ARISE Antenna

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ARISE Mission

Supermassive black holes are among the most spectacular objects in the Universe, and are laboratories for physics in extreme conditions. Understanding the physics of massive black holes and related phenomena is a primary goal of the ARISE mission. The scientific goals of the mission are described in detail on the ARISE web site http://arise.jpl.nasa.gov and in the ARISE Science Goals document edited by James Ulvestad of National Radio Astronomy Observatory (April 1999). The following paper, as the title suggests is not intended to be a comprehensive description of ARISE, but deals only with one aspect of the ARISE mission – the inflatable antenna which may be of greater interest to the attendees of the Large Optics Challenge Workshop.

ARISE Antenna System Requirements

The ARISE antenna must meet several very stringent requirements in the areas of performance, frequency coverage, sensitivity, polarization, calibration accuracy sky coverage and the receiver system temperature.

Observing frequencies are at 5 GHz, 22 GHz, 43 GHz and 86 GHz. These frequencies correspond to wavelengths of 6 cm, 1.4 cm, 0.7 cm, and 0.35 cm respectively. The maximum instantaneous bandwidth observed is 2 GHz. Tunability of the instruments for the ranges 5-10 GHz, 18-26 GHz, 40-45 GHz, 80-95 GHz is desirable. The ARISE design will maximize the instrument sensitivity, within the bounds of technological constraints and mission cost. Antenna size, system temperature, bandwidth and coherent integration time will allow for a detection threshold for a continuum radio source of about 1 mJy at 8 and 22 GHz, 10 mJy at 43 GHz, and 100 mJy at 86 GHz. Dual circular polarization is required. Isolation between the two polarizations should be 3% or better in voltage. Amplitude calibration of the ARISE antenna will have an accuracy of 5% including the antenna gain in the direction of the source and the total system temperature. The receiver will be cooled so that total system temperatures are less than 12 K at 8 GHz, 16 K at 22 GHz, 24 K at 43 GHz, and 45 K at 86 GHz. A Sun avoidance angle of less or equal to 30 degrees is required. The observing duty cycle on a science source must average at least 80% over the course of a full orbit. A typical imaging period is one orbit.

The microwave performance of the antenna will be sufficient to meet the sensitivity requirements at all frequencies. A single antenna beam is necessary with on-axis aperture efficiencies as high as possible. Sidelobe levels are of secondary importance. The “effective” RMS surface error of the overall antenna system (including any correction method) should be 0.22 mm or better

The antenna front-end is composed of a main reflector (antenna) of aperture 25 meters, a mechanically shaped subreflector of diameter 1.6 meters, and of a set of RF receivers (horns) located at the focal plane. The main reflector uses inflatable structure technology (although other options are also being considered), as it permits low mass and low cost. The inflatable antenna is composed of a pressurized lenticular structure (one side is the reflector, the other a RF transparent canopy), and a space rigidizable support structure (struts and torus), as shown in **Figure 1**. Since, at the time of writing, the reflector RMS surface precision exceeds the specified requirement, a mechanically shaped subreflector is presently envisaged to adaptively correct for the main reflector surface distortions. This subreflector is composed of a thin composite sheet, whose shape is driven by a set of actuators. Operationally, the subreflector shape will be calibrated and set before each new source observation and in most cases after each eclipse. A metrology system will be used for calibration of the subreflector. The most promising technique for the metrology systems identified to-date is photogrammetry, involving a video mapping of the reflector surface. Photogrammetry utilizes two or three video cameras located at key points on the spacecraft, one or several light sources, and a surface reconstruction algorithm. Once the subreflector is calibrated, the signal is then focused onto four receivers, one for each frequency band. Optionally, to improve

