VI. Space Systems Architecture and Implementation Approach

Overview

This Architecture Report provides a set of overviews of approaches for building SAFIR. The report develops a point design from the notional SAFIR concept. This point design is not exclusive, but allows us to have a strawman with which future studies can consider trades. These architectural considerations summarize the work that we have done during the course of this Vision Mission study, and bear strongly on the study-funded Team X and work done on our behalf by our industry partners. Earlier work includes, in particular, a 2002 IMDC/IMSL study on a SAFIR concept at GSFC, efforts on the DART architecture funded through JPL, and mirror technology work at MSFC. In this report we have attempted to integrate and distill these efforts. Our efforts have benefited strongly from Northrop Grumman, which was one of our designated SAFIR Vision Mission industry partners, bringing insights about large deployable structures and optical systems based on JWST engineering to our study.

The common aspects of all SAFIR approaches are: (1) it is a ten meter deployable telescope; (2) the optics will be kept cold, ideally at 4K, presenting a serious technology challenge for thermal transfer and control; (3) to be that cold, the telescope is mounted behind a solar shield, while the spacecraft bus is mounted on the Sunward side; (4) the mission will launch into an orbit at Earth-Sun L2; (5) The mission would launch around 2020 with a minimum design life of 5 years and a 10 year design life goal.

To fulfill the requirement of the purpose listed above, several design requirements from the SAFIR design parameters are relevant. These extend the notional requirements listed above in order to fully realize the science that those requirements dictate.

Mission parameters for achieving SAFIR science goals are listed in the table below.

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

Some of the issues highlighted in our study, and identified explicitly during Team X impact the architectures; a representative list is included here for consideration when reviewing the various designs. Approaches to increase confidence in these technologies are presented in our Technology Roadmap section below.

- Thermal control
    - Maintaining stable temperature during measurements
    - Coordinating with thermal shields
    - Mechanical cooler technology and distributed cooling

- Mounting, structures, and interdependencies
    - Interface between the payload and spacecraft
    - Complex movements and deployments, requires unique mechanical attachment techniques
    - Structure too large to test prior to launch

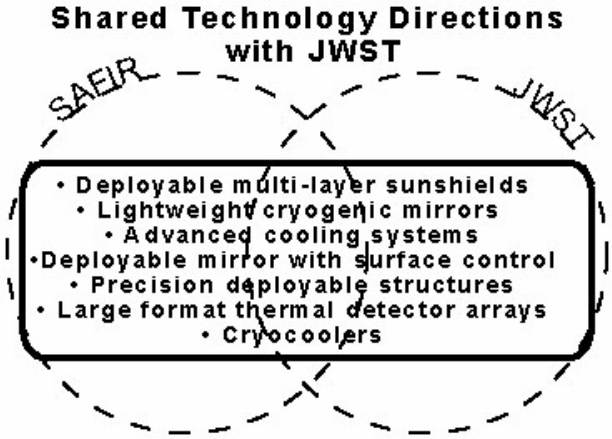
- Sun shield
    - Deployment and deployed support structure
    - Stability of deployed structure (unsupported thin film exposed 5-10 years)
    - Thermal properties after deployment

- Pointing constraints
    - Constraints are very challenging (few arc seconds)
    - Scan rates need to be very slow to minimize the settling time. First the spacecraft should be pointed and then instrument fine pointing would follow.
    - Long duration measurements at arc second constraints will be very difficult for the spacecraft to maintain. In other words, the spacecraft cannot tolerate significant jitter.

- Dependence on JWST success and reliance on JWST analysis

SAFIR's current design focuses on the spacecraft's instrument payload: a cryogenic telescope with a 10-meter single primary deployable mirror mounted behind a large radiating solar shield. The main spacecraft bus is mounted on the side of the shield opposite the telescope. The bus contains large cryocoolers to cool the telescope optics and the cold side of the shield. The telescope houses four instruments: an infrared (wide spectral band) camera; a low resolution spectrometer (LRS); high resolution spectrometer (HRS); and a heterodyne spectrometer (HET).

SAFIR has benefited strongly from our decision to design the mission in such a way as to harvest the maximum amount of mission design from JWST. JWST heritage is traceable to many of our requirements, and technology drivers for JWST are in many respects enabling for SAFIR.



Single Aperture Far Infrared Telescope Architecture Concepts

We list several designs for a single aperture far infrared telescope that have been evaluated over the years, in increasing level of technological ambitiousness. These designs all provide large, mostly filled apertures that maximize the collecting area of the observatory, and are intended to illustrate the breadth of architectures that have be considered. The first two designs flow into the baseline point design, described below, which benefits most strongly from JWST investments, and offer an observatory that builds naturally on the technical accomplishments required for it. The latter three concepts are much more technologically ambitious, and can be considered powerful notional scientific successors to the 2015-2020 SAFIR that we have been asked to study.

1. Early SAFIR concepts were developed at NASA/GSFC using as a basis the Goddard Strawman Next Generation Space Telescope (now James Webb Space Telescope) designs. This design, produced in May 2002, is envisioned with an eight-segment petal deployment. (See Figure VI-1.) The overall diameter is 10 m and can stow/deploy easily from a Delta IV 5 m fairing, however there is some loss of collecting area at large radii. The sun shade is deployed using extending booms and tip spars. This version was described in a paper by Amato et al. (SPIE, 2003). A concept involving a larger number of smaller mirror substrates arranged in rafts is shown in Figure VI-2.

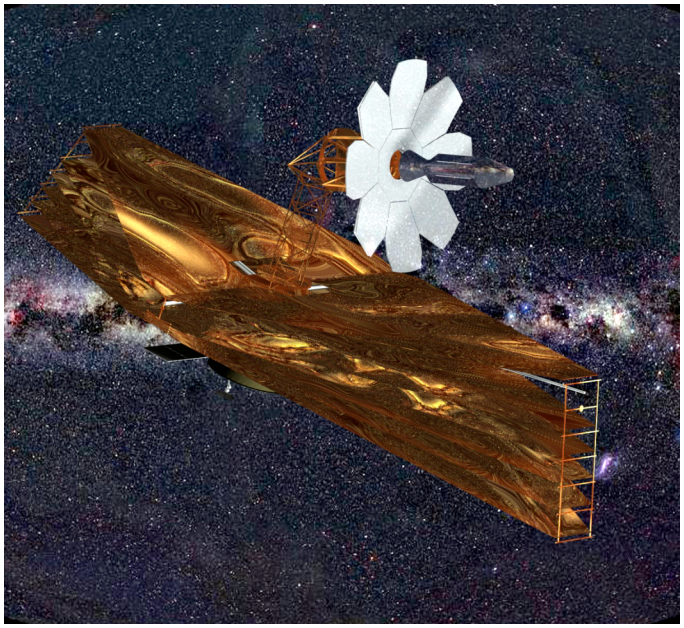


Figure VI-1: SAFIR using an original JWST Strawman heritage, by GSFC. The broadly similar SAFIR concept developed at NASA/GSFC using the Northrop Grumman Next Generation Space Telescope (now James Webb Space Telescope) designs. In this version from July 2002, a table-fold hexagonal primary with two hinge lines is used. The overall equivalent area is 10 m, is a filled aperture, and can stow/deploy easily from a Delta IV 5m fairing. This sun shade is deployed using a multiple fold strut system with tip spars at the ends. This design and the previous design maximize the reuse of JWST technologies.

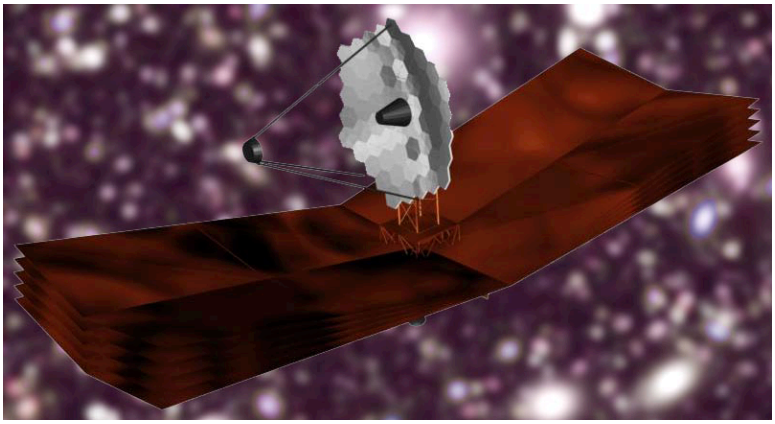


Figure VI-2: SAFIR using a more recent JWST heritage, by GSFC.

