Kivelson et al., page 243, 1995].

As shown in Figure 3.2-2, flux is reconnected at the subsolar point of the magnetopause and swept backward over the Earth by momentum transfer from the solar wind. Dragging of the field line portion frozen into the solar wind flow pulls the magnetospheric portion along (inset: 1 through 6), with substorm events recirculating flux back to the dayside to close the system (inset: 7 through 9).

Recirculation of flux from the tail to replenish the eroded front magnetopause region is not continuous. Southward IMF loads the tail region with flux until such time as an instability or trigger causes the unstable system to unload flux into the inner magnetosphere in a substorm.
event. The injection of substorm accelerated particles from the tail to the inner magnetosphere contributes to ring current enhancement – the current about the Earth caused by particle drift in the mid to outer magnetosphere. Substorms are an elemental part of geomagnetic storm periods that unload stored energy imparted by the solar wind. They are also independent phenomenon in their own right, occurring in isolation during non-storm times. The exact relationship between storms and substorms has yet to be settled.

3.2.1 GEOMAGNETIC STORMS

3.2.1.1 DESCRIPTION AND DEFINITION

Periods of intense geomagnetic activity can disturb the global geomagnetic field with the contribution of a southward-directed component parallel to the dipole axis. Observations of this phenomenon led to the suggestion and discovery of the ring current, which encircles the Earth and enhances during storm times to induce a global depression of pole-aligned H values. The ring current is a collective name for the circular drift motion of particles about the Earth at distances of approximately 3 to 5 Re, with direction of drift dependent on species charge. It is enhancement of this current for periods of the order of days that leads to the characteristic Dst index (see later) depression that indicates the occurrence of a geomagnetic storm. Storms occur during or after periods of strong prolonged coupling between the solar wind IMF and the magnetosphere or as a result of pressure pulses triggering the unloading of unstably stored tail energy.

The following definition has been proposed by Gonzales et al. [1994]:

\[\text{Storm is an interval of time when sufficiently intense and long-lasting interplanetary convection electric field leads, through a substantial energization in the magnetosphere-ionosphere system [i.e. tail storage rather than directly driven], to an intensified ring current strong enough to exceed some key threshold of the qualifying storm time Dst index.}\]

The electric field in the Gonzales definition is due to the transformation of the southward component of the frozen-in IMF moving with the solar wind, into the planetary frame of reference. For average solar wind velocities, the thresholds and Bz parameters could be defined as in Table 3.2-1.
Table 3.2-1 Typical storm categories.

<table>
<thead>
<tr>
<th>Storm Strength</th>
<th>Dst (nT)</th>
<th>Bz (nT)</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intense</td>
<td>&lt;-100</td>
<td>-10</td>
<td>5 days</td>
</tr>
<tr>
<td>Moderate</td>
<td>-50</td>
<td>-5</td>
<td>1 day</td>
</tr>
<tr>
<td>Small (a typical individual substorm)</td>
<td>-30</td>
<td>-3</td>
<td>2 hours</td>
</tr>
</tbody>
</table>

Storms with Dst of order 100 nT occur almost every month, with 150-300 nT storms occurring several times a year. Only a few times per solar cycle does one exceed 500 nT.

Frequently, storm period commencements are characterised by rapid change in solar wind velocity or density or both, causing an increase in the solar wind dynamic pressure. An increase of dynamic pressure on the magnetopause pushes magnetopause currents closer and strengthens them. These currents induce a field opposing the external IMF and reinforcing the dipole field within the magnetosphere. This leads to the characteristic initial increase in Dst at the start of a storm (Figure 3.2-3). Some time afterwards this is followed by energization of the ring current depressing Dst – the main signature of a storm period. A significant proportion of this will come from substorm injections, although other sources such as the energization of in-situ particle populations may contribute or even be dominant [Grande, 1998]. After a period the rate of energization of the radiation belts is once again exceeded by the loss of particles to charge exchange or pitch angle scattering, leading to a recovery in Dst values. Recovery to pre-storm Dst values typically takes several days.
Chapter 3 – Substorms and particle injections

3.2.1.2 SEASONS

Geomagnetic activity as a whole has a seasonal variability with maxima at the equinoxes, where the solar-terrestrial magnetic system is in its least stable configuration. This is especially true of intense storms, and these also show two peaks within the solar cycle – one ahead or at solar maximum, and the other 2 to 3 years after solar max – seen in the yearly number of sudden storm commencements.

3.2.2 SUBSTORMS

3.2.2.1 DESCRIPTION

The depression of Bz due to ring current reinforcement in geomagnetic storms is often sporadic due to the occurrence of more elementary components of storms exhibiting shorter periods of intense geomagnetic activity. Birkeland used the term “elementary polar magnetic storm” to describe their corresponding polar region manifestations and later Akasofu and Chapman introduced the term substorm for the same phenomenon [Kivelson et al., 1995].

Magnetospheric storms exhibit sequences of substorms and these are crucial for the injection of hot plasma into the magnetosphere, however substorms also appear in isolation from magnetic storms. They are more frequent and shorter lived than storms, often only a few hours apart. They are characterised by widespread and intense auroral disturbances spreading from near-midnight, additional ionospheric current systems/a westward electrojet, bulk flows of plasma in the mid tail, a dipolarisation of the near-Earth magnetic field and an influx of higher energy electrons and protons into the magnetosphere from the tail region. The most visible sign of a substorm on Earth is an increase of the auroral activity in the midnight sector. Quiet auroral arcs are often seen there, but following the onset of a substorm, they intensify, and rapidly move poleward. Large localised magnetic disturbances are also observed, up to 1000nT, about 2% of the field in the auroral zone. A worldwide geomagnetic storm may only cause a disturbance of 100nT, weaker as its ring current source is more distant. Some electric currents associated with the substorms are inside the ionosphere and flow at only 120km above magnetometer stations.

Satellites in geosynchronous orbit observe other magnetospheric changes. Those satellites near local midnight at the start of the growth phase see the magnetic field strength drop by up to a half, as the magnetotail is stretched by reconfigurations and enhancements of the magnetospheric current systems. During later stages further reconfigurations can be seen to reverse this effect, and make the field more dipolar in nature. At onset detectors in geostationary space near midnight register the transition of dense currents of energised ions and
electrons with peak fluxes in the energy range of 5 to 50 keV. Particle populations at energy levels as high as 200 to 300 keV also show sharp increases in fluxes as pulses of particles injected in the mid tail drift around the magnetosphere [Reeves, 1997]. Further out in the plasma sheet fast flows of particles are often seen, typically with tailward speeds from 100 to 1000 km/s. These particles have higher than normal energies and are accompanied by rapid and erratic magnetic fields changes. These features, plasmoids, are bundles of magnetic flux and particles, which are ejected from the magnetosphere to maintain the flux equilibrium within the magnetospheric system.

The features of each substorm often have their own unique characteristics and some substorms never 'breakup' to full strength and these are termed pseudobreakups – although some believe these should be regarded as full, but low intensity, substorms in their own right.

3.2.2.2 ENERGY EXCHANGES WITH THE SOLAR WIND

An immense amount of pent-up magnetotail energy is released by substorms, of the order of 4 x 10^{15} joules [Kivelson et al., 1995]. This energy is sourced from magnetospheric reconnection with the solar wind IMF and field line convection. Frozen-in field line sections in the solar wind are swept along dragging magnetospheric sections over the polar caps. The convection of the magnetic field lines leads to magnetic flux being drawn into the tail lobes, leading to their expansion and the storage of magnetic potential energy. On the nightside of the magnetosphere around 100-200 Re down-tail the convected field lines once again reconnect, leaving a section free to travel with the solar wind as before, and importantly, a distended section containing solar wind plasma and magnetic flux energy from the solar wind. It is widely accepted that the expanded lobes provide the main buffer of energy that power substorms. It has been observed by Stern [1990] that after a long quiet period when the IMF turns suddenly southward, one can see this reservoir of energy charge up as the tail field intensifies and magnetic field lines in synchronous orbit become stretched increasingly tailward. This effect has also been observed in this work. Eventually under the long term condition of system equilibrium, some of the magnetic flux added to the tail must be returned to the front of the magnetosphere so the process can continue indefinitely. Substorms fulfil this role, with injection of energy into the magnetosphere occurring as a consequence.
Chapter 3 – Substorms and particle injections

THE SUBSTORM ENERGY DISSIPATION SEQUENCE

SOLAR WIND ENERGY INPUT

SOUTHWARD IMF

STORAGE

CONVECTIVE DISSIPATION

"DRIVEN PROCESS" (GLOBAL)

EXPLOSIVE DISSIPATION

ENERGETIC PARTICLE ACCELERATION

PLASMA SHEET HEATING

JOULE HEATING

PARTICLE PRECIPITATION

“UNLOADING PROCESS”

RING CURRENT INJECTION

PLASMOID FORMATION

AURORAL LUMINOSITY

KILOMETRIC RADIATION

RETURN TO SOLAR WIND

MAGNETOTAIL

IONOSPHERE

Figure 3.2-4 The flow of energy from the solar wind into and through the magnetosphere-ionosphere system. [Baker et al., J. Geophys. Res., June 1996].

The immediate effects of solar wind energy input, ionospheric polar currents, are known as ‘directly driven’ and are caused by solar wind reconnection and the convection of field lines across the cusp regions. These can make significant contributions to the AE index but have no direct relation to the effects associated with substorms. The effects caused by the unloading of energy stored in the magnetotail from convective periods are known as ‘indirectly driven’, and include the substorm current wedge (SCW), field dipolarisation, plasmoid ejection, particle injection and auroral breakup events associated with substorms.

3.2.2.3 PHASES

Substorms are typically divided into three phases: the growth phase, expansion phase and recovery phase, with a substorm onset being the transition from growth to expansion phases. The boundaries between phases are often vague and not rigorously defined – especially during strong or complex activity, although examination of near-midnight geostationary satellite magnetograms can show good phase demarcation for growth and expansion phases.
Chapter 3 - Substorms and particle injections

GROWTH PHASE

The growth phase begins with the IMF turning to the south or already south, connecting the magnetosphere to interplanetary field lines and transferring solar wind energy to the magnetosphere via reconnection. The convection electric field is enhanced during this process. The phase typically lasts for around one hour (geostationary magnetograms indicate this can be increased or decreased by a factor of ten either way). During this time the nightside field lines are stretched tailward by an increased cross-tail current [Kaufmann, 1987], the near-tail nightside magnetic field weakens in the equatorial region with the H component of the magnetic field decreasing in magnitude, and lobe field strength increases. This results in the overall effect of the field becoming more stretched and non-dipolar in configuration.

A thin current sheet less than ~0.1 \( R_e \) in width forms just tailward of the dipole-like field lines between 6-15 Earth-radii, supporting the stretching of the magnetotail. The morphology of trapped particles change as convection increases – notably an Earthward displacement of particles drifting along constant B occurs accompanied by corresponding decreases in flux in some areas or total flux dropouts as sometimes seen around midnight by the LANL geostationary spacecraft. Typically the phase can last minutes or hours depending on the rate of energy input from the solar wind and the unknown mechanisms involved in triggering an onset.

EXPANSION PHASE

This phase lasts typically around 30 minutes (although it can last as little as ten minutes or possibly as long as several hours in stuttered multiple onsets) and is characterised as the unloading of magnetic flux accrued in the growth phase. The term onset is used to define the start of this phase. Onset may be triggered by changes in the IMF and solar wind, or may be governed by a process internal to the magnetosphere. Many define the onset of a substorm as the time of reception of Pi2 pulsation bursts – the appearance of which signifies that onset is impulsive in nature. Pi2 signals are magnetic disturbances which appear as damped wave trains with frequencies between 0.1 to 0.007 Hz at L < 5 and an amplitude varying from ~100nT in the source region to fractions of nanoteslas in low latitudes. It is possible that several Pi2 pulse trains may be associated with each substorm intensification. A Pi2 onset can give a substorm onset time defined to within a minute, although low frequency and low amplitude waves can be difficult to detect.

The growth phase distension of the magnetic field stops abruptly with the field rapidly returning to a dipolar configuration during expansion, and releasing energy stored in the magnetic field. Injections of electric field accelerated (tens to hundreds of keV) particles are seen close to geosynchronous orbit and between -4.3 to -15 \( R_e \) in the tail region [Friedel,
Simultaneous high energy (16-80 keV) field aligned electron beams have sometimes been seen at geosynchronous orbit for short durations of one and a half minutes, from four minutes after onset as defined by Pi2 signatures [Kremser et al., 1987]. Intense fluxes of field aligned electrons have been observed immediately after field dipolarisation, resulting in the injection of significant fluxes of electrons into trapped orbits in the 1-10keV range [Johnstone et al., 1996].

Some observations and models indicate that a ‘near-Earth neutral line’ is formed beyond 15 Re - a magnetically neutral point where stretched field lines reconnect – although this is a point of controversy with some researchers believing other instabilities to cause substorms, and some believing the NENL to be closer to the Earth. Bundles of plasma and magnetic flux have been detected in the far tail and are attributed as plasmoids, circular flux/particle structures which are ejected down tail in response to the NENL forming and the inner magnetic field collapsing inwards. Plasmoids are formed as closed loops or three-dimensional helixes of flux between the distant neutral line some 100-200 Re tailwards, and the postulated NENL at around 15 to 30 Re tailwards or closer, and are then released into the solar wind flow.

Auroral brightening expands from the southernmost arc indicating a mapping to activity in the near-Earth plasma sheet regions. After initial auroral brightening the region of active aurora expands poleward and westwards at speeds of the order of 1 km/s with the westward travelling aurora known as the ‘westward travelling surge’. An enhanced westward ionospheric current causing a large negative bay in the ground magnetic field accompanies this aurora and is known as the westward electrojet. Its expansion continues to the aurora’s most poleward location – maybe relating to the substorm current wedge propagating tailward. Consistent observations of the reduced cross-tail current region expanding tailward and in longitude have been made. The tailward propagation has been seen to be around 200 km/s at r ~ 10 to 20 Re which maps to the 1 km/s speeds seen in the ionosphere.

**RECOVERY PHASE**

This lasts for around an hour, when the magnetosphere gradually returns to its pre-substorm quiet state or ‘ground state’. This is however the most poorly defined phase as other growth phases often interrupt any progress to a ground state, and the magnetosphere has no good indicator of a ground state ever being reached. Continued southward IMF forcing of the system can make the recovery phase impossible to identify. The proposed near-Earth neutral line may retreat tailward at the end of the expansion phase as recovery begins. It may be at this stage that the plasmoid is finally ejected and the near Earth neutral line becomes the distant neutral line, with the magnetospheric field relaxing to a tightly dipolarised form.
3.2.3 EFFECTS

The injection of hot particles into geostationary space around local midnight can cause spacecraft operational difficulties. These particles can charge satellite surfaces negatively to hundreds or thousands of volts, causing flashovers as differentially charged surfaces reach breakdown potential. High-energy particles can penetrate deep within spacecraft, building up and charging dielectric materials within to high voltages with similar internal results. There are over 220 spacecraft in geostationary slots — approximately $40 billion of space based infrastructure, with a vast number of satellites currently or having just been launched to form communications constellations in medium Earth orbits. In 1992 two Telesat Canada communication satellites failed, with these failures being attributed to 'space weather' effects. Anik E-1 and E-2 were simultaneously damaged by an unusually strong electromagnetic storm after a period of deep-dielectric charging of spacecraft insulator material by an enhanced flux of high-energy electrons. The resultant discharge may have blown a transmitter associated with the control of a gyroscopic stabilisation wheel (mounted outside the Faraday's cage of the spacecraft chassis). The Aniks were used by the Canadian Broadcasting Corporation, some US channels, businesses for data transmission and the countries largest telephone company Bell Canada. The loss of the satellites disrupted telephone, television and data transmission services to many cut-off regions of Canadian territory. Later Anik E-1 was partially recovered, but the second remained out of control.

Minor interference with magnetic navigation instruments can be caused during the strongest storms as the magnetic field reacts — with this effect being how the magnetic field-auroral connection was initially made. Regions at high magnetic latitudes and with long cable runs are vulnerable to transient induced currents in electric power lines, telephone lines and north-south pipelines. These induced currents can cause system failures on Earth. Eddy currents caused within transformers can cause meltdowns, and unearthed pipeline currents can cause enhancements to rusting rates. Voltages across Atlantic fibre-optic connections can reach up to 700 volts requiring special precautions to be taken at terminal stations. Substorm associated intense auroral activity and changes to the ionosphere can cause dropouts and changes in the paths of high-frequency communications, increase degradation of radio signals at higher-frequencies and disrupt over-the-horizon radar systems.

3.3 SUBSTORM THEORY

3.3.1 THE SUBSTORM CURRENT WEDGE

Part of the near-Earth cross-tail current disappears as the interrupted current closes via the ionosphere, creating the substorm current wedge (SCW) [McPherron et al., 1973]. A neutral
sheet current normally crosses the magnetotail from east to west. Either the formation of the NENL or an increase in tail resistivity diverts this, and closes the enhanced westward ionospheric current flow. In the NENL model the disruption is caused by the generation of a current opposing electric field associated with the collapse of the magnetic field to a dipolar configuration. This diverts the cross tail current as shown in Figure 3.3-1. At onset current flowing westward across the inner edge of the tail current is diverted along field lines to the ionosphere, travels along of the westward electrojet, and returns to the tail current at a point to the west.

Field aligned currents within the SCW have densities well above $10^6$ A/m², requiring downward electron acceleration by field aligned potential drops. These electrons form active expansion phase auroral displays. The wedge expands longitudinally and radially (mainly tailward). Short period irregular Pi2 pulsations are associated with the development of the substorm current wedge and Fermi acceleration of electrons is expected to occur as the wedge develops. The concept of a substorm current wedge is reinforced by ground magnetic perturbations consistent with magnetic field-aligned currents that are directed downward after midnight and upward before midnight.

Figure 3.3-1 Schematic of the substorm current wedge (SCW) [McPherron et al., 1973].
Chapter 3 – Substorms and particle injections

3.3.2 PROPOSED MODELS

The nature of the sequence of events that constitute a substorm and their initiation continue to be the subject of controversy and debate. There is agreement across all models that solar wind energy is input to the magnetospheric system during periods of southward IMF, that some is immediately manifested in magnetospheric activity and that some is stored for later explosive dissipation in substorms as shown in Figure 3.2-4. Substorm models differ however on the nature of the onset that initiates the explosive unloading of energy, and the timing and location of the key events involved.

Many models and variants of models exist for substorms. None currently satisfy the research community fully. Two models with sizeable camps of support are presented here, along with Lyons' triggering work with a view to solar wind work in a later chapter.

3.3.2.1 CURRENT SHEET DISRUPTION MODEL

In the Current Sheet Disruption model [Lui, 1990, 1991] the cross tail current within the plasma sheet develops an instability which forces its interruption and redirection into the ionosphere via field aligned currents, forming the SCW. The cross-tail current is provided by the adiabatic curvature drift of ~1 keV electrons and as the current sheet thins to around one ion gyroradius non-adiabatic ions are assumed to take over as the major current carriers, prior to current disruption. The azimuthal drift of ions into the plasma sheet supplies the current carriers, which then move from dawn to dusk in the current sheet. It may be that onset is caused by the disruption of the current triggered by an insufficient supply rate of ions for the current [Mitchell et al., 1990]. Alternative reasons are postulated for the current disruption, including Lui's own model where an increase in the resistance of the current sheet is caused by the interaction of counter-streaming particles. Whatever the cause of the interruption of the cross tail current, the high inductance of the tail circuit requires a current to continue to flow and the current diverts into the path of least resistance, the ionosphere, causing the SCW, dipolarisation of the magnetic field and subsequent substorm phenomenon. Observations have been made indicating current-sheet disruption occurs close to synchronous orbit, and expands radially outwards into the tail. This model places the onset region closer than in the NENL model and reconnection has only a minor role on this model, perhaps only in the creation of the plasmoid.

3.3.2.2 NEAR EARTH NEUTRAL LINE (NENL)

The Near-Earth Neutral Line (NENL) model [McPherron et al., 1973] postulates that an X-line forms near Earth in the plasma sheet to act as the substorm onset event.
Field line convection and reconnection at the distant X-line in the far tail leads to an expanded magnetotail, thinned plasma sheet and contributes to a rapid increase of tail flux. Flux erosion of the dayside cross-section results in the compression of the cross sectional area of the magnetotail, further increasing tail field magnitude after the effects of adding flux. As the plasma sheet begins to thin, the tail currents strengthen and move inwards towards the Earth, causing field lines in the near tail to become more stretched, reducing field strength closer to Earth at synchronous orbit. This constitutes the growth phase of the substorm.

As shown in Figure 3.3-2, the upper panel of the diagram shows the current system changes during the growth phase. The lower panel of the diagram shows sites important to the magnetic reconfigurations associated with reconnection and the explosive onset event.

Figure 3.3-2 Events leading to a substorm under the NENL model [Kivelson et al., 1995].
Chapter 3 – Substorms and particle injections

The onset of the substorm occurs when the vertical component of the magnetic field becomes sufficiently small that ions on the cross tail current no longer behave adiabatically. Field aligned currents flow into and out of the ionosphere as a result, with a current into the ionosphere post-midnight and a current out pre-midnight. The model anticipates the existence of the westward electrojet and field-aligned currents to connect the circuit. At the end of the growth phase reconnection commences in the central plasma sheet at a near-Earth X-line. The line’s formation may be due to tearing instability or another non-ideal magnetohydrodynamic mechanism in the thinned current sheet. Magnetic reconnection then occurs between oppositely directed field lines above and below the middle of the plasma sheet. The X-line, at 10 to 15 \( R_E \), acts as a point where the magnetic tension distorting the field line is lost and the field may begin dipolarisation with a resultant plasmoid being ejected out of the back of the magnetosphere. At first reconnection proceeds to cut the field lines of the central plasma sheet slowly, with a more dipolar field line forming Earthwards and a O-type plasmoid field line tailward. The process thins the current sheet, leading in to an exponentially increasing rate of reconnection and the explosive characteristics of a substorm event. Quenching occurs if the reconnection fails to sever the final closed field line resulting in a pseudo-breakup. If the final field line breaks, a full substorm expansion phase occurs.

![Diagram showing plasmoid formation between the NENL and DNLL](image)

The magnetic field accelerates particles with the Lorentz electric fields associated with the rapid collapse of the field, injecting particles radially towards the Earth in a characteristic injection event [Li et al., 1998]. The NENL propagates away from the Earth, with the plasma sheet re-expanding to a stable size in its wake. As the magnetosphere recovers from the event, the neutral line migrates to the far magnetotail to form the distant neutral line for reconnection.
Chapter 3 — Substorms and particle injections

The NENL model conflicts with observations that the signatures of a neutral line, the most crucial element of the model, are typically not found Earthward of 20 \( R_E \). Tailward directed flows that would be expected tailward of a NENL are seldom seen inside of 19 \( R_E \) \cite{Baumjohann,1989}, although Kettmann \cite{Kettmann,1990} sees tailward ion streams occasionally near 16 \( R_E \) with an increasing probability of observation with increasing distance.

3.3.2.3 LYONS TRIGGERING MODEL \cite{Lyons,1995}

Lyons \cite{Lyons,1995} proposes a substorm model where the onset mechanism is a reduction in the large-scale electric field from the solar wind following a \( \geq \)30-minute period growth phase of enhanced electric field. Northward turnings of the IMF or a reduction in the magnitude of its Y component can cause the reduction in electric field magnitude. The reduction disrupts the inward motion and energization of particles that occurs during the growth phase and leads to the formation of the SCW and auroral displays. The SCW results from the magnetic drift of ions and a large azimuthal gradient in mean particle energy that is expected to develop near magnetic midnight during the growth phase, it most likely initiated near the radial distance of the peak particle pressure distribution (\( \sim 6-10 \ R_E \)), propagating tailward.

Growth starts with cross tail current increase caused by the increase of plasma pressure in the region. Particle access is facilitated by electric field drift from the tail to Earth, with the field being generated by a potential drop from the solar wind embedded IMF. It takes 30-45 minutes for the enhanced convection electric field to bring particles to 7 \( R_E \) from 20 to 40 \( R_E \), implying that the plasma pressures near Earth should continue to increase for 30-45 minutes following an increase in the electric field. If an enhanced electric field remained for longer than 30-45 minutes, the rate of cross tail current growth may decline. The cross tail current increases with the increase in plasma pressure, and Lyons model anticipates the expansion phase to begin with the reduction of plasma pressure within a restricted-longitude region forming the interior of the substorm current wedge. The onset event — the reduction of the electric field — causes the ions drifting inwards on horseshoe-shaped orbits about the Earth to adopt circular orbits. It is anticipated that a large azimuthal temperature gradient near midnight, and the new drift track causes a spatial separation of the westward drifting ions in the near midnight region. This is responsible for a significant azimuthal pressure change which the cross tail current circumnavigates by diverting into the ionosphere via field aligned currents, forming the SCW.

Within the SCW the field dipolarises and is associated with a large short-lived induced electric field just Earthward of a particle pressure peak caused by the growth phase. This results in particle energization and inward motion as the dipolarisation carries particles from the high-
pressure region to the electric field and they are accelerated. This model therefore anticipates that particle injection occurs Earthward of the current reduction region of the model.

3.3.3 RESOLUTION OF SUBSTORM ISSUES BY PARTICLE TRACING

A number of issues in substorm mechanics may be brought closer to resolution by particle tracing. Amongst the contentious features models still disagree over are the location of the particle acceleration region, the particle acceleration mechanism and the timing of model features with respect to other onset events including particle injection. Better information regarding the substorm injection region may assist in determining the particle acceleration mechanism.

The location of the particle injection region has been generalised before using particle tracing. A number of papers applying tracing techniques to individual events have been written [amongst others: Reeves et al., 1990, 1992; Friedel et al., 1996]. In Reeves [1990], the authors investigated a substorm using multiple spacecraft (the fleet of geosynchronous spacecraft equipped with LANL CPA/SOPA detectors). Using a drift model without electric fields it was shown that electrons and ions injected during this substorm were injected in a region covering a 90-degree sector centred on midnight. The observations were considered in terms of a standard model of substorm injections – injection occurs in a limited spatial region around local midnight, the injection is impulsive, and ions plus electrons of all energies appear simultaneously.

By determining injection regions using more sophisticated field models for a larger number of substorms will build on the work to perhaps gain a better insight into the substorm mechanism. Does the injection region vary substantially from substorm to substorm or is it a relatively fixed in geomagnetic space? If it is relatively fixed, where is it? If it varies, what governs the location of injection and what are its bounds?

3.4 CHARACTERISATION OF THE SUBSTORM ENVIRONMENT

Identification of substorms requires an exploration of the effects of substorm events, and the derivation of a set of criteria against which to determine if observations constitute a substorm. The following section reviews commonly used descriptions as to what manifestations in data constitute substorm events (biased towards magnetospheric spacecraft data), with a view to the following chapter’s work describing the set of criteria used in this work to establish an event’s credentials as a substorm.
3.4.1 EVOLUTION OF FIELD CONFIGURATIONS

3.4.1.1 MAGNETIC FIELD

During a substorm growth phase the current sheet thins and the cross tail current increases and moves inward, leading to a tailward stretching of field lines in the near-Earth tail. The near-tail magnetic field weakens in the equatorial region where the cross tail current is not present and the lobe field strength increases as flux is added to the magnetotail [Pulkkinen, 1991]. At geosynchronous orbit and magnetic latitudes of up to ~10 degrees the magnetic field changes are characterised by directional changes of the field as it becomes more tail-like. Occasionally during substorm periods the magnetic field can be seen to become parallel to the magnetic equator.

Short duration low frequency field oscillations are seen during onset associated with, although not coincident with, field collapse and injection events. These are Pi2 oscillations. Some observations and models indicate a near-Earth neutral line is formed outside X = -15 Re during the expansion phase, and a substorm current wedge closes the cross tail current via the ionosphere, removing the cross tail current which distorted the magnetic field tailward during growth. Regardless of its cause, a dipolarisation of field lines occurs during expansion with the removal of the cross tail current and the thickening of the current sheet [Pulkkinen, 1994]. During recovery the plasma sheet is observed to rapidly thicken with hot plasma in the mid-tail region, although the new plasma does not carry as much current as the cooler plasma previously in the sheet, and the cross tail current recovers with more resistance to subsequent re-stretching of the tail.

3.4.1.2 ELECTRIC FIELD

Comparatively little work has been done to model the electric field development during substorms as has been for magnetic fields. Post onset magnetospheric electric fields have a short-lived spiked component of several tens of mV/m, or regular pulses of 1-10 mV/m [Pedersen, 1994] superimposed on the background field. Studying data from the electric field instrument on CRRES for fifty substorm events showed results similar to Pedersen[1994]. High frequency disturbances commencing at onset were apparent in a limited number of events and would have made good onset indicators, although noise dominated and made substorm signatures impossible to identify in the majority of cases. It should be noted however that this data was partially reconstructed from magnetometer data using E.B = 0 and hence may have shown such onset features due to disturbances in the magnetic field.
Chapter 3 – Substorms and particle injections

From the work of Birn et al. [1997, 1998] and Li et al. [1998] time-dependent tail electric fields may be shown to be able to betatron-accelerate test particles to reproduce the major phenomenology associated with particle injections. From these and observations [Rowland, 1998] the major driver behind acceleration, and the morphology of the injection region may be these transient electric fields in the magnetic equatorial plane associated with the impulsive dipolarisation of the magnetic field.

3.4.2 SUBSTORM PLASMA PARTICLE ENVIRONMENT

With the detection of magnetic-field dipolarisations during substorm onsets, a simultaneous increase in the flux of energetic particles suddenly occurs [Deforest et al., 1971; Sauvaud et al., 1980; Baker, 1984; Williams et al., 1990]. Such a substorm related flux increase is denoted as a particle injection. The injection of energetic particles into the middle magnetosphere is a characteristic signature of a magnetospheric substorm. It is commonly believed that the injections are caused by the energization of particles in the midnight region of the near-Earth magnetotail [Pfitzer et al., 1969; Barfield et al., 1977; Moore et al., 1981; Mauk, 1986].

3.4.2.1 PRE-INJECTION FLUX DROPOUTS

Prior to the injection, a broad decrease in fluxes may be seen associated with the stretching of the field lines in the tail, perhaps due to the earthward motion of particle trapping boundaries and particle trajectories on lines of constant-B. More severe particle flux dropouts can occur where fluxes drop by orders of magnitude, with the greatest decreases at higher energies. Near local midnight a substorm can be characterised typically by a drop out or decline in the flux of energetic particles during the growth phase [Bogott et al., 1973; Rostoker et al., 1975; Baker et al., 1979; Sauvaud et al., 1996].

A number of substorms exhibit a total flux dropout in the nighttime sectors before onset. Out of 54 candidate substorm events used in preliminary work, nine had in-situ measurements in regions of low fluxes recorded between 2100 and 0600 LT, just prior to injection events. There are some instances of partial recovery of fluxes prior to the main injection, with some evidence of small injection events accompanying these recoveries. Sauvaud et al. [1996] investigated dropouts and argued that their cause was the betatron acceleration caused by the tailward distortion of the magnetotail. They first noted that during one dropout event recorded by AMPTE/CCE close to midnight at around X = -8.5 Re, the proton flux decrease for lower energies (35 – 47 keV) was around one magnitude, whereas the flux decrease for higher energies (211-399 keV) was nearer three orders of magnitude. This was accompanied by an increase in magnetic field magnitude consistent with an intensification of the cross-tail current during growth phase. An induced electric field caused by the stretching of the field lines was
modelled causing drift-betatron deceleration of particles. The flux profiles at 6.6 \( R_E \) produced by the model exhibited similar large magnitude flux decreases for higher energies, and lower flux decreases for lower energies.

### 3.4.2.2 INJECTION CHARACTERISTICS

Injections occur in a limited spatial region around local midnight, and it is often assumed that the injection is impulsive, and both charge species appear simultaneously. Particle analysers generally observe a number of discrete energy bands referred to as channels. Within channels injections appear as a pulse of particles with a distinct onset, an abrupt rise in count rates, a peak and a decline \cite{Deforest et al., 1971; Mauk, 1987, Reeves et al., 1990}. On platforms away from midnight, particle injections reach analysers in higher energies channels first, with lower energy channels showing injection enhancements later. This is termed velocity dispersion and is a consequence of gradient-curvature drift speed being proportional to energy, and causes a coherent pulse of mixed-energy, mixed-pitch-angle particles to disperse in space (and time as seen at the detector). For velocity dispersion to be observed between energies, the distance between sensor and injection point is required to be large enough to manifest itself as a significant timing difference in the resolution of the instrument. It is possible to determine approximate injection times (and hence distance to injection point) by interpolating arrival time as a function of \( 1/\text{energy} \), then determining model arrival time for a particle of near-infinite energy. Rough calculations of curvature and gradient drifts speeds using an idealised dipolar magnetic field can give distances to injection points. Some particle signatures are dispersionless though – indicating they have been observed close to or inside the acceleration regions.

Within energy channels away from injection regions, higher-energies and higher-pitch-angles in the band arrive first, slowly pushing flux readings higher, followed by the highest fluxes sometime later and a tail-off of lower energy, lower pitch angle particles lagging behind their faster counterparts. The pulse width of flux increases can be interpreted as the time it takes the lowest energy particles in the band to traverse the injection region \cite{Reeves et al., 1990}.

Some substorms can appear to have multiple onsets with around 15 minutes between the particle injections. These secondary peaks may be associated with westward expansions of the substorm current wedge, and these expansions may be associated with new dipolarisations in the magnetosphere, each occurring westward of the previous dipolarisation, or serial initiation and quenching of a single event that fails to reach some threshold. Each dipolarisation (the stop-start characteristic of multiple onsets/pseudo break-ups is seen magnetically as well) results in a separate pulse of energetic particles near geosynchronous orbit.
A second source of more longer time-scale multiple peaks in the energetic particle fluxes are drift echoes \cite{Lanzerotti1967, Belian1978} caused by the repeated azimuthal drifting of pulses of energetic particles around the Earth. Discrimination of these features from initial injections is possible due to the pronounced velocity dispersions associated with the process. High-energy particles that have been drifting a long time arrive well before their lower energy associates. Visual inspections of velocity dispersion features eliminate the majority of such echoes from consideration, especially if the precursor injection was observed, and help to identify events. Few drift echoes were observed in this work as dispersion and fresh activity subsume electron injection-pulse signatures within a period of order of one orbit. Proton signatures disperse on a much shorter time scale, with pulses often not apparent on detectors within half an orbit.

### 3.4.2.3 INJECTION ENERGY RANGE

Although a commonly quoted range for injections is 30 to 300 keV, often no definite upper bounds are placed on particle injection energy ranges as the extent of flux enhancement reaches and probably exceeds the energy limits of many detectors. It is clear that as a function of energy, the flux enhancement probably peaks between 43 to 135 keV, tailing off either side of this peak. Baker et al. \cite{Baker1982} reports several injection spikes over the 430 to 630 keV range during some substorms. There is no evidence of a sharp cut-off in the energies to which particles are accelerated.

Szita et al. \cite{Szita1993} used the SEM-2 instrument on Meteosat P2 to perform a superimposed epoch analysis on electron flux enhancement events, over an energy range from 43 keV to 300 keV in five channels. Assuming an unknown, but significant proportion of these events are substorms, this yields indications on the general energy range of substorm particles:

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>Notes</th>
</tr>
</thead>
</table>
| 43 to 60 keV  | Significant peak $1.15 \times 10^6 \text{cm}^2\text{sr}^{-1}\text{keV}^{-1}$  
(3.0x higher than T-5 hours) |
| 60 to 90 keV  | Significant peak $8.5 \times 10^5 \text{cm}^2\text{sr}^{-1}\text{keV}^{-1}$  
(3.4x higher than T-5 hours) |
| 90 to 135 keV | Small peak $3 \times 10^4 \text{cm}^2\text{sr}^{-1}\text{keV}^{-1}$  
(3.0x higher than T-5 hours) |
| 135 to 202 keV| Small peak $1 \times 10^4 \text{cm}^2\text{sr}^{-1}\text{keV}^{-1}$  
(2.0x higher than T-5 hours) |
| 202 to 300 keV| No significant change in log (flux), although an Enhancement is apparent |

Table 3.4-1 Magnitude of superimposed electron flux enhancements over energy, Szita et al. \cite{Szita1993}.
Geostationary studies tend to be prejudiced against the higher energy signatures as shell splitting disproportionately effects high-energy fluxes and can partially remove them from geostationary space. Studying individual injections in the LANL data, the higher energy injections in the 200-300 keV energy range are quite distinct when nearer to midnight. The larger the distance from injection however, the more shell splitting has occurred to produce a similar reduction in the high-energy flux increase as seen above. Analysis of the set of 187 injections identified in this thesis results in energy range profiles that are consistent with Szita et al. [1993] when allowance is made for the log versus linear differences in the two work’s comparisons. In this work, for each injection where a coherent injection signature could be seen by a LANL spacecraft, the pre-injection minima and post-injection maxima flux levels were fitted with a spline function over energy. The maximum energy of an injection was defined as the lowest energy where the maxima spline function flux was less than 5% above the minima spline function flux. This yielded projected highest energies of injection for each event. A histogram of these amounts is presented in Figure 3.4-1.