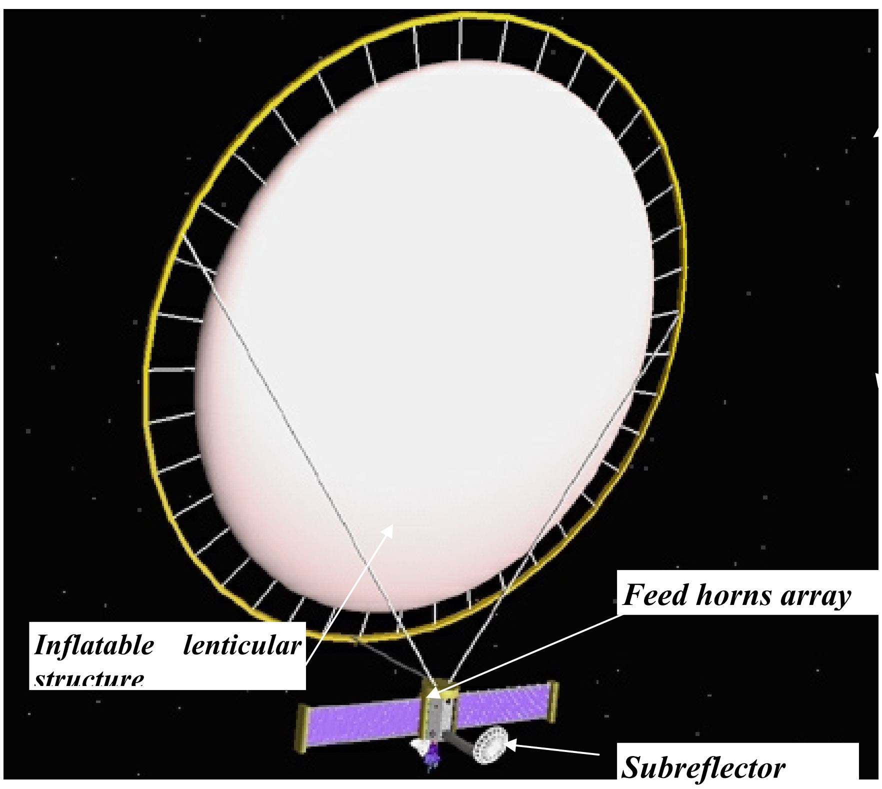
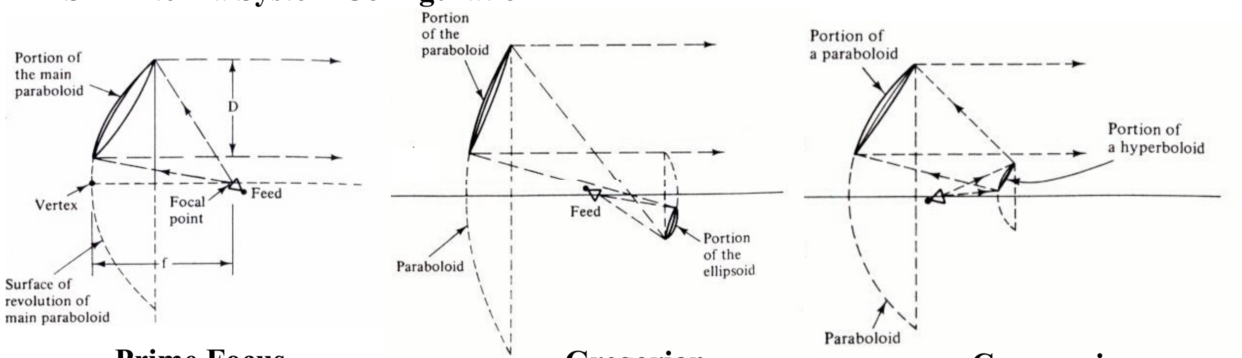


Fig. 1: ARISE “optics” configuration

the performance (antenna overall efficiency) at 86 GHz, an adaptive compensation feed array of 19 elements might be used to electronically compensate for remaining wavefront distortions.