2. A novel concept of a SAFIR architecture using a sparse aperture design with the same area but a larger equivalent diameter, for higher angular resolution imaging (NASA/GSFC; c. Aug 2002). This is shown in Figure VI-3. The effective angular resolution is equivalent to a 16 m telescope. This primary mirror folds up into four strips, enabling an easy deployment of ~6 m-size segments. The sun shade design re-uses JWST heritage design, as in the previous figure. This design, along with those in Figures VI-1 and -2, were described in detail by Benford et al. (2004 Astrophysics & Space Science, 294, 177). From a science perspective, while this telescope could, in principle, offer higher spatial resolution per unit mirror area and a circular aperture, complexities in the point source function for imaging fidelity, and the challenges that this design would lead to both in pupil baffling and aperture spectroscopy, make this design less compelling.

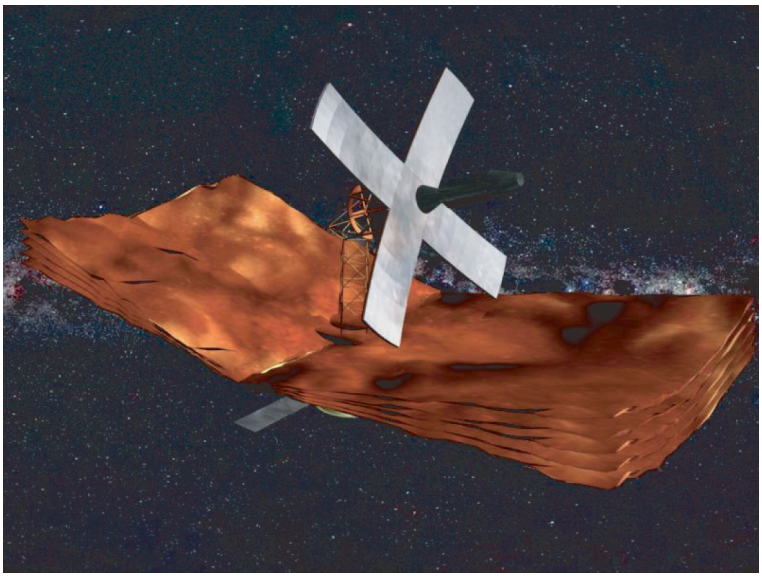


Figure VI-3: Strawman SAFIR with a sparse aperture, by GSFC. This design offers extra aperture baseline at the expense of a filled circular aperture for the same equivalent mirror area.

3. Following on the earlier SAFIR designs, the Filled Aperture Infrared Telescope (FAIR) was posited as a far-stretch mission goal for a single aperture far infrared telescope, including especially ambitious reliance on the stacked mirror deployment strategy (see below) and generous extrapolations of capability in mirror area density technology (~ 5 kg/m^2) to get a 30 m-class telescope to L2 with an EEL and autonomous deployment. Such a telescope could be considered to be on the technology development spiral that would follow both JWST and SAFIR, and focused technology development for SAFIR would be directly applicable to long-term implementation of a FAIR.

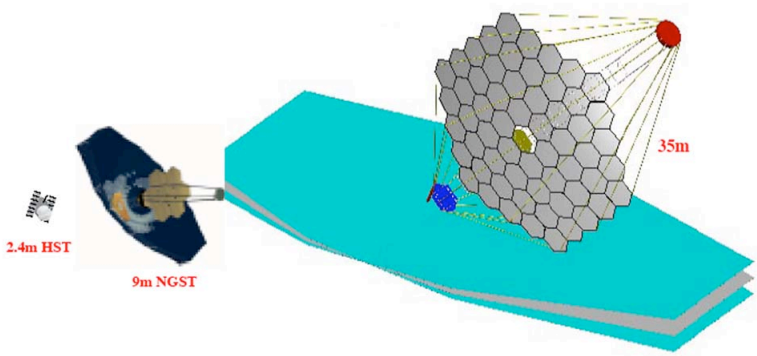


Figure VI-4. FAIR as a stretch goal for a SAFIR, making use of the extensibility of the stacked mirror deployment concept.

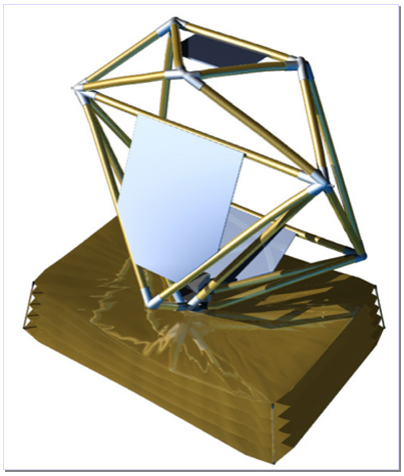


Figure VI-5: SAFIR using a membrane mirror, DART-concept by JPL.

4. One concept that departs from all other SAFIR designs is the Dual Anamorphic Reflector Telescope (DART), developed by team member Marc Dragovan at JPL with the support of Lockheed over the course of several years (this drawing dates from 2002). This approach employs a pair of tensioned membrane mirrors to yield a very low areal density. Each mirror is a parabolic cylinder, at right angles to provide a focus; as shown above, there is a third mirror to accommodate the necessary long focal lengths. Because of the large structure around this telescope, this design may also leverage in-space assembly, and was considered as a strawman observatory for the NeXT (NASA Exploration Team) efforts. DART is discussed by Dragovan et al. (2003 Proc. SPIE, Proceedings of SPIE, Vol.

4850, pp. 170-178) and the SAFIR community regards it with great promise for future large aperture space observatories, is reviewed in Appendix C in some detail, as it presents a convenient path to a very much larger single-aperture telescope.

5. Another large far infrared telescope concept that is very different from other filled aperture designs is the refractive option developed by Tim Hawarden (UK ATC). Such a telescope is based on a giant diffractive fresnel lens, and as such, has technology linkages with similar efforts at shorter wavelengths being studied at LLNL. Such a lens could be composed of ultra high molecular weight polyethylene, which is largely transparent at these wavelengths (especially the submillimeter) and extraordinarily lightweight. Hawarden has proposed the Giant IR and Submillimeter Space Observatory (GISMO) as a 30 m telescope that would take advantage of this technology. The telescope would require precision formation flying of a primary lens spacecraft and a separate field optics collector-corrector spacecraft. At least on the basis of dispersive properties of well understood thin film substrates, a corrector that achromatizes the beam is required to achieve diffraction limited broadband. GISMO would use an f/100 lens, such that the spacecraft separation would be 3 km, with formation flying precision requirements of order 1 mm. As a thin film, deployment of the giant lens is a matter of unrolling and tensioning around the periphery. Passive cooling of the lens is straightforward with a JWST-like sunshield, as the lens material that has residual emissivity at short wavelengths. Of special importance is the fact that the optical tolerances of such a lens are extraordinarily modest, and diffraction-limited performance can be achieved with a flatness of +/-20 cm across the aperture. Nevertheless, the field of regard of the observatory is very small, formation flying and pointing is a major challenge, and areal refractive homogeneity of candidate lens material is not well assured. While GISMO has relatively little technical maturity, we consider it a novel and creative approach to large far infrared telescopes of the future. At least for formation-flying and metrology precision, approximately requisite capabilities are considered vital to other strategically important missions./(e.g. TPF-I).

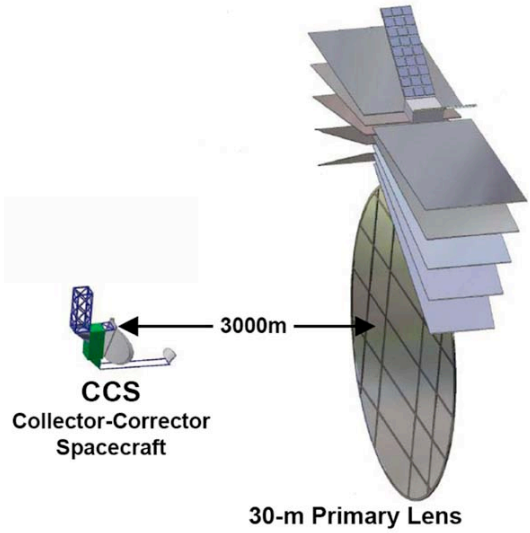


Figure VI-6. GISMO refracting telescope using a fresnel lens made out of a thin film membrane.

