

THE FUTURE OF THE DEEP SPACE NETWORK: TECHNOLOGY DEVELOPMENT FOR K_a-BAND DEEP SPACE COMMUNICATIONS*

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Introduction

Projections indicate that in the future the number of NASA's robotic deep space missions is likely to increase significantly. A launch rate of up to 4-6 launches per year is projected with up to 25 simultaneous missions active [1]. Future high-resolution mapping missions to other planetary bodies as well as other experiments are likely to require increased downlink capacity. These future deep space communications requirements will, according to baseline loading analysis, exceed the capacity of NASA's Deep Space Network in its present form.

There are essentially two approaches for increasing the channel capacity of the Deep Space Network. Given the near-optimum performance of the network at the two deep space communications bands, S-Band (uplink 2.025-2.120 GHz, downlink 2.2-2.3 GHz), and X-Band (uplink 7.145-7.19 GHz, downlink 8.4-8.5 GHz), additional improvements bring only marginal return for the investment. Thus the only way to increase channel capacity is simply to construct more antennas, receivers, transmitters and other hardware. This approach is relatively low-risk but involves increasing both the number of assets in the network and operational costs.

The approach selected by the JPL organization responsible for providing deep space communications service, the Telecommunications and Mission Operations Directorate, is to look to a higher frequency communication link to provide higher bandwidth and/or increased signal-to-noise ratio. This approach is part of the history of the DSN, having driven the uplink and downlink frequency of choice from S-Band to X-Band. Deep space communications bands are already allocated and in use at 31.8-32.3 GHz for downlink and 34.2-34.7 GHz for uplink. To this end significant work, which

is summarized in this paper, is ongoing to provide the technology and hardware required to realize high performance communication links at these frequencies, denoted as K_a-Band.

Advances in Antennas

In order to realize the increased signal to noise ratio that the jump to K_a-Band has to offer a number of advances in the Deep Space Network's set of antennas and microwave components is required. These areas include development of new high-performance feedhorns and frequency selective surfaces for multi-frequency operation. While the decreased antenna beamwidth at K_a-Band is responsible for the improved link margin, a tighter requirement on the pointing capability of the antennas must follow. Operation of the Deep Space Network's 70m antennas efficiently at K_a-Band presents some special challenges. In particular, while the surface deformations induced by gravity as the antenna moves in elevation are insignificant at S and X-Band they are severe at K_a-Band. Two specific gravity compensation systems, a deformable mirror, and an array feed system are currently under consideration. Details on these systems follow.

Feedhorns

Multi-frequency operation in the Deep Space Network is typical. Various systems provide simultaneous downlink/uplink capabilities at S-Band and X-Band and in both bands simultaneously. This trend will continue, moving to simultaneous K_a-Band/X-Band downlink with the possibility of simultaneous X-Band uplink. One approach for providing this capability is to develop multi-frequency feedhorns that provide both diplexing capability and high illumination efficiency for the antenna at all bands. The requirements for these feeds are quite unique due to the dynamic ranges involved. Typical uplink powers are 20 kW CW (73 dBm) and

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the DSN's cryogenically-cooled receivers have noise floors in the 20K range at K_a -Band. Typical requirements call for the feed to provide as much as 130 dB of isolation between the transmitter and receiver ports. The challenges involved in designing this particular type of feed involve obtaining the required isolation, and return loss and efficient antenna illumination in all three bands. Matching is achieved through the use of transition regions with groove depth and width variation, and iris matching structures on the side-coupled ports, [2].

Frequency Selective Surfaces

An alternative approach for separating signals in different bands is by performing the filtering operation in free-space using frequency-selective surfaces (FSS). Two new frequency-selective surfaces have been developed for K_a -Band. Both are of the high-pass variety, where the high frequency radiation passes through an array of tightly packed apertures in a half-wave thick metal plate. This type of FSS is preferred over a low pass structure consisting of metal patches on a dielectric substrate for two reasons. (1) Thick metal plates are quite capable of handling reflection of the high power uplink signal whereas printed structures are not. (2) Metal plates with air-filled apertures offer a low loss structure for the downlink signals that must pass through the plate, no dielectric loss is encountered. One FSS has been designed to pass both the K_a -Band uplink and downlink bands while reflecting the uplink and downlink at both S and X-Band. A second FSS has also been designed to reflect the K_a -Band downlink and transmit the uplink. Due to the small separation between these bands, 32 and 34.5 GHz, a five-layer high-pass FSS has been designed which incorporates a waveguide iris filter inside each of the apertures in the FSS.