ARISE Antenna System Configuration



Prime Focus **Gregorian** **Cassegrain**

Fig. 2: Various off-axis configurations

The ARISE reflector configuration has been selected after evaluation of various reflector antenna geometries, and resulted from early trade-off between on-axis and off-axis configurations. It was determined that an off-axis configuration offered better science performance (less obscuration) and fewer constraints on other factors in the spacecraft design. Four different off-axis configurations were then evaluated: Prime Focus, Gregorian, Cassegrain, and Schmidt Cassegrain (see **Figure 2**). The following criteria were employed: dynamics/structural stiffness, thermal stiffness, RF performance, mass, complexity, deployment reliability and alignment. It was determined that the Gregorian off-axis design uses a smaller and less complex structure and secondary reflector than Cassegrain types. Furthermore, the Gregorian off-axis system offers the possibility of a mechanically shaped secondary that is reasonably sized and controlled. Based on these arguments, a Gregorian dual-reflector antenna system was selected for ARISE. The geometrical parameters, which fully define the reflector are given below:

On-axis “mother” reflector diameter	D = 50 m
On-axis “mother” focal length	F = 11.55 m
Off-axis sub-aperture diameter	D = 25 m
Tilt angle between main reflector and subreflector axis	β = 5.67 deg.
Inter-foci distance	L = 2.4 m
Subreflector eccentricity	ε = 0.555

High Precision Inflatable Reflector

Description

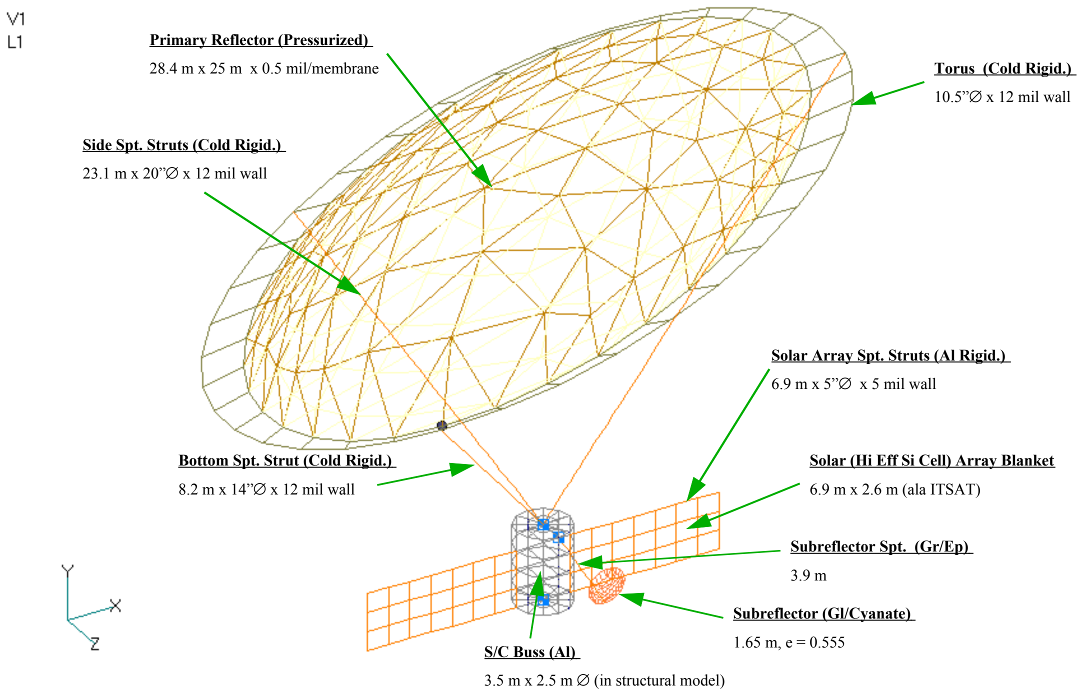


Fig. 3: ARISE structural diagram

The ARISE primary reflector is comprised of a reflective membrane with a RF transparent front canopy to complete the inflated lenticular envelope. The lenticular structure is combined with a tubular peripheral support torus forming a large, lightweight, yet relatively stiff space structure. To minimize membrane stress, the lenticular structure is pressurized with less than 4 x 10^{-4} psi of N_2 and attached to the torus ring with constant force springs in a "trampoline" fashion.

The antenna assembly is aligned and attached to the spacecraft using three tubular support struts that are inflation-deployed from a stowage canister located at the top of the spacecraft bus. At the torus, the antenna support struts are kinematically attached at 120° intervals. They are designed with optimum diameters, wall thickness, and lengths to give mechanical rigidity (bending, torsion) yet minimal obscuration and shadowing of the primary (see **Figure 3**).

