Considerations for a next-generation Great Observatory class space-based double Fourier interferometer for far-infrared astronomy

Berke V. Ricketti [a, b], Locke D. Spencer [b], David T. Leisawitz [c], Lee G. Mundy [d], David J. Wilner [e], Chris S. Benson [b, f], Gerard T. van Belle [g], Colm Bracken [h], Giorgio Savini [i], Jeremy P. Scott [b], William Grainger [j], Hannah Rana [e], Matteo Bonato [k], Duncan Farrah [l, m], and Conor A. Nixon [c]

[a]Disruptive Space Technology Centre, RAL Space, STFC-Rutherford Appleton Laboratory, Didcot, UK

[b]Institute for Space Imaging Science, Department of Physics & Astronomy, University of Lethbridge, 4401 University Drive, Lethbridge, AB, T1K 3M4, Canada

[c]NASA Goddard Space Flight Center, 8800 Greenbelt Rd., Greenbelt, MD, USA

[d]University of Maryland, Department of Astronomy, Room 1113 PSC Bldg. 415, College Park, MD 20742-2421, USA

[e]Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA, USA

[f]School of Physics and Astronomy, Cardiff University, Queen's Building, The Parade, Cardiff, Wales, UK

[g]Lowell Observatory, USA

[h]Experimental Physics Department, Maynooth University, Kildare, Ireland

[i]Optical Science Lab, Physics & Astronomy Dept., UCL, London, WC1E 6BT, UK

[j]RAL Space, STFC-Rutherford Appleton Laboratory, Didcot, UK

[k]INAF-Istituto di Radioastronomia, Bologna, Italy

[l]Department of Physics and Astronomy, University of Hawai'i at Mānoa, 2505 Correa Rd., Honolulu, HI, 96822, USA

[m]Institute for Astronomy, University of Hawai'i, 2680 Woodlawn Dr., Honolulu, HI, 96822, USA

ABSTRACT

Astronomy at far-infrared (far-IR) wavelengths is essential to our understanding of the evolution of the cosmos, from the star formation history of galaxies to how the ice distribution affects the formation of extrasolar planetary systems. The Hubble Space Telescope, James Webb Space Telescope, and the Atacama Large Millimeter Array have already produced ground-breaking astronomical observations with high angular resolution spanning the visible to sub-millimetre wavelength regimes. However, this presents a gap in the far-IR, from roughly $30 - 400$ µm, where ground-based observations are largely intractable due to the opacity of Earth's atmosphere. Indeed, no telescope, observatory, or interferometry array has ever achieved sub-arcsecond angular resolution over this wavelength range. A space-based solution is needed. However, a space-based far-IR telescope capable of sub-arcsecond angular resolution and high sensitivity, at a cost comparable to the largest space missions to date, presents unique physical, practical, and engineering challenges. In this paper, we envisage what a far-IR Great Observatory class mission might look like in the context of the already-studied Origins Space Telescope (OST) and the Space Infrared Interferometric Telescope (SPIRIT). We begin with a historical reflection of far-IR missions, including OST and the recommendations by the Astro2020 Decadal Survey for a de-scoped mission.[1]

Further author information: (Send correspondence to B.V.R.)

B.V.R.: E-mail: berke.ricketti@stfc.ac.uk

Optical and Infrared Interferometry and Imaging IX, edited by Jens Kammerer, Stephanie Sallum, Joel Sanchez-Bermudez, Proc. of SPIE Vol. 13095, 130951T

We use this to motivate the recommendation of a space-based interferometer as a reasonable path towards sub-arcsecond angular resolution at far-IR wavelengths. Using the SPIRIT mission concept as inspiration, we consider multiple point designs for a two element, structurally connected spatial-spectral space-based far-IR interferometer to understand the implications on achieved angular resolution and estimate total mission cost in context of the Decadal Survey recommended far-IR Great Observatory cost cap. This paper illustrates the unique capabilities only possible through a space-based far-IR double Fourier interferometry mission capable of sub-arcsecond resolution.

Keywords: far-infrared, interferometer, great observatories, high angular resolution

1. INTRODUCTION

For decades, the great observatories of humanity have inspired the next generation of astronomers with stunning images of the cosmos that have fundamentally changed our understanding of the universe. From the Chandra X-ray Observatory and the Hubble Space Telescope (HST) to the James Webb Space Telescope (JWST) and the Atacama Large Millimeter Array (ALMA), these instruments of technological ingenuity have unlocked high resolution observations across the electromagnetic spectrum. Indeed, nearly every wavelength from X-rays to radio waves has been observed at sub-arcsecond angular resolution except for one: the far-infrared (far-IR), roughly from 30-400 µm.

The barriers to high angular resolution far-IR astronomy can broadly be summarized by three factors: Earth's atmosphere, noise due to thermal emission radiation, and the diffraction limit at these wavelengths. First, the opacity of Earth's atmosphere at far-IR wavelengths makes Earth-based observations largely intractable. Ground based observatories, like ALMA, must be constructed at high altitudes, and even then, are limited to specific atmospheric windows generally longward of 400 µm. Therefore, a space-based solution is required to access the entire far-IR spectrum (for example, to measure spectral lines in galaxies regardless of their redshift). Second, ambient temperature objects (mirrors, support structures, etc) become a source of emission at these wavelengths; hence, cryogenic cooling systems are required to achieve the high sensitivity astronomical observations. Since any telescope element in the light path to the detector can act as a source of noise, all optics visible to the detector systems must ideally be cryogenically cooled to under 4.5 K, increasing the weight, cost, and design complexity of the overall system. Third, the diffraction limit at far-IR wavelengths means that sub-arcsecond angular resolution can only be achieved with a large primary mirror or an interferometer. For example, a far-IR angular resolution comparable to the HST at 100 µm requires a primary mirror almost 500 m in diameter. This is both technologically and financially infeasible for a space-based mission, even with the largest payload fairing rockets available and state-of-the-art segmented mirror technology.