5. With extra incentive from the Exploration Initiative which would involve the Moon as a testbed for Mars exploration strategies as well as for focused lunar science, proposals to site telescopes on the surface of the Moon have been resurrected. From a scientific and risk management perspective, we see little value for telescopes like SAFIR. Simply put, while the advantages of lunar siting over siting on the surface of the Earth are large because of vacuum, lower gravity, and more easily controllable thermal effects, they are in no way advantageous relative to sites in free space with zero-g, such as

Earth-Sun L2 in particular. Conventional arguments that anchoring on a solid surface simplifies tracking and pointing are antiquated by several decades of precision telescope orientation management in free-space that now use off-the-shelf hardware and software solutions. These arguments have been advanced by Lester et al. (2004 Space Policy 20, 99). While lunar polar craters appear to offer remarkably cold conditions that might be helpful for an infrared telescope such as SAFIR, such thermal conditions are more economically achievable behind a multilayer sunshield at L2, which is the baseline plan for JWST. Such craters would, however, be maximally inconvenient for astronaut access, whether just because of the ambient temperature and perhaps more seriously because the possibility of large amounts of cryo-condensed materials that would be evaporated by warm intervention agents. In short, lunar siting appears to offer mainly dirt and gravity compared to free-space, and neither is of value to large IR telescopes. It is important to understand that astronaut access in free space, whether in LEO, a lunar L1 gateway, or even at L2, is likely to be easier and present less risk than lunar surface operations.

SAFIR and JWST – Seeking a Point Design

In developing a point design for SAFIR, we have decided to focus on those that have the strongest heritage from JWST, with modifications to support the differing requirements of a larger, colder, longer wavelength observatory. While the DART and GISMO versions described above offer enormous opportunities to astronomy, especially for telescopes of much larger scale than SAFIR, we believe that the substantial technology development needed to pursue them and the likely requirement for a precursor mission to validate these technologies puts the large-aperture implementations of these designs in the longer term. Continued technology investments for far reaching concepts like these are strongly recommended as we work towards the most capable facilities.

In this section we broadly address the key decision drivers and technology development foci for the SAFIR optical telescope system. Subsequent sections will address these in more detail. In summary, the three major SAFIR requirements that differ from JWST parameters are the size of the primary mirror, the colder temperature, and the longer wavelength range of operation.

One of the immediate differences between SAFIR and JWST is that in order to achieve the ultimate sensitivity for the difficult spectroscopic observations planned for SAFIR, the telescope and other optics will have to be cooled below 10 K, well below the ≈35 K achieved by JWST's passively-cooled architecture. Both the GSFC IMDC and the JPL Team-X (see Appendix A) conceptual designs for SAFIR use cascaded cryocoolers to provide moderate cooling powers at 40 K, 15 K, and 4 K. The JWST-like sunshade is mounted on the 40 K stage, while a single additional layer of the sunshade is mounted on the 15 K stage. This sunshade provides an environment so well shielded from the Sun that only modest cooling is needed to cool the telescope to 4 K. While our study considered passive cooling opportunities to get below 35K, and there are design strategies that can assist that cooling, it seems clear that the SAFIR that we want will need active cooling to attain the needed sensitivity.

For JWST, there were two methods developed for packaging and deploying a large, rigid primary mirror: petal-like folding or drop-leaf-table-like folding. SAFIR is larger than JWST, the designs must diverge somewhat: a petal design will result in small notches around the outside of the aperture, while a table-fold design may have two small slices off the aperture edges. The GSFC SAFIR design is to reproduce JWST's approach, using a table folding. Other SAFIR options – particularly for a sparse aperture (Figure VI-4 above) – would use a petal fold. The design considered in our Team-X study assumed a turntable stacking. These packaging and deployment strategies are discussed individually in more detail below.

The choice of optical surface is largely independent of the method of deployment and can be deferred until JWST has validated its technology. JWST has selected beryllium mirror substrates, but this

choice was largely dictated by the requirements for surface smoothness and scatter at the short wavelengths that JWST will operate at. Among the other mirror materials under consideration for SAFIR are carbon fiber mirrors and structure (possibly with glass face-sheets), C/SiC mirrors and structure and aluminum. Given that SAFIR does not require diffraction-limited performance at $\lambda<40\mu m$, one option is to duplicate the JWST mirror technology, but without the final polishing process, which adds substantial expense. It is clear that with reduced surface figure accuracy requirements for SAFIR, mirrors that are substantially thinner, lighter and less stiff than for JWST will be possible. Such lighter weight mirrors will be necessary to offset the ~2x larger surface area for the primary mirror, under the constraint of an EELV launcher capability. Especially because of it's more challenging thermal goals, SAFIR design will require special attention to thermal conductivity at temperatures well below that of JWST.

Another key 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 that for JWST, and the lower temperature will reduce thermal distortions that require JWST'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.

While our study goal is to converge on a point design for the mission, our team is aware that the promise of important technology developments in these three areas needs to be weighed against wholesale adoption of designs and technologies that will be proven on JWST. While JWST provides a clear path to a low risk implementation of SAFIR, the promises versus risks of untested designs are considerations that we believe need to be carried forward for this Vision Mission.

Optical Telescope Assembly Design

The optical architecture for SAFIR was considered in our study from the perspective of the JWST optical system, which has been investigated and iterated in great detail. The design trades for SAFIR emphasized a long-wavelength, wide FOV imaging telescope. The trade started looking for about a 0.5º diffraction-limited FOV at 30 µm with a 10 m aperture. A flat field was considered desirable, but not required. The possibility of a chopping secondary was not originally considered, but the ability to do slow secondary mirror is possible with any of the final designs.

The a large number of design forms proposed over the past several decades were examined in a very rough way, including Cassegrains, Gregorians, several two-axis systems such as the Wilson and Delabre, Baker-Paul telescopes and variations thereon, off-axis three-mirror anastigmats (TMAs) such as the JWST design form, and Korsch's double-Cassegrain and several other similar four-mirror telescopes with rather large fields of view. 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. Simplicity soon reduced this to curved-field Cassegrains and Gregorians and off-axis flat-field TMAs of roughly the JWST design plus the most simple of the flat-field on-axis four-mirror designs.

There were a number of deciding issues for selecting the baseline design: FOV, resolution, design flexibility, curvature of field, obscuration, baffling for stray light control, simplicity (fewest mirrors), manufacturability and compact size. All of the designs met the minimum FOV requirement of 0.15°. The TMA had the smallest FOV followed by the Gregorian, the Cassegrain and the four-mirror designs, which had decidedly the largest FOV. The best resolution was that of the four-mirror design and the TMA, with little difference between the Cassegrain and the Gregorian. Design flexibility, by which we mean the widest selection of f-numbers, field curvatures and other optical parameters was greatest for the Cassegrain followed by the Gregorian, while the TMA has a rather limited range of

useful designs. The four-mirror design, given the requirement that the mirrors lie close to the secondary and primary locations, had least of all. The only designs that achieve completely flat field are the TMA and the four-mirror design. The obscuration of the TMA is usually the smallest, followed by the Cassegrain and the Gregorian. The four-mirror system had perhaps an unacceptably large obscuration and there was very little design trade space to decrease it. Off axis systems will have the best stray-light control. In this respect the TMA is best because it is off-axis in field. We didn't consider other off-axis designs as they increased the lateral size of the telescope or interfered with the deployment of the primary mirror if it were a segmented mirror. The four-mirror system can be very well baffled for an on-axis system, followed by the Gregorian with the Cassegrain clearly in last place. The Gregorian, followed closely by the Cassegrain, were the least complex systems and the easiest to manufacture, test and align. The four-mirror design has four powered surfaces, the secondary also being quite large and convex, while the off-axis TMA tertiary is more difficult to manufacture. The two designs are roughly equal in manufacturing difficulty but the TMA overall should be simpler. In overall size, the four-mirror design is short, but has a very large secondary. The TMA and the Cassegrain are about equally compact, but the TMA generally has a smaller secondary and a shorter back focal length. The Gregorian is longer than an equivalent Cassegrain and may not be that much less compact because it has a shorter back focal length.