Rigidizable support structure technologies are used wherever possible on ARISE to minimize the need for "make-up" inflation gas. The primary reflector torus and antenna support struts maintain their mechanical stiffness and shape by using sub glass transition temperature (sub-Tg) rigidizable materials. SubTg rigidization utilizes composite fibers in an elastomeric matrix, which becomes rigid below a tailorable glass transition temperature (Tg). The elastomer is chosen such that its Tg is above the equilibrium temperatures of the deployed structure expected during the entire mission. In this way, the structure will remain rigid through the mission. Generally, the spacecraft temperature before deployment is higher than the deployed equilibrium temperature due to the on-board electronics. Careful selection of the elastomer will place the structure above its Tg before deployment, and below it when deployed, enabling a totally passive rigidization method, requiring no heaters or specialized rigidization hardware. To minimize thermal gradients, these support members will be wrapped in MLI blankets. Because of high temperature conditions, the ARISE solar array blankets will be supported by thin-walled polymer struts laminated with aluminum foil. The strut tubes are initially over-inflated past the aluminum foil yield point. Once the pressure is removed, the stressed aluminum maintains much of the strut's rigidity and shape.

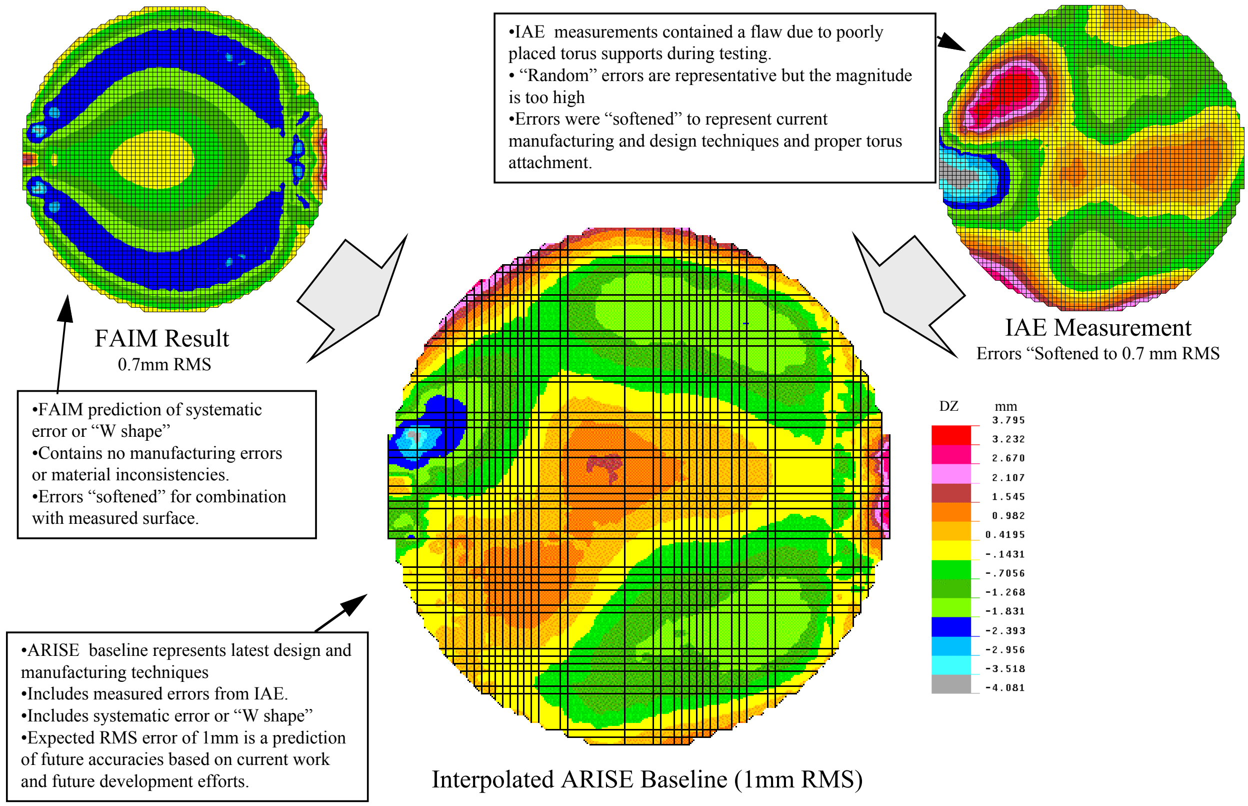


Fig. 4: ARISE Reflector Precision Projection

Reflector surface precision