![Histogram of projected maximum energies for 187 particle injections (E_{max})](image)

Figure 3.4-1 Maximum projected energies injected during substorms

The figure shows that although in some observations substorm injection spectra tail-off before 150 keV, the majority show spectra tail-ends between 150 to 400 keV. A few injections show maximum energies of particle spectra up to 600 keV, with the distribution mode between 350 and 400 keV. It should be noted that this also would be subject to shell splitting effects however – artificially reducing the upper energy cut-off in many cases and indicating the true distribution probably has a higher mode value.
The same LANL measurements show flux increases from 50 keV to 400 keV for ions during particle injections at onset.

### 3.4.2.4 INJECTION REGIONS

Various studies [Reeves et al., 1990, 1991, 1992; Boscher et al., 1996] have placed the injection regions for different substorms around midnight with a range of estimates for their extent. One work finds multiple injection regions associated with separate peaks in the injection signature. It is likely that injections enter the magnetosphere through various nighttime longitudes with regions varying from substorm to substorm. Particles, either dispersed or non-dispersed injection pulses, are most often seen at geosynchronous altitudes but have been observed at orbital distances between $X = -4.3$ to $-15 R_e$.

**REEVES ET AL., 1990**

In Reeves et al. [1990] the authors investigated the substorm region and particle drifts for an event on February 3rd 1983 with three geostationary spacecraft. The event was not part of a multiple onset event but an isolated substorm. The observations were considered in terms of a 'standard model' of substorm injections – injection occurs in a limited spatial region around local midnight, the injections are impulsive, and ions plus electrons of all energies appear simultaneously. The spacecraft observed dispersed signatures for the injection and the particles were given pitch angles of $45^\circ$, which gave good resultant particle convergence in the tail. Invariant-conserving drift shells were then determined and the angular drift velocity at each field line on the drift shell was calculated by numerically integrating the analytical expression for the bounce averaged drift velocity along a model field line [Roederer, 1970]. This tool was used to trace the observed injection signatures particles back from satellite observation along drift shells to convergence point – the assumed particle injection point. Proton injection positions determined the western edge of the injection region, and electron injection positions the eastern edge. The area indicated was $90^\circ$ wide centred on midnight.

Good agreement was found with the western boundary of the region – the three sets of proton traces from three separate spacecraft yielded injection sites within a few degrees of each other. The electron injection boundaries, however, were spread by nearly three hours of local time. This may have been due to the absence of electric fields or the lack of a relativistic treatment in the tracing code, or the lack of solar wind information and the subsequent inaccuracy regarding the exact state of the bow-side magnetic field. It may also be the case that the lower energy range slower electrons may have been subjected to more changes in the magnetic field or other dispersive effects. Also, it was noted that the model electron drifts were consistently too slow.
in comparison with measurements – maybe due to the wrong choice of pitch angles (45° was found to be good for ions, but a value of 90° maybe more appropriate for electrons).

The time for lowest-energy-particle-of-channel traversal of the 90° of injection region was compared with the timing derived from the initial pulse width. Initial pulse widths were however larger than calculated injection region traverse times would indicate. Reeves et al. [1990] infer this to indicate that injection was not instantaneous, although it could also be interpreted that a range of pitch angle particles were injected, with lower pitch angle particles composing the tail of the pulse.

REEVES ET AL., 1992

In Reeves et al. [1992] an April 24 1979 multi-onset substorm was investigated (further to a CDAW 7 workshop and several in-depth studies of ISEE and ground based data). The substorm examined had three separate injections. Using the same method as the previously described papers, Reeves obtained the easternmost edges of the injection regions. Lack of a proton sensing spacecraft close to the western edge prevented the determination of the western edge of the injection region. The three peaks originated 10 degrees east of midnight, -1 degrees and 0 degrees using an assumed pitch angle of 45 degrees in tracing (a higher pitch angle would have placed them further west). The injection local time extents, the ranges over which particles were injected, were determined using an injection pulse-width analysis method and found to be to be 25 degrees +/- 5, 28 degrees +/- 5, 110 degrees +/- 10 respectively for the three peaks.
Chapter 3 - Substorms and particle injections

**Figure 3.4-2** The longitudinal extents of the three injections seen in Reeves et al. [1992]. The radial extents are arbitrary.

**REEVES ET AL., 1991**

In this paper a substorm of October 16th 1983 was studied using the drift tracing of ion and electron injection signatures, and was found to have an injection region between -48° and -2° longitude (-ve - west).

**3.4.3 EVENT FREQUENCY**

Statistical analysis of substorms in Borovsky et al. [1993] has shown the most probable (mode) time between particle injections, as seen by LANL CPA/SOPA detectors onboard geostationary spacecraft, is $\Delta t = 2.75$ hours. This is interpreted to be the period between cyclically occurring substorms during prolonged southward IMF periods. Statistical analysis of the $\Delta t$ values also finds a probability for the occurrence of individual substorms, with a mean time between
random substorms of 5.74 hours. It is speculated that this random occurrence may be caused by a property of the solar wind that varies randomly with an approximately 5-hour time scale. Roughly half of all substorms have been classified as cyclical substorms, and about half as occurring randomly, with 1530 events occurring per year. Hargreaves [1996] used riometers to detect auroral electrons by measuring their modulation of cosmic radio noise. The paper’s findings include a variation of the frequency of substorms with the inferred speed of the solar wind (as a function of Kp) – indicating frequency varies with $V^2$. Using a typical average solar wind speed of 440 km/s, the derivation yields a frequency of 1300 pa ($\Delta t = 6.75$ hours). The 15 hours prior to each of the 187 substorm events identified in this work were analysed for injections (just using particle signatures) and this yielded the frequency histogram shown in Figure 3.4-3.

In the 15 hours periods prior to each event, 709 injections were identified, resulting in a rate of one injection every 3.96 hours. The average solar wind speed during this sample was 497 km/s, decreasing the comparable figure from Hargreaves[1996] to $\Delta t = 4.76$ hours. Borovsky’s work indicates a lower $\Delta t$, for cyclically occurring substorms. As the 187-injection identification process favoured locating easily differentiated substorms during non-storm times for tracing, this is not seen as contradictory. Borovsky’s comparable statistics was a mean of around one substorm every 5 hours. The three works give a good indication that injections occur with a mean frequency of one every 4 to 5 hours, with known solar wind velocity (energy input) dependence and an increased frequency during storm times.
3.4.4 AE, AU AND AL INDICES

Substorms are associated with enhancements of the auroral ionospheric currents. Enhancement of ionospheric current activity is reflected in the 1-minute resolution AU, AL and AE indices [Davis et al., 1966] and hence these indices can act as indicators of enhanced substorm activity. The Auroral Electrojet (AE) index is obtained from a number of magnetometer stations distributed in local time at northern-hemisphere auroral zone latitudes. For each of the stations the north-south magnetic perturbation, H, is recorded as a function of time. Superposition of these data from all the stations enables a lower bound or maximum negative value for H to be determined – the AL index. Similarly, an upper bound or maximum positive value of H is determined – the AU index. The difference between the two indices, AU-AL, is the AE index.

The dominant features of auroral variations are the transient and irregular occurrence of an eastward current during local afternoon/evening, parallel to the auroral zone and a westward current during the local late evening/early morning. These currents, or electrojets, flow within the low ionosphere and are linked to remote current sources in the magnetosphere through field aligned currents. Physically, the AU index gives a good representation of the maximum magnetic perturbation generated by the eastward electrojet usually found in the afternoon sector. Similarly AL represents the maximum magnetic perturbation generated by the westward electrojet in the morning and midnight sectors. The eastward and westward electrojets appear to fluctuate independently of one another [Rostoker, 1972], so it may be useful to use AL independently for the purposes of identifying substorms.

An averaged profile of AE index development during the development of a substorm can be seen in Figure 3.4-4.
Figure 3.4-4 Average AE index development [Koskinen, 1994].
CHAPTER 4 – IDENTIFICATION OF SUBSTORM EVENTS

4.1 CHAPTER OBJECTIVE

Borovsky et al. [1993] found the mean rate of substorm occurrence was 4.2 per day. Using this figure as a guide would indicate that over the fifteen month lifetime of CRRES around 1900 substorms occurred. This chapter develops criteria against which to identify the observable fraction of those 1900 events. The application of criteria to data results in the selection of 187 candidate substorm events, although this number of events is too high to trace within the time available. A subsequent reduction is applied to further lower the number of events to a manageable amount and maximise results from a limited number of injection traces.

4.2 CRITERIA FOR SUBSTORM IDENTIFICATION IN DATA

One of the driving forces of this work was the availability of CRRES data. This provides a starting point when searching for substorms and considering the use of other data sets: CRRES flew for a 15-month period and provides a defined epoch within which to search for other relevant data sets. A number of data sets are available for that period and we continue below by describing relevant instrument data sets available for that period, discussing their suitability for identifying substorms and the methods used to identify substorms therein.

The data sets readily available for the August 1990 to October 1991 epoch:

- CRRES magnetometer data,
- GOES 6 and 7 magnetometer data,
- CRRES/LEPA particle data,
- CRRES/EPAS particle data,
- LANL/SOPA-CPA particle data,
- Meteosat/SEM-II particle data,
- Ground magnetometer data (including Pi2’s),
- AE, Kp and Dst indices.

For more information on these instruments please see Chapter 2.
4.2.1 CRRES MAGNETOMETER DATA

The magnetometer was active throughout the CRRES mission and gave high-resolution data products in a +/- 45,000 nT range. The data obtained for this work was a set of ASCII Cartesian vector-triples of one-minute resolution. The VDH system is used for the data (H/Z parallel to magnetic dipole axis, +ve north; D/Y perpendicular to radius vector R and Z; V/X +ve east completing the right handed Cartesian system).

Magnetic data products can be used to identify times of enhanced substorm activity by the observation of growth phases contrasting with subsequent dipolarisation signatures. Magnetic field lines are stretched towards the tail and then suddenly recover to a dipolar configuration with resulting pseudo-periodic oscillations in some field components. The tailward stretching of magnetic field lines can be seen as a weakening in the H component of magnetic field data in the midnight tail region, and the dipolarisation as a strengthening of the same. Plotting graphs of $B_{\text{H-Measured}} - B_{\text{H-Model}}$ best show this effect [after Yeoman et al., 1994] and removes the majority of magnetic field structural effects caused by the motion of a satellite through field gradients.

A number of complicating factors cause magnetometer data to be difficult to interpret in isolation however, and the GTO of the CRRES platform further complicates interpretation of this magnetometer’s data set. Systematic errors are often shown in the data, such as spacecraft manoeuvres changing the spin orientation of the satellite and causing regular sinusoidal distortions that are easily discounted although result in long periods of bad data. CRRES magnetometer data is dominated by the dipolar field at low L-shells making its use for magnetospheric diagnostics impossible during a large fraction of each orbit (~2 hours). Its inertially locked orbit makes local time coverage vary on a seasonal basis, with the best (tailward) coverage in the midlife of the CRRES mission. Because of the annual and diurnal changes of the angle between the Earth-Sun line and the geomagnetic dipole axis, the magnetic latitude of CRRES continually varies. This makes interpretation of the magnitude and nature of disturbances difficult to diagnose as each CRRES apogee is in a different magnetic regime, which makes the building of expertise data interpretation difficult. Even with magnetic latitude information available and the Yeoman et al. [1994] $B_{\text{H-Measured}} - B_{\text{H-Model}}$ technique, it is difficult to develop experience in diagnosing the magnetosphere’s state from single-point magnetic measurements.

Some local particle currents in LEPA data appear to coincide with magnetic disturbances that could be interpreted as substorm-like – on a number of orbits there were indications that ion currents were causing dipolarisation-like magnetic field signatures. This leads to a problem
when trying to differentiate between dynamic substorm structures with magnetic signatures, and standing magnetospheric currents that appear dynamic due to the motion of the spacecraft close by or through, as both exhibit some magnetic characteristics. The measurement of magnetic fields in locations other than the plasma particle injection measurements reduces the chances of such effects contaminating an event database. In spite of these difficulties CRRES magnetometer data was used to diagnose a significant number of events. The data was used in parallel to the GOES data below, providing good tail coverage for a significant fraction of time.

4.2.2 GOES 6 AND 7 MAGNETOMETER DATA

The GOES magnetometer data set has similar advantages and limitations for diagnosing magnetospheric substorm states but does not suffer from the limitations of a transfer orbit, nor is it co-located with any of the plasma instruments used to detect injections. The GOES instrumentation provides 0.275 second three-dimensional measurements of the magnetic field at a number of geostationary ring positions in a variety of magnetic local times. There have been nine GOES satellites launched to date and up to five were active in orbit during the CRRES epoch. \cite{Wilkinson et al., 1994}. Due to the geostationary nature of GOES positioning, the magnetic latitudes of the two spacecraft were constant, at a maximum of $10^\circ$ - aiding the interpretation of data.

Minute resolution data from two of the GOES satellites was available for this study. The $B_{Meas} - B_{H-Model}$ technique (above) was again used with this data to locate dipolarisation signatures. The starts and ends of dipolarisation signatures observed in this data set were further used to define growth, expansion and recovery phase timings for each substorm identified.
Figure 4.2-1 Plotting graphs of $B_z$ measured – $B_z$ model show the effects of field loading (stretching) during the growth phase, followed by dipolarisation during expansion [after Yeoman et al., 1994].

Figure 4.2-1, a plot of GOES-6 and GOES-7 data, shows dipolarisation at ~0530 after a prolonged stretching of the field from before 0000. The expansion phase lasted around 15 minutes. Magnetospheric magnetometer data such as this was used to give phase timings for the 187 events identified, and used to adapt Tsyganenko's 1996 field model to substorm conditions.

4.2.3 CRRES LEPA PARTICLE DATA

The CRRES mission’s Low Energy Particle Analyser (LEPA) provided the first full pitch angle coverage for the electronvolt to 28.5 keV range of electrons and ions. LEPA particle data (in mode ten, the predominantly used mode) is categorised into three look directions; field-aligned towards the Earth, field-aligned towards the magnetic equator and perpendicular to the field. This selection occurred in orbit with magnetometer data prior to telemetry download. Particle injections are seen in the data, predominantly in the 90-degrees look-direction, although attributing them as substorms without corroborating data is difficult due to their large velocity dispersions and delays which often merge them with other injections. Many injections however occur without any dispersion and can clearly be seen down to sub-keV ranges. Injection event velocity dispersion fronts can be seen in the data, although the low energy range of the LEPA instrument often make drift echoes difficult to recognise prior to degradation of the injection pulse (the drift periods involved are 2 hours to days for the < 5 keV electrons). Dropouts are seen in the data with approximately the same frequency as in the LANL CPA/SOPA data sets.
Chapter 4 – Identification of substorm events

Due to the difficulties associated with the velocity dispersion and time delay of signatures in LEPA’s energy range, substorm selection was not constrained by requiring a recognisable signature in LEPA data. However, of the large number of substorms identified, those with spacecraft (including CRRES) in the tail region were favoured. This led to some events having clear electron injection signatures in the 28.5 keV to ~1 keV energy range in the LEPA data set.
The LEPA background channel is shown in Figure 4.2-2, representing relative levels of activity throughout the mission. Outbound and inbound sweeps of the spacecraft are separated to avoid interference, and month/orbit numbers marked at the edge of the plots with colour representing...
flux intensity. The major storm of March 1991 is clearly shown, injecting 15 MeV particles and energising an inner radiation belt for some months.

4.2.4 CRRES EPAS PARTICLE DATA

The CRRES mission's Electron/Proton Angle Spectrometer (EPAS) instrument provided high-resolution three dimensional particle distributions in the energy range of 21-285 keV for electrons and from 37 keV to 3.2 MeV for protons, using ten (four) look directions and respectively fourteen (twelve) channels for electrons (protons) [Korth et al., 1992]. At high L shells, good quality abrupt electron injections can be seen in EPAS data, along with dispersed injection signatures and echoes throughout the energy range of the instrument. The two top energy channels are sometimes noisy and injections are difficult to discern, although for most events EPAS provides a good instrument for the identification of injections as seen by CRRES, and compliments the LEPA energy range.

After initial dipolarisation selection, events were only retained in the event database if they showed injections in LANL data or a clear electron injection signature in the 21 to 208 keV energy range in EPAS data. However, in particle tracing EPAS was mostly used in the injection region to confirm the timing of event onsets and the duration of injection events.

Figure 4.2-3 shows a typical EPAS plot for one orbit. Different electron channels (21-285 keV) are recorded as different line traces, the highest energy channel having the lowest fluxes and hence the bottom trace. This makes the initial injection and subsequent echo (2157 to 2355)
easy to see. The dispersionless injection seen initially indicates CRRES was probably inside the injection region for at onset this event.

4.2.5 LANL SOPA/CPA PARTICLE DATA

Charged Particle Analyzers (CPA) and Synchronous Orbit Particle Analyzers (SOPA) have been flown on a series of spacecraft with a constellation spatially distributed around the geostationary ring. During CRRES’s lifetime up to five spacecraft were available at any one time, designated by their international satellite designator numbers (year + launch number that year). The instrument platforms had a spin period of 10.24 seconds with the spin axis pointed towards Earth, and with a spin-based accumulation period the instruments had a temporal resolution of the same. The most noticeable feature of the data set is the frequent impulsive injections typically seen close to midnight or just eastwards/westwards for electrons/protons. These are seen as increases in particle fluxes across several energy channels. Velocity dispersion and drift echoes are often visible in the data. Dropouts are sometimes visible in the data, with nine out of 54 events selected in a provisional iteration of work associated with dropouts observed by the LANL sensors. Injections are also seen in proton data although their dynamic range is much less than for electrons during simultaneous injections.

After initial magnetic dipolarisation selection, CPA/SOPA data was used alongside CRRES-EPAS data to eliminate those events that did not correlate with a clear electron injection signature or proton injection signature.

Figure 4.2-4 An injection as seen in the CPA/SOPA data set (protons blue, electrons red, x-axis UT, y log flux with ions and electrons artificially separated by an offset).
Figure 4.2-4 shows a collection of simultaneous CPA/SOPA readings for three spacecraft. The injection seen occurs at ~1120, with 1989-046 closest to the east. 1990-095 is closest to the west and sees the proton injection, and 1987-097 is further to the west and sees the dispersed proton injection first, then the dispersed electron injection.

4.2.6 METEOSAT SEM-II PARTICLE DATA

Meteosat SEM-II was initially used in conjunction with CRRES data at the start of this work. It was determined that the low data resolution of one frame of data per 10 minutes for electrons in the range 30 to 300 keV was far too low to be useful for particle tracing work. The use of the data in this work was discontinued.

4.2.7 GROUND MAGNETOMETER DATA

Ground based magnetometer measurements can be used to derive several indices that describe magnetic activity and substorms in the Earth's environment, and used directly to identify individual events in regions which map to station locations. However, the effort required identifying, acquiring and processing data sets of the required resolution for the entire epoch was not a viable proposition. In-situ magnetometer measurements from spacecraft were already available and showed variations in magnetic field conditions for wider regions than would be possible from individual station's data. Although data from a number of geographic locations would translate to useful information on the state of multiple points within the magnetosphere, data was not readily locatable on the Internet nor would the volume of data have been easy to manage. No data of the resolution required to resolve Pi2 pulsations (of order 10 seconds) could be located at WDC-C2 Kyoto. Ground magnetometer data, and Pi2's were therefore not used in this study.

4.2.8 AE, KP AND DST INDICES

4.2.8.1 AE INDEX

See 3.4.4 AE, AU and AL Indices.

The AE index is computed from auroral-zone data, and hence is the best index-indicator of substorm activity. However non-ideal coverage of magnetometer stations lead to a number of network gaps (eastern North America, 336.0° East to 24.3° East, and central Russia, 191.4° East to 237.1° East) and latitudinal displacement of electrojets can cause substorms to be missed. Substorm current systems can be quite localised in spatial extent so well defined substorms can be lost in the background noise of the index. Such circumstances could occur if the substorm current system is localised in longitudinal extent, and the intensified portion of the
electrojet is located over network gaps, at high latitudes well poleward of the AE stations or during intense storms as the oval may move far south away from observatories. The imperfect coverage of the magnetometer networks used to determine the auroral electrojet indices [Mayaud, 1980] makes it likely that substorm signatures can be missed when the electrojets move equatorward or poleward [Rostoker, 1972]. As with the Kp index, a low AE index does not rule out a substorm, but a high AE index generally indicates the presence of substorm activity.

Also, a fraction of AE/AL index activity, the most suitable of the indices for substorm work, is directly driven by the solar wind [Rostoker et al., 1987; Goertz et al., 1993]. Pronounced DP-2 current system contamination can occur during periods of solar wind convection – often the periods of interest in substorm studies. AE signatures cannot reflect the strength of individual events. Indeed, a preliminary statistical analysis of the amplitude of the particle-injection signatures for each substorm in Borovsky et al. [1993] indicated that particle injections are more reliable gauges for substorm occurrence than are the auroral electrojet indices.

Initially no AE index data was available to this study for the CRRES epoch and became available only in its later stages. For this reasons the AE index was not used for substorm identification purposes in the current work, although with the above arguments of incomplete coverage and directly driven ionospheric interference the index may have ruled out even if available.

4.2.8.2 DST INDEX

Although Kp and AE indices are primarily indicators of magnetospheric substorm activity, the Dst index was developed to give an indication of ring current strength alone. This can be used to indicate that substorm activity has occurred as a result of particle injection enhancement of the ring current by a decrease in the Dst index. The Dst index is obtained from a network of near-equatorial geomagnetic observatories that measures the intensity of the globally symmetrical equatorial electrojet, or ring current. At such latitudes the H component of the magnetic perturbation is dominated by the intensity of the magnetospheric ring current. The Dst index is a direct measure of the hourly average of this perturbation. Hourly H-component magnetic variations are analysed to remove annual secular change trends from records of the worldwide array of low-latitude observatories. A cosine factor of the site latitude transforms residual variations to their equatorial equivalents and harmonic analysis isolates the term used as the Dst index. Sugiura et al. [1964] described the derivation of Dst values.
Chapter 4 – Identification of substorm events

Large negative perturbations are indicative of an increase in the intensity of the ring current and typically appear on time scales of about an hour. The index shows the effect of the globally symmetrical westward flowing high altitude equatorial ring current, which causes the ‘main phase’ worldwide H-component depression during large magnetic storms. The time resolution of the data is not high enough for the identification of individual injection events, although it can be used to show periods when injection events can be expected to have occurred.

4.2.5.3 KP INDEX

The KP index is obtained from a number of magnetometer stations at mid-latitudes. The Kp index is derived from the K index. The K index is the largest difference between the maximum absolute and the absolute minimum covered by any component of the magnetic vector in the three-hour period. The K indices for each three hour interval for a certain range of stations are standardised through the means of a ‘Frequency Distribution Reference’. This is a statistical tool to distribute certain percentages of the data into the index range from 0 to 9. The resulting range of Kp values are averaged over a number of stations to produce Kp values. FDRs are made up for each season and station and are used to normalise other variations out of the data. If the auroral zone expands equatorward the stations used can record the effects of the auroral electrojet current system, the magnetospheric ring current and field-aligned currents connect the magnetosphere to the ionosphere. These are termed magnetically disturbed periods and show as times when Kp values are elevated. Substorm effects will increase the Kp index value, although the temporal resolution of the index makes it little use in identifying individual substorms. Its primary use is in identifying storm periods and periods of turbulent solar wind conditions and other than as an input to some field models, no use could be made of the index here.

4.3 SUBSTORM IDENTIFICATION BY CONSENSUS

Each method for identifying substorms above, has advantages and disadvantages chiefly reliant on data interference (as in the case of the AE index) or spacecraft positioning (for in-situ particle and magnetometer data). It is argued here that exclusive reliance on one data source or type of data to identify substorms can result in misidentifications. A better approach is to identify a number of candidate events in one data set, and then to eliminate events which do not meet identification criteria in another simultaneous data set. This is achieved in practice by first identifying a large number of dipolarisation-like events in GOES and CRRES magnetic data, and then attempting to identify corresponding particle injection signatures with the CPA/SOPA and EPAS instruments to come to a consensus as to the nature of the events observed. This approach is specifically aimed at later particle tracing work, where it is essential that each event
be identified as substorm injection with a high degree of confidence, although it is not essential that all events be identified.

4.3.1 METHOD

4.3.1.1 SPACECRAFT MAGNETIC FIELD DATA

Magnetic field data sets from CRRES, GOES 6 and GOES 7 magnetospheric spacecraft were acquired for use in this study. The data were ordered chronologically and compared with the Tsyganenko 1989 model field. Dipolarisation signatures were located in the combined data set by calculating $B_{Z-\text{MEAS}} - B_{Z-\text{MODEL}}$ values for each spacecraft throughout the CRRES epoch of operations. Tsyganenko 1989 is a function of Kp index, position and tilt angle of the dipole field with respect to the Sun. To maximise the prominence of dipolarisations in $B_{Z-\text{MEAS}} - B_{Z-\text{MODEL}}$ traces, it was not desirable that the model field reflect any effects of the level of magnetospheric activity, potentially masking the events sought. Kp value was therefore set to a moderately active level and left constant – also removing 3-hour boundary ‘steps’ from the traces caused with Kp changes. The one to five minute telemetry position data for CRRES were interpolated to give a smooth input variable to the Tsyganenko model and CRRES data from within 4.25 Re was excluded to avoid minor model errors giving disproportionate trace spikes in a region of large field values. Figure 4.3-1 shows the typical dipolarisation signatures located.
As shown in Figure 4.3-1, GOES-6, GOES-7 and CRRES are the red, blue and green traces respectively, and the double vertical lines show local midnight crossings. Orbits 154 and 159 show dipolarisations (~06:40 and ~0700 UT) and data features around 0850 UT caused by GOES-6 moving into eclipse and solar cell currents changing. Orbit 458 shows a typical quiet orbit, and orbits 481 and 531 show dipolarisations near the dotted lines (531 without a significant decrease prior to onset. Orbit 593 is a significantly active orbit with a marked dipolarisation.

To speed identification and classification of events the three $B_{Z\text{-MEAS}} - B_{Z\text{-MODEL}}$ traces were analysed by a pattern recognition program looking for sizeable increases in the value after a decrease or plateau. Each potential event so identified was offered for visual inspection, and
rejection or acceptance. The application of such an algorithm removed some subjectivity from the interpretation of the data. Some obvious dipolarisations were not recognised however and an override was permitted to add events the program missed (usually due to a dipolarisation occurring over a compressed time-scale). The identification of events used data smoothed with an 11-minute moving boxcar average to avoid the effects of noise. The rules expressed in the pattern recognition code for a time to be initially identified as possibly containing a dipolarisation were:

- a potential event must be preceded with an average gradient less than +0.5 nT/minute which is more than seven minutes long (stretching),
- there must be a gradient of at least 2.2 nT per minute at some point within the following 40 minutes, prior to the gradient becoming zero (dipolarisation, ignoring multi-onset/pseudo-breakup like structures),
- the total increase between trace minima and maxima must be at least 30nT (the dipolarisation must be big enough to rule out other fluctuations).

The code rules erred on the side of caution and produced a high number of potential events (two to three times the number eventually accepted). The final rule, although necessary to rule out minor blips in the magnetospheric field, may have prejudiced the study against small substorms. The rules make assumptions about the time scales of substorms. The signatures seen were complicated by position changes of the spacecraft distorting the dipolarisation signatures seen. An identical disturbance to the field could occur on two separate occasions, with spacecraft in different local times, and significantly different signatures may be seen. The extent of this distortion might make it impossible to identify an event as a dipolarisation. With a number of spacecraft evenly distributed in local time this method would detect the majority of dipolarisations during the CRRES epoch. However, only two geostationary spacecraft with a local time separation of 2 hours are available. This method therefore will not detect a large number of events whilst CRRES is in the inner magnetosphere and the GOES satellites are in dayside geostationary space.

This algorithm located the majority of events judged by eye as dipolarisations. The initial sweep of the program identified 327 events and with only an additional 30 or so events later added manually.
INITIAL OBSERVATIONS

Figure 4.3-2 The distribution of dipolarisation signatures seen in GOES-06, GOES-07 and CRRES data. The dashed line represents the averaged maximum changes in $B_{Z,\text{Meas}} - B_{Z,\text{Mod}}$ for each local time hour (i.e. average over events $(\max (B_{Z,\text{Meas}} - B_{Z,\text{Mod}}) - \min (B_{Z,\text{Meas}} - B_{Z,\text{Mod}}))$. This measure indicates the noon events differ in nature to their midnight counterparts.
Figure 4.3-3 Distribution and average intensity of dipolarisations as seen by GOES-6, GOES-7 and CRRES in Solar-Magnetic co-ordinate local time (LT markers shown).

Figure 4.3-3 shows the distribution of the dipolarisations identified. The individual events are marked as blue diamonds and the average intensity increase in \( B_{\text{meas}} - B_{\text{mod}} \) is assessed by binning values into a 0.5 Re grid and red-shading the squares such that lighter red represents a higher intensity. A clear concentration of detections can be seen between 1800hrs and 0300hrs LT where 289 events were detected, against 67 events in the remaining 14 hours (it should be emphasised that these are the positions of the spacecraft detecting dipolarisations, and not events themselves). The LT distribution shows a peak at 2100-2200hrs LT and a minimum at 1400hrs. CRRES data was unavailable for the area from 0700-1300hrs although this is not thought to have significantly contributed to the low numbers of detections present throughout 0300 to 1600hrs. The bias of peak local time towards the evening sector may correlate with observations indicating the most dramatic auroral effects are distributed around 2200 to 2300hrs, and that morning injections appear less organised. Overlaid on Figure 4.3-3 is a plot of the average intensity of event. The intensity of an event is a measure of the observed size of the dipolarisation, post-onset maximum \( (B_{\text{Z,MEAS}} - B_{\text{Z,MODEL}}) \) - pre-onset minimum \( (B_{\text{Z,MEAS}} - B_{\text{Z,MODEL}}) \). The plot shows a maximum of over 100nT centred on 1000hrs. This corresponds with a region with low numbers of identified dipolarisations that may actually be other events.
such as encounters with the magnetopause. Throughout the region with a high number of
dipolarisation observations, dipolarisations are characterised by average increases of 30 to
50nT (note however that the pattern recognition program’s criteria cut-off anything below
30nT).

For a number of dipolarisations the effects of magnetic field reconfiguration could be seen at
CRRES’s inner magnetosphere position several minutes before they manifested themselves at a
GOES magnetometer. The shape of the dipolarisation region and its motion was confused by
GOES frequently being several hours off local midnight, but the observations were compatible
with dipolarisation starting in the inner magnetosphere and propagating outward.

**DISCUSSION**

The signatures were distributed between spacecraft as follows: 94 CRRES; 164 GOES-6; 98
GOES-7. The disproportionately large number of high intensity events observed for GOES-6 is
attributed to it having consistently low magnetic latitude of less than 5 degrees. GOES-7 has
magnetic latitude of nearly 10 degrees, and coupled with the dipole tilt with respect to the Sun
this may be enough to remove it from regions of tail stretching and dipolarisation or reduce the
magnitude of changes seen in \( B_z \) during some periods. The nearby GOES-6 sees more events
with larger changes in \( B_z \), as it is more likely to be in a better place to view them. CRRES’s
magnetic latitude varies between +/-30 degrees and its orbit takes it into the inner
magnetosphere for significant periods, explaining its low figure.

GOES-6 sees a number of localised high \( B_{z,\text{MEAS}} \) features +/-40 minutes of local midnight
during certain orbital ranges centred on midnight (Figure 4.3-1, orbits 154 and 159). If it were
not for their consistency and odd recoveries they could be mistaken for dipolarisation events.
The orbital seasons for these events centre and maximise on the dates 15th September, 12th
March and 13th September respectively – spacecraft eclipse periods. The enhancements of \( B_z \)
are probably due to currents in the solar panels stopping, removing an induced \( B_z \) component
[Singer, 1998]. Some features that fit the overall profile for dipolarisations were seen, although
with different time-scales. A number of events were seen by all three spacecraft close to
midnight (although not centred upon it) with a prolonged (~3 hrs) decrease in the measured
magnetic field strength (~30nT) followed by a gradual reversal process not rapid enough to be
recognised as a traditional dipolarisation. This was either the spacecraft moving through a
region of stretched magnetic field and back out, or the drawing out of the magnetotail (loading)
without catastrophic unloading in the form of substorms, with a gradual relaxation returning the
system to equilibrium state.
The detection coverage-range of the spacecraft can be derived from the number of dipolarisations seen and estimates of the rate of general substorm activity. Borovsky [1993] gives an average frequency for substorm events as ~5 hours. The number observable dipolarisations will therefore be a function of the local time coverage the satellites, the period of observations and the average frequency figure. The CRRES mission was ~425 days giving a total number of substorms that would have typically occurred as 2050. 356 magnetic dipolarisation events were seen (some of which will not have been substorms). This indicates detection coverage of less than 17 %.

Two reasons may explain this:

- Ignoring the coverage provided by CRRES, and assuming that detection coverage is proportional to the local time range covered by the geostationary satellites, the GOES pair covered 4 hours of local time (17 %). Given their separation is two hours, the spacecraft could be assumed to see 1 hour of local time to either side. Given the highest concentrations of dipolarisations are seen between 1700 and 0300hrs, this would require the injection point or centre of dipolarisation to vary between 1800 and 0200hrs, the westward extent of which is unlikely.

- A large number of weaker dipolarisations have been missed by this study perhaps due to magnetic latitude displacement of the satellites in the tail region combined with too high an intensity threshold for identification. Thirty nanotelsas was the cut-off point employed in the program, and the average dipolarisations seen during nighttime local time space vary between 30 to 50nT, perhaps indicating this cut-off was too low. This argument is reinforced by the large discrepancy between the number of events seen by GOES-6 and GOES-7, indicating that latitudinal displacement greatly affects ability to see smaller magnitude dipolarisations.

A combination of the angular coverage and dipolarisation threshold arguments is seen as the most plausible explanation for the number of events seen.

The dayside dipolarisation events are not easily explained, other than as misidentifications. 16% of the 356 events were during the dayside hours and may have been caused by magnetopause crossings. This figure is a useful indicator of the overall misidentification rate for the entire exercise. Some of the events seen could be contamination of the magnetic field readings by local ion or electron currents. The dayside events may well be so, as magnetopause currents would have such effects if structures were moving close to or through the spacecraft position or vice-versa. A number of discontinuities in the direction of the magnetic field can be
directly associated (by identical start and end times) with plasma currents in the magnetosphere. On some CRRES orbits there were indications that ion currents were causing the magnetic field signature to change.

4.3.1.2 SPACECRAFT PARTICLE DATA

The dipolarisation list was used to form a list of candidate substorms by looking for clear coincident particle injection signatures. To be further included an event must have had a clear growth-phase signature (decline in electron fluxes or no significant activity) at the satellite nearest to local midnight, followed by a rapid increase in fluxes to levels higher than pre-growth levels. A second corroborating injection signature must also have been shown on another satellite.

METHOD

Particle analyser data for CRRES/EPAS, CRRES/LEPA, LANL/CPA, and LANL/SOPA for the two-hour periods either side of the 356 candidate dipolarisation events was obtained. An attempt to use pattern recognition routines to identify particle injections in the same manner as dipolarisations failed due to complexity. Automatic identification was complicated by the subtleties of some injection signatures. An injection appears as an increase in the flux levels of an energy channel with a delay approximately proportional to $1/E^2 - 1/E_1$ before being seen at lower energy channels. The signature peak also broadens as dispersion exaggerates the difference in arrival times of the extremes of the energy bands. These effects, although easily apparent to the experienced eye, are difficult to code into a set of rules to be applied to data. An alternative method of presenting particle data for each of the 356 events with inspection by eye was used. For each injection seen the minima and maxima in each energy channel before and after each onset on each instrument was manually highlighted. The identification of the pre-injection minima and mid-injection maxima, for each energy channel allowed for further attributes of each injection to be derived.

By fitting cubic splines to the fluxes as a function of energy to the minima and maxima, and line fitting flux increase arrival times as a function of $1/\text{energy}$, two other values were derived. With the line fit the arrival time of theoretical 30 MeV particles was determined, giving a comparable start time for an injection event no matter where in local time the signature was seen. With the flux as a function of energy splines, two measures for the magnitude of the substorm were determined: the flux increase that would be seen for 40 keV particles; the maximum energy where a 5% increase in particle fluxes occurred. These measures may however have been effected by shell splitting preferentially removing high energy, high pitch angle particles from the injection pulse (see Chapter 7).
Chapter 4 – Identification of substorm events

Figure 4.3-4 An example of how the minima and maxima of a substorm injection were indicated in two LANL spacecraft CPA data set traces.

