The 6-Meter Breadboard Antenna for the Deep Space Network Large Array

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Development of very large arrays of small antennas has been proposed as a way to increase the downlink capability of the NASA Deep Space Network (DSN) by two or three orders of magnitude, thereby enabling greatly increased science data from currently configured missions or enabling new mission concepts. The current concept is for an array of 400 × 12-m antennas at each of three longitudes [1]. The DSN array will utilize radio astronomy sources for phase calibration and will have wide-bandwidth correlation processing for this purpose. A program currently is under way to develop the technology and prove the performance and cost of a very large DSN array. The program includes a three-element interferometer to be completed by late 2004. This article describes the design and development of the low-cost 6-meter breadboard antenna to be used as part of the interferometer.

I. Introduction

The baseline breadboard antenna is a 6-m hydroformed symmetrically shaped dual-reflector system utilizing Gregorian optics. The heritage for this antenna lies in the Allen Telescope Array (ATA) project that plans to build 350 6-m antennas usable up to 11 GHz. Hydroforming is the process of forming aluminum to a rigid and precise mold by using a fluid or gas under pressure. It has been highly developed for use in production of low-cost reflectors for satellite communications, and thousands of antennas in the 1- to 4-m range have been manufactured. This project improves the rms of the surface to extend the usable frequency range to 40 GHz. The backup structure utilizes 9 equally spaced aluminum struts connecting a center yoke to the rim of the dish. The pedestal consists of a central pipe tucked under the dish with a central bearing for azimuth motion and a jackscrew for elevation control.

Also under consideration, as an alternative design for the hydroformed dishes, is an antenna manufactured from composite materials. Composite materials have proven mechanical and structural properties that are superior to metals, at a reduced weight. The major challenge with this type of structure is the cost, but new manufacturing processes and novel implementations are expected to reduce the cost of manufacturing considerably. Other challenges that need to be resolved include the environmental performance and the finding of a suitable material to incorporate as the reflective surface.

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The feed is a dual-frequency horn covering X-band (8 to 9 GHz) and Ka-band (30 to 40 GHz). The X-band will be a coaxial waveguide-fed corrugated horn, and Ka-band will utilize a dielectric rod in the center of the corrugated horn.

Both the feed and associated low-noise amplifiers are cryo-cooled.

II. RF Optics Design

An early version of the antenna[4] was designed for maximum gain. This design had a gain of 52.82 dB and a gain-to-noise temperature ratio (G/T) of 38.49 dB/K (assuming a 240-K ambient temperature and an amplifier noise temperature of 15 K). It was calculated that an antenna designed for optimal G/T would yield a G/T of 40.9 dB/K. However, the main reflector profile of the early design had already been given to a vendor for fabrication. Therefore, to provide the maximum G/T attainable, the antenna was redesigned by reshaping the subreflector and moving the feed location, while retaining the main reflector design.

The basic techniques for dual-reflector shaping given in [2] and [3] were used to ascertain the G/T attainable using the dual-frequency feed designed for this antenna [4] if both the main reflector and subreflector could be reshaped. This then provided the goal for the redesign when only the subreflector could be changed.

A description of the redesign technique is given in [3]. Essentially the rear spillover is reduced by reshaping the subreflector so that the illumination from the subreflector edge falls inside the main-dish aperture. It is also necessary to move the feed position forward of the original design point to reduce the forward spillover. With the redesigned optics that maintain the given main-reflector shape, the G/T is 40.82 dB/K as compared to 40.90 dB/K if the main reflector were to be changed. Thus, there is less than a 0.1-dB/K penalty for keeping the original main-reflector shape.

A. *G/T* Estimates

Estimates of performance were made using both calculated and measured feed patterns including the expected uncertainties and were reported in [3]. A typical estimate for the system noise temperature is shown in Table 1, and a typical efficiency budget is shown in Table 2. Utilizing the data from these tables, along with the physical optics (PO)-calculated gain as a function of frequency using the theoretical feed patterns, the maximum and minimum estimated G/T's are shown in Fig. 1. Further details on sensitivity performance can be found in [3].