An essential element of the ARISE design is the reflector precision. At the time of writing, L'Garde has built a 7 meter reflector with 1.7 mm RMS accuracy, and is predicting 1mm RMS accuracy on reflectors of 25 meter or more with appropriate development effort. Ground measurements have yielded surface shape accuracies between 0.67 mm and 1.3 mm RMS for gored 3 meter diameter systems, with 0.8 mm to 0.96 mm as typical RMS values. This is the RMS deviation of the measured surface from a best-fit paraboloid. Measurements also demonstrate that surface slope errors of 1 milliradian or less are feasible. It must be noted that these surface accuracies and surface slopes were achieved using off-the-shelf materials with the reflector formed from flat gores. Although inflatable reflectors using current technology do not have the required accuracy for use as space telescopes, L'Garde believes that the enabling technologies such as improved material properties, better material uniformity, and greatly-improved manufacturing processes are in the very near future. At present, inflatable reflectors are fabricated using flat gores joined together at the seams. The use of doubly-curved gores will yield better accuracy.

To generate a credible estimate of the magnitude and distribution of the 25 meter ARISE antenna error, ground measurements from the 14 meter Inflatable Antenna Experiment (IAE) reflector were utilized. The IAE reflector shape is shown in the top right of **Figure 4**. It was measured during a ground test in preparation for flight. During the test, one of the torus supports slipped and was not discovered until after the measurements were taken. Nonetheless, it is considered representative of the types of errors seen in this class of reflector, albeit somewhat exaggerated. As a projection of the type of errors that will be seen in future reflectors, which are expected to be more systematic, a FAIM software model prediction of the reflector shape has been utilized.

