An Engineering Concept and Enabling Technologies for a Large Single Aperture Far-Infrared Observatory (SAFIR/FAIR)

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ABSTRACT
"To take the next step in exploring this important part of the spectrum [30-300μm], the committee recommends the Single Aperture Far-Infrared Observatory (SAFIR)." – *Astronomy and Astrophysics in the New Millennium, 2001*[1]. In response to this recommendation, we have undertaken a study of the enabling technologies for a large single aperture far-infrared telescope such as SAFIR. A broad list of science investigations was produced and used to generate an explicit list of science requirements, from which top-level engineering requirements were derived. From these requirements, we developed a conceptual design for the SAFIR observatory based on NGST's current designs. A detailed analysis has been made of the changes and technologies necessary to produce SAFIR. Crucial technologies requiring innovation include lightweight deployable optics, cryogenic cooling of optical elements and instruments, and large arrays of sensitive detectors. Cryogen-free refrigeration technologies are necessary for SAFIR's long mission lifetime, and will have to provide significant (~100mW) cooling power at 4K to cool the mirrors while providing very low temperatures (~50mK) for detector arrays. The detector arrays require wide wavelength coverage, thousands of continuum elements, and compatibility with broadband and spectroscopic instruments.

Keywords: SAFIR, FAIR, NGST, far-infrared, submillimeter, cryogenic optics, bolometer arrays.

1. INTRODUCTION
In this decade, we will see the launch of three new observatory-class far-infrared facilities: SIRTF, SOFIA, and the Herschel Space Observatory, each of which will provide substantial advances in sensitivity and/or angular resolution. Each, however, is also far from what can be envisioned in aperture and sensitivity. The astronomical community has recommended a larger, more sensitive observatory variously called the Filled Aperture Infrared (FAIR) Telescope or, more commonly, the Single Aperture Far-Infrared (SAFIR) Observatory. These recommendations recognize the exciting science opportunities offered by the promise of a dramatic increase in sensitivity and angular resolution of a large, cryogenically cooled observatory facility in the far-infrared spectral region.

The National Academy of Sciences has endorsed the Single Aperture Far-Infrared Observatory in its Astronomy Decade Review as a successor to NGST. SAFIR is a 10m-class far-infrared observatory that would begin full-scale development late in this decade, for launch in ~2015. Its large aperture, operating temperature of 4K, and capable instrument complement would be optimized to reach the natural sky confusion limit in the far-infrared with diffraction-limited performance at $\lambda \approx 40\mu m$. SAFIR proposes to use state-of-the-art technology in optical engineering, cryogenic cooling, mechanical engineering, and the most recent detector technology improvements to enable an observing speed improvement over present-day missions of order 100,000.

2. SCIENCE MOTIVATION
Numerous science questions are addressable – in some cases uniquely – by observations in the far-infrared spectral region[2]. A far-infrared optimized NGST-class facility promises a dramatic increase in sensitivity and angular resolution for tackling these science questions. SAFIR's science goals are driven by the fact that youngest stages of almost all phenomena in the universe – from the assembly of galaxies in the early Universe to the formation of planets in the present – are shrouded in dust that obscures visible, ultraviolet, and near-infrared light. These phenomena can be studied by their emission from cool dust and gas that emits strongly in the mid-infrared to millimeter, at wavelengths of 20μm to 1mm.

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The earliest stages of galaxy formation appear to result in powerful rest frame far-infrared emission indicative of substantial metal enrichment early in the history of the universe[3,4]. The combination of strong dust emission and large redshift (up to z~5) of these galaxies means that they can only be studied in the far-infrared and submillimeter where SAFIR will provide the sensitivity and angular resolution to perform imaging and spectroscopic studies in detail. As the universe evolves, the most active galaxies appear to be those whose gaseous disks are interacting in violent collisions, and whose central black holes are the most active. The details of merger and AGN phenomena are obscured to shorter wavelength observatories by the large amounts of dust in the interstellar medium of the system. Spectroscopic observations with a sensitive far-infrared telescope will unambiguously study the driving energy sources of these galaxies.

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.

To convert these science goals into a set of observatory requirements, we have developed the following list of observations and what they require.

1.0 Formation and Evolution of AGNs

- 1.1. Detect H_2 lines at 17 & 28.2 µm at redshifts up to z~20 (early cloud collapse) with line strength of 10^{-23} W/m^2
  - 1.1.1. Line strength implies telescope diameter of >8m
  - 1.1.2. Spectroscopy of R~1000 at 20-600µm
  - 1.1.3. Broadband-tunable spectroscopy a necessity.
- 1.2. Determine continuum emission/absorption at long wavelengths for L>10^{11} $L_\odot$ in order to discriminate between AGN and Starburst phenomena.
  - 1.2.1. Brightness implies confusion limited observations requires ~3" resolution at 100µm, hence a diameter of 8.5m minimum.
- 1.3. Detect fine structure lines of Neon at 12.8/15.6/14.3µm at $1 \leq z \leq 5$. Strength is only ~10^{-21} W/m^2 at z=5.
  - 1.3.1. Line strength requires >3m to detect at 10σ
  - 1.3.2. Spectroscopy of R~3000 at 25-100µm
- 1.4. Achieve sufficient resolution to detect and identify galaxies: confusion limit at 60µm sets requirement of about 2" resolution.
  - 1.4.1. Diameter >7.5m; diffraction limited at λ>60µm