III. Feed Design

The basic requirements for the feed are to optimally cover the Deep Space Network (DSN) X-band (8.4- to 8.5-GHz) and Ka-band (31.8- to 32.3-GHz) frequency receive bands and to provide usable performance over the 8- to 9-GHz and 30- to 40-GHz frequency bands. The polarization is dual circular at both bands with ellipticity $<$0.75 dB over the DSN bands. The return loss is to be better than 20 dB over the usable bands. The target illumination function of -12 dB at 42 deg off the main-beam direction was selected to be the same as the ATA feed, so there was the possibility of using the ATA offset reflectors. Considerations for low-cost mass production also were to be included in the design.

After exploring several options, the selected design was an X-/Ka-band coaxial feed that includes a dielectric rod for Ka-band radiation, as shown on Fig. 2. The radiation pattern at X-band was controlled

[4] V. Jamnejad, "Shaping of 6-m Reflector," *Monthly Reports* (internal document), DSN Array Task, Jet Propulsion Laboratory, Pasadena, California, January 2003.

Table 1. Typical noise temperature budget at zenith.

Element	Noise, K		Note
	X-band, 8.4 GHz	Ka-band, 32 GHz	
Cosmic background	2.5	2.0	Effective blackbody
Atmosphere	2.2	7.0	Goldstone (average clear)
Forward spill	0.3	0.0	6% at X-band
Main reflector rear spill	3.6	1.0	
Main reflector ohmic loss	0.1	0.2	Aluminum
Subreflector ohmic loss	0.1	0.2	Aluminum
Quadripod scatter	2/4	2/4	Estimated
Feed/amplifier contribution	6.1/12.4	18.6/30.2	Reference [3]
Total noise, K	16.9/25.2	31.0/44.6	

Table 2. Typical efficiency budget.

Element	Noise, K		Note
	X-band, 8.4 GHz	Ka-band, 32 GHz	
P.O. computed	0.777	0.780	100% = 54.59 X-band 100% = 66.21 Ka-band
Main reflector			
Ohmic loss	0.999	0.999	
rms	0.988	0.846	12 mils rms
Subreflector			
Ohmic loss	0.999	0.999	
rms	0.999	0.8982	4 mil rms
Blockage	0.85/0.9	0.85/0.9	Estimated
Feed VSWR	0.999	0.999	
Efficiency	0.650/0.688	0.549/0.581	
Gain, dB	52.72/52.97	63.61/63.85	

by slot depth and flare angle to produce saturated operation, and the radiation pattern at Ka-band was controlled by the dielectric rod profile. X-band enters the horn throat via a TE_{11} coaxial mode, and Ka-band enters conventionally. Both bands use a commercial fin-type polarizer. A photograph of the prototype feed is shown in Fig. 3. More details of the feed design and performance can be found in [4].

IV. Cryogenic Design

The following describes the design and performance of a prototype low-noise amplifier (LNA) system for the Deep Space Network (DSN) Large Array Task. The system cools a dual-frequency feed system equipped with high-electron mobility transistor (HEMT) low-noise amplifiers and the associated support electronics. The system was designed to be manufactured at minimum cost. The design considerations, including the cryocooler, the vacuum system, microwave interconnects, mechanical components, and radiation shielding, are discussed. Further details can be found in [5].