While staying realistically within the budgetary constraints of the largest missions to date, as well as the total cost cap for a far-IR Great Observatory class mission recommended by the Decadal Survey, these three restrictions produce a far-IR trilemma, where only two of the three requirements can be achieved: a space-based telescope, a large primary mirror, and a cryogenically cooled system. Indeed, no past, current, or planned mission is capable of solving this far-IR trilemma. For example, the Herschel Space Observatory, the largest space far-IR mission to launch, had a primary telescope diameter of 3.5 m and an angular resolution of about 7 arcseconds at 100 µm, but with the primary mirror cooling to ~ 85 K.[2] Meanwhile, the Spitzer Space Telescope and the Wide-field Infrared Survey Explorer (WISE) were cryogenically cooled space-based telescopes, but were only a fraction of the size at 0.85 m and 0.4 m, respectively. Finally, ground based observatories, like JCMT and ALMA, can achieve high angular resolution with large primary mirrors or interferometric baselines, and can also utilize cryo-cooled detectors (like the Submillimetre Common-User Bolometer Array 2 in the case of JCMT), but cannot access the 30-400 µm far-IR gap due to Earth's atmospheric opacity.

In this paper, we propose a solution to this far-IR trilemma, capable of sub-arcsecond angular resolution at far-IR wavelengths, a far-infrared interferometer in space. We begin by reviewing the heritage of far-IR telescopes and concepts to date, including the Origins Space Telescope (OST), as well as the Decadal Survey's recommendation for a descoped OST mission.[1] Next, we employ the Stahl-Allison parametric mission cost model, along with the catalogue of specifications for previous far-IR missions, to understand the implications of the Decadal Survey's recommended total mission cost for a far-IR Great Observatory class mission.[3] We use this to motivate the recommendation of a space-base interferometer as the only reasonable path towards overcoming the far-IR trilemma, all while maintaining sub-arcsecond angular resolution as a fundamental requirement of the mission concept. Using the the Space Infrared Interferometric Telescope (SPIRIT)[4,5*], and the Far Infrared Space Interferometer Critical Assessment (FISICA)[6] mission concepts as inspiration, we consider three point designs for a two-element, structurally connected spatial-spectral space-based far-IR interferometer capable of high angular resolution observations, while still being within the cost cap presented by the Decadal Survey. A future space-based far-IR interferometer will deliver ground-breaking observations to the astronomy community to help humanity answer profound and enduring questions about the origins and evolution of our Universe and planetary systems such as our own.

2. PARAMETRIC COST MODELS FOR MONOLITHIC FAR-IR SPACE MISSIONS

Following Low's seminal work developing cooled infrared detectors in the mid 1960s,[7] the lineage of far-IR space telescopes began in 1983 with the launch of the Infrared Astronomical Satellite (IRAS). With a 0.57 m diameter primary mirror (and a collection area 37 times smaller than Herschel and almost 100 times smaller than JWST), IRAS mapped the sky in wavelengths never before observed. In the decades that followed, a number of far-IR missions were launched, including the Infrared Space Observatory (ISO, 1995),[8] *Spitzer* (2003),[9] AKARI (2006),[10] and eventually culminated in *Planck* and *Herschel* (2009). *Planck* and *Herschel* were launched together on May 14, 2009, with *Herschel* currently the largest far-IR space telescope to date. The Balloon Experimental Twin Telescope for Infrared Interferometry (BETTII, 2017),[11] the Balloon-borne Large Aperture Submillimeter Telescope (BLAST, first scientific launch in 2005),[12] and the Stratospheric Observatory for Infrared Astronomy (SOFIA, 2014–2022)[13] also served to partially cover the far-IR window from the upper stratosphere. Each of these missions was challenged by the far-IR trilemma, needing to make the difficult trade-off decision between telescope size and cryogenic cooling within a target cost.

Today, there are no active far-IR space observatories, despite previous work on mission concepts like the Space Infrared telescope for Cosmology and Astrophysics (SPICA).[14] Studied by ESA and JAXA as an M-class mission concept, SPICA was to have a 2.5 m cryogenically cooled primary telescope, but was dropped from consideration in 2020[†]. The current lack of far-IR missions is unfortunate given the recognition of far-IR potential in successive decadal and long range plans.[1,15–20] However, the current US Decadal Survey includes a recommendation for the restoration of the Great Observatories program, including a new far-IR Great Observatory class mission.[1]

The OST mission concept is one such space telescope proposed to the Decadal Survey for consideration.[21–23] With a 5.9 m cryogenically cooled primary mirror, OST[‡] would be the largest far-IR mission to date, capable of achieving approximately 4 arcsecond angular resolution at 100 µm.

However, for any mission, observatory specifications are only one part of the story, and financial constraints and budgetary cost caps must also be considered. Estimating total mission costs can be complex without a full master equipment list or grass roots cost estimates, but parametric cost models for space missions can provide a preliminary starting point in the right direction. Here, we will use the parametric cost model for ground and space telescopes developed by Stahl and Allison[3§], but other models like NASA's Instrument Cost Model (NICM) are also widely used.[24] Using a historical list of telescope parameters for both ground and space based observatories, Stahl and Allison developed a parametric cost model for the optical telescope assembly (OTA) expressed in terms of $M for FY17, given by,

$$OTA\$(FY17) = \$20M \times 30^{(S/G)} \times D^{1.7} \times \lambda^{-0.5} \times T^{-0.25} \times e^{-0.028(Y-1960)}, \quad (1)$$

[*] Additional documents and comprehensive study results from the SPIRIT mission concept are available here.

[†] The decision to cancel SPICA was not well received by many members of the scientific community.

[‡] Preliminary interferometric versions of Origins were under consideration within the community, prior to settling on the current monolithic telescope design.

[§] At the time of this submission, we have been made aware of a revised parametric cost model by Stahl et al. for monolithic telescopes. Parametric models such as these are an imperfect art and are only as good as the data from which they are drawn. As such, we would like to highlight the year of publication for the model we used in this work.

