Far-Infrared Interferometry in Space: The Next Big Thing (NBT) For The NRAO?

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Executive Summary

The scientific case is strong for a far-infrared (FIR) interferometer in space capable of (1) imaging the region inside the "frost" or "snow" line where $T \sim 150$ K (about 5 AU from a solar-mass star) in circumstellar disks at distances ~ 100 pc and (2) studying the evolution of star formation and AGNs in obscured galaxies back to $z \sim 3$. The required angular resolution $\theta \leq 0.02$ arcsec at $\lambda \sim 100$ μm implies km-length baselines between either free-flying or tethered telescopes.

Incoherent direct-detection interferometers can be extremely sensitive if located near the Sun-Earth Lagrange point L2 about 2.4 million km from Earth and all optical components are actively cooled to $T \sim 5$ K. The cryogenic SPICA single-dish telescope is a technological prerequisite for cryogenic direct-detection interferometers. SPICA will not be launched before 2025, so the first direct-detection interferometers will have to wait until the 2030's. "Double-Fourier" Michelson interferometers have inadequate spectral resolution $R = \lambda / \Delta\lambda \sim 3000$ (velocity resolution $\Delta v \sim 100$ km s^{-1}); $R = \lambda / \Delta\lambda \sim 3 \times 10^5$ (velocity resolution $\Delta v \sim 1$ km s^{-1}) is needed for Galactic sources. Also, no one has yet imaged faint extended sources with incoherent adding interferometers. SPIRIT is the simplest and cheapest (proposer-estimated \$1.25 billion in FY09 dollars) space-based direct-detection interferometer, but it does not satisfy the scientific requirements above for angular or spectral resolution. More ambitious direct-detection interferometers such as SPECS are NASA "flagship" class missions like JWST costing ~ \$$10^{10}$, and they lie many decades in the future.

Coherent heterodyne interferometers are capable of very high spectral resolution but do not have enough instantaneous bandwidth for extragalactic spectroscopy above $\nu \sim 3$ THz, and their sensitivity is badly degraded by quantum noise at frequencies above $\nu \sim 1$ THz. On the other hand, they could be located in near-Earth orbits, close to the International Space Station for example.

The infrared community recognizes that ALMA and the JVLA nicely complement proposed FIR interferometers in space. Although space-based interferometry is too expensive and too far in the future to be the NRAO's NBT, the NRAO should engage the FIR community when designing NBT-class upgrades for both ALMA and the JVLA.

The Science Case for a Far-Infrared Interferometer in Space

The Far-Infrared (FIR) Community Plan "Far-Infrared/Submillimeter Astronomy from Space: Tracking an Evolving Universe and the Emergence of Life" (Harwit et al. 2009) for the 2010 Astronomy & Astrophysics Decadal Survey remains the best published summary of the FIR science case in 2014. The top three goals of the space FIR community are:

1) **Evolution of Galaxies** from Early Times to the Present
2) **The Obscured Universe**: Dust-Shrouded AGN tori and the Formation of Stars and Planets
3) **Origins of Biogenic Molecules** and chemical evolution of the universe

The scientific objectives for the proposed Space Infrared Interferometric Telescope SPIRIT (Leisawitz et al. 2009) are similar:

1) to revolutionize our understanding of the formation of planetary systems and enable us to "**follow the water**" as these systems develop;
2) to find and characterize **exoplanets** based on their sculpting effects on protoplanetary and debris disks; and
3) to make unique and profound contributions to our understanding of the formation, merger history, and **star-formation history of galaxies**.

The goal of exploring planet formation and the chemical precursors of life (water in particular) was endorsed as the "killer app" (the new buzzword replacing "transformational science") by the well-attended May 12–13, 2014 workshop "Bringing Fundamental Astrophysical Processes Into Focus: A Community Workshop to Plan the Future of Far-Infrared Space Astrophysics" (http://asd.gsfc.nasa.gov/conferences/FIR/) organized by David Leisawitz at the Goddard Space Flight Center in Greenbelt, MD. The strongest criticism of this FIR goal is that the *real* science/PR goal is answering the NASA Roadmap (NASA 2013) question "How did we get here?" by finding habitable planets with water, not just water vapor in protoplanetary disks. Exoplanets are too faint in the FIR, so the JWST and the Large Ultraviolet/Optical/Near Infrared telescope (the proposed successor to the HST) are better suited to finding watery planets.

About half of the electromagnetic energy emitted after the big bang is in the FIR, as (1) dust continuum emission peaking near $\lambda = 100\ \mu$m in the source frame and (2) rotational or fine-structure lines. FIR imaging of galaxies is essential to follow the evolution of obscured star formation, especially in the redshift range $1 < z < 3$ dominated by dusty luminous galaxies. Even the largest FIR telescope in space, the $D = 3.5$ m Herschel telescope, has a beamwidth $\theta \sim \lambda / D \sim 3 \times 10^{-5}$ rad ~ 6 arcsec FWHM at $\lambda \sim 100\ \mu$m which is bigger than distant galaxies, and source confusion quickly limits FIR continuum sensitivity. Consequently, there must eventually be a FIR interferometer in space. The main NBT questions are only (1) How soon is it practical? and (2) How might the NRAO contribute?

Technical Requirements for FIR Interferometry

Angular resolution finer than $\theta \leq 0.1$ arcsec FWHM for water lines is the bare minimum needed to see into the region inside the "frost" or "snow" line where $T \sim 150$ K (about 5 AU from a solar-mass star) in circumstellar disks at distances between 50 pc (TW Hydrae) and 140 pc (Taurus-Auriga, Ophiuchus, and Chamaeleon), and $\theta \leq 0.02$ arcsec would be much better.

Characterizing exoplanets based on their sculpting effects on protoplanetary and debris disks needs comparable resolution at wavelengths long enough that the disks are not opaque, which may be $\lambda > 850$ μm (Cossins et al. 2010).

Ultraluminous starburst galaxies can be quite compact—the two nuclei of Arp 220 are each ~ 0.3 arcsec in diameter and optically thick below $\lambda \sim 1100$ μm (Downes & Eckart 2007). Distinguishing the warm dust heated by a single AGN from the cooler dust heated by a compact starburst requires angular resolution $\theta < 0.2$ arcsec even for the nearest galaxies (Condon et al. 1991).

