HETERODYNE RECEIVER REQUIREMENTS FOR THE SINGLE APERTURE FAR-INFRARED (SAFIR) OBSERVATORY

Dominic J. Benford
NASA – Goddard Space Flight Center, Code 685, Greenbelt, MD 20771

Jacob W. Kooi
Caltech, MC 320-47, Pasadena, CA 91125

In the next few years, work will commence in earnest on the development of technology for the next generation large cryogenic far-infrared telescope: the Single Aperture Far-Infrared (SAFIR) Observatory. SAFIR's science goals are driven by the fact that youngest stages of almost all phenomena in the universe are shrouded in absorption by cool dust, resulting in the energy being emitted primarily in the far-infrared. The earliest stages of star formation, when gas and dust clouds are collapsing and planets forming, can only be observed in the far-infrared. Spectral diagnostics in the far-infrared are typically quite narrow (~1 km/s) and require high sensitivity to detect them. SAFIR is a 10m-class telescope designed for cryogenic operation at L2, removing all sources of thermal emission from the telescope and atmosphere. Despite its limited collecting area and angular resolution as compared to the ALMA interferometer, its potential for covering the entire far-infrared band cannot be matched by any ground-based or airborne observatory. This places a new challenge on heterodyne receivers: broad frequency coverage. The ideal mixer would be able to detect frequencies over several octaves (e.g., 0.6THz-12THz) with near quantum-limited performance at all frequencies. In contrast to ground-based observatories, it may not be necessary to strive for high instantaneous bandwidth, as direct detection spectroscopy is preferable for bandwidths of $\Delta\nu/\nu \geq 10^{-4}$ (e.g., 1GHz at 10THz). We consider likely directions for technology development for heterodyne receivers for SAFIR.

Keywords: heterodyne receiver, SIS mixer, HEB mixer, SAFIR, far-infrared, submillimeter

JUSTIFICATION FOR SAFIR

The earliest stages of star formation occur when thick, dusty gas clouds collapse towards the central protostar. The beginnings of this central star can only be observed at wavelengths in the far-infrared and longward. A host of diagnostics of the physical and chemical parameters of protostars can teach us about the processes that allow stars to form. Additionally, the cool dust that will eventually form planetary systems, as well as the cool debris disks that indicate the likelihood of planet-sized bodies around more developed stars, can only be observed at wavelengths longward of 20μm. A hint of the richness of the far-infrared spectrum is given below in Figure 1.

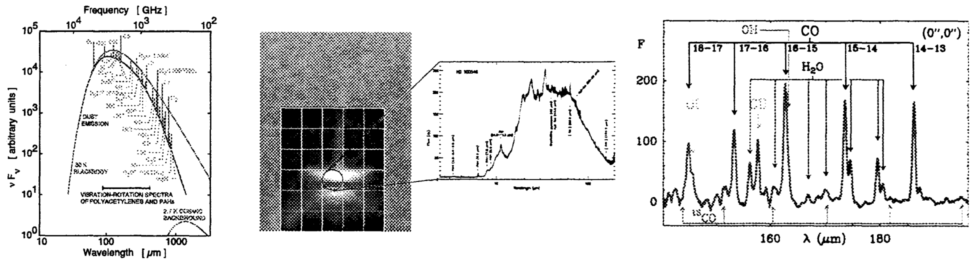
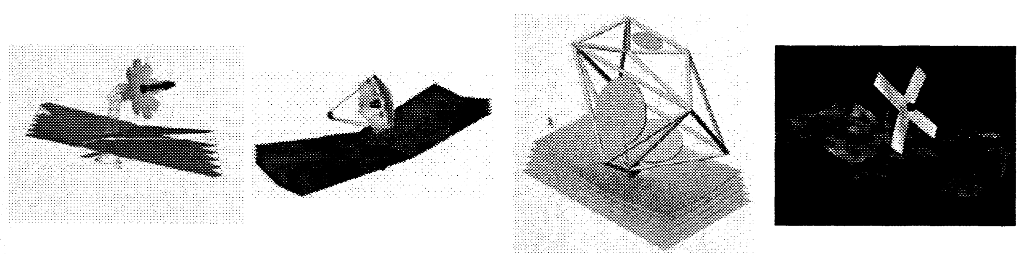


FIGURE 1. [Left] Synthetic molecular cloud spectrum, from Phillips & Keene (1992). [Center] Zooming in on a protostar with SAFIR (Burrows et al. 1996; Malfait et al. 1998) [Right] ISO/LWS spectrum or Orion-IRC2 (from Cernicharo et al. 1999).