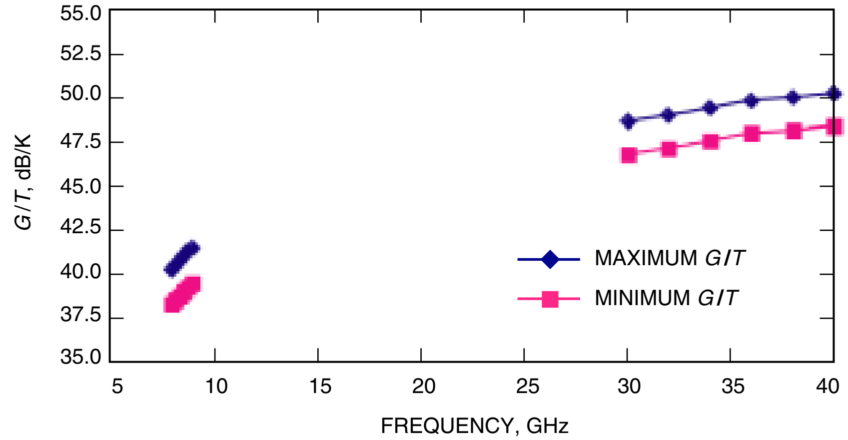

Fig. 1. Maximum and minimum *G/T*.

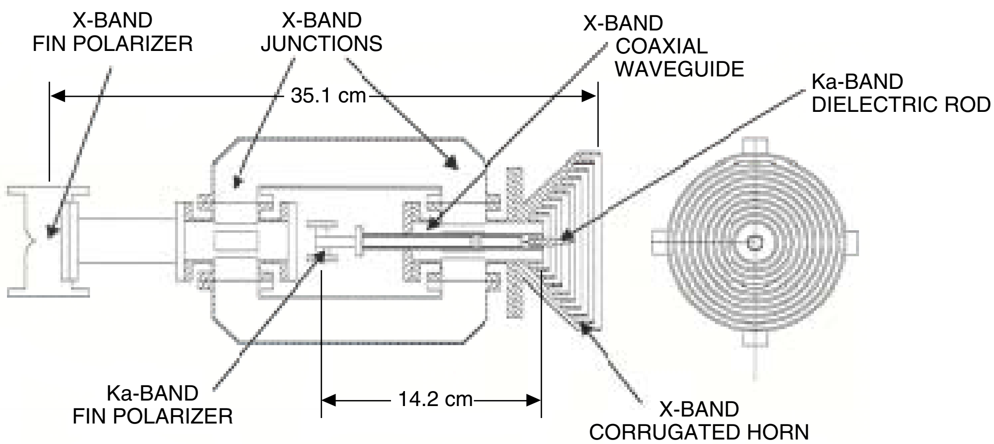

Fig. 2. The X-/Ka-band coaxial feed.

A. Cryocooler Selection

One challenge in the design of the Large Array LNA system is minimizing the cost of electrical power. Estimates of the operations cost of an array with hundreds to thousands of array elements show that power costs for LNA cooling are the biggest single operating cost of the LNA system. Two refrigerators showed promise. Both were Gifford–McMahon two-stage coolers with first-stage operating temperatures near 50 K and second-stage temperatures near 15 K.

The CTI Cryogenics model 350 system produces 3 W of cooling at 15 K. The input power requirement is 1.8 kW. The design has been used in hundreds of LNA systems over a 40-year span. The units typically operate for 18,000 hours before requiring maintenance.

The second cooler was a Cryomech Inc. model GB-15 system. The GB-15 is similar to the original Gifford–McMahon cooler evaluated by JPL in the 1960s. These are Gifford–McMahon (GM) systems that produce 1.5 W of cooling at 15 K. The power consumption is 1.2 kW.