In summary, the FIR community appears to recognize that $\theta \leq 0.02$ arcsec is the proper requirement for imaging the distribution of water vapor in protoplanetary disks, even though that implies uncomfortably long baselines $D_l \sim \lambda / \theta \sim 1$ km at $\lambda \sim 100$ μm. Most proposals for FIR interferometers in space explicitly call for km baselines between free-flying or tethered telescopes: the Submillimeter Probe of the Evolution of Cosmic Structure **SPECS** (Leisawitz et al. 1999) is a direct-detection Michelson interferometer covering the wavelength range 40 μm < λ < 500 μm using three 3 m cooled telescopes on tethers, the Exploratory Submm Space Radio-Interferometric Telescope **ESPRIT** (Wild et al. 2005) is a heterodyne interferometer with four to six 3.5 m free-flying telescopes in a 3-D configuration, and the Far-Infrared Interferometer **FIRI** (Helmich & Ivison 2008) is a direct-detection Michelson interferometer with three cold 3.5 m apertures "orbiting a beam-combining module, with separations of up to 1 km, free-flying or tethered." All would operate near the Sun-Earth Lagrange point L2 about 2.4 million km from Earth, making them extremely ambitious missions comparable with the James Webb Space Telescope (JWST) in cost and complexity. Leisawitz et al. (2013) is the best and most recent published review of these planned interferometers.

In contrast, the much smaller **SPIRIT** direct-detection Michelson interferometer recommended in the Harwit et al. (2009) white paper has two 1 m reflectors on a rigid boom of length $D_l \sim 36$ m and a claimed angular resolution $\theta \sim \lambda / (2\, D_l) \sim 0.1$ arcsec at $\lambda \sim 30$ μm. Note that this claimed "Rayleigh criterion" resolution for a single baseline is twice as fine as the $\theta \sim \lambda / D_l \sim 0.2$ arcsec FHWM resolution actually obtained in a synthesis image. Also, the primary science targets, circumstellar disks, are quite opaque at $\lambda \sim 30$ μm (Cossins et al. 2010). They are better observed at wavelengths $\lambda > 150$ μm, where the realistic angular resolution of SPIRIT is only $\theta \sim \lambda / D_I > 1$ arcsec. SPIRIT was presented as a pathfinder for SPECS in the 2002 Community Plan (Benford & Leisawitz 2003), and Leisawitz et al. (2006) stated "SPIRIT was intended by the astronomical community as a less ambitious yet extremely capable mission, and a natural step in the direction of SPECS". Leisawitz et al. (2009) estimated the lifetime cost of SPIRIT as $1.25 billion FY09 dollars.

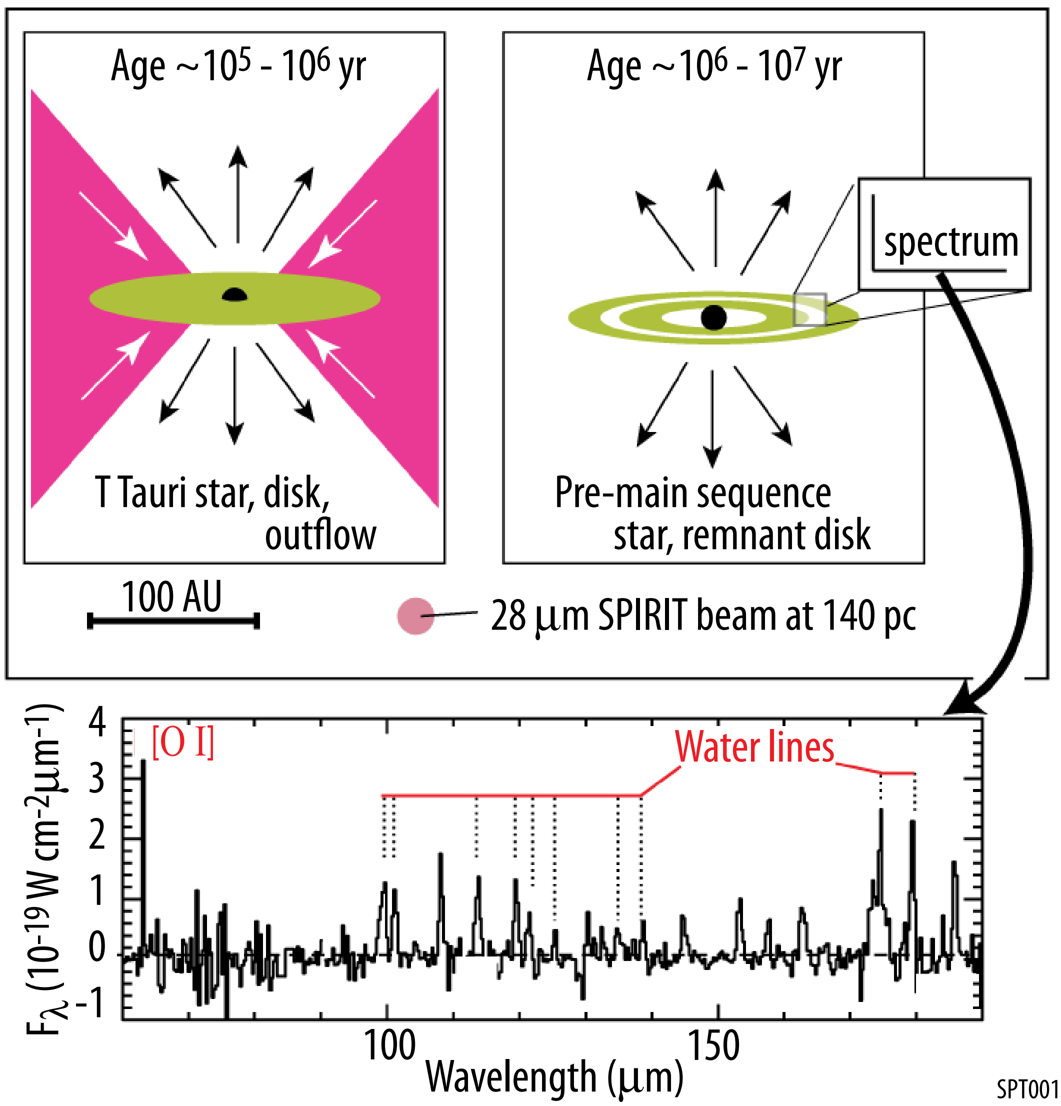

Figure 1: The main science goal of SPIRIT is high-resolution imaging and spectroscopy of water vapor in forming planetary systems (Leisawitz et al. 2009). To reach this goal, the angular resolution should be $\theta < 0.02$ arcsec and the velocity resolution should be $\Delta v < 1$ km s^{-1} (spectral resolution $R > 3 \times 10^5$). Unfortunately, SPIRIT will do neither, so it is really just a pathfinder.

Spectral resolution $R = \lambda / \Delta\lambda \sim 3 \times 10^5$ (velocity resolution $\Delta v \sim 1$ km s^{-1}) is needed to separate and resolve water lines in the 100 to 180 μm wavelength range (Fig. 1). Coarser spectral resolution $R \sim 3000$ (velocity resolution $\Delta v \sim 100$ km s^{-1}) is often sufficient for lines in spatially unresolved distant galaxies. Heterodyne spectrometers can easily achieve $R > 3 \times 10^5$, but "double-Fourier" direct-detection interferometers are limited to $R \sim 3000$ (Mather et al. 1998).