SAFIR MISSION CONCEPT

SAFIR is best thought of as a set of scientific objectives that answer key questions in astrophysics by means of measurements in the far-infrared. Its implementation can be determined only by thoughtful study of multiple mission concepts, taking into account the science goals, technological capabilities, and programmatic feasibility. Several preliminary concepts have been produced, at varying levels of fidelity, as shown in Figure 2 below (all to scale).



A B C D

FIGURE 2. SAFIR concepts [A] Petal-deployed telescope based on the NGST Strawman Design (Amato et al. 2002); developed at NASA/GSFC. [B] Table-fold telescope based on the JWST (TRW) Design; developed at NASA/GSFC. [C] Stretched membrane telescope "DART" (Dragovan 2002); developed at NASA/JPL. [D] Strip-mirror mission concept using a sparse-aperture telescope for high angular resolution; developed at NASA/GSFC.

More in-depth consideration of SAFIR mission designs will be needed before a single approach can be selected. A high-fidelity but preliminary mission concept for SAFIR has been developed, derived from the technology heritage of JWST (Amato et al., SPIE, 2002). A full discussion of this mission is beyond the scope of this paper, but a few points are important. First of all, the design provides for a 10m diameter with >80% effective area used. Furthermore, the entire optical surface is cooled to 4 K, so that thermal emission in the far-infrared is negligible.

REQUIRED HETERODYNE RECEIVER PERFORMANCE

In order to satisfy the science goals listed above, SAFIR needs high resolution ($\lambda/\delta\lambda \sim 10^6$) spectrometer covering the wavelength range 25-520μm (575GHz-12THz). An instrument with a small number of diffraction-limited beams in a sparse pattern would be sufficient to provide a reasonable imaging speed, but the detectors, if heterodyne, will need to be nearly quantum-limited so that the spectrometer can take advantage of the very low background in space.

When building a high resolution spectrometer for a wavelength longward of ~300μm (ν<1THz), it is common to use coherent spectrometers. If the instantaneous bandwidth desired is narrower than $\lambda/\Delta\lambda=10^4$ (30km/s), the bandwidth of the intermediate frequency amplifier and backend spectrometer need be only ~100MHz, easily achievable by today's standards. Given sufficient technology investment, could a coherent spectrometer be developed to cover the SAFIR bands (25μm-520μm) to provide information via very high resolution observations? This is possible for the case of Galactic observations, where line strengths relatively large though line widths are narrow. SAFIR's detection limit in a 1km/s line in 10^4s is about 1mK at 300μm with a heterodyne spectrometer. However, in distant, extragalactic sources where linewidths are larger but sources are fainter, the quantum limit makes the detection of lines a difficult proposition.

Using the background power for a 4K, 10m telescope, we calculate a total effective power (including quantum noise fluctuation power) to produce a photon-limited noise equivalent flux density (NEFD). The result is shown in Figure 3 below for a spectral resolution of $\lambda/\Delta\lambda=3\cdot10^5$, or a 1 km/s resolution. To put the comparison into scientific terms, the predicted fluxes of bright far-infrared fine-structure lines as they are redshifted towards submillimeter wavelengths are also shown. It is clear that a heterodyne spectrometer will pay a severe sensitivity penalty as compared to the natural photon background. In the quantum-limited case, a 270K telescope is about as good as a 4K telescope, and so ALMA will be more sensitive than SAFIR anywhere they overlap. However, practical issues mandate that at very high spectral resolutions, heterodyne spectroscopy is preferred (see, e.g., Zmuidzinas (2003) for details).

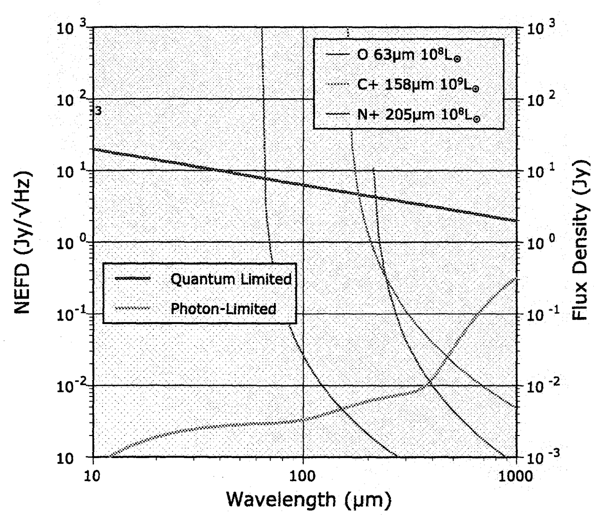


FIGURE 3. NEFD for a $\lambda/\Delta\lambda=3\cdot10^5$ (1km/s resolution) spectrometer using photon-limited direct detectors compared with quantum-limited coherent detectors. Predicted fluxes for redshifted fine-structure lines are shown for reference.