"where S/G = 1 for space and 0 for ground telescopes, D = diameter, λ = diffraction limited wavelength, T = operating temperature and Y = year of development".[3] Equation 1 provides an upper bound of the OTA cost with 50% confidence, and higher confidence levels can be achieved by multiplying by an appropriate scaling factor.[3] While this model presents no direct scaling from the OTA cost to total mission cost, Stahl and Allison have shown that there is a trend between the diameter of the primary mirror and OTA as a percentage of total mission cost.

Table 1: Specifications and parametric cost calculations for a selection far-IR space-based missions, past and future. Some far-IR missions (e.g. ISO and AKARI) are not included due to differences in how total mission costs are reported. Parameter specifications are associated with the variables in Eq. 1. Cost values have been rounded to the nearest $M. OTA calculations are at a 50% confidence level, per the original publication.[3] Here, D is the telescope diameter, λ is the diffraction limited wavelength, T is the operating temperature, and YOD is the year of development.

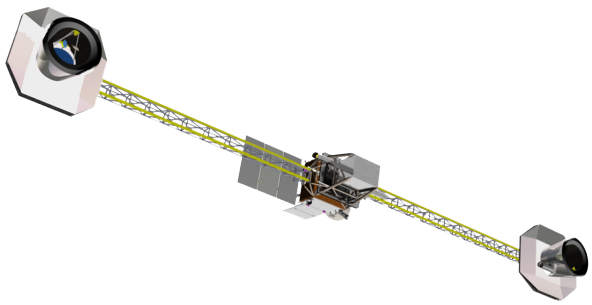
Mission	D (m)	λ(µm)	T (K)	YOD	Angular Resolution at λ (arcsec)	OTA $M FY20	Total Mission Cost ($M FY20)	OTA % of Total Mission Cost ($M FY20)
IRAS	0.57	8	4	1977	3.0	$43	$ 586	7.3%
Spitzer	0.85	6.5	5.5	1995	1.6	$52	$1,360	3.8%
WIRE	0.3	24	12	1995	16.9	$4	$114	3.3%
Herschel	3.5	80	80	2001	4.8	$71	$1,910	3.7%
Planck	1.7	300	40	2001	37.3	$13	$955	1.4%
WISE	0.4	2.75	17	2002	1.5	$14	$436	3.2%
OST	5.9	30	4.5	2025	1.1	$297	OST: $6,700 TRACE: $10,600	OST: 4.4% TRACE: 2.8%

Table 1 gives a summary of key parameter specifications for past far-IR space missions, along with OST as a comparison, as well as their OTA cost and total mission cost. The total mission cost cap by the Decadal Survey was $3-$5B (FY20),[1] so all OTA calculations and total mission costs have been scaled for parity to their equivalent FY20 value using average annual Consumer Price Index values published by the Federal Reserve Bank of Minneapolis.[25]

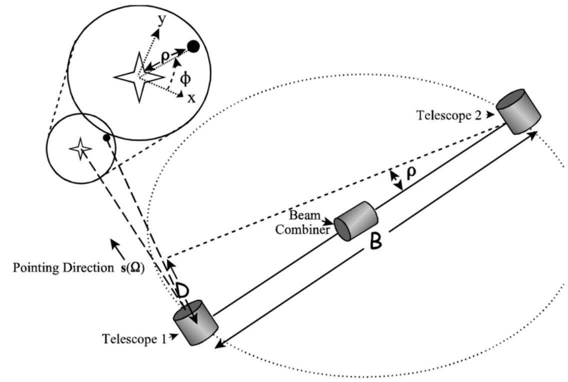
Two total mission costs are presented for OST. The first is the value (labeled "OST") was reported by the Origins team in their mission concept and is based on their master equipment list.[23] The second value (labeled "TRACE") was reported by the Decadal Survey based on an independent Technical Risk and Cost Evaluation. In either case, total mission cost is above the upper bound of the recommended cost cap for a future Great Observatory class mission presented by the Decadal Survey. Based on these cost estimates, Table 1 shows that no monolithic space telescope is capable of resolving the far-IR trilemma within the budget of $3-$5B. Indeed, a new design must be considered for the next far-IR Great Observatory: a space-based interferometer.

3. DESCRIPTION AND POINT DESIGNS

Mission concepts for a space-based interferometer have been studied for decades and can be divided into two camps: a structurally connected interferometer (SCI) and a free-flying (or formation-flying) interferometer (FFI). SCIs, studied for mission concepts like Optimast,[26,27] SPIRIT, and FISICA, generally have an extendable or foldable boom with collecting telescopes on either end and a central beam combiner. Their collapsible design allows for loading into rocket fairings while still being capable of large baselines once fully deployed. Meanwhile, FFIs rely more heavily on multiple individual elements operating together. While they are more ambitious from a mission design standpoint, FFIs can achieve significantly longer baselines (e.g., 1 km or more) and can incorporate multiple telescope collector elements. Examples of FFIs include spatial-spectral (double Fourier)



(a) SPIRIT Design Concept.[37] The two collectors are structurally connected by a folding boom (shown here at a maximum baseline of 36 m for illustration) to a central beam combining bus.



(b) Two-element SCI sketch. As the space craft rotates, the telescopes remaining pointing at the target of interest. The craft rotation and change in baseline length populates the u-v Fourier plane so aperture synthesis can be performed.