2.0. Emergence of Stars and Galaxies

- 2.1. Determine reddening corrections for highly redshifted objects
  - 2.1.1. Broadband spectroscopy for 20-100µm
- 2.2. Measure star formation rate at high redshift by total bolometric luminosity.
  - 2.2.1. Best traced by FIR dust emission; wide field imaging at $60 \leq \lambda \leq 600$µm
- 2.3. Determine evolution of PAH emission at $1 \leq z \leq 5$
  - 2.3.1. Features will have fluxes greater than 0.1µJy or 10^{-20} W/m^2. This requires a low-resolution (R~50) spectrometer covering $20 \leq \lambda \leq 100$µm.
- 2.4. Detect dust from L* galaxies out to z=5.
  - 2.4.1. Flux is such that, neglecting confusion, galaxies can be seen in 1min observations with a >5m telescope.
  - 2.4.2. Field of view >1' on a side, in order to find objects in a field.
- 2.5. Confusion noise low enough to see dust emission at z=5 for L* galaxies.
  - 2.5.1. The detection can be made at any of several wavelengths with appropriate sensitivity; this works out to be ~10m diameter (wavelength insensitive).
  - 2.5.2. In order to meet confusion noise in a reasonable amount of time (e.g., 10ks), telescope temperature must be cold enough to permit confusion-limited observations. Spectroscopy will drive the sensitivity most strongly; to be below natural sky backgrounds, the telescope must be cooled to <4K.

3.0. Dynamical & Chemical Evolution of Stars and Galaxies

3.1. Diagnose the chemical evolution of metals with tracers such as the 158μm line of C^+, the 122μm & 205μm lines of N^+.

3.1.1. Requires R~3000 spectroscopy for $100 \leq \lambda \leq 800$μm.

3.1.2. Field of view >1'

4.0. Birth of Stars and Planetary Systems

4.1. Provide imaging of ≤100AU at 100pc at 40μm.

4.1.1. Resolution implies diameter 10m, diffraction-limited at $\lambda \geq 40$μm.

4.1.2. Mid-IR imaging camera with 1" resolution, 1' FOV.

4.2. Trace gas cooling lines from H_2O (25-180μm) OI (63μm and 145μm) and CO *J*>6 (170-520μm).

4.2.1. High resolution (R>10,000 or 30km/s) spectroscopy covering 20-600μm.

4.3. Observe infall/outflow from collapsing clouds

4.3.1. Resolution at R~100,000 (3km/s).

5.0. Evolution of Planetary Systems and the Origin of Life

5.1. Detect Kuiper belt objects; measure albedo and temperature

5.1.1. Broadband, wide-field imaging at 60-200μm. Wide field ought to be >1' at diffraction-limited resolution.

5.2. Study mineralogy of nearby debris disks

5.2.1. 20-35μm spectroscopy at ~1" resolution; R~200

3. OVERALL SAFIR CONCEPT DRIVERS

From the science requirements above, other basic SAFIR engineering requirements have been derived. Many of these derived parameters are summarized below.

Telescope parameters

- Approximately 10m aperture diameter – Req 2.5
- Diffraction limited at greater than 40 microns – Req 4.1
- Temperature of telescope ≤8K (≤4K in order to yield optimum sensitivity for spectroscopy)
- Sufficiently low stray light to avoid increasing the overall background above dark sky levels.
- Field of regard of order steradians

Instrument parameters

- Instrument A: "CAM": Broadband camera with spectral resolution of R~5 covering 20 to 600 microns, field of view ~1-4' – Reqs 2.1, 2.1, 5.1
- Instrument B: "LRS" Low resolution spectrometer with spectral resolution of ~100 covering 20 to 100 microns, field of view ~10'' (req 4.1 drives this), Reqs 2.1, 2.3, 5.2, 4.1
- Instrument C: "HRS" Moderate resolution spectrometer with spectral resolution of ~2000, covering 20 to 800 microns. Reqs 1.1, 1.3, 3.1. Field of view ~1' (req 3.1 drives this)
- Instrument D: "HET" High resolution spectrometer with spectral resolution of ~100,000 covering 25 to 520 microns, field of view at least 1 beam on the sky, possibly with beam steering mirror to fill in the array – assuming a single-moded feedhorn-coupled heterodyne spectrometer. – Req 4.3 and 4.2

Mission parameters

- Located in thermally stable orbit such as L2
- 5 year minimum lifetime, 10 year design lifetime
- Observation modes to include pointed observations and slow slew scans
- Absolute pointing control to within 1"
- Differential pointing knowledge to within 0.1"

4. SAFIR MISSION DESIGN AND NECESSARY TECHNOLOGIES

The National Academy has recommended that a SAFIR design draw on NGST technology. Since this is the first SAFIR mission design, building on NGST provides the highest fidelity design on the shortest time scale, and is a suitable point of departure for other designs. A 10 meter diameter, 4K telescope with a far infrared instrument suite of three spectrometers and a broadband camera is challenging. An obvious question arises when the telescope and instrument parameters are studied: what of the NGST design and technologies might be re-used for the SAFIR observatory? This is a necessary exercise to pursue in order to show the feasibility of SAFIR and to lend credibility to the design, with its estimated parameters, cost, and schedule. We have developed a SAFIR conceptual design that is heavily based on many NGST designs. We think this approach makes sense, since NGST will spend a great deal of time and money making its design and technologies work in advance of SAFIR. It is expected that this approach has the potential to reduce SAFIR development time and costs significantly. Other concepts are also being pursued, some of which will be included, along with this concept, in a future report.