The four-mirror design was eliminated because of the large secondary and obscuration, as well as complexity. The Gregorian was eliminated in favor of the Cassegrain because of length, and because the longer back focal length of the Cassegrain could be accommodated in the instrument cavity using a reflective field splitter. The TMA is a closely competitive design to the Cassegrain, but the simplicity of the Cassegrain was favored generally over the TMA largely because of two other issues: flat field and stray light. We didn't have at this point a requirement for a flat field, which is a quality of the TMA but not the Cassegrain. The stray light advantage of the TMA can be of importance if the celestial background dominates the telescope background, and this is the case for shorter wavelengths only depending on the telescope temperature. These are trades that require further study. Given this set of rough trades, we favored the simpler Cassegrain design. While the details are open to iteration, we present a reasonable point design below for a SAFIR baseline.

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

For future trades, the most important ones are to decide if a flat field telescope is required and to examine the stray-light background for SAFIR. The issue of flat field performance, or more specifically the tolerance of the instrument designs for field curvature, needs to be examined by the instrument designers to produce some consensus for that specification. The stray light performance

needs to be revisited to determine if the SAFIR telescope would benefit significantly from better rejection design. This is in large part a thermal trade as the critical issue is the temperature of the telescope structure compared to the effects of the zodiacal light background. Early scattering models for JWST exist that could give a quick estimate of this, given temperature profiles of the sunshade and telescope primary mirror, secondary mirror and telescope structures.

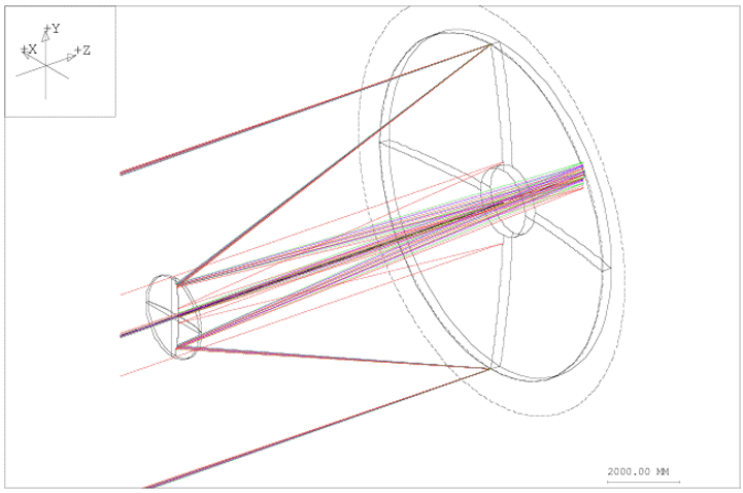


Figure VI-7: Layout for the SAFIR Cassegrain point design described by parameters above. This design offers fewer mirrors than other designs, ease of fabrication and alignment, and assuming the primary is imaged on the secondary, that latter mirror can be used as a chopper.

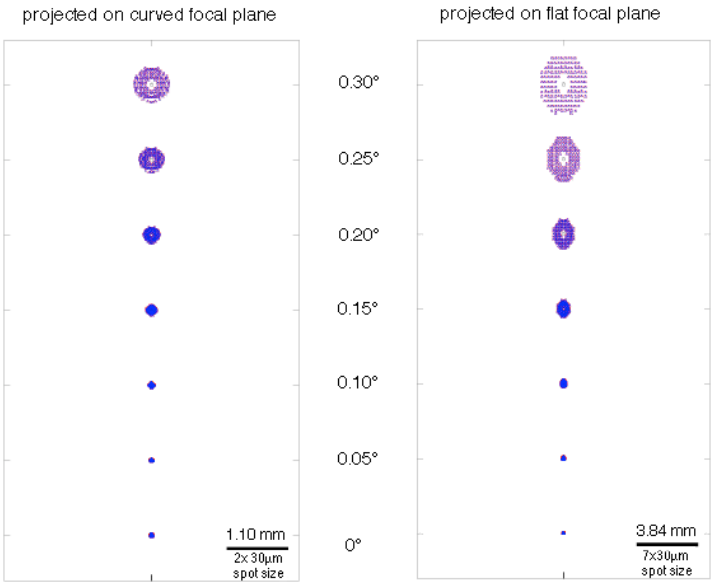


Figure VI-8: Spot diagram for the SAFIR point design described above. Spots are shown as a function of field angle and are compared to the 30µm diffraction spot using the scale bars at bottom right. At left, the image is projected onto an optimally curved focal plane, and at right the image is projected onto a flat focal plane. A flat focal plane allows diffraction-limited performance over a much smaller field of view.

Primary Mirror

The large primary mirror for SAFIR brings special challenges. We assume segmented primary, with several options for packing and deployment as detailed below. The semi rigid segments themselves have a high optical quality, and permit ground testing at 1 g before launch. In any packing scheme, the size of the segments is limited by the launch shroud size, but having the fewest number of large segments minimizes the number of actuators and associated cabling required for on-orbit figure maintenance. In other respects, we adopt a JWST-class architecture for the integration of the primary mirror in the telescope, and intend to benefit from investments in JWST mirror engineering wherever possible.

By assuming a JWST class architecture, one can define mirror design parameters such as segment size, stiffness, dynamic survival, etc. The table below extrapolates some technical requirements for SAFIR in comparison to the requirements for the JWST and the achievements of Advanced Mirror System Demonstrator (AMSD) program. The Advanced Mirror System Demonstrator (AMSD) program was a collaborative project between NASA, Air Force, and NRO to develop lightweight mirror technology that would enable potential space optical missions for all three agencies. The relevance of this program to SAFIR technology development is detailed in the Technology Roadmap section.

SAFIR Primary Mirror Requirements				
Parameter	AMSD achievement	JWST baseline	SAFIR requirement	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

SAFIR requires mirrors that can be either passively or actively cooled to an operating temperature of 4-10 K in order to achieve cosmic background limited performance. Segment size and areal density are driven by aperture diameter, packaging configuration and launch 'up-mass.' A very important difference is that the diffraction limit for SAFIR is 20 μm versus 2 μm for JWST. This significantly relaxes the mirror surface figure requirement.

Technically, JWST (or AMSD) mirrors could be used for SAFIR. JWST has selected beryllium for its primary mirror – a material that has been demonstrated at 4 K on Spitzer. And, AMSD has already demonstrated both beryllium and ULE mirrors with the appropriate diameter, areal density and most importantly cryogenic surface figure. The cryogenic mirror figure achieved on AMSD completely satisfies the SAFIR requirement without the need for expensive cryo-null figuring (CNF).

The problem for SAFIR is that the JWST primary mirror is anticipated to cost $3M to $4M per square meter and SAFIR will have twice to four times the total mirror area. SAFIR cannot afford a $200M to $400M primary mirror. Cost models indicate that the longer diffraction limit will reduce cost by approximately 3X. But, for SAFIR to be truly affordable, its mirror cost needs to be reduced from JWST by an order of magnitude. This will be achieved by a combination of new mirror substrate materials and fabrication processes. There are multiple candidates for both, such as silicon carbide or magnesium graphite, syntactic glass foam and replication or beryllium casting, gas infusion glass or reactive atomic polishing or magneto-rheological finishing.

