Science Promise and Conceptual Mission Design for SAFIR – the Single Aperture Far Infrared Observatory

Dan Lester[a*], Dominic Benford[b], Harold Yorke[c], C.M. Bradford[c], K. Parrish[b], H. Stahl[d]

[a]Department of Astronomy, University of Texas, Austin TX
[b]Lab for Astronomy and Solar Physics, Infrared Astrophysics Branch,
NASA Goddard Space Flight Center, Greenbelt MD
[c]Division of Earth and Space Sciences Jet Propulsion Laboratory, California Institute of Technology,
Pasadena CA
[d]NASA Marshall Space Flight Center, Huntsville AL

ABSTRACT

We report on completion of the SAFIR Vision Mission study, as organized by the NASA Science Mission Directorate. This study resulted in a focused baseline design for this large aperture space observatory that capitalizes on architectures being actively developed for JWST and other missions. Special opportunities for achieving thermal performance of this <10K telescope are reviewed, as well as efforts to understand capabilities and needs for focal plane instrument and I&T on this large (10m-class) telescope.

Keywords: observatory, infrared, astronomy, telescope

1. STUDY AND PROGRAMMATIC CONTEXT

The Single Aperture Far Infrared (SAFIR) telescope facility targets the critical far infrared far infrared and submillimeter spectrum between that covered by the James Webb Space Telescope (JWST) at shorter wavelengths, and the Herschel Space Observatory and ground based telescopes at longer wavelengths. Such astrophysically important wavelengths are largely inaccessible from the ground because of atmospheric water vapor. The science enabled by this 10m-class low temperature telescope would build upon ongoing far- and mid-infrared work with the Spitzer Space Telescope (SST), at sensitivity levels several orders of magnitude higher, and with more than an order of magnitude higher spatial resolution. Though the baseline concept for SAFIR would be a non-serviceable mission, it would offer vastly higher sensitivity, and at least a factor of three higher spatial resolution than the accessible but ambient temperature Stratospheric Observatory for Infrared Astronomy (SOFIA), now approaching first-light. In almost two decades of the electromagnetic spectrum between 20μm and 1mm wavelength, SAFIR would serve as a flagship observatory facility, limited for all but the highest spectral resolution by natural background levels from zodiacal dust, distant galaxies, and the cosmic microwave background. SAFIR can be considered the logical extension of these other space science missions, and builds scientifically on the foundation that they establish. In particular, Spitzer is revealing the richness of the sky at the faintest flux levels, and Herschel will augment and extend this discovery space to the terahertz band. Both of these missions, along with the development of JWST, hone our engineering capabilities for cryogenic space telescopes and thermal control that are directly applicable to a mission like SAFIR. SOFIA will offer an important test bed out of which new generations of large format and high sensitivity infrared sensors will be proven, and it is these sensors that are crucial to optimal use of an observatory like SAFIR.

Endorsed as an achievable long-range national priority for observational astrophysics by the 1990 Decadal Study of the National Research Council—"Astronomy and Astrophysics in the New Millenium"[1] , SAFIR has been considered in

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[*] dfl@astro.as.utexas.edu; phone 1-512-471-3442; fax 1-512-471-6016 http://www.as.utexas.edu

[1] *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington D.C., 2001.

NASA strategic planning studies to be a notional goal for the 2015-2020 time frame. With this in mind, SAFIR was identified as a "Vision Mission" for the agency, and a team was assembled to refine the scientific goals of the mission, demonstrate consistency with identified agency strategic goals, to provide a technically credible and achievable baseline architecture, and to map out strategic technology investments that would advance the mission, and develop a technological heritage that could advance even more ambitious missions. Consistent with the NASA 2006 Strategic Plan, SAFIR would play a key role in the agency goal to "discover the origin, structure, evolution, and destiny of the universe, and search for Earth-like planets." This paper summarizes the results of the SAFIR Vision Mission Study report, which was submitted to NASA in June 2005 (Lester et al. 2005), highlighting some of the more challenging aspects of the mission. A more complete version of the report will be published at a later date. This study extends previous efforts on mission definition (most recently Lester et al. 2004, Benford et al. 2004, Amato et al. 2003, Harvey et al. 2003).

The SAFIR Vision Mission Team was composed of science stakeholders from NASA and academia, bringing background from four NASA centers (GSFC, JPL, JSC, and MSFC). Industry partners from Ball Aerospace, Boeing, Lockheed Martin, and Northrop Grumman provided additional engineering contributions, as well as explicit experience drawn from deep involvement in relevant missions such as Spitzer, Herschel, JWST, as well as plans for human and robotic capabilities that draw from the Vision for Exploration.

As a telescope with a single contiguous aperture, SAFIR would offer uniform baseline coverage and robust imaging with high sensitivity for a range of focal plane instruments covering large focal plane fields of view. In this respect, SAFIR would complement more specialized future far infrared and submillimeter space interferometers, such as the Space Infrared Interferometry Trailblazer (SPIRIT) and, in the longer term, the Submillimeter Probe of the Evolution of Cosmic Structure (SPECS). SPIRIT was studied as an Origins Probe and SPECS as another Vision Mission (Harwit et al. 2005). These missions would provide higher spatial resolution than SAFIR at far infrared and submillimeter wavelengths, but with a more limited collecting area and field of view. The complementarity of SAFIR and space interferometers is well understood (e.g. Leisawitz, 2004, Lester 2006).

As reported earlier (Lester, Friedman & Lillie 2005), our study carefully considered possible enabling advantages extending from human and robotic developments from the Vision for Space Exploration. While such opportunities might not have been considered before modern architectures for lunar return had been advanced, and our study baselined a SAFIR point-design that was autonomously deployable out of a single launch vehicle, such developments could offer important scientifically profitable augmentation and life extension options. We believe that while the lunar surface itself offers no advantage to this kind of astronomy (and, with regard to gravitational stresses, particulates, and thermal inconveniences, distinct disadvantages) the architectures to get our country there and support us there could. We believe that it is in the national interest to look at plans for lunar return in this broad way.

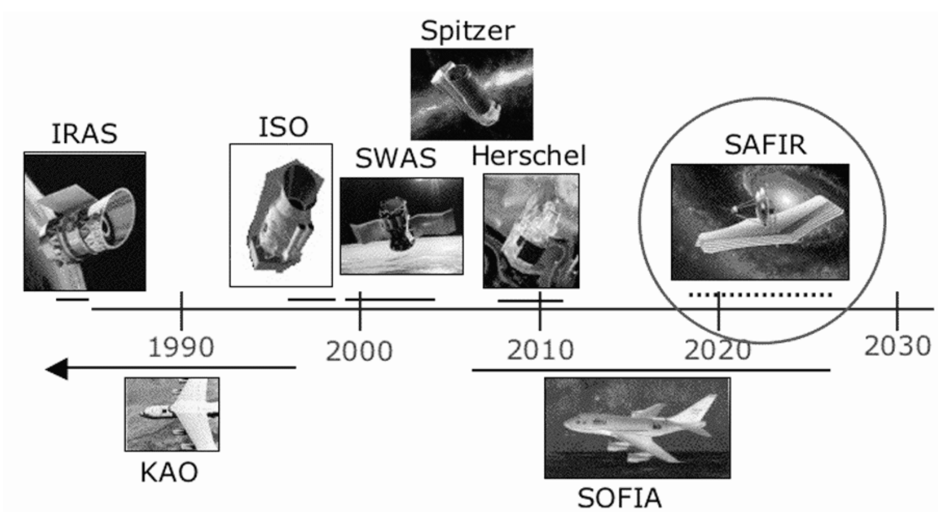


Figure 1: A contextual timeline for SAFIR, showing relevance to other agency far infrared and submillimeter investments. Not shown on this plot for convenience are scientifically relevant missions at other wavelengths, such as JWST, Con X, and TPF.

