X. Observatory Deployment

While the packaging and deployment of the primary mirror of SAFIR has been discussed in Section V, we present here a discussion of the deployment of the observatory as a whole.

Observatory Systems
The deployment of the telescope mirror subsystem has been described above. JWST will demonstrate several of the observatory deployments needed for SAFIR apart from the alternate mirror deployment strategies described above.

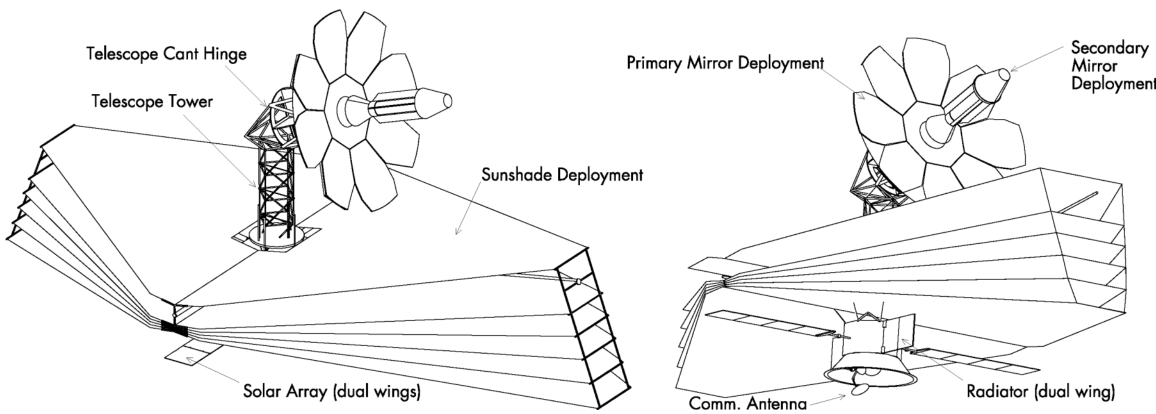

Figure X-1: Deployments expected for SAFIR (JWST-like observatory design used for reference).

The largest deployment will be the sunshade, which for SAFIR can be much like the current JWST designs with one likely addition. The sunshade, and its role in the thermal control of the spacecraft, is described in more detail in Section VII above. An additional inner layer will be attached to a stage slightly higher up on the telescope tower, cooled to 15 K by active refrigeration, in order to achieve the lowest telescope temperatures. This is shown as the innermost shield in Figure X-1.

There have been two sunshade deployment concepts investigated for JWST. One concept uses four extending booms to unfurl a thin multi-layered blanket. A second concept, which is the selected method, uses sets of unfolding beams with tip spars at the ends to space the various layers. The design layer spacing and opening angles of the sunshield must be achieved as a result of unfolding in order to provide the thermal performance that is needed. The details of this approach do not appear in the above figure; either is compatible with our telescope designs. Aspects of the SAFIR sunshield that bear on deployment are the same as for JWST. The sunshield is stowed in a folded configuration, so rip-stop material that is tear resistant on folding and unfolding is required to maintain structural integrity during deployment. For the refrigerated shield, cooling lines affixed to the shield will have to retain their performance after being folded and unfolded. Low emissivity coated layered polyimide layered films such as Kapton and Uniplex are being considered for the JWST sunshield, and are assumed in the baseline thermal and structural design for SAFIR.

If a scaled-up version of JWST architecture is adopted, including a similarly scaled optical design and field of regard for the observatory, the sunshield will be larger in proportion to the aperture size ratio of the telescopes.

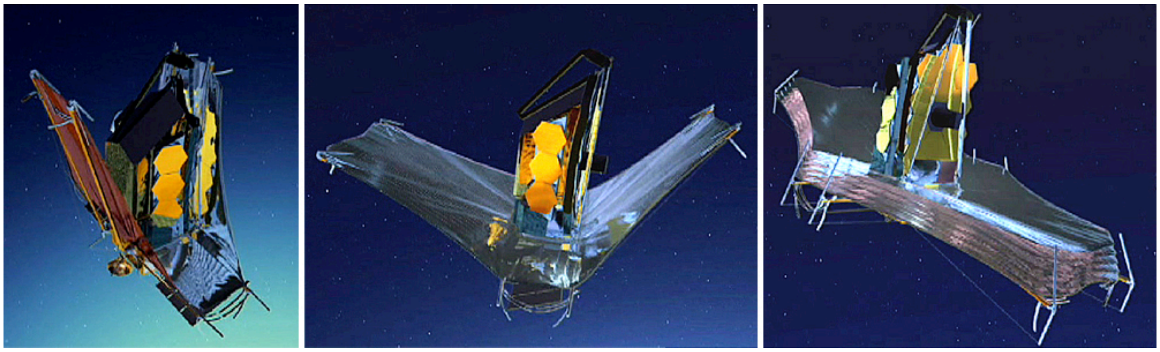

Figure X-2: Sunshield deployment envisioned for JWST. A similar deployment mechanism will work well for SAFIR, as the sunshield material and geometry is identical for the two missions.