Figure 4.3-4 shows an example of the splining method. The two horizontal axes in black show the local time for the two LANL spacecraft and the traces above each show electrons fluxes for a number of energy channels (highest energy gives lower y-value trace). The dashed vertical line represents the time of observation of the dipolarisation. The black and green squares are slideable inputs to the spline/line fitting algorithms representing the minima and maxima of the injection. Plots of the flux spline over energy/time-of-observation line fit over 1/Energy are shown in black.

INITIAL OBSERVATIONS

A number of events were clearly identified as being due to changes in the dynamic ram pressure of the solar wind and could be seen to cause flux increases across the magnetosphere instantaneously at 1 minute resolution, simultaneously across a number of spacecraft.

Figure 4.3-5 An instantaneous magnetosphere-wide increase in fluxes at SOPA/CPA energies probably caused by a change in the solar wind dynamic pressure. Several spacecraft see the flux increase at once.
Chapter 4 – Identification of substorm events

A different interpretation was placed on instantaneous increases across all energies for a single spacecraft. Where this was not accompanied by a prior flux dropout this was assumed to be an injection originating close-by. Where a clear flux dropout was observed, normally around midnight, it was assumed the spacecraft was moving from a substorm current wedge region or the tail current sheet or some other structure to a normal region of the plasma sheet rather than an injection. A number of events featured magnetopause crossings into magnetosheath or solar wind regions.

4.4 RESULTS

See Appendix A for a listing of events.

4.4.1 COMPARISON WITH OTHER CRRES SUBSTORM LISTS

Two sizeable CRRES substorm lists exist for comparison, one based on CRRES/EPAS data and one based on CRRES/MICS data. Both lists show fewer substorms, although specifically deal with dispersionless injections as seen by CRRES. Both show good agreement with this work's list close to tail region local times with ~45% of events having identical timing, and indicating similar events are being identified. This contrasts with a comparison of the MICS and EPAS lists where only 25% of events agree.

4.4.1.1 CRRES/MICS DISPERSIONLESS INJECTION LIST

This list was provided by Perry [1997]. It is a compilation of 112 identified dispersionless injections as seen by the Medium-energy Ion Composition Spectrometer instrument between CRRES orbits 417 and 847. Of the events on the list, 52 are identified here as dipolarisations with 42 classified as substorms. The MICS list entries have onset times delayed between 2-30 minutes with respect to the dipolarisation timings here. During the same period in this work 93 events are listed, 45% of which agree with MICS timings. The disagreements may be due to several reasons: CPA/SOPA readings being needed to corroborate this work's CRRES injection signatures; CRRES being in the inner magnetosphere and not seeing injections seen by CPA/SOPA instruments at geostationary altitudes; or no GOES spacecraft being sufficiently close to midnight to see the dipolarisation associated with the CRRES/MICS injection.

4.4.1.2 CRRES/EPAS DISPERSIONLESS INJECTION LIST

This list was provided by Friedel and Reeves [1996]. It is a compilation of 94 dispersionless injections as seen by the EPAS instrument. Of the events on the list, 32 are identified here as dipolarisations, including 25 classified as substorms. The EPAS list entries have onset times delayed between 2-20 minutes with respect to the dipolarisation timings here. Poor agreement
is seen during the early period in the CRRES mission when the spacecraft was in the dawn sector, although the evening sector onwards shows much better agreement. During the period from orbit 443 to 811, with CRRES in the tail/towards the evening sector, 56 events were seen by EPAS, 21 agreeing with this work’s timing. The reason for the dawn sector discrepancy is unknown.

4.4.2 ORDERING OF EVENTS FOR PARTICLE TRACING

187 events were identified above, providing a wide selection of injection events to trace back to probe the location and extent of the injection region. Time would be better spent pursuing some rather than others however. The locations of spacecraft during some events provide better conditions for tracing than for other events, and the various signatures are clearer for some rather than others. A prioritisation and selection of events for tracing is therefore needed to maximise the results obtained whilst keeping the work feasible.

The factors which could be used to order events:

- prior magnetospheric activity level,
  (minimises uncertainty of magnetic field state)
- number of spacecraft seeing injections,
  (more positions for tracing – better definition of injection region)
- number of spacecraft seeing dipolarisations,
  (better accuracy for magnetic field fit – see Chapter 6)
- dipolarisation and injection magnitude,
  (different sized events may have different mechanisms)

Particle tracing work relies upon the magnetosphere being in a known and relatively quiet state such that its electric and magnetic fields are in a state reflected in the substorm modified models fields in use. Tracing in a highly disturbed stormtime where fields are at variance with average models and particle invariants are not preserved due to the dynamism of the event’s environment would produce results which could be anticipated to be less accurate than if other events were used. This leads to the adoption of a strategy of favouring events where a long time has elapsed since the last substorm or other activity eliminating times when the magnetosphere was highly active and frequently reconfiguring the tail region. Discriminating against events
with more than 350 minutes — over Borovsky’s [1993] isolated mean — between recognisable (albeit detected) injections, reduces the list to 51 events and eliminates periods during and after the March 1991 storm event which led to a reconfiguration of the magnetosphere and the establishment of a new radiation belt.

However, it may be desirable to trace mid-storm events for certain conclusions to be drawn. If activity has a different or substantially modified underlying mechanism or region depending on immediately prior magnetospheric unloading — a small group of these events could be traced for comparison. The injection point may be nearer if the NENL has only just transformed to become the DNL in the neutral line paradigm, and particle tracing could show effects reflecting this. Selecting events for various sets of characteristics, such as strength or frequency of onsets will allow a variety of conclusions to be drawn from injection region tracing work, rather than just one category which may provide a reduced set of conclusions. For this purpose a second set of events with more than 60 and less than 120 minutes since the last substorm was selected (Borovsky’s Δt figure for cyclically occurring substorms was 165 minutes). Tracing this category proved outside the scope of this thesis, although is a topic for future work.

As a measure to further maximise the accuracy of the magnetic field model, a bias is shown to events with both GOES satellites and CRRES in the tail at good (>3.5 Re) altitudes. This also favours CRRES in a good position to detect either proton or electron injections, although due to the LT of apogee this can prove impossible to satisfy during parts of its mission. As this work chiefly deals with the electron component of injection signatures (see Chapter 6), LANL spacecraft should be in good position in the dawn/early morning sectors to detect electrons from injection, maximising the positions to trace from. The GOES and LANL local time requirements though, are often mutually exclusive due to the almost constant relative positions of the two sets of spacecraft, and the large number of data dropouts for the LANL spacecraft immediately to the east of the GOES pair (1982-019). The result is a compromise between GOES positioning for maximum field-fitting/dipolarisation diagnosing effectiveness, and particle detector positioning — increasing the importance in having CRRES in the eastern tail region. As a result electron signature coverage in the eastern hemisphere is often not provided until the mid-morning sector, which although not ideal is not an obstruction to successful tracing of the event.
Figure 4.4-1 shows a good distribution of spacecraft for the purposes of tracing. Note the GOES pair in the magnetotail, CRRES vertically above the 6 Re radius line to the east, and 1982-019/1987-097 further to the east. 1989-046 is to the west should proton tracing be required.

The events selected for tracing are presented in Chapter 7.

**4.5 CONCLUSIONS ON SUBSTORM IDENTIFICATION**

Three major factors effect the classification of substorms. The immaturity of substorm theory causes the derivation of concrete criteria as to what constitutes a substorm to be problematic. If a single triggering feature were known to be present in all substorms or a single mechanism, we could look for that and use it as a simple flag for substorm activity. However such a single feature or mechanism is not defined, and we depend on a number of phenomena associated with, but not universally accepted as mandatory for, substorms. To complicate matters further, data sets have frequent gaps, are difficult to access, or simply of poor location coverage for substorms. Finally, the complexity of the magnetosphere provides another obstacle. One index or measurement may never completely classify a substorm because of interference from other phenomenon. Even with the magnetometer data care had to be taken to rule out current induced features by reference to other indicators. With some CRRES particle signatures it was impossible to rule out that flux increases were not from other sources. LANL particle signatures were clearer, although they too could be swamped complex magnetospheric activity.
Chapter 4 – Identification of substorm events

Substorm onsets could be determined from other data such as satellite observations of magnetic field dipolarisations, images of auroral brightenings, ground-based magnetograms or riometer signatures. However, the data coverage for each of these other methods is non-continuous and many substorms would be missed. It is possible that researchers seeking to identify substorms identify differing phenomena with differing techniques. Even when the same individual technique is applied to a single data set, some misidentification will occur – each technique having strengths and weaknesses in different orbital positions and at different times, and different susceptibilities to interference.

This work uses as key indicators of substorms, dipolarisations of the magnetotail and a subsequent or coincidental particle injection. This method maximises confidence that what are identified are in the majority view substorms within a reasonable level of effort. Comparisons with other’s lists confirm this. However, the spacecraft coverage is less than total, and will have missed many events as comparison with Borovsky et al. [1993] rates suggest. Until we have high time resolution near-midnight magnetometer data and nearby particle detector data, or some other method of substorm detection, continually available we will continue to have trouble diagnosing the state of the magnetosphere – and even then complex activity will cause difficulty in interpretation. The multi-spacecraft constellation missions currently under discussion in many parts of the ISTP community should provide an invaluable diagnostic tool for the state of the magnetosphere and an invaluable resource for understanding substorm dynamics.

4.5.1 A NOTE ON THE PROJECTED MAXIMUM ENERGY MEASURE

Using the spline fits for flux as a function of energy for the pre-onset minima and the post-onset maxima, a guide to the maximum energy of the particles contained within the injection pulse was derived. The definition of $E_{\text{max}}$, the maximum energy of injection, was the lowest energy at which the difference between the two splines was less than 5% of the minimum. This technique, although a useful measure of the magnitude of the substorm did not take into account the relative local time position of the LANL geosynchronous satellite that the instrument was on. This weakens the accuracy of the measure as closer to injection measured fluxes are subject to less velocity dispersion and shell splitting before detection. Drift velocity will be faster for higher energy particles within an energy channel, and slower for lower energy particles, spreading out the injection pulse as seen by one channel, reducing the maximum fluxes seen as the pulse travels.

Allowing for theoretical velocity-dispersion effects, the time from beginning to end for the injection pulse to pass should be proportional to local time since injection. The injection flux
enhancement above background levels, with a normal distribution of energies within the channel, will decrease roughly in proportion to $1/(1 + k\Delta t)$ where $\Delta t$ is the local time the injection has moved through, and $k$ is a constant. The pre-injection minima are closely related to each channel’s background and without dropout events can be approximated to constant throughout geostationary space. Therefore, if $k$ were large and satellites of varying local times saw the particle pulse, it might be argued that they would see fluxes differ accordingly – with a reduction on the $E_{\text{MAX}}$ value for those furthest from the injection region. However, the most important input data points to the splines were at the higher end of the energy scale in the hundred's of keV energy range. For electrons in the CPA LoE6 channel (200keV and 300keV) the simple-model orbital drift times are 17 to 35 minutes and 11 to 25 minutes respectively (the range of times comes from pitch angle distribution). This means that for an entire orbit of the Earth, the spread time becomes 24 minutes for the highest channel. For each event the eastward spacecraft closest to midnight was used for $E_{\text{MAX}}$ computation. Often the spacecraft used before 0600LT, although not within the injection, will have reduced velocity dispersion effects. As we are in general dealing with drifts over less than ~6 LT hours, the spread for the highest channel will be less than 6 minutes, implying $k$ is small and has only a minor effect on the $E_{\text{MAX}}$ value.

Shell splitting effects may however effect this measure during periods of high dynamic pressure, where high pitch angle high-energy particles (100 keV+) are preferentially removed from the injection pulse. Such effects increase as observations move east through the midnight-dusk sector, and would also effect the estimated time of injection from particle signatures. Unfortunately no record was made as to which instrument/spacecraft was used to derive each $E_{\text{MAX}}$ value, so a relationship between $E_{\text{MAX}}$ and LT cannot be comprehensively investigated. A survey of some injections and the corresponding $E_{\text{MAX}}$ seen by a number of spacecraft show these effects to be less important than initially thought, with no clear relationship between $E_{\text{MAX}}$ and local time in the first eight hours after midnight. Szita et al. [1996], Figure 4.5-1, corroborated this showing a similarly reduced-relationship between LT and peak flux of injection signatures. For the first twelve hours of local time no major drop-off in maximum fluxes is observed, contrary to an assumption based on velocity-dispersion reduction of peak fluxes. The observed effect may indicate this is not a serious threat to the validity of the measure. Doubts exist over the measure however given results in correlations with the solar wind in the next chapter that yielded no significant relationships.
It is also noted that during a period of intense substorm activity the background fluxes for each energy channel will be elevated. This will in turn elevate the minima spline functions without substantially increasing the injection maxima seen. This will reduce the $E_{\text{MAX}}$ values seen during high activity periods, although these periods were avoided in this study.
CHAPTER 5 – SUBSTORM RELATIONSHIP TO SOLAR WIND

5.1 SUBSTORM ENERGY

Substorms dissipate energy built up from solar wind input to the magnetosphere and substorm activity varies with solar wind conditions. This chapter addresses how solar wind energy is converted to substorms – indirectly – by attempting to determine how magnetospheric substorms vary in response to variance in the solar wind. This is achieved by correlating various measures of substorm activity with a number of solar wind attributes, after some preliminary work that characterises average solar wind conditions surrounding an onset with superimposed epoch analysis techniques. The superimposed epoch analysis, and immediacy of requisite data, lead to a consideration of substorm triggering and a contribution to its ongoing debate.

5.2 IMP-8 SOLAR WIND DATA

IMP-8 solar wind measurements were obtained for each of the 187 events identified as candidate substorms. NASA Goddard’s web site (http://nssdc.gsfc.nasa.gov/omniweb/ow.html, SPyCAT/NDADS) provides access to a compilation of data from various spacecraft for IMF values, energetic particle fluxes, plasma data and indices. IMP-8 Bx, By, Bz, solar wind density (\(\rho_{SW}\)), speed (\(V_{SW}\)) and ephemeris data were retrieved from this site for the solar wind-substorm investigation. IMP-8 spends a large fraction of its 12.2-day orbit in the solar wind and during the period under study had telemetry coverage of 70% – resulting in good data for 130 substorm onsets. IMP-8 rarely entered the magnetosphere, but data was excluded should the spacecraft near locations tail magnetic fields could interfere (an exclusion zone of a infinitely long 15 \(R_E\) radius cylinder tailward of Earth was used). Data resolution was 2-minutes for particle data and 15 seconds for magnetic field data, with the high variance of the magnetometer data leading to the use of a 13-point moving boxcar average.

IMP-8 ranges between \(X = +38\) to \(X = -38\) \(R_E\). Three methods were investigated to adjust for the time differential (\(T_{delay}\)) between when data was taken at the spacecraft and when it can be assumed to be typical of the solar wind at the subsolar point:

\[
\text{i. } T_{delay} = \frac{(X_{GSM} - 15R_E)}{V_{SW}},
\]

\[
\text{ii. } T_{delay} = \frac{(X_{GSM} - 15R_E)}{V_{SW}} + \frac{1}{\Omega_{Sun}} \cdot \tan^{-1} \left( \frac{Y_{GSM}}{(X_{GSM} - 15R_E)} \right)
\]

[Baker, 1983; after Zwickl, reference therein],

81
Method iii. gave the most coherent superimposed epoch analysis results, used little computational time to calculate (a problem with method ii.) and was used throughout the rest of this work. The equation defines the magnetopause subsolar point 15 Re ahead of Earth, and assumes a Parker Spiral angle of 45°, causing positive \( Y_{GSM} \) displacement to have an effect equal to positive \( X_{GSM} \) displacement.

5.3 SOLAR WIND SUPERIMPOSED EPOCH ANALYSIS

5.3.1 LITERATURE REVIEW

Foster et al. [1971] selected 54 substorms in the period June to December 1967 using the AE index and magnetograms as indicators of substorm activity. Using auroral zone magnetograms from stations closest to midnight, \( T_0 \) was defined as the time of a negative bay sharp onset in the H component of more than 200 gamma. Data from the IMP-4 spacecraft was considered 4 hours either side of each \( T_0 \), and a superimposed epoch analysis conducted for the \(|B|\), V, n and T parameters of the solar wind. No significant structure in these parameters was found – all parameters varied within one standard deviation although it is noted that \( n \), number density had a peak around \( T_0-2.5 \). Further work involving \( B_z \) and the AE index led to a significant correlation being seen (Figure 5.3-1).
Chapter 5 – Substorm relationship to solar wind

Figure 5.3-1 As per inset caption. From Foster et al.[1971].

The average profile of $B_Z$ during substorms involves a 1 hour sharp decrease from $B_Z = 0$ to min $B_Z$ and a two to three hour recovery to lower than pre-feature levels. AE index values showed a peak at $T_0 + 40$ minutes, and was interpreted as the end of substorm expansion. The gradual (~70 min) increase in AE prior to $T_0$ (min $B_Z$) was interpreted as supporting evidence for the existence of a substorm growth phase.

In conclusion Foster et al. stated that solar-wind proton data, the interplanetary magnetic field magnitude and equatorial-plane components do not exhibit any significant morphological features that can be related to substorm development. They confirmed that there was a strong relationship between a southward IMF and the occurrence of substorms.

Caan et al. [1978] selected substorms using digitised magnetograms and a pattern recognition program. The program scanned the data set looking for periods of nightside positive bays in the H component of magnetograms. These bays were clustered into substorm groupings, with the onset of the substorm defined as the earliest bay in the cluster.
This technique was applied to data from 1967 to 1969, producing 1800 substorm onset times. These times were used to perform superimposed epoch analyses of substorm signatures in a variety of space and ground data sets, including AE data sets and IMF Bz data sets. AE data showed a similar response to that reported by Foster et al. [1971].
Data from Explorer 33 and Explorer 35 was used to determine the behaviour of the IMF during substorms. The uppermost trace represents the superimposed epoch average of the IMF $B_z$ (GSM) component for which IMF data were available. Below this average are displayed respectively, the $B_z$ component for separated onsets, and the $B_z$ behaviour using random times as onsets. The shape of the IMF $B_z$ curve with separated onsets begins above zero, indicating the graph of all onsets includes some substorms that are part of multiple substorm/onset features. Caan notes a correlation between the average magnitude of the southward field (and the total preceding southward IMF flux) and the magnitude of the substorms, as measured by ground magnetometer bays.

It was concluded that a distinct southward component of the IMF was associated with substorms, that the component reached a peak negative value about twenty minutes prior to the
average expansion onset. It is noted that this does not include any propagation delay times. This would have 'smeared' the result given the study was conducted over two years of data and the spacecraft should have been behind and in front of the Earth an equal amount. The majority of the delay is more likely to be composed of the 4-14 minute response time of the magnetosphere as seen by Sergeev et al. [1986]. Caan speculates that the proximity of the northward recovery of Bz to substorm onset may be indicative of a triggering mechanism, and pointed to a previous study (Caan et al. [1977]) where 60% of eighteen individual substorms were seen to be accompanied by northward fluctuations.

5.3.2 METHOD

A superimposed epoch analysis was conducted on the five measured variables and two derived variables – dynamic pressure ($P_{dyn} = \rho_{sw} V_{sw}^2$) and convection electric field strength ($E_{sw}$) from T-15 to T+5 hours with respect to onset. This analysis contained no discrimination of onset tilt angle, however three other superimposed epoch analyses were conducted, discriminating between the onset solar wind data included by dipole tilt angle:

i. tilt < -8 degrees away from the Sun,

ii. tilt > +8 degrees away from the Sun,

iii. tilt > -8 and tilt < +8 degrees.

It should be noted that the calculation of $E_{sw}$ did not use $V \times B$ as would be expected. $E_{sw}$ was calculated using:

$$E_{sw} = |B| V_{sw}$$

Equation 5.3.2-1

rather than using a cross product due to a lack in direction information for $V_{sw}$. It could be assumed that the $B_X$ could be omitted as $V_{sw}$ should predominantly be in the GSM X direction, although the above equation gave $E_{sw}$ structures which had a sharper relief.

To establish the significance of any structure seen in the data, the values for the events were analysed in ten minute-average blocks. For each ten-minute period in the T-10 to T+5 hour range, the subset of ten minute averaged values for each event was compared with the entire 187 x 20 hours of data available. The comparison was made using the Kolmogorov-Smirnov statistic, which is a non-parametric comparison of the distribution functions of two data sets – a measure of the probability of a data set (the 187 ten minute periods used to get the superimposed graph) coming randomly from a second data set (the entire 187 x 20 hours). A
5% significance level was applied to the results of the test, indicating that highlighted superimposed data had a less than 5% chance of coming randomly from the entire data set. It is noted that this was a comparison between individual ten-minute blocks and solar wind data near substorm events, rather than normal data from the solar wind – a necessary shortcut to save time.

In order to eliminate systematic features, three runs were made with random event onset times. The graphs produced showed no coherent structure in the data.

5.3.3 RESULTS

Figure 5.3-4 shows the results of including data points when the dipole tilt angle is less than -8° at onset. A number of features significant at the 5% level can be seen:

- elevated solar wind velocity T-15 to T-4 hours,
- $B_z$ structure T-1 to T+1 hour (minimum -9.5 nT),
- $E_{sw}$ structure T-1 to T+1 hour.

Although the all-data set average is +0.35 nT for $B_z$, and the data subset local to substorms (T-15 to T+5) has an average of -2.2 nT, reinforcing the reconnective energy input-substorm link.

Figure 5.3-5 shows the same, although for data when the dipole tilt angle was away from the Sun. The statistically significant features seen are:

- solar wind density increase T-4.5 to T-3 hours,
- $B_z$ structure T-1.3 to T-0.3 hours (minimum -3.9 nT),
- $E_{sw}$ structure T-0.5 to T+0.5.

Statistical significance values were not calculated for the case of no tilt discrimination due to execution time requirements, although it is anticipated that the $E_{sw}$ and $B_z$ seen therein are significant. The third case of tilt discrimination (for data points between tilt > -8° and tilt < +8°) merely showed characteristics between the two extreme cases and these results are not presented here.
Figure 5.3-4 The results of a superimposed epoch analysis, centred on substorm onsets, of solar wind parameters from IMP-8 (tilts < -8°).

The graph (Figure 5.3-4) shows time from T-15 hours to T+5 hours around onset (the vertical dashed line). The vertical scale shows values from -250 to +750, nominally km/s although scaling factors and other units are shown in the key for other variables. The tilt < -8° (i.e. the
north-pole is towards the Sun) constraint reduces the number of data points in the average around onset to 25. Significant structures in the data are described in section 5.3.3 above.

Figure 5.3-5 As per Figure 5.3-4, although for data points when the dipole tilt was more than +8°.
Figure 5.3-6 As per Figure 5.3-4, although no tilt discrimination was made for data used.

5.3.4 DISCUSSION & CONCLUSIONS

The particle and field structures seen in the above figures do not represent the behaviour seen in any one substorm. Rather, the graphs are average pictures built-up from many different
Chapter 5 – Substorm relationship to solar wind

events, and can be used to indicate features prevalent in the periods leading up to onset (but not necessarily obligatory for an onset).

The most apparent feature comparing the graphs is that for the tilt < -8° analysis the traces are noisier and the features seen have greater vertical scale. This effect is greater than the increase in deviation that would be expected simply based on the reduced number of data points. This may be due to long term changes in solar wind conditions or the tilt angle presented to the Sun [Taylor et al., 1996]. The former may well be the case as data for the tilt < -8° analysis arises in the period from April-August 1991 that included a number of large storms. The epoch followed a large storm in March 1991 injection of 15 MeV particles into a long lasting radiation belt that may have effected the long term global magnetospheric response (Figure 5.3-7). The tilt discriminated analysis requires a set of events from a time period of several years to determine if the tilt-dependency seen is a significant feature.

For the tilt < -8° superimposed epoch analysis: the most notable features of the results are the structure of $B_z$ and $E_{sw}$ around $T = 0$. Prior to $T = 0$ $B_z$ is significantly negative, far below the 0.35 nT entire data set average, for at least 3 hours. At $T = -1$ $B_z$ takes a sharp downwards turn to values around -8 to -9 nT, with the minima lasting for around 40 minutes before a rapid ~15 minute increase in values to pre-substorm values. The post-onset rapid increase in $B_z$ values should not be interpreted as a sign of triggering (although the relatively small spike just prior to onset may be so). The data combined in this superimposed epoch analysis was selected on the basis that at $T = 0$ they share a common feature of a magnetospheric injection. If common solar wind features exist prior to this, which they appear to, then they should be betrayed in the superimposed epoch analysis. This causes values of $B_z$ less than zero to be favoured, although
after onset there is no such selection and the superimposed epoch trace reverts to a value closer to the data set average. If common solar wind features exist at onset, then these too may show up in the analysis, but events long after the $T = 0$ point should be treated as spurious unless the solar wind is cyclical in nature or substorms are cyclical (which they can be). This reasoning may be invalidated by many events (about half according to Borovsky [1993]) being part of cyclical storms composed of many substorms, and explains why the progress of $B_Z$ to positive values is gradual rather than dramatic – some events are just one in a series that is continuously being powered by southward IMF.

For the no tilt discrimination superimposed epoch analysis: the $B_Z$ feature around $T = 0$ is of similar structure compared with the results of Foster et al. [1971] work. A significant depression in $B_Z$ values occurs from approximately $T-1.5$ hours (although it may be interpreted as starting at $T-3.5$ hours) and is indicative of a reconnection driven growth phase. A post onset recovery of $B_Z$ values from around $-4.7$ nT is seen that takes less than 20 minutes. The $B_Z$ features mimic the structure seen in Foster et al. [1971] and Caan et al. [1978] results except for duration and magnitude, indicating that these events are probably the same class of event they saw. Those reported in Foster et al. [1971] had initial decreases lasting around 2 hours and recoveries in $B_Z$ lasting 2 hours, with Caan et al. observing 2 to 3 hours and 1.5 hours respectively. The features in the superimposed epoch analyses here are of shorter duration. This is taken to indicate that these onset timings are more accurate, and the lower minimum $B_Z$ values reinforces this, though may also indicate fewer non-substorms have got through this selection process or this collection exhibits more extreme solar wind characteristics than those in Foster et al. [1971] and Caan et al. [1978].

The $E_{SW}$ structure around onset, shared by each of the three superimposed epoch analysis, is characterised by a significant increase in the convection electric field, chiefly due to an increase in magnetic field strength rather than solar wind velocity. $E_{SW}$ values for the tilt < $-8^\circ$ case were twice those of the $> +8^\circ$. It is noted though that tilt $> +8^\circ$ discrimination decreased the scale of the $B_Z$ structure around onset, and removed the rapid post-onset increase in $B_Z$, the shape of the $E_{SW}$ trace with peak at $t = 0$ remains common across tilt discriminations due to changes in the other magnetic field components. Although the magnetic field direction changes for the two extreme cases were on average quite different, their $E_{SW}$ profiles were similar. The increase of $E_{SW}$ at least one hour prior to onset is indicative of reconnection activity coinciding with growth as would be anticipated.
5.4 TRIGGERING

5.4.1 THE TRIGGERING DEBATE

As has already been reviewed, Caan et al. [1978] indicated the proximity of the northward recovery of $B_z$ to onset may be indicative of a causal link between IMF direction changes and onset, and points to a prior study—Caan et al. [1977]—where 60% of 18 individual substorms were seen to be accompanied by northward fluctuations. Rostoker et al. [1983] investigated this phenomenon further by isolating three clear-cut examples of individual substorms where evidence of the substorm triggering effect was apparent. This was to dispel doubts that previous examples of northward turning triggers were an inevitable result of the highly volatile IMF. They noted that northward turnings of the IMF triggering energy deposition in the ionosphere seems, at first sight counterintuitive as it is customary to associate substorm expansive phases with episodes of southward IMF. However, if the rate at which energy can be dissipated in the ionosphere and deposited in the ring current is less than the rate at which energy is entering the magnetosphere, energy should be stored in the magnetotail magnetic field. This would allow for the energy to power a substorm expansion phase even after the shutoff of energy input after a northward IMF trigger turning. Rostoker et al. [1983] concludes by suggesting that the energy needed to power the substorm expansive phase is stored in the magnetotail during periods of southward IMF and its release to substorm activity can be triggered by northward swings in IMF. While southern IMF powers the growth of substorms, from this work it is the northward turning of the IMF that leads to the impulsive release of energy stored in the magnetotail and reconfiguration of magnetotail current systems.

McPherron et al. [1986] notes that although sharp substorm onsets (as detected by the AL index) occasionally appear to be independent of northward turnings in the IMF, they more frequently appear to be triggered by them. Identifying substorms as minima in the AL index, sharp onsets (decreases of order 100 nT or larger) are observed to occur in 45% of these. The sharp changes in the AL index are interpreted as indicating a sudden substorm initiation. Treating these as a subset of all substorms, 44% of these correlated with northward turnings in the IMF. McPherron et al. [1986] determines that it is not necessary for the IMF to turn completely northward for an apparent triggering to occur, that northward turnings do not always trigger an onset in AL, and a number of events have no evident solar wind trigger—demonstrating that a sudden expansion onset does not require an obvious northward turning of the IMF. McPherron et al. [1986] also reports other work where the azimuthal component of the IMF can also have significant effects on the AL index, and some preliminary evidence indicates that $B_y$ was more likely to be negative at the time of triggered onset.
However, Lyons [1996] argues the case for IMF triggering of all substorms. It is noted that on average B\textsubscript{Z} remains negative for a significant period of time prior to onset, and that it appears to be a significant increase of B\textsubscript{Z}, rather than a full turning to the north that is associated with onset. Other work’s examples of substorms without northward turnings are called into question in two ways in the paper. Lyons questions whether the AL index, as used by many papers to identify substorms, is capable of distinguishing substorms from other types of auroral activity and cites that the scale size of IMF structures can be less than the scale size of the magnetosphere in the directions perpendicular to solar wind velocity. This would allow satellites measuring the solar wind a few tens of R\textsubscript{E} away to sample a different localised IMF environment to that which the magnetosphere is being subjected — occasionally missing IMF changes and triggers that hit the Earth. This has been seen in multisatellite observations of the IMF in the vicinity of the Earth.

Perreault et al. [1976] studies inhomogeneities in the solar wind IMF of the scale of the magnetosphere during substorms using two satellites. IMF observations seen on one satellite appear to relate to those on another, but are clearly not identical. During substorm activity as expressed by the AE index, the IMF B\textsubscript{Z} component recorded in the noon-dusk sector of the magnetosphere appears more relevant than variations recorded in the dawn-noon sector. The authors note previous studies have assumed the IMF is uniform across the magnetosphere. They conclude from their substorm correlations that the magnetosphere may be more sensitive to IMF B\textsubscript{Z} variations in the dusk sector of the magnetosphere. In this thesis and many other works a single-point in-situ measurement of the IMF is taken and assumed to reflect the environment of the entire magnetosphere. Perreault et al.’s result indicates caution should be observed in such practice.

Lyons [1996] attributes changes in the B\textsubscript{Y} component as another source of inadequately explored substorm triggers — with a reduction in the B\textsubscript{Y} value to near zero appearing to cause substorms in some opponents work. The paper singles out an example in McPherron et al. [1986] that illustrates stable IMF conditions during a substorm onset. Investigating B\textsubscript{Y} values at the time (which McPherron does not record doing) it is found that B\textsubscript{Y} swings through zero at the time of onset. Lyons concludes that if substorms are distinguished from other disturbances, published studies taken together suggest that ‘most if not all substorm expansion phases’ are triggered by convection electric field reduction, showing substorms in general are not the result of an internal magnetospheric instability.

Henderson et al. [1996] shows typical substorms can occur without identifiable triggers in the solar wind. Henderson uses a much more comprehensive set of data to unambiguously identify
substorms, including the LANL geosynchronous orbit particle detectors, and midlatitude Pi2 pulsation data. This is in acknowledgement of Lyons [1996] comments that some sharp decreases in the AL index during intervals of steady IMF/solar wind may not be substorms, but enhancements of the convection driven DP 2 current system. Henderson claims to use the IMP-8 data set to measure solar wind parameters only when IMP-8 is close to the Sun-Earth line of sight, to remove ambiguities caused by small-scale variations in the solar wind on the scale of the magnetosphere (after Perreault et al. [1976]), however at least one event uses data from 25 Re away. Henderson states that Lyons questioning of McPherron et al. [1986] results (who found 29% of substorms occurred when the IMF was measured to be steadily southward) was motivated by a desire to reconcile these observations with his recent substorm model. However, some of Lyons objections are found to be valid, and hence Henderson is motivated to unambiguously find onsets without triggers, such that some substorms could be the result of a purely internal magnetospheric instability. Henderson et al. [1996] attempted to show this with a set of six substorm observations from multiple locations in the magnetosphere and the ground, and IMP-8 measurements. Of the six examples, in one IMP-8 is 25 Re away from the Sun-Earth line and may not be measuring the IMF to which the magnetosphere is exposed, and one has a 3 nT disturbance in Bx, and three have IMF changes 0.5 or 1 hour ahead of onset. The most convincing case has a 3 nT disturbance in Bx, although this may be too minor to be implicated. With Sergeev et al. [1976] and other work showing substorm onsets can lag IMF discontinuity contact with the magnetopause by 4-14 minutes for 90% of events, the later three examples could be IMF triggered, with a lag in response. The time scale of the substorm mechanism after any such trigger is unknown, although it is reasonable to assume given the body of work on the matter that it is less than an hour – within scope of some of the disturbances seen for the three example events.

Henderson et al. does arguably show substorms without IMF triggers, but these are perhaps another subclass to the substorms of Lyons theory. These substorms show that either the process from trigger to onset may require time to develop, or that a fraction of substorms are the result of some process, phenomenon or mechanism intrinsic to the magnetosphere – i.e. internally triggered. This raises the possibility that some substorms that occur during disturbed solar wind/IMF periods are incorrectly attributed as immediately triggered in prior studies.

The triggering debate is still unresolved, and may continue to be so until the substorm mechanism(s) are finalised. Lyons contends that ‘most, and perhaps all, expansions are triggered by IMF changes’, although much work shows that not all substorms are triggered by reductions of the solar wind electric field. The volatility of the solar wind and the inevitability of having a culpable feature near any onset during active periods hamper the work.
5.4.2 SOLAR WIND TRIGGERING OF THE 187 EVENT COLLECTION

Links have been shown to exist between southward periods of IMF and substorm growth phases as well as between solar wind disturbances and expansion phase onsets. It is still under debate as to whether decreases in the solar wind electric field accompany all substorm onsets. IMP-8 and ISEE-1 do not always detect such turnings in association with all onsets, possibly because the scale of triggering features is smaller than spacecraft distance from the magnetosphere, or the lag time for the response is longer than we assume. It has been shown that a substantial number of substorms are prefaced by a northward turning of the IMF. It is therefore reasonable to look for confirmation of this in the collection of substorm events identified here, and the solar wind data readily to hand.

This will sub-classify the events into triggered and non-triggered. As this work is an investigation of the substorm mechanism or mechanisms, if injections are invoked in different ways the mechanism may behave with according variation, hence sub-classification may highlight the differences when interpreting results.

5.4.2.1 RESULTS

Plots of the IMF conditions for the 187-event collection of injections used elsewhere in this work were analysed for conspicuous IMF events that could be identified as triggers.

Classification of the 187 events:

<table>
<thead>
<tr>
<th>Bz condition</th>
<th>-ve-</th>
<th>+ve-</th>
<th>-ve++</th>
<th>+ve++</th>
<th>-ve</th>
<th>+ve</th>
<th>No data/indiscernible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events</td>
<td>14</td>
<td>11</td>
<td>31</td>
<td>5</td>
<td>12</td>
<td>4</td>
<td>110</td>
</tr>
</tbody>
</table>

Table 5.4-1 IMF conditions at time of onset for the 187-event collection.

The column headers indicate the sign of Bz and that of its gradient, with no ‘-’ or ‘++’ symbol indicating the IMF Bz component was broadly stable (e.g. -ve++ indicates negative but increasing). Some events were clearly associated with dynamic pressure increases. By far the largest number of events were disqualified from the evaluation due to noisy solar wind conditions making categorisation impossible.

By values were also assessed and found to show that a large number of events (47%) occurred when By was stably negative, and 25% when stably positive with no implications for triggering.
5.4.3 CONCLUSIONS ON SOLAR WIND TRIGGERING OF SUBSTORMS

The relationship between the solar wind, particularly the orientation of the IMF, and substorm activity has been extensively investigated. The accumulated evidence illustrates the non-linear nature of the solar wind’s connection with the magnetosphere. Assuming that magnetic activity was driven linearly by the southward IMF component would lead to a conclusion that such activity should decrease when the interplanetary magnetic field turns north. Assuming instead that reconnection stores energy within the magnetotail, allows for solar wind trigger events to initiate stored energy release. The essential role of the magnetotail in substorm physics is to power substorm processes through release of stored magnetic energy. It is noted that since many onsets appear to occur during steady solar wind conditions, a process internal to the magnetosphere causes substorm onsets. However, since many onsets are correlated with changes in the interplanetary environment, it is reasonable to conclude that this internal process can be influenced by external factors.