2. MEETING KEY SCIENCE OBJECTIVES

The key science objectives for the SAFIR mission that dictate mission design requirements are listed below. These key objectives are

- Resolve the far infrared cosmic background - trace formation and evolution of starforming and active galaxies since the dawn of the universe, and measure the history of star formation.

The mid- and far-infrared part of the spectrum, galaxies emit powerful thermal continuum radiation from their warm and cool interstellar dust grains. In fact, in the integrated spectrum of the sky (see Figure 2 below), the SAFIR key spectral region from 20µm-1mm is seen to contain a substantial fraction of the energy output of the universe. This far infrared peak in the integrated spectrum is largely due to galaxies, mostly primeval galaxies at large distance rapidly forming their first generation of stars.

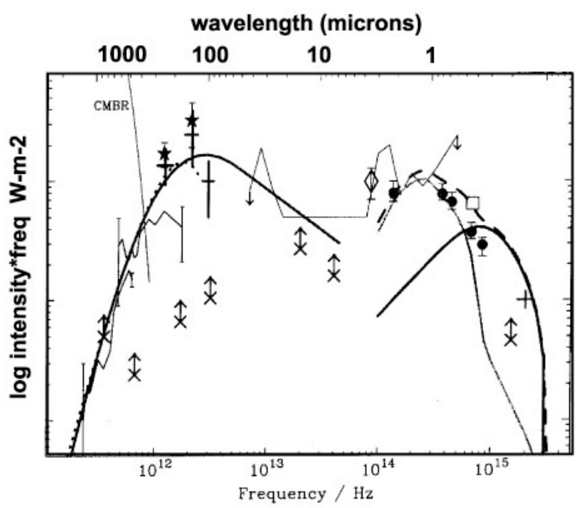


Figure 2: The integrated energy spectrum of the universe shows a strong peak in the far-infrared and submillimeter. This energy is largely emitted by distant primeval star forming galaxies. Galaxy counts at optical wavelengths scaled to representative far infrared intensity (**x**) are unable to account for the integrated emission, represented by the solid line. This suggests that the galaxies the primeval galaxies that produce this peak are largely invisible at optical wavelengths.

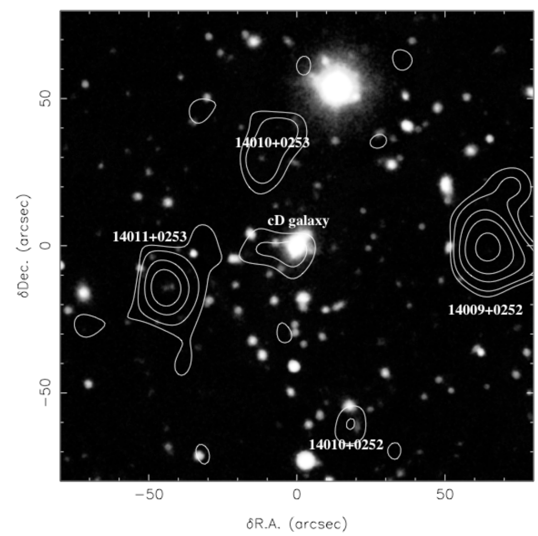


Figure 3: A multicolor picture combining a Palomar 200-inch image of the core of the cluster A1835, with white contours showing detections of background galaxies at 850 µm. The lack of overlap between optical and submillimeter sources shows the importance of combining far-IR and optical/near-IR views (Ivison et al. 2000; MNRAS; 315, 209).

With the great sensitivity of SAFIR, it will be able to detect galaxies similar in luminosity to our own out to a redshift of 3-4, and the very first luminous galaxies out to redshifts at which galaxies are just starting to form. A key advantage of SAFIR in doing an unbiased census of star formation in the universe is that, working at long wavelengths, it will detect galaxies that are heavily obscured in the visible bandpass because of newly formed dust grains (see Figure 3). In addition, SAFIR will explore the global properties of star formation in our own and nearby galaxy in great detail, offering visibility deep into the obscured regions of molecular clouds out of which they form.

- Probe the earliest epochs of metal enrichment and see the galaxy-forming universe before metals. Understand the origin of dust grains in the universe.

Before the first generation of stars are formed, and seed the newly formed galaxies with heavy elements, out of which dust grains are formed, the galaxies are composed of mostly hydrogen and helium, warmed by gravitational contraction. We have never yet seen such a galaxy, though we know they must exist. In such warm galaxies, a main coolant would be the 21μm fundamental line of molecular hydrogen. At the redshifts at which we anticipate such galaxies (z~10), this line is shifted into the far infrared. Simple models of massive primordial galaxies suggest that such an emission line might be detectable by a telescope like SAFIR. As an extension of the goal of establishing the history of star formation, SAFIR would use fine structure line emission to map the chemical enrichment of stellar systems, including the elements that contribute to dust grains. By tracking the reprocessing of energy by dust grains in the most distant systems, SAFIR would provide clues about the epoch at which such grains become important contributors to the cooling of galaxies.

• Explore the connection between embedded nuclear black holes and their host galaxies. Understand the relationship of active nuclei to galaxy formation.

SAFIR provides a unique opportunity to investigate active galaxies using a variety of diagnostic infrared spectral features as probes. In such galaxies, accretion onto a supermassive black hole from material in a dense confining torus is thought to be the energy generating mechanism. With a 10m aperture, the spatial resolution of SAFIR in the far infrared is sufficient to resolve the cores of local active galaxies, to use these probes to understand the relative role of rampant star formation in the energy generation and ideally see the molecular signature, in lines of hot molecular species, that would reveal the confining torus, as represented in the artist conception in Figure 4. In this context, SAFIR is an ideal tool for understanding ultraluminous infrared galaxies, a class of galaxies only recently identified, and among the most powerful objects in the universe, with far infrared luminosities exceeding that of our own galaxy by a factor of a thousand or more.

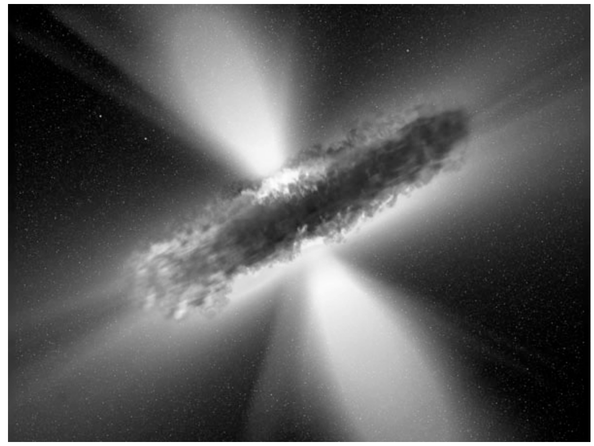


Figure 4: Artist's conception of the doughnut-shaped torus that confines the emission from an active nucleus. The accreting massive black hole is confined within a dense atomic and molecular torus. (Credit ESA.)

