

A LARGE S-BAND ANTENNA FOR A MOBILE SATELLITE

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When a satellite system communicates with a very small earth terminal such as a handheld or automobile based unit, a high power flux density on the ground is required for a high quality link to be established. For the case of Digital Audio Radio Satellites (DARS) that operate at S-band, a combination of high power amplifiers and a large aperture reflector antenna on the satellites provides the required flux density. This paper will discuss the design challenges that a large aperture reflector and its integration on the satellite create for the design team.

The satellite will provide digital audio, video and data broadcasting services to the regions of Japan and Korea, while tightly controlling the radiation pattern to avoid interference to other regions in Asia. This is accomplished by use of an array feed illuminating a 12 m offset paraboloid reflector. This design needs to be approached from a system perspective with well thought-out integration, alignment, and test practices. The paper will discuss some of the issues that arise when pursuing a proper system design, and the verification technique that has led to a successful In-Orbit-Test (IOT) for this antenna system.

Introduction

Some communication satellites require a large aperture main antenna. The case of an S-band communication link covering a small region on the earth with a high flux density is one such application. A mobile satellite to provide S-band communication to small user terminals on the ground in Japan and Korea has been successfully designed and launched. In order to achieve the high flux density required by a hemispherical beam receive antenna mounted on automobiles, a combination of high satellite antenna gain and high satellite power is used. The result is excellent link quality as the automobile maneuvers its path within the roadways of the coverage region. The large aperture antenna is the subject for this paper. A 12 m projected aperture paraboloid AstromeshTM reflector is used on the satellite to achieve high beam directivity over the desired coverage regions. This structure is much larger than the satellite and it is necessary to stow this unfurlable structure into a relatively small volume in order to fit into the launch vehicle fairing. The packaging of this stowed structure, and the reaction caused by the deployed structure when operating in-orbit, provide interesting design challenges. These

challenges will be discussed in detail in the following paragraphs.

A System Solution is the Correct Approach

This is truly a multi-faceted design problem. Structural and electrical design solutions have been traded for the following specific areas:

- The reflector must be stowed in a small volume for launch.
- The stowed reflector is inherently offset from the center of mass of the satellite and must not cause problems in the severe vibration environment.
- The mechanisms that deploy the reflector on orbit must be ultra reliable, and accurately position the reflector surface.
- The deployment control system should be coordinated with the mechanism such that a reliable system of detecting fault and reacting to contingencies exists.
- Once deployed the impact of the large structure on the satellite control system must be minimal.
- An acceptable process that couples test results with analyses needs to be developed to predict antenna performance since direct measurement is impractical.

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In general, an optimum solution for any one of these design problems will be non-optimum for the other areas. This requires a system design approach to be adopted where the solution for each design problem has acceptable impacts for the other areas of concern.

A Small Stowed Volume is Required

The selected reflector configuration is an expandable truss structure that compresses into less than 0.4% of the deployed volume when stowed. The small stowed volume allows the use of standard spacecraft bus and launch vehicle fairings which minimizes cost and improves reliability. The design challenges involved are numerous and must address many mechanical, structural, thermal and reliability issues, but first the deployment configuration must allow free movement of the membrane that becomes the deployed reflecting surface. This must be accomplished in a very reliable way so that there is no concern of tearing the membrane during deployment. This will be discussed in a later section devoted to the reflector design.

The Stowed Configuration is a Mass Offset from the Satellite Axis

To satisfy this design constraint, the method of attachment and the number and placement of the attachments needs to be designed in concert with the satellite structural design. A satisfactory arrangement of hold-down positions was determined that provided high enough reflector assembly natural frequencies to be sufficiently decoupled from the satellite natural frequencies during launch. This was an iterative process with mutual cooperation between the satellite structural designer and the reflector structural designer. A later figure (Fig. 2) will show the reflector on the satellite in its stowed and deployed views. This solution was satisfactory to structural designers, antenna mechanisms designers, and the reliability experts.

The Deployment Mechanisms Must be Ultra Reliable

The deployment of the reflector requires a number of precision motions to take place. First the boom used to deploy the reflector from the satellite must allow for the first motion of the assembly away from the satellite upon release of the launch restraints. Next, the boom hinges are actuated through a set of coordinated motions to bring the boom to its final position, which includes a full rotation of the reflector bundle. Finally the stowed reflector, must be expanded at the end of the deployed boom, to provide the final reflector configuration with the reflecting mesh surface in its final position. This sequence of events will be explained in more detail in the reflector design section.