Since our current baseline SAFIR concept is an NGST-like concept, we must consider needed technologies and technology development with an eye on what NGST will already need to have completed prior to its launch. Below is a description of the SAFIR conceptual design (Figure 1), highlighting needed technologies, their development status today and the needed status prior to NGST launch. Several technologies – most notably the detectors and cryocoolers – will require developments specific to SAFIR and future far-infrared missions.

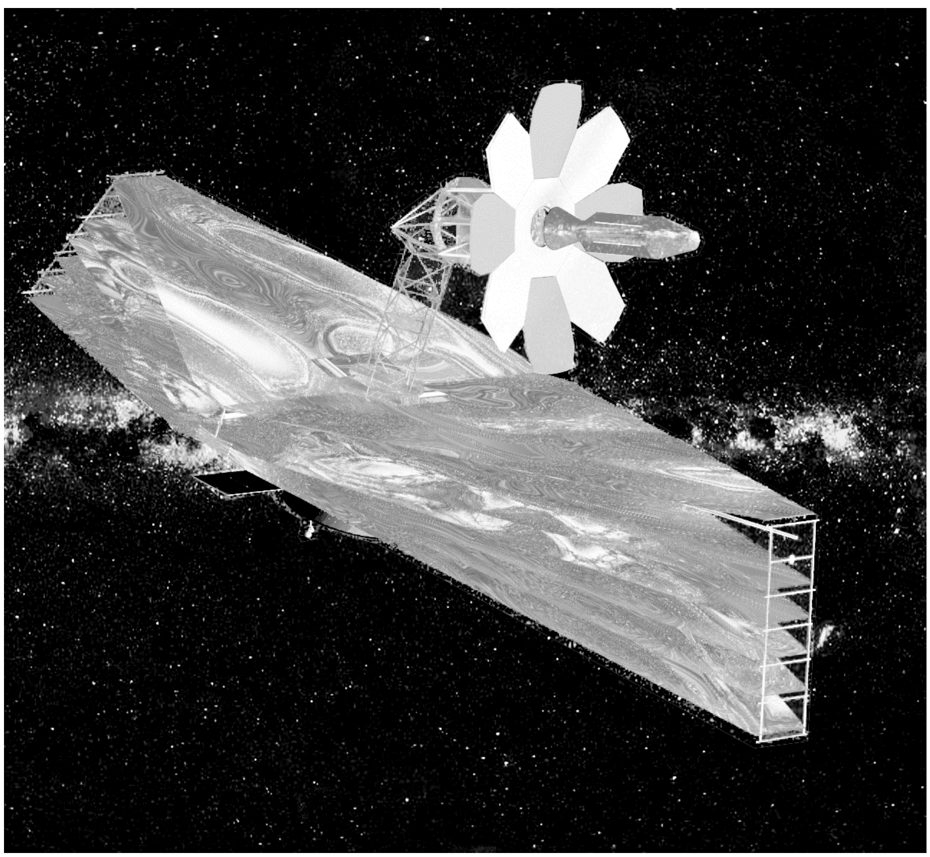

Figure 1. SAFIR concept

Telescope

The telescope is the most fundamental part of a large observatory. If the premise of an initial SAFIR concept is to take advantage of any designs and technologies of NGST which make sense for SAFIR, than we must allow for both of the NGST designs under consideration. One design segments the primary mirror into eight "petals" which fold forward and aft; the second design uses hinged folding sections. At the time of writing the primary contractor selection for NGST is still 2 weeks away. However, the concepts are not substantially different for our purposes and both can be used as a basis for a SAFIR mission.

Two primary SAFIR requirements that will differ from NGST parameters are the size of the primary mirror and the colder temperature required. With the exception of the caveat mentioned above, both proposed NGST approaches can be used to deploy a larger telescope. The basic SAFIR concept uses designs not greatly different from current NGST concepts to deploy the larger SAFIR telescope.

Telescope Technologies

The telescope requires development in three distinct technology areas to realize a lightweight, cryogenic 10m observatory. Most of these will be addressed by NGST developments. First, the method of folding and deploying the primary mirror will require careful mechanical design and substantial ground testing. SAFIR will use the same approach as NGST, but with a larger primary mirror diameter. If the mirror is segmented into petals, a 10m diameter mirror can be stowed into a launch vehicle fairing, but with notched regions around the outer edge. If the mirror is segmented into leaves, it will be constrained to a maximum size of around 9m, but with a completely filled aperture.

The second technology involved is the method of phasing and controlling the mirror surface, which requires sensitive detection of position errors and precision actuation of the segments. SAFIR's longer wavelengths make this task roughly ten times less precise, and the lower temperature will reduce thermal distortions that require NGST's mirror to be rephased periodically. It is likely that the mirror will need to be phased only once and left for the mission duration, but the actuators will probably still be needed as a contingency measure.

The third technology – and the most unknown – is the mirror surface material. Several options have been investigated for NGST, including glass face-sheeted composites, C/SiC, and Beryllium. SAFIR may be able to use polished aluminum as well, if the figure can be made smooth enough. NGST will choose a technology that works well at ~35K and is lightweight but stiff; SAFIR needs adequate thermal conductivity at 4K, and would prefer lower areal density materials at the expense of some stiffness. This will be investigated further after NGST has made its selection.