• Track the chemistry of life. Follow prebiotic molecules, ices, and minerals from clouds to solar systems.

The sequence of events beginning from the collapse of a gravitationally unstable clump within a molecular cloud is still poorly known. SAFIR will allow us to follow, with high spatial resolution, diagnostic spectral lines and bands that trace both cloud cooling and chemical evolution. Detailed line profile shapes will enable the study of the structure and dynamics of nascent molecular disks.

Observations of complex molecules will provide us with important clues about their formation mechanism, and their ability to survive in the interstellar medium. For example, amino acids have been shown to be formed when interstellar

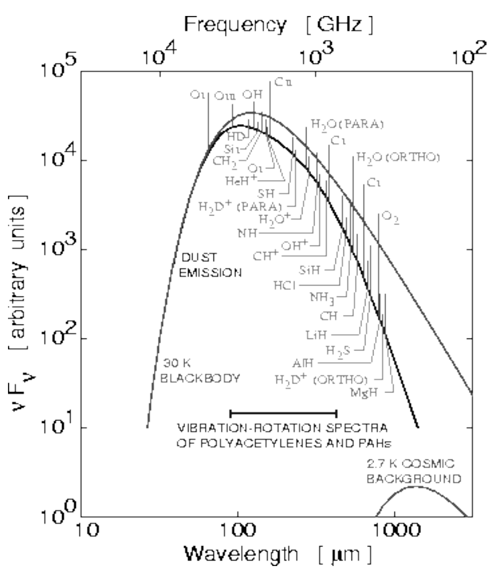
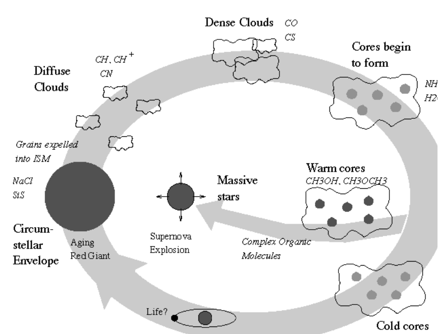


Figure 5 (at left): The far infrared and submillimeter part of the spectrum is rich in astrophysical tracers of interstellar chemistry.

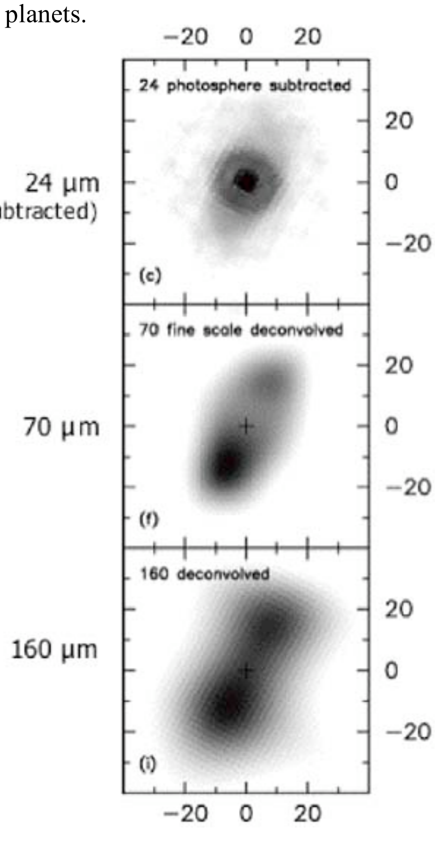
Figure 6 (below): These molecular probes can help define complex chemical processing in the interstellar medium, leading to the development of prebiotic materials.



ices are irradiated by UV photons. Such photons are likely to destroy such free complex molecules, but they may survive in shielded regions, protected from destruction deep within interstellar clouds, or locked within the ice in which they form. SAFIR is uniquely placed with an ideal wavelength coverage and high sensitivity to make a significant contribution to our understanding of the organic chemistry of the interstellar medium.

- Identify young solar systems from debris disk structure and map the birth of planetary systems from deep within obscuring envelopes. Assess the degree of bombardment they face, and the degree of habitability.

Debris disks around middle-aged stars like our Sun are now understood as being fairly common. These dusty disks, for which our own zodiacal cloud and Kuiper Belt are an example, are signatures of planetesimal formation in star systems around these stars. This is understood because such disks are effectively cleared by radiation pressure, and their existence requires a replenishment mechanism, perhaps the result of mutual collisions between planetesimals or evaporation of comets. This warm dust radiates thermally in the infrared, and SAFIR will be superbly suited to detecting and mapping them. While incipient structure has been barely seen by the Spitzer Space Telescope in the far infrared debris disk of the nearby main sequence star Fomalhaut (see Figure 7 below), the spatial resolution of SAFIR will be an order of magnitude higher, allowing us to explore the structure of these disks in detail. The detailed structure of these disks can be highly revealing, as planet-sized bodies are expected to have important dynamical effects on the debris clouds. This is illustrated by the simulation shown in Figure 8 below, in which a notional Neptune-mass planet has cleared the inner part of a debris cloud, and produced resonant clumps in the debris material ahead of and behind it. High spatial resolution studies of nearby debris clouds with SAFIR could use this kind of clearing and resonances to identify extrasolar planets.



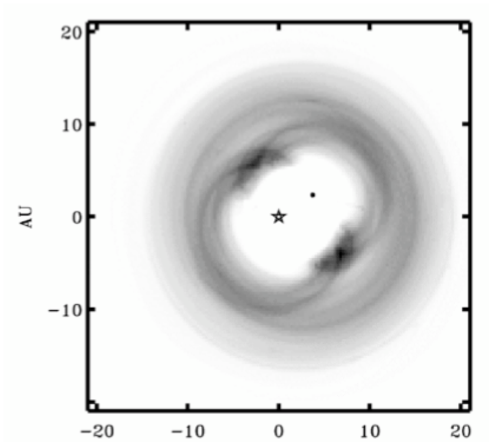


Figure 7 (at left): Spitzer images of Fomalhaut show a circularly symmetric central hot region dominated by the star itself at short wavelengths, metamorphosing into an extended disk with clumps (perhaps are determined by dynamical resonances) at long wavelengths. The spatial resolution of SAFIR will be an order of magnitude higher than this. (From Breyer et al. 2004.)

Figure 8 (above): A simulation of resonant clumping in a debris disk around a Fomalhaut-like star. The model included a planetary mass a few times larger than Jupiter with an eccentric orbit that has imposed a dynamical structure on what would have been a radially and azimuthally uniform disk. (From Kuchner 2003.)

While the detailed requirements for SAFIR are driven by the key science objectives that it would perform, these requirements are bounded by practicalities, economies, and natural limits. We thus begin with the notional mission for SAFIR as a 10 m-class filled aperture telescope operating in a diffraction-limited ($1.22\lambda/D=0.5''$ at 20µm) mode between the JWST long wavelength limit and the ground-based submillimeter short wavelength limit, and photon limited on the celestial background at all wavelengths. The size of the telescope is chosen as one that can fit in an EELV using at least some JWST architecture heritage, and offers spatial resolution on the order of a primordial galaxy size in the far infrared. The background-limited goal for SAFIR is a strong driver on the operating telescope temperature. The telescope would be equipped with diffraction-limited wide field direct detection imagers, low-moderate resolution ($R \sim 10^{2-3}$) direct detection spectrometers, and high resolution ($R \sim 10^6$) heterodyne spectrometers.