The deployment control system should be capable of monitoring boom and reflector deployment health via

load sensors and other telemeters, and if predetermined parameters are exceeded, deployment should be stopped without requiring the explicit interaction of ground controllers.

The Deployed Reflector Assembly must be Compatible with the Satellite

This is a satellite design issue and primarily affects the satellite control system. The unbalanced nature of the large aperture reflector on one side of the satellite, with no counter-balance on the other side, challenges the control system. During solar flares, a significant force is generated on one side of the satellite and the resulting torque must be counteracted by the on-board momentum wheels. This design challenge has been satisfied by using a four momentum wheel system and by minimizing the drag offered by the reflector. The extremely efficient structural design of the Astromesh™ offers minimum blockage in the form of structural cross section. It also results in an antenna mesh that is highly transmissive to solar pressure and atmospheric drag yet still provides a near-perfect reflector of the S-band RF signals.

An Acceptable Electrical Test Scenario Needed to be Devised

The large aperture makes direct measurement of the antenna radiation pattern testing impractical. The RF analysis tools available today however are excellent and the reflector surface contour measured during ground test is insignificantly distorted from that displayed in-orbit. The parameters that really need to be known accurately are the exact primary pattern from the feed, and the in-orbit reflector surface contour and its location relative to the feed and satellite. Much care was taken to characterize the reflector surface contour by photogrammetric techniques, and the boom mechanisms were tested to characterize the final location of the reflector in the zero gravity environment. This knowledge, coupled with very accurate feed pattern measurements, lead to credible predictions of the secondary patterns to be expected from this antenna assembly in service.

The excellent correlation of these predictions with in-orbit measurements shows that this procedure was appropriate. This represents a cost effect, time saving approach to secondary pattern performance determination.

The Antenna Geometry and Feed Design

In order to achieve a shaped secondary beam from a parabolic reflector, a multi-element feed is used to illuminate the reflector. In general, the outline of the feed array will resemble the footprint of the secondary beam. The geometry for this shaped beam S-band antenna is shown in Fig. 1. It uses a multiple element feed array to provide the two overlapping shaped secondary beams, one for Japan and one for Korea. These two beams are operated