In McPherron et al. [1986], 44% of substorm onsets correlate with northward turnings of the IMF after a period of southward pointing. Similar work by Caan et al. [1976] gave a figure of 60% of observed substorms, and in this work 47% of the 187 substorms where solar wind data was available appear to have northward turning triggers. 32% appear to be coincident with southward turnings, and 20% are associated with stable Bz.

The two groups (triggered/non-triggered) identified in other work are identical in all properties, such that non-triggered events cannot be said to be different from substorms. Also, there is no dependence of triggering or non-triggering of substorms on location of the monitor, contrary to Lyons’ concerns over displacement from the Sun-Earth line [McPherron & Hsu, private communication]. They conclude that the substorm onset is an internal process susceptible to external perturbation.

Lyons view of a drop in the cross-tail electric field being the exclusive substorm trigger contradicts many current views, as do observations of ~70% of events being triggered by northward turnings. One danger of substorm trigger studies is the IMF’s extreme volatility. When surveying the 187-substorm collection it was noted how easy it was to allow an error-margin for a slightly incorrect onset time, and allow a little too much trigger-propagation time. With such an extended window, it became almost inevitable that there would be at least one northward turning that would be readily attributable as a trigger – if not many. This could lead to the attribution of unsuitable solar wind structures as triggers. In an effort to guard against this, magnetic dipolarisation timing was rigorously used to define substorm onsets. Allowing a margin of 8-14 minutes for the effects of a trigger to propagate through the magnetospheric
system [Sergeev et al., 1976], did however still result in a large window within which to look for candidate trigger events. It was noted that other work too had marginally negotiable onset times permitting for the possibility of unintended enhancement of results.

Therefore this work would appear not to support Lyons theory for substorm triggering, but reinforces the idea that reconnection pushes the magnetospheric equilibrium into an unstable equilibrium. When any of a number of variations in the solar wind occurs, the equilibrium becomes unsuitable for conditions, and substorm activity may result from the system reverting to a new equilibrium. A northward turning of the IMF is not mandatory for an event to occur and many are caused by other perturbations, a number of which appear to be purely internal.

5.5 CORRELATION OF SOLAR WIND ATTRIBUTES WITH ONSETS

It is known that the solar wind drives substorm processes indirectly through magnetotail storage of magnetic flux energy. Solar wind convection of flux from reconnection at the magnetospheric subsolar region to the magnetotail stores energy for substorm processes, and is proportional to the product of the solar wind velocity and southward magnetic field strength. If the assumption is made that plasmoids remove a roughly constant proportion of the available energy, a correlation between the energy imparted to the magnetosphere over certain periods and the dissipation of energy by substorms should be demonstrable.

This work involved characterising substorm activity for the fifteen-hour period prior to the 187 identified onsets by determining the rate at which onsets were occurring and the magnitude of the injections involved. The rate and magnitude data, along with IMP-8 solar wind data, was used to examine the linkage between the solar wind and the resultant magnetospheric response.

5.5.1 INTRODUCTION

One of the first major discoveries of the space age, that of the solar wind, quickly led to work showing that long term averages of geomagnetic activity were related to averages of the solar-wind velocity. Studies of the link between the solar wind and general magnetospheric activity have been conducted in the past using such long term averages as geomagnetic indices. However, comparison of high temporal resolution geomagnetic index data and solar wind velocity showed no such correlation until Dungey indicated that the IMF was also important in controlling geomagnetic activity. Dungey’s suggestion of solar wind-magnetospheric reconnection during periods of southward IMF led to work examining the relationship of magnetic indices and the direction of the $B_z$ component. Arnoldy [1971] used correlation analysis between hourly averages of the AE index representing substorm activity, and various solar wind parameters with time lags for subsequent effects to manifest themselves. The results
Chapter 5 - Substorm relationship to solar wind

of AE index correlations (r) with solar wind speed, density, IMF magnitude, and hourly integrals of B_N and B_S are shown in Figure 5.5-1. B_N and B_S are respectively the magnitudes of the Z_GSM component when it is greater than zero and less than zero.

![Figure 5.5-1 Correlation of various solar wind parameters and AE](image)

This work highlighted the integral of B_S in the preceding hour as having the highest correlation with the hourly averages of AE (r = 0.8). Arnoldy also points out that the integral appears to be linearly related to the AE hourly average and correlation was highest when IMF components in the GSM system were used. He interprets the hour lag shown for correlation maximum as indicating that energy is not accrued for more than about 1 hour before it appears in a substorm (or, rather is manifested in the AE index).

Baker [1981] used eight months of IMP-8 data in a similar study, although with greatly improved temporal resolution. The paper investigated the V_{SW} correlation with AE and found little significant (values ranging from r = 0.1 to 0.4 with one rogue result at r = 0.7). B_Z was found to have a more consistent correlation in the range of r = 0.4 to 0.6 although with a 40 minute lag between B_Z and AE index. B_Z V_{SW} was found to be a good correlator with AE data, reaching slightly higher correlations (r = 0.6) than \varepsilon, the power input to the magnetosphere (r = 0.54). Both peaked with a 40-minute lag. Further work based on studies between solar wind parameters and geomagnetic indices using dimensional analysis led Akasofu to propose that the coupling function be expressed in units of power input to the magnetosphere. An expression for the power input to the magnetosphere derived by Vasyliunas et al. [1982] and Bargatze et
al. [1985] relates to the solar wind dynamic pressure and the electric field using principles of dimensional similitude, and simplifies to:

\[ \varepsilon = k p_{sw}^{1/6} E_{sw} \cdot g(\theta) = k (\mu r^2)^{1/6} uB \]

Equation 5.5.1-1

Where \( k \) is a constant, \( p_{sw} \) is the solar-wind dynamic pressure, \( E_{sw} \) is the solar wind induced electric field and \( g(\theta) \) is an angular gating function for reconnection between the solar wind and magnetosphere, where \( \theta \) is the IMF clock angle and \( B \) is the southward magnetic field component. \( g(\theta) \) acts to increase the value during periods of southward IMF and reduces it to zero during northward IMF periods. This function gave the highest correlation between interplanetary conditions and the AE index.

Baker [1983] built on this and his earlier work using ISEE-3 data and differentiated between correlations during quiet and disturbed magnetospheric conditions. It was found that AE correlations were significantly enhanced during quiet periods (to \( r = 0.7 \) to \( 0.8 \) with \( \mu, V.B_g \) and \( V^2.B_s \)) but during active periods \( V.B_g \) was reduced to correlations of around 0.6, and \( \varepsilon \) less than 0.4. Quiet periods characterised by small Dst and Kp, low peak AE levels and isolated substorm activity were found to be highly predictable, contrasting with disturbed periods showing low AE correlations. A better correlation during active periods was obtained by using \( U_T \) – the total energy dissipation rate of the magnetosphere calculated in terms of the sum of the ring current energy injection rate, ionospheric joule heating and auroral particle energy flux using the DST and AE indices. This gave a much higher correlation (\( r > 0.6 \)) with all solar wind parameters during disturbed times. The characteristic lag between AE and solar wind parameter during quiet times, of 25 to 40 minutes, was reduced in \( U_T \) correlations to less than 15 minutes during disturbed periods.

5.5.2 CORRELATION METHOD

The IMP-8 data set (detailed earlier) and three other derived variables were use for correlation:

i. Dynamic pressure \( (V_{sw} \times \text{density}) \),

ii. Power#1: \( k_1.(p.V_{sw}^2)^{1/6} V_{sw} (-1).B_z \),

\( (\varepsilon, \text{a simplified Equation 5.5.1-1}) \),

iii. Power#2: \( k_2.(p.V_{sw}^2)^{1/3}.V_{sw}.B_z^2 \).
Chapter 5 - Substorm relationship to solar wind

The power equations represent terms for the square of the stand-off distance to the magnetopause \( (l_c^2) \) indicating a surface area through which energy is being transferred, the solar wind kinetic energy flux representing the rate of incidence of energy on that area, and a gating function for switching off power during periods of northward IMF. Equation iii, from Freeman [1998], has a similar derivation to the first, but uses what might be a better choice for \( l_c^2 \), \( l_c^2 = k.(\rho.V_{SW}^2)^{1/3} \).

Prior work had established onset times for 187 substorm events. The onset times were determined from dipolarisation and particle injection analysis of data from CRRES and GOES magnetometer data sets, CRRES EPAS, and LANL CPA/SOPA data. For each of the 187 events the particle signatures were analysed to give characteristic attributes. The minima just prior to each energy channel's substorm-characteristic flux elevation were identified, and the following continuous cubic-spline functions fitted to the discrete time/energy/flux values:

\[
\begin{align*}
t(e) &= \text{min\_time\_spline}(e), \\
f(e) &= \text{min\_flux\_spline}(e).
\end{align*}
\]

Where \( e \) is the channel's maximum energy, \( t(e) \) is the energy channel's time of arrival at the sensor, \( f(e) \) the electron flux in that energy channel prior to the injection, and \( \text{flux\_spline}(e) \) and \( \text{time\_spline}(e) \) are the fitted functions. Similar function fitting was applied to the injection channel maxima to get \( \text{max\_time\_spline}(e) \) and \( \text{max\_flux\_spline}(e) \). The resulting functions were used to identify the following electron injection characteristics:

- Time of injection, \( t_0 = \text{min\_time\_spline}(10^{10} \text{ keV}) \),
- Flux increase at 40 keV, \( \Delta f_{40} \) = 
  \[
  \text{(max\_flux\_spline}(40 \text{ keV}) - \text{min\_flux\_spline}(40 \text{ keV}) \),
- Maximum energy of injection, \( E_{\text{max}} = 
  \frac{\text{(max\_flux\_spline}(e) - \text{min\_flux\_spline}(e))}{\text{min\_flux\_spline}(e) \equiv 5\%}.\)

The \( E_{\text{max}} \) was defined so as to represent the upper energy bound of the particles injected into the magnetosphere, and was the lowest energy above 20 keV where the difference between the minimum pre-injection flux and the injection maximum was less than 5%.

The rate of substorms was measured in two ways. One was the number of injections in the 15 hours prior to onset \( (R) \), giving figures from one to eight (with a mode of 4 substorms in 15
hours). Another, more localised measure was to determine the minutes since the last injection ('TSLSS' or time since last substorm).

Each event had initially been surveyed for magnetic signatures, resulting in two magnetic dipolarisation attributes: the magnitude of the $B_z$ increase seen ($\text{Mag}_\text{DIP}$), and the rate of that change ($\text{Mag}_\text{DIP}$-$\text{RATE}$). It was noted however, that the magnetic latitude and longitude of the observing platform could adversely affect these measures. Elsewhere in this thesis, the magnetic field is fitted to each individual event for particle tracing purposes. The coefficients used to obtain a closer fit between average-model and measured field would provide a better correlator free from platform-location complications. However as these values exist only for a small subset of the 187 events under examination, and the technique for obtaining them is not considered fully mature, they were not included in the correlation.

These eight event attributes, $\text{Mag}_\text{DIP}$, $\text{Mag}_\text{DIP}$-$\text{RATE}$, $E_{\text{max}}$ (ions \& electrons), $\Delta f_{\text{core}}$ (ions \& electrons), $R$, and TSLSS along with growth phase and expansion phase duration were compared with the solar wind attributes using Spearman's Rank correlation method, and a T-test to assess the significance of the correlations seen.

The solar wind attributes were evaluated prior to each of the 187 events in a number of different periods, reflecting a number of different theories regarding the way solar wind energy is imparted to the magnetosphere. The attributes were evaluated over five different periods:

i. all prior 15 hours,

ii. the $B_z$ trough immediately prior to onset,

iii. the period since the last substorm,

iv. the period until the next substorm ([Freeman 1998]),

v. a sliding window, beginning between 180 and 10 minutes prior to onset and lasting 10 to 120 minutes.

The latter period evaluates the correlations over variable lags between correlating variables to search for maximum correlations and hence time delayed cause-effect relationships. Following results from superimposed epoch analysis work indicating a dependence of the solar wind signature up to onset with dipole tilt to the Sun, the events in the correlations were separated by onset dipole tilt:

- tilt > +8 degrees
Chapter 5 – Substorm relationship to solar wind

- tilt $<-8$ degrees
- No tilt discrimination

Solar wind variables were assessed by the use of both integrals and averages over the periods under consideration. Bad data periods of more than 2.5 minutes were excluded from any statistic, and if bad data persisted in an evaluation period, the entire event was discarded from the correlation.

Finally, the assessment could vary whether the solar wind attributes were assessed when the IMF was coupled with the magnetosphere or not. This ‘gating’ added the solar wind values to the average or sums dependant on whether $B_z$ was negative, reflecting the expectation that gating would effect an attribute’s ability to influence substorm makeup. From clarity, all results presented are from a gated assessment unless stated otherwise.

5.5.3 ANTICIPATED RESULTS

Increased energy or flux input to the magnetosphere should on average be balanced by increased energy dissipation from the magnetosphere, a fraction of which will be manifested in the form of substorms. Whether the result will be increased substorm magnitude or an increased rate of substorms or a combination of the two effects was unknown. An increase of either or both should be seen subsequent to elevated convection electric field values. Under Dungey’s model such increase in flux transport leads to the need for greater rates of substorm activity to impulsively recycle flux from the tail to the bow reconnection point. In current substorm models, flux builds-up in the magnetotail to provide energy for substorms with longer periods of southward pointing IMF, or greater magnitudes of $B_z$ or faster convection providing more power. A correlation between substorm activity and the integral of $B_z$ would therefore be expected ($B_z = B_Z$ when $B_Z < 0$ and $B_z = 0$ when $B_Z >= 0$). $B_y$ magnitude may also show a correlation with substorm energy dissipation, with variations in electric field strength in the polar ionosphere being a result from its modulation. $B_x$ magnitude does not contribute to the convection electric field, and no correlations would be anticipated.

5.5.4 RESULTS

The results are first considered for substorm-measure inter-correlations, with each attribute correlated with the others over all 187 events. Substorm-solar wind correlations for the fixed periods were then assessed, and finally the variable width-lag sliding-window results are reduced and considered. Correlations are noted only if they are higher than $r = 0.5$, and the $T$-test significance was less than 2.5% – indicating the result have a better-than one-in-forty chance of being representative given the statistical distributions involved.
5.5.4.1 INTER-CORRELATION OF SUBSTORM MEASURES

The auto-correlation was again divided by dipole tilt. All correlations r >= 0.30 which give a good (< 2.5% probability of error) significance are in bold. Dipole tilt is positive when the magnetic north pole is away from the Sun.

### Table 5.5-1 r-values for auto-correlation of substorm measures, divided by dipole tilt.

<table>
<thead>
<tr>
<th>Events</th>
<th>Onset tilt</th>
<th>$\Delta Bz/T$</th>
<th>$E_{max}$</th>
<th>$\Delta Flux$</th>
<th>Rate</th>
<th>$T_{SLSS}$</th>
<th>$\Delta A$</th>
<th>$T_{UNSS}$</th>
<th>$\Delta T_{Growth}$</th>
<th>$\Delta T_{Exp}$</th>
<th>$\Delta T(Bz&lt;0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>62</td>
<td>Onset tilt &lt; -8°</td>
<td>0.58</td>
<td>-0.22</td>
<td>0.15</td>
<td>-0.08</td>
<td>-0.03</td>
<td>-0.07</td>
<td>-0.16</td>
<td>0.18</td>
<td>0.33</td>
<td>-0.06</td>
</tr>
<tr>
<td></td>
<td>Dipolarist'n $\Delta Bz$</td>
<td>0.58</td>
<td>-0.31</td>
<td>0.12</td>
<td>0.08</td>
<td>0.03</td>
<td>-0.19</td>
<td>-0.16</td>
<td>0.09</td>
<td>0.09</td>
<td>-0.05</td>
</tr>
<tr>
<td></td>
<td>$E_{max}$</td>
<td>Injection</td>
<td>-</td>
<td>-</td>
<td>0.37</td>
<td>-0.40</td>
<td>0.03</td>
<td>-0.04</td>
<td>0.11</td>
<td>0.13</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>$\Delta Flux @40keV$</td>
<td>-</td>
<td>-</td>
<td>-0.24</td>
<td>0.05</td>
<td>-0.05</td>
<td>0.1</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>Rate (T-15 =&gt; T=0)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-0.54</td>
<td>-0.18</td>
<td>0</td>
<td>-0.16</td>
<td>-0.05</td>
<td>-0.09</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>$T_{SLSS}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.06</td>
<td>0.06</td>
<td>0.1</td>
<td>-0.07</td>
<td>-0.08</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>$\Delta A$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.19</td>
<td>-0.16</td>
<td>-0.25</td>
<td>0.22</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>$T_{UNSS}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.02</td>
<td>-0.13</td>
<td>-0.18</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$\Delta T_{Growth}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.54</td>
<td>0</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\Delta T_{Exp}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.86</td>
<td>0</td>
<td>0.07</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>47 Events</th>
<th>Onset tilt &gt; +8°</th>
<th>$\Delta Bz/T$</th>
<th>$E_{max}$</th>
<th>$\Delta Flux$</th>
<th>Rate</th>
<th>$T_{SLSS}$</th>
<th>$\Delta A$</th>
<th>$T_{UNSS}$</th>
<th>$\Delta T_{Growth}$</th>
<th>$\Delta T_{Exp}$</th>
<th>$\Delta T(Bz&lt;0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipolarist'n $\Delta Bz$</td>
<td>0.37</td>
<td>0.25</td>
<td>-0.13</td>
<td>-0.05</td>
<td>-0.13</td>
<td>0.30</td>
<td>0.04</td>
<td>-0.07</td>
<td>0.33</td>
<td>-0.04</td>
<td></td>
</tr>
<tr>
<td>Rate $\Delta Bz/T$</td>
<td>-</td>
<td>0.21</td>
<td>0.1</td>
<td>0.07</td>
<td>0.08</td>
<td>0.25</td>
<td>0.25</td>
<td>-0.01</td>
<td>-0.16</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>$E_{max}$</td>
<td>Injection</td>
<td>-</td>
<td>-</td>
<td>-0.09</td>
<td>0.07</td>
<td>0.18</td>
<td>0.16</td>
<td>0.2</td>
<td>0.09</td>
<td>0</td>
<td>0.03</td>
</tr>
<tr>
<td>$\Delta Flux@40keV$</td>
<td>-</td>
<td>-</td>
<td>0.29</td>
<td>-0.07</td>
<td>0.2</td>
<td>-0.1</td>
<td>-0.07</td>
<td>0.2</td>
<td>-0.07</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>Rate (T-15 =&gt; T=0)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-0.51</td>
<td>0.1</td>
<td>0.06</td>
<td>0.04</td>
<td>0.08</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>$T_{SLSS}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-1.11</td>
<td>0.02</td>
<td>0.18</td>
<td>-0.15</td>
<td>-0.04</td>
<td></td>
</tr>
<tr>
<td>$\Delta A$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.16</td>
<td>-0.21</td>
<td>0.11</td>
<td>-0.04</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>$T_{UNSS}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.04</td>
<td>-0.02</td>
<td>-0.18</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>$\Delta T_{Growth}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-0.1</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta T_{Exp}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.07</td>
<td>0</td>
<td>-0.01</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>187 Events</th>
<th>No tilt discrim.</th>
<th>$\Delta Bz/T$</th>
<th>$E_{max}$</th>
<th>$\Delta Flux$</th>
<th>Rate</th>
<th>$T_{SLSS}$</th>
<th>$\Delta A$</th>
<th>$T_{UNSS}$</th>
<th>$\Delta T_{Growth}$</th>
<th>$\Delta T_{Exp}$</th>
<th>$\Delta T(Bz&lt;0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipolarist'n $\Delta Bz$</td>
<td>0.51</td>
<td>-0.06</td>
<td>0.03</td>
<td>0.00</td>
<td>-0.04</td>
<td>0.11</td>
<td>-0.03</td>
<td>0.02</td>
<td>0.24</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Rate $\Delta Bz/T$</td>
<td>-</td>
<td>-0.08</td>
<td>0.02</td>
<td>0.1</td>
<td>-0.03</td>
<td>0.08</td>
<td>-0.1</td>
<td>-0.12</td>
<td>-0.12</td>
<td>-0.01</td>
<td></td>
</tr>
<tr>
<td>$E_{max}$</td>
<td>Injection</td>
<td>-</td>
<td>-0.03</td>
<td>0.17</td>
<td>-0.06</td>
<td>-0.06</td>
<td>0.14</td>
<td>-0.01</td>
<td>0</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>$\Delta Flux@40keV$</td>
<td>-</td>
<td>-</td>
<td>0.15</td>
<td>-0.01</td>
<td>0.06</td>
<td>0.1</td>
<td>-0.02</td>
<td>0.06</td>
<td>-0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rate (T-15 =&gt; T=0)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-0.48</td>
<td>-0.11</td>
<td>-0.15</td>
<td>-0.13</td>
<td>-0.06</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>$T_{SLSS}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.06</td>
<td>0.21</td>
<td>0.24</td>
<td>-0.06</td>
<td>-0.08</td>
<td></td>
</tr>
<tr>
<td>$\Delta A$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.08</td>
<td>-0.13</td>
<td>-0.01</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>$T_{UNSS}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.04</td>
<td>0.01</td>
<td>-0.19</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>$\Delta T_{Growth}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.07</td>
<td>0</td>
<td>0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta T_{Exp}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.07</td>
<td>0</td>
<td>0.01</td>
<td></td>
</tr>
</tbody>
</table>

Bold shows correlations where r >= 0.30 and significance < 0.025, italics show weaker relationships where r >= 0.15 and significance < 0.10.

**DISCUSSION**
Chapter 5 – Substorm relationship to solar wind

Considering first the case with no tilt discrimination, the correlations showed little or no relationships between the substorm measures except those between related measures (e.g. TSLSS and the rate of substorms in the prior fifteen hours).

In the case where the tilt was away from the Sun (tilt > +8°) a relationship between the size of the observed magnetospheric dipolarisation and the length of the expansion phase becomes apparent, implying the larger dipolarisations require more time occur as would be expected.

In the case where the tilt was towards the Sun (tilt < -8°) three relationships with the $E_{\text{Max}}$ measure were demonstrated. However, as this measure appears compromised in this and other work, and these relationships are not (even remotely) exhibited in the other tilt-angle divisions of the data it is thought too tenuous to conclude from.

A more persistent albeit weak correlation is shown across all three comparisons between the flux increase at 40 keV and substorm rate, indicating the magnetosphere probably reacts to increased energy input with a greater number of more populous injections.

### 5.5.4.2 CORRELATIONS WITH SOLAR WIND PARAMETERS

#### DIPOLARISATION INCREASE $\Delta B_z$

<table>
<thead>
<tr>
<th>Solar Wind</th>
<th>$r$</th>
<th>Events in correlation</th>
<th>Tilt discrimination</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMF $B_z$</td>
<td>-0.57</td>
<td>32</td>
<td>&lt; -8°</td>
<td>Trough</td>
</tr>
<tr>
<td>Power#1</td>
<td>0.49</td>
<td>32</td>
<td>&lt; -8°</td>
<td>Trough</td>
</tr>
<tr>
<td>Power#2</td>
<td>0.52</td>
<td>32</td>
<td>&lt; -8°</td>
<td>Trough</td>
</tr>
<tr>
<td>IMF $B_z$</td>
<td>-0.35</td>
<td>116</td>
<td>None</td>
<td>Trough</td>
</tr>
<tr>
<td>Power#1</td>
<td>0.36</td>
<td>116</td>
<td>None</td>
<td>Trough</td>
</tr>
<tr>
<td>Power#2</td>
<td>0.38</td>
<td>116</td>
<td>None</td>
<td>Trough</td>
</tr>
</tbody>
</table>

Table 5.5-2 Significant correlation values for solar wind attributes and substorm dipolarisation $\Delta B_z$.

Good correlations are obtained between the power input to the magnetosphere and magnetospheric dipolarisation when integrated over the IMF $B_z$ trough immediately prior to onset and IMF $B_z$ shows a good anticorrelation with the dipolarisation measure. Together these are interpreted as indicating that the more energy input to the magnetosphere or flux convected to the tail, the larger the resultant dipolarisations.

#### PROJECTED MAXIMUM INJECTION ENERGY $E_{\text{Max}}$

<table>
<thead>
<tr>
<th>Solar Wind</th>
<th>$r$</th>
<th>Events in correlation</th>
<th>Tilt discrimination</th>
<th>Period</th>
</tr>
</thead>
</table>

105
As anticipated the peak energy seen in an injection shows a relationship with the amount of energy absorbed by the magnetosphere. However, the result returned was a strong anticorrelation with the integrated power function. The sign (or sense) of this relationship was consistent across many different ways of assessing the correlation with different periods, averaging, and gating (often with larger numbers of events in the correlation). This may indicate that the maximum energy of injections may actually decrease with the addition of energy to the magnetosphere although this is thought unlikely. A more probable explanation may come from a weakness in the $E_{\text{Max}}$ measure, where a high-speed solar wind imparting more energy to the magnetosphere, will also increase the magnetopause dynamic pressure. From work in the tracing chapter, this is known to increase shell splitting – an effect which preferentially affects higher energy particles – removing them from the particle signature giving the appearance the injection peters-out at a lower energy during high dynamic pressure periods. This scenario would explain why the measure reduces with increased energy input.

**FLUX INCREASE AT 40 KEV**

<table>
<thead>
<tr>
<th>Solar Wind</th>
<th>$r$</th>
<th>Events in correlation</th>
<th>Tilt discrimination</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMF Bz</td>
<td>-0.49</td>
<td>32</td>
<td>$&gt; +8^\circ$</td>
<td>Trough</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.50</td>
<td>32</td>
<td>$&gt; +8^\circ$</td>
<td>Trough</td>
</tr>
<tr>
<td>Power#1</td>
<td>0.48</td>
<td>32</td>
<td>$&gt; +8^\circ$</td>
<td>Trough</td>
</tr>
<tr>
<td>IMF Bz</td>
<td>-0.45</td>
<td>35</td>
<td>$&gt; +8^\circ$</td>
<td>TSLSS</td>
</tr>
<tr>
<td>Power#1</td>
<td>0.44</td>
<td>35</td>
<td>$&gt; +8^\circ$</td>
<td>TSLSS</td>
</tr>
<tr>
<td>IMF Bz</td>
<td>-0.27</td>
<td>123</td>
<td>None</td>
<td>TSLSS</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.30</td>
<td>123</td>
<td>None</td>
<td>TSLSS</td>
</tr>
<tr>
<td>Power#1</td>
<td>0.29</td>
<td>123</td>
<td>None</td>
<td>TSLSS</td>
</tr>
<tr>
<td>Power#2</td>
<td>0.27</td>
<td>123</td>
<td>None</td>
<td>TSLSS</td>
</tr>
</tbody>
</table>

A relationship is shown between variables connected with or representing the power input to the magnetosphere and the flux increase for 40 keV electrons. This indicates that the magnetosphere responds to increased energy input with greater injection fluxes, with the power input during the period of southward IMF immediately prior to onset appearing the most
significant. It is notable however that this relationship did not manifest itself whilst the dipole was pointing towards the Sun.

**RATE OF SUBSTORMS IN PRIOR 15 HOURS**

<table>
<thead>
<tr>
<th>Solar Wind</th>
<th>r</th>
<th>Events in correlation</th>
<th>Tilt discrimination</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic pressure</td>
<td>0.50</td>
<td>32</td>
<td>&lt; -8°</td>
<td>Trough</td>
</tr>
<tr>
<td>Power#2</td>
<td>0.38</td>
<td>32</td>
<td>&lt; -8°</td>
<td>Trough</td>
</tr>
</tbody>
</table>

Table 5.5-5 Significant correlation values for solar wind attributes and substorm rate.

<table>
<thead>
<tr>
<th>Solar Wind</th>
<th>r</th>
<th>Events in correlation</th>
<th>Gating</th>
<th>Tilt discrim.</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity</td>
<td>0.67</td>
<td>29</td>
<td>X</td>
<td>&lt; -8°</td>
<td>All 15 hrs</td>
</tr>
<tr>
<td>Dynamic pressure</td>
<td>0.66</td>
<td>29</td>
<td>X</td>
<td>&lt; -8°</td>
<td>All 15 hrs</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.63</td>
<td>31</td>
<td>X</td>
<td>&lt; -8°</td>
<td>Trough</td>
</tr>
<tr>
<td>Dynamic pressure</td>
<td>0.59</td>
<td>31</td>
<td>X</td>
<td>&lt; -8°</td>
<td>Trough</td>
</tr>
</tbody>
</table>

Table 5.5-6 Significant correlation values for solar wind attributes and substorm rate. Gating solar wind data on Bz < 0 was suspended for these correlations.

The rate measure returned relatively high correlations with the solar wind velocity, dynamic pressure and power variables. It is noted that all significant results were returned when discriminating for events that occurred when the Earth was tilted towards the Sun. Although correlations were seen at other tilts, none were above the correlation and confidence thresholds. Removal of gating on Bz < 0 increased the correlations, with the highest correlation occurring between the solar wind assessed over the full 15 hours without gating (rate is a determined from the full 15 hours of data, and hence this is expected).

Averaging solar wind attributes over all 15 hours, rather than integrating them as above, resulted in good correlations (0.67 \(> r > 0.49\)) between rate and solar wind velocity and power input.

**TIME SINCE LAST SUBSTORM (TSLSS)**

No significant results.

**AE MAGNITUDE**

No significant results.

**EXPANSION PHASE DURATION**

No significant results.

**GROWTH PHASE DURATION**

107
Chapter 5 – Substorm relationship to solar wind

No significant results.

TIME UNTIL NEXT SUBSTORM (TUNSS)

No significant results.

DISCUSSION

When considering the correlations with solar wind parameters, it is clear that substorm attributes are most closely associated with IMF $B_z$ and solar wind velocity and hence power input and dynamic pressure on the magnetosphere. However many correlations resulted in $r$-values which fluctuated more widely over tilt discriminations than would be expected, or were based on few events, or in the case of the $E_{\text{max}}$ correlation, based on a possibly inexact measure. The conclusions therefore must be cautious.

The $E_{\text{max}}$ anticorrelation is dismissed due to doubts over the measure – probable shell splitting effects. The correlation exercise gave good indications that the size of the dipolarisation seen, and the magnitude of the 40 keV electron flux increase in the injection pulse, are dependent on the energy input during the $B_z$ trough or time since the last substorm – although the lack of any such correlations with the $\Delta A\varepsilon$ measure is difficult to explain, which may be due to convection current contamination of AE data. After Arnoldy [1971] the lack of any correlations seen with the $\Delta A\varepsilon$ measure would indicate the results shown in Figure 5.5-1 is largely due to the DP-2 current system rather than a correlation directly with substorm activity.

The rate of substorm injection is also connected with solar wind velocity, dynamic pressure and energy input. The division of correlation batches by tilt angle proved inconclusive and the changes in results may be indicative of changes in magnetospheric behaviour or merely due to long-term changes in the solar wind during different seasons. This is discussed elsewhere.
5.5.4.3 VARIABLE LAG/INTEGRATION PERIOD CORRELATIONS

![Diagram showing correlation values for dipolarisation delta-Bz and solar wind power equation#1, with variable integration periods over variable lags.](image)

**DISCUSSION**

The work allowing various time lags between solar wind variable and substorm attribute attempts to show the time periods involved within which the substorm mechanism acts. This assumes that the periods involved have broad averages and that their variances are not great with respect to the sample number of events.

*Arnoldy* [1971], using an arbitrary energy accrualment period of 1 hour, showed a peak correlation lag time to be in the region of one hour prior to resulting activity as expressed by the AE index. *Sergeev et al.* [1976] and other work show substorm onsets can lag IMF discontinuity contact with the magnetopause by 4-14 minutes for 90% of events. *Arnoldy* [1971] indicates that the energy storage mechanism may take over four times longer than that from input of energy to output. *Bargatze et al.* [1985] shows through a linear prediction filter (LPF) study of the AL-indices reaction to solar wind input that the best responses are seen between T-2.5 hours to approximately T-1 hours, for stored/unloading effects. The results of this study are presented in Figure 5.5-2 and show the peak correlations with dipolarisation $\Delta B_z$ are seen by integrating solar wind power in the range T-2 hours to T-30 minutes. The ranges on this result are consistent with both *Arnoldy* [1971] and *Bargatze et al.* [1985].

Chaotic correlation surfaces over lag/duration space were seen with other substorm measures indicating similar relationships, although these are not presented as they lacked clear
conclusions. This may indicate that the initial assumption of only a small variance in the lag and duration times over many substorms for the charging-period to be incorrect, or that the number of events was insufficient to produce consistent results.

### 5.5.5 DISCUSSION OF TILT ANGLE EFFECTS

The use of tilt angle discrimination in the correlation work has resulted in some correlation result differentiation. Coupled with the results from super-imposed epoch analysis where similar discrimination resulted in quite different average solar wind signatures, this may indicate that the substorm sets identified by use of tilt angle differed in their nature.

It is quite clear that although the statistical significance levels used were quite strict (1%) it would be preferred to have many more events. Selection for periods without long bad data periods and for specific tilt angles reduced the number of events for some statistics. A number of high correlations values with only a few events contributing were rejected with the significance measure, but to draw conclusions that different species of substorms occurred with different tilt angles would be premature with one study with as few as 13 events in some correlations. These results have a high likelihood of being a statistical selection effect.

The use of tilt discrimination may show differences in results due to the occurrence of intense magnetic storms during the spring season of CRRES's mission (as has been discussed with respect to superimposed epoch analysis results). It can be seen from Figure 2.5-1 CRRES experienced various levels of geomagnetic activity during its mission. This variation is most noticeable around the March 22nd 1991 storm event. This or seasonal variation in activity may be the cause of a differentiation in the results divided by tilt, rather than the angle the Earth's dipole presented to the Sun itself, which would have merely acted as a selector for season in the analysis. As CRRES lasted only one year, the study has an inherent ambiguity of season versus solar wind conditions at that time. Certainly the magnetospheric state was changed with the formation of a new intense radiation belt after the storm, that lasted for a number of months – perhaps with ramifications for magnetospheric energy storage or onset triggering.

### 5.5.6 PROGRESSION OF STUDY

Although 187 events were used within this study, IMP-8 data dropouts and further selection based on tilt effects reduced the events eligible for correlation substantially such that some were inconclusive. Further, the validity of some substorm measures, such as $E_{\text{max}}$ remains in question. However, this type of correlative study if conducted with adequate magnetospheric and solar wind data coverage could provide a key to the substorm mechanism, and is worth further pursuit. To advance this correlative work, the techniques used here should be applied to
Chapter 5 – Substorm relationship to solar wind

a much larger database of solar wind and magnetospheric events over several years and many seasons of tilt angle – including periods without substorms. The latter will remove the bias in the data toward substorm periods, and presumably toward southward IMF periods. As southward IMF probably results in more energy for substorms, the inclusion of periods devoid of substorms would probably correlate with northward IMF would strengthen the technique’s results accordingly.

A strategy would be to go through the LANL data set for a number of years, identify substorms (perhaps with an automated method) and then conduct rate and magnitude correlations of the results with IMP-8 data. An attempt to automate the identification of substorms within this data set proved problematic.

Another improvement to the above technique may be to measure the substorm magnitude with some form of total-flux measure. A variant of the spline functions used to determine E_max and the flux change at 40 keV could be used to determine the total energy of the particle pulse below the injection signature. This may provide a less local time dependent measure subject to reduced dispersive effects – especially if events are constrained such that a spacecraft is near the eastern injection boundary to reduce shell splitting effects. As the attribute measured would be a direct measure of the energy of one component of the substorm (i.e. it will be the sum of all the energies of the particles modelled as having been in the injection by the spline) it may provide a better correlation with the energy input to the magnetosphere.

A number of the substorm measures employed rely on platform positioning to be effective (e.g. size of dipolarisation, E_max). The ideal situation would be to have good tail coverage for each and every injection event providing unbiased measurements of the field changes and injection fluxes prior to the effects of shell splitting. This would entail near-saturation of the magnetosphere with spacecraft and is not possible. However, Swarm – a current magnetospheric mission proposal – or one of the other large magnetospheric constellation missions, if launched will advance substorm/solar wind studies considerably with magnetometer/plasma packages well distributed in GTO space.
CHAPTER 6 – PARTICLE TRACING

6.1 PARTICLE DRIFT THEORY

6.1.1 GUIDING CENTRE APPROXIMATION

The motion of a particle of charge $q$, through a magnetic field $B$ and an electric field $E$ subject to an external force $F$ is defined by the equation:

$$\frac{d}{dt} \left( m \frac{dr}{dt} \right) = q \left( \frac{dr}{dt} \times B + E \right) + F$$

Equation 6.1.1-1

The solution of this equation for trapped particles in magnetospheric fields results in three periodicities. In order of decreasing frequency they are:

- cyclotron motion of the particle in the plane perpendicular to the magnetic vector,
- bounce motion of the particle up and down the magnetic field line between mirror points,
- and azimuthal drift motion of the particle about the Earth.