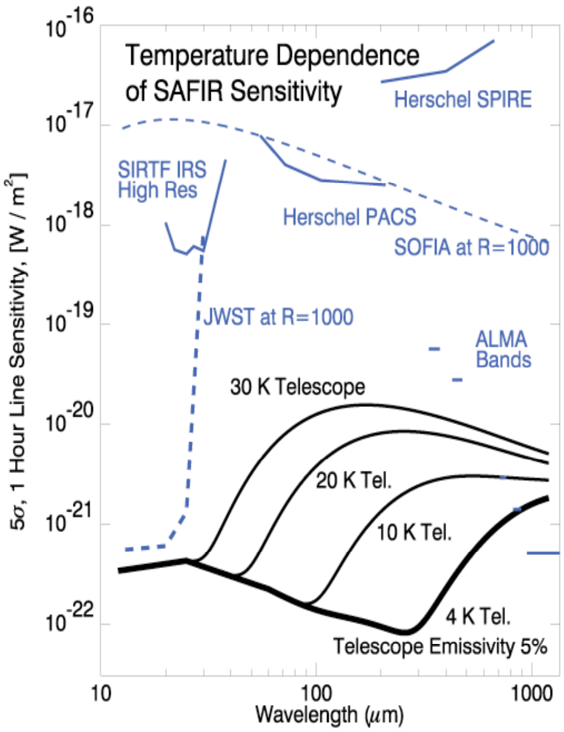


Figure 9: The temperature dependence of SAFIR point-source sensitivity is shown as a function of wavelength for R=1000 spectroscopic applications, and compared with capabilities of other observatories. At this spectral resolution, SOFIA sensitivity is not limited by extragalactic source confusion at the long wavelengths, which is the case for broad-band imaging. The bold line at the bottom of the figure is the celestial background, dominated at short wavelengths by relatively warm zodiacal grains, and at the long wavelengths by the cosmic microwave background.

This figure shows that the sky is especially dark in the far infrared, and in order to be able to take advantage of this, the telescope temperature should be less than 10K. The very steep loss in SAFIR performance with increasing telescope temperature is thus a primary driver for the SAFIR concept.

In order to realize the full advantage of this dip in the celestial background, detector sensitivities that are at least a factor of ten better than currently available are required. The trajectory of current detector technology suggests that this could be realizable with appropriate investment.

SAFIR is seen in this figure to offer sensitivity in the far infrared several orders of magnitude higher than that of currently planned observatories.

3. SPACE SYSTEMS ARCHITECTURE OF THE SAFIR OBSERVATORY

In developing a point design for SAFIR we have chosen a strong heritage from JWST. It was concluded that extrapolating JWST to a slightly larger, slightly colder telescope was technologially credible, especially in view of the much lower optical precision required of the longer-wavelength SAFIR. This strategy offered obvious opportunities for building on the engineering investments in JWST. As an observatory like JWST, in which low temperature and thermal stability was an important concern, Earth-Sun L2 is an optimal venue for operations. At Earth-Sun L2, the Earth and Sun are in generally the same direction, and are mutually shieldable. With a mass similar to JWST (the larger diameter is offset, as a mass driver, by the lighter mirror segments and lower requirements for structural stiffness) injection into a halo orbit at L2 follow very similar propulsion requirements.

Figure 10: This figure shows the nominal JWST-like architecture for SAFIR, in which the telescope is linked to the spacecraft and sun shields at fixed orientation. This baseline was used for the optical telescope assembly design, and the thermal design, and maximizes the reuse of JWST technologies. As done for JWST, the five-layer sunshade is deployed using extending booms and tip spars. Given that SAFIR does not need diffraction limited performance at >40μm as does JWST, structural, as well as mirror surface finishing economies should be realizable.

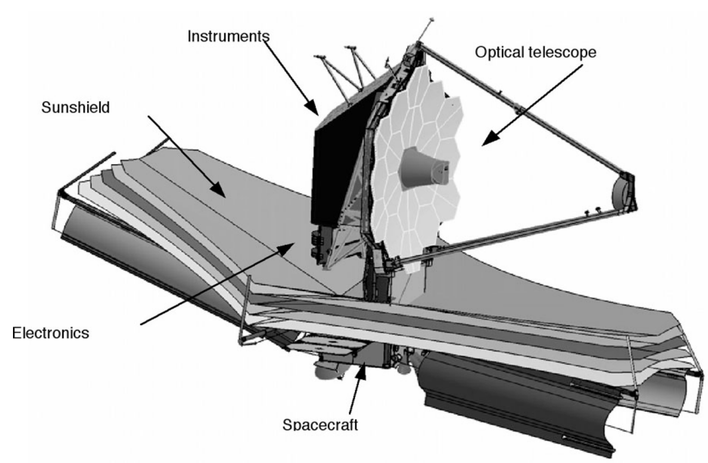
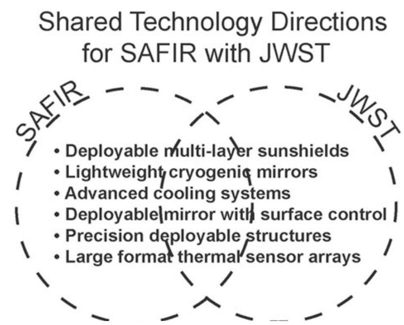


Table 1 - SAFIR Mission

Primary mirror diameter	10 meters
Telescope temperature	Allowing cosmic bknd-limited
Wavelength coverage	30 to 800 microns
Angular Resolution	1" at $\lambda \leq 40\mu m$, diff. lim @ $>40\mu m$
Science instrumentation	Camera and Spectrographs
Mission duration	5-10 years
Orbit	Earth-Sun L2
Planned launch year	2020 (approximate)
Pointing Stability	1'' 3s knowl; 0.001''/sec drift



Although SAFIR, like JWST, is baselined as an autonomously deployed telescope operating at the Earth-Sun L2 venue, consideration has been given to the possibility of using Exploration architectures – human and robotic, for expanding the basic mission of SAFIR, and enabling greater science potential. In particular, the use of humans and robots for servicing and maintaining SAFIR, much as is now done for the Hubble Space Telescope, has been reviewed by a number of authors (see Lester, Friedman, and Lillie 2005, and Lillie 2006).

The optical telescope assembly design for SAFIR was considered in great detail from the perspective of JWST, detailed designs were contributed by Ball Aerospace. The design trades emphasized a long-wavelength, wide FOV imaging telescope. The trade started looking for a 0.5º diffraction-limied FOV at 30µm with a 10m aperture. A flat field was considered desirable, but not required. A large number of formal designs were proposed over the past several decades were examined. . Consideration of alternative optical designs that specifically minimize out-of-beam pickup is ongoing (Goldsmith et al 2006).The study soon focused on four general types: Cassegrains, Gregorians, off-axis TMAs and on-axis four mirror systems with mirrors only in the neighborhood of the primary or secondary. The four mirror designs were elminated because of the large secondary mirror it would require. The Gregorian was eliminated because of length, compared iwht the Cassegrain. The Cassegrain offered stray light advantages that the TMA did not. Given this set of rough trades, we converged on a satisfactory Cassegrain design

SAFIR Cassegrain
Baseline Telescope Parameters
On-axis Cassegrain IV
with a conic primary and aspheric secondary
(hyperbola-hyperbola)