Instantaneous bandwidth $\Delta\nu / \nu > 1/300$ ($\Delta v > 1000$ km s^{-1}) is the minimum for spanning Doppler-broadened spectral lines from interacting galaxies. Direct-detection interferometers have much larger instantaneous bandwidths, but the IF bandwidths of heterodyne interferometers using hot electron bolometer (HEB) mixers are only $\Delta\nu \sim 3$ GHz today and will probably never exceed $\Delta\nu \sim 10$ GHz. The $\Delta\nu / \nu > 1/300$ requirement for heterodyne spectroscopy implies frequency upper limits $\nu < 1$ THz today and $\nu < 3$ THz in the foreseeable future.

Sensitivity $S \sim 10$ μJy / beam (5σ) in 24 hours is sufficient to detect the dust continuum emission and the redshifted C^+ line emission from a 10 $M_\odot$ yr^{-1} starburst galaxy at $z \sim 4$ (Mather et al. 1998). A spectral-line brightness detection limit $T_b \sim 100$ K (5σ) in 24 hours is the bare minimum for thermal lines whose brightness temperatures are necessarily lower than the kinetic temperature of the emitting gas. The spectral resolution needed for observing lines in distant galaxies is so low — $\Delta v < 100$ km s^{-1} (or $R > 3000$) — that even small direct-detection interferometers such as SPIRIT (two D =1 m telescopes) can detect the C^+ line in distant starburst galaxies. Less-sensitive heterodyne interferometers need more and larger dishes for high-resolution spectroscopic imaging; e.g., ESPRIT calls for six D = 3.5 m dishes.

Imaging speed is a problem for space-based interferometers because it takes ~ 24 hours to synthesize reasonably good (u,v)-plane coverage with only a few telescopes, and the instantaneous field-of-view is only ~ 1 arcmin even with array detectors. *Participants at the 2014 Community Workshop (Leisawitz 2014) indicated the number of targets that could be imaged during the five-year lifetime of a cryogenic mission would be unacceptably small.*

Wavelength coverage: In practice, the FIR spectrum spans $\nu \sim 1$ THz ($\lambda \sim 300$ μm), the continuum frequency limit of most ground-based "radio" observatories such as ALMA, to $\nu \sim 10$ THz ($\lambda \sim 30$ μm), the boundary with the mid-infrared band and also the longest wavelength covered by the JWST. Below 1 THz, ground-based spectroscopy is difficult or impossible near the zero-redshift spectral lines of many common molecules, and the sky is opaque within 60 km s^{-1} of the 557 GHz water line even at stratospheric balloon altitudes (30–40 km). *Thus detecting water in nearby protoplanetary disks can be done only from space.*

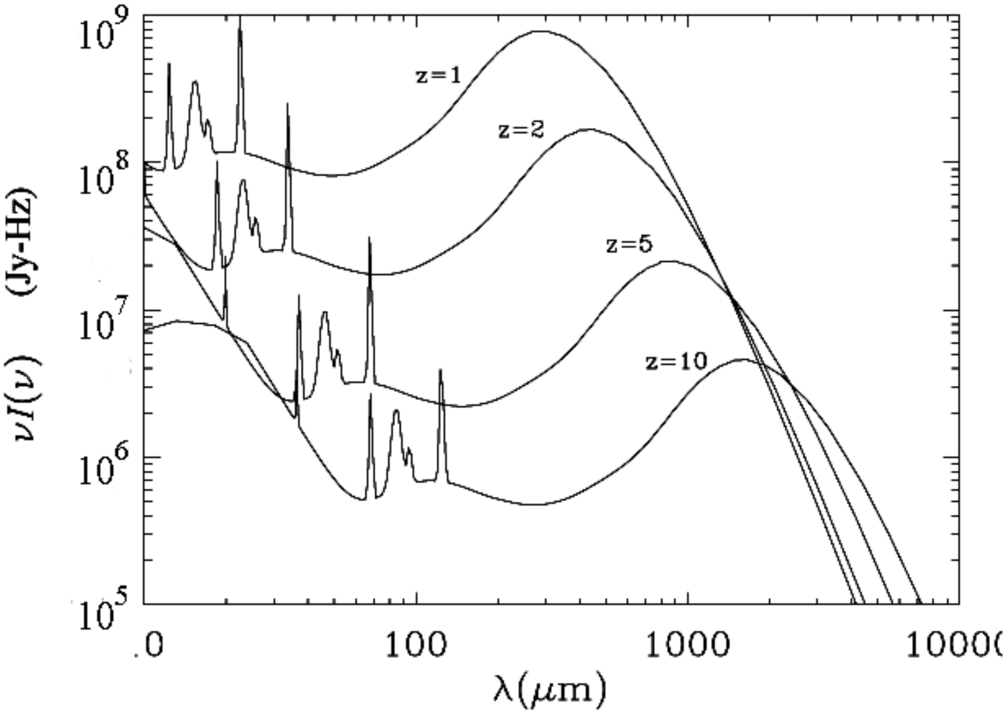

Figure 2: The FIR/submillimeter spectra of galaxies like our own placed at redshifts z = 1, 2, 5, and 10 (Leisawitz 2009). At z ~ 2, our Galaxy would have a continuum flux density S ~ 10 μJy near λ = 100 μm (ν = 3 THz). For galaxies at higher redshifts, ALMA is very competitive because our Galaxy would have a similar flux density at z = 5 and λ = 850 μm (ν = 350 GHz).

The FIR community recognizes the strengths of ALMA (high sensitivity from ~ 10^4 m^2 collecting area, angular resolution $\theta \leq 0.02$ arcsec at $\lambda \leq 1$ mm from D_l ~ 10 km maximum baselines, good imaging speed and fidelity from N > 50 antennas, and high spectral resolution) at frequencies up to 1 THz. FIR astronomers criticize ALMA because it samples only the Rayleigh-Jeans tail of dust continuum emission from most sources, which is a good dust-mass indicator, but not the Wien's-law peak wavelength λ ~ 100 μm needed to determine dust temperature and total luminosity. ALMA also samples lower-J CO lines and redshifted C^+ lines. Wide and complete submm/FIR frequency coverage is important for spectroscopy because lines at different frequencies carry information about different physical conditions (e.g., temperature, pressure, density, excitation,...). Consequently ALMA and space-based FIR interferometers complement each other well. Leisawitz et al. (2006) noted "With JWST, SPIRIT, and ALMA working in tandem, the astronomical community will have an extremely powerful arsenal of observing tools." *The NRAO should stay in touch with the FIR community, expand ALMA's frequency coverage, especially Bands 9 and 10, and do more to promote the JVLA's capabilities.*