Structural and thermal analysis

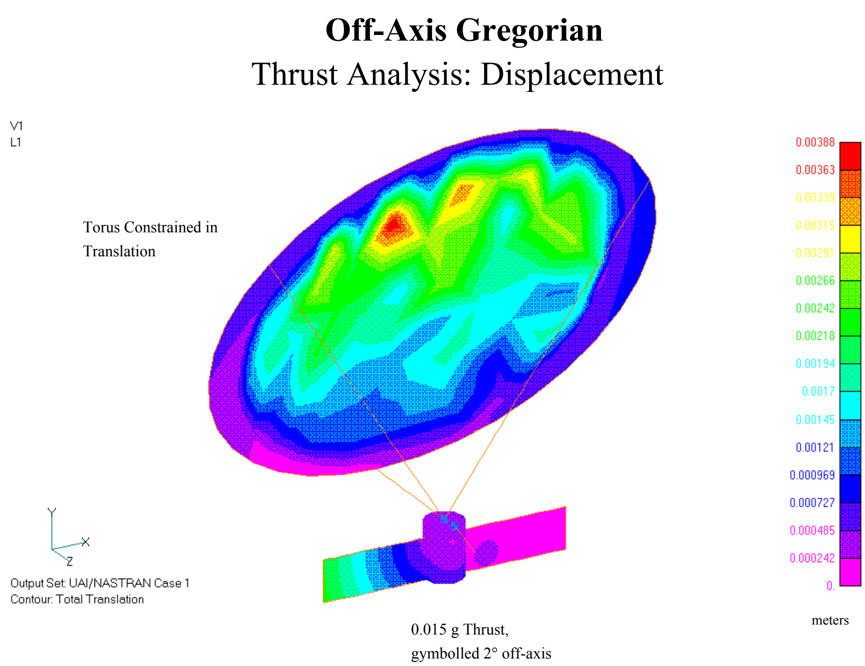


Fig. 5: Structural displacements due to a static thrust maneuver loading

Of special concern were dynamic response, inertial static loading, and thermal distortion effects on antenna shape and alignment. Because of the "soft" nature of inflatable structures, and the temperature sensitivity of polymeric membranes, structural and thermal analytical models were created that had more resolution than simple static diagrams and lumped masses. The structural model consisted of over 700 elements that closely approximated off-axis parabolic curvatures, strut orientation, subreflector alignment, solar array geometry, and spacecraft mass distribution. Special attention was given to membrane elements, polymer properties, and tubular geometries, all critical to inflatable structural behavior. The thermal model was based on the same nodal geometry and properties, allowing a direct one-to-one correspondence between temperature profiles and structural elements.

Figure 5 shows the resulting structural displacements due to a conventional, static (without transients) thrust maneuver loading. A thrust vector of 0.015g at 2° off-axis was applied at the base of the spacecraft bus in order to study worst case asymmetric inertial loading. A maximum displacement of 4 mm was predicted. Since thrust maneuvers will not be performed during science observations, it was felt, based on these preliminary results, that thrust/slewing maneuvers would not create critical/catastrophic stress or strain conditions.

Thermal analysis

Another issue effecting on-orbit reflector surface precision is the thermal load expected during the mission. In the highly elliptic orbit utilized by the ARISE configuration, and the unlimited pointing directions required for the mission, significant thermal gradients are endured by the reflector. In the elliptic orbit the equilibrium temperature of the spacecraft can vary quickly and off-pointing sun angles and shadowing can cause dynamic thermal gradients. The effect on the reflector is to expand in hot regions and to contract in cooler regions distorting the reflector shape.

Deployment

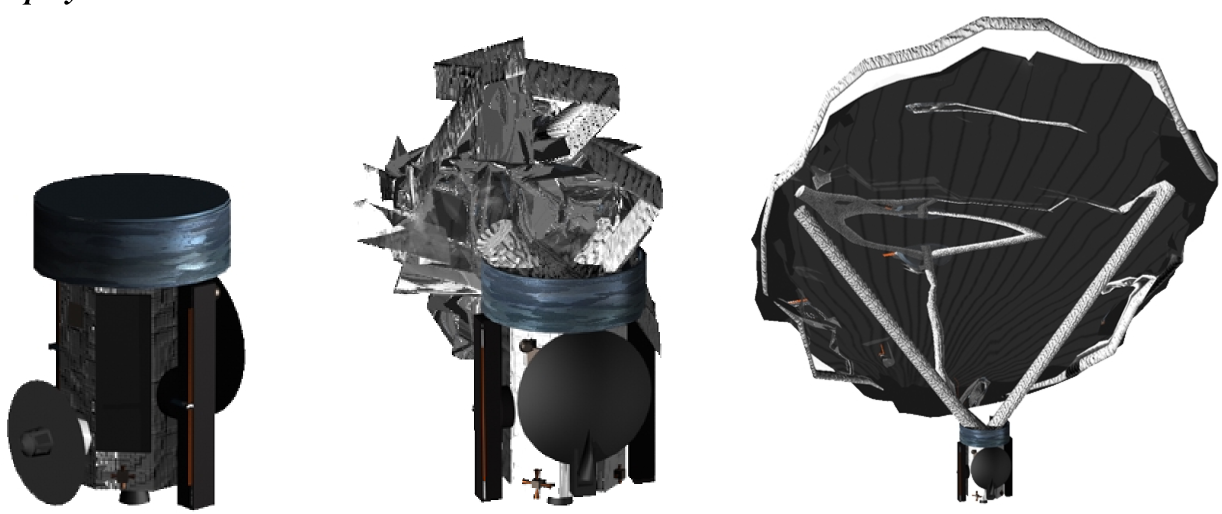


Fig. 6: Inflatable antenna deployment sequence (by TDM Inc.)