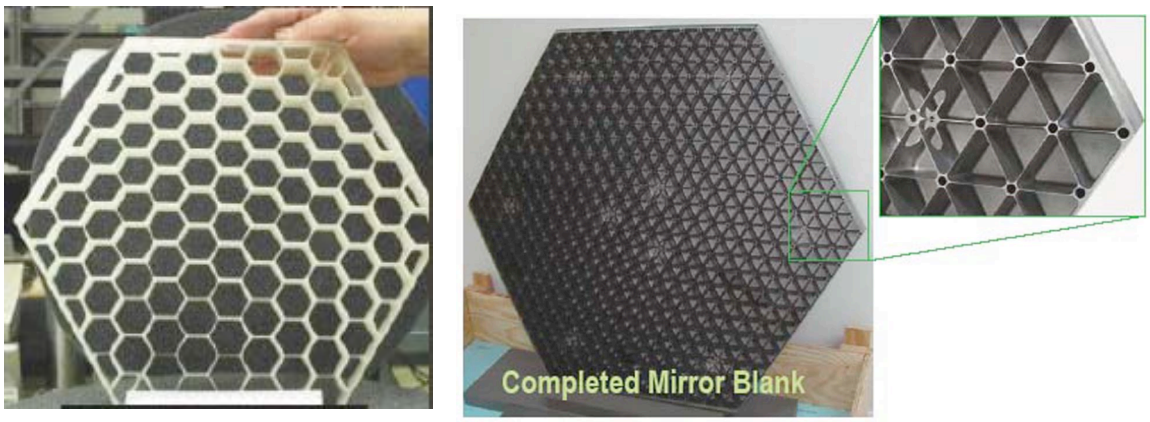


Figure IV-9: (left) Kodak waterjet cut AMSD ULE mirror (minus the 1 mm facesheet) and (right) Ball Aerospace lightweighted beryllium mirror. Each of these test mirrors are on a size scale of ~1m achieve JWST precision at low temperatures, and including mirror supports and actuators to allow that precision, achieve areal densities of less than ~15 kg/m^2 . These AMSD mirrors show that technology to achieve SAFIR mirrors appears to be realizable.

An issue related to cost is production rate. JWST will make 25 m^2 of mirror in about 4 years. SAFIR requires 50 to 100 m^2. JWST is solving its schedule problem by setting up 8 parallel production lines. If SAFIR were to start immediately upon the completion of JWST production (in approximately 2008), sufficient learning may have occurred to manufacture 50 square meters of mirror in less than 4 years. But, if there is any delay in starting such a production run then at least learning will be lost and maybe the entire production line. Thus, SAFIR requires a process to mass produce mirrors.

Finally, a very critical issue is that JWST mirrors are too massive for SAFIR. Because SAFIR has 2 to 4 times more area than JWST, its areal density must be 2 to 4 times lower. SAFIR requires mirrors that have an areal density of 7.5 to 15 kg/m^2. AMSD has already demonstrated mirror substrates in the 10 to 12 kg/m^2 region. As a point of reference, JWST fully intended to fly AMSD class mirrors. But, it was necessary to increase their areal density to both survive launch loads and to provide on orbit pointing stability. With SAFIR's longer diffraction limit, pointing stability may allow some mass relaxation. And, SAFIR should be able to take advantage of a current Air Force program to minimize launch load acoustic loading. Or, there are alternate architectures that can better protect mirror segments during launch.

Currently, no mirror technology has been completely demonstrated (size, areal density, cryogenic performance) that can enable SAFIR at an affordable cost and schedule. Fortunately, a concerted effort is underway by the Space Technology Alliance Large Optics Working Group (NASA, Air Force, Army, NRO and DARPA) to fund via SBIR the development of multiple potential candidate space mirror technologies. Several of these candidate mirror technologies show promise of scalable to 2 m diameters and achieving SAFIR specific structural, optical, thermal and programmatic requirements.

We believe that the efforts to date show great promise for achieving the SAFIR mirror requirements, and that satisfying these requirements provides value to a host of high priority NASA space science missions. Our recommended strategy to move the technology from TRL 2 to approximately TRL 4-5 is detailed in the SAFIR Technology Roadmap section below.

Thermal Design Summary

JWST 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 4 K telescope and instrument temperatures requires better isolation from solar radiation and active cooling to get below the ~7 K ambient (non-solar) background at L2. The details of SAFIR thermal design are referred to only briefly here in anticipation of detailed development in Section VII below for both telescope and instrument cooling.

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. JWST has designed a sunshade to attenuate this light by ~3.5 orders of magnitude, 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 ~100 K 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 15 K or colder, which puts a much greater burden on the sunshade. To meet this requirement, we have mounted a JWST-like sunshade on a 40 K actively-cooled stage. The sunshade's sunward side heats up significantly from 40 K, but the inner layer is quite cold. An additional layer is added to the sunshade, mounted on a 15 K actively-cooled stage. This layer reaches an equilibration temperature of around 15 K 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.

Trade studies and thermal analysis have identified a few design features which improve the performance of a JWST-like sunshade. The spacing between sunshade layers will need to be increased slightly as compared to JWST's, to improve radiative cooling of the warmer layers. 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 JWST. The extra inner layer could use a simple separate deployment if necessary.

As previously mentioned, the sunshade is conductively cooled by a 40 K and 15 K 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 4 K. With the sunshade and cryocoolers in operation, a set of Continuous Adiabatic Demagnetization Refrigerators (CADRs) is sufficient to cool the instrument and telescope to 4 K and the detectors to the even lower temperatures they require.

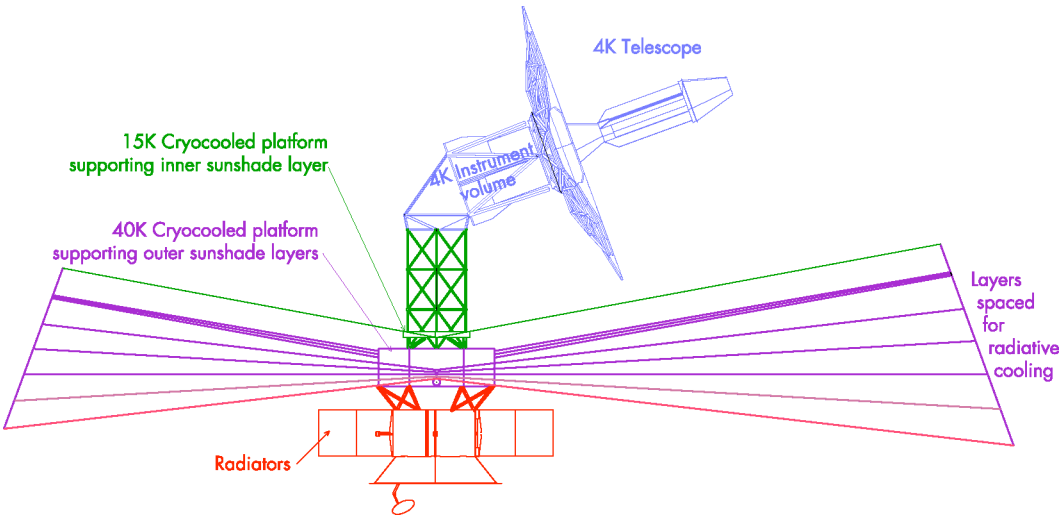


Figure VI-10: Thermal design for SAFIR (observatory design of Figure VI-1 used for reference).

Launch Packaging Options and Telescope Deployment

A large design constraint for SAFIR is the packaging within an existing launch vehicle fairing, for which the largest existing diameter is 5 m. The size of SAFIR makes such packaging a key technological hurdle, without relying on in-space operations for deployment and assembly out of multiple launch payloads. Our study examined the potential for packaging a circular aperture 10 m telescope in this shroud, and considered the simplifications that would be possible with larger shrouds. Such larger shrouds have, in fact, been proposed for both Atlas V and Delta IV-H EELVs by their manufacturers as a realizable large-lift pathway. Such potential opportunities bear consideration given the large volume-to-orbit needs of the Exploration Initiative. We note that while servicing opportunities for SAFIR using in-space operations are highly enabling for the mission (see below), we envision entirely autonomous deployment of the observatory.

It was found in the earliest SAFIR studies that the simple trifold arrangement with folds along segment chords that will be used to package the 6.5 m diameter JWST in a 5m fairing will not be adequate for a nominal 10 m diameter SAFIR primary. That is, a simple scaled-up version of JWST telescope architecture won't fit in an EELV with an available fairing. Using similar hinge and actuator technology a more complicated multi-fold arrangement would suffice, as shown in Figure VI-11, but this would entail additional deployment risks, as well as somewhat less reliable performance under launch loads than for the trifold.

Consistent with EELV manufacturer plans for commercially applicable fairing growth options, we investigated more conventional trifold packing strategies with other fairing sizes. Figure VI-12 shows that a 10 m SAFIR primary, assuming JWST-type architecture, could be fit in a 7.5m diameter fairing, which we understand to be the largest possible with exiting pad and infrastructure. It is noteworthy that with an existing 5 m fairing, our studies show that an 8.4m SAFIR could be fit with conventional JWST-style trifold packaging.