Figure 1: Two-element SCI design concepts

interferometers: the Submillimeter Probe of the Evolution of Cosmic Structure (SPECS)[28] and the Far Infrared Interferometer (FIRI),[29] and nulling interferometers, like ESA's Darwin,[30] NASA's Terrestrial Planet Finder (TPF),[31] and the Large Interferometer For Exoplanets (LIFE).[32]

Regardless of the design choice or operating wavelength, no space-based interferometer has ever been launched. Despite years of study and advances in the technical readiness level (TRL) of their sub-systems, including experimental testbeds[33–36] and balloon pathfinders,[11] there is no existing space flight heritage for an interferometer to build upon, unlike its monolithic counterpart. Thus, a logical starting point from the perspective of mission risk reduction for the first ever space-based interferometer would be a simpler design concept. Of the two design styles described above, a structurally connected interferometer is the simpler design with the most thorough investigation from previous studies of SPIRIT and FISICA. Therefore, in this paper, we will use the SPIRIT and FISICA as our starting point, and focus on the concept of a two-element far-IR SCI with aperture plane light combination, all within the Decadal Survey's cost cap of \$3-\$5B (FY20).

We will consider three point designs for our far-IR SCI: 36 m, 50 m, and 100 m. The underlying fundamentals of each design will be largely the same, and follow the SPIRIT design of a spatial-spectral interferometer with cryogenically cooled collector telescopes and central combining bus, along with detector systems with spectral coverage from 25-400 µm. As our figures of merit here continue to be high angular resolution and the price cap of \$3-\$5B FY20, we will primarily be focusing on changes to total baseline length and the sizes of the primary telescope collectors[¶]. Figure 2 summarizes the angular resolution of these three point designs in comparison to other past and present observatories.

3.1 Point design 1: 36m baseline

This point design follows directly from the SPIRIT design published in 2007. Indeed, the work done by the SPIRIT team shows that with a 36 m baseline and 1 m diameter primary telescopes, this point design would single handedly be capable of overcoming the far-IR trilemma with sub-arcsecond angular resolution at 100 µm. The SPIRIT team also provided a full breakdown of mission cost estimates, given in FY09 terms.[37] When adjusted for inflation to FY20, the estimated total mission cost of this point design would cost approximately \$1.6B. This includes the launch vehicle, a cost adjusted to be \$215M, but recent and future advances in commercial payload fairings have very likely changed this aspect of the estimate. Reserves have also been appropriately scaled to be \$274M, which accounts for $\sim 20\%$ margin of the total cost before the launch vehicle.

[¶]A wider solution space has already been considered by the SPIRIT team.[5]

A far-IR interferometer like SPIRIT would offer 0.3 arcsecond angular resolution at 100 µm, as well as high spectral resolution (R $\sim$ 3000) across the entire wavelength band. The merits of such a point design, as well as the benefits to far-IR astronomy, have been well documented in the literature. However, at just $1.6B, there is plenty of room to expand the mission design closer to the cost recommendation of the Decadal Survey.

3.2 Point design 2: 50m baseline

The SPIRIT team also explored the idea of a "facility-class" mission by scaling up their 36 m mission concept. With an upgraded 10 year operational life and a 40% longer baseline, out to 50 m, this point design would cost approximately $2.1B FY20 [‖]. With an improved angular resolution of 0.2 arcseconds at 100 µm, as well as sub-arcsecond angular resolution **across the entire wavelength range**, the scientific benefits would be enormous.[5, 29, 38] Furthermore, the increased mission lifetime would be more in-line with what is expected for a Great Observatory, allowing a full decade of high angular resolution astronomy at far-IR wavelengths.

However, it should be noted that longer baselines necessitate larger primary collecting mirrors due to diffraction of the collected light. Indeed, optical modelling analysis of the far-IR SCI design concept studied by the FISICA project shows the delicate interplay between maximum baseline size, diameter of primary mirrors, and the required aperture size of the central combining bus.[39, 40] For some fixed maximum baseline, the choice of collector mirror style and size must be balanced against the window size of the beam combiner, which in turn increases the surface area exposure of the internal cryo-cooled beam combiner optics. These increased size requirements (e.g. 2 m collectors for a 50 m), would drive up development cost, as higher performing or larger cryo-coolers would be needed, as well as design complexity. This increased scaling of the maximum baseline, along with the collectors and beam combiner aperture, must also be considered for the larger point design 3, described later.

This point design also presents a nice symmetry with JWST; with a baseline about 10 times longer than JWST's segmented primary mirror, and operating at wavelengths about 10 times longer, the synergy presented by this point design allowed it to nicely fill the far-IR gap between JWST and ALMA. Yet at $2.1B, we still have room for an even more ambitious mission concept, something that will push to the upper limit of the Decadal Survey's recommendation.

3.3 Point design 3: 100m baseline

A point design with a 100 m baseline is probably the upper limit of what is conceivable for a SCI before one considers moving towards a FFI. Beyond this, the structural limitations of the boom might be a limiting factor and increase mission risk. Furthermore, a boom of this length could employ a collapsible, articulating architecture to fit into the payload fairing of modern launch vehicles, rather than a segmented, foldable boom. But at an ambitious 100 m, staying in the realm of SCIs allows us to scale the SPIRIT design even further.

At 100 m, this point design would have 0.1 arcsecond angular resolution at 100 µm, a 100 fold improvement in angular resolution compared to SOFIA.[13] Indeed, such an ambitious size is only fitting for a Great Observatory class mission. Considerations for further improving mission performance could include increasing the size of the primary collecting mirrors from 1 m to 2 m, enabling more light collection and increased sensitivity to faint sources, or decreasing the minimum baseline length, which would help populate the center of the u-v Fourier plane, allowing for better image reconstruction and detail in the final observations.

Costing a mission this large is beyond the considerations of previous work done by the SPIRIT team, but we can make the quick calculation that a 100 m baseline mission should cost no more than two 50 m baseline missions. Given that we costed the 50 m design in the previous section at $2.1B FY20, then our preliminary upper limit here is approximately $4.2B. Finally, we have entered the cost range given by the Decadal Survey, falling in the center.

Using the costs and maximum baselines of the previous two designs as data points, and assuming a linear relation between cost and baseline length, we can make another cost estimate by extrapolating out to 100 m. In this case, our calculated total mission cost is $3.9B FY20. Again, within the range recommended by the Decadal Survey, but slightly below our previous calculation.