Several optical designs for the telescope are possible, but we are using an NGST-like three mirror telescope as a baseline, shown at left in Figure 2. This design is slightly off-axis, but features a flat steering mirror which can be used for fine pointing correction. The field of view of this design is large, permitting ample space for the four instruments (Figure 2, Right) and a focal plane star sensor (not shown).

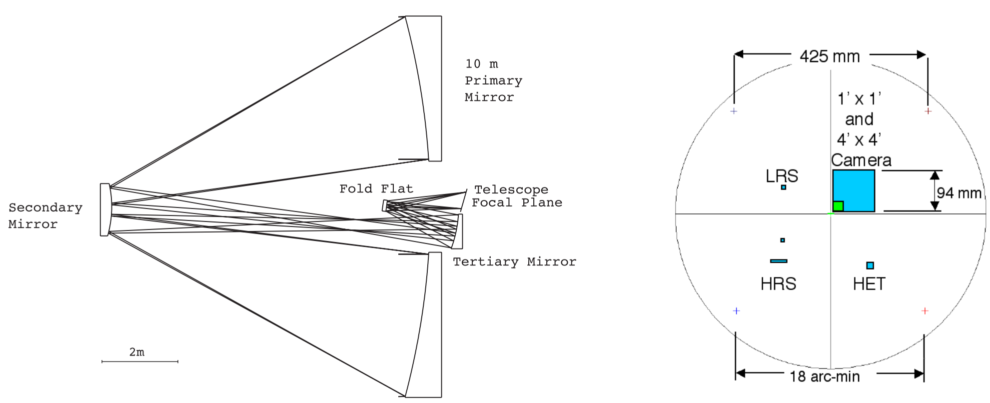

Figure 2. (Left) Optical layout of SAFIR telescope. (Right) Focal plane arrangement of instruments.

Instruments and Detectors

In order to cover the wide range of wavelengths and spectral resolutions, SAFIR may need four instruments, summarized below:

- Instrument A: "CAM": Broadband camera with spectral resolution of R~5 covering 20 to 600 microns, using simultaneous two-wavelength imaging with a 1' field of view (20-100μm) and a 4' field of view (140-600μm). A filter wheel with 6 positions will permit the selection of any band over the entire range.
- Instrument B: "LRS" Low resolution spectrometer with spectral resolution of ~100 covering 25 to 100 microns, using two simultaneous integral field grating spectrographs. The field of view will be about 6" on a side from 25-50μm and 12" on a side from 50-100μm.
- Instrument C: "HRS" Moderate resolution spectrometer with spectral resolution of ~2000, covering 20 to 720 microns. At short wavelengths (20-120μm), HRS features an integral field grating spectrometer with an 18" field of view, while at longer wavelengths (120-720μm), it will use a long slit grating spectrometer with an adjustable slit up to 18"x96" in size.
- Instrument D: "HET" High resolution spectrometer with spectral resolution of ~100,000 covering 25 to 520 microns. A heterodyne spectrometer is the most likely technology for this application, and would have a sparsely-sampled array of single-moded detectors with at least 2x2 format, each pixel being one diffraction-limited beamwidth. A beam steering mirror is used to fill in the array.

Instruments and Detector Technologies

It is unlikely that any NGST detector-related technology can be used for SAFIR with the exception of a 2μm camera for star tracking. In order to realize these instruments, the following technological investments need to be developed specifically to enable SAFIR:

- For CAM, large format arrays covering the 20-600μm range are needed. Formats of 128^2 pixels, each with a noise equivalent power (NEP) of $3\cdot10^{-19}$ W/√Hz are required. Superconducting bolometer arrays can, with sufficient development funding, meet these requirements.
- For HRS, large format arrays covering the 20-720μm range are needed. Formats of 64^2 pixels, each with a noise equivalent power (NEP) of $1\cdot10^{-20}$ W/√Hz are required. It may be necessary to develop novel approached to detectors to meet this sensitivity requirement.
- For LRS, similar large format arrays to HRS must be developed, but with lower sensitivity for higher photon background.
- For HET, single-moded coherent detectors operating near the quantum limit over the 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 bolometers are the most promising current technology for this purpose, if they can be manufactured with near-quantum noise. Additionally, backend spectrometers using low-power digital autocorrelators should be developed.

Thermal Design

NGST will use an all-passive design to achieve a telescope temperature of ~35 K. This is a reasonable practical limit for a telescope relying on radiative cooling alone. Reaching the more challenging 4K telescope and instrument temperatures requires better isolation from solar radiation and active cooling to get below the ~7K ambient background at L2.

The dominant heat load on the SAFIR observatory is from the Sun; its light must be attenuated by ~6 orders of magnitude in order to keep the telescope cold. NGST has designed a sunshade to attenuate ~3.5 orders of magnitude of this light, using multiple separated radiatively-cooled reflective blankets. This sunshade is deployed from the warm spacecraft, and radiatively cools until the inner layer is at a temperature of ~100K in its warmest place. This "hot spot" is the dominant source of stray light at mid-infrared wavelengths. For SAFIR, the equivalent "hot spot" must be 15K or colder, which puts a much greater burden on the sunshade. To meet this requirement, the NGST-like sunshade is mounted on a 40K actively-cooled stage. The sunshade's sunward side heats up appreciably from 40K, but the inner layer is quite cold. An additional layer is added to the sunshade, mounted on a 15K actively-cooled stage. This layer reaches an equilibration temperature of around 15K across its entire surface, and thereby prevents stray light from entering the telescope and reduces the radiative load on the cold portions of the observatory to an acceptable level. The thermal design is shown in Figure 3.