While our baseline goal is to develop a SAFIR that reuses the largest amount of JWST engineering, as laid out in Figure X-1 above, we wish to look for far-reaching but highly enabling architectural opportunities that might be considered for development. We believe that boom-deployment, such as has been proposed in our study by Northrop-Grumman is such an opportunity that deserves consideration. A unique feature of this design is a 8 to 10 m long positioning boom that provides the mechanical interface between the spacecraft bus and the SAFIR telescope and instruments. The positioning boom has a natural frequency of 0.1 to 0.3 Hz and provides both thermal and dynamic isolation of the payload from the spacecraft bus. A single-axis gimbal at the top of the positioning boom permits changes to the telescope's line of sight relative to the surface of the sunshade, which is kept normal to the Sun-line. This boom-architecture is illustrated in Figure X-3 below.

A gimbal at the bottom of the positioning boom permits the center of mass of the telescope and instruments to be moved relative to the center of the sunshade in order to minimize reaction wheel momentum buildup due to misalignments between the center of (solar radiation) pressure and the center of mass. By intentionally displacing the center of mass relative to the Sun-line, SAFIR can even use solar radiation pressure to unload reaction wheels, possibly relaxing requirements on on-board propellants for orientation management as well as station-keeping. This design also greatly improves the field-of-regard of the observatory, as the telescope no longer has a fixed orientation with respect to the sunshield, and can be pointed with much greater freedom behind it in the shadow. In the fixed telescope mode of JWST, the field of regard is somewhat restrictive, allowing 100% of the sky to be available only in contiguous blocks of 1.5 months. In addition, by pointing in the counter-Sun direction the telescope presents a smaller cross section to the Sun than it would in the more conventional JWST design, and could allow a significantly smaller sunshield to be used. As shown in Figure X-2, this design can still capture a large fraction of JWST spacecraft bus and shield engineering.

We consider the boom-deployment architecture to be a challenging, though credible stretch goal for the mission architecture, as is the rotational deployment of the primary mirror. In this sense, we adopt it as an extension of the SAFIR baseline. As we do this, it should be understood that boom deployment is not a requirement for the mission, but may offer certain simplifications in design and operations that a more thorough trade study will be able to assess.