Blind Pointing Upgrades

While the increased antenna gain afforded at K_a -Band improves the link margin the accompanying decrease in beamwidth demands more accurate antenna pointing. The full 3dB beamwidth of a 34m-diameter antenna at 32 GHz is approximately 16 mdeg. Once a signal is received from the spacecraft monopulse tracking may be used as a pointing aid, as discussed below. The antenna must point unaided (blind point) to within the pull-in range of the monopulse. In order to achieve blind pointing accuracy in the milidegree range a number of antenna improvements are being investigated. Elevation encoder hysteresis has been identified as one of the factors limiting blind-pointing capability of some of the existing antennas in the DSN. Likewise discontinuities in the data gear which is used to provide azimuth position have also been

identified. Both of these effects are currently under investigation. Thermal disturbances, particularly differential heating of the structural member supporting the alidade portion of the antenna have also been identified as a source of pointing errors. Two approaches have been investigated to mitigate these thermal effects. (1) Experiments to investigate the effect of insulating the key structural members have been carried out. (2) An active system using temperature sensors on the key members and calculations based on a structural model of the antenna has also been used to update the antenna pointing in real time. The flatness of the azimuth track has also been identified as a source of pointing error. A pointing correction system using inclinometers on the track and a look-up table has also been implemented on an experimental basis. Finally, the simple linear models used in the pointing look-up table have been upgraded to carry spherical harmonic terms of up 4th order. Work in the blind pointing area is ongoing and the final decision on which improvements will be included in the operational systems is yet to be made.

Gravity Compensation Systems

The largest antennas in the DSN, the 70m diameter dual-shaped antennas, offer the highest link margin due to their large collection area. Unfortunately they were not constructed with operation at K_a -Band in mind, and gravity loading on the structure causes deflections in the surface. At K_a -Band the deflections cause a gain loss of as much as 8 dB at high elevation angles and 2.5 dB at low elevation angles, far from the rigging angle of 45 degrees. In order for these antennas to offer the required performance at K_a -Band a gravity compensation system must be employed. Work on two such systems, a deformable mirror and an array feed with real-time combining is described below.

Deformable Mirror

The first approach to gravity compensation uses an actuated flat plate in the beam path. The plate is deformed as the antenna tips in elevation in order to pre-distort the beam phase so that when it is reflected by the distorted main reflector flat phase is restored. The shape of the deformable mirror is computed at a number of elevation angles for which the main reflector surface has been measured using microwave holography. The computation of the mirror shape is carried out using geometrical optics. Once the ideal shape is found the best possible set of actuator displacements is found using a finite element structural model that takes into account the thickness of the plate, location of the actuators, and plate thickness. The key mechanical design parameters are

the plate thickness, the number of actuators, and their location. Knowledge of the actual main reflector surface is essential for this approach to be effective. In practice the system would be implemented by adjusting the plate via a lookup table and the current elevation angle, and hence provides no real-time correction for factors such as wind and temperature. A deformable mirror was designed and tested at the 34m research and development antenna several years ago. [3]. Recently the same mirror was installed on the 70m antenna on a temporary basis. Although the design was known to be sub-optimum for the 70m antenna geometry gain improvements of as much as 3.7 dB were observed at high elevation angles, and all results were in reasonable agreement with theory. Before actual implementation a re-optimization of the mirror design for the 70m application would be necessary.

Array Feed Compensation System

A second approach for gravity compensation is an array feed compensation system [4]. In this case an array of 7 feeds is located in the antenna's focal plane. Energy that is defocused due to the main reflector distortions is captured by the additional 6 feeds surrounding the central feed. Signal processing techniques are employed to determine the optimum weights for recombining the 7 received signals based on their individual signal-to-noise ratios. The advantages of this system include the ability to correct for real-time effects such as wind and temperature. No main reflector surface measurements are required. Disadvantages include the need for 7 cryogenically cooled LNAs, and the limited fill-factor of the array feed in the focal plane. This system has been extensively tested on the 34m research and development antenna and was recently installed on the 70m antenna along with the deformable mirror. A gain improvement in the vicinity of 3-4 dB was observed at high elevation angles, and 2 dB at low elevation angles with this system, also in good agreement with theoretical predictions.

Advances in Electronic Equipment

In addition to the antennas improvements a number of improvements/additions to the Deep Space Network's electronic components are also required. Three major areas that need development are transmitters, low noise amplifiers, and monopulse tracking systems. Some details regarding these systems are provided below.

Transmitters

The near-term application of the K_a -Band uplink capability is in radio science. The first such

experiment will involve the Cassini spacecraft. The initial development transmitter for this application provides 80 W CW at the feedhorn and is based on a commercially available 100 W TWTA. One of the most stringent and atypical specifications placed on the transmitter is long term frequency stability, which is expressed as Allan variance, $(\Delta F/f)$, versus time interval. For the specific radio science experiment under consideration the important time interval is the round trip light time to the spacecraft. Frequency stability requirements of one part in 10^{15} for time intervals of 100-1000 seconds are typical. Currently an 800 W CW transmitter based on a 1 kW klystron amplifier is under development to replace the 80 W system. In order to meet the stringent stability requirements with this type of amplifier particular attention is being paid to power supply stability and coolant temperature stability.