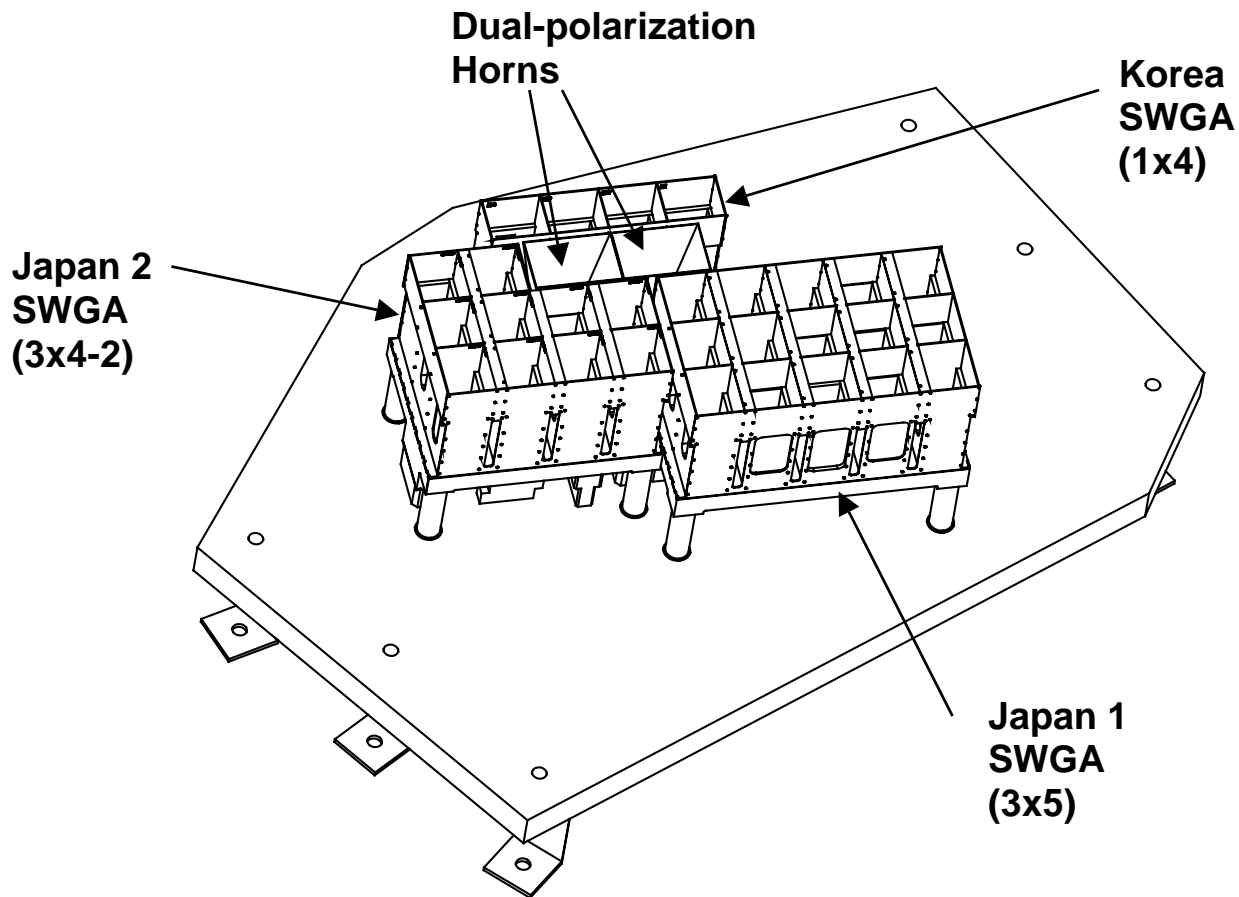


Fig. 1 Multiple beam feed array. The meanderline polarizer and polarizer support structure are not shown.

on orthogonal circular polarizations and use two pyramidal horns in common. This is accomplished by exciting the two horns with an ortho-mode junction (OMJ) that couples the two orthogonal linear polarizations into the common radiating horn. The single linearly polarized radiators are a patented SS/L design that combines the high efficiency compact characteristics of a waveguide slot array (WGA) with the phase control of a waveguide lens. A 15-element unit and a 10-element unit, along with the two common horns, are used for the Japan beam generation. The Korea beam used a 4-element WGA along with the two common horns.

The combination provides low electrical insertion loss with arbitrary amplitude and phase excitation of each individual radiator. These features of the feed are best seen by viewing Fig. 1 which illustrates each of these components.

The dual linear polarizations radiated by the feed are converted to dual orthogonal circular polarizations by use of an external meanderline polarizer fitted in front of the feed radiator. This assembly of components provides the dual orthogonal circularly polarized beams for coverage of Japan and Korea. The feed assembly was

thoroughly tested to characterize the radiation patterns for both polarizations, before and after exposure to the environmental acceptance tests. This data was then used as input to the electromagnetic computer model of the S-band antenna to provide predictions of the secondary beam performance.

Reflector Antenna Design

The system approach required a reflector assembly capable of performing under the following requirements:

RMS Surface Accuracy	< 2.54 mm
Pointing Accuracy (const. + environmental)	< 0.085°
Mass (incl. launch support struct. & boom)	< 110 kg
Stowed Frequency	> 30 Hz
Deployed Frequency	> 0.37 Hz

Reflector Design

The MBSAT Astromesh™ reflector comprises a 12 m projected circular aperture formed by a parabolic mesh surface suspended on a perimeter truss system. The efficiency of the perimeter truss supporting a back-to-back geodesic dome configuration allows a high stiffness-to-mass ratio to be achieved. The cable-deployed truss system provides efficient deployed-to-stowed volume, high