[‖] More details on the "facility-class" SPIRIT mission can be found in the SPIRIT team's discussion on mission design.[5]

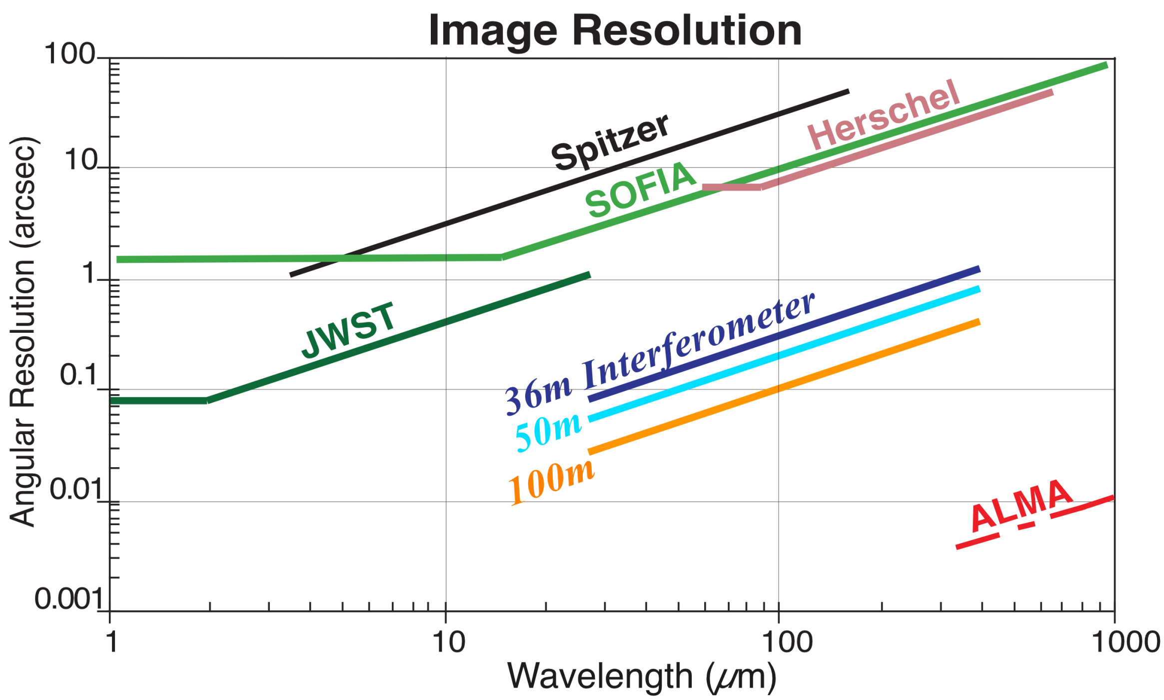


Figure 2: Angular resolution of observatories past and present. Three baseline lengths for a far-IR space-based SCI are presented for comparison, based on the SPIRIT mission concept.

Table 2: Summary of far-IR space-based SCI point design specifications and estimated costs.

Point design	Maximum baseline (m)	Angular resolution at 100 µm (arcsec)	Estimated total mission cost ($B FY20)
1	36	0.3	1.6
2	50	0.2	2.1
3	100	0.1	3.9-4.2

4. CONCLUSION

A space-based interferometer is not a question of if, but of when. The scientific hunger for higher and higher angular resolution observations at increased detection sensitivity has driven technological innovation for decades, and will continue to do so far into the future. While every wavelength band can benefit from the high angular resolution achievable by a space-based interferometer, the far-IR trilemma uniquely cripples high angular resolution at far-IR wavelengths. Indeed, no monolithic telescope is capable of overcoming the far-IR trilemma, and the only solution is a space-based interferometer. The high angular resolution achievable by a space-based far-IR SCI, at a total mission cost all within or below the Decadal Survey's recommendation, would revolutionize far-IR astronomy in ways not seen since the first infrared observations by IRAS in 1983. The Great Observatories of humanity should rewrite textbooks and fundamentally change our understanding of our place in the universe, and only a space-based far-IR interferometer is capable of delivering such groundbreaking results within the far-IR region, to complement advancements progressing through observations throughout the full EM spectrum bands.

ACKNOWLEDGMENTS

B.V.R. would like to thank H. P. Stahl for his informative feedback on the context and progress of his parametric cost model. We would like to acknowledge "FISICA-FP7 Grant agreement no. 312818 SPA.2012.2.2-01 : Key technologies enabling observations in and from space". This development has been supported by Canada Research Chairs (CRC), Canada Foundation for Innovation (CFI), Alberta Research Capacity Program (RCP), Alberta Innovates (AI), and Natural Science and Engineering Research Council of Canada (NSERC) grants.

REFERENCES

[1] National Academies of Sciences, Engineering, and Medicine, [*Pathways to Discovery in Astronomy and Astrophysics for the 2020s*], The National Academies Press.

[2] Pilbratt, G., Riedinger, J., Passvogel, T., Crone, G., Doyle, D., Gageur, U., Heras, A., Jewell, C., Metcalfe, L., Ott, S., et al., "Herschel Space Observatory-An ESA facility for far-infrared and submillimetre astronomy," **518**, L1.

[3] Stahl, H. P. and Allison, M. A., "Parametric cost model for ground and space telescopes," in [*Modeling, Systems Engineering, and Project Management for Astronomy IX*], Angeli, G. Z. and Dierickx, P., eds., 41, SPIE.