FUTURE SUBMILLIMETER FACILITIES

We compare the predicted sensitivity of SAFIR's heterodyne spectrometer to those of other facilities available in the next decade. In Figure 4 below, we have made an estimate of the NEFD for an upgraded CSO instrument suite (Kooi et al. 2003), a hypothetical ALMA suite with receivers at all frequencies available from the ground, a hypothetical optimized SOFIA heterodyne spectrometer covering the whole 300 GHz – 3 THz band, and the HIFI instrument on Herschel. NEFD is chosen rather than noise temperature, as the point source sensitivity of each facility is the more relevant parameter. As can be seen, SAFIR will provide a substantial gain in sensitivity at frequencies above 1THz, enabling new science at these frequencies. Where ALMA is operational, its sensitivity and high angular resolution are superior, but the availability of the >1THz windows is not common.

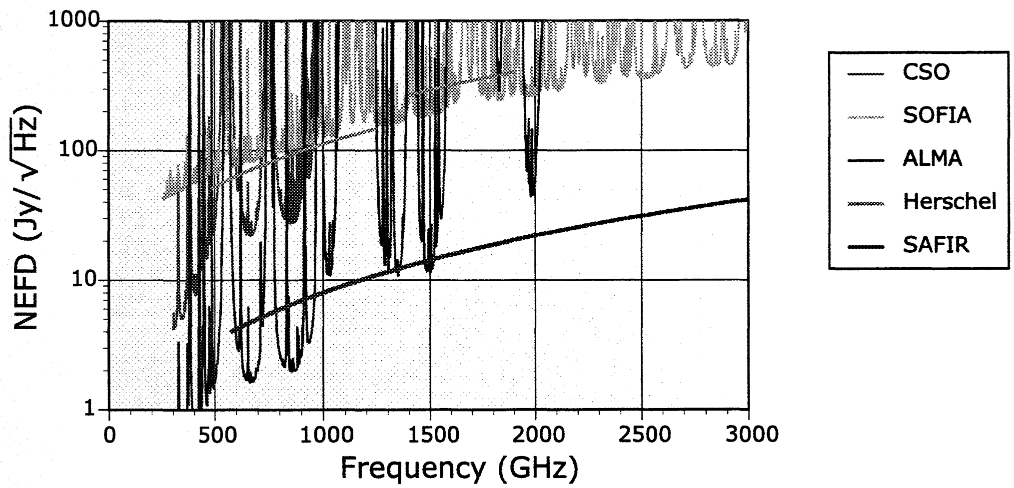


FIGURE 4. Flux density sensitivity at 1km/s resolution from 300 GHz to 3 THz (100 μm to 1 mm) of several facilities envisioned for the coming decade, as compared to the sensitivity of the SAFIR observatory.

It is worth noting that all of these facilities are quantum-limited except where the atmospheric emission is strong. For this reason, a warmer but larger implementation of SAFIR would yield better sensitivity for its heterodyne instruments. Figure 2(C) shows a tensioned membrane telescope, which yields a very low areal density but more difficult cooling problems. This, the NASA/JPL "DART" concept, might be easily scaled to a larger (10-30m), warmer (~30K) telescope than the baseline 10m, 4K SAFIR.

TECHNOLOGIES FOR HETERODYNE INSTRUMENTS

Significant progress on the development of heterodyne technologies has been made (see, e.g., Siegel 2002). However, to achieve the required sensitivity and bandwidth for SAFIR, many of the needed components will need to be developed by NASA. These include:

- Tunerless (waveguide or quasioptical) mixers (SIS and HEB) with large fractional RF bandwidth
- High efficiency local oscillators for the 0.6 THz – 12 THz range (e.g., laser photomixed sources)
- Low noise cryogenic amplifier (e.g., 4 – 8 GHz)
- Combined wideband (e.g., also 4 – 8 GHz) IF matching network, DC-break, bias tee, etc.
- Broadband coupling techniques
- Low power, compact multichannel backend spectrometers

One of the most difficult aspects of the development of a heterodyne spectrometer for SAFIR is the broad wavelength coverage required. It is typically possible to achieve a bandwidth of nearly an octave with a single tuning and amplifier network. SAFIR's requirement of 4.3 octaves implies that >5 bands will be needed, all well-matched to each other. An example of this approach is given by Kooi et al. (2003), and is reproduced here (Figure 5). The calculations assume optimized balanced twin-junction Nb SIS receivers. Further development of broadband quasioptical coupling techniques may enable mixers to operate over even broader ranges.