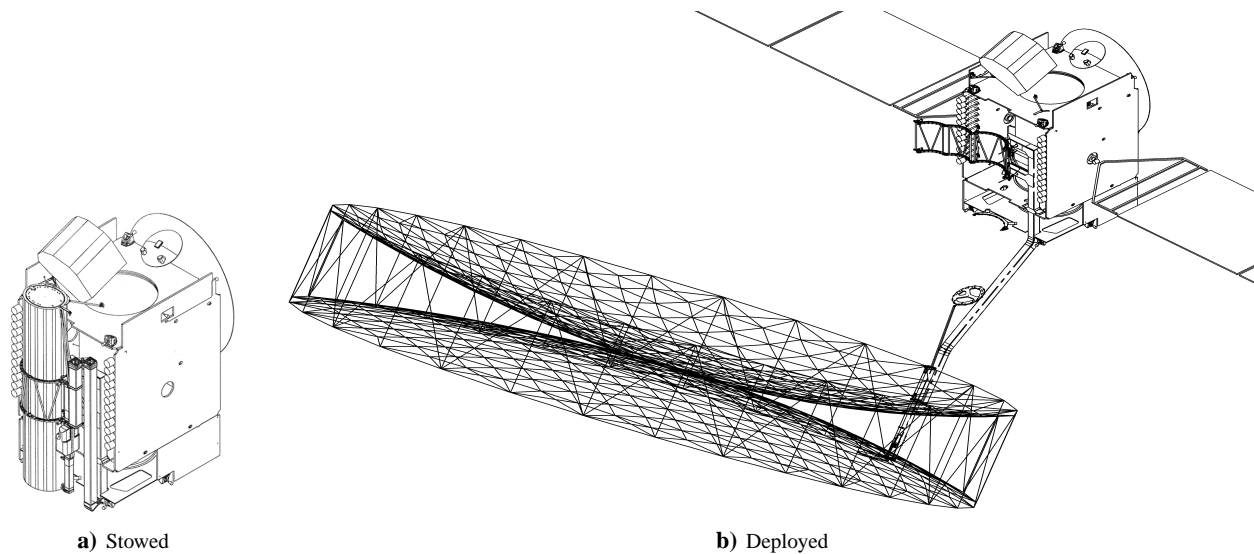


Fig. 2 Reflector/satellite stowed and deployed configurations.

deployment reliability, and comfortable force margins. Two motors were available to deploy the reflector bundle from the stowed to the deployed configuration in less than 40 min. Fig. 2 shows the Astromesh™ reflector system.

The reflector is deployed in three phases: the initial bloom, the deployment phase, and lockout. A set of pyrotechnically activated cable cutters allow the reflector bundle to initially deploy under the stored strain energy of the perimeter truss to approximately 40% of the full diameter. The motorized drive system is then activated to complete the reflector to 100% of the full diameter while the telemetry and spacecraft deployment control monitors the cable tension as an indicator of deployment health. When the perimeter truss has fully formed, the motorized drive system completes the final latch and lockout of the joints.

Mesh management is achieved using a combination of anti-s snag shields and clips, which provide passive release of the mesh bundle as the perimeter truss expands. The mesh bundle is stowed and restrained in vertical folds for launch, with the perimeter truss acting as lateral supports.

Boom Design

The MBSAT boom system comprises an articulated, cable-deployed hinge system which provides preloaded locking joints at full deployment. This high stiffness, folding design was key to providing a stowed configuration consistent with the envelope requirements, while achieving a highly stable and accurate configuration in the deployed state. Two motors were available to deploy the boom in less than 15 min, and satisfying the redundancy requirement. Fig. 3 shows the boom system.

At initial release, the boom system is pushed out of the launch support structure using a ratchet mechanism

to control the initial deployment and then the motorized drive system activated to deploy the boom to the final configuration until a latch and locking load is detected in the cable tension sensors.

Launch Support Structure Design

The launch support system comprises a main cradle system and end support cradles. The design is thermally compliant to the all-graphite reflector truss while capable of resisting launch loads with the required stowed frequency. A set of pyrotechnically activated rod and cable cutters release the launch support system in sequence.

Telemetry Design

The MBSAT reflector telemetry consists of:

1. Tension sensors to monitor the cable loads in both the reflector and boom.
2. Motorized drive position sensors to monitor the cable intake rate and status.
3. Temperature sensors to monitor key components.

The cable tension sensors were used as an indication of normal system operation. Motor operation would be terminated if pre-established limits were exceeded. Normal telemetry signatures were gathered during ground testing and were used during the mission. During in-orbit deployment, telemetry feedback provided confidence that the reflector system had successfully deployed, thus allowing the spacecraft to continue in its other operations.

Reflector Level Testing and Analysis

Due to the large size and complexity of the reflector system, it was impractical to validate the reflector via system level tests for all the anticipated conditions.