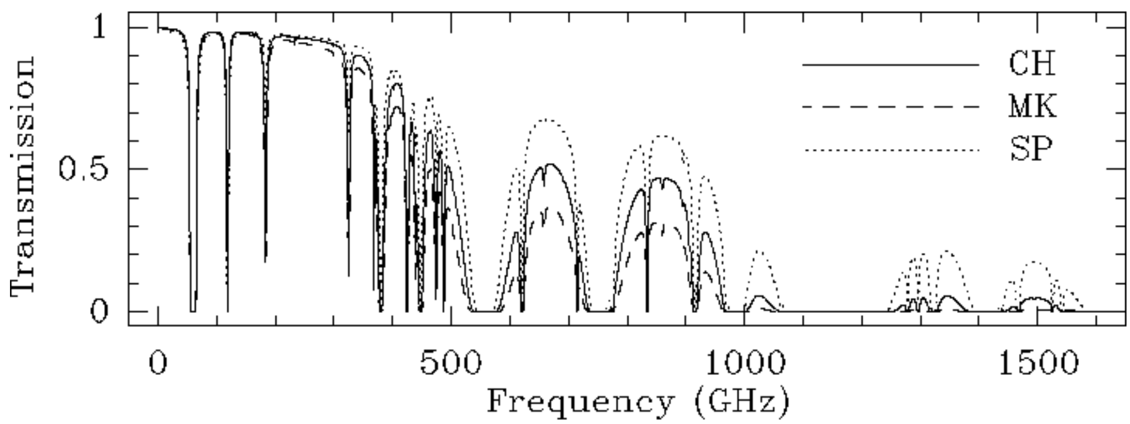

Figure 3: Ground-based astronomy from the ALMA site at Chajnantor (CH), Mauna Kea (MK), and the South Pole (SP) is limited by atmospheric transmission.

Could continuum observations near the Wien-law peak wavelength λ = 100 μm be made from anywhere on the Earth's surface? Figure 4 below is a copy of Figure 7 from Lawrence (2004); it shows the FIR atmospheric transmission at the world's best "accessible" sites in the Burton (2010) review of Antarctic astronomy. The second highest curve in Fig. 4 shows Antarctic Dome A in the best weather, when there is only 30 μm of water vapor. Unfortunately, atmospheric opacity in the continuum windows between water lines scales roughly as λ^{-2} for wavelengths longer than 100 μm, by which wavelength the atmosphere has become nearly opaque. Thus reaching the Wien-law peak to measure the temperature of dust emission from nearby galaxies may never be possible from the ground.

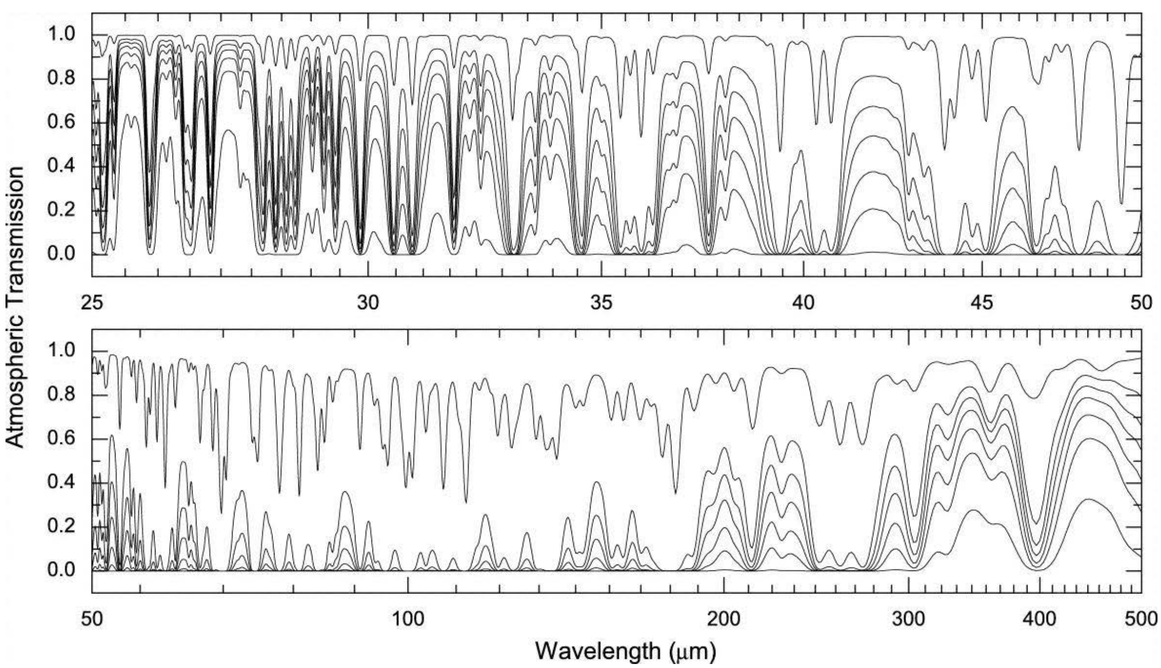

Figure 4: FIR atmospheric transmission from the ALMA site (lowest curve) through the South Pole, Dome C, Dome Fuji, Dome A (average weather), Dome A (best weather – 30 μm pwv), and SOFIA (highest curve), copied from Figure 7 of Lawrence (2004).

Direct-detection Versus Heterodyne Interferometers

Two distinct flavors of interferometers compete at FIR frequencies:
(1) Direct-detection, or incoherent, interferometers bring the radiation beams from two or three telescopes together and add them to produce fringes before incoherent detection, which does not preserve phase information.
(2) Heterodyne, or coherent, interferometers consist of multiple telescopes with phase-preserving detectors whose electronic outputs are heterodyned to a lower frequency range, amplified, distributed, and then multiplied to produce fringes.

Examples of direct-detection and heterodyne interferometers are Michelson interferometers such as SPIRIT and radio synthesis arrays such as ALMA, respectively.

Background-limited direct-detection telescopes are so sensitive that the whole telescope must be actively cooled to $T \sim 5$ K and located far from the Earth—near the Earth-Sun L2 Lagrange point, for example. No direct-detection FIR telescope has yet come within two orders-of-magnitude of background-limited sensitivity. The proposed Space Infrared Telescope for Cosmology and Astrophysics (SPICA) is a background-limited cyrogenic ($T \sim 5$ K) update of the passively cooled ($T \sim 80$ K) Herschel telescope (see http://www.ir.isas.jaxa.jp/SPICA_HP/index_English.html). Because SPICA will be the first fully cryogenic FIR telescope, "Successful completion of the SPICA mission is likely to be a [technological] prerequisite for both SAFIR and SPIRIT" (Harwit et al. 2009). SPICA is a collaboration between ISAS/JAXA and ESA, and "Discussion between ISAS/JAXA and ESA in 2013 concluded that the scheme for SPICA was not compatible with a time and robust implementation of the mission... It was therefore decided to stop all support activities on SPICA at ESA in early Autumn 2013" (http://sci.esa.int/cosmic-vision/53635-spica/). SPICA is being reconsidered, but its earliest launch date has been pushed back to 2025 (see http://www.sron.nl/press-releases-news-754/3927-a-new-start-for-the-spica-mission).