Diameter:	**10 meters**
F-Number:	**f / 7.500**
Focal Length:	**75000 mm**
Back Focal Length:	**2800 mm**
DL FFOV @ 30 µm:	**0.50 deg**
Vertex Separation:	**11237.2 mm**
Focal Plane:	**Curved, Rc = - 2766.3 mm**
Linear Obsc Ratio:	**0.25 (minimum ~ 0.217)**
Primary F-Number:	**f / 1.400**
Secondary F-Number:	**f / 1.709**

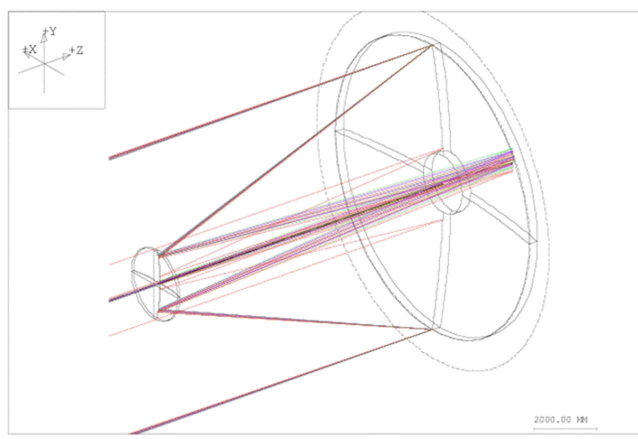


Figure 10: The optical prescription for the Cassegrain layout. This design requires fewer mirrors than other designs, and ease of fabrication and alignment. Assuming the primary is imaged on the secondary, the secondary can be used as a chopper. The resulting spot diagram (for a flat field focal plane) is shown. A curved focal plane allows diffraction limited performance over a slightly larger field of view.

The large primary mirror for SAFIR makes for special challenges. We have assumed a segmented primary as for JWST, and several options for folding the primary mirror into a launch shroud and deploying it were considered. The segments are assued to be semi-rigid, permitting ground testing at 1g before launch. A key trade was the number of segments versus segment size, as smaller segments are more easily contained in a launch shroud, while a larger number of segments requires a larger number of actuators and associated cabling for figure maintenance. A size range of 1.2-2m was adopted as a requirement on the individual mirrors. The primary mirror requirements were compared with the JWST baseline, and with the achievements of the Advanced Mirror System Demonstrator (AMSD) program. This comparison is summarized in Table 2 below.

Table 2 -- SAFIR Primary Mirror Requirements

Parameter	AMSD achievement	JWST baseline	SAFIR reqt	Units
Primary Diameter	NA	6.5	10	meter
Segment Diameter (FF)	~ 1.2	1.3	1.2 to 2	meter
Area	~ 1.25	25	50 to 100	meter^2
Mirror Areal Density	~ 12	< 30	7.5 to 15	kg/m^2
Assembly Areal Density	~ 18	< 50	12.5 to 25	kg/m^2
Diffraction Limit	~ 0.6	2	30	μm
Ambient Surface Figure	< 0.02	NA	NA	μm rms
Cryogenic Surface Figure	< 0.200	< 0.024	~ 0.25	μm rms
Wavelength Range	0.6	0.6 to 40	30 to 800	μm
Operating Temperature	30 to 300	< 50	< 10	K
Areal Cost	~ $ 4M	$3 to $4M	< $500K	$/m^2
Production Rate	~ 0.05	> 0.5	> 2	meter^2/mo
Segment Stiffness	~ 180	> 250	> 200	Hz
Seg Dynamic Survival	NA	< 20	< 20	G's

Technically, JWST mirrors could be used for SAFIR, but these were chosen to be fabricated out of beryllium in order to provide additional stiffness that would handle launch loads and on-orbit stability. But beryllium is extraordinarily expensive, and the much larger area of SAFIR would amount to serious cost burden. It is likely that following AMSD technology developments for new mirror materials, such as silicon carbide, magnesium graphite, glass foam, or gas infusion glass will be viable candidates. While these materials are not as stiff as beryllium, the ten times lower figure tolerance on SAFIR mirrors compared with JWST suggests that they will be suitable. While JWST mirrors have areal density of approximately 15 kg/m^2, AMSD has demonstrated mirrors much lower than this and with mirror figures preserved to well within the SAFIR figure requirement at cryogenic temperatures. Currently, no mirror technology has been completely demonstrated (size, areal density, cryogenic performance) that can enable SAFIR at an affordable cost and schedule, but concerted efforts are being made through NASA and DoD via SBIR that show great promise for SAFIR, including scalability to 2m diameter.

One of the immediate differences between SAFIR and JWST is that SAFIR needs to be cooled well below 10K, ideally to 4K, compared to the ~40K temperature baselined for the JWST telescope. This is a reasonable practical limit for a telescope relying on passive cooling alone. The dominant heat load on SAFIR is from the Sun. It's light must be attenuated by about six orders of magnitude in order to keep the telescope cold. We have baselined a JWST-like sunshade. An additional inner layer was orignally added to the sunshade, mounted on a 15K actively cooled stage. This layer reaches an equilibration temperature of about 15K across the surface, reducing radiative load on the cold telescope to an acceptable level. An additional refrigerator (likely a set of Continuous Adiabatic Demagnetization Refrigerators – CADRs) cools the telescope and the instrument volume to a nominal temperature of 4K.

Optiomization of passive cooling is essential to the performance of SAFIR. The fundamental design of the main sunshield is very similar to JWST – five layers of highly reflective material in a 5º opening angle V-groove configuration with a total extent of 40x20m. The optical properties of this shield are of paramount importance to the thermal performance. We baseline a sun-facing surface of the warmest shield to be coated with silver-teflon, which provies the best available ratio of solar absorbtivity and thermal emittance. Degradation in solar reflectivity has been evaluated, and results in an increase in temperature of the coldest shield by of order 2-3K over the five year nominal lifetime of the mission.

Building on the JWST thermal engineering, we considered carefully shield designs that could offer higher performance. In particular, we have evaluated alternative designs for coupling the observatory to the spacecraft through the sunshield that allows a minimum heat transfer through it. In particular, the sunshield carry-through structure is needs to be stiffer to carry launch loads than for operational loads, and following launch such launch load paths could be detached. We consider a mechanical strut system that extends form the spacecraft bus through the sunshield in the form of a ring-terminated deployable hexapod. Using standard composite materials (GFRP, CFRP) such a strut system would strongly minimize heat transfer into the inner shield from the spacecraft. Combined with suitably multiplexed control lines to the instrument on the back of the telescope, total parasitics can, in principle, be kept substantially smaller than for JWST. On this basis, our models show that with these upgrades on the baseline JWST design, no active cooling of the shield may, in fact, be entirely necessary.