The solution of the equation is a helical motion about a field line representing the cyclotron motion of the particle. The guiding centre of the particle’s motion travels along this field line. The average radius of the circular orbit of the particle about its guiding centre is called the Larmor radius or gyroradius ($\rho_c$), and the time it takes to orbit the guiding centre the cyclotron period.

Figure 6.1-1 Cyclotron motion (from Roederer, 1970)
The guiding centre of the particle has a velocity parallel to the magnetic field (parallel velocity) equal to the component of the particle’s velocity parallel to the field. The perpendicular component of the guiding centre’s velocity is termed the drift velocity \( V_d \), and is discussed below.

Adequately tracing particles using Equation 6.1.1-1 is numerically intensive for comparatively low levels of accuracy. Instead, tracing the guiding centres of particles by calculating their drift velocities provides a method that generally provides a more accurate trace for a given effort.

### 6.1.2 ADIABATIC INVARIANTS

#### 6.1.2.1 FIRST ADIABATIC INVARIANT \( \mu \)

If spatial field variations are very small at the scale of a particle’s gyroradius, and any time-dependency is very small during intervals of the order of its gyroperiod, it can be shown that:

\[
\mu = \frac{P^*}{2m_0B} = \text{const.}
\]

Equation 6.1.2-1

Where \( P^* \) is the particle’s momentum in the guiding centre system frame of reference, \( \mu \) represents the relativistic magnetic moment and the first adiabatic invariant [Roederer, 1970].

#### 6.1.2.2 SECOND ADIABATIC INVARIANT \( J \)

If temporal field variation is very small at the time-scale of a particle’s gyroperiod, it can be shown that the quantity \( J \) in Equation 6.1.2-2 is an adiabatic invariant that is conserved during the drift of a trapped particle:

\[
J = \int_{S^\prime_M} p \cdot \cos \alpha \, ds = \text{const.}
\]

Equation 6.1.2-2

Where \( S_M \) is the mirror point and \( S^\prime_M \) its conjugate. \( J \) is the second adiabatic invariant [Roederer, 1970]. (\( \alpha = \text{pitch angle}, \ p = \text{momentum}, \ s = \text{dame path} \))

#### 6.1.2.3 CONSERVATION OF ADIABATIC INVARIANTS IN TRACING

The first adiabatic invariant is used to calculate magnetic mirror points for particles on new field lines after energy exchanges with the electric field due to drift motion, and hence is implicitly conserved in this particle tracing algorithm:
Chapter 6 – Particle tracing

\[ B\mu = \frac{p^2}{2m_0}. \]

\[ B_{\text{MIRROR,}_n}\mu = B_{\text{MIRROR,}_n}\mu + \Delta W. \]

\[ B_{\text{MIRROR,}_n} = \frac{B_{\text{MIRROR,}_n}\mu + \Delta W}{\mu}. \]

Equation 6.1.2-3 (\( \mu = \text{particle energy} \))

The second adiabatic invariant is user-monitored through the particle trace by evaluation and comparison with the initial value. The third adiabatic invariant (flux encompassed by a guiding drift shell of a particle remains constant) is a longer-term invariant and is not considered here.

6.1.3 GUIDING CENTRE DRIFTS

Particles trapped within the magnetosphere move under the influence of external forces, inhomogeneities in the magnetic field and time-dependencies of electric and magnetic fields. This leads to the characteristic motion or drifts, of particle injections about the Earth, and an energy dependency of drift velocity results in the dispersed signatures seen in injection events.

6.1.3.1 FORCE DRIFT

Under the influence of an external force \( \mathbf{F} \) and ignoring any external electric fields the perpendicular component of Equation 6.1.1-1 is:

\[ \frac{dp}{dt} = F_\perp + qv_\perp \times B. \]

Equation 6.1.3-1

To determine the resultant force drift of the particle’s guiding centre, \( \mathbf{V}_F \), it is necessary to transform into the frame of reference of the guiding centre travelling at \( \mathbf{V}_F \) where the particle executes a circular motion under the action of the Lorentz force alone. Finding \( \mathbf{V}_F \) requires that a frame of reference travelling with the guiding centre is found where the external force, \( \mathbf{F}_\perp \), is balanced by the induced electric field caused by the drift of the guiding centre through the magnetic field (\( qE' = qV_F \times B \)):

\[ qE' + F_\perp = F_\perp + qV_F \times B = 0. \]

Equation 6.1.3-2

Multiplying throughout this equation by \( e/qB \):
Chapter 6 – Particle tracing

\[ V_F = \frac{F \times e}{qB} \]

Equation 6.1.3-3

Where \( e \) is the unit vector in the unit vector in the direction of \( B \).

![Cycloid motion diagram](image)

Figure 6.1-2 Cycloid motion of a particle subject to a perpendicular force, resulting in a guiding centre force drift (Roederer, 1970).

The particle moves with a constant velocity \( V_p \) that is perpendicular to both \( B \) and \( F \). No net work is done on the particle and particles drift independently of mass and energy. If the direction of the perpendicular force is not charge dependent then positive and negative particles drift in opposing directions.

6.1.3.2 ELECTROSTATIC DRIFT

If however the electric field provides a charge dependent force, particles drift independently of charge:

\[ V_F = \frac{E \times e}{B} \]

Equation 6.1.3-4

Electric field drift is in the same direction regardless of particle charge. If there are no parallel field components, a 90° pitch angle particle will drift along equipotential lines in a uniform magnetic field where electrostatic potential energy varies little over a cyclotron orbit compared with the particle’s energy. Equation 6.1.3-4 represents the particle motion even if the electric field is not electrostatic, but time varying [Roederer, 1970].
Chapter 6 – Particle tracing

6.1.3.3 GRADIENT DRIFT

If particle motion is modelled within a non-uniform magnetic field with a gradient perpendicular to the magnetic field, at some points in the particle’s gyratory motion its Larmor radius will contract in stronger magnetic field regions (Q and S), and will grow in weaker field regions (P and R). The result will be a net particle motion perpendicular to both the magnetic field and the gradient (Figure 6.1-3).

![Diagram showing effect of perpendicular gradient on particle motion](image)

Figure 6.1-3 The effect of a perpendicular gradient in the magnetic field on the cycloidal motion of a particle (Roederer, 1970).

In Figure 6.1-3, $\rho_c$ is the gyroradius of the particle. For a 90° pitch angle particle in a magnetic field with a perpendicular gradient, a gradient drift occurs at right angles to both gradient and field. The gradient drift velocity $V_G$ is shown in Equation 6.1.3-5, as derived in Roederer [1970] by replacing the effect of the gradient with an equivalent force and calculating the resultant force drift as above.

$$V_G = \frac{1}{2} \frac{mv}{qB} \mathbf{e} \times \nabla B$$

Equation 6.1.3-5

This drift is dependent on both the particle’s energy and charge.
6.1.3.4 CURVATURE DRIFT

If the guiding centre followed a curved field line, any mass in the guiding centre (non-inertial) frame of reference would experience an inertial (centrifugal) force:

\[ F_c = \frac{mv^2}{R_c} \mathbf{n} \]

Equation 6.1.3-6

This force will cause a curvature drift:

\[ \mathbf{V}_c = \frac{mv}{qB^2} \mathbf{e} \times \nabla_\perp \mathbf{B} \]

Equation 6.1.3-7

Again with energy and charge dependencies.

6.1.3.5 SECOND ORDER DRIFTS (INCLUDING POLARISATION)

Second order drifts are caused by time-dependent variations in the drift velocity of particles, such as changes caused by a dynamic magnetic, electric field or a direction-changing drift along a curved equipotential. When a particle is accelerated in this way, an observer in the guiding-centre frame of reference would see an inertial force \(-m\,d\mathbf{V}/dt\). In order to induce a countering electric field in the guiding-centre frame (using the same technique as above to evaluate the resultant drift), the drift must change with the addition of:

\[ \mathbf{V}_s = -\frac{m}{qB^2} \dot{\mathbf{V}} \times \mathbf{B} \]

Equation 6.1.3-8

Figure 6.1-4 A diagram showing a guiding centre’s motion on a curved field line. \(R_c\) is the radius of curvature, \(\mathbf{e}\) is the unit magnetic field vector and \(\mathbf{n}\) its normal [Roederer, 1970].
Chapter 6 – Particle tracing

Polarisation drifts, caused by a time-dependent electric field, are included within this drift term. Note – the coarse time variations of electric field or magnetic field models caused by changes in input parameters (e.g. indices or solar wind values) may cause occasional massive dV/dt's. In order to avoid an unphysical representation, the variations in input parameters were smoothed with time.

6.1.3.6 OTHER DRIFTS

Other drifts such as gravitational drift exist, but contribute minimally to the overall drift velocity of the particle (gravitational drift is negligible for anything over a few eV). These are ignored for the remainder of this work.

6.1.3.7 OVERALL DRIFT VELOCITY EQUATION

When taking into account relativistic considerations, this becomes:

\[ V_D = \frac{e}{qB} \times \left[ -E_q + \frac{m_0\gamma}{2B}(v_\perp^2 + 2v_\parallel^2)B + m_0\dot{\gamma}V_D \right] \]

Equation 6.1.3-9

Where \( m_0 \) is the particles rest mass, \( \gamma = (1 - \beta^2)^{-1/2} \), and \( \beta = v/c \) (relativity becomes important above a few tens of keV).

The inclusion of the dV/dt term results in the solution of the equation being iterative. The initial value of dV/dt is an unknown and is assumed to be zero.

6.1.3.8 CONSTRAINTS

For general guiding centre motion calculations the time variations of fields must be small with respect to the gyroperiod and spatial variations must be small with respect to the gyroradius. For guiding centre gradient drifts, the magnetic field intensity must vary little along the cyclotron orbit:

\[ \rho_c \frac{\nabla B}{B} \ll 1 \]

Equation 6.1.3-10

For curvature drift, the radius of curvature of the field must be much greater than the gyroradius of the particle:
Equation 6.1.3-11

\[ R_c \gg \rho_c \]

In injection signature regions (beyond 4R_e) outside of the particle acceleration region it can be assumed that the above constraints are satisfied for the energy range under consideration.

### 6.1.4 BOUNCE AVERAGING

![Diagram showing a particle trapped in a magnetic bottle between two magnetic mirror points \( \text{Roederer, 1970} \).](image)

Figure 6.1-5 represents the behaviour of trapped particles in the magnetosphere, with magnetic mirror points towards the poles and their positions dependent on the particle's equatorial pitch angle. \( \alpha_i \) is the pitch angle of the particle at the magnetic minima, and \( \alpha_m \) the pitch angle at the magnetic mirror points (90°), where \( B_m \) is the associated field strength.

Drift velocity varies over the full bounce of a particle in the magnetosphere. Between the top and bottom of a bounce the magnetic field strength changes and the orientation of the magnetic field to electric field differ. For the average drift velocity of the particle to be accessed, the drift velocity must be determined for a number of positions along the field line, weighted for the time the particle spends there during a bounce (as \( V_i \) varies), and averaged.
Chapter 6 - Particle tracing

Equation 6.1.4-1  $\tau_b$ represents the time for one complete bounce motion, and $s$ an arc-length of the field line between $S_m$ and $S_m'$, the mirror points.

6.1.4.1 NUMERICAL SOLUTION

One method of bounce average velocity determination is to numerically evaluate the average. The field line is traced until the $|B_{\text{Mirror}}|$ value for the particle is passed. At each node of the field line trace the drift velocity ($V_D$) of the guiding centre is evaluated. To determine the average for the bounce, a weighting value $W$ is approximated from the parallel particle velocity:

$$\frac{1}{2} W_n = \frac{2|N_n - N_{n+1}|}{V_{p n} + V_{p n+1}}$$

Equation 6.1.4-2

Where $N$ represents the position vector of the nodes. Special care is paid to the final weighting for the drift velocity between the final node and the $B_{\text{Mirror}}$ position (determined by linear interpolation) with the particle occupying this region of space a disproportionate amount of time. The treatment of this area is complicated by the presence of a singularity at the $B_{\text{Mirror}}$
point in functions giving time-occupied as a function of distance divided by parallel velocity. This could be circumvented by approximating the guiding centre of the particle as a point mass with an initial velocity, under the action of a retarding force provided by the bunching of magnetic field lines in the region, and treating the final weighting as equal to twice the time the force takes to decelerate the mass to zero in the parallel direction:

\[
\frac{1}{2} W_n = \frac{V_{\|m} m v}{|q V_{\perp} \times B_{p-R_L}|} \cdot \hat{B}
\]

Equation 6.1.4-3 Where \( B_{p-R_L} \) represents the magnetic field assessed one Larmor radius away.

However, guiding centre drifts using this method were too fast and hence this method for handling the singularity \( w \ll s \) dropped. Instead the field line is assessed with over 1,000 nodes to reduce the significance of the region between the final node and bounce point. Calculation of local \( V_\| \) and \( V_\perp \) is made using the magnetic moment and pitch angle for a point \( s \), from:

\[
\sin^2 \alpha_0 \left( \frac{B(s)}{B_0} \right) = \frac{\sin^2 \alpha(s)}{|B(s)|}
\]

Equation 6.1.4-4

\[
v_\| = v \left( 1 - \frac{\sin^2 \alpha_0 B(s)}{B_0} \right)^{\frac{1}{2}}
\]

\[
v_\perp = v \left( \frac{\sin^2 \alpha_0 B(s)}{B_0} \right)^{\frac{1}{2}}
\]

Equation 6.1.4-5

\(<V_D> \) is then calculated:

\[
<V_D> = \frac{\sum_{i} \frac{1}{2} W_i (V_{d_i} + V_{d_{i+1}})}{\sum_{i} W_i}
\]

The resultant bounce-averaged drift vector is applied to the minima point (nominally the guiding centre position). The new position vector is field-line traced to locate a new minima which becomes the new particle position.
Another bounce averaging scheme exists [Roederer, 1970]. In this an equation for the drifts, through a field-geometric argument is transformed into the bounce average equations shown below.

\[
\langle V_D \rangle = \frac{(m_0 \gamma_0 \dot{V}_{D_0} + qE_0) \times \hat{B}_0}{qB_0} + \frac{2m_0 \gamma_0 \nu}{q \tau_b B_0} \nabla_0 I \times \hat{B}_0
\]

Equation 6.1.4-6

Where \( \tau_b \) is the bounce time of the particle, and \( \nabla_0 I \) is the gradient of the invariant integral. It is required that the assessment of \( \nabla_0 I \) is at a high enough resolution that the singularity at the mirror points is well handled. The equation is simply assessed at the magnetic equator (subscript 0 denoting values at the same), however as it requires four field traces it is time consuming.

6.1.4.3 COMPARISON

The two methods are theoretically equivalent methods implemented in different ways. Both ways were used in early testing, typically with up to 1500 field line steps involved for each bounce-averaging operation – dependent on pitch angle. The analytical method was found to be noticeably slower in execution, and produced faster guiding centre velocities than the numerical method. It is noted that prior work has favoured the analytical implementation from Roederer [1970], although as the numerical method gave better fits to multiple observations of echo times, the faster-executing numerical method was used for all work.

6.2 TRACING ALGORITHM

6.2.1 RUNGE-KUTTA TECHNIQUE

The Runge-Kutta technique is used to give higher accuracy when integrating an ordinary differential equation. The particle trajectory tracing involves the integration of a drift velocity equation to get position, and hence the Runge-Kutta method is applicable and provides improved accuracy when compared with Euler’s method.

\[
P_{n+1} = P_n + hf'(P_n)
\]

Equation 6.2.1-1 Euler’s method, where \( P \) represents the time-series position of the particle, \( f' \) is the velocity function, and \( h \) is the interval through which the solution is to be advanced.
Chapter 6 – Particle tracing

Figure 6.2-1 Top panel: Euler method of solving a differential equation: iterative evaluation of the function incrementing the position in steps of length $h$. Bottom panel: Runge-Kutta method where a 'trial step' of $\frac{h}{2}$ is first tried to get to (2) and the function re-evaluated there to give a result used to get from (1) to (3). [Numerical Recipes, Press, 1986].

The second order Runge-Kutta method advances the solution initially by only $\frac{1}{2}h$ to evaluate the differential equation at a midway point, and uses that evaluation to advance from one iteration position to the next.

$$k_1 = hf'(P_n)$$
$$k_2 = hf'(P_n + \frac{1}{2}k_1)$$
$$P_{n+1} = P_n + k_2$$

Equation 6.2.1-2

The method results in a greater accuracy when tracing curved lines, for a low penalty in terms of algorithmic complexity. The second order technique doubles computational load compared with the Euler method for the same step size, but this is acceptable for the improved accuracy in evaluating velocity drifts and tracing curved field lines. Higher order Runge-Kutta techniques exist, but were judged unnecessarily complicated for this application, and this could easily be translated to implementation errors.
6.2.2 ADAPTIVE STEP-SIZE TIMING MECHANISM

Many particle tracing algorithms work on the basis of fixed time slices and the solution of
differential equations for each full time step. This is acceptable for tracing the progress of a few
particles of relatively narrow energy range. However, if a particle of much higher energy is
encountered, the fixed time step can cause the particle to sweep through a great distance per
iteration, perhaps with resultant inaccuracies. Conversely, a particle of much lower energy may
only crawl along taking an unnecessarily long computation time to travel through a relatively
mundane region of the magnetosphere. The solution implemented in this work was to specify
the accuracy of the tracing not in terms of a fixed time-slice for each iteration, but a fixed
distance the particle must move each iteration. Specifying a scale-length for particle movement
allowed the algorithm to treat the paths of high energy and low energy particles with the same
level of relative accuracy, and allowed the accuracy of each trace to be specified in terms of a
scale-length of the local magnetosphere.

6.2.3 CO-ORDINATE SYSTEM

The co-ordinate system chosen in which to conduct the particle tracing was the Solar Magnetic
(SM) system:

<table>
<thead>
<tr>
<th>Axis</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>In the Sun-Earth line/dipole axis plane, perpendicular to the dipole axis</td>
</tr>
<tr>
<td>Y</td>
<td>Completes the right handed system (roughly opposite to Earth’s orbital motion)</td>
</tr>
<tr>
<td>Z</td>
<td>Anti-parallel to the magnetic moment (positive northward)</td>
</tr>
</tbody>
</table>

Table 6.2-1 The SM co-ordinate system.

The solar magnetic co-ordinate system is aligned to the Earth’s magnetic field which dominates
near Earth particle motion, and motion in the near Earth tail regions. The Geocentric Solar
Magnetospheric system could have been used – the external magnetic field models are supplied
in this system – but the SM system was selected as it is the natural system of the dominant
dipolar field component. Frequently executed internal magnetic field models $B_{\text{int}}$ generate
results with inputs and outputs in the SM system, as does the co-rotational electric field model
(by dependency on $B_{\text{int}}$). This resulted in the SM system being the default to minimise
computational overheads and inaccuracies introduced by conversions. The use of this co-
ordinate system reduces the need for any consideration of the dipole tilt angle close to the Earth
when interpreting results, as would be required for interpreting results presented in the
Geocentric Solar Magnetospheric system (where the x-component is parallel to the Earth-Sun
line). Care however must be taken interpreting results in the tail region as the dipole tilt angle
will pitch the tail above and below the $z = 0$ plane with yearly and diurnal periods.
6.2.4 TRANSFORMATIONS

The above decision required that values from models and data sources in other systems be converted to and from the SM system. The Geographic/Solar Magnetic/Geocentric Solar Magnetospheric set of transformations used in the tracing program were derived from Hendrix [1996]. The transformations are derived and implemented as a series of component rotations [Hapgood, 1992], which are a function of date, time, and tilt angle.

6.2.4.1 VALIDATION OF TRANSFORMATIONS

Validation was conducted by ensuring the transformations used together with inverses resulted in near-unity matrices being generated. As a precautionary measure against accidental inaccuracies being introduced, a continuous check occurs within the tracing program. Every time a CRRES ephemeris record is read the transformations are run with random parameters and the results input to the inverse transformation. The output is compared with the initial random parameters and processing is stopped if a discrepancy is found.

The transformations are also compared with the position for CRRES as given in the spacecraft's ephemeris data in various geocentric co-ordinate systems. Discrepancies of 500 to +500 km occur between these values over an orbit – this is assumed to be attributable to the ephemeris data using a transformation system which takes into account the 400 km offset in the magnetic dipole's position and the spin axis. A 400km inaccuracy is assumed insignificant for the purposes of particle tracing and accounting for the offset would complicate and slow the tracking program to an extent unwarranted by the gain in accuracy.
Chapter 6 – Particle tracing

6.2.5 ALGORITHM

```plaintext
if (time to move particle again) {
    old_P = P
    V(P) = Bounce_Averaged_Drift_Velocity(P)

    // Adaptive Timing Algorithm - Make particle move by set distance (ΔD)
    ΔT = ΔD / V(P)
    ΔP = (V(P) / 2) * (double) ΔT
    P' = P + ΔP

    // Delta_Position is the offset to the Runge Kutta mid-point
    V(P') = Bounce_Averaged_Drift_Velocity(P')
    ΔT = ΔD / V(P')
    ΔP = V(P') * ΔT

    // New position is the B_MIN on the field line we’ve just moved onto
    Trace_Field_Line(P+ΔP)
    P = B_Min_Position
    ΔP = P-old_P

    // Calculate the new parameters for the particle, taking into account energy transactions with the electric field
    ΔW = E(P).q.ΔP
    if (((y - 1) * m * c * c + ΔW < 0)
        kill particle - its out of energy
    else{
        γ = (γ * m * c * c + ΔW) / (m * c * c)  // Assess (non + rest mass) energy
        W = (y - 1) * m * c * c  // 'Non-relativistic' energy
        V = √((c * c * (1 - 1/γ²))

        // Calculate new mirror point magnetic field magnitude from first adiabatic invariant and energy gain/loss
        B_Mirror = γ² * V * V * m / (2μ)  // Perp kinetic energy / μ
    }
}
```