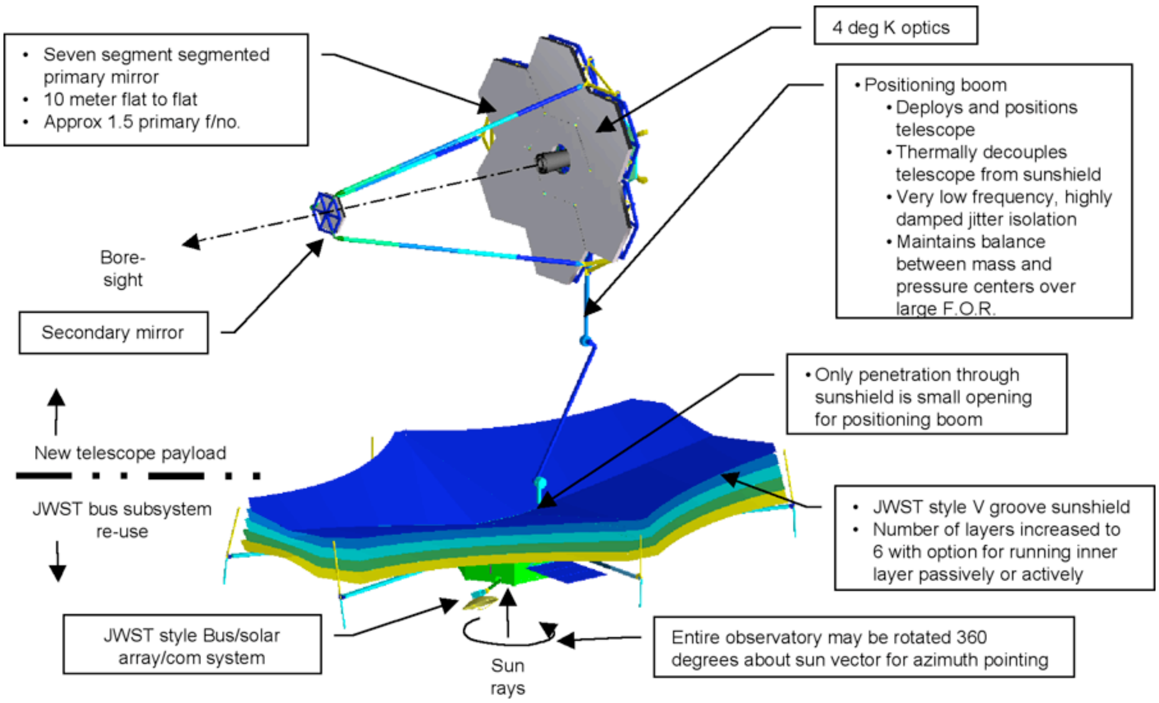

Figure X-3: Alternate concept of SAFIR telescope deployment. The telescope is coupled to the spacecraft on an articulated boom. This deployment may be highly enabling with respect to SAFIR design and operations.

Alternative Orbital Venues

SAFIR benefits strongly from the careful consideration of orbital venues for JWST, and a halo orbit around Earth-Sun L2 is chosen for a number of reasons. The L2 location is an equilibrium point 1.5 $\times 10^6$ km (0.01 AU, 236 R_E) from the Earth where forces are balanced in the dynamical equations of motion. Viewed in the Earth-Sun rotating frame, centrifugal forces balance gravitational forces here. The dynamics of the Lagrange points are well understood, as is the natural environment there, and four missions have been sent to two of the three collinear libration points – L1 and L2 (ISEE-3, SOHO, ACE, and WMAP) – which are symmetrically placed on the Earth-Sun line. While the Lagrange points are easy to model as the circular restricted three body problem, other forces, such as radiation pressure, other gravitational perturbers (Moon, Jupiter, etc.) and orbital non-circularity cause perturbations. As a result of these, and since the L2 point is a saddle point of gravitational potential, some stationkeeping is required to stay there. The most important point is that as a result of our study efforts, we see no reason why an L2 venue for SAFIR would be any less enabling than it has been determined to be for JWST.

There are many trades that need to be considered for optimum orbital venues for large infrared observatories and, in the spirit of early planning, we briefly address alternative venues here.

While LEO and GEO are the most accessible venues in terms of launch and deployment, and offer high bandwidth data links, they are clearly unsuitable for SAFIR, as well understood from JWST studies. Passive cooling to the degree needed for these telescopes is very difficult in close proximity to the Earth. For a Sun-synchronous polar orbit (e.g. IRAS), which is energetically somewhat disadvantageous compared to a more equatorial orbit, the observatory could be continually rotated to keep both Earth and Sun directions constant in the spacecraft reference frame. This would require two large radiation shields for the OTA, on the Earth side, and one on the Sun side. For a telescope fixed to the solar shields, as for JWST, and even for a boom-deployed telescope as described above, the relatively short orbital period would not permit integration times of more than a few minutes on a given astronomical source, and would seriously compromise the field of regard of the observatory. More equatorial orbits would not permit both the Sun and Earth to be shielded simultaneously, and would add the thermal equilibration and power complexity of working through shadow passages. While the data bandwidth from such orbits is, in principle, very high, ground stations would have only short period access to the observatory without reliance on a TDRS system. Finally, the very large shields required for SAFIR and JWST, and their intolerance for penetrations, make space debris in LEO a very significant mission threat – a threat that is orders of magnitude higher than the meteoroid threat in either GEO or at L2.