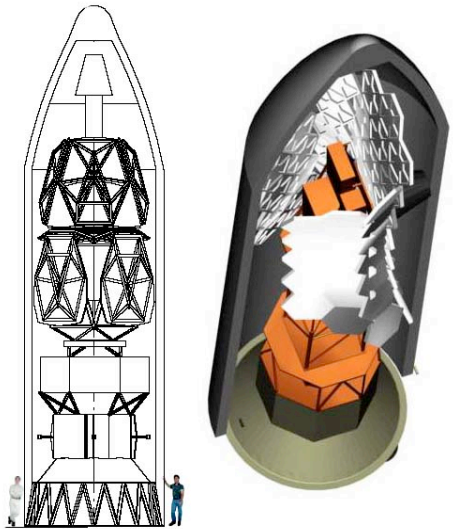


Figure VI-11: Alternative multifold packaging strategies for a 10m SAFIR in a 5m shroud.

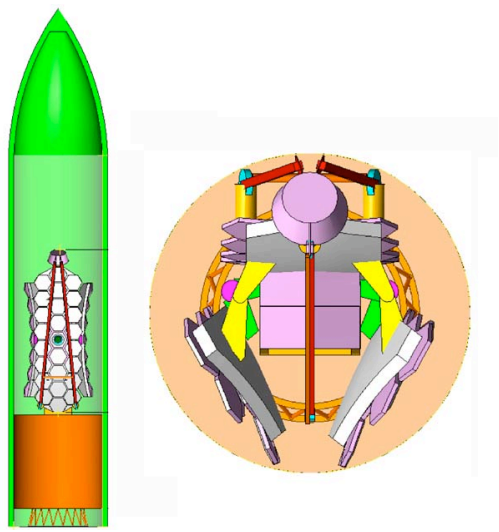


Figure VI-12: JWST trifold-packaged 10m SAFIR in a 7.5m evolved EELV shroud.

A novel architecture that was considered by the study team is one that was developed for early JWST studies, and we regard such an architecture as being highly enabling not just for SAFIR but for even larger autonomously deployed space structures. In this design (see Figure VI-13), the primary mirror elements are deployed using a rotational-translational joint located at a corner of each mirror segment. This deployment scheme was demonstrated in the 1989-1992 studies for NGST by TRL (now Northrop Grumman), and is now known as the Rotating Stack Deployment System (RSDS). In this system, the mirror elements are stacked one above the other for launch, and then deployed on orbit by raising the six-mirror stack (in the case of SAFIR, with seven 3m hexagonal segments), rotating the stack 120º, and lowering it so the bottom segment can be latched to the central hex. This process is repeated with the remaining segments until all six outer segments have been lowered in place and latched onto the central hex. Simple design studies of this design have been undertaken and, with 10 km/m2 mirror substrates, a 2 m diameter secondary mirror with 13 m focal distance, in a

support structure with 3 actuators per mirror, a system mass of ~3500 kg is derived. Dynamical performance is good, with 0.1 degree/sec slews possible with minimal excitation of resonances.

This technology is scalable to larger segments (a maximum segment size of 4 m in a 5 m fairing would allow for a 12 m aperture), and is extensible to larger mirrors with larger numbers of mirror rings, though the deployment risk increases with the number of segments. This extensibility was the basis of the ~30 m FAIR concept (see above) for a single aperture far infrared telescope, in which the EELV shroud was filled vertically, as well as laterally, with very lightweight mirror elements. It is noteworthy that the stacked optics package in this design concept offers more resistant to launch loads than does the chord fold design. Such stacked mirror deployment is an example of the creativity that can be brought to bear in packaging a large, lightweight single aperture telescope in a comparatively small launch shroud, and such technologies can be highly enabling for large future space telescopes.

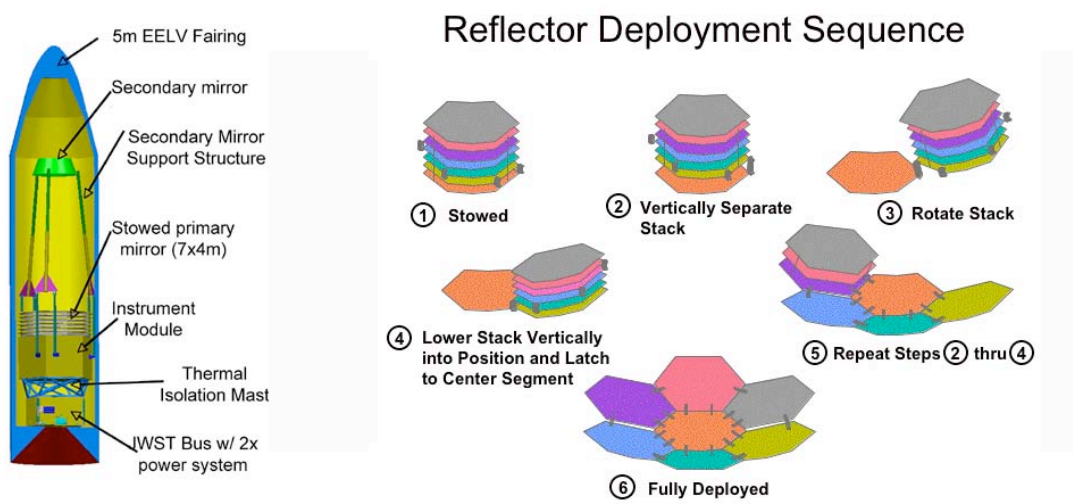


Figure VI-13: Rotationally stacked mirror deployment results in high strength, compact launch package for SAFIR (at left). The sequence for primary mirror deployment is shown at right.

In this design, the secondary mirror support structure consists of three telescoping tubes attached to yokes that fold out of the way during primary mirror deployment, and then rotate back to latch up to the primary mirror backing structure.

Data Systems

Data systems for SAFIR spacecraft operations can be baselined using JWST as a starting point. Data rates from SAFIR instruments are however, considerably smaller than JWST because of the smaller format sizes for detector arrays that are envisioned. These science data rates completely dominate the required bandwidth and storage requirements, and our baseline instrument suite allows us to target a data collection rate of about 927 kbps, including housekeeping and overhead. In order to accommodate a DSN downlink at least every four days (baseline calls for one contact every two days), this would require a conventional rad-hard solid state recorder with 280 Gb capacity. This is roughly five times smaller than JWST because, as noted above, of the smaller science arrays. We baseline the data volume for any two instruments as a maximum of about 70 Gb per day

Several telecommunication strategies are available, but we adopt the JWST baseline, which provides for X-band uplink at 2 kbps to the 2-axis gimbaled 0.5 m high gain antenna. Downlink would be by Ka-band to the high gain antenna, offering up to 30 Mbps performance. This would require 5 W of spacecraft transmitter power and would additionally offer simultaneous ranging data for stationkeeping maintenance. This would allow the solid state recorder to be completely transmitted in about an hour of 2-element 12 m DSN ground station connect time. Safe mode operations is accommodated by a low gain, omnidirectional antenna, which would provide for ~10 bps uplinks and downlinks. These are modest requirements, and assume communication technology available now. The operational framework for telecommunication is presented in the Operations section below.

These modest data rates also allow confidence in using JWST heritage command and data handling system. These rely on standard spacecraft computers (2 for redundancy) requiring 14W of power. No new technology developments are required to meet any mission requirements for the data systems.

Power System

The power system for SAFIR is based on solar arrays with secondary batteries. The solar cells are assumed to be standard multi-junction InGaP/GaAs/Ge cells with 32% operational efficiency and 85% packing factor, mounted on deployable rigid panels. We assume a buildup loss (wiring loss, fab mismatch) of 6%. These calls presently exceed the state-of-art somewhat, but represent a reasonable extrapolation to 2013 technology. Because the operational orientation of SAFIR is fixed to the Sun in order to achieve optimal thermal shielding, the logical place for such solar arrays is on the sunward side of the sunshield, as for JWST. It is noteworthy that as a result of this location, they do not have a rear view factor to space, so they can dissipate heat only from the sunward side. In addition, the panels are exposing to the spacecraft radiator panels. This results in an elevated 1 AU operational temperature for the solar panels of ~90C, which will cost several percent in performance compared to a less insulated arrangement that can more easily cool passively. The panels are assumed to be fixed in orientation relative to the sunshield and spacecraft bus. As a result of the baseline "wide" halo orbit, we assume that the array is canted at a ~20° angle to the Sun at any one time.