if (B_Min < B_Mirror) // Is movement
    α₀ = |sin⁻¹ (ν(B_Min/B_Mirror))| // Use sin⁻¹ (90) / B = sin⁻¹ (PA) / B_MIN to get new pitch angle
else {
    b_mirror = b_min * 1.01 // Steals energy from perpendicular motion, and a bit more
    α₀ = |sin⁻¹ (ν(B_Min/B_Mirror))|
    μ = γ² * V² * m / (2.B_Mirror) // Here is a forced alteration of μ
}
```

// Adaptive Timing Algorithm - Make particle move by set distance. Assume the particle moves at the same speed for
the next iteration, and work out when to next calculate its movements
```
```
```n
if (boundary_and_earth_atmospheric_collision_checks(P))
```

Figure 6.2-2 Particle tracing algorithm – the particle movement algorithm is executed for each particle in
an incrementing time-loop.

126
6.2.6 HANDLING OF SPECIAL CASE SITUATIONS

6.2.6.1 OUT OF PARALLEL ENERGY

During the execution of the algorithm energy can be gained or lost to the electric field. If the particle runs out of energy, tracing is suspended. If however the simulated particle still has energy, but has exhausted its parallel energy (i.e. its new \( B_{\text{mirror}} \) value would be less than the minima on the field line) then energy must be extracted from the perpendicular velocity – this violates the first adiabatic invariant. The only other alternative would be to drift along an equipotential – although the rationale for doing this in favour of violating \( \mu \) is weak, and it would cause additional processing. This is a non-ideal resolution of the problem – a wave-particle interaction or high frequency change to the magnetic field could promote the particle to another \( \mu \)-state when considering the particle moving forward in time, although this is an imprecise argument. Communications with another researcher actively engaged in particle tracing in electric fields has shown no obviously better solution. When particle drift requires that the first adiabatic invariant be violated, this may actually be a case of tracing a particle that could not exist with the specified start parameters in the specified start place – as is discussed in Chapter 7.

6.2.6.2 MIRROR POINT BELOW SURFACE /OUT OF BOUNDS

Should the particle mirror within atmospheric altitudes or leave a bounding box surrounding the Earth, particle tracing is halted. The box extends for 13 Earth radii in all directions, except for the \(-x\) direction where up to 30 Earth radii downtail is permitted (although simulations rarely proceed that far).

6.3 MAGNETOSPHERIC MAGNETIC FIELD MODELS

The tracing of particle paths in the magnetosphere requires magnetic field models as a function of time and position. Magnetospheric field models are usually supplied as external components induced by magnetospheric current systems, and internal components caused by the magnetic-dipole, and are superimposed to produce a composite field model. Tracing particles during substorm events, where by definition the magnetosphere is undergoing considerable magnetic reconfiguration, adds considerable complexity to obtaining good particle traces. This section addresses the problem by attempting to adapt existing field models to reflect substorm magnetic field development.

6.3.1 INTERNAL FIELD MODEL

The internal field model used is the standard International Geomagnetic Reference Field (IGRF) 1990 empirical model assessed to the thirteenth harmonic. The model uses spherical
harmonics to represent the scalar potential in geocentric co-ordinates, with coefficients based on data from magnetic stations, satellites, marine vessels and aircraft. The IGRF models are weighted means of models developed by various agencies around the world. Coefficient sets exist for each five-year period from 1945 to 1995. During the periods between consecutive models, linear interpolation is recommended. In this implementation however, the 1990 set of coefficients have been used exclusively, with a drift adjustment for the number of days elapsed since 1\textsuperscript{st} January 1990. This was sufficient for the CRRES epoch that extended only as far as October 1991. Although a number of other models exist, the IGRF model is de facto standard in the field. The IGRF model has a relatively insignificant evaluation time in comparison with external models, and is highly accurate in comparison with external field model discrepancies.

6.3.2 EXTERNAL FIELD MODELS

The following external magnetic field models were considered for particle tracing work:

- Olson-Pfitzer dynamic [Olson and Pfitzer, 1982; Pfitzer et al, 1988],

- Tsyganenko 1989c [Tsyganenko, 1989],

- Tsyganenko 1996a [Tsyganenko, 1996],


The latter model has substorm adaptations fitted to GOES 6, GOES 7 and CRRES magnetometer data with a SCW module included. After performance and comparison with candidate-substorm period magnetic field data, this variant of Tsyganenko’s 1996a model was used for the particle tracing work due to its close fit to the measured data.

6.3.2.1 TSYGANEKO 1996 MODEL

Tsyganenko 1996 is a data-based geomagnetospheric magnetic field model with an explicitly defined magnetopause; ring current; tail current; large-scale Region 1 and 2 Birkeland current systems; and IMF penetration across the magnetopause boundary. Respectively the contributions of these current systems to the overall Tsyganenko 96 model are shown below.

\[
\mathbf{B}_{\text{External}} = \mathbf{B}_{\text{Magnetopause}} + \mathbf{B}_{\text{RingCurrent}} + \mathbf{B}_{\text{Tail}} + \mathbf{B}_{\text{BirkelandRegion}_1} + \mathbf{B}_{\text{BirkelandRegion}_2}
\]

Equation 6.3.2-1
Each term is a function of its own set of indices and/or solar wind parameters, and the net model field was least squares fitted to a statistically applied database of spacecraft magnetometer data, dipole tilt angle, geomagnetic indices and solar wind measurements. This least squares fitting resulted in regression coefficients for each input parameter for the response-functions. However, geomagnetic indices can often be imprecise indicators of magnetospheric state and substorm activity, and hence this fitting results in a model that may not reflect magnetic configuration in substorms. Rather, this model returns an average of the magnetospheric state derived from the range of database points corresponding to the input permutation of parameters.

The calibration of the predicted fields by using in-situ magnetometer data leads to less reliable models in regions or under conditions where few observations exist, e.g., high-latitude lobes, or extremes of solar wind pressure. It should be noted that model predictions could also be unreliable in highly time-variable situations such as substorms, although attempts can be made to devise individually event-tailored models by using contemporary magnetometer data to calibrate current systems within the models.

This model responds to a number of parameters. Previous Tsyganenko models [Tsyganenko, 1989] were calibrated only by Kp-index, and hence did not allow proper modelling of solar
wind effects. This model is a function of solar wind IMF orientation in the YZ plane, solar wind dynamic pressure, dipole tilt, and Dst index (in particle tracing work the solar wind variables come from IMP-8 data where possible).

6.3.3 GROWTH/EXPANSION/RECOVERY PHASE ADAPTATIONS

Prior to and during substorm injections the magnetic field deviates from average conditions. Magnetic field models provide only a limited imprecise response to substorm conditions through the use of geomagnetic indices. Tsyganenko [1996] and other models make no specific allowance for substorm stage. This poses a difficulty for particle tracing during substorms, as only averaged magnetic field models are available in distinctly non-average situations. Pulkkinen [1991, 1992, 1994] makes data-fitted adjustments to the model current systems to allow for the theorised global magnetic development of substorms from growth through to recovery stages, providing a more accurate field model for substorm particle tracing. This methodology is followed here.

During the growth phase the magnetic configuration is observed to change with an increase of the tail flux, and a thinning of the near-Earth current sheet. The expansion phase sees a rapid thickening of the current sheet, decrease in tail flux and the activation of the substorm current wedge. During the recovery phase the alterations to the magnetospheric current systems subside. To reflect these changes, substorm-time dependent modifications are made, on the basis of magnetometer data, to the effected current systems providing contributions to the Tsyganenko 1996 model.

6.3.3.1 CURRENT SHEET THINNING

Current sheet half thickness, D, contributes to the ring current \( (B_{rc}) \) and tail current \( (B_T) \) terms in Tsyganenko [1996] (Equation 6.3.2-1). Pulkkinen [1991, 1994] moderates the contribution of D with a coefficient that is temporally and spatially dependent:

\[
D 
\rightarrow f(X,Y,t) \cdot D
\]

\[
f(X,Y,t) = \left[ 1 + \frac{A(t)}{\cosh^2 \left( \frac{X - X_m}{\Delta X} \right) + \frac{1}{(\frac{Y}{\Delta Y})^2}} \right]
\]

Equation 6.3.3-1 A variation on Pulkkinen's modifier for D, current sheet half thickness [1991, 1994].

\( X_m \) defines the location, and \( \Delta X \) and \( \Delta Y \) the scale size of the thinned region with X and Y the co-ordinates of the evaluation point. From spacecraft observations it has been deduced that \( X_m \approx -10 \, R_E \), although \( X_m, \Delta X \) and \( \Delta Y \) are all variables which may be fitted to each individual
subsection from example in Pulkkinen [1991] $\Delta X$ and $\Delta Y$ can have values of 8 $R_E$ and 4 $R_E$ respectively.

\[
\begin{align*}
A(-T_G) &= 0 \\
A(0) &= A_{\min} \\
A(T_E) &= A_{\max} \\
A(T_R) &= 0
\end{align*}
\]

**Equation 6.3.3-2**

$A(t)$ is a function decreasing from zero to a value of $A_{\min}$ over the growth phase ($t = -T_G$ to 0), increasing to $A_{\max}$ over the expansion phase ($t = 0$ to $T_E$) and then decreasing back to zero over the recovery ($t = T_E$ to $T_R$). The time evolution of $A(t)$ is assumed to be linear.

### 6.3.3.2 TAIL FLUX INCREASE

The increase of tail flux implies an increase in the cross-tail current, and requires that the tail field term $B_T$ be increased:

\[
B_T \rightarrow (1 + f_T(t))B_T
\]

**Equation 6.3.3-3**

Where $f_T(t)$ is a function starting at zero at the beginning of the growth phase, reaching maximum at onset ($f_{T-MAX}$), decreasing to a minimum at the end of expansion ($f_{T-MIN}$), and returning to zero after recovery.

\[
\begin{align*}
f_T(-T_G) &= 0 \\
f_T(0) &= f_{T-MAX} \\
f_T(T_E) &= f_{T-MIN} \\
f_T(T_R) &= 0
\end{align*}
\]

**Equation 6.3.3-4**

As the cross tail current closes across the magnetopause, the surface magnetic field term (the result of the return current over and under the magnetopause) must increase by a corresponding amount. In Tsyganenko’s 1989 model an independent mathematical construct exists for the term ($B_{Sc}$) allowing this corresponding increase. In Tsyganenko’s 1996 model this does not exist. Instead a potential is fitted to a defined magnetopause shape generating tail shielding field, reacting to any increase in the $B_T$ term and solely multiplying this by the modifier maintains model consistency.
6.3.3.3 RING CURRENT MODIFICATION

The ring current term $B_{rc}$ is allowed to decrease or increase over the expansion phase:

$$B_{rc} \rightarrow (1 + f_{rc}(t))B_{rc}$$

Equation 6.3.3-5

The decision to allow the ring current term to either increase or decrease post-onset arises from the expectation that substorm activity will increase the ring current, and Pulkkinen's [1994] approach which results in the term decreasing the ring current at the end of the expansion phase. Pulkkinen [1998] indicates Tsyganenko's model current systems and real magnetosphere current systems fail to map as their mutual naming suggests they should. The result of modifying the coefficient in terms of increasing or decreasing $B_z$ depends upon the position of the model ring current and the model evaluation position. In T96 the ring current is modelled with a maximum current between 6 – 8 Re. This results in a decrease in the ring current causing $B_z$ to increase inside geostationary space – i.e. the effect at the start of the onset and allowed for by Pulkkinen's negative coefficients. Regardless of this, ring current activity should increase, not decrease, and to keep the adapted model aligned to theorised phenomenological development the ring current term was allowed to be positive should the fitting require this. All values fitted to substorm conditions were positive values, although due the arbitrary distribution of fit values, no conclusions are drawn from this.

$f_{rc}(t)$ is a function starting at zero at onset, assumed reach a maximum/minimum ($f_{rc}^{\text{MAX}}$) at the end of the expansion phase and decreasing in magnitude over a time-scale much longer than that of recovery, such that the coefficient may be effectively regarded as constant over the recovery phase. This is a second departure from Pulkkinen's scheme [1994] where the term $f_{rc}$ reduces to zero over the recovery phase and was made as the ring current may retain current fluxes long after a recovery phase has ended, keeping the modification scheme as physically realistic as possible.

$$f_{rc}(0) = 0$$
$$f_{rc}(T_E) = f_{rc}^{\text{MAX}}$$
$$f_{rc}(T_R) = f_{rc}^{\text{MAX}}$$

Equation 6.3.3-6

This is in keeping with observations that Dst values decay over periods of order hours to days or months as the ring current decays after a storm, with pitch angle scattering of ions into the loss cone by neutral interaction.

132
6.3.3.4 SUBSTORM CURRENT WEDGE COMPONENT

The formation of a substorm current wedge after onset is believed to be the principal cause of major reconfiguration of the magnetospheric field on the nightside. Dynamic model representations of the magnetosphere magnetic field would be incomplete without this component, but the substorm current wedge has been missing in all available models, partly due to its geometrical complexity. Tsyganenko has provided an implementation of a simple analytical model for the magnetic field produced by the substorm current wedge.

The key element of the wedge is the vector potential of a pair of current loops. Applying appropriate shift, rotation, and stretch transformations makes it possible to obtain a suitable geometry for the system, including field-aligned currents. The model current wedge has a variable longitudinal width and can be further generalised by including warping effects due to the tilt of Earth's dipole. The model can be added to Tsyganenko data-based models of the magnetosphere and makes it possible to reproduce the fast restructuring of the near-Earth field during the explosive phase of a substorm [adapted from abstract Tsyganenko, 1997]. The model contains a number of parameters to vary the geometry of the wedge, and one parameter that adjusts the strength of the wedge field. To simplify fitting to magnetometer data, the geometry parameters are constant at Tsyganenko's suggested values, and the amplitude term is fitted to a maximum value.

The amplitude parameter:

\[
Ampl(t) = Ampl_{MAX} \cdot f_{SCW}(t)
\]

Equation 6.3.3-7

Where \( f_{SCW}(t) \) is varied linearly with:

\[
f_{SCW}(0) = 0
\]
\[
f_{SCW}(T_E) = 1
\]
\[
f_{SCW}(T_R) = 0
\]

Equation 6.3.3-8

6.3.3.5 EVALUATION OF SUBSTORM FIELD MODIFIERS

Individual parameters were varied and their effects on \( B_{MEAS} - B_{MODEL} \) plotted to determine their individual effects and magnitudes. The \( f_{T\text{MIN/MAX}} \) (tail flux) parameters were significant manipulators of the Tsyganenko model, with co-efficients between -1 and +1 capable of causing the characteristic pre-onset decrease, and the post-onset increases. The variation of \( A_{MIN} \) and \( A_{MAX} \) (current sheet thickness) produced variation in the senses expected, and were
as significant as the tail flux parameters. Ring current decrease by a negative \( f_{\text{RC-MAX}} \) was found to increase model values at geostationary orbit in the tail – the effect observed in dipolarisation data during the expansion phase. Results from changing AmplMAX gave ambiguous results, and effects that were far smaller in magnitude than changing the other free parameters.

6.3.3.6 Fitting Substorm Field Modifiers to Magnetometer Data

In summary, for the theoretical scheme of magnetic development in the magnetosphere the temporal evolution of the free-parameters in the modifications is as follows:

![Diagram showing the duration of individual modifications to the magnetospheric current systems in T96 and SCW modules.](image)

Note the relative magnitudes of each modification are incidental to the schematic. Applying the SCW and Pulkkinen modifications to the T96 model required identification of the starts and durations of the substorm phases. The free parameters in the above equations were fitted to 1-minute data from GOES 6, GOES 7, and CRRES where available and appropriately positioned in the tail (MLT = 00 +/-6 hours, and L > 5 Re).

The free parameters fitted to each substorm were \( A_{\text{MIN}}, A_{\text{MAX}}, f_{\text{MIN}}, f_{\text{MAX}}, f_{\text{RC-MAX}}, \) and AmplMAX, along with the three parameters associated with current sheet thinning geometry.

Fitting was done with two different merit functions:

\[
\sum_{i=1}^{N} \int_{t=T_i}^{T_i+T} \left( B_{\text{MEAS}} - B_{\text{MODELS}}(P, A_{\text{MIN}}, A_{\text{MAX}}, f_{\text{MIN}}, f_{\text{MAX}}, f_{\text{RC-MAX}}, \text{AmplMAX}) \right)^2 dt
\]

Equation 6.3.3-9 Least squares fit of \( B_{\text{MEAS}} \) - \( B_{\text{MODELS}} \). \( P \) represents spacecraft position.
Equation 6.3.3-9 provided a merit function whose least-squares fit proved susceptible to noise in the magnetometer data sets and was overly biased with noise spikes (averaging was not possible in the fitting program). Equation 6.3.3-10 provided the best fit judged numerically and by eye. The parameter sets provided by the least-difference fit were used in later work.

Parameter-space was searched with the objective of minimising the fitting functions. A full search of all parameter space would have taken 100,000 years for all 187 events, so a partial search was made for each of a subset of 56 events selected for possible tracing (on the basis of spacecraft positioning and magnetospheric activity). This resulted in a more acceptable run time of days. The partial search varied each parameter in turn, whilst others were kept at fixed values (either initial values, or the values determined from prior iterations). The order of parameters searching was defined by the significance they had on the overall field model, with the significant parameters being searched first, and hence favouring them in case that more than one local minima exists in parameter space. Table 6.3-1 represents the scope and order of the parameter search.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bound#1</th>
<th>Bound#2</th>
<th>Increment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{T\text{-MAX}}$</td>
<td>0.00</td>
<td>2.20</td>
<td>0.01</td>
</tr>
<tr>
<td>$f_{T\text{-MIN}}$</td>
<td>0.00</td>
<td>-1.00</td>
<td>-0.05</td>
</tr>
<tr>
<td>$X_M$</td>
<td>-5</td>
<td>-15</td>
<td>+0.50</td>
</tr>
<tr>
<td>$\Delta X$</td>
<td>2</td>
<td>15</td>
<td>+0.50</td>
</tr>
<tr>
<td>$\Delta Y$</td>
<td>0.5</td>
<td>8</td>
<td>+0.50</td>
</tr>
<tr>
<td>$A_{\text{MAX}}$</td>
<td>0.00</td>
<td>15.00</td>
<td>0.05</td>
</tr>
<tr>
<td>$A_{\text{MIN}}$</td>
<td>0.00</td>
<td>-1.00</td>
<td>-0.005</td>
</tr>
<tr>
<td>$f_{E\text{MAX}}$</td>
<td>-1.00</td>
<td>6.00</td>
<td>0.20</td>
</tr>
<tr>
<td>$\text{Ampl}_{\text{MAX}}$</td>
<td>0.00</td>
<td>1400</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 6.3-1 Scope of the parameter search for T96 model fitting.

The above search strategy assumes that the merit function evaluated over parameter space has only one local minima: with the complexity of magnetic field data and the possibly contrary effects of the parameters, this may not be the case. To reduce the possibility of a local minima being found, a second pass was made with the fitting algorithm using the set of parameters found in the first pass as a starting point. Variations in the two sets were minimal, and mostly attributable to using a coarser increment for each variable in the first pass.
## 6.3.3.7 RESULTS

<table>
<thead>
<tr>
<th>Event</th>
<th>A&lt;sub&gt;min&lt;/sub&gt;</th>
<th>A&lt;sub&gt;max&lt;/sub&gt;</th>
<th>f&lt;sub&gt;max&lt;/sub&gt;</th>
<th>f&lt;sub&gt;min&lt;/sub&gt;</th>
<th>f&lt;sub&gt;remin&lt;/sub&gt;</th>
<th>Ampl&lt;sub&gt;max&lt;/sub&gt;</th>
<th>ft&lt;sub&gt;delta X&lt;/sub&gt;</th>
<th>ft&lt;sub&gt;delta Y&lt;/sub&gt;</th>
<th>ft&lt;sub&gt;Xmin&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>-0.81</td>
<td>0.2</td>
<td>1.6</td>
<td>-0.4</td>
<td>0</td>
<td>7</td>
<td>5</td>
<td>-12</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>15</td>
<td>0.2</td>
<td>0</td>
<td>300</td>
<td>4</td>
<td>1</td>
<td>-11.5</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>2.8</td>
<td>0.125</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>4</td>
<td>11.5</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>0</td>
<td>1.4</td>
<td>0</td>
<td>2</td>
<td>300</td>
<td>4</td>
<td>1</td>
<td>-12</td>
</tr>
<tr>
<td>11</td>
<td>-0.55</td>
<td>0.8</td>
<td>1.4</td>
<td>0</td>
<td>0</td>
<td>12</td>
<td>5</td>
<td>-12</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>-0.15</td>
<td>2.3</td>
<td>0.925</td>
<td>0</td>
<td>0.75</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>-12</td>
</tr>
<tr>
<td>14</td>
<td>-0.75</td>
<td>0.1</td>
<td>1.35</td>
<td>0</td>
<td>0.5</td>
<td>100</td>
<td>12</td>
<td>5</td>
<td>-12</td>
</tr>
<tr>
<td>17</td>
<td>0</td>
<td>0</td>
<td>1.45</td>
<td>0</td>
<td>3.75</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>-12</td>
</tr>
<tr>
<td>18</td>
<td>0</td>
<td>0</td>
<td>1.625</td>
<td>0</td>
<td>2.5</td>
<td>0</td>
<td>4</td>
<td>5</td>
<td>-12</td>
</tr>
<tr>
<td>21</td>
<td>0</td>
<td>0.9</td>
<td>0.4</td>
<td>0</td>
<td>1.25</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>-7</td>
</tr>
<tr>
<td>28</td>
<td>-0.99</td>
<td>0</td>
<td>1.1</td>
<td>0</td>
<td>1.25</td>
<td>0</td>
<td>8.5</td>
<td>2</td>
<td>-12</td>
</tr>
<tr>
<td>31</td>
<td>0</td>
<td>2.1</td>
<td>1.475</td>
<td>0</td>
<td>0.75</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>-12</td>
</tr>
<tr>
<td>32</td>
<td>-0.94</td>
<td>0</td>
<td>1.275</td>
<td>0</td>
<td>1.75</td>
<td>0</td>
<td>12</td>
<td>5</td>
<td>-12</td>
</tr>
<tr>
<td>33</td>
<td>-0.99</td>
<td>0</td>
<td>1.325</td>
<td>0</td>
<td>8</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>-12</td>
</tr>
<tr>
<td>34</td>
<td>-0.89</td>
<td>0</td>
<td>1.05</td>
<td>0</td>
<td>0</td>
<td>12</td>
<td>5</td>
<td>-9.5</td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>0</td>
<td>0</td>
<td>0.75</td>
<td>0</td>
<td>2.25</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>-12</td>
</tr>
<tr>
<td>43</td>
<td>-0.96</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2.25</td>
<td>0</td>
<td>4</td>
<td>5</td>
<td>-9</td>
</tr>
<tr>
<td>49</td>
<td>-0.92</td>
<td>0</td>
<td>0.775</td>
<td>0</td>
<td>6</td>
<td>0</td>
<td>12</td>
<td>5</td>
<td>-9</td>
</tr>
<tr>
<td>51</td>
<td>0</td>
<td>1.3</td>
<td>0.65</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>-7</td>
<td></td>
</tr>
<tr>
<td>52</td>
<td>0</td>
<td>1.3</td>
<td>0.65</td>
<td>0</td>
<td>0</td>
<td>12</td>
<td>5</td>
<td>-9</td>
<td></td>
</tr>
<tr>
<td>65</td>
<td>0</td>
<td>2.5</td>
<td>0.325</td>
<td>0</td>
<td>0.25</td>
<td>600</td>
<td>4</td>
<td>1</td>
<td>-12</td>
</tr>
<tr>
<td>67</td>
<td>0</td>
<td>0</td>
<td>0.75</td>
<td>0</td>
<td>300</td>
<td>4</td>
<td>1</td>
<td>-12</td>
<td></td>
</tr>
<tr>
<td>74</td>
<td>0</td>
<td>6.5</td>
<td>0.75</td>
<td>-0.35</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>-12</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>0</td>
<td>5.5</td>
<td>0.8</td>
<td>-0.3</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>-12</td>
<td></td>
</tr>
<tr>
<td>81</td>
<td>-0.15</td>
<td>3</td>
<td>0.7</td>
<td>-0.05</td>
<td>0.25</td>
<td>4</td>
<td>1</td>
<td>-7</td>
<td></td>
</tr>
<tr>
<td>83</td>
<td>-0.99</td>
<td>5.3</td>
<td>0</td>
<td>-0.5</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>-7</td>
<td></td>
</tr>
<tr>
<td>84</td>
<td>-0.15</td>
<td>3.9</td>
<td>0.925</td>
<td>0</td>
<td>0.75</td>
<td>12</td>
<td>7</td>
<td>-7</td>
<td></td>
</tr>
<tr>
<td>88</td>
<td>0</td>
<td>1.7</td>
<td>0.65</td>
<td>-0.1</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>-7</td>
<td></td>
</tr>
<tr>
<td>92</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>102</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>8</td>
<td>0</td>
<td>4</td>
<td>5</td>
<td>-12</td>
<td></td>
</tr>
<tr>
<td>106</td>
<td>-0.75</td>
<td>0</td>
<td>1.85</td>
<td>0</td>
<td>6</td>
<td>0</td>
<td>4</td>
<td>5</td>
<td>-12</td>
</tr>
<tr>
<td>112</td>
<td>-0.99</td>
<td>0</td>
<td>0.8</td>
<td>0</td>
<td>1.25</td>
<td>0</td>
<td>12</td>
<td>5</td>
<td>-7</td>
</tr>
<tr>
<td>129</td>
<td>-0.05</td>
<td>0.7</td>
<td>0.275</td>
<td>-0.86</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>-7</td>
<td></td>
</tr>
<tr>
<td>139</td>
<td>0</td>
<td>0</td>
<td>0.375</td>
<td>-0.75</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>-7</td>
<td></td>
</tr>
<tr>
<td>141</td>
<td>0</td>
<td>3.8</td>
<td>0.45</td>
<td>-0.6</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>-7</td>
<td></td>
</tr>
<tr>
<td>142</td>
<td>0</td>
<td>3.6</td>
<td>0.15</td>
<td>-0.2</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>-7</td>
<td></td>
</tr>
<tr>
<td>145</td>
<td>0</td>
<td>1.8</td>
<td>0.2</td>
<td>0</td>
<td>1.75</td>
<td>400</td>
<td>4</td>
<td>2</td>
<td>-12</td>
</tr>
<tr>
<td>151</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>152</td>
<td>-0.1</td>
<td>5.7</td>
<td>0.4</td>
<td>-0.15</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>-12</td>
<td></td>
</tr>
<tr>
<td>153</td>
<td>0</td>
<td>10.2</td>
<td>0</td>
<td>-0.45</td>
<td>0</td>
<td>4</td>
<td>4.5</td>
<td>-11</td>
<td></td>
</tr>
<tr>
<td>155</td>
<td>0</td>
<td>1.7</td>
<td>0.3</td>
<td>-0.35</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>-7</td>
<td></td>
</tr>
<tr>
<td>158</td>
<td>0</td>
<td>10.1</td>
<td>0</td>
<td>-0.25</td>
<td>0</td>
<td>4</td>
<td>1.5</td>
<td>-10.5</td>
<td></td>
</tr>
<tr>
<td>160</td>
<td>0</td>
<td>14.4</td>
<td>0</td>
<td>-0.88</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>-10</td>
<td></td>
</tr>
<tr>
<td>163</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>166</td>
<td>-0.75</td>
<td>4.4</td>
<td>0.025</td>
<td>-0.97</td>
<td>0</td>
<td>4.5</td>
<td>5</td>
<td>-11.5</td>
<td></td>
</tr>
<tr>
<td>167</td>
<td>0</td>
<td>10.8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>168</td>
<td>-0.99</td>
<td>1.25</td>
<td>0</td>
<td>1.75</td>
<td>0</td>
<td>12</td>
<td>5</td>
<td>-7</td>
<td></td>
</tr>
<tr>
<td>170</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.75</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>171</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.75</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>173</td>
<td>0</td>
<td>11</td>
<td>0</td>
<td>-0.3</td>
<td>1</td>
<td>800</td>
<td>4</td>
<td>1</td>
<td>-12</td>
</tr>
<tr>
<td>180</td>
<td>-0.99</td>
<td>2.1</td>
<td>0.525</td>
<td>0</td>
<td>3.75</td>
<td>400</td>
<td>4</td>
<td>1</td>
<td>-12</td>
</tr>
<tr>
<td>181</td>
<td>-0.87</td>
<td>0</td>
<td>0.175</td>
<td>0</td>
<td>1.25</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>-7</td>
</tr>
<tr>
<td>185</td>
<td>-0.35</td>
<td>0</td>
<td>0</td>
<td>-0.99</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>-7</td>
<td></td>
</tr>
<tr>
<td>186</td>
<td>0</td>
<td>10.8</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
<td>4</td>
<td>1.5</td>
<td>-10.5</td>
<td></td>
</tr>
</tbody>
</table>

Averages: 
-0.27821, 2.428571, 0.620536, -0.18893, 1.21875, 57.41286, 4.785714, 1.919643, -8.61607

Table 6.3-2 Magnetic field fitting coefficients.
6.3.4 COMPARISON WITH SPACECRAFT DATA

The average disagreement ($\Delta B_{AV}$) for each event was assessed between $t = -1$ to $t = +1$ hours relative to each onset as per Equation 6.3.4-1. This was done for each of the four external models (plus the IGRF 1990 internal model). The IGRF model was also assessed in isolation. As this study chiefly concerns particle motion in the outer magnetosphere and the inner magnetospheric regions can have disproportionately large absolute errors for small relative model errors, data and models were only compared when CRRES was at L-shells greater than 4 $R_E$. The total disagreements for each model, summed over all events, are presented in the following table. Computational time indices are also shown for comparison.

$$\Delta B_{AV} = \frac{\sum_{t=-1}^{t=+1} \sum_{CRRES, GOES} \int_{t}^{t+1} (B_{MEAS} - B_{MODEL}(P)) \, dt}{N}$$

Equation 6.3.4-1 Comparison of magnetometer data and model values. $P$ represents spacecraft position.

<table>
<thead>
<tr>
<th>Model</th>
<th>Average difference per data point</th>
<th>Normalised</th>
<th>Execution time ($t_{in} + t_{on} / t_{on}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGRF 1990</td>
<td>146</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Olson-Pfitzer 85</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Tsyganenko 89c</td>
<td>123</td>
<td>0.84</td>
<td>2.26</td>
</tr>
<tr>
<td>Tsyganenko 96a</td>
<td>109</td>
<td>0.74</td>
<td>15.99</td>
</tr>
<tr>
<td>Tsyganenko 96 fitted Pulkkinen adaptations and SCW module</td>
<td>99</td>
<td>0.67</td>
<td>16.11</td>
</tr>
</tbody>
</table>

Table 6.3-3 Comparison of magnetic field models against CRRES/GOES magnetometer data and relative execution times.

As shown in Table 6.3-3, Tsyganenko’s 1996 model with adaptations is an improvement over T96 and T89 (IGRF internal model shown for comparison) for minimal extra processing time. The implementation of Olson-Pfitzer 85 used gave frequent mathematical exceptions excluding it from the comparison. The fitted model with substorm adaptations produces the best results and is assumed to give the most realistic representation of the magnetosphere during events. It is the most computationally expensive, although not prohibitively so.
In Figure 6.3-3 lighter colours represent $B_{\text{MEAS}} - B_{\text{MODEL}}$ component vectors prior to fitting, darker colour after and the vertical bars mark onset and end of expansion from left to right. The fit reduces model-measured $B_z$ disagreement considerably. The $f_{\text{T-MAX}}$ value of 1.330 and the $A_{\text{MIN}}$ of -0.91 are responsible for the removal of the stretching signature, and their subsequent removal responsible for the dipolarisation increase in $B_{\text{MEAS}} - B_{\text{MODEL}}$. The fit for GOES-6 (-2330 LT) is better than that for GOES-7 (-0130LT), perhaps due to slow propagation of the real disturbance outwards, and the instantaneous global nature of the disturbance/fit in the model. The CRRES magnetometer measurements suffer from a spin related error during this time.
Figure 6.3-4 A cartoon showing the modelled magnetic development of event 32 according to the magnetic fit.

As shown in Figure 6.3-4 growth starts at 0720, onset occurs at 0814, the end of the (short) expansion phase is at 0824, with recovery some time after that. The top panel shows the pre-growth magnetosphere, the middle growth-stretching, and the bottom panel the effects of the current sheet thinning and tail flux increase.
As shown in Figure 6.3-5, the top panel shows the pinching off of a plasmoid-like object in Tsyganenko’s model at onset. It should be noted that the NENL-type features are purely features of the model. The middle panel shows the inner magnetosphere dipolarised at the end of the expansion, and the bottom panel shows the magnetosphere having returned to normal.
6.3.5 DISCUSSION

The fitting of magnetic field models to substorm dipolarisations is a developing technique needing further refinement, but already allows for better injection particle tracing with a minimal increase in trace-processing time. Tsyganenko’s models are an average of magnetospheric activity rather than an accurate representation of magnetic field vectors in all positions at all times, and the introduction of data-fitting for substorm epochs gives a closer alignment of these models to real data that reflects substorm modifications to the magnetosphere. This gives an additional order of approximation on top of Tsyganenko’s models, but still has results with frequent deviations in magnetic vector direction and magnitude (an average of 33nT per component over all events) when compared with magnetometer data from the nightside magnetosphere. This will be due to a number of effects:

- the magnetic ramifications of old events will still be apparent in the magnetosphere some time after the original events have ended and will not always be reflected in the Dst index,

- magnetopause compressions will occur and be missed in solar wind pressure data due to spacecraft displacement from the Earth-Sun line or data outages,

- the magnetic field is often a great deal more complex and dynamic than modelled and postulated substorm effects would suggest.

Figure 6.3-6 shows a magnetic dipolarisation occurring whilst superimposed on other activity.
In Figure 6.3-6 the lighter colours represent $B_{\text{MEAS}} - B_{\text{MODEL}}$ component vectors prior to fitting, darker colour after and vertical lines show onset and end of expansion times. Note how GOES-6 (~2100LT) and 7 (~2300LT) Z-components failed to automatically fit due to the 'ground state' of the magnetospheric magnetic field being altered with a high measured value (trace is initially above zero). GOES-6 $B_X$ and $B_Y$ values are or are close to being off-scale indicating effect of other magnetic field distortions.

Although the free parameters fitted to the magnetic field could provide a measure of the magnitude of magnetic effects in the magnetosphere, many fittings fail to produce convincing results with the distribution of individual coefficients appears eccentric. Fitting variables are therefore not used as a measure of the magnetic activity for solar wind correlation work. The magnetic field model fitting is simplistic, with the effects of changes in the current systems propagating instantaneously throughout the entire magnetosphere, when results indicate that dipolarisations, for example, spread from the inner magnetosphere outwards. Effects of dipolarisations can be seen to reach spacecraft at different locations at different times, with different magnitudes in the data set used in this study, even with the two GOES satellites separated by only two hours of local time.
Future adjustments to the technique would include the introduction of some term to reflect the shift in ground state. The weighting of data used to fit the model for proximity of spacecraft to local midnight would also be desirable. This would reduce interference from noisy measurements closer to the magnetopause, which are currently given as equal a weighting as those close to midnight, and are probably less relevant to substorm magnetic developments that happen in the tail. The use of both the SCW module and individual current alterations was a belt-and-braces approach, and both sets of measures may interfere, explaining the eccentric distribution of coefficients. One further direction may be to separate these and examine them individually for the best-fit. Due to the importance of having accurate magnetic field information for particle tracing, the T96 model with individual event fitting was used for all tracing work.

6.4 MAGNETOSPHERIC ELECTRIC FIELD MODELS

The large-scale electric field is not as well modelled as the magnetospheric magnetic field and particle-tracing work has frequently either ignored its effects or used fast simple models. Electric field models allow particle-tracing algorithms to take into account guiding centre ExB drift and also the energy gained/lost to the electric field.

The electric field is approximated by the sum of two components:

- the co-rotation component induced by the rotation of the dipole,
- and the convection component caused by the solar wind dragging of magnetospheric field lines, and the subsequent return motion of flux to the front of the magnetopause.

Volland-Stern [1973], a simple numerical model, is frequently used for the convection field. More sophisticated (and computationally expensive) models of the convection electric field exist [Weimer 1995; Heppner-Maynard-Rich (Heppner and Maynard, 1987 / Rich et al, 1989)]. These are orientated to ionosphere work, but may be used at magnetospheric altitudes by tracing equipotential magnetic field lines [Toivanen et al., 1997].

6.4.1 COROTATION FIELD MODEL

This is represented by:

$$E_{Corot} = B_{int} \times V_{FL}$$

Equation 6.4.1-1
Where $V_{FL}$ is the velocity vector of the field line due to the rotation of the Earth. This field component is dominant within $\sim 2$ $R_E$ of Earth, and its contribution can be clearly seen in Figure 6.4-1 as a large radially inward directed vectors below this altitude.

6.4.2 CONVECTION FIELD MODELS

6.4.2.1 VOLLAND-STERN

Volland [1973] and Stern [1974] proposed the following large-scale potential field as representative of solar wind convection:

$$
\Phi_E = A . R^\gamma \cdot \sin(\phi)
$$

$$
E = -\nabla \Phi_E
$$

$$
A = \frac{0.045}{(1 - 0.159Kp + 0.009Kp^2)^\gamma}
$$

Equation 6.4.2-1 Volland-Stern convection potential

A is a coefficient which determines the electric field intensity and is a function of Kp (a non-attributable example is shown above), R the radial distance from the Earth's centre, and $\phi$ the local time in radians. The value for the exponent $\gamma$ was determined by both Volland and Stern to be 2. Figure 6.4-1 shows the effect of this field in the mid to distant tail regions, and other regions outside of the dominant co-rotational field, as an east-west directed field vector. Kp values are smoothed prior to input to the above to produce a closer fit to real data.
6.4.2.2 IONOSPHERIC MODELS AND EQUIPOTENTIAL TRACING

Under stable conditions the points on magnetospheric magnetic field line can be assumed to be electrical equipotentials and this may be used to map calculation of electric field vectors or potentials throughout the magnetosphere. Ionospheric potential models such as Rich et al. [1989] or Weimer [1995] can be used with magnetospheric mapping algorithms to provide more realistic representations of electric field structures than simpler solutions [Maynard, 1995; Toivanen et al., 1997, 1998]. However, using field lines tracing imposes a significant computational overhead when compared with simpler models.

Electric field models provide potential values determined from measurements derived from satellite passes above the poles. To extend these to magnetospheric altitudes and electric field vectors, Equation 6.4.2-2 must be evaluated at the modelling point:
To determine the local field gradient for a point \( (P) \) in magnetospheric space, three points are located relative to \( P: P_x, P_y \) and \( P_z \). All three points are mapped using field line tracing to geomagnetic footprints on the Earth's surface in the northern hemisphere \((P', P_x', P_y', P_z')\). The potentials for points \( P', P_x', P_y', P_z' \) are then determined and the gradient between on the points in the magnetosphere, which have potentials equal to their traced footprints, calculated.

Due to the use of sounding rockets and ground-based radars to investigate the polar electric field, the high-latitude ionospheric convection field is normally represented in a co-rotating reference frame. As a result, a corotational component must be added to the above to obtain a valid electric field vector for the magnetosphere. The entire plasma sheet maps to a very narrow latitudinal band at ionospheric altitudes, and small electric field structures in the ionosphere map to large regions in the magnetosphere. Therefore changes due to growth phase magnetic field stretching can have a significant impact on the large-scale magnetospheric electric field.

### 6.4.2.3 WEIMER-96

Weimer 96 gives polar cap electric potentials in kV as a function of geomagnetic latitude and geomagnetic local time; IMF magnitude; IMF clock angle (degrees from northward toward GSM +Y); solar wind velocity and dipole tilt (positive north towards Sun). The model uses a least squares fitted finite series of spherical harmonics to represent the potential function on the ionospheric-sphere based on the DE-2 data set [Weimer, 1995]. The position inputs to the model are corrected geomagnetic co-ordinates and are essentially the same as invariant co-ordinates. Both are determined by tracing the field line to zero altitude in the SM system.

The Weimer-96 model by default gives the potential field for the northern hemisphere, although reversing the sign of both the \( B_y \) component in IMF clock angle calculations and the dipole tilt angle will result in the potential field for the southern hemisphere being generated.
As shown in Figure 6.4-2, dots indicate pointing direction of vectors. Note the regions at the top where field-line tracing is not possible/inaccurate. Both $B_y$ and $B_z$ were negative during the rendering of the model, with $B_T = 4.02$ nT and $V_{SW} = 577$ ms$^{-1}$.

### 6.4.2.4 HEPPNER-MAYNARD-RICH

This model provides the electric field potential poleward of 60° geomagnetic latitude based on OGO-6 and DE-2 electric field measurements. Seven different modes of potential map exist for different IMF $B_y/B_z$ conditions and hemispheres [Rich et al., 1989].
Spherical harmonics represent the potential field as a function of MLT and MLat. Models for the two hemispheres may differ under the same conditions, and resolving the field value using field line mappings in either direction may give different results.

**Figure 6.4-3** Equatorial projection in SM co-ordinate system of corotational field model with superimposed HMR model 1.
6.4.3 INDUCTIVE COMPONENT DUE TO MAGNETIC FIELD EVOLUTION

A temporally evolving magnetic field fitted to magnetometer values during growth and expansion phases provides the opportunity to approximate the inductive component of the electric field due to a dynamic magnetic field [Li et al., 1998]. However, the fit of model to substorm magnetic field data would need to reflect only the immediate substorm reconfiguration of the magnetosphere, and no other effects, as is suspected with the current fit. Deriving electric field values from changing magnetic field model values would involve a MHD solution to the fields or the integration of Faraday's Law over the source region $\frac{\delta B}{\delta t}$ [Toivanen, 1997], both of which are beyond the scope of this work.

6.4.4 ELIMINATION OF PARALLEL ELECTRIC FIELD COMPONENTS

The sum of $E_{Corr}$ and $E_{Conv} (E_{Total})$ may contain an unrealistic component parallel to the total magnetic field $B_{Int} + B_{Ext}$ with some models. This is eliminated in the particle tracing program by:

$$E_{Corrected} = \left( |B| \times E_{Total} \right) \times |B|$$

Equation 6.4.4-1
6.4.5 COMPARISON WITH CRRES ELECTRIC FIELD DATA

As shown in Figure 6.4-4, the electric field portrayed is extremely complicated, although the broad convectional/corotational pattern can be seen, as well as a null region towards 1500hrs LT. Data in 1990 is generally unavailable due to quality problems.

Electric field data exists for the duration of the CRRES mission in 1991, and may be used to judge the accuracy and usefulness of the composite models available. In order to provide a measure of disagreement ($\Delta E_{AV}$) for each event Equation 6.3.4-1 was assessed between $t = -1$ to $t = +1$ hours relative to 42 of the 56 onsets selected for possible tracing. This was done for each of the three convectional models with corotational components. As this chiefly concerns particle motion in the outer magnetosphere, data and models were only compared when CRRES was at L-shells greater than 4 Re. The total disagreements for each composite model
summed over all events where data was available and comparative computational time indices are presented in Table 6.4-2.

\[
\Delta E_{AV} = \frac{\int_{t=+1hr}^{t=-1hr} \sum_{X,Y,Z} |(E_{MEAS} - E_{MODEL}(P))| dt}{N}
\]

Equation 6.4.5-1 Comparison of model and CRRES electric field data. P represents the spacecraft position.

| Model                        | Average difference per data point $\frac{\sum |\Delta E_x| + |\Delta E_y| + |\Delta E_z|}{N}$ (V/m) | Normalised $\Delta E_{AV}$ | Normalised Execution time |
|------------------------------|-------------------------------------------------------------------------------------------------|-----------------------------|---------------------------|
| Volland-Stern + Corotational | 7.940e-4                                                                                       | 1.00                        | 1.00                      |
| Weimer-96 + Corotational     | 1.733e-4                                                                                       | 0.218                       | 488                       |
| H-M-R + Corotational         | 1.753e-4                                                                                       | 0.221                       | 488                       |

Table 6.4-2 Model accuracy and computation time comparison.

Figure 6.4-5 The convection field models values, with corotational component included, along $Y = 0/Z = 0$ at a substorm onset.
Chapter 6 – Particle tracing

**Electric field profile (X = 0), at onset (Tsy96 modified)**

![Electric field profile graph](image)

- 1.00E-05
- 1.00E-02
- 1.00E-03
- 1.00E-04
- 1.00E-05

Y, Earth Radii

- Volland-Stern Weimer96 Heppner-Maynard

Figure 6.4-6 The convection field models values, with corotational component included, along X = 0/Z = 0 at a substorm onset.

As shown in Figure 6.4-6, the increase in values on the dawn side is due to convection. Note the Volland-Stern model and the equipotential models disagree at Y = 6 \( R_E \).

**Electric drift speed profile (Y = 0), at onset (Tsy96 modified)**

![Electric drift speed profile graph](image)

- 1.00E+05
- 1.00E+04
- 1.00E+03
- 1.00E+02

X, Earth Radii

- Volland-Stern Weimer96 Heppner-Maynard

Figure 6.4-7 Resulting E cross B drift speeds.

6.4.6 CONCLUSIONS

The more sophisticated models provide a more accurate field model during substorm phases, although the Volland-Stern model used significantly less computation time. To allow a large number of particles to be traced in a reasonable time, the Volland-Stern model was used for the remainder of the particle tracing work whilst noting more accurate results may be possible with the equipotential models.
6.5 TESTING

To establish the validity of this implementation of guiding centre drift for substorm conditions, non-trivial tests have been conducted using the timing of particle signatures detected by multiple instruments at various local times. The tests use the detection of a drifting injection pulse at one instrument, a trace of particles back to one or more other instruments and a comparison of the simulated particle arrival times with observations. All tests use the modified Tsyganenko 1996 model, the Volland-Stern electric field model and numerical bounce averaging.

6.5.1 ECHO TRACE TO INJECTION OBSERVATIONS

6.5.1.1 EVENT 35 (ONSET 1019, 080191)

