Detection of Coherent Light in an Incoherent Background

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1. Motivation

Detection of a laser emission in daylight clutter in Infrared Search and Track Systems (IRSTs) is usually carried out[1] by measuring the energy from the scene in the instrument field of view. When the emitter is at a considerable distance or the reflected sunlight is intense, the target cannot be detected[2] by this method. This paper describes a more sensitive method based on detecting the coherence properties of the incident radiation.

2. Theory

The interference pattern[3] arising from two partially coherent sources is $I = I_1 + I_2 + 2.\sqrt{(I_1 I_2)}.\mathrm{Re}(\gamma_{12}(\tau))$, where $\gamma_{12}(\tau)$ is the complex degree of coherence. For a single source, the light can be split, delayed and recombined to give $\gamma(\tau)$, the self-coherence function, a complex function of the optical path difference, τ. The Fourier Transform of this function is the power spectrum of the light source[3]. If incident white incoherent light is passed through a rectangular bandpass spectral filter of bandwidth, Δk, and transmission, A, the self-coherence function resulting is a sinusoidal carrier, at k_0, with a sinc function envelope,

$$\gamma(\tau) = \int_{k_0-\Delta k/2}^{k_0+\Delta k/2} A.e^{-j\tau k}dk = \frac{2A}{\tau}\sin(\frac{\tau.\Delta k}{2}).e^{-j\tau k_0} = A.\Delta k.\mathrm{sinc}(\frac{\tau.\Delta k}{2}).e^{-j\tau k_0},$$

The envelope's first minimum occurs when $\tau_r.\Delta k/2=\pi$, or $\tau_r=2\pi/\Delta k$, which we call the "reference" path difference. If the light spectrum is not flat across the filter bandwidth[4], then the position of this minimum is different. This occurs when a highly coherent source such as a laser is introduced into the white light background. In this paper the change in position of the self-coherence function minimum is used to detect the presence of a coherent source, rather than the change in the strength of the self-coherence function at the reference path difference[4].

3. Description of the Approach

The system (Fig 1) uses both optical and digital signal processing. The optical section is an interferometer to measure the self-coherence function of the incident radiation to give an interferogram, and uses a narrow band filter to produce the sinc envelope already mentioned. The photodetector only detects power, which is the square of the modulus of γ. So the region between the main lobe and the first sidelobe of the envelope appears as a minimum rather than as a zero crossing where the envelope changes sign. The enclosed carrier undergoes a π phase shift at this point, which we use to define the point more accurately.

The post detector section comprises 40 dB signal amplification with a 1kHz low pass filter, 8 bit A/D conversion at a 500Hz sampling rate and a demodulation MATLAB algorithm, giving phase and instantaneous frequency signals as a function of optical path difference. The MATLAB program employs a built-in 5^{th} order Butterworth low pass 80Hz filter to reject noise. The algorithm calculates the overall average of the samples and subtracts it from each sample to eliminate any DC level. The number of zero crossings of the signal is counted and is used to determine the carrier frequency. The carrier frequency is used in a built-in phase demodulation routine. The frequency deviation is obtained by differentiating the phase signal with a first order difference equation. Threshold detection is used to find the location of the frequency spike, which is compared to the reference path difference to give the phase step shift. A conversion factor which depends on the piezoelectric driver (Fig 1) and the mirror scanning frequency converts sample number into path difference.

4. Experimental System

An experimental system (Fig. 1) was built in the visible band, employing a Michelson Interferometer, an interference filter centered in the red, and a silicon photodetector. Path difference scanning was performed by a piezoelectric transducer driving one of the interferometer mirrors normally with a 2Hz triangular waveform. Fig. 2(a) shows two sections of interferograms recorded from a 20W quartz halogen lamp, filtered by a 632.8 nm centered, 11 nm bandwidth interference filter. Fig. 2(b) is the unwrapped phase, and Fig. 2(c) is the modulus of instantaneous frequency, all as functions of path difference. Fig. 2(c) shows frequency "spikes" at the phase step points. Each plot has two graphs, the lower with the white light alone and the upper with both a laser and the white light. Various neutral density filters were introduced in the laser path to achieve different signal to clutter ratios.

5. Results

The results were averaged over up to 50 scans, depending on the relative visibility of the white light and laser fringes, to reduce the scan to scan variability. Amplifier gain was introduced to reduce quantisation noise. However, the relevant noise in this system is exhibited as fluctuations in phase step position not due to the laser. These factors

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might be temporal changes in the background spectrum, filter response variation with temperature, effect of vibration on the interferometer and most seriously transducer hystheresis and backlash.

Fig. 3 shows the shift in the phase step position as the signal to clutter ratio is varied. This is the ratio between the laser and the white light power within the filter bandwidth and was varied by changing the attenuation in the laser path. Five measurements of the phase step shift were averaged and plotted with their standard deviation as the error bar in Fig. 3. Below –29dB signal to clutter ratios the curve is roughly flat but has large error bars due to noise. Above -29dB the curve rises showing that a coherent light source has been detected in the incoherent background, an increase in path difference (taken as positive in the ordinate) meaning increased coherence.

For comparison, the usual method[1] involves measuring the total power from the scene and noting any increase larger than the normal noise fluctuations. The power detected from the white light source via the filter fluctuated from -16.12dBm to -16.07dBm. The laser power measured via the filter was -4.72dBm. Using an attenuation of 29.31dB in the laser path the power detected from the laser and white light via the filter was -16.06dBm in order to be just above the source fluctuations. The minimum detectable laser power is then -34.03dBm, giving a minimum detectable signal to clutter of –17.93dB. The minimum using the phase step shift method is -28.63dB giving an advantage of 10.7dB. It is worth pointing out that these results were obtained with materials already available, obtained at very low cost, without being custom made. It is expected that the error bars in fig. 3 will decrease considerably if a transducer with position feedback and negligible backlash were to be employed. In the phase step technique it is also important to notice that, unlike Fourier Transform Spectroscopy[5], only a small portion of the interferogram needs to be swept, around the phase step position; which also yields the advantage of higher scan rates, allowing signal to noise ratio improvement by integration.

6. References

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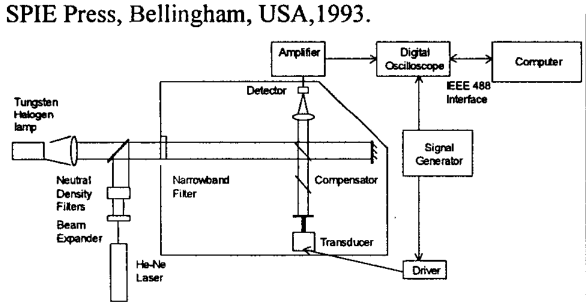

Figure 1 System Block Diagram

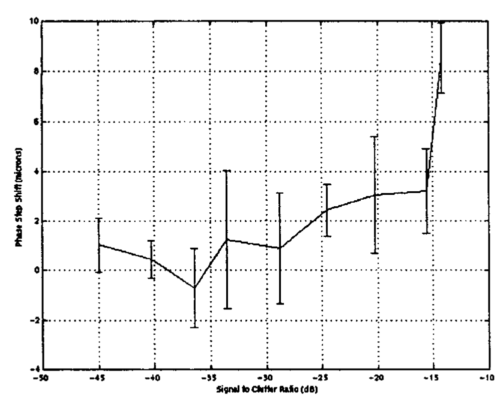

Figure 3 Phase step shift versus signal to clutter ratio

Figure 2 - Self-Coherence Function Signals