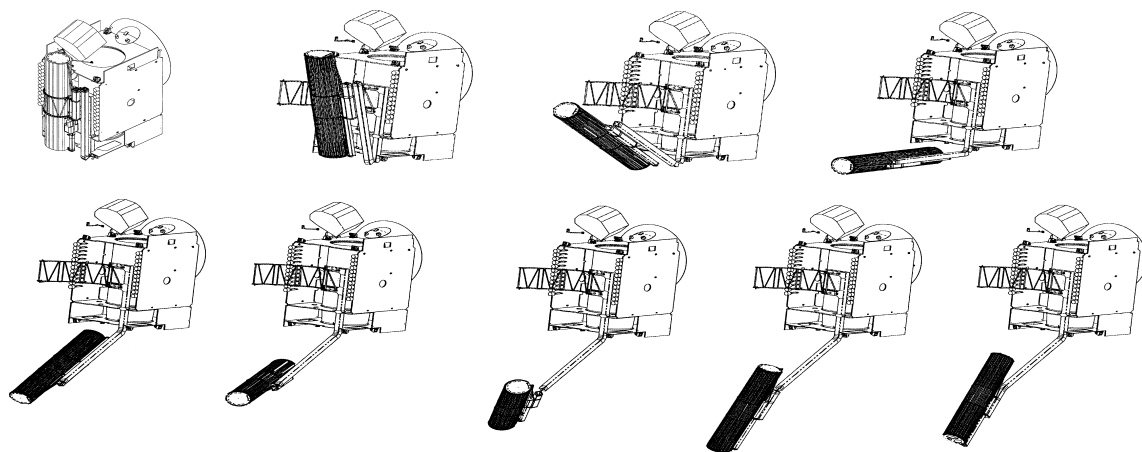


Fig. 3 The reflector boom system.

The robust environmentally insensitive design allowed the use of analyses and selected component level tests for correlation to provide the confidence required for in-orbit success.

The reflector assembly was divided into three test areas to achieve qualification: the reflector, the boom, and the first motion release.

First motion release testing verified the operation of the release mechanisms and the pretensioned forces of the reflector bundle and boom against the kinematic model. Fig. 4 shows the test setup that was used to validate the first motion response.

Boom tests verified the deployment of the boom mechanisms and pointing accuracy between the root to the reflector interface against the kinematic model and the pointing model. Fig. 5 shows the test setup and a plot of the measured response, which was very similar to that predicted.

Reflector tests verified the deployment of the reflector truss and the reflector surface position. Fig. 6 shows the test setup and a plot of the measured response. It is worthwhile to note that, due to the deployed stiffness of the reflector design, offloading is only required at the perimeter truss during photogrammetry while measuring the parabolic antenna shape accuracy in a 1 g gravitational field. These tests were performed before and after exposure of the hardware to the environmental tests and confidence was established in the analytical models through test correlation. The models were therefore used as the basis of predicting performance under various other conditions.

Reflector Integration with the Satellite

The design and testing of the reflector discussed in the previous section took place at Astro Aerospace utilizing a spacecraft sidewall simulator. This section will discuss the integration and testing done at the spacecraft level at the SS/L facilities in Palo Alto.

The successful integration of this complex subsystem required a team effort by Astro and SS/L, and advanced planning was critical in assuring that the integration and test flow would meet technical and schedule requirements. An integrated Astro and SS/L team performed the reflector integration and testing. Astro performed the tasks related to the reflector using their fixtures and procedures, and SS/L was responsible for all spacecraft handling, interface connections, spacecraft alignment measurements, and spacecraft commanding. Spacecraft time is valuable so it was important that fit and function risks were reduced to a minimum prior to spacecraft integration.

The flight hardware, test equipment, and facilities were CAD-modeled to assure the proper fit during the design phase. The test procedures and fixturing (Figs. 4 and 5) were checked out during the subsystem testing at Astro, and the interface with the spacecraft relied on the CAD models. The value of these models was confirmed when the hardware interface was successfully validated.

The reflector was delivered to SS/L with the reflector surface contour characterized and the boom-to-spacecraft attachment points located in the spacecraft coordinate system. Shimming and match drilling at these locations allowed any fixed manufacturing errors to be identified and eliminated. Once the boom was mounted to the spacecraft and deployed in a simulated zero-gravity condition, the alignment was verified using photogrammetric techniques.

Once the reflector was fully installed in the stowed configuration, a release and first motion test was performed to confirm proper installation and to validate the spacecraft release commands. The spacecraft was then exposed to dynamics testing, where both SS/L and Astro engineers monitored and compared the reflector responses with those seen during the subsystem level testing. The previous subsystem testing was designed to be more severe than the spacecraft level tests to assure