Event 35 showed a good injection signature at spacecraft 1982-019, 1987-097 and 1984-129 with spacecraft 1989-046 appearing to be within the injection region (approximate local times: 0900, 1200, 1600 and 0000 respectively). Particles from the leading extent of the injection pulse seen at 1984-129 were traced backward through the location of spacecraft 1987-097 and 1984-129. The results are shown below in Figure 6.5-2, with a freeze-frame of the tracing in Figure 6.5-1. No solar wind data exists after January 5th for dynamic pressure, although in early part of the month it was varying between 1.1 and 3 nPa. By 0800 on the 10th it was 3 nPa. A dynamic pressure of 1.18 nPa was found to produce the best fit.
As shown in Figure 6.5-1, five particles were selected from the leading edge of an injection signature at 1984-129 (lower spectrogram). Spacecraft passing times were noted and compared with the observation times from two other spacecraft and were found to be in close agreement.
Magnetic field dipolarisation was observed to begin at 1055, and particle convergence at or prior to 1059, between 0300 and 0130 local time.

Varying the pitch angles (α₀) of leading edge particles has a significant impact on comparison times, altering drift velocities near local midnight up to a factor of 1.4 over the full pitch angle range. As the relative differences in the drift speeds of different pitch angle particles change and sometimes reverse with local time [Reeves et al., 1991], the pitch angles of the leading edge of an injection pulse could change accordingly as some pitch angles fall behind others at various points. It is likely however, that the leading particles will be those with highest pitch-angle (the fastest particles), so it is intuitive to choose the highest possible values. The magnetic latitude of the observing spacecraft reduces the particles that can be seen to those that do not mirror prior to spacecraft encounter. This provides a maximum to the pitch angles that can be seen – particle pitch angles must be less than or equal to that of a particle mirroring at the spacecraft’s location. The observed particles were therefore assumed to be mirroring at the spacecraft and the traced particles α₀ set accordingly.

Figure 6.5-2 shows the level of agreement between modelled particles and data, within the error limits of trace particle selection/attributing flux rises as substorm injections. The particles were assigned values of α₀ ≈ 62° based on 1984-129’s magnetic latitude precluding the observation of lower pitch angles. The timing discrepancies seen at 1987-097 may be due to its lower magnetic latitude allowing the observation of higher pitch angle (faster guiding centre velocity) particles in the passing injection pulse.
6.5.1.2 EVENT 13

Event 13 is a simple injection signature that has components from within the 30-200 keV range of the CPA instrument, and can be seen travelling between 1984-129 and 1987-097. Particles from the leading edge of the injection as seen by 1984-129 were identified and traced backwards. A coincidence was defined as when an observing spacecraft and a modelled particle passed each other in local time. A single pitch angle value was attributed to the particles observed at 1984-129, and this value was iteratively decreased until the best match between modelled coincidence time and instrument observation time was seen for the 95 keV particle. The two other particles gave resultant spacecraft local time coincidences with differences to observations close to instrument resolution.

![Figure 6.5-3](image)

**Figure 6.5-3** Comparative schematic showing the modelled and actual arrival times of particles at sensors for event 13.

6.5.1.3 CONCLUSIONS

The tracing model/program using the modified Tsyganenko 1996 model, Volland-Stern and numerical bounce averaging produces results of acceptable quality for injection tracing during substorm conditions. In testing over extended distances the timings between observed and modelled particles agreed within a few minutes. Of the discrepancies seen these may be attributable to incorrect energy assignment, or possibly shell-splitting effects. Indications from the first test are that the time a geostationary spacecraft sees an injection will be effected by up to a few minutes by its magnetic latitude precluding seeing high pitch-angle fast particles.

Also, a programming error led to the discovery that varying the solar wind dynamic pressure input to the Tsyganenko model has a substantial effect on overall particle speeds. A reduction in dynamic pressure (nominally of order 1-10 nPa) leads to faster particles and an increase to
slower particles. This is due to solar wind alteration to the geometry of the dayside magnetosphere, and a modulation of particle curvature drift velocity.

6.6 ERROR ANALYSIS

6.6.1 MODEL INACCURACIES

6.6.1.1 MAGNETIC FIELD MODEL INACCURACIES

Inaccuracies exist within magnetospheric field models close to component currents and mathematical discontinuities in the Tsyganenko models, such as the tilted-tail hinge in the T89 model. Tsyganenko's latest model T96 eliminates some discontinuities (such as the tail hinge with a tail warping function), but the ramping of various model currents to fit the field to magnetometer data may have exacerbated existing or caused new discontinuities. It is not possible to establish whether the model field values for the locations each traced particle moves through are correct, however during tracing the field is constantly evaluated to determine if the field values supplied to the guiding centre drift algorithm are reasonable. As less sophisticated models without event fitting have been used to get satisfactory results in previous particle tracing work, it is hoped that this approach to substorm magnetic field modelling is at least as if not more accurate.

6.6.1.2 ELECTRIC FIELD MODEL INACCURACIES

Previous tracing work has generally used Volland-Stem's average model to represent the electric field for particle tracing (if the electric field has been taken account of at all), although Toivanen et al. [1997] uses a more sophisticated equipotential tracing of ionospheric electric field models. This approach has been tested with CRRES data and found more accurate, although time consuming. Due to the consideration of computational time, the Volland-Stern model has been used for this work. This field is not fitted to substorm conditions and does not react to solar wind inputs. This is therefore assumed to be one of the major sources of discrepancy between model conditions and real conditions in the magnetosphere. Some substorm models [Reeves et al., 1998] have NENL-like collapse caused electric fields driving acceleration within geostationary regions at onset. If this is representative of real conditions tracing close to onset times and regions electric field model values could be expected to diverge from real values.

6.6.2 INSTRUMENT DATA ERRORS

Magnetometer and particle instrument data is an important component of this work. Magnetometer data is used to identify substorms and adapt models during substorm periods and if the data has persistent errors this will effect these operations accordingly. Any artificial
increase in model field strength will incorrectly decrease the drift speed of the particles leading to longer modelled travel times than actually occur, with a decrease causing modelled particles to be faster, and vector direction inaccuracies causing direction-of-drift errors. Such increases and decreases could be caused by incorrect model adaptation from bad magnetometer data, although this would have to be of a large magnitude to be significant. The magnetometer data however is indicated to be calibrated and no errors suspected, except during periods of eclipse for GOES [Singer, 1998], and it is expected such errors do not significantly affect model fitting work.

Particle instrument data is used to identify events and supply candidate particles for tracing. Calibration errors in absolute particle fluxes have no consequence in this work as substorm injection signatures are notable mainly due to their relative effects across energy levels and their temporal evolution with respect to background levels. More reliance however is placed on the energy levels of channels, with the particle energy being important for guiding centre drift equations. However, there are no suspicions that any of the LANL or CRRES energy band ranges are incorrect. The difference in energy levels between channels forms the basis for the large differences of particle arrival times at sensors, and this timing difference which is exploited to triangulate back to injection points. As channel energy levels are usually in geometric sequence, an error of a few percent in each figure will be insignificant compared with the differences between those channels, implying any such calibration errors to be insignificant.

It is noted that this work relies on large volumes of particle and magnetometer data and studies it at a coarse resolution. Many studies of smaller timescale events have taken place using EPAS, LEPA, LANL, GOES and CRRES magnetometer data, giving good grounds to believe instrument results interpreted in this context.

6.6.3 PROGRAM ERRORS

The tracing program developed for this application uses data from many spacecraft (10) and instruments (13) in many co-ordinate systems, calculates sophisticated field models, simulates the guiding centre motion of drifting particles and presents a graphical user interface capable of tracing backwards or forwards in time. In such a complex construction it is anticipated some errors have occurred in coding, some of which will still exist. In coding though, the rigour of graphically displaying data and model results has led to an immediate test of all work – 'making it look right'. A number of errors that would not have been easily detected numerically have been diagnosed from their visual effects, including a number of original looking magnetic field model configurations. Further, a defensive method of programming was adopted, with
data files checked for out-of-bounds values; function inputs validated and transformation inverses checked every hundred iterations to ensure they continue to produce unity matrices (as a guard against bug introduction). Mathematical model errors have been guarded against by testing with real data, and in the case of magnetic field models, plotting to ensure the field line configurations were as expected. Magnetic field, electric field and guiding centre drift models have all been tested against real data to establish gross errors do not exist in the program.

6.7 SELECTION OF TRACE PARTICLES

6.7.1 PREFERENTIAL USE OF ELECTRONS AS TRACE PARTICLES

This work concentrates on the use of electrons as preferred tracers, although in principle protons might be just as suitable. There are a number of reasons for this:

- ion injections are often less distinct and enhancements weaker compared with backgrounds fluctuations,
- as a function of local time, ion injection signature enhancements decay to noise levels faster, making identification difficult and echoes rare,
- in the NENL model electrons are accelerated after ions, during dipolarisation, and hence start drifting on more normal field lines,

[Friedel et al., 1996].

Ions allow better establishment of the western extents of injection regions, and an attempt is made to trace a few protons from injections for that purpose where possible.

6.7.2 SELECTION FROM TYPICAL PULSE SIGNATURES

Particles from different parts of a dispersed injection signature can yield different information about the substorm injection region. Making the assumption that particles of all energies and pitch angles are injected simultaneously throughout the injection region allows the pulse widths of each channel to be used in conjunction with proton tracing to provide two different indications as to the approximate size of the injection region.

Electron injections are composed of particles between keV and hundreds of keV, and a range of pitch angles. The slower drift speeds of keV particles will cause them to take longer to reach an instrument, with those from the farthest extent of the injection region taking the longest. Conversely, the fast high-energy particles will take the least time to reach the spacecraft, with those from the nearest extent of the injection region taking the least time of all. Similarly, low
pitch angle particles will take a long time, and high pitch angle particles a short time. The resultant injection signature is seen in Figure 6.7-1.

Figure 6.7-1 Differential drift of electrons of differing energies from different parts of the injection region.

Figure 6.7-1 shows particles within a single energy channel injected at different locations within an injection region [Birn et al., 1997]. A and C are at the higher end of the channel’s spectrum and have high pitch angles, B and D the lower end. A and B are at the easternmost edge of the injection region. Particles such as A reach the spacecraft first, forming the initial rise in counts, C gets to the spacecraft before B and D eventually get to the sensor some time later, perhaps being lost in an echo or subsequent injection. The overall result of a large number of such particles and those with attributes between those described is the characteristic humped signature.

To get information on the size of the injection region, a particle from the leading edge and, where possible, the trailing edge of each channel are selected for tracing. These give bounds for injection regions, which may be partially corroborated with proton traces when coherent proton signatures are identifiable.
CHAPTER 7 - TRACING OF SUBSTORM EVENTS

Prior chapters have been leading towards the goal of using particle tracing to obtain information on the morphology of injection regions. This chapter brings the threads of those chapters together to trace selected event signatures to their injection points.

In Chapter 3, the phenomenology of substorms was reviewed in order to, in Chapter 4, formulate a set of rules by which substorms could be identified. Chapter 4 also applied those rules to produce a list of 187 substorm events. That number being impractical for tracing, the chapter concluded by cherry picking the best thirteen events such that the magnetospheric environment and distribution of spacecraft was most conducive to successful tracing. Chapter 5 examined the solar wind-substorm relationship. This was a slight aside to the main objective of the work – taking advantage of the fact that all data required was to hand. It did however afford an understanding of the solar wind-magnetospheric connection during the growth phase, which proved useful in the analysis of conditions for tracing. Chapter 6 formulated and tested algorithms for the tracing of particles from observations to their convergence points. These convergence points are to be interpreted in this chapter as where particles cease to be accelerated in the injection region, or at least the point where the bulk transport of particles into the magnetosphere ceases – effectively demarcating the edges of the injection-process region.

This chapter applies the particle tracing methodology to the identified, tracing-friendly injections in an attempt to identify the injection region eastward electron boundary or boundaries.

7.1 PRIOR PARTICLE TRACING WORK

Other work has used near geostationary particle tracing to derive a number of different results. Amongst others, results notable for this work are:

- individual injection region width/location determination using electron leading-edge tracing, protons and injection pulse widths, Reeves et al. [1990, 1991, 1992],

- simulations of particle trajectories in growth and recovery phases – tracing in a time evolving magnetic field, Toivainen et al. [1994],

- acceleration of electrons and ions in MHD simulations of the fields associated with neutral line formation and dipolarisations, to produce the major observed characteristics of a substorm injection, Birn et al. [1998].
This work analyses injection signatures seen on multiple spacecraft, and uses inter-spacecraft drift times to provide pitch angle information to help determine the injection regions easternmost extent.

7.2 SHELL SPLITTING

Azimuthal asymmetry of the Earth's magnetic field introduces pitch angle dependence in particle drift orbits. Particles of differing pitch angle, starting at the same radial distance drift on shells with radial distances that vary as a function of local time. Magnetospheric populations such as substorm injections are subject to this effect, which is termed shell splitting [Takahashi, 1997]. The effect exerts a detrimental effect upon coherent injection pulses travelling around the magnetosphere, with a radial dispersion that can remove high pitch angle particles from the observable pulse. It has a correspondingly detrimental effect on particle tracing as the technique needs to make assumptions regarding leading edge pitch angles. Shell splitting introduces a factor that can change leading edge pitch angles for different injection pulses, and also causes leading edge pitch angles to vary across energies. The extent of radial-distribution of an injection is dependent on the particle energies involved (Figure 7.2-2), the magnetospheric state (Figure 7.2-3 – in this model, most effected by \( D_s \) and solar wind dynamic pressure), and radial distance from the Earth (Figure 7.2-1). Particle populations closer to the Earth show less shell splitting due to the more symmetric field.
Chapter 7 – Tracing of substorm events

Figure 7.2-1 The three panels show the increasing effects of shell splitting on 200 keV particles as a function of radial distance from the Earth.

In Figure 7.2-1, panels are SM co-ordinate system equatorial planes with the Sun to the left. The three coloured lines represent electrons of various pitch angles released simultaneously in the tail (blue 60°, red 30°, and black 5°). Descending down the panels, they show electrons
released at 6.5, 5.5 and 4.5 \text{Re} tailwards. During tracing, the electrons moved radially outwards and gained up to several kiloelectrovolts of electric field energy, changing pitch angle accordingly.

Figure 7.2-2 The two panels show the effect of energy on shell splitting, with 200 keV particles in the topmost panel, and 45 keV particles below. The 200 keV particles are dispersed more readily than lower energy particles.
In Figure 7.2-3, the top panel shows the drift paths of three 200 keV electrons (blue 60°, red 30°, and black 5° pitch angles) when the Dst is uniformly −80 nT, and the solar wind dynamic pressure is a constant 9.45 nPa. The bottom panel shows the same particles under a Dst of −10 nT and a solar wind dynamic pressure of 1.25 nPa.

Shell splitting will be greatest for the high energy, high pitch angle component of the population during periods of low Dst values or high dynamic pressure. If radial penetration of the injection region is minimal, this may remove high pitch angle (would be leading edge) particles from an injection as seen at geostationary orbit in the morning-noon sector.
7.3 RESULTANT PITCH ANGLE DISTRIBUTION SEEN AT GEO

The CRRES/EPAS instrument provides a full pitch angle distribution for electrons between 21 keV and 285 keV, allowing a study of the pitch angles seen in substorm injections for an energy range close to that of the LANL data. A requirement for this study is that CRRES should be near the geomagnetic equator when the particle pulse passes – ensuring the effect of spacecraft magnetic latitude on the pitch angle distribution seen is minimal. Another two requirements were that the spacecraft needed to be at near-geostationary altitude and at a high enough local time so that the effects of shell splitting might become apparent. This set of requirements reduced the 187-event list to just one suitable event at the beginning of the mission. Event 3 is a particle pulse seen by EPAS at approximately 0335, with CRRES at 0642 MLT, 4.05° SM-latitude and 6.11 $R_E$. This is not ideal – the latitude of the spacecraft discounts seeing particles of $\alpha_0 > 78^\circ$, and the altitude and local time of observations would both ideally be greater. However, the effects of shell splitting extend lower than $\alpha_0 > 78^\circ$ and may be seen in Figure 7.3-1.

The earliest component of the pulse as seen by the instrument, between 242-285 keV, exhibits a near-isotropic distribution, but as energy decreases, the leading edge distribution becomes more field aligned. This is interpreted as showing the effects of shell splitting. High energy, high pitch angle particles drift around the outside of the spacecraft and are removed from the region observed by the instrument. This leads to the eroded appearance of the high energy leading edges of some particle pulses as seen at LANL spacecraft and requires that care be taken in assigning these particles high pitch angles for tracing.
Figure 7.3-1 The three panels above show plots of the observed pitch angle distribution against time (minutes:seconds) for the particles within the injection pulse of event 3, for three energy bands. The pitch angles are those of the particles at the spacecraft rather than at the magnetic minima.
7.4 DETERMINATION OF LEADING EDGE PITCH ANGLES

The magnetic latitude of some observations precludes high pitch angles from being observed and provides a high bound to the pitch angle distributions seen. Pitch angles that are too high lead to the violation of $\mu$ as particle motion around the dawn-midnight sector results in loss of energy to the electric field, increasing $\alpha$ to 90°. This provides another maxima for the leading edge pitch angle. Often the leading edge appears to be less than both of these however, and inter-spacecraft timing of the pulse is used to determine the approximate values to use for tracing particles to the injection region. With two or more observations, pitch angle values are iterated until a simulated particle matches the timing seen by each spacecraft, and a maxima for the leading edge is found. This process is usually conducted on only one or two particles. To individually determine the pitch angle for each channel would be time-intensive, and many second observations are degraded by dispersion to such an extent that only one energy channel's flux increase can be clearly identified. This technique assumes that the effects of shell splitting are only minimal between the two spacecraft used. The assumption is founded on the low (~6hr) local time separation of the spacecraft most often used, and their displacement away from the midnight-dawn sector where the effects of shell splitting are most apparent. If this assumption breaks down, the result will be a particle trace with too low a pitch angle, and a convergence that is too far to the east. This is the same bias in the technique which will occur if higher energy channels see significantly lower pitch angles compared with other channels (this technique assigns the same pitch angle to each channel). Therefore, these results are an upper limit to the eastward injection boundary rather than an exact position.

7.5 METHODOLOGY & RESULTS PRESENTATION

After initial work considering shell splitting and pitch angles (which carried implications for the accurate tracing of particles) thirteen events were traced backward to their injection regions using the methodology developed in Chapter 6. The method and format of the results is largely generic to all events, hence to aid comprehension an explanation of methodology and results are presented here, using event 6 as an example.
7.5.1 EVENT 6 (ONSET AT 0805, 6.9.90)

7.5.1.1 SPACECRAFT POSITIONS

When an event is traced, consideration is first paid to the distribution of spacecraft (Figure 7.5-1). One or more GOES spacecraft are required to be close to the tail for accurate magnetic field measurements and model fitting. LANL spacecraft/CRRES are required to be located so that they either see the injection pulse at a number of local time locations (for the derivation of leading edge pitch angles) or to assist by observing the injection region in the tail. In event 6’s Figure 7.5-1 above, the GOES satellites are placed either side of local midnight (right) – providing good data for dipolarisation observations and model adaptation to the event. CRRES (towards dawn) and the LANL spacecraft (1987-097, 1984-129) are expected to see dispersed electron injection signatures.

7.5.1.2 MAGNETOSPHERIC CONDITION

MAGNETIC FIELD CONDITIONS

Magnetic conditions are investigated next, firstly to gain timing information with respect to growth phase length, onset time and expansion phase duration. This is used to give phase timings for onset and expansion and also during interpretation to place the timing seen for convergence into the context of the dipolarisation development. During tracing the timing data is used to give upper limit constraints to the time duration of particle tracing. A second function of investigating the magnetic field conditions is to determine the effectiveness of field model fitting to magnetometer data.
Figure 7.5-2 shows the dipolarisation associated with event 6. The two vertical solid black lines represent onset (left), and the end of the expansion phase (right). The horizontal timescale varies for each of this graph type to maximise the detail seen although the vertical scale is fixed at +/- 97nT. From magnetometer data, the growth phase is 89 minutes long and expansion 8.3 minutes. When this plot was generated, onset was incorrectly judged to be at 0822 UT, although was subsequently moved to the beginning of the disturbance as seen at GOES-6 at 0805 UT. The GOES-6 Bz measured-model trace (light green, middle panel) shows a staggered dipolarisation.

**SOLAR WIND CONDITIONS**

Solar wind conditions are analysed due to their importance as inputs to magnetic field models and if data is unavailable due to data dropouts it is interpolated. This can be a questionable practice: some dropouts were for days and it would be expected that some substorms would be triggered by non-average short-lived solar wind conditions (perhaps short term pressure increases) that would not be reflected in data many hours either side of the onset. However, this practice is the only option and is the one adopted.

For event 6, the IMF Bz component is +10nT at 0640 and monotonically reduces to -7nT by the time of onset (0805). The duration of the decrease in Bz correlates with the growth phase duration (although the time that Bz is southward is shorter than the growth phase). Velocity ($V_{SW}$) and density ($\rho$) information is not available from September 1\textsuperscript{st} to September 7\textsuperscript{th}. 

---

Figure 7.5-2 Measured minus modelled magnetic field vectors for event 6, pre (light) and post (dark) model fitting.
Dynamic pressure was set at a level between readings at either end of this period ($P_{\text{dyn}} = 1.85$ nPa).

### 7.5.1.3 INJECTION SIGNATURES & SELECTION

The next step was to select particles from LANL spectrograms. Usually the injections selected showed signatures of differing levels of dispersion (and coherence) at two local time separated spacecraft. This allowed the pitch angles of the leading edge of the particle pulse to be estimated (see 7.4, Determination of leading edge pitch angles). One or more particles were selected from the leading edge of the second observation for this purpose, and three or more particles were selected from the primary injection signature for tracing. For a very limited number of events, when the trailing edge was not swamped by other activity, a few particles were selected for tracing the point where the final particles were injected.

![Figure 7.5-3 Particle injection as seen by the LANL instruments for event 6, and particles selected for tracing.](image-url)
Chapter 7 - Tracing of substorm events

In event 6's Figure 7.5-3 above, coloured bands represent particle spectra, with high-energy particles towards the top (electrons upper six rows of each plot, ions lower) and the colour intensity showing relative flux levels (red = highest, green = moderate, blue/burgundy/black = low). Log flux line plots (easier for seeing injection event timing) are overlaid with lower energies towards top. For example, on 1987-097's panel (top) the six traces are log base-10 electron fluxes, with particles from the 140-200 keV channel through to 45-65 keV channels selected (coloured circles).

The top panel shows observations of the events, with a strong injection signature between 0815 and 0840, and three particles selected, representing the leading edge of the pulse. The higher energy channels have no such selections, as their leading-edge pitch angles will differ most with respect to the other channels (due to shell splitting). The middle panel shows 1989-046's observations immediately to the west of the injection region, with a depression in electron fluxes centred on onset, although the injection pulse disperses before reaching the spacecraft. This spacecraft also sees ion injection flux increases indicating a non-dispersive injection was seen around 0807 UT. 1984-129's lower panel shows a more dispersive injection signature than that seen at 1989-046's. One particle from this signature is used to determine the pitch angle which best maps one signature to the other, and hence the pitch angle to use for tracing.

EPAS data was also studied with each event (although for event 6 nothing traceable was seen hence no example is presented). For some events EPAS was deep in the injection region and capable of providing good timing information for the expansion phase injection of particles. In one event the leading edge particles converged when EPAS first observed activity associated with injection, and the trailing edge particles converged when intense flux readings from EPAS ceased. However no tracing from EPAS signatures was possible due to noise in the data set, and the swamping of injection signatures by inner radiation belt activity. Identification of signature rising edges was not possible.

7.5.1.4 PARTICLE TRACING

Particle tracing largely involved the correct determination of the pitch angles to use for leading edge traces. Trailing edge traces were simpler: an assumption that these were the lowest pitch angles possible led to the selection of 4° - 5° pitch angles (the lowest which did not get absorbed by the atmosphere during tracing). The determination of leading edge particle pitch angles required the initial assignment of the maximum pitch angle that a spacecraft of given magnetic latitude could see. During the initial tracing process this was iteratively decreased until the particle(s) from the second (most dispersed) observation mapped to the observations of the least dispersed signature.
Tracing proper resulted in a dynamic graphical display of the progress of the injection pulse around the magnetosphere, backwards in time, until the particles seen in an injection signature at different times, converged at (approximately) one local time in the tail. The traces of each injection is represented in this account as LT versus UT plots.

![Fig 7.5-4](image)

Figure 7.5-4 Particle tracing for event 6, y-axis position in local time against UT. Time decreases left (post onset) to right (near onset).

Figure 7.5-4 shows four traces representing the journey of particles from injection signature observation to the leading edge of the particle pulse. The first particle (dark blue, tallest line) is the particle traced from 1984-029 to 1987-097 to obtain pitch angle information ($\alpha_0 = 36^\circ$). The last three are traced from 1987-097, and during the progression of the trace as each of these particles had yet to be co-located with the spacecraft as time progressed backwards, maintained constant local time positions (hence the flat lines). As time passed the observation times of each particle, their motion in local time began. The trace for event 6 converges just prior to the onset at 2700 LT corresponding to 0300 LT, as broadly indicated by the crossing point, and identifying this point as the easternmost electron injection boundary. Care must be taken with the time scale of these plots. As the differing energy particles take different time-steps to complete the specified program distances, as each new faster particle becomes active in the simulation, the time scale of the plots decreases. Hence the plots are non-linear due to the varying time steps the program takes. It should also be noted that a local time value of 24 hours and over represents midnight-dawn sector values plus 24 hours.
Chapter 7 – Tracing of substorm events

7.6 IDENTIFIED EVENT INJECTION TRACINGS

7.6.1 EVENT 13 (ONSET AT 0537/0545, 6.10.90)

7.6.1.1 SPACECRAFT POSITIONS

**Figure 7.6-1** Equatorial projection of spacecraft positioning at onset.

7.6.1.2 MAGNETOSPHERIC CONDITION

**MAGNETIC FIELD CONDITIONS**

**Figure 7.6-2** Measured minus modelled magnetic field vectors, pre (light) and post (dark) model fitting.
Chapter 7 – Tracing of substorm events

From magnetic measurements, the growth phase was judged to be ~33 minutes long, expansion 25 minutes. The two vertical solid black lines represent onset, and the end of the expansion phases. GOES-7, centrally placed in the tail, shows the noisy dipolarisation that magnetically identified this event. One third of the way through expansion a more rapid correction to $B_Z$ occurs (0545). The initial magnetic timing on this event is therefore thought doubtful.

**SOLAR WIND CONDITIONS**

Solar wind data begins shortly after this event at 0624, after a dropout of coverage. At that time (and prior to the dropout earlier that day) the $V_{SW} = -500 \text{ kms}^{-1}$, $\rho = -4$ parts/cc and $B_Z$ is weakly positive.

7.6.1.3 **INJECTION SIGNATURES & SELECTION**

![Particle injection as seen by LANL satellites](image)

*Figure 7.6-3 Particle injection as seen by LANL satellites. Explanation as per equivalent plot for event 6.*
In Figure 7.6-3, 1989-046 shows a feature at 0553 UT, with a decrease in fluxes appearing instantaneously across all energies and later evidence of the injection pulse drifting around to its position. 1987-097 sees the injection pulse first (with particles selected for tracing shown) and 1984-129 sees the signature a little later. The highest energy channel is not selected as it is most prone to shell splitting effects.

In Figure 7.6-4, the electron data (upper panel) shows a near-dispersionless injection observed as CRRES swept outwards (although prior radiation belt observations may mask any dispersive features). The feature is seen between 05:50 to 05:51. The signature lacks the dispersion required for tracing, and indicates that the injection occurred close to the west of CRRES. The lower panel (proton data) shows a dispersed signature.
7.6.1.4 PARTICLE TRACING

![Particle tracing for event 13](image)

Figure 7.6-5 Particle tracing for event 13 (X axis non-linear).

The tallest three lines represent particles from 1984-129, and the three traces with horizontal components particles from 1987-097. Particles converge at approximately 2845 LT (corresponding to 0445), identifying this point as the easternmost electron injection boundary.

7.6.2 EVENT 18 (ONSET AT 0930, 15.10.90)

7.6.2.1 SPACECRAFT POSITIONS

![Equatorial projection of spacecraft positioning at onset](image)

Figure 7.6-6 Equatorial projection of spacecraft positioning at onset.
Chapter 7 – Tracing of substorm events

7.6.2.2 MAGNETOSPHERIC CONDITION

MAGNETIC FIELD CONDITIONS

![Graph showing magnetic field conditions](image)

**Figure 7.6-7** Measured minus modelled magnetic field vectors for event 18, pre (light) and post (dark) model fitting.

From magnetic measurements the growth phase for this event was judged to be approximately 130 minutes long and expansion 8.3 minutes. The GOES-6 Bz measured-model trace (light green, middle panel) shows a distinct dipolarisation.

SOLAR WIND CONDITIONS

![Graph showing solar wind conditions](image)

**Figure 7.6-8** Solar wind density, velocity, dynamic pressure and Bz conditions for event 18.

The solar wind IMF is southward and decreasing from 0725 UT through to onset reaching a minima at approximately 0845UT, matching the observed growth phase. Density is 6-8 cm\(^{-3}\), and \(V_{SW} = 400\) to 450 ms\(^{-1}\), with a corresponding moderate \(P_{dyn} = 2\) to 3 nPa.
In Figure 7.6-9, 1987-097 shows a dispersed injection with leading edge and trailing edge particles marked for tracing. The dispersed injection pulse seen by 1984-129 was traced back to 1987-097 to confirm pitch angle allocation (60°) and tracing algorithm accuracy. 1989-046 is within the injection region and appears to indicate a 30 minute period of intense tail region activity from 0930 to 1000 hours. CRRES/EPAS observed the injection, although noise precluded using the data to identify the timing of leading/trailing edge particles.
7.6.2.4 PARTICLE TRACING

![Event 18, Particle location (LT) versus time (UT)](image)

Figure 7.6-10 Particle tracing for event 18, both leading edge (right) and trail edge (left) signatures.

In Figure 7.6-10 the first three lines from the left show low pitch angle slow particles from the trailing edge of the injection. The last five are high-energy, high pitch angle particles leading edge particles, one of which comes from 1984-129 to establish the leading pitch angle. The low energy particles are seen to converge at approximately local midnight (1000 UT). The high-energy particles converge between 2730 and 2700 LT four minutes after the observed magnetic onset (0930).

7.6.2.5 OBSERVATIONS

Spacecraft 1987-097 observed a dispersed injection signature in this event, and 1984-129 saw the same pulse sometime later. A leading edge element of the signature seen by 1984-129 was traced with various pitch angles to establish the probable leading edge pitch angle for the pulse in this region. The trailing edge particles progressed at much lower speeds in the 95-140 keV band and were best matched with 5° particles (4° was within the loss cone).

Allowing the pitch angle distributions above, and top-channel energies for the leading edge/bottom-channel energies for the trailing edge, resulted in a trace of leading edge particles that coincided closer after the start of activity as seen by 1989-046. Conversely, the trace of the trailing edge particles resulted in a coincidence at the end of activity. The eastern edge of the injection region was at approximately 0330LT to 0300LT, with the end of pulse particles coming from midnight.
Chapter 7 – Tracing of substorm events

7.6.3 EVENT 21 (ONSET AT 0858, 25.10.90)

7.6.3.1 SPACECRAFT POSITIONS

Figure 7.6-11 Equatorial projection of spacecraft positioning at onset.

7.6.3.2 MAGNETOSPHERIC CONDITION

MAGNETIC FIELD CONDITIONS

Figure 7.6-12 Measured minus modelled magnetic field vectors for event 21, pre (light) and post (dark) model fitting. GOES-06 shows the small disturbance identified.
Chapter 7 – Tracing of substorm events

SOLAR WIND CONDITIONS

Solar wind data is unavailable for this period. Solar wind density and velocity are available on the 23rd (\( \rho = 10 \) parts/cc, \( V_{SW} = 470 \) kms\(^{-1} \)) and 28\(^{th} \) (\( \rho = 5 \) parts/cc, \( V_{SW} = 410 \) kms\(^{-1} \)) of October. IMF data is available on the 25\(^{th} \), although a gaps exists from 08:33 (\( B_{XYZ} = -17, -0.28, -2.58 \) nT) to approximately 20:00 (\( B_{XYZ} = -14, -0.44, -1.36 \) nT). The solar wind dynamic pressure used for this trace was 2.81 nPa.

7.6.3.3 INJECTION SIGNATURES & SELECTION

![Particle injection as seen by LANL satellites.](image)

1989-046 shows a non-dispersive disturbance across all energies shortly after onset, and a highly dispersed signature 45 minutes later. 1987-097 observes the injection signature first with 1984-129 seeing it later. The particles marked for tracing represent the trailing edge of the injection.

182
7.6.3.4 PARTICLE TRACING

Event 21 - trailing edge, Particle location (LT) versus time (UT)

Figure 7.6-14 Trailing edge particle tracing for event 21. The right hand side cut-off is the onset as determined from the magnetic disturbance. The western edge of the electron injection was at approximately 2118 LT.

Event 21 - leading edge, Particle location (LT) versus time (UT)

Figure 7.6-15 Leading edge particle tracing for event 21 (X axis non-linear).

7.6.3.5 OBSERVATIONS

The trailing edge signature of this event was clear of interference and used to investigate the western extent of the electron injection region. Trailing edge identification was however difficult, and a trace of similar particles from 1984-129 was used to aid selection. It is unclear why the injection pulse was observed only once and no echoes are apparent in the traces, nor why the injection pulse has no component above 140 keV. It is possible that the slightly raised flux in the channel after the mid-energy particle selection is part of a dispersed echo. The trace
of these particles cut off at the time identified by magnetic disturbance as onset, at the exact time they all converged at approximately 2118LT.

The leading edge trace for this event was conducted with pitch angles determined as applicable for this dynamic pressure and these approximate spacecraft locations (63° from event 13). The trace converged between approximately 2830 and 2600LT.

7.6.4 EVENT 28 (ONSET AT 0725, 5.12.90)

7.6.4.1 SPACECRAFT POSITIONS

GOES-06 and GOES-07 were well positioned for magnetic field fitting/sensing and 1987-097 data was used for tracing after pitch-angle calibrating with 1984-129.

7.6.4.2 MAGNETOSPHERIC CONDITION

MAGNETIC FIELD CONDITIONS
Figure 7.6-17 Measured minus modelled magnetic field vectors for event 28, pre (light) and post (dark) model fitting.

From magnetic measurements, the growth phase was judged to be 66 minutes long, expansion 14 minutes. The GOES-6 and GOES-07 Bz measured-model traces (light green middle panel) show a distinct dipolarisation.

**SOLAR WIND CONDITIONS**

The solar wind IMF is southward from ~0620 throughout the substorm episode, and turns southward at the approximate beginning of the growth phase. Density is high at 9 parts per cc, and $V_{SW} = 500 \text{ ms}^{-1}$, with a corresponding (high) $P_{dy} = 4 \text{ nPa}$. 
Figure 7.6-19 Event 28's particle injection as seen by LANL satellites, and particles selected for tracing.
Figure 7.6-20 shows the first usage of EPAS data. The upper panel shows electrons, the lower protons. Energies for the spectrogram descend from top to bottom, with the reverse true of line plots. No noticeable particle substorm effects are apparent at CRRES until 0750-0800UT, with a notable dropout in the period correlating broadly with the growth phase of the substorm (and well into the recovery phase). The dropout and lack of particle pulse signature observation are explained below. CRRES/EPAS did not observe the leading edge of the pulse due to its magnetic latitude placing it on field lines that did not map within the magnetosphere due to substorm magnetospheric reconfiguration.
As shown in Figure 7.6-21, the grey circle represents the approximate location CRRES. CRRES/EPAS’s flux dropout (and lack of early observation of the injection pulse) is likely to be the growth phase stretching of the magnetic field, placing CRRES on open field lines for a large fraction of the growth and expansion. The modelled field dipolarises such that CRRES is on closed field lines some time before a flux elevation is seen, indicating that this substorm’s growth phase may be longer than determined from magnetic field measurements, or the particle pulse is not present near the magnetopause. It should be noted that the X-line feature at 7 \( R_E \) is
Chapter 7 – Tracing of substorm events

a model and probably unreal feature (although it gives a good fit to the GOES-6 and GOES-7 data).

7.6.4.4 PARTICLE TRACING

Figure 7.6-22 Particle tracing for event 28, y-axis position in local time against UT.

The first three lines from the left show low pitch angle, slow particles from the trailing edge of the injection. The last four are high energy, high pitch angle particles (one of which is from 1984-129 and was used to determine the leading pitch angles to use). Low energy trailing particles converge at 2500LT at 0814UT, and high-energy leading edge particles at 2815LT, 0728UT.

7.6.4.5 OBSERVATIONS

Proton measurements on spacecraft 199-095 indicate that the expansion period (as measured by the existence of injection region activity) may well be longer than initially thought (0725 to 0740UT versus 0730 to 0800). Assuming leading edge particles come from the start of expansion and the trailing edge from after the end of expansion, this particle trace corroborates a longer expansion phase. Re-examination of the magnetic traces from GOES-06 and GOES-07 indicate it may be up to twice as long as initially thought.
Chapter 7 – Tracing of substorm events

7.6.5 EVENT 32 (ONSET AT 0814, 23.12.90)

7.6.5.1 SPACECRAFT POSITIONS

<table>
<thead>
<tr>
<th>Tilt</th>
<th>Kp</th>
<th>Dst</th>
<th>Pdy</th>
<th>Bx</th>
<th>Bz</th>
</tr>
</thead>
<tbody>
<tr>
<td>-29.677577</td>
<td>2.476296</td>
<td>5.288889</td>
<td>1.508544</td>
<td>1.130000</td>
<td>2.995000</td>
</tr>
</tbody>
</table>

![Equatorial projection of spacecraft positioning at onset.](image)

7.6.5.2 MAGNETOSPHERIC CONDITION

**MAGNETIC FIELD CONDITIONS**

![Measured minus modelled magnetic field vectors](image)

Figure 7.6-24 Measured minus modelled magnetic field vectors pre (light) and post (dark) model fitting.
GOES-06 shows a good dipolarisation signature, as does GOES-07, although 2 to 3 minutes later. The growth phase lasts 51 minutes and expansion 10 minutes.

**SOLAR WIND CONDITIONS**

Solar wind data is unavailable for this period. Solar wind data is available on the 22nd (δ = 6 parts/cc, V\(_{SW}\) = 350 km s\(^{-1}\), B\(_{GSM-XYZ}\) = -0.29, -0.74, 6.06) and 23rd at 1600 UT (δ = 6 parts/cc, V\(_{SW}\) = 360 km s\(^{-1}\), B\(_{GSM-XYZ}\) = -6.76, -2.26, 5.99) of October. The solar wind dynamic pressure used for this trace is 1.5 nPa.
Chapter 7 – Tracing of substorm events

7.6.5.3 INJECTION SIGNATURES & SELECTION

1982-019 shows a dispersive signature, 1987-097 a fraction of the pulse after more dispersion and 1984-129 the same again. 1989-046 shows a disturbance across all energies exactly at onset.

Figure 7.6-25 Particle injection as seen by LANL satellites.
7.6.5.4 PARTICLE TRACING

Figure 7.6-26 Leading edge particle tracing for event 32 (X axis non-linear).

7.6.5.5 OBSERVATIONS

This event has 4 LANL spacecraft observing the injection pulse and region. Particle signatures from both 1982-019 and 1987-097 were traced, providing indications regarding the extent of shell splitting and two locations for the eastern injection boundary. 1984-129 is used to provide pitch angle information for spacecraft 1987-097. Spacecraft 1982-019 is at a magnetic latitude that cuts off everything above 60° (assumed to be a larger effect than shell splitting could cause at this location), although 1987-097 is on the magnetic equator. Initial traces indicated that the particles passing between the two spacecraft were slower than 90° pitch angle particles – hence 1984-129 was required to determine the upper pitch angle ceiling. 1987-097 and 1984-129 were at approximately symmetrical locations with respect to the Y = 0 plane, and simulations earlier in this chapter indicate that shell splitting is symmetrical in nature, so the pitch angles first seen at the two spacecraft should be the same. The maximum pitch angle 95 keV particle that could pass between the two spacecraft in the (slow) time indicated by the data was determined to be 15°, and this was used for particle tracing from 1987-097. This indicated a greater degree of shell splitting than anticipated, although would be consistent with a substorm with less magnetotail radial penetration that had been previously seen.