Trade studies and thermal analysis have identified a few design features which improve the performance of an NGST-like sunshade. The spacing between sunshade layers will need to be increased slightly as compared to NGST's. The extra layer on the cold side is mounted to the telescope tower further up from the spacecraft. The deployment of the sunshade layers will draw on the design used by NGST. The extra inner layer could use a simple separate deployment if necessary.

As previously mentioned, the sunshade is conductively cooled by a 40K and 15K mounting point, which is actively cooled by closed-cycle cryocoolers. An additional refrigerator cools the entire telescope and instrument volume (which has its own radiation shield) to 4K. With the sunshade and cryocoolers in operation, a set of Continuous Adiabatic Demagnetization Refrigerators (CADRs) is sufficient to cool the instrument and telescope to 4K and the detectors to even lower temperatures.

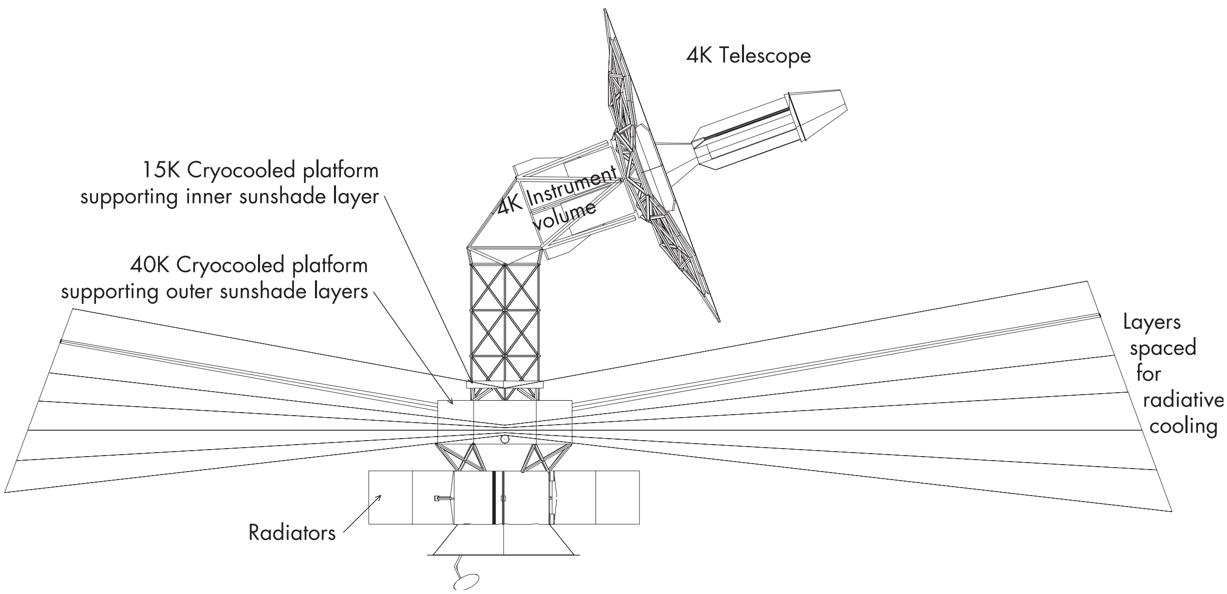

Figure 3. SAFIR thermal design, showing temperatures of stages between the warm spacecraft and the 4K telescope.

Thermal Technologies

There are several options for space qualifiable cryocoolers for this temperature range which must be evaluated. Cryocoolers of the reverse turbo-Brayton cryocooler (RTBC) type (already flying on HST NICMOS) are being developed for operation down to ~10K temperatures as a part of the Advanced Cryocooler Technology Development Program (ACTDP). Initial trades have led us to baseline the following possible configuration, using the RTBC expected efficiency as a reference point:

- 6 ACTDP-type coolers operating between 300 K and 40 K
- 4 ACTDP-type operating down to 15 K
- 3 Advanced CADRs operating down to .05 K and providing telescope cooling to 4K

Very conservative assumptions have been made about the abilities of the Advanced CADRs and the ACTDP coolers. The capabilities needed for SAFIR will likely be demonstrated in the next 3 to 4 years. ACTDP requirements call for a single cooler able to lift 250mW at 18K and 7.5mW at 6 K with a near flight ready model ready by 2005, 10 years before the SAFIR launch. Single shot ADRs have been developed for flight for XRS-1 and sounding rockets and will be flown in 2005 on XRS 2. Continuous ADRs have been demonstrated in the lab operating from warm end temperatures of ~6 K, and an advanced continuous ADR operating from a 15K heat sink is believed to be within current manufacturing capabilities. By the time SAFIR enters phase B both of these coolers should have been demonstrated in flight and be more capable than is assumed in the concept.

The cryocoolers will produce substantial amounts of heat which must rejected at 300 K by radiators mounted on the sunward side of the sunshield. They will be deployed just as the solar panels are but oriented perpendicular to the sun line.