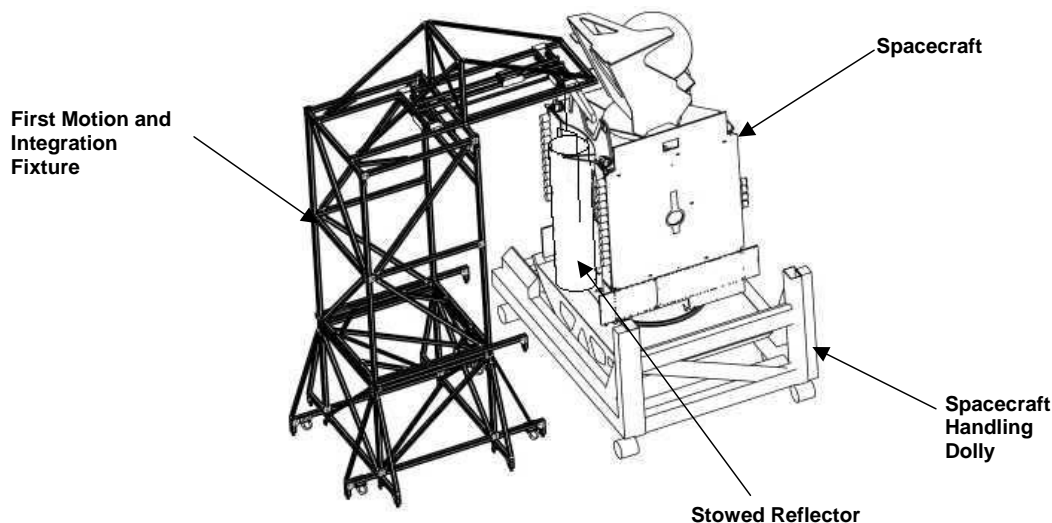


Fig. 4 First motion release test configuration.

success during this critical spacecraft level test. The reflector and spacecraft performed as predicted.

Post-dynamics testing consisted of a first motion and release test, then the reflector was separated from the boom at the repeatable interface and sent to Astro for reflector deployment testing and post-dynamics surface contour and position measurements. This latter testing required the large Astro specialized facility. The spacecraft and boom remained at SS/L where a boom deployment and alignment check was performed using the mission spacecraft command sequences. The use of the actual command sequences from the database was critical in validating the commands prior to launch. The reflector was then returned to SS/L and integrated onto the spacecraft, where a final release and first motion test was performed prior to the final stowage.

Mission Planning

This large reflector has significant impact on the spacecraft operation. Early in the system design phase it was realized that careful consideration must be given to the interaction between the reflector and the spacecraft. Detailed coupled-loads analysis was required to define the environments for both the reflector and the spacecraft. A detailed thermal analysis was critical in defining the test environments as well as helping to shape the in-orbit deployment plan. These thermal conditions were important in developing the ideal deployment environment to minimize risk. A nominal plan was created with allowable deployment time windows that were driven primarily by temperatures. The expected spacecraft and reflector responses during deployment phases were predicted to allow real-time evaluation during the deployment. Failure scenarios were envisioned and contingency plans were developed. Both the nominal and the contingency mission plans were rehearsed multiple times

to ensure that the team was ready for the in-orbit deployment. The expected telemetry responses were known and go/no-go criteria were defined.

The deployment went as predicted, and all responses matched the predictions. The thorough planning and detailed predictions had yielded the desired result—an incident-free deployment. The planning and predictions had helped to reveal issues early enough to develop solutions, and had provided a more robust system design.

In-Orbit Performance Verification

This satellite has been successfully launched and is now in service. Prior to the transfer of title to the satellite from SS/L to MBCO, the satellite underwent in-orbit testing. Among other tests, the in-orbit verification measured the radiation pattern for the S-band system. This test was performed by systematically pitching and/or rolling the satellite to a predetermined orientation and then allowing it to drift in one axis only, at a precise rate. The signal received at a fixed ground terminal as a function of time is therefore representative of the radiation pattern in that plane. Enough planes were tested to adequately describe the total radiation patterns for both the Japan beam and the Korea beam. The results showed outstanding correlation with predictions.

Figs. 7 and 8 show the predicted and in-orbit measured radiation pattern cuts for two pattern planes. These results are equal or superior to the pattern correlation that is normally experienced for in-orbit testing of a satellite. A computer model that uses the feed radiation pattern, the reflector surface contour, and the geometric relationship of these components generated the predicted pattern for this case. This level of correlation is clear evidence of the validity of this technique for predicting the antenna's secondary pattern.