The particle trace of the two sets of particles is shown above. The traces indicated two identical azimuthal locations (2800LT) although with two differing injection times (Δt = 4 minutes).
Chapter 7 – Tracing of substorm events

7.6.6 EVENT 33 (ONSET AT 1033, 31.12.90)

7.6.6.1 SPACECRAFT POSITIONS

Tilt: 23.307753, Kp: 2.665556, 31/12/90 UT: 10:34:00


Figure 7.6-27 Equatorial projection of spacecraft positioning at onset.

7.6.6.2 MAGNETOSPHERIC CONDITION

MAGNETIC FIELD CONDITIONS

Figure 7.6-28 Measured minus modelled magnetic field vectors for event 33, pre (light) and post (dark) model fitting.
GOES-06 shows the disturbance that identifies this event. The growth phase is 92 minutes long, and expansion 31 minutes (although this is somewhat arbitrary due to the unclear nature of this disturbance).

**SOLAR WIND CONDITIONS**

Solar wind data is unavailable for this period. Solar wind density and velocity are available on the 30th of December ($p = 12$ parts/cc, $V_{SW} = 450$ kms$^{-1}$) and 3rd of January ($p = 8.6$ parts/cc, $V_{SW} = 330$ kms$^{-1}$). IMF data is available on the 31st (B$_{XYZ} = -8$, -3, -3 to -5 nT). The solar wind dynamic pressure used for this trace is 2.24 nPa ($p = 10$, $V_{SW} = 340$ kms$^{-1}$).

**7.6.6.3 INJECTION SIGNATURES & SELECTION**

![Figure 7.6-29 Particle injection as seen by LANL instruments.](image)

**7.6.6.4 PARTICLE TRACING**

195
7.6.6.5 OBSERVATIONS

Spacecraft magnetic latitude gave pitch angle maxima of 66° for the leading edge trace, the results of which were convergence at between approximately 2800 and 2730LT at 1028 to 1027 UT.

7.6.7 EVENT 41 (ONSET AT 0815, 24.1.91)

7.6.7.1 SPACECRAFT POSITIONS
Chapter 7 – Tracing of substorm events

For event 41, GOES satellites are placed either side of local midnight, CRRES is in the tail, 1989-046 is in a position to see a proton signature/be in the proton injection and the other LANL spacecraft is expected to see electron injection pulses.

7.6.7.2 MAGNETOSPHERIC CONDITION

MAGNETIC FIELD CONDITIONS

![Magnetic field vectors](image)

Figure 7.6-32 Measured minus modelled magnetic field vectors for event 41, pre (light) and post (dark) model fitting.

From magnetic measurements, the growth phase was judged to be 133 minutes long, expansion 12 minutes. The GOES-6 Bz measured-model trace (light green middle panel) shows a distinct dipolarisation, although the onset has been misidentified by 9 minutes (it is actually at 0806 and expansion is 10 minutes long).

SOLAR WIND CONDITIONS

![Solar wind conditions](image)

Figure 7.6-33 Solar wind density, velocity, dynamic pressure and Bz conditions for event 41.
The solar wind IMF is southward from ~0640 and throughout the substorm episode. Density is off the scale high at 15-20 parts/cc indicating anomalous solar wind conditions, and solar wind velocity is around 400 m/s, with a corresponding (very high) solar wind pressure of 9 nPa.

7.6.7.3 INJECTION SIGNATURES & SELECTION

1989-046 is within the periphery of the injection region with observations of a non-dispersed ion injection feature (the timing of which indicate onset at 0807). The same satellite shows an electron dropout event. The other LANL instruments see the electron injection pulse pass by.
The upper panel shows electrons, the lower protons. Energies on the spectrogram descend from top to bottom, with line plots showing lowest energies at the top. CRRES is within the injection region at onset, and confirms the timing to be 0807 as per the corrected interpretation of magnetic signatures. CRRES is centrally placed at local midnight and sees both ion and electron enhancement, with ions showing no dispersion, but electrons taking some five minutes to penetrate high energies. The vertical white line shows the time when the leading edge particles converged (as the electron signature reached its highest energies).
7.6.7.4 PARTICLE TRACING

Figure 7.6-36 Particle tracing for event 41, y-axis position in local time against UT.

The four traces are for particles from the leading edge of the particle pulse observed by 1987-097, with pitch angles of 55°. The trace converges far to the east at 3000LT.

The relatively high dynamic pressure of this event led to its use in a comparative study. In Reeves [1991] the guiding centre drift velocities of various pitch angles were compared as functions of local time and it was found that high bow pressure could flatten the geometry of the dayside magnetosphere. In the models employed this reduced the drift speeds of high pitch angle particles around noon such that, in some cases, they were less than the drift speeds of low pitch angle particles.

Figure 7.6-37 shows the results of a similar analysis for event 41. The total period shown is of the order 220 minutes or two particle orbits. The first orbit occurs during a time when the tail field was stretching during event 41’s growth phase, causing more curvature drift (hence the difference in the speeds for the two orbits), and both orbits occur during an episode of high dynamic pressure. Comparing the figure with Reeves [1991], this is contrary to the result indicating high α₀ particles can drift significantly slower than low α₀ particles under noon field compression conditions. The discrepancy may well be due to the differing field models in use.

This indicates that the leading edge particles of an injection pulse will always be composed of the highest pitch angle particles, and the tail composed of low pitch angle particles – there are no areas where the differing pitch angles can reverse speed order.
Chapter 7 – Tracing of substorm events

7.6.7.5 OBSERVATIONS

This event was of interest due to the magnetopause compression caused by the high solar wind dynamic pressure. As the event was examined it was noted that the compression pushed the
model subsolar magnetopause in to around 9 \( R_E \), and created a new magnetic minima towards the lobes, where particles could migrate to (rather than the equatorial minima) during full-orbit testing. Identification of trailing edge particles was not possible due to considerable signal noise, although the leading edge trace proved good and converged just as CRRES/EPAS observed the substorm injection region intensify at higher energies.

7.6.8 EVENT 51 (ONSET AT 1022, 27.2.91)

7.6.8.1 SPACECRAFT POSITIONS

Figure 7.6-38 Equatorial projection of spacecraft positioning a little after onset.

7.6.8.2 MAGNETOSPHERIC CONDITION

MAGNETIC FIELD CONDITIONS
Chapter 7 – Tracing of substorm events

Figure 7.6-39 Measured minus modelled magnetic field vectors for event 51, pre (light) and post (dark) model fitting.

From magnetic measurements, the growth phase was judged to be 134 minutes long and expansion 20 minutes. The two vertical solid black lines represent onset, and the end of the expansion phases. The CRRES BZ measured-model trace (light green middle panel) shows a weak localised dipolarisation, although the onset has been misjudged by 14 minutes (it is actually at 1022). The GOES-06 ‘rectangular-BZ’ feature during the growth phase was caused by a change in the spacecraft solar cell magnetic field in eclipse.

SOLAR WIND CONDITIONS

Figure 7.6-40 Solar wind conditions for event 51.

Although the solar wind IMF is seen to be continually southward, velocity and density data were unavailable for this day. The last available data (for 25.02.91) showed quiet time values of $V_{SW} = 440 \text{ m s}^{-1}$, $\rho = 3.5 \text{ parts/cc}$ and $P_{dyn} = 1.25 \text{ nPa (low)}$ and the next (for 2.03.91) showed near-identical steady values. Although a long extrapolation, the solar wind was assumed to be steady over the data dropout period (LANL data showed the period to be magnetospherically quiet).
Chapter 7 – Tracing of substorm events

7.6.8.3 INJECTION SIGNATURES & SELECTION

Figure 7.6-41 Event 51’s particle injection as seen by LANL instruments. This graph shows ion traces overlaid in yellow.

1989-046 is in the central injection region with observations of non-dispersed injections feature for both ions and electrons (the timing of which indicate onset at 1021). Spacecraft 1990-095 shows a slightly dispersed ion injection pulse. 1987-095 shows a dispersed electron injection – with only minimal dispersion given the spacecraft’s location at approximately 1100LT. A rise in the lowest energy channel, 50 to 75 keV, of the middle panel spacecraft at approximately 1150 was interpreted as a weak echo of the initial injection and traced back to the original observation (1021) to within three minutes.
Chapter 7 – Tracing of substorm events

7.6.4 PARTICLE TRACING

Event 51, *Proton* location (LT) versus time (UT)

Figure 7.6-42 CRRES/EPAS fluxes for event 51. Both species show non-dispersed signatures at 1021.

Figure 7.6-43 Proton tracing for event 51, y-axis position in local time against UT.
Figure 7.6-43 three traces are for protons from the leading edge of the ion injection observed by 1990-095, with pitch angles of approximately 70° (minimum to avoid violation of \( \mu \)). Ten-second resolution plots were required to select the particles. The alterations in the trace gradients are a function of higher-resolution reports when higher energy particles are being traced. The trace converges at 2200LT. Due to the short period the trace occurs over and the resultant lack of dispersion in the signature, the result should be treated with caution.

![Event 51, Electron location (LT) versus time (UT)](image)

Figure 7.6-44 Electron tracing for event 51. Convergence occurs at 2800LT.

7.6.9 EVENT 61 (ONSET AT 1021, 08.3.91)

It was not possible to establish the maximum pitch angle of this injection pulse’s leading edge (due to noise around the second signature’s flux increases masking the time the pulse passed). The results from this trace are therefore not reported.
Chapter 7 – Tracing of substorm events

7.6.10 EVENT 67 (ONSET AT 0653, 13.03.91)

7.6.10.1 SPACECRAFT POSITIONS

Figure 7.6-51 Equatorial projection of spacecraft positioning at onset.

7.6.10.2 MAGNETOSPHERIC CONDITION

MAGNETIC FIELD CONDITIONS

Figure 7.6-52 Measured minus modelled magnetic field vectors, pre (light) and post (dark) model fitting.

GOES-07 shows a distinct onset at 0626, with a growth phase of 95 minutes and an expansion phase of 12 minutes. Retrospectively however, the traced signature is more likely associated
with the second set of activity at 0653. This work was therefore done without good magnetic field adaptations in place.

**SOLAR WIND CONDITIONS**

Solar wind density, velocity and IMF data are available for this event. They indicate a large decrease in dynamic pressure prior to onset, and an increase in $B_z$ from negative to positive values, either of which could be attributed as triggers. The solar wind dynamic pressure indicated from the data is approximately 3 nPa at onset.

**7.6.10.3 INJECTION SIGNATURES & SELECTION**

Figure 7.6-54 Particle injection as seen by LANL satellites (only one saw a signature).
7.6.10.4 PARTICLE TRACING

Event 67, Particle location (LT) versus time (UT)

Figure 7.6-55 Leading edge particle tracing for event 67.

7.6.10.5 OBSERVATIONS

No secondary spacecraft observations of this injection were available for this injection pulse. Comparable solar wind dynamic pressure and local time of observation values had been recorded for event 18, and therefore event 18’s pitch angle (60°) was assumed applicable to this event also. The resulting trace converged at approximately 2800 LT.

7.6.11 EVENT 88 (ONSET AT 1011, 2.4.90)

An injection trace was not possible for this event with the injection signature leading edge indistinguishable from other features.
Chapter 7 – Tracing of substorm events

7.6.12 EVENT 181 (ONSET AT 0639, 5.10.91)

7.6.12.1 SPACECRAFT POSITIONS

![Spacecraft Positions Diagram]

Figure 7.6-56 Equatorial projection of spacecraft positioning at onset.

7.6.12.2 MAGNETOSPHERIC CONDITION

MAGNETIC FIELD CONDITIONS

![Magnetic Field Conditions Chart]

Figure 7.6-57 Measured minus modelled magnetic field vectors for event 181, pre (light) and post (dark) model fitting (growth/expansion: 102/20 minutes).
GOES-06 shows a good dipolarisation, although from an apparently already relaxed state (possibly an effect of the high solar wind dynamic pressure conditions). The onset time was adjusted from 0637 (which was used to generate the above graph) to 0639 after closer examination of the onset signature for GOES-06. GOES-07, although presumably better placed, saw less activity indicating the dipolarisation was asymmetrically displaced westward.

**SOLAR WIND CONDITIONS**

![Solar wind conditions for event 181](image)

Figure 7.6-58 Solar wind conditions for event 181.

Density is off the scale for the build up and duration of this event, on average at 31 parts/cc for the duration of the event, pushing dynamic pressure up to values around 11 nPa. Bz shows small values up until onset, and then shows a southward turn.

**7.6.12.3 INJECTION SIGNATURES & SELECTION**

![Event 181's particle injection as seen by LANL satellites](image)

Figure 7.6-59 Event 181's particle injection as seen by LANL satellites.


Chapter 7 – Tracing of substorm events

7.6.12.4 PARTICLE TRACING/OBSERVATIONS

This event shows the degree of uncertainty introduced by lack of leading edge pitch angle information. This injection pulse was observed clearly on only one satellite – giving no option for determining the pitch angle distribution from the inter-spacecraft speed of the pulse. Also, no experience was built up with tracing in an environment with dynamic pressure of 12 nPa. Therefore the leading edge pitch angles could be anywhere from a few degrees through to the maximum which does not require \( \mu \) violation prior to convergence (71°).

\[
\begin{array}{|c|c|}
\hline
\alpha_0 & \text{Convergence} \\
\hline
10^\circ & \sim0400LT \\
30^\circ & \sim0300LT \\
40^\circ & \sim0200LT \\
71^\circ & \sim0000LT \\
\hline
\end{array}
\]

Table 7.6-1 Illustration of variable local time of convergence obtainable with different pitch angles for event 181.

These results, dependent on an unknown variable, were not carried forward to influence conclusions.

7.7 COMPOSITE RESULTS AND CONCLUSIONS

As can be seen from Table 7.7-1 and Figure 7.7-1 the particle traces for each event broadly agree, with the eastward extents of the particle injection regions seen ranging from 0300 LT around to 0600, with an average of 0400 LT.

\[
\begin{array}{|c|c|c|c|c|c|c|c|}
\hline
\text{Event} & \text{Convergence (LT)} & \text{Leading edge } \alpha_0 & \text{Dst} & \text{Dynamic} & \text{S/C01} & \text{S/C02} & \text{Proton boundary/trailing} \\
& & & & \text{pressure} & \text{LT} & \text{LT} & \text{edge signature origin (LT)} \\
\hline
6 & 0300 & 36 & -54 & 1.85 & 8.9 & 13.0 & - \\
13 & 0445 & 35 & -1 & 2.04 & 6.5 & 10.0 & - \\
18 & 0300 & 60 & 10 & 2.47 & 10.3 & 14.5 & 0000 (trailing) \\
21 & 0300 & 63 & -15 & 2.81 & 9.9 & 14.0 & 2130 (trailing) \\
28 & 0415 & 30 & -3 & 3.80 & 8.45 & 12.0 & 0100 (trailing) \\
32 & 0400 & 15 & 5 & 1.50 & 6.0 & 13.5 & - \\
33 & 0345 & 66 & 14 & 2.24 & 8.4 & 11 & - \\
41 & 0600 & 55 & 7 & 9.00 & 8.8 & 13 & - \\
51 & 0400 & 65 & -8 & 1.25 & 10.9 & 17 & 2200 (proton) \\
61 & - & - & - & - & - & - & - \\
67 & 0400 & 60 & -38 & 3.0 & 7 & - & - \\
88 & - & - & - & - & - & - & - \\
181 & - & - & 12 & - & - & - & - \\
\hline
\end{array}
\]

Table 7.7-1 Particle convergence points from event tracing.
Chapter 7 – Tracing of substorm events

The tracings done with trailing edge particles indicate a westward extent of 2130 to 0100 LT at the end of expansion phases, with an average of 2300 LT. The corresponding electron injection regions are marked in Figure 7.7-1, and show substantial variation from one event to another, indicating injection regions vary with each substorm. The one trace of the westernmost point of the ion injection region shows another injection region similar in extent to the regions seen between leading and trailing edge electrons.

The distribution of dipolarisation event observations is in contrast to the apparent average electron injection region. Viking and CRRES/LEPA data indicate that substorm auroral electrons associated with dipolarisations and visible emissions occur in the region from 2100 to 2300 LT. These electrons are sub-10 keV in range. The distribution of the higher electron injection regions indicated above is quite different from the local time distribution for this low energy component. This may be explained in one of two ways: the mechanisms which accelerate the two populations differ, or the transport mechanism from acceleration to injection region exerts a local time segregation on the particles. The latter case would be consistent with a distant acceleration of particles, and normal gradient-curvature-electric field drifts as the particles moved towards the Earth from the tail, favouring substorm high energy electrons to be displaced to the east, and low energy particles to the west. Birn et al. [1998] describes simulations of tail acceleration and transport which produce this energy versus local time distribution from electron acceleration and cross tail transport of high energy particles.
The majority of particle tracing work uses LANL high energy detector data and yields tracing results consistent with those above. A future direction may be to apply such tracing to low energy electron injections as seen by CRRES/LEPA and determine if injection regions differ – and adding weight to the arguments of Birn et al.

No correlation is apparent between the pitch angles determined for the traces and local time of observation or dynamic pressure/Dst. It is assumed the data set is too small to highlight any relationship or the shell splitting relationship is more complicated than assumed here. Another hypothesis tested was that the time from dipolarisation observation to particle injection may correlate with the local time of injection – relating to some form of propagation of particles from dipolarisation acceleration to injection. Such work was inconclusive due to the observed time of dipolarisation being partially dependent on the local time of the magnetometer bearing spacecraft.

Some substorm growth phase commencements coincided with southward turnings of the IMF when comparing in-situ tail magnetometer data and IMP-8 data, confirming the nature of these periods as reconnective chargings of the magnetosphere.

Guiding centre velocity versus local time analysis for a number of energy/pitch angle combinations have shown that the leading edges of particle pulses will always be composed of high pitch angle particles, and the trailing edge will always be composed of low pitch angle particles. Reeves [1991] indicated that when the magnetic field geometry of the dayside was flattened due to high dynamic pressure, this reduced the drift speeds of high pitch angle particles around noon such that, in some cases, they were less than the drift speeds of low pitch angle particles. This work's results are contrary, indicating high $\alpha_0$ particles always drift faster than low $\alpha_0$ particles, even under noon field compression conditions.
CHAPTER 8 – CONCLUSIONS

This thesis has examined the particle injections and solar wind conditions associated with substorms observed during the CRRES mission. The objective of this work was to investigate the morphology of substorm injection pulses and injection regions by identifying and using particle injection signature observations and particle tracing. The main tool developed for use in these studies was a particle tracing code, with relativistic guiding centre drift equations including realistic magnetic models and a representation of the electric field. The conclusions derived from this work, and the subsidiary studies of the solar wind-substorm relationship are presented here.

8.1 SUBSTORM CHARACTERISATION

One hundred and eight-seven substorm injections have been identified in the CRRES epoch using data from GOES 6, 7 and CRRES magnetometers, five LANL geostationary spacecraft CPA/SOPA instruments, and CRRES/LEPA and CRRES/EPAS instruments. From this set of carefully identified substorms, injections have been characterised as having energy ranges of up to 550 keV, with the majority of events reaching 250-350 keV. This mode value may be artificially low due to shell splitting removing higher energy elements of some injections from geostationary space. No records of the local times associated with each maximum-energy-of-injection projection were made, although it is anticipated that the higher projections used data nearer injection, and the lower projections were based on observation further from midnight and partially influenced by greater shell splitting. Hence the mode figure may be closer to 550 keV.

Injection events are not instantaneous but occur over periods of order 30 minutes. This conclusion is drawn from the convergence timing of leading edge particles compared with the corresponding times from trailing edge particles, and is corroborated by the duration of features seen by injection-region spacecraft. Particle tracing produced results consistent with the leading edges of injection pulses being composed of high energy, high pitch angle particles from the start of injections, and the pulse-tail particles being composed of low energy, low pitch angle particles injected at the end of the activity.

8.2 THE SOLAR WIND – SUBSTORM RELATIONSHIP

It has been observed by Stern [1995] that after a long quiet period when the IMF turns suddenly southward, one can see the magnetotail reservoir of energy charge up as the tail field intensifies and magnetic field lines in synchronous orbit become stretched increasingly tailward.
Chapter 8 – Conclusions

Comparing in-situ tailward magnetometer data and IMP-8 data in Chapter 7, a number of substorm growth phase commencements coincide with southward turnings of the IMF confirming the nature of this phase as a charging of the magnetosphere by reconnection. The magnetotail acts as an energy store, although the relationship between the triggering of substorm onset and solar wind energy input is non-linear [Chapter 5 – Correlations]. The mechanism responsible for the release of this energy is internal, although this internal process is susceptible to external factors such as northward turnings of the IMF. A northward IMF turning is not mandatory for an event to occur and many are caused by other perturbations, a number of which appear to be purely internal [Chapter 5 – Triggering]. This conclusion is based on studies using IMP-8 – which maybe away from the Earth-Sun line – and hence maybe vulnerable to unobserved small-scale structures in the solar wind causing effects without attribution. However, other studies have shown no dependence of triggering or non-triggering of substorms on the location of the monitor [McPherron and Hsu, 1998], hence this work does not support the $E_{SW}$ reduction theory for the triggering of substorms [Lyons, 1996].

The magnetosphere reacts to increased energy input with a larger number of higher flux particle injections, and larger dipolarisations [Chapter 5 – Correlations]. This work indicates that the size of the dipolarisation seen was most greatly influenced by the solar wind power input between T-2 hours and T -30 minutes. Few measures of the magnitude of a particle pulse correlate with solar wind energy input however, except for the projected flux increase seen at 40 keV.

The solar wind characteristics associated with substorm onsets seen during the lifetime of CRRES varied with dipole tilt to the Sun [Chapter 5 – Superimposed Epoch Analysis]. This may be explained in three possible ways. The dipole tilt could alter the geometry of the magnetospheric system such that solar wind conditions required to precipitate onset are varied, long-term seasonal changes could occur in the solar wind over CRRES’s lifetime or the formation of a new long-lived inner radiation belt of 15 MeV particles in March 1991 could have modified the magnetospheric response to solar wind changes. Although this interesting result may have implications for the onset mechanism, no further conclusions can be drawn without further study. A longer-term solar wind/substorm study spanning several years is required to resolve this season versus tilt angle ambiguity inherent in a CRRES epoch study.

The full resolution of the relationship between solar wind and substorms will require solar wind data closer to the subsolar region with fewer dropouts. This will reduce doubts over magnetosphere-scale solar wind structures, enabling the triggering debate to be fully resolved.
and will also provide a better basis for correlative studies, from which storm and substorm prediction models may be built.

### 8.3 MORPHOLOGY AND VARIATION OF PARTICLE INJECTIONS AND REGIONS

Particle injections are a major component of substorms and magnetospheric physics. Injections periodically populate the inner magnetosphere with hot particles and expose spacecraft to bursts of radiation. The events studied in this work have highlighted specific points with respect to the pitch angle evolution of injection pulses and the location of the eastern electron injection boundary.

By self consistently tracing particle injections through multiple observations, it has been found that the pitch angles of signature leading edges need to vary for observations and models to be consistent [Chapter 7 – Event 13]. Different pitch angle particles are observed to lead particle pulses. This is due to shell splitting radially distributing particles on drift shells dependent upon energy and pitch angle [Chapter 7 – Shell Splitting] with this effect magnifying with LT progress of the injection pulse. High-energy high-pitch angle particles leading the injection pulse drift further out and are removed from geostationary space. Particle pulses will be radially dispersed as a function of energy, pitch angle, local time and dynamic pressure, resulting in a radially structured injection pulse passing through local time. Drift shells are elongated by various extents at noon, resulting in spacecraft in circular geostationary orbits at different local times seeing different particles at different times. High energy, high pitch angle particles travel faster further out than others in the pulse with low-energy low pitch angle particles on the inside, resulting in a pulse with a sheared appearance as it progresses around local time and spacecraft away from midnight seeing only a subset of the pulse. This effect is confirmed by injection simulations with particles of various energies and pitch angles under differing dynamic pressures [Chapter 7 – Shell Splitting].

Alterations in the dynamic pressure exerted on the magnetosphere can alter the extent of shell splitting particle pulses are subject to and results in the modification of injection signatures seen. Pitch angle considerations must be taken into account in tracing work with assumptions regarding the leading edge pitch angle distribution substantially effecting the local time of particle convergence [Chapter 7 – Event 181]. Prior studies have applied a single pitch angle to all signature observations over multiple local times and solar wind conditions, as well as over all energies. Although this is unavoidable in most circumstances, it may compromise results. Shell splitting effects are of greatest magnitude for the high-energy (100 keV+) component of
Chapter 8 – Conclusions

particle pulses. High-energy particles wrongly attributed with higher pitch angles, will converge prior to the lower energy particles at a more eastward local time.

Pitch angle distributions are a function of energy, local time and Dst/dynamic pressure (hence magnetic field configuration). With high-resolution pitch angle distributions for geostationary injection pulses it would be possible to model this function for use in particle tracing work, or use such pitch angle information directly for accurately tracing particles to injection points. However, such an instrument does not exist in geostationary orbit for this epoch, and the EPAS instrument positioning largely excludes its use for this application. Particle injection pulses may however be traced by inferring leading edge pitch angles from inter-spacecraft pulse transition times.

Thirteen events were selected, on the basis of spacecraft position and magnetospheric activity level, from the 187 previously identified. These events were traced and the results are presented in Chapter 7 and above. The results are upper limits [Chapter 7 – Determination of leading edge pitch angles] that show that the easternmost extent of the injection region is westward of between 0300 and 0600 LT (mean 0400 LT). It is anticipated that this upper limit is not far from the actual extent of the region. This is consistent with other work.

An upper limit for the injection region eastward extent is between 0300 LT and 0600 LT. This is contrary to the distribution of dipolarisations (1900-0100LT). The injection regions show substantial variation from one event to another, indicating injection regions vary with each substorm. Viking and CRRES/LEPA data indicate that substorm auroral electrons associated with dipolarisations and visible emissions occur in the region from 2100 to 2300LT. These electrons are sub-10 keV in range. The distribution of the higher electron injection regions indicated by this work is different from the local time distribution for the sub-10 keV component. Either the mechanisms that accelerate the two populations differ, or the transport mechanism from acceleration to injection region exerts local time segregation on the particles. The latter case would be consistent with normal gradient-curvature-electric field drifts of particles from a tail acceleration towards Earth, favouring substorm high energy electrons to be displaced to the east, and low energy particles to the west. Birn et al. [1998] describes simulations of tail acceleration and transport which produce this energy versus local time distribution from electron acceleration and cross tail transport of high energy particles.

The low distribution of leading edge pitch angles seen imply that geostationary orbit may be close to the limit of injection region radial penetration in some events. The lower pitch angles seen indicate that more shell splitting occurred in the motion of the pulse from its injection point or that minimal radial penetration occurred reducing the particles available to shell-split...
out to the observation point and replace those removed to higher altitudes by the same process. This may be due to differing magnetospheric configurations (i.e. more dynamic pressure), or it may indicate that the injection had less radial penetration. More work is required, although determining the pitch angles seen and modelling the shell splitting function may result in a method of remotely determining the radial extent of injections into the inner magnetosphere.

8.4 PARTICLE TRACING

Particle tracing is a powerful tool for determining the origin of phenomenon seen in the magnetosphere. The essential physics of tracing particles appears sound with a number of drift echoes mapping to each other via tracing. It does however require careful implementation and a large amount of information to obtain consistent results. Accurate magnetospheric field models are essential along with continuous solar wind data. This is an important requirement in determining the configuration of those models — with solar wind dynamic pressure having an acute effect on the geometry of the dayside and hence the drift speeds of particles. The magnetic field models provided by Tsyganenko [1989, 1996] are fast accurate models of average conditions. Substorm conditions are however distinctly non-average, particularly in the tail region, hence magnetic field models need fitting to data from these periods for confidence in tail-region guiding centre speeds to be expressed. As solar wind dynamic pressure and the IMF is important in magnetic field configuration, and this having such a large impact on guiding centre drift speeds, in retrospect it is unfortunate that such a large fraction of events were traced where such data had to be extrapolated. In future work only events where a good history of solar wind data is available will be traced.

Electric field models require work, or an increase in computing speeds, to be accurate portrayals of the substorm field. Comparison with CRRES data showed the Volland-Stern model to have discrepancies with real data, and this will be exacerbated during substorms. The electric field is essential in the dynamics of both lower energy particles, and those with high pitch angles. The field can remove energy from parallel motion and hence have a large effect on pitch angles, changing pitch angles as particle moves either with or against the electric field. Pitch angle in turn has a large effect on drift speeds — a particle of 60° travels 20% slower than a 90° pitch angle particle. In this study, electrons traced through the dawn sector lost substantial amounts of energy to the electric field and exhibited changes in pitch angle of order 25°, often causing difficulties if they migrated to 90° and required the violation of $\mu$ to continue. The Volland-Stern model reacts poorly to changes caused by increased convection and is a function solely of Kp value. Therefore the real electric field — stimulated by short-term changes in the solar wind — may have significant effects not seen in the tracing code. When computationally
viable, tracing codes should use one of the equipotential-traced ionospheric electric fields, dependent on solar wind variables to obtain better results.

As described above, during the process of tracing particle injections of unknown pitch angles, it was noted that low energy, high pitch angle particles often evolved into 90° pitch angle particles and further progress required either the violation of the first adiabatic invariant, or drift along equipotentials. The former solution was adopted, although after work modelling shell splitting, a decrease of initial pitch angles was favoured under the assumption that what was being seen was not an inaccuracy of the tracing process or real violation of μ, but the tracing of particles that did not exist. Initial traces often assumed the leading edges of particle pulses as seen by the spacecraft involved a distribution of pitch angles from 90° downwards, with the magnetic latitude of the spacecraft and mirroring acting as a filter blocking the highest pitch angles from the spacecraft's observation. It was concluded however that this was incorrect and that the pitch angle distribution was being radially sorted at geostationary altitudes by shell splitting. This would remove high pitch angles from the local distribution and cause the high pitch angle assumption to become invalid, causing the non-physical requirement to violate μ purely by tracing particles of the wrong pitch angle.

The method for establishing the leading edge pitch angle relies on tracing the leading edge as seen travelling between two spacecraft observations. This assumes that no shell splitting occurs between the two spacecraft in question - this is often a valid assumption, although inaccuracy may arise if the distance between the two spacecraft is great and shell splitting removes a large fraction of the distribution in the distance between the two spacecraft. The result will be the attribution of pitch angles that are too small, and a resultant convergence more to the east than it should be.

Figure 8.4-1 An example of the difficulties posed in identifying the leading edges of injection pulses.
Chapter 8 – Conclusions

As shown in Figure 8.4-1, the injection pulse signatures are masked by other positive-gradient features in the lowest two energy channels (top lines traces). Increases in the gradient differentiate these features, although their attribution is still questionable.

Particle selection by eye represents a possible source of bias in the technique. It is required that particles be defined as the leading edge of an injection, although as the leading edge is only a small increase in fluxes it can often be lost in noise unless the magnetosphere is extremely quiet. Also, the steep flux gradient of the leading edge of a particle pulse can start within another shallow gradient feature (such as in Figure 8.4-1). In cases where the start of an increase in an energy channel is somewhat ambiguous, it is often tempting to select particles such that they fit into the preconceived model injection front indicated by the other selected particles – causing convergence to be artificially good. In an attempt to avoid this, all particle selections have been presented along with data in results such that selection may be challenged and justified if perceived to be incorrect.

The tracing code developed was found to be sound in all work conducted. In a number of cases features seen in the simulations were originally doubted, and later found to have footing in real physical phenomenon (such as above the change in pitch angle leading to violation of \( \mu \) being due to an incorrect pitch angle assumption). This has resulted in a valuable tool to conduct future research such as radiation belt modelling and forward-time simulations of substorm injections.

8.5 SUMMARY OF CONTRIBUTIONS OF THIS WORK

- Particle injections have been characterised as having energy ranges of up to 550 keV, with the majority of events reaching at least 250-300 keV.

- Injection events are not instantaneous uniform injections of particles, but processes that can last for periods of order 30 minutes.

- A number of substorm growth commencements coincide with southward turnings of the IMF – confirming this phase’s nature as a reconnective charging of the magnetosphere. The magnetotail acts as an energy store, although the relationship between onset triggering and the solar wind energy input is non-linear. The mechanism responsible for the release of this energy is internal although susceptible to external factors.

- The magnetosphere reacts to increased energy input with a larger number of higher flux particle injections, and larger dipolarisations. The greatest influence of solar wind on size of dipolarisation occurs between T-2 hours and T-30 minutes with respect to onset. Few
measures of the magnitude of a particle pulse correlate with solar wind energy input, except the projected flux increase at 40 keV.

- A variation in the solar wind structures associated with substorm occurrence was seen with dipole tilt angle to the Sun. This may indicate the dipole tilt effects the onset mechanism or that long-term seasonal changes occurred in the solar wind over the CRRES lifetime or the formation of a new 15 MeV inner radiation effected the mechanism.

- A sophisticated model of magnetospheric particle motion has been developed, using realistic magnetic field models, a representation of the electric field, and relativistic guiding centre drift equations. In addition to encompassing many features seen on other models (although rarely all in one model), the new code attempts to modify the magnetic field to allow for expansion phase changes to the field.

- This model provides traces of injection signatures back in time with excellent convergence given the input of particles from diffuse dispersed injection signatures This indicates particles drift within the magnetosphere in accordance with current understandings of the physical processes involved.

- A comprehensive analysis of particle injection signatures has been made, including the tracing of particles between spacecraft to get pitch angle information for subsequent tracing of signatures to injection points. Work on the relative drift speeds of particles of differing pitch angles over local time indicate the larger pitch angle particles are consistently faster than lower pitch angle particles. This indicates that the leading edge of particle pulses are always composed of high $\alpha_0$ particles and trailing edges are always composed of low $\alpha_0$ particles.

- The effects of shell splitting may compromise particle tracing. Shell splitting can divert high-energy, high-pitch angle particles outside of geostationary orbit and hence reduces leading edge pitch angles as a function of local time travelled, energy and solar wind dynamic pressure. Simulations of this effect were corroborated by the eroded leading edge appearance of some injection signature high-energy components. Tracing is effected such that the resultant local times are upper limits of the eastward extent of the injection region.

- An upper limit for the injection region eastward extend is between 0300 LT and 0600 LT. This is contrary to the distribution of dipolarisations earlier observed between 1900-0100LT with a mean of 2100LT. The injection region varies substantially from one
substorm to the next. No correlations of local time of injection boundary with substorm attributes could be seen.

- Substorm auroral electrons (sub-10 keV) associated with dipolarisations and visible emissions are observed with a more westward local time distribution than the injection regions indicated by this work for the higher energy injected component. Either the mechanisms that accelerate the two populations differ, or the transport mechanism from acceleration to injection region exerts local time segregation on the particles as a function of energy consistent with Birn et al. [1998].

8.6 POSTSCRIPT

Lack of adequate data coverage is often restricts the progress possible in magnetospheric research. In the case of this study, a vast amount of data was gathered and processed and still found to have data gaps, or there were long periods when spacecraft were non-ideally distributed or conditions not conducive to particle tracing. Better magnetometer, electric field and plasma analyser coverage of the geostationary nightside/tail region would advance future studies substantially. Substorm magnetic field models and electric field models would benefit, as would the analysis of injection regions and pulses prior to substantial shell splitting effects. At the time of writing, the UK Swarm mission proposal would assist in many of these matters. It proposes that over 30 small inexpensive spacecraft with magnetometers and combined electron/ion E/q analysers be distributed throughout and beyond magnetospheric space. It is hoped that this, or one of the other magnetospheric constellation missions will be brought to fruition to assist solving the puzzles of substorm dynamics.

Magnetospheric substorms are subject to intensive world-wide study. The objective of this effort was to assist in the determination of the mechanism by which magnetotail energy is converted into substorm phenomena such as dipolarisations, particle injections and ionospheric currents. Achieving this will lead to better models for predicting magnetospheric conditions, contributing to the prediction of magnetospheric effects such as those important to spacecraft operation as well as power and telecommunications networks on the ground. Progress is made in a piecemeal fashion with individual studies building upon one another, adding weight to (often opposing) lines of argument regarding substorm development. This thesis contributes to this process with conclusions drawn from the study of 187 events, with data from thirteen instruments spread over nine magnetospheric and one heliospheric spacecraft. It is hoped that this work in concert with many other such efforts may help to resolve the substorm puzzle.
ACKNOWLEDGEMENTS

My thanks go to my mother and father for putting up with an awkward southerner son all these years, over 258 miles down south.

I owe a debt of gratitude to Alan Johnstone and Gordon Wrenn for being my supervisors and providing many resources to make this work possible – not least their advice and guidance which allowed a naive graduate to become someone who can do a passing impression of a space scientist of sorts. My thanks go to others for such help over the years: Andrew Coates, David Rodgers, and Andrew Sims. I would like to thank Paul Carter and Andrew Fazakerley for giving me such wide latitude in my role in Cluster/Cluster-II that completion of this work was possible. My thanks also go to the founders, staff and alumni of the International Space University and Roger Highfield, the science editor of the Daily Telegraph – for contributing two unique and ongoing experiences to the course of my PhD.

Thanks go around the globe to those that helped me with data or many an emailed interrogative: Reiner Friedel, Geoff Reeves, Mervyn Freeman, Howard Singer, Nikolai Tsyganenko, Doug Rowlands, Nick Watkins, Petri Toivanen, Tuija Pulkkinen, Larry Lyons, Dan Weimer, Daniel Heynderickx et al. I’m glad I arrived after the Internet.

I would also like to thank the many at MSSL who showed me the ropes, supported my work in any indirect way, helped me figure things out, or were plain just friends: Sarah, Ady, Geraint, Dave, Phil, Matt, Encarni, Steve, Andy, Gavin, and the main office staff (Ros, Libby, Pat, Julie, Sue and Judy) – in no particular order other than the way I typed it. I’d also like to thank Debbie for clearing off (desk space is at a premium here), and Tom/Sue/Louise for allowing me to work late in their House. To my other friends who I have neglected over these (too long) years I’d like to say thanks for keeping my spirits up and my glass filled – I’m sure the parties I had to miss out on were no fun anyway.

I am grateful to PPARC and DERA for financial support of my studentship.


References


Dungey, J.W., et al., The structure of the exosphere or adventures in velocity space, Geophysics, the Earth's environment, New York: Gordon & Breach, 1963.


Friedel, R. H., Reeves, G.D., Private communications, 1996.


References


Johnstone, A.D., et al., Observations in the equatorial region of field aligned electron and ion distributions in the energy range 100 eV to 5 keV associated with substorm onsets, *manuscript*, 1993.


227
References


McPherron, R.L and Hsu, Private communications, 1998.


Parks, G. K., Physics of space plasmas, page 84, Addison-Wesley, 1994.


References


Roederer, Dynamics of geomagnetically trapped radiation, Springer-Velag, 1970.


Rowland, D, private communications, 1998.


References


Tsyganenko, N.A., Data-based models of the geospace magnetic field: Where are we standing now?, *London Space Plasma Seminar*, May 1996.


References


Corrigenda


<table>
<thead>
<tr>
<th>Event</th>
<th>Onset from dipolarisation</th>
<th>Onset projected for particle injection</th>
<th>Dipolarisation event size (nT)</th>
<th>Rate of dipolarisation (nT/min)</th>
<th>Projected flux change at 40keV (diff. energy flux)</th>
<th>Projected max energy of injection (keV)</th>
<th>Time Since Last Substorm (minutes)</th>
<th># substorms in preceding 15 hours</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Appendices**

APPENDIX A - 187 EVENTS IDENTIFIED AS SUBSTORMS