The inflatable antenna deployment sequence is shown in **Figure 6**. L'Garde has developed a new flexible enclosure canister. The concept promises significant weight savings over the solid canister designs. The lenticular structure and torus are stored inside a membrane container designed to withstand the increased internal pressure during ascent of the payload. Upon deployment, the top portion of the membrane is released by a pyrotechnic event. The petals open, releasing the lenticular structure and torus. Some residual gas in the lenticular structure is possible (as was experienced in the IAE flight experiment) and the lenticular structure is expected to billow out slightly to relieve any internal pressure. After initial deployment the L'Garde Deployment Devices (LDD) are initiated. The next picture in the sequence of **Figure 6** shows the LDDs deploying the struts. Note the torus and lenticular structure are still uninflated and suspended between the extending struts. The next pictures show the struts at full deployment and the torus partially inflated. The lenticular structure is still not inflated. The inflatable solar array then gets deployed (for a simpler combined inflation system), followed by the inflation of the lenticular structure. Development of the deployment sequence draws extensively on the lessons learned from the IAE flight experiment.

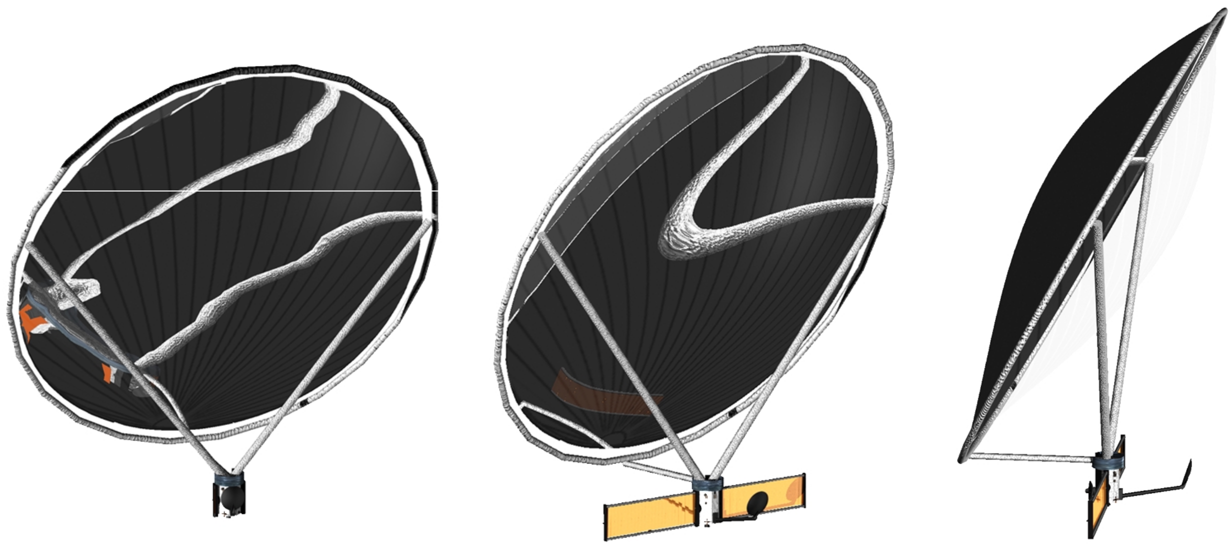


Fig. 6 Continued: Inflatable antenna deployment sequence (by TDM Inc.)

Subreflector (Mechanically Shaped)

The sub-reflector design is adaptive to compensate for mirror figure distortions in the primary mirror and opto-mechanical structure system. The inflatable primary mirror may require compensation for two different types of distortions. The first of these are those distortions that are relatively stable with respect to time. These errors will be seen at the time of the first inflation of the primary, and to a certain degree can be predicted by modeling. The second group of mirror figure deformations are those time-varying deformations resulting from thermal effects such as solar heating of the primary or its support structure, dynamic effects relative to spacecraft pointing, or structural creep and relaxation of strains in the structure.

This second group of deformations in the system is time-varying. However these variations are very slow relative to the rate of response of contemporary "adaptive" systems. The responsiveness of "adaptive optics" in the sense in which the term is normally used is in the 10's of kilohertz regime. These contemporary adaptive systems respond to rapid phenomena, such the movement of the atmosphere in a high-energy laser beam. The adaptive optics system for ARISE responds to changes which occur at a frequency around a hundredth of a hertz or less. Therefore the "adaptive" aspect of compensating for these errors is a relatively simple one, given there is over six orders of magnitude difference between what is required for ARISE relative to other contemporary adaptive systems.