Low Noise Amplifiers

Two types of low noise amplifiers are currently under development at K_a -Band, solid-state amplifiers based on High Electron Mobility Transistors (HEMT), and high performance maser amplifiers. HEMT amplifiers are currently operating at physical temperatures of 15K and providing equivalent noise temperatures referenced to the feed input of 21K. When antenna spillover, loss, and sky contributions are included operational noise temperatures are in the 38-45K range for these solid state LNA systems. A K_a -Band maser LNA is available as well, running at a physical temperature of 2K, a noise temperature of 5K referenced to the feed, and an overall operating temperature of 22-29 K. Recent maser work is focused on increasing bandwidth and moving to more reliable closed-cycle refrigerators. Any further improvements in maser noise performance would be quite marginal since these devices are presently operating near the quantum limit with respect to noise temperature.

Monopulse Pointing

As was discussed earlier pointing the DSN 34m and 70m antennas accurately at K_a -Band is a significant challenge. Fortunately a downlink signal from the spacecraft is generally available to aid in pointing. The monopulse tracking system planned for implementation is based on a corrugated horn with a cryogenically cooled TE_{21} tracking coupler, and dual HEMT LNAs. Error signals from the difference channel are then used to provide pointing corrections to the antenna controller in real time. The pull-in range of the monopulse system is approximately 10mdeg, well within the blind pointing goal for the antenna.

An Operational 34m Antenna at K_a -Band

Figure 1 below depicts the layout in the pedestal area of one of the 34m beam waveguide antennas which is already operational at K_a -Band and will be used in conjunction with the Cassini spacecraft to perform radio science experiments employing both K_a -Band and X-Band uplink and downlink. Shown in the leftmost position are a K_a -Band transmitter and feed which illuminates the left most curved mirror. This radiation then passes through the first FSS which reflects the K_a -Band downlink signal into the K_a -Band receive feed and LNA. Both K_a -Band signals pass through a second FSS that reflects both the uplink and downlink X-Band signals into an X-Band feed and waveguide diplexing system. This X-Band waveguide system is then connected to a high power X-Band transmitter and X-Band LNA. Currently one operational antenna and the 34m research and development antenna are capable of K_a -Band operation. In addition to the radio science experiments planned for Cassini, which is currently in transit to Saturn, one or both of these antennas have tracked several other spacecraft at K_a -Band. Three spacecraft, Mars Observer, Mars Global Surveyor, and Deep Space 1 have flown or are flying K_a -Band downlink technology demonstration systems and have been tracked by successfully these antennas.

Conclusions

A short description of several of the key components required that will make deep space communication at K_a -Band for the Deep Space Network a reality has been given. As ongoing experiments and research are completed, final implementation details are under consideration, with implementation of K_a -Band into the Deep Space Network taking place during the next decade.

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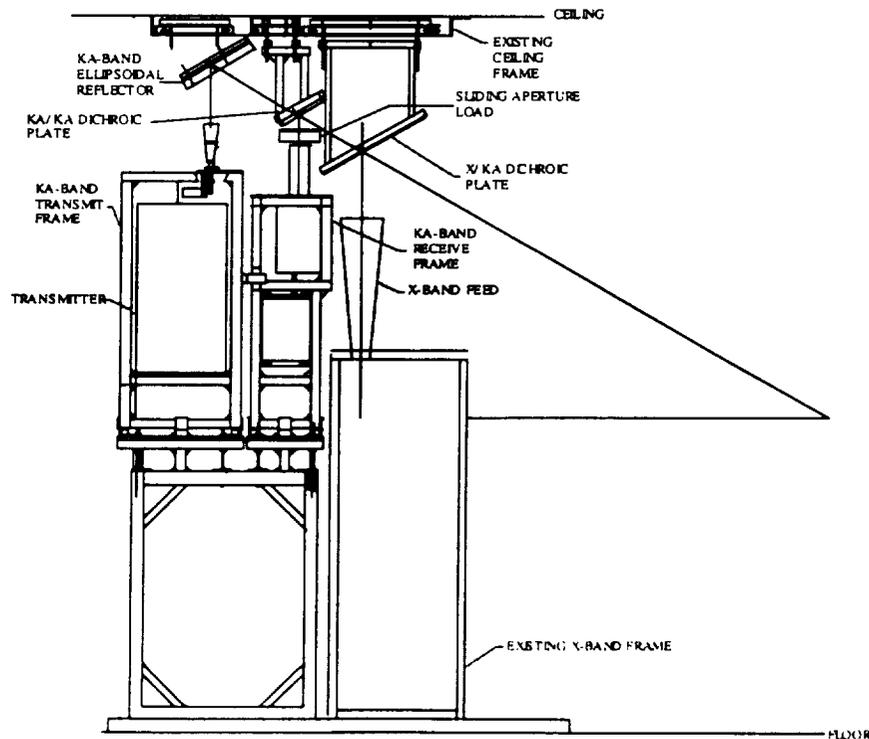


Figure 1. K_a -Band uplink/downlink, X-Band uplink/downlink system layout.