SPIRIT is a cryogenic background-limited direct-detection interferometer that brings together the collimated light beams from two 1 m telescopes and adds them prior to incoherent detection by a bolometer array, as shown in Figure 5. In contrast, heterodyne interferometers such as ALMA multiply the input signal from each telescope by the sine wave from a local oscillator. The mixer output is a phase-coherent replica of the input signal, only shifted to a much lower intermediate frequency (IF) range where it can be coherently amplified and multiplied by the IF signals from one or more other telescopes to produce fringes. The instantaneous bandwidth of a direct-detection interferometer is comparable with the observing frequency, so the coherence length is very short, $\sim \lambda$. Consequently, the baseline orientation of a direct-detection interferometer must be controlled very precisely in real time to stay on the "white light" fringe.

SPIRIT's central beam combiner is so large that SPIRIT's minimum baseline length is D_m = 7 m. This limits the angular dynamic range of SPIRIT to D_l / D_m ~ 5:1, so a large single telescope such as the proposed D = 10 m **SAFIR** (Single Aperture Far-Infrared Telescope; http://safir.jpl.nasa.gov/) or its off-axis successor **CALISTO** (Cryogenic Aperture Large Infrared Space Telescope Observatory; see http://safir.jpl.nasa.gov/technologies.shtml) is needed to fill the hole in SPIRITs (u,v) plane. Also, the R ~ 3000 spectral resolution of SPIRIT corresponds to a spectral channel velocity width Δv ~ 100 km s^{-1}, which is much too coarse for resolving lines from circumstellar disks or galactic molecular clouds.

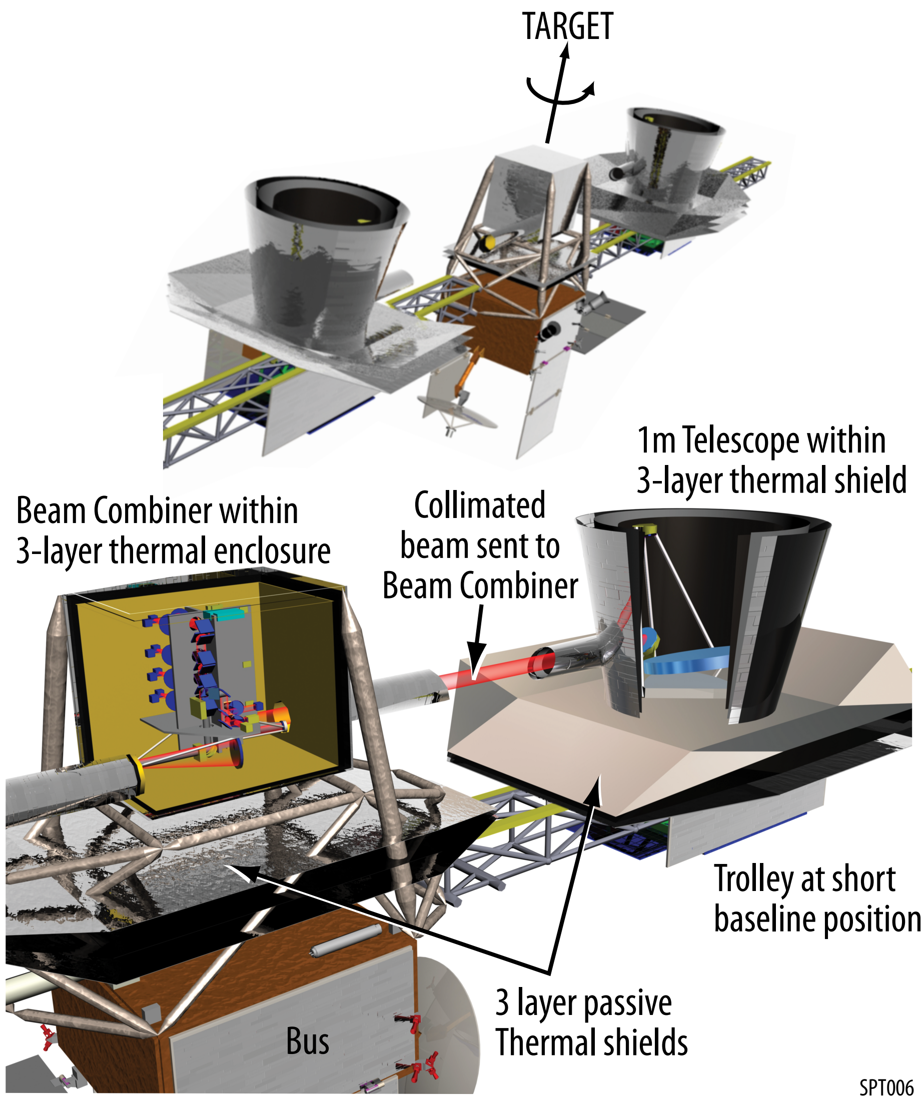

Figure 5: The SPIRIT interferometer (Leisawitz et al. 2009).

Quantum noise sets a floor below the system temperature

$T_s > h\,\nu\,/\,k \sim 50$ K / THz

of any heterodyne receiver (Kerr et al. 1997). This quantum noise is not just the Poisson fluctuation in photon counts, which affects both heterodyne and direct detectors. Rather, it is a consequence of the uncertainty principle because phase-preserving heterodyne receivers "know too much" about the location and momentum of each incoming photon. Imagine an ideal coherent maser amplifier in which each signal photon triggers a cascade of photons by stimulated emission. Although each signal photon can be counted reliably, spontaneous emission within the maser also produces photon cascades, at the rate of one false signal photon per second per Hz of bandwidth. At FIR and shorter wavelengths the false photon signal is much stronger than the astronomical background, and even ideal heterodyne interferometers are much noisier than background-limited direct-detection interferometers (Fig. 6).