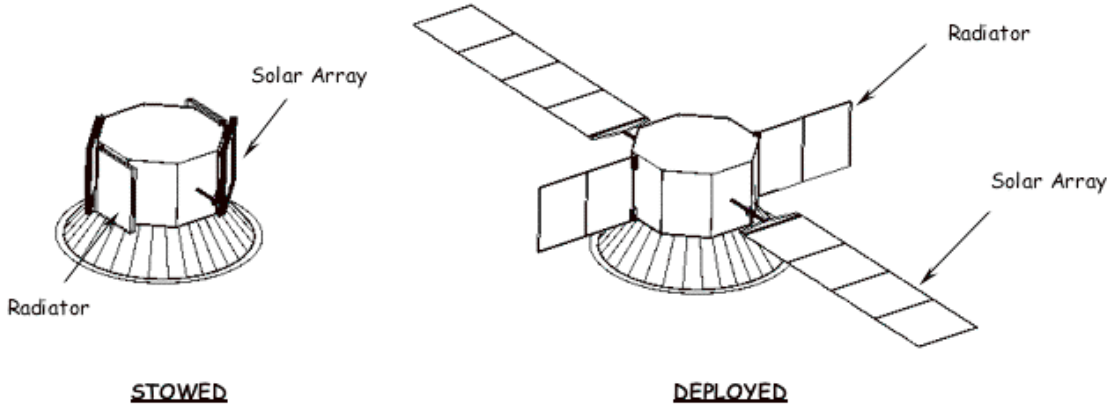


Figure VI-14: The solar arrays deploy from a stowed position around the spacecraft bus above the interstage payload attach fitting, as shown in this sketch (in which the solar shield, which would be on top, is removed for clarity). In this version, we show radiators that would be used to dump electronics and cryocoolers heat as being deployables. Other configurations could have them as fixed on the bus wall.

For a ten-year mission, array degradation and loss factors must be considered. We assume an end-of life efficiency degradation of 14% (BOL/EOL=0.86). Because of the small number of thermal cycles

(leading to structural fatigue) and minimal micrometeoroid losses, this degradation is dominated by radiation effects.

While bare, and very thin Si arrays have been proposed, and offer substantially higher W/kg and lower $/W, this advantage is somewhat offset by their lower W/area leading to deployment complexities, and the fact that they are significantly less rad-hard.

The power load for the observatory is dominated by the active coolers and, as a result, is strongly dependent on the efficacy of passive cooling and operational efficiency of the coolers. These are discussed in the thermal architecture section of the report, and we assume a baseline operational need (including contingency) of about 1300W. Our baseline operational mode is to have two of the four instruments powered up at any one time, and this allows for some economies on total load.

The load breakdown, as a function of operating mode, are listed below, taken from the Team X effort (Appendix A).

	Baseline Science (2 instruments)	All Instruments	Telecom Downlink	Safe Mode	Launch + 3 hours
ACS	130.2	130.2	127.0	27.0	27.0
C&DH	67.0	67.0	67.0	67.0	27.0
Instruments	556.0	912.0	0.0	0.0	0.0
Propulsion System	1.3	1.3	1.3	37.3	37.3
Telecomm	12.0	12.0	33.3	33.3	33.3
Thermal	1279.6	1279.6	1279.6	371.6	371.6
Power Subsystem	133.0	156.1	98.0	34.8	32.2
TOTALS	2179.1	2558.2	1606.2	571.0	528.4
Subsystem Contingency	30%	30%	30%	30%	30%
Subsystems with Contingency	2832.8	3325.7	2088.0	742.3	686.9
Systems with Contingency	2866.6	3359.5	2121.8	776.0	720.7

Meeting this total system load of 2866 W at EOL under baseline science operations can be achieved with a total panel area of about 12.5 m^2 assuming solar cell characteristics listed above. Using state-of-art technology would increase this by only about 12%. Redundancy is assured by additional circuit strings.

Because of the stability of the spacecraft and solar panels with respect to solar angle, and an eclipse-proof orbit, batteries are needed mainly for providing power during launch, before array deployment, and also to provide power during a safe-mode. We specify three 70 A-hr Li-Ion batteries, two of which (for redundancy) would provide launch loads, and the necessary three hour safe mode margin.

Attitude Control System

In order to fulfill the science missions of SAFIR, which include diffraction-limited performance over integration times of order hours, we require a 3σ pointing knowledge of 1", with a pointing stability of 0.001"/sec. The ACS must offer full redundancy for the lifetime of the mission, and must offer a bandwidth an order of magnitude lower than the lowest structural mode. While gimbaled telescope deployment on a boom might allow for low frequency modes of high amplitude, there are strategies that can be used for active damping. Assuming an orbital venue that does not require rapid position changes, we assume that telescope slews will be slow enough to avoid exciting structural modes and to obviate the need for large angular momentum storage capabilities. The SAFIR ACS is intended to derive strongly from that developed for JWST and Chandra. Of primary concern for the ACS is that the Sun be kept behind the sunshield, with respect to the telescope, such that no parts of the telescope are ever in direct sunlight. While of less impact on the thermal equilibrium for SAFIR, both Earth and Moon should be kept behind the shield as well, in order to reduce scattered light. As noted above, if a

gimbaled design is used for SAFIR, it presents the operations plan with an opportunity to tune the center-of-mass of SAFIR to minimize solar torques, and even use those solar torques to dump angular momentum. Should it be used this way, this puts an additional constraint on the ACS, as the system will have to be aware of the changing mass balance in the spacecraft as a whole.

We envision three control modes for the ACS. A Sun acquisition mode is provided by a set of Coarse Sun Sensors (CSS) with an associated Inertial Reference unit. These will drive the thrusters to null the roll rate and point the solar array at the Sun. This can be considered a safe-hold option, and it can be assumed that the telescope is locked to the spacecraft bus and solar shield when this is happening. A coarse science mode is needed for acquisition and target capture in the fine guidance system. We envision this as having an acquisition range of 1-1.5'. This is a 3-axis stabilized mode using a stellar reference. The star tracker and gyro are used for attitude determination. If the telescope is deployed on a gimbaled boom, both telescope and spacecraft will have to move independently to allow for coarse pointing at the target while keeping the Sun behind the shield. Slew rates and trajectories will be chosen specifically in order to reduce excitation of structural modes which would be difficult to damp. If the spacecraft and telescope can retain relative orientation to within the course science mode acquisition range, the star tracker for that can be on the warm side, and an off-the-shelf unit.

The attitude control problem will be similar for all versions of the SAFIR design: the majority of the momentum storage will be located in the spacecraft bus, far away and well removed from the object to be pointed: the telescope. While, a gimbaled telescope design could substantially relax requirements on the size of the reaction wheel system and peak power requirements for it we have found that a non-gimbaled (JWST-like) observatory system would be quite feasible. A set of eight standard high torque reaction wheels, each with 0.7 Nm 20 Nms capability, would allow 2°/min slews, and offer redundancy for the ~5500 kg observatory and, with induced uncompensated solar torques, would require momentum dumping only once every few weeks.

Based on the studies done at GSFC's IMDC and (somewhat) independently at JPL's Team-X, it is very likely that pointing drift errors between the spacecraft bus and the telescope will preclude any form of fine guidance being done from the spacecraft side. Hence, a focal plane guide camera will be used to provide fine pointing knowledge for the telescope, and control provided (at least for the majority) by wheels on the spacecraft bus. This places requirements on the stiffness of the structure connecting the bus to the telescope. We baseline a fine steering mirror on the telescope for the last stage of control. The gimbaled mount in which the telescope is deployed on an articulated boom allows more dimensions of freedom in attitude control, much of which is used to allow a large field of regard (roughly half the sky at any time) while maintaining ideal sun shielding conditions.

Spacecraft Propulsion System

Our study finds that SAFIR needs only a single mono-propellant chemical propulsion system for its operational lifetime of 10 years. It must provide trajectory correction maneuvers (TCM) over the ten year life of the mission up to a total of about 175 m/s. The following table summarizes the flight dynamics for L2 insertion (see also Figure X-5 in a following section).