[4] Leisawitz, D., Baker, C., Barger, A., Benford, D., Blain, A., Boyle, R., Broderick, R., Budinoff, J., Carpenter, J., Caverly, R., Chen, P., Cooley, S., Cottingham, C., Crooke, J., DiPietro, D., DiPirro, M., Femiano, M., Ferrer, A., Fischer, J., Gardner, J. P., Hallock, L., Harris, K., Hartman, K., Harwit, M., Hillenbrand, L., Hyde, T., Jones, D., Kellogg, J., Kogut, A., Kuchner, M., Lawson, B., Lecha, J., Lecha, M., Mainzer, A., Mannion, J., Martino, A., Mason, P., Mather, J., McDonald, G., Mills, R., Mundy, L., Ollendorf, S., Pellicciotti, J., Quinn, D., Rhee, K., Rinehart, S., Sauerwine, T., Silverberg, R., Smith, T., Stacey, G., Stahl, H. P., Staguhn, J., Tompkins, S., Tveekrem, J., Wall, S., and Wilson, M., "The space infrared interferometric telescope (SPIRIT): High-resolution imaging and spectroscopy in the far-infrared," **40**(5), 689–703.

[5] Leisawitz, D., Hyde, T. T., Rinehart, S. A., and Weiss, M., "The Space Infrared Interferometric Telescope (SPIRIT): The mission design solution space and the art of the possible," 701028.

[6] Savini, G., Baccichet, N., Juanola-Parramon, R., Swinyard, B., Guisseau, A., Pascale, E., Ade, P., Griffin, M., Hargrave, P., Sudiwala, R., Holland, W., Grainger, W., Ivison, R., Lightfoot, J., Walker, D., Jones, M., McMillan, A., O'Sullivan, C., Bracken, C., Donohoe, A., Murphy, A., Trappe, N., Spinoglio, L., Liu, S., Pezzuto, S., Dohlen, K., Lemerrer, J., Madec, D., Rakotonimbahy, E., Rossin, C., Vives, S., Zavagno, A., Iafolla, V., Schito, D., Naylor, D., Gom, B., Spencer, L., and Veenendaal, I., "Far Infrared Space Interferometer Critical Assessment https://www.ucl.ac.uk/˜ucapgsa/fp7-ko.htm."

[7] Low, F. J., "Low-Temperature Germanium Bolometer," **51**(11), 1300–1304.

[8] Kessler, M. F., Steinz, J. A., Anderegg, M. E., Clavel, J., Drechsel, G., Estaria, P., Faelker, J., Riedinger, J. R., Robson, A., Taylor, B. G., and Ximénez de Ferrán, S., "The Infrared Space Observatory (ISO) mission.," **315**, L27–L31.

[9] Werner, M. W., Roellig, T. L., Low, F. J., Rieke, G. H., Rieke, M., Hoffmann, W. F., Young, E., Houck, J. R., Brandl, B., Fazio, G. G., Hora, J. L., Gehrz, R. D., Helou, G., Soifer, B. T., Stauffer, J., Keene, J., Eisenhardt, P., Gallagher, D., Gautier, T. N., Irace, W., Lawrence, C. R., Simmons, L., Cleve, J. E. V., Jura, M., Wright, E. L., and Cruikshank, D. P., "The Spitzer Space Telescope Mission," **154**(1), 1.

[10] Murakami, H., Baba, H., Barthel, P., Clements, D. L., Cohen, M., Doi, Y., Enya, K., Figueredo, E., Fujishiro, N., Fujiwara, H., Fujiwara, M., Garcia-Lario, P., Goto, T., Hasegawa, S., Hibi, Y., Hirao, T., Hiromoto, N., Hong, S. S., Imai, K., Ishigaki, M., Ishiguro, M., Ishihara, D., Ita, Y., Jeong, W.-S., Jeong, K. S., Kaneda, H., Kataza, H., Kawada, M., Kawai, T., Kawamura, A., Kessler, M. F., Kester, D., Kii, T., Kim, D. C., Kim, W., Kobayashi, H., Koo, B. C., Kwon, S. M., Lee, H. M., Lorente, R., Makiuti, S., Matsuhara, H., Matsumoto, T., Matsuo, H., Matsuura, S., MÜller, T. G., Murakami, N., Nagata, H., Nakagawa, T., Naoi, T., Narita, M., Noda, M., Oh, S. H., Ohnishi, A., Ohyama, Y., Okada, Y., Okuda, H., Oliver, S., Onaka, T., Ootsubo, T., Oyabu, S., Pak, S., Park, Y.-S., Pearson, C. P., Rowan-Robinson, M., Saito, T., Sakon, I., Salama, A., Sato, S., Savage, R. S., Serjeant, S., Shibai, H., Shirahata, M., Sohn, J., Suzuki, T., Takagi, T., Takahashi, H., TanabÉ, T., Takeuchi, T. T., Takita, S., Thomson, M., Uemizu, K.,

Ueno, M., Usui, F., Verdugo, E., Wada, T., Wang, L., Watabe, T., Watarai, H., White, G. J., Yamamura, I., Yamauchi, C., and Yasuda, A., "The Infrared Astronomical Mission AKARI*," **59**, S369–S376.

[11] Rinehart, S. A., Rizzo, M., Benford, D. J., Fixsen, D. J., Veach, T. J., Dhabal, A., Leisawitz, D. T., Mundy, L. G., Silverberg, R. F., Barry, R. K., Staguhn, J. G., Barclay, R., Mentzell, J. E., Griffin, M., Ade, P. A. R., Pascale, E., Klemencic, G., Savini, G., and Juanola-Parramon, R., "The Balloon Experimental Twin Telescope for Infrared Interferometry (BETTII): An Experiment for High Angular Resolution in the Far-Infrared," **126**(941), 660.

[12] Devlin, M. J., "A balloon-borne large aperture submillimeter telescope," *arXiv preprint astro-ph/0012327* (2000).

[13] Gehrz, R. D., Becklin, E. E., Pater, I., Lester, D. F., Roellig, T. L., and Woodward, C. E., "A new window on the cosmos: The Stratospheric Observatory for Infrared Astronomy (SOFIA)," **44**(4), 413–432.

[14] Nakagawa, T., "SPICA: A new space telescope for mid- and far-infrared astronomy," **30**(9), 2129–2134.

[15] National Academies of Sciences, Engineering, and Medicine, [*Astronomy and Astrophysics in the New Millennium*], The National Academies Press.