Drift-away heliocentric orbits, as has been used for Spitzer, were considered for SAFIR. The Spitzer Earth-trailing orbit, in which the spacecraft drifts away from the Earth at about 0.1 AU/yr offers obvious simplifications in terms of station keeping and orbit maintenance compared with L2, and shares with L2 a relatively constant and simple thermal environment. The large distance places a serious constraint on comm links to the observatory, however. While Spitzer is baselined for an average data rate of 85 kbps, larger science arrays on SAFIR lead to data rates at least ten times higher (see Section VI). Furthermore the lack of expendable cryogens on the baseline SAFIR allow for a scientific lifetime that substantially exceeds the fixed 5-year lifetime of Spitzer, by which time the communication baseline is already much of an AU for such a drift-away orbit. Of some interest for a drift-away option is an out-of-plane trajectory. While such a trajectory adds energetic difficulty to the communication difficulty, it offers some value to high ecliptic latitude science in terms of lower zodiacal background. It is this background which limits performance for short wavelengths. Models of zodiacal emission suggest, however, that the zodiacal cloud at 1 AU is fairly thick, with a Lorentzian half-height of almost 0.3 AU (Clark et al. 1993 Astron. J. 105, 976). As such, SAFIR would gain only modestly in background reduction at the price of a large distance. We note that a drift-away orbit is inconsistent with any possibility of servicing for SAFIR.

A larger benefit in background reduction is achieved from larger heliocentric distances, although the penalty on data rates would be even more substantial. We have considered, as a strawman example, advantages in stationing SAFIR at 3 AU. Aside from extended transit time, propulsion requirements for sending SAFIR to large radial distances are not much more challenging than to send it to L2. At such a distance passive cooling would be vastly more efficient because of the reduced insolation, and to the extent that supplementary active cooling is a major component of the SAFIR power budget, that largely offsets the penalty in power generation from solar panels. While models of the dust distribution suggest that the zodi optical depth is only a factor of two or so lower at 3 AU, the dust is much colder, so the photon background loading on the Wien side of the curve is dramatically reduced. As shown in the schematic figure below, this can be substantial at short wavelengths, but not highly enabling even at the short wavelength end of the SAFIR bandpass, and virtually irrelevant in the submillimeter. While larger heliocentric distances may offer advantages in telescope cooling, we believe that it will always be cheaper to add more sunshades to a SAFIR than to go to large distance from the Sun.

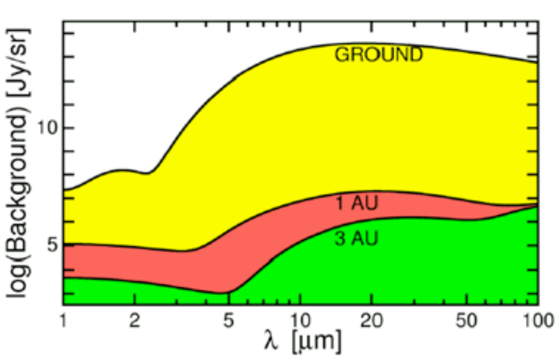

Figure X-4: Model of the zodiacal background at 3 AU is compared with that for 1 AU and, for scale, with a simple model of the ground-based sky brightness. It can be seen that for a zodi-limited telescope at short wavelengths, there is value in a 3 AU site, but this advantage largely disappears for SAFIR wavelengths.

More speculative opportunities for SAFIR operations that deviate substantially from the JWST venue deserve mention.

The Earth-Moon L1 location puts both the Earth and Moon at large enough distances that, if unblocked, they would contribute only slightly to the temperature of SAFIR, but would offer challenges for scattered light management. While we do not propose SAFIR operations at E-M L1, such a site has been proposed for a "gateway" facility in the context of the Exploration initiative and possible human involvement for SAFIR servicing and on-orbit testing. Such a concept is discussed in more detail in a Section XIV below.

Stationkeeping of SAFIR exactly along the Earth-Sun line at Earth-Sun L2 would achieve blockage of 90% of the light from the Sun (angular size 0.526°) by the Earth (angular size 0.487°) and, like for large heliocentric distances, could thus offer simplifications in thermal control. The precision required for stationkeeping is challenging both from a navigation and propulsion perspective, however. The Earth Atmospheric Observatory (EAO), an RASC concept developed at LaRC has addressed this question, and is of interest in this regard. The EAO concept is to view the limb of the Earth's atmosphere as illuminated from behind by the Sun. Baselined for operation in this region of 90% shadow, EAO would use a 2-3 kWe Stirling radioisotope generator to provide power for spacecraft bus ops including comm as well as solar-electric thrusters for precision stationkeeping (within 200 km of the Earth-Sun line!) Assuming the availability of such a power source, the possibility arises of stationkeeping SAFIR not exactly at L2 (1.53×10^6 km from Earth), but just inside the umbral apex (1.37×10^6 km from Earth) where the Sun is entirely eclipsed. Such a site would be profoundly cold, and could allow SAFIR to work with a minimal shield and no active cooling at all. While we have not done the flight dynamics analysis of this option to derive a propulsion requirement, we believe it deserves investigation. The fact that solar radiation pressure forces disappear at such a location allows some simplification compared with an illuminated site. While the solar umbral apex is inside of the Earth-Sun L2 point, the gravitational potential energy saddle is quite broad, and may not require a large increase in propulsion over that needed for stationkeeping at the L2 distance. It is worth noting in this regard that while the umbral apex is inside of L2 for the inner planets, it is *outside* of L2 for the gas giant planets, such that the L2 point along the solar vector at those planets is entirely in shadow, a fact that may be advantageous to some descendant of SAFIR.