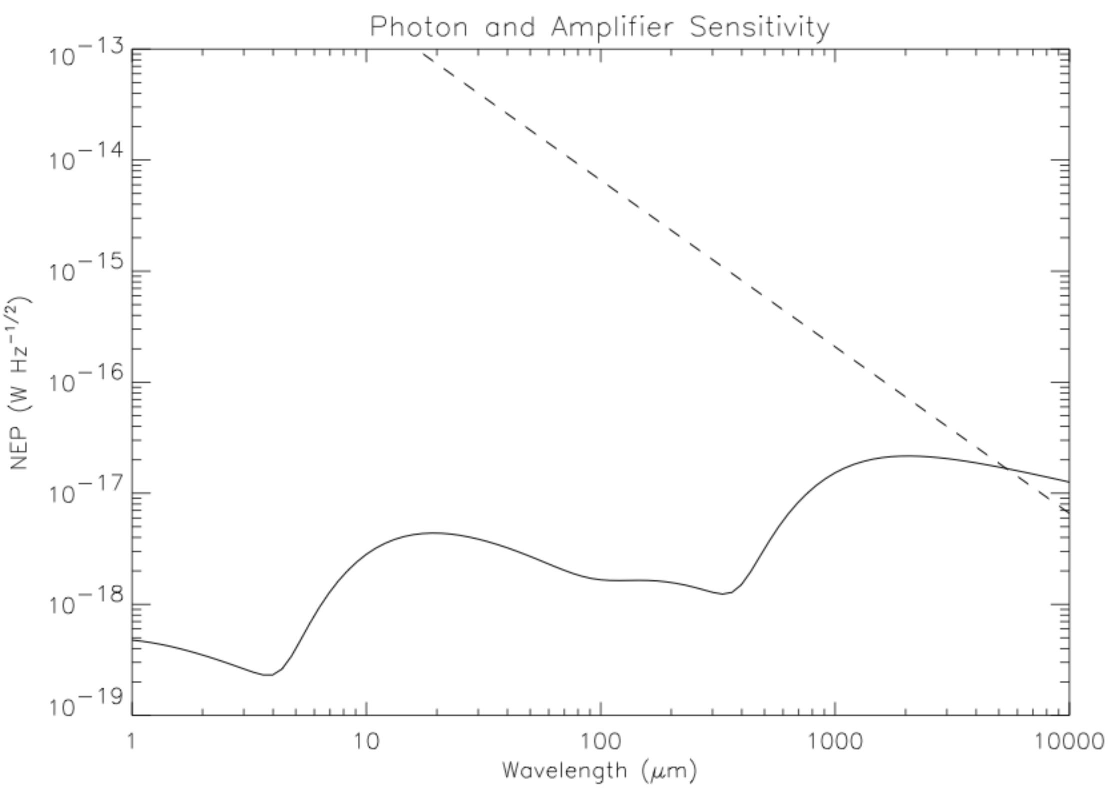

Figure 6: Noise equivalent power (NEP) from quantum noise (dashed line) and from astronomical backgrounds at L2 (solid curve) for 100% bandwidth $\Delta\nu = \nu$, two polarizations, and diffraction-limited telescopes with $A\Omega = \lambda^2$ (Mather et al. 1998). Ideal heterodyne detectors are almost 10^4 times noisier than background-limited direct-detection interferometers at $\lambda = 100$ μm.

The quantum noise penalty is so heavy at $\lambda \sim 100\ \mu$m that only one heterodyne FIR space interferometer (ESPRIT) has been considered in any detail (Wild et al. 2005). It covers the frequency range 0.5 – 1.5 THz with SIS mixers and 1.5 – 6 THz with hot-electron bolometers (HEBs). Even with six 3.5 m telescopes and receiver noise only a few times the quantum limit, its continuum sensitivity at λ = 100 μm ($5\sigma \sim 0.02$ Jy in 24 hours) is ~100 times worse than ALMA's at $\lambda \sim 450$ μm; it does not come close to meeting the continuum sensitivity specification for studying distant starburst galaxies. Because the continuum sensitivity and angular resolution of ALMA are so much better than those of any plausible space-based heterodyne interferometer, and because much of the information contained in FIR continuum emission is available at ALMA wavelengths, the primary use of a heterodyne interferometer in space will probably be high-resolution spectroscopy at frequencies below $\nu \sim 3$ THz.

An upside to the poor sensitivity of heterodyne interferometers is insensitivity to thermal emission "backgrounds" from the Earth and the telescope itself. Heterodyne interferometers might use passively cooled telescopes in near-Earth orbits (e.g., at the International Space Station) or even at stratospheric balloon altitudes of 30–40 km over Antarctica.

The primary advantage of heterodyne interferometers is their arbitrarily high spectral resolution: $R > 3 \times 10^5$ is easily attained. In contrast, direct-detection interferometers like SPIRIT use scanning optical delay lines to do "double-Fourier" spectroscopy. The bandwidth $\Delta\nu$ of a spectral channel is determined by the "stroke" length L of the optical delay line; it is $\Delta\nu = c / (4\ L)$. An impractically large L = 15 m delay-line stroke is needed for the $\Delta\nu$ = 10 MHz channel width corresponding to $R = 3 \times 10^5$ at λ = 100 μm. The maximum spectral resolution achievable is also limited by the beam divergence at the beam combiner, because the path difference is multiplied by the cosine of the angle of each ray from the central ray, and a range of angles corresponds to an apparent range of wavelengths (Mather et al. 1998). The step length ΔL of the scanning delay line must be less than $\Delta L = c / (4\ \nu)$. For example, at ν = 3 THz (λ = 100 μm), $\Delta L <$ 25 μm. The detector must be read out at each step, so a very fast detector is required. The practical resolution limit of a direct-detection double-Fourier interferometer appears to be $R \sim 3000$ ($\Delta v \sim 100$ km s^{-1}), which is good enough for spectroscopy of distant galaxies but not of Galactic sources. Finally, only one delay is sampled at each time, unlike heterodyne spectrometers, which store and combine all relevant delays digitally.

The instantaneous bandwidth of heterodyne receivers is still too small for spectroscopy of galaxies at frequencies above ~1 THz because the bandwidth of HEB mixers is limited by phonon diffusion — essentially the sound crossing time of the mixer film. $B \sim 3$ GHz today and might eventually reach 10 GHz (Kawamura et al. 2000). $B \sim 3$ GHz spans a velocity range of only $\Delta v \sim 300$ km

s^{-1} at ν = 3 THz, while merging galaxies can emit lines whose widths approach Δv ~ 1000 km s^{-1}.

The large instantaneous bandwidths of direct-detection interferometers imply small coherence lengths $c / \Delta\nu$, and strict real-time metrology is needed to control the baseline orientation relative to the source to within a synthesized beamwidth. In contrast, the much narrower channel bandwidths of heterodyne interferometers permit large after-the-fact phase corrections to the data.

Heterodyne interferometers excel at high-fidelity aperture synthesis imaging with $N >> 1$ telescopes because the output of each telescope can be amplified coherently before it is distributed among the other telescopes. Direct-detection interferometers with N telescopes must distribute the light from each among the (N-1) remaining telescopes, dividing their effective collecting areas by (N-1). For this reason, proposed direct-detection interferometers have only N = 2 or N = 3 elements. An interferometer with N = 2 cannot measure closure phases, and imaging complex sources with N = 3 is slow and yields marginal image fidelity.

Direct-detection interferometers are adding interferometers, so the detected fringes sit on top of the "DC" offsets from extended source emission, the cirrus foreground, instrumental emission, etc. Coherent interferometers use multiplying correlators to eliminate any DC offsets. We don't know how well incoherent detectors can separate weak fringes from the DC offsets and what requirements this separation implies for telescope pointing accuracy and detector gain stability.