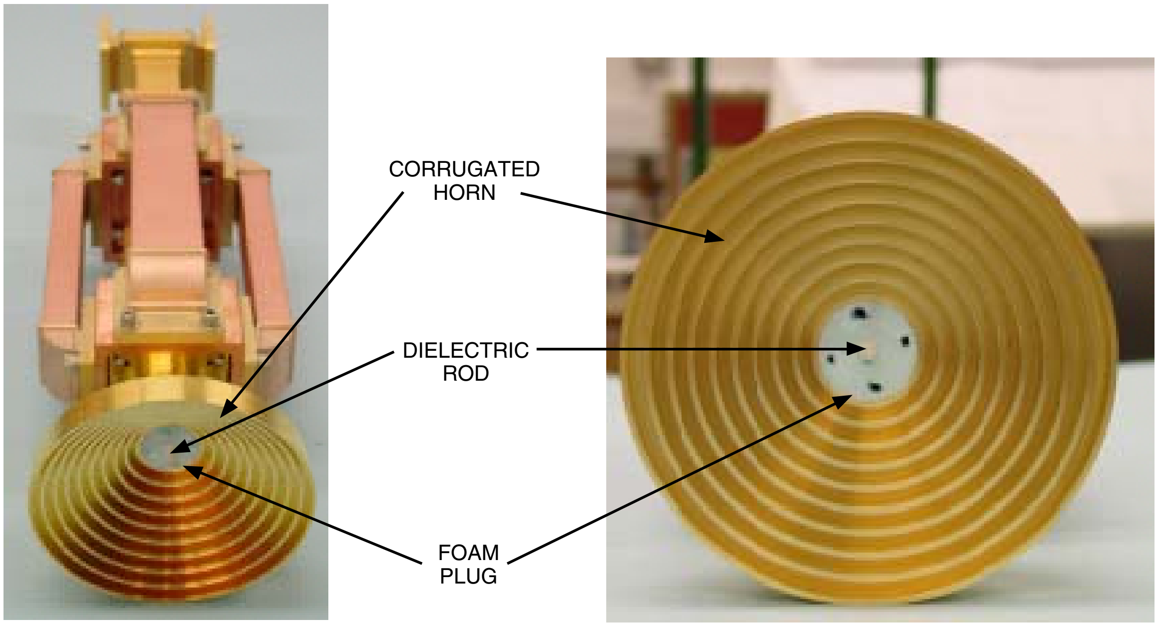

Fig. 3. Prototype feed.

B. Mechanical Layout

To evaluate both coolers, the prototype cooler was designed to accept both the CTI 350 and the Cryomech GB-15 with only bolt-in modification. The package is in a 25-cm-diameter, 42-cm-long round vacuum housing. In the breadboard unit, the feed and cooler were offset to provide the most usable space in the cold volume.

The vacuum housing chosen for the breadboard system is constructed using aluminum tubing. It eliminates welding and the problems associated with vacuum leaks and warping. In production runs, this technique can be cost effective. It provides the benefit of minimum weight and allows the vacuum housing to be sized optimally.

The end plate for the vacuum housing uses the JPL standard machined aluminum plate design. The plate is fitted with simple gland-seal O-ring connections. It uses commercial coaxial interface connectors. The feed is supported mechanically from the base plate with G-10 fiberglass supports. The feed installed is shown in Fig. 4. There is no mechanical connection from the opposite end plate. This design has several advantages: It provides minimal heat conduction to cooled components; it also allows the package to be easily assembled; and it minimizes mechanical stress due to thermal expansion.

In an effort to reduce manufacturing costs, the mechanical hardware was constructed using sheet-metal technology wherever possible. The radiation shield is a simple rolled cone. It is attached to the flanges, which are also simple sheet-metal parts, with screws. It eliminates costly and time-consuming welding or silver brazing used in traditional DSN designs. Normally copper is used for shields. The radiation shields for the prototype are constructed of 1100F alloy aluminum. The aluminum provides acceptable thermal conductivity for the application, provides higher resistance to oxidization, and is lighter than copper. The radiation shield installed on the cooler is shown in Fig. 5.