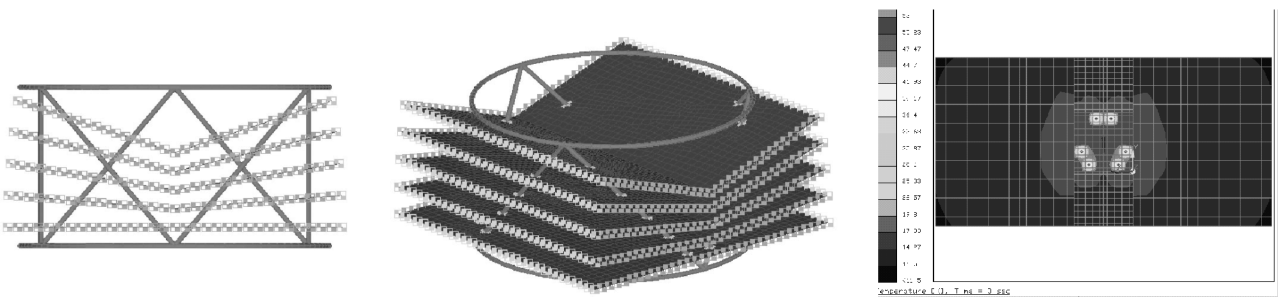


Figure 11: The notional low-parasitic composite hexapod structure for coupling the SAFIR telescope through the radiation shields to the spacecraft is shown at left and center, showing how the deployable structure penetrates the five-layer shield. In the rightmost panel, the results of the thermal modeling are shown as a temperature distribution for the innermost shield. While most of the shield is around 10K, very small spots, corresponding to the locations where the hexapod struts penetrate the shield are somewhat warmer, of order 30K. The area of these penetrations is so small, these spots do not add substantially to the telescope thermal loading.

As shown in Figure 11 above, our models indicate that sheild temperatures of 15K or less can be reached passively, with appropriate design. An important consideration is the emissivity of the inner-face of the inner shield. A low emissivity results in a higher mean temperature of ~13K, but with a small amount of power loading on the telescope. A high emissivity results ina lower mean temperature of order 7K, but with larger power loading on the telescope because of power absorbed by the zodiacal background. From a scattered light perspective, both contribute similar amounts at 200µm, which is the darkest part of the infrared sky.

As evident from Figure 9 above, however, lower temperatures for the telescope structure are strongly enabling in terms of observatory sensitivity, and active cooling will be required to get there, at least at the operational location of Earth-Sun L2. Prior telescopes whichy have required cooling to such temperatures (e.g. ISO, Sptizer, etc.) have all been much smaller, and cooled by expendable cryogens. This approachis impractical for a 10m SAFIR, and the life-limiting use of expendable cryogens is unacceptable. Development of mechanical cryocoolers capable of providing 4K is an enabling technology for SAFIR. The Advanced Cryocooler Technology Development Program (ACTDP) has produced promising results, but more work is needed to prove their usability at lower temperatures and remote cold heads. A decision has been made for JWST to use a remote cold head cooling system for MIRI, and such engineering design is expected to provide significant relevant experience to SAFIR. A notional plumbing arrangement for the SAFIR primary mirror is shown in Figure 14 below.

Deployment of the fluid loop could occur in the same way as for the mirror segment wiring. Thermal modeling has already shown that at least 1m diameter segments of relevant mirror substrate materials will posess adequate thermal conductance at low temperatures that only a single heat excchanger on each segment will be required.

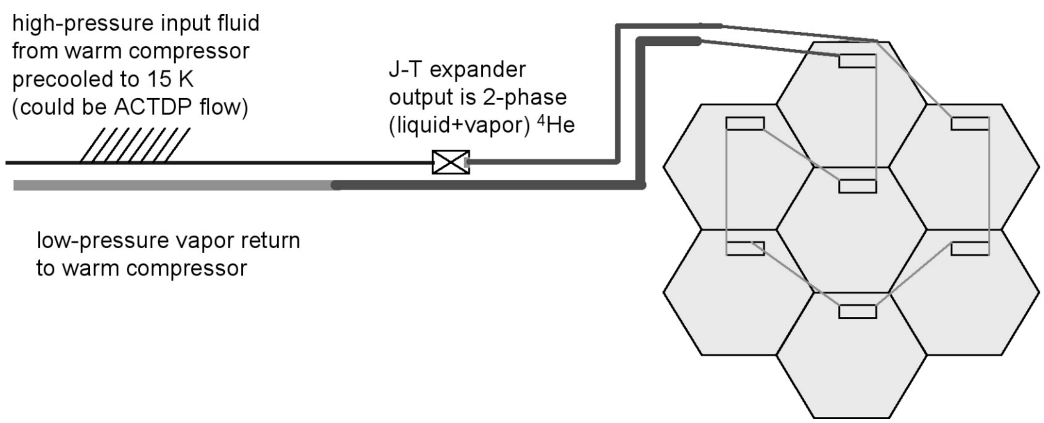


Figure 12: Schematic diagram of forced flow cooling loop for the SAFIR telescope. This involves flow with precooling, J-T expansion, and liquid evaporators. The system is coupled to individual mirrors on the segmented primary.

The mechanical coolers for SAFIR will demand a significant fraction of the 800-1000 W of cooler compressor and electronics power as waste hear. The SAFIR study team has developed a strategy for doing this using a series of heat pipes to transport the cooler heat through flexible bellows to a deployable radiator system on the spacecraft bus, oriented perpendicular to the Sun-line. Variable conductance heat pipes are self-regulating, and would eliminate the need for suplpemental power when the coolers are not operating.

Packaging of SAFIR into an existing launch vehicle fairing is major design constraint for the observatory. It was found in the earliest SAFIR studies that a simple trifold JWST-type packaging arrangement could allow a 10m version to fit into a 7.5m fairing, with is being considered as an upgrade path for EELV vehicles. Since SAFIR is very much volume constrained, rather tha weight constrained, this is a credible option. It is noteworthy the the presently available 5m diameter fairings can accomodate an 8.4m SAFIR in this way. A novel architecture that was considered by the study team was one developed for early JWST studies, using a rotational-translational joint to unforld stacked mirror segments. This Rotating Stack Deployment System was demonstrated in the 1989-1992 studies for NGST by TRL (now Northrop-Grumman). In this system (see Figure 13 below), the mirror elements are stacked one above the other for launch, and then deployed in orbit by rasing the mirror stack, rotating it 120º, and lowering it so the bottom segment could be latched to the central hex. This process is repeated until the seven segments are all deployed. Simple design studies show that in such a structure the dynamical performance necessary can be achieved. The rotational deployment system is extensible to larger numbers of mirror elements, though the deployment risk obviously increases with complexity. It is noteworthy that such a stacked mirror design offers more resistance to launch loads than a chord-fold design .

In addition to the rotational deployment of the primary mirror, a novel concept for observatory deployment has also been advanced by Northrop-Grumman. The JWST telescope is coupled in fixed orientation relative to the sun shield, such that the telescope is pointed by moving the entire structure. Since the solar shield must stay at least roughly perpendicular to the sun-line, and cannot conveniently be greatly oversized, such an arrangement put strong constraints on the observatory field of regard. The possibility of deploying SAFIR on an articulated 8-10m long positioning boom (see Figure 14) is one that is highly enabling in several respects. First is that the telescope can have a large field of regard, as the telescope can point anywhere as long as it stays in the shadow of the sun shield. The boom allows the SAFIR telescope to be farther from the inner shield, is a lower thermal conductivity link with the spacecraft than the support platform for JWST. Both of these lower the thermal load of the spacecraft and residual emission from the sun shield on