Spacecraft

A large but basic spacecraft bus can accommodate SAFIR requirements. The spacecraft will have to cope with the control of massive instrument payload. Maintaining the proper pointing is one of the greatest challenges – but one which NGST will solve before SAFIR. A combination of instrument-located star tracking and large reaction wheels can solve this problem. The spacecraft will also house the warm electronics for the instruments and the warm end of the cryocoolers. The power handling system for SAFIR is proposed to use a MAP-style system upgraded to 4kW@ 120VDC operation, supplied by deployed solar panels with a total area of around $17m^2$. Cooling is provided by deployed radiators. A large payload attachment fixture, a design of which is shown in Figure 4, is required to handle the high Center of gravity and large mass of a SAFIR observatory

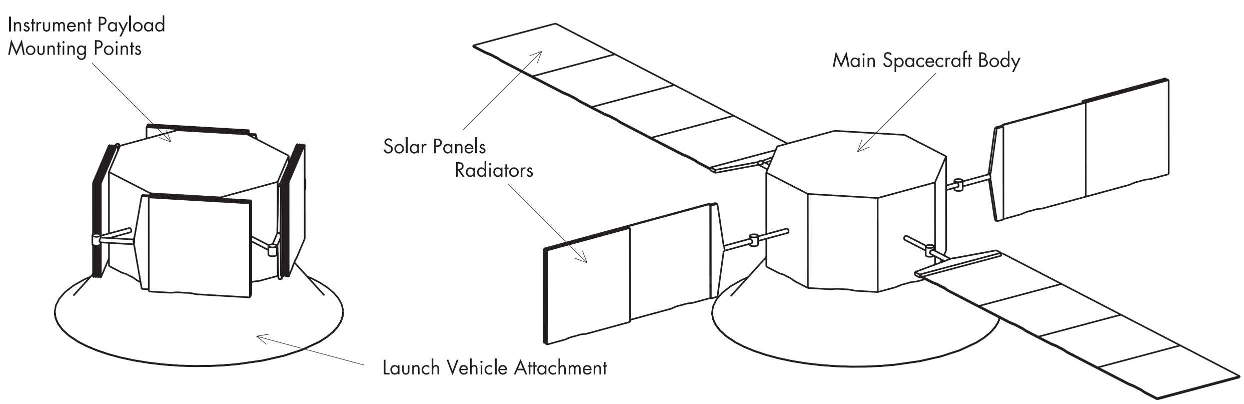

Figure 4. SAFIR spacecraft bus (Left) illustrating the large structure required to support the observatory during launch, and (Right) illustrating the deployed solar arrays and radiators.

Pointing Control

The estimated pointing requirement for SAFIR is to point absolutely to within about 1”. This assumes that the smallest field of view is about 5”, and desired point source ought to lie within it. In order to remove the expected jitter and drift of the telescope, it is desirable to have relative pointing knowledge to within 0.1”, about 1/10 of the smallest diffraction-limited beam. Achieving this requires a cold star sensor rigidly mounted to the telescope, so as to provide subarcsecond boresite knowledge.

The conceptual design includes a 2μm camera in an unoccupied portion of the focal plane to sense the nearest 2MASS point source (as determined by a spacecraft-mounted warm star tracker) and detect its motion to 0.1” precision to enable shift-and-add image reconstruction for the science data. Eight momentum wheels are required to meet the requirements on the slew rate of the observatory, assuming redundancy.

Orbit

After studying a variety of orbits, an L2 orbit meets all of SAFIR’s requirements for many of the same reasons it meets NGST requirements. This orbit is thermally stable, is always well-illuminated, has a nearly constant distance to the Earth, and the field of regard to space is adequate. The orbit selection is driven primarily by thermal considerations. An L2 orbit allows a large – but feasible – deployed sunshade to create the thermal conditions necessary to allow the telescope to operate at the 4 to 8 K range. The orbit also allows reasonable launch vehicle, communications and power solutions.

Communications

Calculated data rate estimates are around 800kbps at most, assuming two instruments observing simultaneously at maximum rate. With an L2 orbit – $1.77 \cdot 10^6$ km distant – a ~1m dish using 6W at X-band can download this to a 34m

DSN base station with one 1.1 hour pass a day with a factor of two reserve on board memory (140Gb). During the beginning of the mission, sufficient power to run two instruments simultaneously will be available, although towards the end of the mission, degradation in the solar array efficiency will prohibit more than one instrument from operating at a time.

Launch Vehicle and Fairing

The launch mass of SAFIR is estimated very coarsely at 5000kg, but this is a conservative mass with substantial margin for growth allowed. The limiting factor for launch vehicle selection, however, is the fairing volume. When stowed, SAFIR will be about 5m in diameter by 17m tall (Figure 5). All of the deployment and packaging options of our basic concept require a fairing volume only possible with one available fairing, the Delta-IV Heavy 19 meter fairing. It is possible the mass of the current concept might have been reduced enough to fly on the next lower Delta but the packaging was not feasible. The mass-to-L2 of 9400 kg far exceeds SAFIR's projected mass. SAFIR will carry a monopropellant or cold gas system for station keeping.