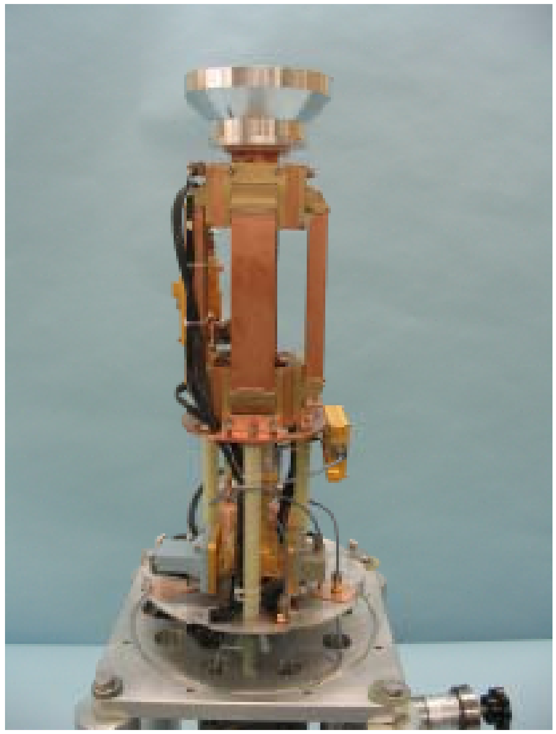

Fig. 4. Feed installed in the LNA assembly.

Fig. 5. Radiation shield installed.

C. Feed Window Design

The vacuum window is a critical component in the package design. A foam-backed membrane window was chosen for the prototype design. In this approach, the film strength of a material such as Kapton provides the vacuum seal and the mechanical strength. Low-loss, low-density foam acts as a thermal insulator and provides additional compressive strength.

To determine the required Kapton thickness, burst tests were performed on a typical clamped ring joint. The expected burst pressure for a 14-cm Kapton window was extrapolated from burst measurements of 2.2 cm and 9 cm. To provide a burst pressure safety factor of 3, the window would require 0.08- to 0.13-mm Kapton film.

Kapton windows lose mechanical strength when exposed to the Sun. To solve this problem, a thin Teflon cloth is used as an outer layer over the Kapton. Gore manufactures a reduced-density Teflon cloth with an advertised 30-year life in radome service.

The prototype window is constructed of 0.08-mm Kapton covered with 0.38-mm Teflon cloth and is backed by 25 mm of polystyrene foam. The resulting noise temperature of the window is less than 1 K. Figure 6 shows the cooler/LNA with the window installed.

Fig. 6. Vacuum window installed on the LNA assembly.

V. Mechanical Subsystem

The critical technology in the mechanical system for the reflector is the dish manufactured from a process called hydroforming. This is the process of forming aluminum to a rigid and precise mold by using a fluid or gas under pressure. The advantages are (1) high rigidity due to the one-piece aluminum shell (consider the stiffness of thin metal bowls or woks compared to the stiffness of flat sheets), (2) accuracy largely determined by the mold rather than human error (the repeatability of the process was verified by fabricating three dishes with an rms of less than 0.2 mm), and (3) low costs for both raw material and labor.

For the DSN breadboard, the dish aperture is 6.048 m or 20 ft (see Fig. 7). The dish is connected to a rigid truss structure at two places. The dish is hard mounted to the truss structure at its center. Spars connect the rim of the dish to the rear of the truss structure. The truss structure is connected to the petal yoke at the elevation pivot point. There is a linear actuator or jackscrew mechanism attached to the rear of the yoke. As the jackscrew extends or contracts, the elevation of the main dish is changed. The yoke is connected to the petal base through a slew bearing, with gears on the outer ring. Two opposing motors, mounted inside the yoke, drive the azimuth axis. The dish, truss structure, and spars are made of aluminum. The yoke and pedestal base are made of steel. The total weight of the antenna is approximately 4000 kg. See Fig. 8 for a drawing of the complete antenna.

Fig. 7. Hydroformed dish.

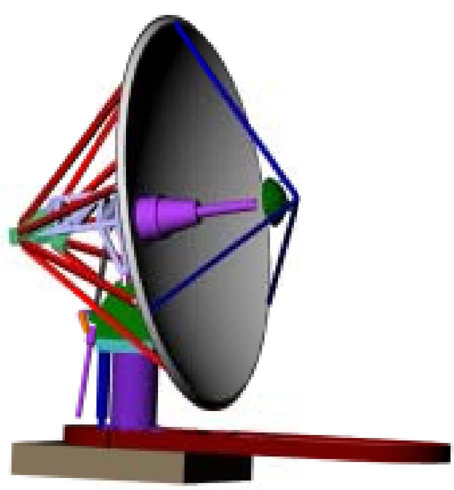

Fig. 8. The 6-meter breadboard antenna.