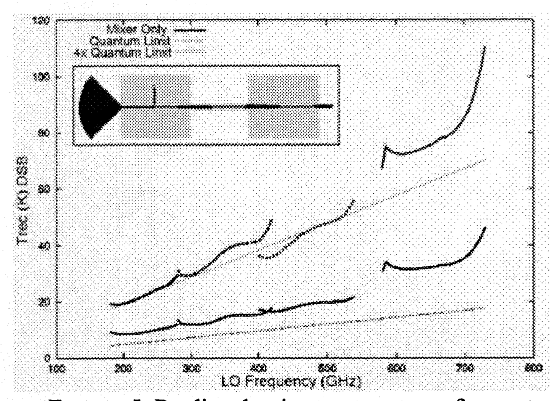


FIGURE 5. Predicted noise temperatures for next-generation mixers and receivers at the Caltech Submillimeter Observatory (Kooi et al. 2003).

As shown above, across the 200–700 GHz (430µm–1.5mm) range, the predicted receiver temperature is about four times the quantum limit. If we extrapolate the calculation to the SAFIR bands, the entire region from 575 GHz–12 THz (25µm-520µm) can be covered with seven contiguous bands. We have assumed similar performance: a noise level of four times the quantum limit over the entire frequency span, and coupling limited in bandwidth by waveguide techniques. Considering the 575 GHz–8 THz (38-520µm) bands, we find the receiver noise shown in Figure 6.

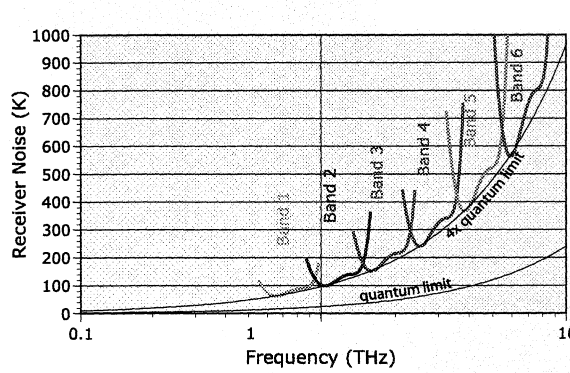


FIGURE 6. Layout of the lowest six bands of the SAFIR heterodyne spectrometer. Each receiver is assumed to operate at four times the quantum limit at its best frequency.

STATE-OF-THE-ART

The current state-of-the-art receiver performance (Figure 7) is excellent for SIS mixers operated at frequencies below ~500 GHz (600μm). Once into the SAFIR bands, however, the best receivers are HEBs, which typically have substantially more noise. This sensitivity reduction is so substantial that it may reduces the advantage SAFIR has over a larger ground-based facility such as ALMA. Technology to fill this sensitivity gap must be developed to enable a heterodyne instrument for SAFIR.

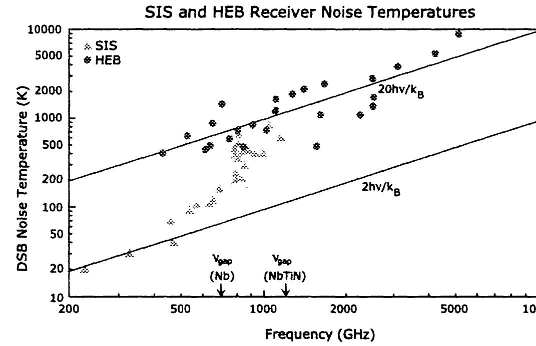


FIGURE 7. Current (early 2003) state of the art performance for heterodyne receivers.

CONCLUSION

For SAFIR, single-moded coherent detectors operating near the quantum limit over the 575GHz–12THz (25–520μm) range are needed. To this end, increasing the tunable bandwidth of detectors and local oscillator sources is a key research investigation to be undertaken. HEB or SIS mixers are the most promising current technology for this purpose, if they can be manufactured with near-quantum noise at such high frequencies. Additionally, backend spectrometers using low-power digital autocorrelators should be developed.

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