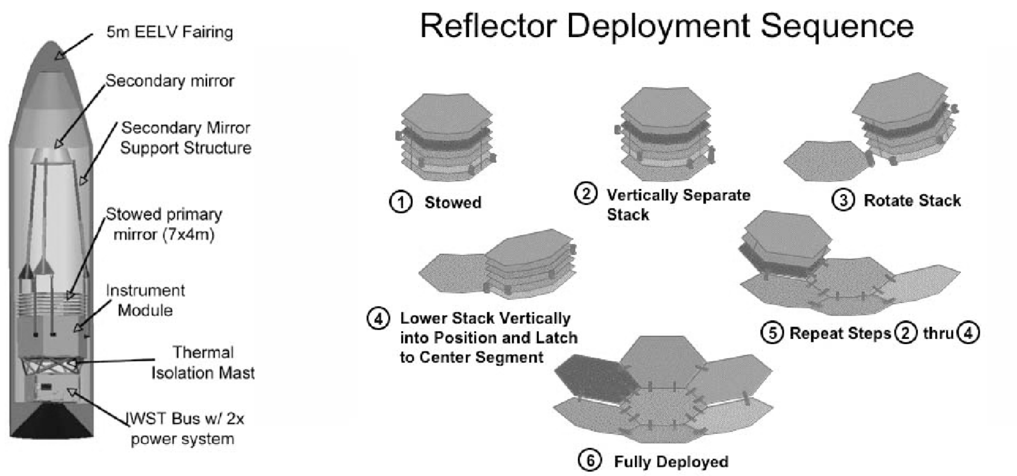


Figure 13: Rotationally stacked mirror deployment results in a high strength, compact launch package for SAFIR. The sequence for mirror deployment is shown at right.

reaction wheels, possibly relaxing requirements on on-board propellants for orientation management and station keeping. With a large sunshield, the radiation pressure on JWST, for example, is an important force on the observatory, introducing torques that have to be managed with propellant.

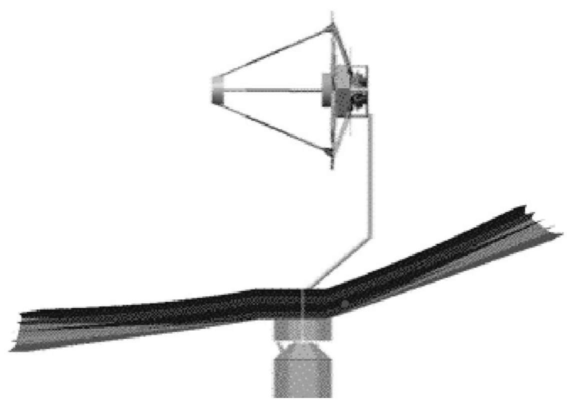


Figure 14: Boom deployment for SAFIR as an alternative option. The telescope is coupled to the spacecraft on an articulated boom that is used for pointing and positioning. In this design, the sunshield stars exactly perpendicular to the Sun, and the telescope is pointed while staying in its shadow. The telescope is strongly thermally decoupled from the shield.

4. SAFIR SCIENCE INSTRUMENTS

A key aspects of the SAFIR mission will be the focal-plane instruments. The exquisite sensitivity made possible with the large cold telescope must be matched with cameras and spectrographs accommodating high-sensitivity, large-format far-IR / submillimeter arrays from approximately 30-1000 µm. Here we describe our philosophy for SAFIR instrumentation, the desired measurement goals, and the strawman instrument suite that can meet SAFIR's needs.

1. High efficiency instruments and significantly improved infrared detectors are required in order to take full advantage of the low IR background offered by the SAFIR Observatory.

The fundamental sensitivity limit for a cold telescope in space is photon noise from the diffuse astrophysical backgrounds: thermally emitting dust in the solar-system, the Galaxy, and the aggregate of dusty galaxies at all redshifts. Detectors for SAFIR must have intrinsic noise which is comparable or below these very low photon NEPs. The requirements for the continuum imaging are within the achieved sensitivities of existing devices running in the laboratory, but for dispersive spectroscopy, the requirements exceed the demonstrated sensitivities of any devices. Fortunately, there are several detector approaches which are promising for meeting SAFIR's needs -- some proven in flight, others in development.

2. Astrophysical capability is increased with large-format arrays and high-throughput instruments to accommodate them.

Detector array formats are also rapidly evolving with new technologies and approaches, and SAFIR will have the potential to make a huge leap forward here. While FIR arrays for Spitzer and Herschel have 30--1000 elements, typically individually assembled, the technology for SAFIR will likely allow arrays with 10,000 or more elements through the use of lithographed detector and multiplexer architectures. Such array sizes are under construction for ground-based submillimeter instruments such as the SCUBA-2 camera.

3. Spectral information is crucial in the far-IR, and sensitive spectroscopy is a natural niche for the single-aperture telescope.

Observations with SAFIR in the continuum will quickly be limited by source confusion, especially at the longer wavelengths. Spectroscopy provides a third dimension to distinguish multiple sources in an otherwise confused field, and thereby allows probing much deeper than in the continuum. Direct-detection spectroscopy takes two approaches: a low-resolution spectrometer (LRS) suite, which provides R~100 along with some imaging capability, and a moderate-resolution spectrometer (called HRS) suite which provides R~2000. R~100 provides sensitivity to spectral-energy distributions and the broad solid-state dust features, while R~2000 provides sensitive capability for spectral lines in distant galaxies.

SAFIR's science goals are broad, and require multiple capabilities: large field imaging across the entire wavelength band for deep surveys and maps; low resolution spectroscopy at short wavelengths to probe broad continuum and solid state features in debris disks; and medium resolution sensitive spectroscopy for measuring extragalactic emission lines from cosmologically distant sources. The measurement goals for SAFIR's direct direct-detection instruments are generated assuming optimistic detector array development and are presented below. Spectral regions are split up typically by octaves, and a detector technology along with the focal-plane assembly, pixel size, and operating temperature is listed for each range. An important constraint is the size of the instruments: the entire suite is must fit in to SAFIR's fiducial instrument chamber – an assumed 4 m diameter by 3 m tall enclosure located directly behind the Optical Telescope Assembly. The instruments for SAFIR are summarized in the table below.

The initial conceptual design for the cameras is straightforward, based on the NICMOS (HST) imaging channels (confocal parabolas and a field mirror to relay the pupil) and the concepts for both sub-modules – Cam1 and Cam2 – are similar. As a result of what we consider to be relative optical simplicity, we present only a top level concept. The camera concept consists of a field separator at the telescope focal plane, a dichroic separating the Cam1 and Cam2 spectral regions, a field mirror, collimator, camera mirror, and fold mirror, and the arrays. The backends of Cam1 and Cam2 are similar in concept but slightly different in detail.

Our SAFIR short wavelength LRS concept is based on a ruled reflection grating and has three sub-bands (LRS1a, LRS1b, and LRS1c) covering the 20-100 µm regime at a resolving power of 100. The three modules are first order, long slit spectrometers with pre-slit integral field slicing units**.** The first optical element is included to relay the image (for packaging purposes) onto the dichroic beam splitter assembly, which separates the incoming light into three sub-bands. The three fields of view (FOVs) of the three sub-bands are co-boresighted to provide instantaneous broadband coverage on the sky. After spectral separation, an image slicer assembly re-packs the area FOV into line pseudo-slits for subsequent spectrometer dispersion. At this location, magnification can be changed if required. The properties of the conceptual camera and direct detection spectrometers are listed in Table 3 below.