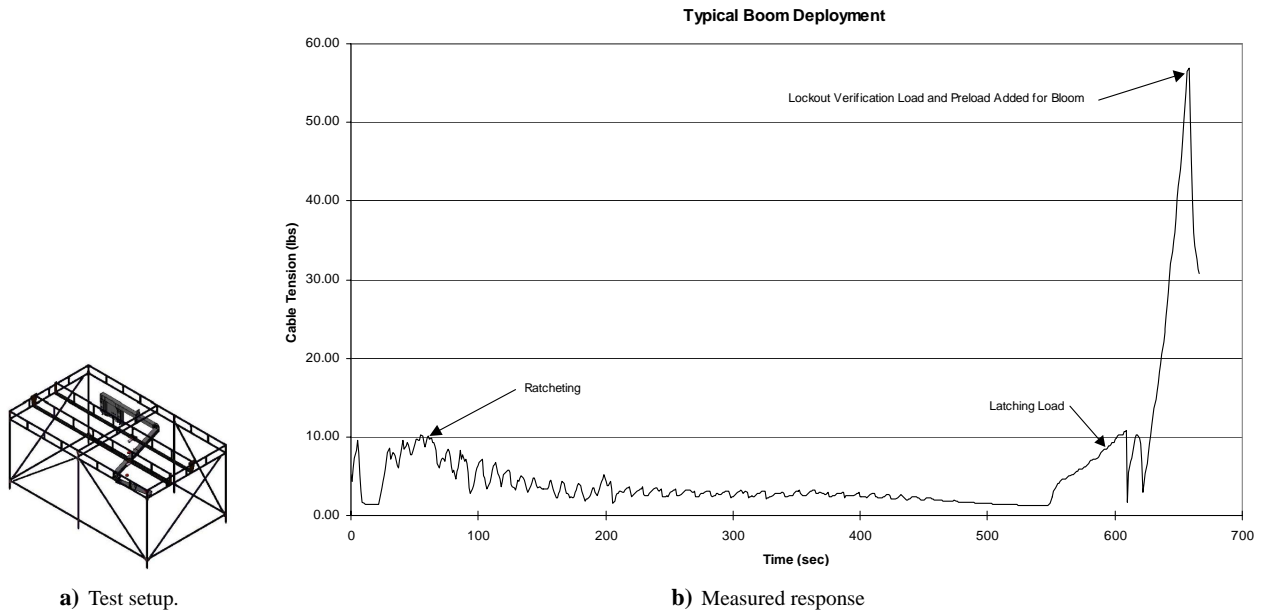


Fig. 5 Boom deployment test setup and plot of measured response.