[16] National Academies of Sciences, Engineering, and Medicine, [*New Worlds, New Horizons in Astronomy and Astrophysics*], The National Academies Press.

[17] Canadian Astronomical Society, [*Unveiling the Cosmos: A Vision for Canadian Astronomy, Report of the Long Range Plan 2010 Panel*].

[18] Barmby, P., Gaensler, B., Dobbs, M., Heyl, J., Ivanova, N., Lafrenière, D., Matthews, B., and Shapley, A., "Discovery at the Cosmic Frontier: Canadian Astronomy Long Range Plan 2020-2030," **2020**, 68.

[19] European Space Agency, [*Cosmic Vision - Space Science for Europe 2015-2025*].

[20] Tacconi, L., Arridge, C., Buonanno, A., Cruise, M., Grasset, O., Helmi, A., Iess, L., Komatsu, E., Leconte, J., Leenaarts, J., Martin-Pintado, J., Nakamura, R., and Watson, D., "Voyage 2050: Final recommendations from the Voyage 2050 Senior Committee."

[21] Wiedner, M. C., Aalto, S., Birkby, J., Burgarella, D., Caselli, P., Charmandaris, V., Cooray, A., De Beck, E., Desert, J.-M., Gerin, M., Goicoechea, J., Griffin, M., Hartogh, P., Helmich, F., Hogerheijde, M., Hunt, L., Karska, A., Krall, Q., Leisawitz, D., Melnick, G., Meixner, M., Mikako, M., Pearson, C., Rigopoulou, D., Roellig, T., Sakon, I., and Staguhn, J., "Origins Space Telescope: From First Light to Life – ESA Voyage 2050 White Paper."

[22] Leisawitz, D., Amatucci, E., Allen, L., Arenberg, J., Armus, L., Battersby, C., Beaman, B. G., Bauer, J., Bell, R., Beltran, P., Benford, D., Bergin, E., Bolognese, J., Bradford, C. M., Bradley, D., Burgarella, D., Carey, S., Carter, R., Chi, J. D., Cooray, A., Corsetti, J., D'Asto, T., Beck, E. D., Denis, K., Derkacz, C., Dewell, L., DiPirro, M., Earle, C. P., East, M., Edgington, S., Ennico, K., Fantano, L., Feller, G., Flores, A., Folta, D., Fortney, J., Gavares, B. J., Generie, J., Gerin, M., Granger, Z., Greene, T. P., Griffiths, A., Harpole, G., Harvey, K., Helmich, F., Helou, G., Hilliard, L., Howard, J., Jacoby, M., Jamil, A., Jamison, T., Kaltenegger, L., Kataria, T., Knight, J. S., Knollenberg, P., Lawrence, C., Lightsey, P., Lipscy, S., Lynch, C., Mamajek, E., Martins, G., Mather, J. C., Meixner, M., Melnick, G., Milam, S., Mooney, T., Moseley, S. H., Narayanan, D., Neff, S., Nguyen, T., Nordt, A., Olson, J., Padgett, D., Petach, M., Petro, S., Pohner, J., Pontoppidan, K., Pope, A., Ramspacher, D., Rao, A., Rieke, G., Rieke, M., Roellig, T., Sakon, I., Sandin, C., Sandstrom, K., Scott, D., Seals, L., Sheth, K., Staguhn, J., Steeves, J., Stevenson, K., Stokowski, L., Stoneking, E., Su, K., Tajdaran, K., Tompkins, S., Turner, J., Vieira, J., Webster, C., Wiedner, M., Wright, E. L., Wu, C., and Zmuidzinas, J., "The Origins Space Telescope," in [*UV/Optical/IR Space Telescopes and Instruments: Innovative Technologies and Concepts IX*], **11115**, 184–195, SPIE.

[23] Leisawitz, D. T., Amatucci, E. G., Allen, L. N., Arenberg, J. W., Armus, L., Battersby, C., Bauer, J. M., Beaman, B. G., Jr, R. M. B., Beltran, P., Benford, D. J., Bergin, E., Bolognese, J. A., Bradford, C. M., Bradley, D. C., Burgarella, D., Carey, S. J., Carter, R. C., Chi, D., Cooray, A., Corsetti, J. A., D'Asto, T., Beck, E. D., Denis, K. L., Derkacz, C., Dewell, L. D., DiPirro, M. J., Earle, C. P., East, M., Edgington, S., Ennico, K., Fantano, L. G., Feller, G., Folta, D. C., Fortney, J., Gavares, B. J., Generie, J. A., Gerin, M., Granger, Z. A., Greene, T. P., Griffiths, A., Harpole, G. M., Harvey, K., Helmich, F. P., Hilliard, L. M., Howard, J. M., Jacoby, M. S., Jamil, A., Jamison, T. L., Kaltenegger, L., Kataria, T., Knight, J. S., Knollenberg, P. J., Lawrence, C. R., Lightsey, P. A., Lipscy, S. J., Mamajek, E., Martins, G. E., Mather,

J. C., Meixner, M., Melnick, G. J., Milam, S. N., Mooney, T., Moseley, S. H., Narayanan, D., Neff, S. G., Nguyen, T., Nordt, A. A., Olson, J. R., Padgett, D. L., Petach, M. B., Petro, S., Pohner, J., Pontoppidan, K., Pope, A., Ramspacker, D., Rao, A., Roellig, T. L., Sakon, I., Sandin, C., Sandstrom, K., Scott, D., Seals, L. T., Sheth, K. J., Sokolsky, L., Staguhn, J. G., Steeves, J. B., Stevenson, K. B., Stoneking, E. T., Su, K. Y. L., Tajdaran, K., Tompkins, S. D., Vieira, J. D., Webster, C. M., Wiedner, M. C., Wright, E. L., Wu, C. K., and Zmuidzinas, J., "Origins Space Telescope: Baseline mission concept," **7**(1), 011002.