Maneuver	***Allowance***	***Date***	***Purpose***
TCM-1 (large halo)	<100 m/s	launch + ~ 1 days	main trajectory injection
TCM-2	<15 m/s	launch + ~7 days	contingency burn
TCM-3	<10 m/s	launch + ~60 days	halo orbit insertion
Orbit Maintenance	50 m/s	5/yr * 10 yrs	perturbations, unload
TOTAL	175 m/s		

We assume a hydrazine system with blowdown pressurization. This has been used successfully on spacecraft for many years, and so offers extensive flight heritage. It is a simple system in which helium is used to initially pressurize the fuel to ~400 psi, but does result in a slow decrease in feed pressure over the lifetime of the system as the fuel is used up, and the volume filled by the helium vapor increases. We specify a 3:1 blowdown ratio to ensure adequate performance over the lifetime of the mission.

We see the main TCM burns as being done by ~5N 228 sec I_{sp} monoprop thrusters, and we specify four of these thrusters. For ACS maneuvers and reaction wheel unloading, we envision 12-16 ~1 N monoprop thrusters. The burn allowance described above requires 550 kg of hydrazine in a four tanks, totaling 50 kg. These tanks are connected to a single feed manifold, and baselined as ultralightweight carbon with titanium liner. Such tanks are currently under development, and are baselined for the Mars Science Laboratory. The multiplicity of both thrusters and tanks assures redundance.

The thrusters all fire away from the spacecraft to prevent contamination and, because of the sunshield, can only fire generally in the sunward direction. The very low temperature of the SAFIR telescope compared to JWST leads to some additional concerns about scattered plume contamination. The possibility of warm-side contamination of the sunshield, which must retain a high reflectivity in order to operate properly, is a concern that is shared with JWST.

While cold helium gas thrusters would, in principle, be preferable from a contamination standpoint, the thrust per unit weight is much lower, and would require a several hundred kg increase in propellant mass. The low thrust budget required in the mission does, however, at least allow us to entertain the possibility of such a design.

As noted above, if boom deployment of the telescope is used we see major benefits on propulsion and stabilization requirements. Much of the orbit maintenance propulsion budget is connected with unloading reaction wheels, and if the telescope is deployed in a manner that allows the center of gravity of the spacecraft to be shifted with respect to the shield, solar radiation pressure can be used to unload the reaction wheels, and the entire spacecraft can be balanced to reduce the necessary size of those wheels.

Contamination Issues for SAFIR

As a cryogenic observatory, in which molecular deposition is a risk factor for the optical system, contamination issues for SAFIR can be particularly acute. Many of these issues arose during the Phase A and early Phase B design of the James Webb Space Telescope (JWST) and are addressed here as an early "lessons learned" discussion. An important note about contamination control is that it is very much a systems-level discipline that does not stand on its own but is part of every subsystem. Contamination issues are raised both for assembly, I&T, launch, and in the operations phase, and are relevant both to the telescope structure and instruments. A key challenge is developing a contamination budget that takes into account both scientific and facility performance.

The instrument contamination requirements are derived from the overall observatory throughput requirements, minus allowances for stray light and degradation with age. A contamination budget for IR instruments can be difficult to develop since the requirements vary significantly with the type of contaminant; a small amount of one contaminant can blind an instrument while a significant amount of another contaminant does not affect the operation at all. While far infrared operations are generally more tolerant of thin contaminant layers and dust grains, both for transmission and scattering, a full trade study will need to be made that takes into account all optical elements, with attention paid to the contamination potential for each. The goal of this trade study is to determine the allowable End of

Life contamination requirements for each element. Facility, purge, outgassing and personnel requirements will be derived from these numbers. SAFIR will need to carry individual budgets for particulate, molecular and, very likely, water ice. The overall contamination budget must be allotted over many years of assembly, I&T and launch operations (plus on-orbit operations for molecular contaminants), with consideration given to the potential "recovery" of surfaces by cleaning or bakeout.

From a contamination control perspective, instrument doors are the first line of defense in an effective contamination control program. Doors protect the critical surfaces during ground and early on-orbit operations. Doors also affect the purge system design, as they help the instrument maintain a positive pressure with a relatively low purge gas flow rate. Since nitrogen is usually the purge gas of choice, the flow rate has personnel safety ramifications. Ideally, SAFIR instruments will be designed with doors. Because of concerns about mechanism reliability at extremely low temperature, it may not be possible to have doors on these instruments that are closed during launch. In this case, red-tag covers or Integration and Test (I&T) doors may be used to protect the optics and detectors. Contamination control during assembly, integration and test is planned carefully to minimize risk to the instruments. It is also desirable to be able to recover from a localized event by cleaning the surface. Therefore, access to the instruments (and the vicinity of other critical surfaces) is important

In designing an observatory of this size, the need for access is often in direct competition with the science stray light budget and the requirement to control mass and size. A potential compromise is to have access panels in the instrument module and I&T doors on the instruments. I&T doors could be used as needed during assembly, integration and test, but remain open during launch and on-orbit operations.

Material choices for this observatory will be key to the success of the mission. The issues will be low temperature performance and outgassing, including water content, versus mass. For JWST, the cyanate ester composite chosen for the structure has good performance at the required temperatures but is fairly hygroscopic; water is 0.15% of the total mass of the material. This amount of water added to the always-present water from MLI, paints and harnesses can lead to ice deposition in the typically closed environment in a telescope instrument module. Another challenge on JWST has been materials qualification. Many heritage coatings must be re-qualified at the low temperatures required for the JWST mission, as the existing data was often taken using liquid nitrogen-cooled systems.

The SAFIR telescope will have an active thermal system in order to reach the required temperatures. The cooldown profile for the telescope will have a direct impact on the molecular deposition to the optics. Ideally, the structure should lead the way cold with the optical elements and detectors lagging significantly behind in order to prevent the outgassing species from condensing on the critical surfaces. Even small changes to the thermal design can create—or solve—a molecular deposition problem. On JWST, a change in the thermal strapping of the instruments, made to simplify the thermal system, eliminated the possibility of ice deposition to the detectors. The active thermal system may make it possible to have an on-orbit outgassing phase early in the mission. This would mitigate any risk from latent or absorbed contaminants, including water, in the observatory materials. This cannot take the place of component-level thermal vacuum bakeouts, but is still an effective tool in managing risk to the instruments.

The I&T plan (see below) will also play a part in determining the detailed contamination budget. Each lift or move adds more contamination risk to the hardware than typical highbay operations. The thermal vacuum chambers, acoustic cells and vibration test facilities are not usually as clean and controlled as the environments in the highbay cleanrooms. Therefore, long test preparation times can add significantly to the contamination accumulated on the flight hardware. Cross-country transport

adds yet another layer of risk. The open telescope structure is not particularly amendable to contamination mitigation using a purge system. Regular cleaning of the telescope mirrors in the I&T system is impractical because of size. JWST is currently planning to place a HEPA filter bank near the optical telescope elements during assembly and I&T to provide the cleanest air possible around the optics, and SAFIR is likely to adopt that.

Since SAFIR will not undergo thermal cycling on-orbit, the initial cooldown will be the critical period for molecular deposition. The prospect of a significant amount of water ice deposition came as a surprise to the JWST project. This potential problem was discovered early enough in the program that the solution could evolve with the telescope design. A significant amount of water ice deposition, mostly originating from the structure material was identified as a potential problem. This ice accumulated during the first few days of the cooldown. For SAFIR, several options exist, in addition to the ideal one, which would be to identify a structural material that did not absorb water.

- delaying sunshield deployment to allow warm bakeout time--also delays primary mirror deployment and, at the time, limited cryogen life on one instrument

- deploying the sunshield and then spinning the observatory to delay the cooldown—risky and limited cryogen life

- adding active thermal control to create an outgas mode—too heavy and costly

- adding small heaters to initially hold the instrument optics and detectors at a higher temperature than the structure—option chosen initially

These options are still being evaluated for JWST, but we anticipate that the solution for JWST will be directly applicable to SAFIR, or at least direct our engineering efforts.

At the low temperatures required by SAFIR, everything will condense except helium. It is possible that some otherwise benign species could cause problems. The JWST mid-infrared instrument, for example, noted a sensitivity to carbon monoxide and methane. The science team and contamination engineers will work together to narrow the field of potential problem contaminants.