The moderate/high-resolution spectrometer (HRS) modules employ ruled Echelle reflection gratings. Initial concepts for the shorter bands (1a, 1b, and 1c) were long slit spectrometers using an integral field spectrograph approach with a pre-slit slicing mirror assembly. There is a coarse Echelle for the main dispersion and grating cross-disperser for order

Table 3 - SAFIR Focal Plane Direct Detection Instruments

Instrument	Wave-length range (um)	Spectral resolving power (R)	Field of View (FOV) (arcsec)	IFOV (arcsec)	Detector physical size (um)	FPA format NxN	FPA type	FPA temp (K)	Comments
CAM	20 - 600								Simultaneous image in two fields of different size
CAM1	20 - 100	R~5	60x60	0.47	500	128x128	Ge:Ga?	<2?	Plus six postion filter wheel
CAM2	140 - 600	R~5	240x240	1.88	1000	128x128			Plus six postion filter wheel
LRS	20 - 100								Two simultaneous integral
LRS1a	25 to 40	100	6 x 6	0.4	40	< 512 by 512	Si:Sb	4?	field (image slicer)
LRS1b	35 to 70	100	9 x 9	0.7	1000	128 x 128	bolometers	0.1	spectrographs
LRS1c	60 to 100	100	12 x 12	1	500	128x128	Ge:Ga	1.8?	
HRS	20 - 720								
HRS1a	20 to 40	2000	18 x 18	0.4	40	< 512 by 512	Si:Sb		
HRS1b	35 to 70	2000	18 x 18	0.7	1000	8 by TBD	bolometers	0.1	
HRS1c	60 to 120	2000	18 x 18	1.2	500	8 by TBD	Ge:Ga	2?	
HRS2a	120 to 240	2000	18x96	2.4	1000	8 by TBD	bolometers	0.1	
HRS2b	200 to 400	2000	18x96	4	1000	8 by TBD	bolometers	0.1	
HRS2c	360 to 720	2000	18x96	7.2	1000	8 by TBD	bolometers	0.1	

separation, followed by a wide field of view camera re-imaging optics assembly focusing the light onto the detectors. At present, the optical models assume a first order perfect lens for the camera. As the design matures, this will be replaced with a true wide-field all-reflective camera system, likely a three-mirror antistigmat (TMA) or Schmidt camera.

Members of the SAFIR team are demonstrating a more compact technology. The Waveguide Far-IR Spectrometer (WaFIRS) uses a single curved grating in a parallel-plate waveguide to provide a spectrum of a point source, as shown in Figure 15. The concept benefits from the fact that at long wavelengths, the grating surface can be machined which allows for good optical performance at fast F#, and without the need for the additional optics that a ruled grating requires. Limiting the spatial extent to a single point source, propagation in the spectrometer can be put into waveguide, and the system becomes entirely two-dimensional. SAFIR science team members are prototyping a WaFIRS system for ground-based observations in the 1-1.6 mm band. Extensibility to shorter wavelengths appears straightforward.

The moderate/high-resolution spectrometer (HRS) modules employ ruled Echelle reflection gratings. Initial concepts for the shorter bands (1a, 1b, and 1c) were long slit spectrometers using an integral field spectrograph approach with a pre-slit slicing mirror assembly. There is a coarse Echelle for the main dispersion and grating cross-disperser for order separation, followed by a wide field of view camera re-imaging optics assembly focusing the light onto the detectors. At present, the optical models assume a first order perfect lens for the camera. As the design matures, this will be replaced with a true wide-field all-reflective camera system, likely a three-mirror antistigmat (TMA) or Schmidt camera.

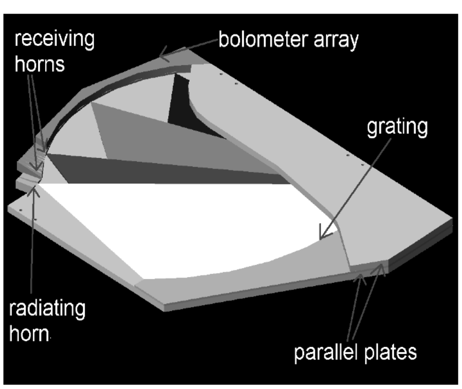


Figure 15: Waveguide far-IR spectrometer (WaFIRS) concept. Light propagates in a 2-D parallel-plate waveguide, and is diffracted and focused by a custom machined grating surface on one side. Detectors are arrayed on the other side, and span a bandwidth of 1:1.6 or greater.

The use of heterodyne spectrometers on SAFIR is justified somewhat differently. All heterodyne systems suffer quantum noise--in the THz regime, this is orders of magnitude greater than the photons noise from the astrophysical backgrounds, so a cold SAFIR is not required for optimal heterodyne use. Nevertheless, heterodyne spectroscopy is the only way to get very high velocity resolution (~ 1 km/s) required for unique galactic astrophysics experiments such as probing dynamics of cloud collapse and star formation. While heterodyne spectroscopy does not drive the thermal management of SAFIR, it is highly enabled by the size of the collecting area. Table 4 below outlines a potential suite of heterodyne instruments for SAFIR.

Table 4 - SAFIR Heterodyne Instruments

Instrument	Wave-length range (um)	Spectral resolving power	Field of View (FOV) (arcsec)	IFOV (arcsec)	Detector physical size (um)	FPA format NxN	FPA type	FPA temp (K)	Comments
HET	25 - 520								Five Fields with field sharing
HET1	20 to 40	100,000	4	1.65	f/1.5 beam onto the detector	2 x 2 array nearly close packed	Hot electron bolometers (HEBs)	0.1	Sparsely sampled array of single moded detectors with each pixel being one diffraction limited beamwidth (2 lambda / D)
HET2	40 to 80	100,000	8	3.3	f/1.5 incoming beam onto the detector	2 x 2 array of bolometers nearly close packed	Hot electron bolometers (HEBs)	0.1	Sparsely sampled array of single moded detectors with each pixel being one diffraction limited beamwidth (2 lambda / D)
HET3	80 to 160	100,000	16	6.6	f/1.5 incoming beam onto the detector	2 x 2 array of bolometers nearly close packed	Hot electron bolometers (HEBs)	0.1	Sparsely sampled array of single moded detectors with each pixel being one diffraction limited beamwidth (2 lambda / D)
HET4	160 to 320	100,000	32	13	f/1.5 incoming beam onto the detector	2 x 2 array of bolometers nearly close packed	Hot electron bolometers (HEBs)	0.1	Sparsely sampled array of single moded detectors with each pixel being one diffraction limited beamwidth (2 lambda / D)
HET5	300 to 520	100,000	64	22	Make an f/1.5 incoming beam onto the detector	2 x 2 array of bolometers nearly close packed	Hot electron bolometers (HEBs)	0.1	Sparsely sampled array of single moded detectors with each pixel being one diffraction limited beamwidth (2 lambda / D)

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5. SUMMARY

We have presented the highlights of the SAFIR (Single Aperture Far Infrared) Vision Mission study, an effort to characterize and conceptualize a flagship infrared and submillimeter space astronomy mission. While SAFIR is larger than any observatory yet built, the architecture can be considered a slight extrapolation on that now being baselined for the James Webb Space Telescope. While slightly larger and colder, operation in the infrared makes the optical tolerances on SAFIR at least an order of magnitude easier than for JWST. We find that with appropriate technology investment, this 10m-class low temperature telescope is realizable, offering orders of magnitude of sensitivity greater than presently achievable, and addressing high priority science questions. SAFIR is an observatory that will take full advantage of the steep trajectory of technology development for infrared sensors, as well as for deployment and thermal management of large structures.

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