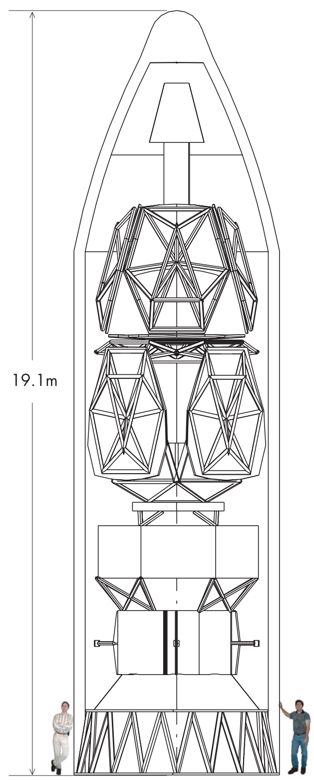

Figure 5. SAFIR concept packaged into DELTA 4 - Heavy 19-meter Fairing

Deployments

NGST will demonstrate most of the deployments needed for SAFIR. While we cannot know the exact execution until the NGST prime contractor has been chosen, we do know what these deployment mechanisms must achieve and their initial conceptual designs. The largest deployment will be the sunshade, which for SAFIR will be much like the current NGST designs with one addition. The additional inner layer mentioned earlier will be attached to a stage slightly higher on the telescope tower cooled to 15K by active refrigeration. There have been two sunshade deployment concepts investigated for NGST. One concept uses four extending booms to unfurl a thin multi layered blanket. A second concept may use sets of unfolding beams with tip spars at the ends to space the various layers. The deployment of the telescope – which includes the primary mirror, secondary mirror and telescope cant hinge – will follow the approach of NGST very closely but perhaps with a simpler phase-up routine allowed by SAFIR's coarser figure requirement. Figure 6 shows one of our SAFIR concepts using the petal deployment approach. The telescope tower for this SAFIR conceptual design is very similar to the NGST telescope tower and deploys in the same way, using the same mechanism carrying with it the cold end of the 40K and 15 K refrigerators. SAFIR will also deploy a small antenna for transmission of data from the bottom of the spacecraft. On the side of the spacecraft, there are solar panels for power collection and radiator panels for heat rejection using a solar panel deployment mechanism.

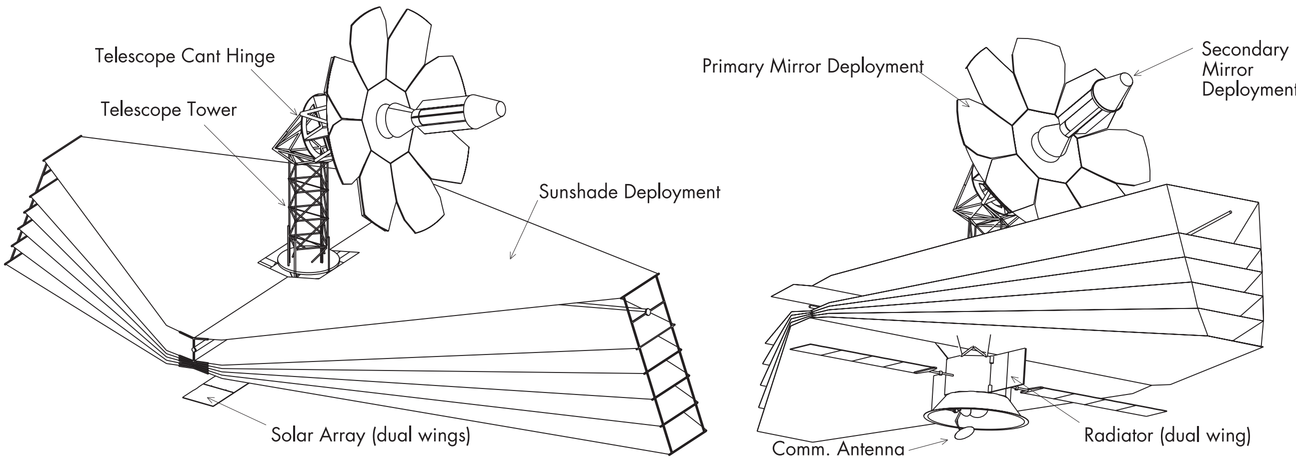

Figure 6. Deployments expected for SAFIR.

Integration and Testing

Because our primary conceptual design is based largely on NGST, it is not surprising that SAFIR integration and testing has many of the same challenges. A great deal of work has already been done to design and plan for NGST integration and testing. If one maps out a detailed integration and test plan for the SAFIR concept discussed above, it looks almost the same as NGST's plan.

The assembly of SAFIR can follow the same basic flow and use many of the same solutions as NGST. Some of the assembly challenges are made easier because of SAFIR's less stringent optical requirements. Some will be made more difficult because SAFIR is larger than NGST.

NGST's testing procedure can also be used as a basis for testing the SAFIR observatory. The purpose of any verification program is to ensure the required performance of the system will be achieved in its flight environment. The size (10 m vs. 6.5 m) and operational temperature requirements (4K vs 35K) of SAFIR do not ensure that every facility designed for NGST won't have to be further modified to accommodate SAFIR. NGST will require thermal test capabilities ranging from ambient temperature to liquid helium temperatures. The Plum Brook Facility at NASA Lewis and the Raytheon 50' diameter spherical thermal vacuum chambers have some promise of being able to accommodate SAFIR testing with the modifications made for NGST. The basic NGST approach, which uses other facilities designed for the testing of the sunshade and instrument structure, could also be potentially used for SAFIR, with many of the same facilities and setups. 'A Strawman Verification, Integration and Test Program For NGST'[5] describes an NGST integration and test plan including facilities, setups and reasoning. Due to the lightweight nature of the NGST telescope and its resultant flexibility, operation in gravity will require the use of carefully designed test supports and self-weight compensators, which would equally apply to SAFIR.