A. Performance Requirements

Surface accuracy of the dish after manufacturing must be less than 0.2-mm rms. For either gravity, wind, or temperature, the change in rms cannot be greater than 0.13 mm. The antenna is required to operate year-round at temperatures from −10 to 55 deg C. The pointing accuracy must be less than 0.01 deg. The rigid-body displacement of the main dish between antennas must be less than 0.5 mm. Displacement of the subreflector relative to the main dish must be less than 0.5 mm. Displacement of the feed relative to the main dish must be less than 1-mm axial and 0.5-mm radial. The antenna must have a range of 10 to 90 deg in elevation and 0 to 450 deg in azimuth. The antenna is designed to operate in up to 48-km/h (30-mph) winds, can drive to stow in an 80-km/h (50-mph) wind, and can survive a 160-km/h (100-mph) wind.

B. Analysis

Finite-element analysis (FEA) was used to predict the performance of the antenna with gravity, wind, and thermal loads. For any given load case, the deformations of the dish's reflective surface are extracted. The path-length rms of these deflections is then determined. These predictions include the entire azimuth and elevation range. In addition, the frequencies of various bending modes were calculated. The FEA model is shown in Fig. 9 and some typical results in Table 3. Figure 10 shows the two lowest-order resonance modes.

C. Truss Structure and Spars

The truss structure is the main load-bearing substructure for the antenna. It shares an interface with the dish, feed, spars, and pedestal. The elevation axis is located at the lower part of the truss structure. The loads from the jackscrew are reacted through the truss structure. The spars, truss structure, and main dish are a structural system. They work together to give the system rigidity. The spars minimize deflection at the outer rim of the dish by transferring loads to the rear of the truss structure.

D. Feed Tower

The feed tower has two main structures. The cylindrical section houses the feed/LNA cryogenics assembly. The conical section houses some of the electronics. The conical section is removable to allow access to service the cryogenics assembly without disconnecting it from the antenna. The cantilever loads from the feed are reacted into the truss structure. The cryogenics assembly can be removed from the antenna without disconnecting the dish from the truss structure.

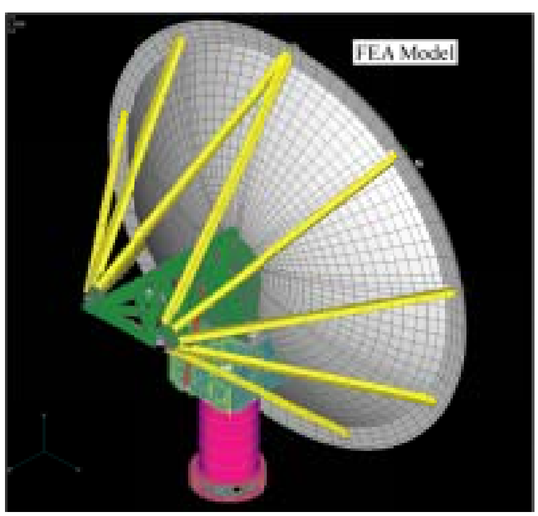

Fig. 9. The FEA model.

Table 3. Typical results from the FEA model.

X-tilt, deg	Y-tilt	Surface rms including focus error, mils	X-translation, mils	Y-translation, mils	Z-translation, mils
Gravity load elevation = 0 deg, azimuth = 0 deg					
−0.03	0	0.73	0	0	−21.5
Gravity load elevation = 60 deg, azimuth = 0 deg					
−0.04	0	0.94	0	29	−33.9