[24] Habib-Agahi, H., Mrozinski, J., and Fox, G., "NASA instrument cost/schedule model Hamid Habib-Agahi," in [*2011 Aerospace Conference*], 1–19.

[25] Federal Reserve Bank of Minneapolis, "Historical data from the era of the modern U.S. consumer price index (CPI)."

[26] van Belle, G., Hillsberry, D., Kloske, J., Kugler, J., Patané, S., Paul-Gin, N., Piness, J., Riley, D., Schomer, J., Snyder, M., and Tobiassen, T., "Optimast structurally connected interferometry enabled by in-space robotic manufacturing and assembly," in [*Optical and Infrared Interferometry and Imaging VII*], **11446**, 571–585, SPIE.

[27] van Belle, G., Hillsberry, D., Piness, J., and Kugler, J., "Sub-milliarcsecond astronomical imaging: Advancing space-based astronomical optical interferometry observatories with Optimast," in [*Optical and Infrared Interferometry and Imaging VIII*], **12183**, 495–507, SPIE.

[28] Leisawitz, D., Abel, T., Allen, R., Benford, D., Blain, A., Bombardelli, C., Calzetti, D., Dipirro, M., Ehrenfreund, P., II, N., Fischer, J., Harwit, M., Hyde, T., Kuchner, M., Leitner, J., Lorenzini, E., Mather, J., Menten, K., Jr, S., and Yorke, H., "SPECS: The kilometer-baseline Far-IR interferometer in NASA's space science roadmap," 1527–1537.

[29] Helmich, F. P. and Ivison, R. J., "FIRI—A far-infrared interferometer," **23**(1), 245–276.

[30] Lund, G. and Bonnet, H., "DARWIN – The infrared space interferometer," **2**(1), 137–148.

[31] Unwin, S. C. and Beichman, C. A., "Terrestrial Planet Finder: Science overview," in [*Optical, Infrared, and Millimeter Space Telescopes*], **5487**, 1216–1225, SPIE.

[32] Quanz, S. P., Ottiger, M., Fontanet, E., Kammerer, J., Menti, F., Dannert, F., Gheorghe, A., Absil, O., Airapetian, V. S., Alei, E., Allart, R., Angerhausen, D., Blumenthal, S., Buchhave, L. A., Cabrera, J., Carrion-Gonzalez, O., Chauvin, G., Danchi, W. C., Dandumont, C., Defrère, D., Dorn, C., Ehrenreich, D., Ertel, S., Fridlund, M., Muñoz, A. G., Gascón, C., Girard, J. H., Glauser, A., Grenfell, J. L., Guidi, G., Hagelberg, J., Helled, R., Ireland, M. J., Janson, M., Kopparapu, R. K., Korth, J., Kozakis, T., Kraus, S., Léger, A., Leedjärv, L., Lichtenberg, T., Lillo-Box, J., Linz, H., Liseau, R., Loicq, J., Mahendra, V., Malbet, F., Mathew, J., Mennesson, B., Meyer, M. R., Mishra, L., Molaverdikhani, K., Noack, L., Oza, A. V., Pallé, E., Parviainen, H., Quirrenbach, A., Rauer, H., Ribas, I., Rice, M., Romagnolo, A., Rugheimer, S., Schwieterman, E. W., Serabyn, E., Sharma, S., Stassun, K. G., Szulágyi, J., Wang, H. S., Wunderlich, F., Wyatt, M. C., and collaboration, t. L., "Large Interferometer For Exoplanets (LIFE): I. Improved exoplanet detection yield estimates for a large mid-infrared space-interferometer mission," **664**, A21.

[33] Leisawitz, D. T., Frey, B. J., Leviton, D. B., Martino, A. J., Maynard, W. L., Mundy, L. G., Rinehart, S. A., Teng, S. H., and Zhang, X., "Wide-field imaging interferometry testbed I: Purpose, testbed design, data, and synthesis algorithms," in [*Interferometry in Space*], **4852**, 255–267, SPIE.

[34] Grainger, W. F., Juanola-Parramon, R., Ade, P. A. R., Griffin, M., Liggins, F., Pascale, E., Savini, G., and Swinyard, B., "Demonstration of spectral and spatial interferometry at THz frequencies," **51**(12), 2202–2211.

[35] Scott, J., Benson, C., and Spencer, L., "Design, Operation, and Characterization of a Laboratory Spatial-Spectral Fourier Transform Interferometer," **13**(6), 636–644.

[36] Ohta, I. S., Hattori, M., and Matsuo, H., "Development of a multi-fourier-transform interferometer: fundamentals," *Applied optics* **45**(12), 2576–2585 (2006).

[37] Leisawitz, D. and SPIRIT Origins Probe Mission Concepts Study Team, "The Space Infrared Interferometric Telescope (SPIRIT): A Far-IR Observatory for High-resolution Imaging and Spectroscopy."

[38] Leisawitz, D., Bonato, M., Farrah, D., Hyde, T. T., Lee, A., Lovell, J. B., Matthews, B., Mundy, L. G., Nixon, C., Pokorny, P., Ricketti, B. V., Savini, G., Scott, J., Shivaei, I., Spencer, L., Su, K., Urry, C. M., and Wilner, D., "The science case for a far-infrared interferometer in the era of JWST and ALMA," in [*Infrared Remote Sensing and Instrumentation XXXI*], **12686**, 68–78, SPIE.

[39] Bracken, C., O'Sullivan, C., Murphy, J. A., Donohoe, A., Savini, G., Lightfoot, J., and Juanola-Parramon, R., "Quasi-optical analysis of a far-infrared spatio-spectral space interferometer concept," **77**, 171–178.

[40] Bracken, C. P., Lightfoot, J. F., O'Sullivan, C., Murphy, J. A., Donohoe, A., Savini, G., Juanola-Parramon, R., and Consortium, o. b. o. F., "Multimode simulations of a wide field of view double-Fourier far-infrared spatio–spectral interferometer," **4**(1), 018004.