The instantaneous fields-of-view and hence imaging speeds of both SPIRIT and SPECS are multiplied by factors ~10^2 to 10^4 by large detector arrays. SPIRIT plus SAFIR does seem well matched to the scientific goal of understanding the formation, merger history, and star-formation history of galaxies.

Sophisticated aperture-synthesis heterodyne interferometers like the VLA and ALMA were not and could not have been designed and built from scratch; they emerged following decades of theoretical analysis and practical experience gained by making astronomical observations of faint complex sources with simpler interferometers. Direct-detection Michelson interferometers have been used to observe strong and simple sources (to measure the diameters of the brightest stars, for example), but the problem of imaging faint sources against bright backgrounds with a multi-element adding interferometer has not been explored. The long history of radio astronomy and interferometry suggests that astronomically useful direct-detection imaging interferometers will have to be developed in stages over a period of decades following the launch of SPICA no earlier than 2025. Direct-detection interferometers are not likely to be ready for launch before the 2030's.

Near-Earth Heterodyne Interferometers in the FIR?

Heterodyne interferometers are so noisy that their telescopes can be passively cooled; and they can be used anywhere above most of the atmosphere, such as flying under stratospheric balloons near the South Pole, on or near the International Space Station (ISS), or on the far side of the Moon. However, the heterodyne receivers themselves (SIS or HEB mixers, IF amplifiers) must be still be cooled cryogenically.

Long-duration Stratospheric Balloon(s) Over Antarctica

BETTII (Balloon Experimental Twin Telescope for Infrared Interferometry) is an uncooled D_I = 8 m Michelson interferometer (Fig. 7) designed to fly under a high-altitude (30 – 40 km) stratospheric balloon. It will cover the wavelength range 30 μm < λ < 90 μm with claimed angular resolution ~ 0.5 arcsec, although $\theta = \lambda / D_I$ ranges from 0.8 to 2.3 arcsec. The optical delay line allows spectral resolution up to R = $\lambda / \Delta\lambda$ ~ 200.

BETTII was conceived as a test bed to advance key technologies and techniques to readiness for space-based interferometry, and it also addresses some of the challenges for and constraints on (see the Columbia Scientific Balloon Facility web page http://www.csbf.nasa.gov/) balloon-borne instruments.

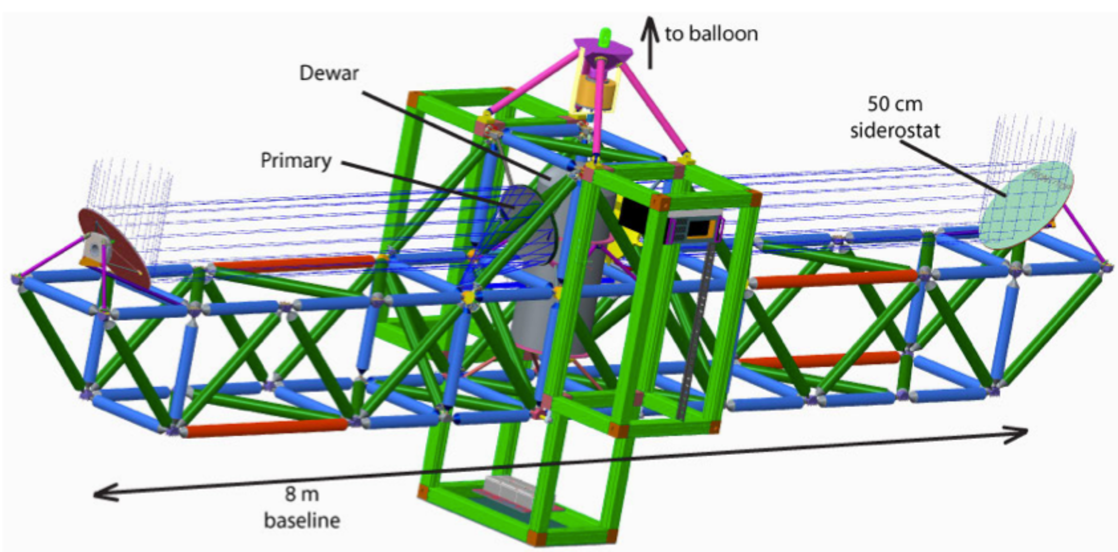

Figure 7: The BETTIE balloon-borne interferometer (Rinehart et al. 2012). See also http://asd.gsfc.nasa.gov/bettii/index.html and http://www.astro.cardiff.ac.uk/research/astro/instr/projects/?page=bettii.

Challenges for balloon-borne interferometers include:

1) Pendulation of the gondola causes pointing oscillations with amplitudes ~ 10 arcmin which must be offset by the delay line and siderostat pointing.
2) The entire payload, including the receiver Dewar, must withstand 10 g of acceleration when it is parachuted to the ground for recovery. This limits the maximum truss length = maximum baseline length of an interferometer supported by a single balloon to a few times 10 m.
3) The payload is recovered by a small airplane that can land on snow. The maximum recoverable weight is ~ 1000 kg, and the recovered payload must fit through a cargo door ~ 2 m wide and 1.5 m high into a cabin ~ 11 m long. Again, this limits the maximum truss length and maximum baseline length of the interferometer it supports to a few times 10 m.
4) The balloon diameter expands to D_b ~ 140 m at altitude (Fig. 8). Multiple gondolas must be separated by at least this much, leaving unacceptably large gaps in the (u,v) coverage that might be obtained by combining multiple small (D_l << 70 m) interferometers flown simultaneously.