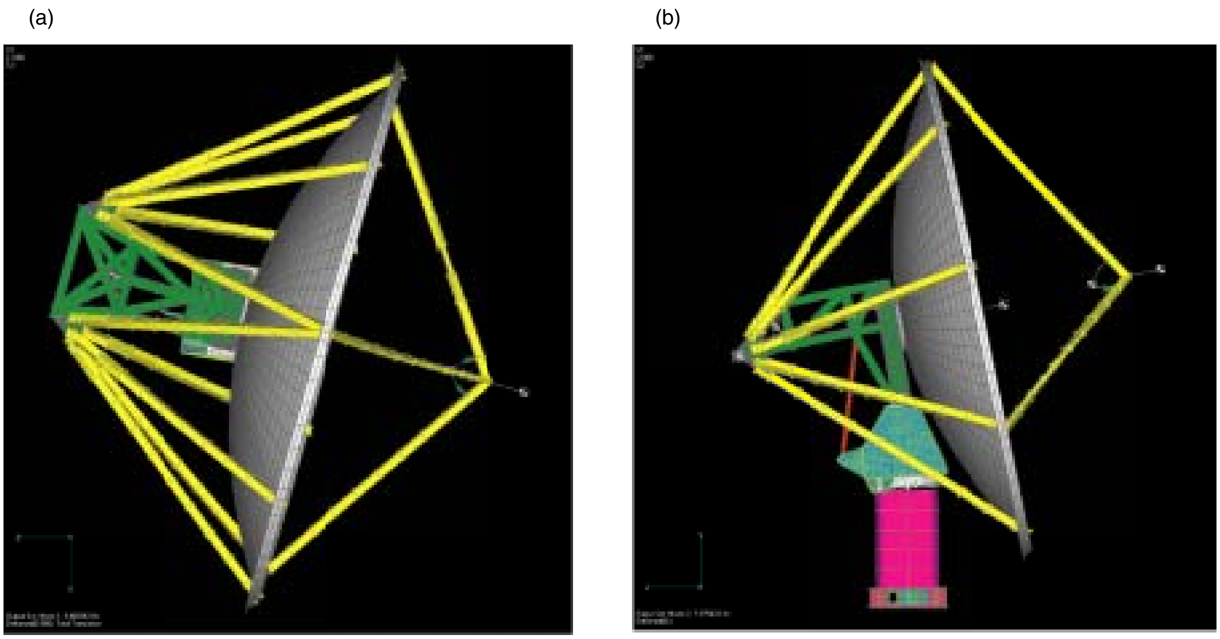

Fig. 10. The lowest-order resonance modes: (a) Mode 1, 5.46 Hz (rotation about the azimuth axis) and (b) Mode 2, 7.08 Hz (rocking fore and aft).

E. Pedestal

The pedestal consists of a yoke and base. The base is stationary while the yoke rotates about the long axis of the base. There is a large bearing with gears that connect the yoke to the base. Motors mounted inside the yoke drive the azimuth axis. There are pivots at the top of the yoke about which the dish and spar rotate in the elevation axis.

F. Cable Management System

The azimuth axis range of motion requirement is 450 deg. The cable management system forces the cable bundle to expand and contract in a planar spiral pattern. A rigid tube is connected to the yoke. This tube extends from the yoke down to the bottom of the pedestal. The bottom of the tube is flared to act as a stress relief for the cable. The cable bundle is routed through this tube.

G. Servo Motors and Actuators

Both the azimuth and elevation axes use the same motor design. The motors are DC servo with 110-V AC input. The maximum horsepower is 2.0 hp. The stall torque is 18.65 N-m. These motors can run continuously at 5.65 N-m and 2000 rpm. The motors have 3000-counts/rev encoders built in. Also, each motor has a 27.12 N-m brake. There are external encoders attached at each axis. These encoders have 144,000 counts/rev and can resolve 9 arcsec or 0.0025 deg. On the azimuth axis, there are two motors that work together to eliminate backlash. The motors maintain a constant counter torque. These two motors are connected to an 87:1 reducer. A pinion is connected to the output of the reducer. The motor reducer–pinion combination drives a large slew bearing.

A linear actuator or jackscrew is attached to the rear of the yoke on a pivoting gimbal. The jackscrews have an 18,140-kg capacity and require 48 revs at the input for 2.54 cm of raise. The previously described motor drives a geared belt and pulley system, which in turn drives the jackscrew. The ratio of the geared belt and pulley system is 1.895:1. To reduce jackscrew backlash, a 900-kg ballast mass is attached to the rear of the truss structure. This ballast mass keeps the linear actuator in compression for all gravity- and wind-load cases. The azimuth-axis drive train and elevation-axis jackscrew are shown in Fig. 11.