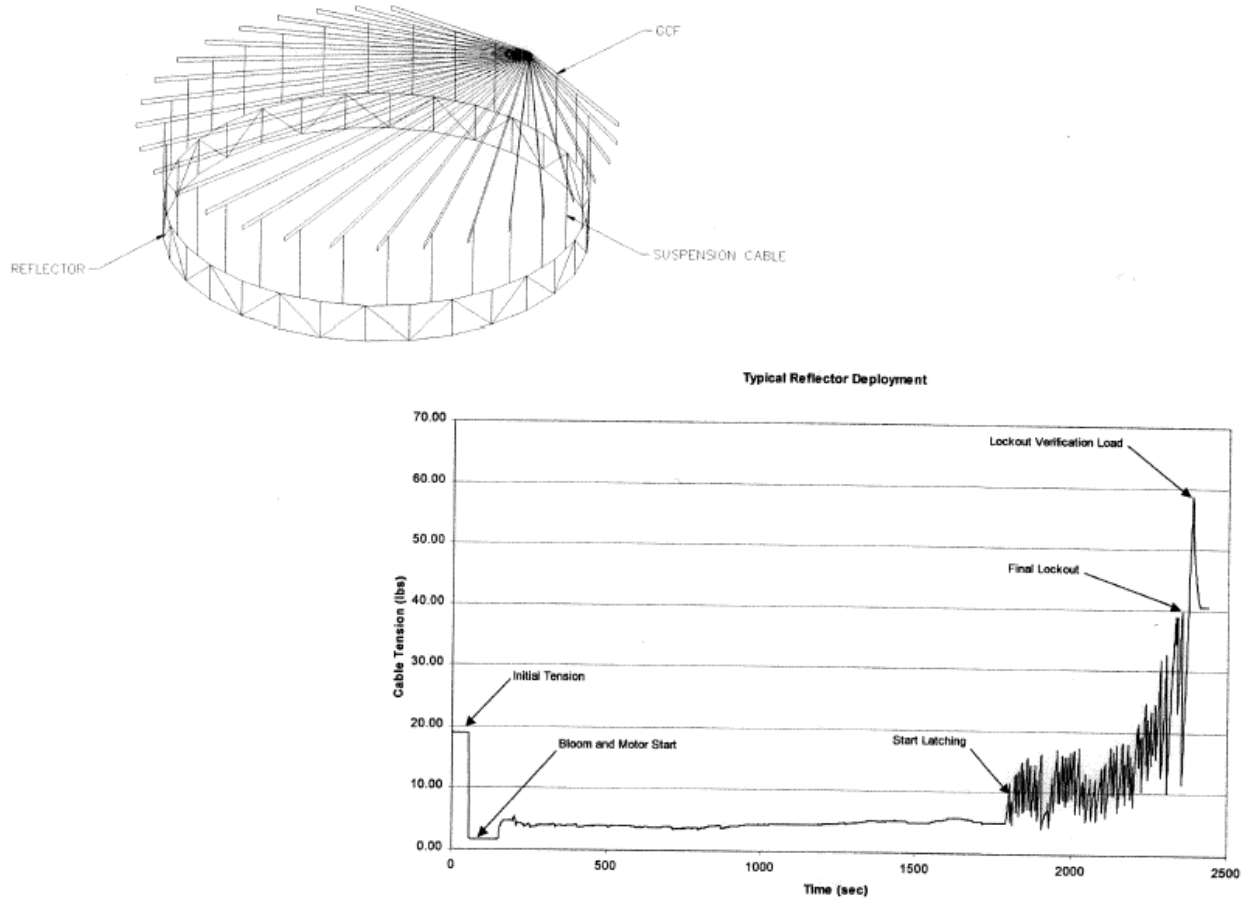


Fig. 6 Reflector test configuration and plot of measured response.

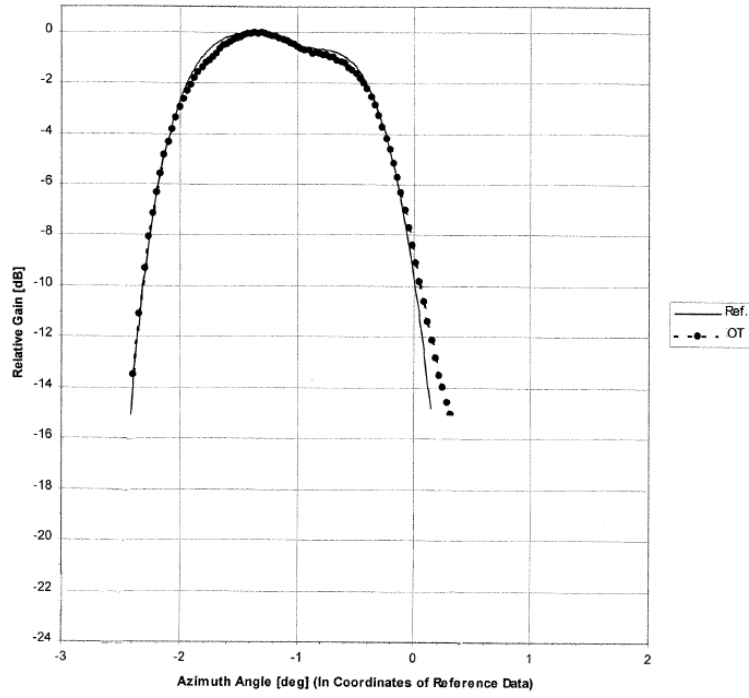


Fig. 7 Predicted and measured (from in-orbit testing) pattern cuts.

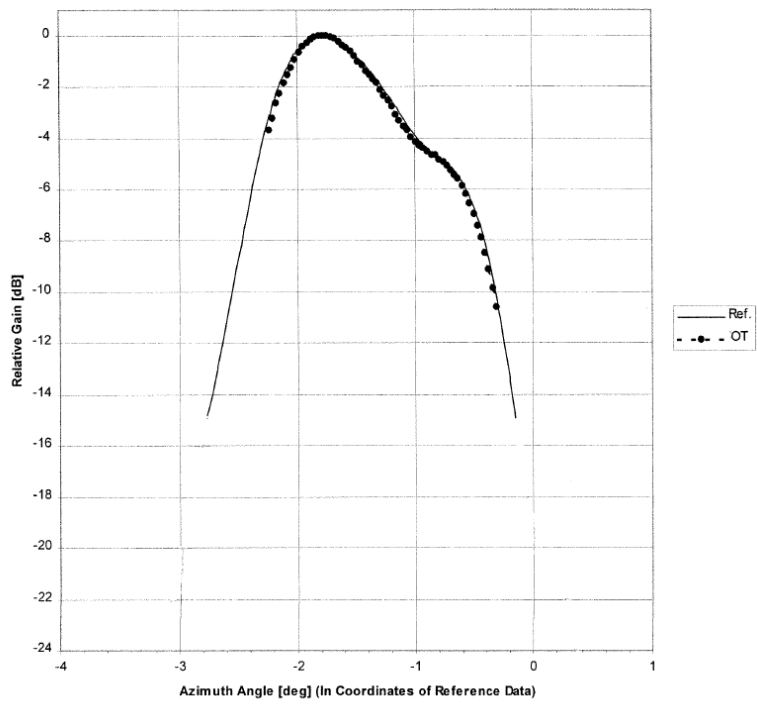


Fig. 8 Predicted and measured (from in-orbit testing) pattern cuts.