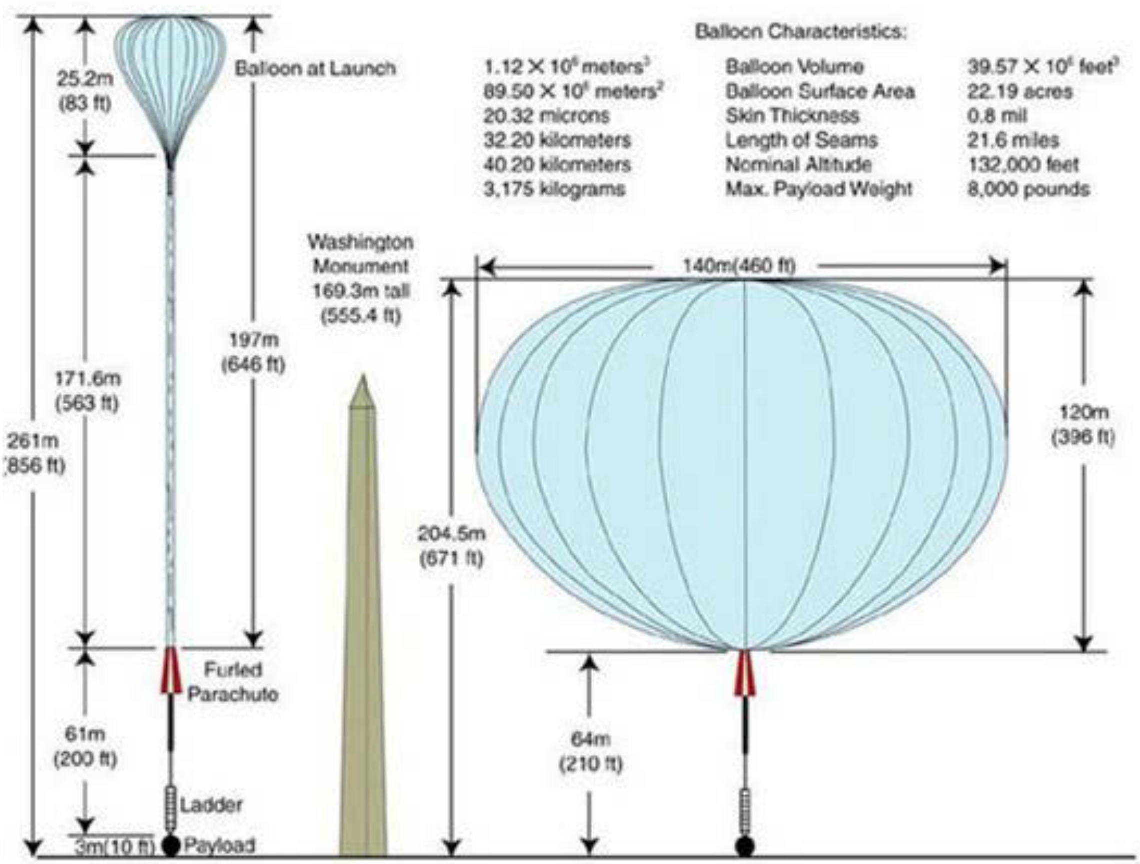

Figure 8: NASA's balloons grow to 140 m diameter at observing altitudes.

In summary, a balloon-borne interferometer must overcome severe mechanical challenges (e.g., building a pair of D_l ~ 70 m interferometers each weighing < 1000 kg that can withstand 10 g acceleration, and flying them under two coupled balloons) before it can approach even θ ~ 0.1 arcsec FWHM resolution. Also, the sky is opaque within 60 km s^{-1} of the 557 GHz water line even at stratospheric balloon altitudes.

On or Near the International Space Station (ISS)

The NRAO is the world leader in designing, building, and operating heterodyne interferometers, but it is far behind NASA in designing and flying direct-detection interferometers. Consequently, any NRAO NBT proposal is likely to involve heterodyne interferometry. For example, in 1988 the NRAO proposed the HISAT (High-resolution Imaging Spectroscopy At Terahertz frequencies) interferometer (Brown et al. 1990) to be mounted on the upper truss of Space Station Freedom (Figure 9). HISAT was designed to produce spectroscopic images of submillimeter lines of C (492 and 809 GHz), O (2060 GHz), and C^+ (1901 GHz) "to determine the origin and propagation of ultraviolet radiation in the Galaxy by studying the excitation of atomic carbon and oxygen at submillimeter wavelengths."

Figure 9: NRAO's proposed HISAT interferometer has two 2 m telescopes attached to Space Station Freedom on reconfigurable baselines from 5 to 30 m to achieve length for angular resolution θ ~ λ / D_l ~ 2 arcsec at ν ~ 1 THz.

An interferometer operating at ν ~ 2 THz (λ ~ 150 μm) to observe the spectral lines shown in Figure 1 with θ ~ 0.1 arcsec angular resolution must have baselines up to D_l ~ 300 m. This is larger than the ~ 100 m ISS itself, so at least part of the interferometer must be tethered or free flying. Advantages of the of the ISS over L2 orbits or balloons include (1) higher weight and size limits, allowing more telescopes for better (*u,v*)-plane coverage and larger total collecting area for higher sensitivity, and (2) longer lifetime because cryogens could be replaced, electrical power can be provided, and simple equipment repairs are possible. On the other hand, the ISS platform faces an uncertain scientific and political future.

What is the minimum effective collecting area A_e needed for a heterodyne interferometer to satisfy the primary technical specifications for spectroscopy of circumstellar disks near ν ~ 2 THz?

The practical system noise temperature above ν ~ 1 THz is likely to be $T_s \sim 10\, h\, \nu / k \sim 1000$ K. At ν ~ 2 THz the bandwidth of a $\Delta v = 1$ km s^{-1} velocity channel is $\Delta\nu \sim 6.7$ MHz. The rms receiver noise σ_T after a full day ($\tau = 86400$ s) of integration with 2 polarizations will be slightly higher than $\sigma_T \sim T_s / (2\, \Delta\nu\, \tau)^{1/2} \sim 9 \times 10^{-4}$ K. The corresponding rms channel noise for an array with collecting area A_e m^2 is $\sigma \sim \sigma_T\, (2760 \text{ m}^2 / A_e) \sim 2.5 / A_e$ Jy/beam

The continuum rms in a 3 GHz bandwidth is $\sigma \sim (0.12 / A_e)$ Jy/beam, which is sufficient to detect many circumstellar dust disks in Taurus-Auriga (Andrews & Williams 2005) but falls far short of the SPIRIT sensitivity specification or ALMA.

Detecting a line source with T_b ~ 100 K (5σ) in 24 hours needs $T_b \sim 100 \text{ K} \sim \lambda^2\, (5\, \sigma) / (2\, \text{k}\, \Omega\, A_e)$, where $\Omega \sim 1.13\, \theta^2$ is the beam solid angle for a Gaussian beam with FHWM = θ. Thus the effective collecting area of the interferometer must be at least $(A_e / \text{m}^2) \sim 3.8\, (\theta / 0.1 \text{ arcsec})^{-2}$

The effective collecting area of an *N*-element interferometer is proportional to $[N\, (N\text{-}1) / 2]^{1/2}$, so 3.8 m^2 is about equal to the collecting area of a 2-element interferometer with D = 3 m telescopes having 50% aperture efficiency, and a 4-element interferometer would be about 2.5 times as sensitive. A coherent FIR interferometer consisting of four 3 m dishes on baselines up to 300 m should just meet the SPIRIT specifications for high-resolution spectroscopy of circumstellar disks if located near the ISS.

On the Moon

The Bély et al. (1996) study for ESA compared free-flyer and Moon-based versions of kilometer-baseline optical and IR interferometers. The Moon had been regarded as a stable platform for interferometry, but it has problems:
(1) A lunar Michelson interferometer must have long delay lines to compensate for the Moon's rotation, and it would require protection from the large temperature swings experienced during the lunar day/night transitions.
(2) The Moon is not a stable platform mainly because of strong tidal and meteoroid-induced seismic disturbances.
(3) Supersynthesis on the Moon is too slow because the lunar day ~ 28 Earth days.
The study concluded "that the free-flyer is better suited for an implementation in the near of mid-term future, but that the Moon-based version should be considered in the long term in conjunction with a manned lunar infrastructure."

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