VI. Composites as an Alternative Antenna Design

With newer technologies and lower materials costs, composite materials are now an affordable, viable alternative for structural fabrication of small- to medium-sized antennas.

Composite antennas can be fabricated with integrated backup structures to provide the stiffness required for high-accuracy dish surfaces and reduce the fabrication process.

Since the thermal coefficient of expansion of carbon fiber composite materials is almost negligible, another advantage for using this material is the significant reduction of thermal effects to avoid undesirable distortions of the reflective surface.

Also, composite antennas provide a lighter structure with high rigidity, which helps in reducing the gravity deformations of the antenna.

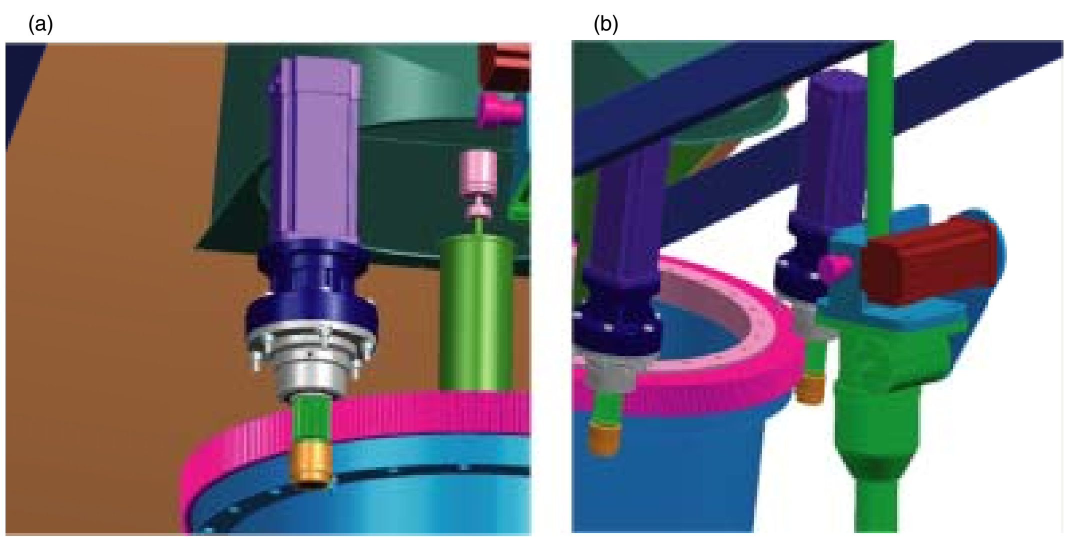

Fig. 11. Servo system: (a) azimuth axis drive train and (b) elevation axis jackscrew and motor pulley system.

The low-cost solution for the array antennas is to use one of the various infusion technologies that have been recently developed by composite structures fabricators. Some of the advantages include a low-cost process (room temperature curing, no need for an autoclave) and materials (prepegs), and high material-utilization factors; composite infusion is a repeatable, controlled process that uses low-cost tooling. The infusion transfer processes include vacuum-assisted resin transfer molding (VARTM), resin transfer molding (RTM), and resin film infusion (RFI).

To add stiffness to the structure without compromising the weight, the cross section of the structure may be increased by using lightweight foam or metallic cores sandwiched between the carbon fiber laminates.

Several approaches are being investigated to provide the reflective structure of the dish; these include embedding conductor materials onto the carbon fiber laminates, aluminum foil, and meshes integrated in the material.

VII. Summary

Currently, three antennas are under construction at JPL. The three dishes have been received, and the truss structure and spars have been fabricated. The feed tower and pedestal are under construction. The breadboard feeds were fabricated and tested. A prototype cryogenic system has been fabricated and tested with the breadboard systems under construction.

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