Detailed Considerations of Earth-Sun L2 as the Optimal SAFIR Venue

As discussed briefly above, Earth-Sun L2 appears to be an optimal site for SAFIR operations. The thermal stability, with the Earth and Sun in generally the same direction and mutually shieldable, abundant ground contact opportunities at a modest distance, virtual absence of human-deposited debris, and minimal stationkeeping requirements contribute to this optimality. We briefly review other considerations. The natural environment at L2 has been considered in some detail for JWST, and is summarized in a recent report by the Space Environments Team at GSFC (Evans 2002).

The orbit envisioned for SAFIR is identical with that proposed for JWST – a halo orbit around the L2 point. Ideally such an orbit would be one which circulates around the L2 point in a closed loop that repeats itself in the YZ plane, such that the spacecraft would never see eclipses of the Sun. The radius of this loop is an operational trade. See Figure X-5 below. A larger radius (e.g. 7.5×10^5 km, which is our operational baseline) puts more constraints on solar shielding, since the Sun and Earth are more than 20° apart, but requires a low delta-V for trajectory injection (we budget 35-50 km/s). A small radius (e.g. 3×10^5 km) keeps the Sun and Earth closer to each other as seen from SAFIR, simplifies a solar radiation shielding strategy and provides an optimal field of regard, but requires a much larger injection delta V. With a mass similar to JWST, injection into a halo L2 orbit would follow closely the flight dynamics requirements for that mission, and propulsion requirements (launcher, etc.) are reviewed below.

If boom deployment is not used, and SAFIR uses scaled JWST architecture, the sunshield will be substantially larger. This bears on stationkeeping for SAFIR, as the main perturbing force on the observatory is radiation pressure on the shield (even larger than perturbations from the Moon and other planets). At 1 AU, with high reflectivity shields normal to the Sun, a radiation pressure of $\sim 10^{-5}$ N/m^2 will come to bear, totaling several millinewtons for the entire structure. This corresponds to about 2×10^{-5} of the gravitational acceleration from the Sun. It is worth noting in this context that the force from radiation pressure at L2 is several orders of magnitude larger than the force of the quiescent solar wind. Even in a solar storm, the pressure of the solar wind would not be comparable to radiation pressure. The outward directed (+X) solar radiation pressure on SAFIR has the nonintuitive effect of biasing the otherwise balanced orbit in the sunward direction, slightly inside of the nominal L2 distance.

The plasma environment at L2 is also an important factor, though the charged particles in the solar wind do not have sufficient energy to penetrate normal spacecraft shielding. While the Earth's magnetotail, in which there is some concentration of charged particles, points towards L2, that Lagrange point is relatively far from the main magnetosphere, which is largely at $<20R_E$ distances. It can be assumed that as SAFIR executes a halo orbit around the Sun-Earth line, perturbations of the solar wind will put it occasionally in the magnetopause. The main effect that can be anticipated from this particle flux is a slow degradation of solar panels and shield reflectivity. We believe, however, that the plasma environment at L2 is relatively benign compared to that which would be encountered in LEO. In particular, the low kinetic energy results in little risk for spacecraft charging.