Mass & Power

Running the cryocoolers, instruments, and the spacecraft subsystems requires substantial power. Trade studies have led us to decisions which require more power but fewer deployments and design complexity. The power is not hard to obtain given the size of the SAFIR observatory. Solar arrays with total area of $17 m^2$ on two standard deployed booms meet the current calculated design estimates with 40% reserve. Table 1 below shows the current top level calculated power estimates. Table 2 below shows the estimated mass of the observatory subsystems and masses with contingencies added.

Table 1. SAFIR observatory conceptual design current power estimate

ITEM	Average Power and contingency (W)
PAYLOAD	
CAM (assuming 2 inst on at a time max)	102
Contingency	76
LRS (assuming 2 inst on at a time max)	20
Contingency	15
HRS (assuming 2 inst on at a time max)	51
Contingency	38
HET (assuming 2 inst on at a time max)	60
Contingency	45
Telescope	–
Thermal subsystem:	
Cryocoolers (8)	2000
Cryocooler radiators (2)	10
ADR's (2)	20
Sunshield & mechanisms	–
Misc. (blankets, heaters, etc.)	60
PAYLOAD TOTAL	2499
SPACECRAFT & OTHER SUBSYSTEMS	-
PSE	212
Contingency	42
Harness Loss	29
Contingency	6
Command & Data Handling	16
Contingency	3
Attitude Control	220
Contingency	44
Com, X-band HGA, HPA, Transponders	51
Contingency	10
Propulsion	2
Contingency	1
BUS TOTAL	1053
TOTALS (BUS + PAYLOAD)	**3552**

Table 2. SAFIR observatory conceptual design current mass estimate

	Estimated Mass (Conservative) (kg)	Mass w/Contingency (kg)
PAYLOAD TOTAL	2430	2916
SPACECRAFT BUS TOTAL	1403	1684
Observatory Dry Mass	3833	4600
PROPELLANT	260	311
TOTALS (BUS + PAYLOAD)	**4093**	**4911**
Delta IV Heavy capability to L2	9410	9410
Margin [kg]	5317	4499
Margin [%]	56.5	47.8

5. SUMMARY

We have developed a conceptual design for the SAFIR observatory, starting with the National Academy's recommendation: "To take the next step in exploring [the far-infrared], the committee recommends the SAFIR Observatory, a… telescope that builds on the technology developed for NGST.[6]" Based on NGST's current designs, a detailed analysis has been made of the changes necessary to produce SAFIR. A broad list of science investigations was produced and used to generate an explicit list of science requirements, from which top-level engineering requirements were derived.

The differences between SAFIR and NGST are simple to summarize. Primarily, SAFIR must be much colder, and therefore will require active coolers and a more capable sunshade. The sunshade itself, the largest component of NGST, can be remarkably similar in architecture. The coolers are all feasible using near-future technology. Secondly, SAFIR requires a different complement of instruments, which will take new detectors needing substantial development. SAFIR's telescope will be larger than NGST's, but the launch vehicle selected can accommodate this change. Other aspects of SAFIR – the mirror itself, the pointing requirements – are made simpler by the longer wavelengths and therefore less stringent requirements of SAFIR versus NGST. Table 3 summarizes the salient parameters of the SAFIR mission.

Table 3. Mission parameters for achieving SAFIR science goals:

Primary mirror diameter:	~10 meters
Wavelength coverage:	20 to 800 microns
Science instrumentation:	Camera and Spectrographs
Mission duration:	5-10 years
Orbit:	L2 libration point halo, 870,000km Y amplitude
Payload mass:	4900 kg (conservatively, with contingency)
Average power:	3600W (with contingency)
Planned launch year:	2015 (approximate)
Launch vehicle:	Delta-IV Heavy, 19m fairing

Funding, technology developments, and the schedule of NGST will all drive the launch date of SAFIR. Based on NGST's 15 year start-to-launch timescale, and assuming some improvement due to NGST's technology developments, SAFIR could launch as early as 2015. "SAFIR will study the relatively unexplored region of the spectrum between 30 and 300µm… the combination of its size, low temperature, and detector capability makes its astronomical capability about 100,000 times that of other missions and gives it tremendous potential to uncover new phenomena in the universe.[7]" SAFIR will make profoundly important contributions to the goals of both the Structure and Evolution of the Universe and the Origins themes of NASA space science, through realizable technology developments of a moderate scale. We have demonstrated that the NGST-based SAFIR concept being developed at NASA's Goddard Space Flight Center is a feasible approach to achieving this important mission.

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REFERENCES

1. *"Astronomy and Astrophysics in the New Millennium"*, National Academy Press, Washington, D.C. 2001
2. Harvey, P.M., Rieke, G.H, Lester, D.F., & Benford, D.J., 2002, *"Single Aperture Far-Infrared Observatory (SAFIR)"*, these proceedings
3. Benford, D.J. et al. 1999, ApJ 518 (2), L65-68, *"350 Micron Dust Emission from High-Redshift Objects"*
4. Bertoldi, F. & Cox, P. 2002, A&A 384, L11-14, *"Dust emission and star formation toward a redshift 5.5 QSO"*
5. *"A Strawman Verification, Integration and Test Program for NGST"*, M. Menzel, K. Triebes, D. Leary, M. Krim, NGST Monograph #4, 2000
6. *"Astronomy and Astrophysics in the New Millennium"*, National Academy Press, Washington, D.C. 2001, p.110
7. *"Astronomy and Astrophysics in the New Millennium"*, National Academy Press, Washington, D.C. 2001, pp.39, 110