Adaptive secondaries for radio telescopes have been investigated by the NRAO, the MIT/Haystack Observatory, and elsewhere. The goals of these activities have been primary mirror gravity-sag compensation schemes, which permit a lower cost primary. Recently Composite Optics, Inc. (COI) of San Diego has been working with radio telescope surface adjustment technologies for several years. This COI effort has been highly successful, and has demonstrated surface adjustment on surfaces as large as 3.3 meters, using software to define adjustment changes that reduce the surface RMS deviations. Given a defined surface goal, the adjustment process can be utilized to change a given surface into the desired corrected surface. Moreover, the predictive models for these changes in surface are sufficiently accurate that the mechanical surface adjusters may be run open loop. This present device demonstration at COI establishes that a flight version may be engineered as an extension of technology in existence at the time of writing.

Subreflector Description

The proposed subreflector design has a lightweight reflective surface comprised of graphite composite. This mirror surface, supported by a backup structure or "strongback," will form the secondary reflector surface. The reflective surface will be fabricated to a shape that compensates for the known primary surface errors, and will be fitted with adjusters between the backup structure and the mirror surface to permit precise regulation of the secondary mirror shape. A subframe behind the strong back will permit solid body motion of the mirror in tip, tilt, and piston directions, as shown in **Figure 7**.

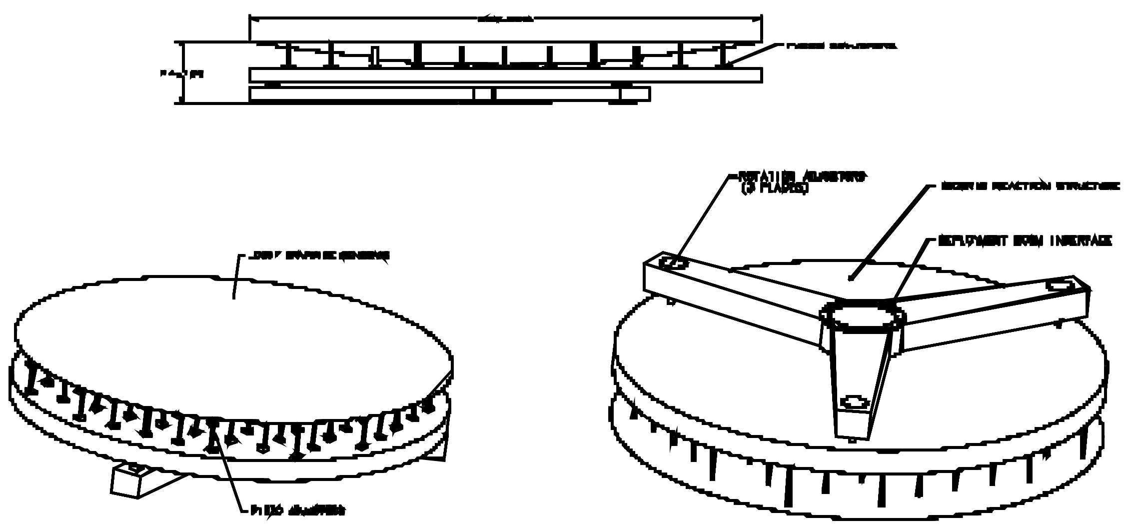


Fig. 7: Subreflector with adjustable surface figure, Technology demonstration concept with Picomotors^{TM}

Conclusion

The ARISE team comprehensively studied structural, thermal and environmental effects of an inflatable antenna as part of an overall spacecraft system. The ARISE inflatable antenna is also one of a few concepts currently under study that meet the large optics challenge goals: the diameter of the structure is 25 meters and its aerial density approximately 0.44 kg/m^2. The effective surface accuracy of the antenna is 0.2 mm RMS, which is almost three orders of magnitude lower than what is desired for optical surfaces. The challenge in the upcoming years will be to make great improvements in the surface accuracy of inflatable reflectors building on the ARISE technology development efforts.