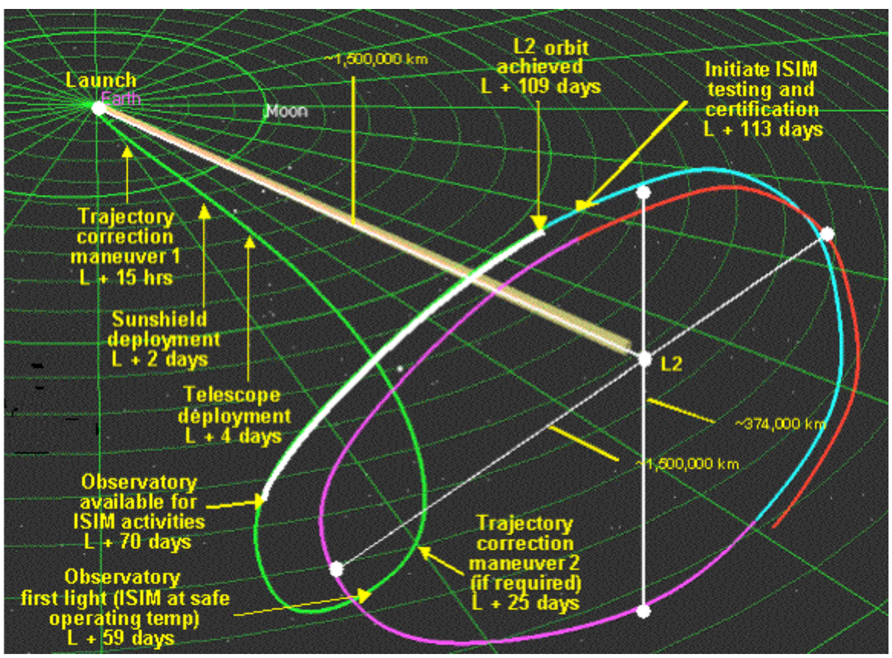

Figure X-5: The insertion trajectory of SAFIR can be considered to be identical to that for JWST, which is shown in this figure. SAFIR will orbit L2 at a large enough radius to avoid eclipses, and all such orbits around L2 have periods of six months. Operations in the Integrated Science Instrument Module (ISIM) can be started before deployment into the L2 orbit is complete.

Because of the very strong reliance on the sunshield for passive cooling by SAFIR, degradation of the sunshield at L2 must be considered. These considerations are largely identical to those for JWST.

While gradual degradation of the optical properties of the shields are expected, and can be managed, large holes in the shield from complete penetrations could seriously compromise the mission, especially if a large penetration of all shields happened. While the penetration properties of several mil Kapton film are not well understood, impact rates of order 1 m^2/yr for 0.1 mm meteoroids are anticipated and 0.0001 m^2/yr for 1mm meteoroids. These must be assumed to have velocities of order 20-30 km/s. Similar considerations apply to design studies of inflatable and membrane space structures, which are receiving new attention.

Although not part of the SAFIR baseline concept, Sun-Earth L2 offers opportunities for telescope servicing, repair, or retanking, either in situ (more likely by robots than humans) or via low delta-V transport to a service shipyard ("gateway") facility at Earth-Moon L1. This option is discussed in more detail in Section XIV below.

Launch Vehicles

Assuming the need for a commercially available ~5m fairing (see Section VI above), and the capability to send ~7700 kg (wet mass at launch including contingency allowance, see Team X report) to Earth-Sun L2, launcher needs can be established. As for JWST, we envision direct injection to L2 as described above which, depending on the exact circumstances (e.g. halo diameter, lunar assist), corresponds to a c_3~-0.7 orbit. These capabilities can be met with existing U.S. EELV commercial configurations. A Delta IV 4050H-19 (launched out of a continental US site), which offers a 4.57 m ID usable payload diameter fairing in a 19 m usable length easily meets our needs. This configuration involves the standard Delta IV core including a cryogenic second stage, with two additional common booster core strapons. This performance of this configuration exceeds the mass-to-L2 requirement for SAFIR by at least 20%. In the Delta family, the next smaller commercial configuration is presently the Delta IV 4450-14, a single core with strapon solids. This configuration provides significantly less thrust than needed for our baseline SAFIR, and the smaller fairing length would likely require a much higher degree of folding for the secondary truss supports.

Within the presently available Atlas family, the Atlas V 551 with a 5 m diameter short (20 m length) payload fairing can also meet our propulsion needs, though only marginally. This configuration uses a standard booster core with solid strapons. The proposed Atlas V-H with two strapon common booster cores has a similar configuration architecture and projected capability to that of the Delta IV-H, but has not yet been tested. Outside of the EELV umbrella, and assuming availability of international options, the Ariane V offers similar performance to the Delta IV 4050H-19, and would offer similarly large performance margins to the SAFIR program.

As noted above, non-commercial versions of these launch vehicles with larger shroud sizes have been proposed, and such implementations would be highly enabling to SAFIR, which is more volume-limited in launch capability than it is mass-limited. Implementation pathways for the new Vision for Space Exploration have considered development of new heavy lift systems, and such systems would likely offer a SAFIR program attractive options.