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KA-BAND HIGH-RATE TELEMETRY SYSTEM UPGRADE FOR THE NASA DEEP SPACE NETWORK

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ABSTRACT

The NASA Deep Space Network (DSN) has a new requirement to support high-data-rate Category A (Cat A) missions (within 2 million kilometers of Earth) with simultaneous S-band uplink, S-band downlink and Ka-band downlink. The S-band links are required for traditional TT&C support to the spacecraft, while the Ka-band link is intended for high-data-rate science returns. The new Ka-band system combines the use of proven DSN cryogenic designs, for low system temperature, and high data rate capability using commercial telemetry receivers. The initial Cat A support is required for the James Webb Space Telescope (JWST) in 2013 and possibly other missions. The upgrade has been implemented into 3 different 34-meter Beam Waveguide (BWG) antennas in the DSN, one at each of the complexes in Canberra (Australia), Goldstone (California) and Madrid (Spain). System test data is presented to show that the requirements were met and the DSN is ready for Cat A Ka-band operational support.

I. INTRODUCTION

The NASA Deep Space Network (DSN) has a new requirement to support Category A (Cat A) missions (within 2 million kilometers of Earth) with simultaneous S-band uplink, S-band downlink and Ka-band downlink. Several 34-meter beam waveguide (BWG) DSN antennas have previously been upgraded to support the Category B (Cat B or deep space) Ka-band, at 31.8 - 32.3 GHz, referred to as Ka1. However, this upgrade task, referred to as Ka-band Phase 2 or Ka2, is the first time the DSN will be used to support the Cat A downlink band at 25.5 - 27.0 GHz. The S-band links are required for traditional Telemetry, Tracking and Command (TT&C) support to the spacecraft, while the Ka-band link is intended for high-data-rate science returns. The advantages of the BWG antenna configuration for the DSN have been well documented [1]. The BWG antenna construction is easily adapted to multiple frequency bands, due to the space available in the pedestal room for the installation of additional mirrors and feeds (see Fig. 1). The addition of a new

S/Ka dichroic mirror has enabled the simultaneous operation in the S and Ka2 bands. A photo of one of the upgraded antennas, the DSS-24 antenna at Goldstone, is shown in Figure 2. The initial Cat A support is required for the James Webb Space Telescope (JWST) in 2013. TT &C Support for NASA lunar missions is also a possibility.

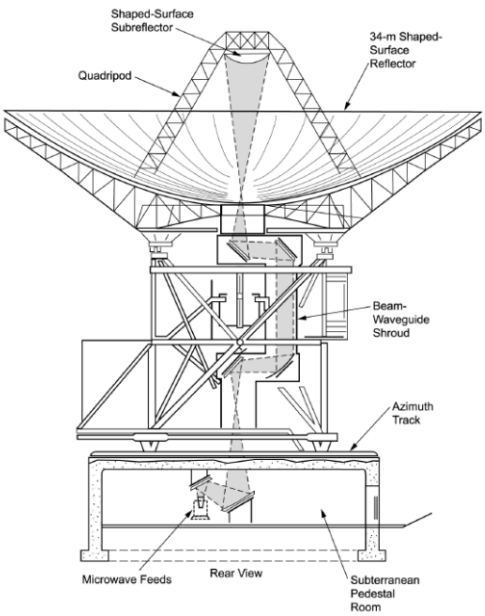


Figure 1. 34-meter Beam Waveguide Antenna with Mirror Configuration

Figure 2. DSS-24 Antenna at Goldstone

II. REQUIREMENTS FOR KA-BAND HIGH-RATE TELEMETRY

The current mission requirements for the Ka2 upgrade dictate a low-noise, cryogenic system on the front end and a high-data-rate system on the back end. The system noise temperature is specified for a vacuum condition, i.e. not including atmosphere and cosmic background noise. In reality, the actual system temperature will be a strong function of weather, atmospheric conditions and antenna elevation angle for the 26 GHz Ka2 frequency band [2]. The key requirements for the Ka2 system are as follows:

Receive frequency band: 25.5 – 27.0 GHz

Channel select step size: <= 1 MHz

Receive input power range:

High-gain mode: 50 dBm, max.

Low-gain mode: -75 dBm, max.

RF system gain: (LNA input to telemetry receiver input)

High-gain mode: 57 +/-2 dB

Low-gain mode: 37 +/-2 dB

System linearity : < 0.5% (for -90 dBm ambient load noise input)

G/T >= 60.7 dB/K (vacuum) at 45 deg elevation

System noise temperature (vacuum) <= 36 K

Passband flatness: < 2.0 dB over 400 MHz

Receive polarization: RCP or LCP (not simultaneous)

Antenna pointing accuracy < 5.5 mdeg (mean radial error)

Antenna gain measurement accuracy < 0.4 dB

Compression point dynamic range > 135 dB-Hz (in a 1 Hz bandwidth)

Data rate: 1 to 150 Mbps, QPSK

Symbol rate: up to 350 Msym/sec, QPSK

Modulation types: BPSK, QPSK, OQPSK

Waveform types: NRZ-L, M, S

Decoding formats: Viterbi (7, ½), Reed Solomon

Local data storage: 5 Tbytes

Doppler measurement accuracy < 0.05 mm/sec, 1 sigma

System noise temperature measurement accuracy: 5%

Data delivery probability: 95% (within 10 sec. of Earth receive time (ERT))

III. SYSTEM DESIGN

a. Optical Design

The Ka2 task has added a new dichroic reflector (M6A) and flat plate mirror (M8), as well as a feed/LNA subsystem to enable simultaneous Cat A S-band transmit, S-band receive and Ka-band receive. The notional mirror configuration is shown in the system block diagram in Figure 3. The new M6A mirror is selectable, using a shuttle mechanism, so that the antenna can operate in any of 3 modes (up/down/down): S/S/X, X/X/Ka1 or S/S/Ka2. For Ka2 band operation, the M7 mirror is moved out of the beam path into stow position.

The M6A mirror is a new design that is optimized for performance (< 10K noise contribution across the band) and manufacturability for relatively lower cost. Whereas previous large dichroic plates for the DSN have been done using electrostatic discharge machining (EDM), which is time consuming and expensive, the M6A plate was fabricated using a standard milling machine. The return loss test setup for the plate is shown in Figure 4. The resulting return loss performance is shown in Figure 5, showing very good agreement with the theoretical model. The null in the return loss response is placed near 25.9 GHz by design, since this is the downlink frequency of the primary mission (JWST).

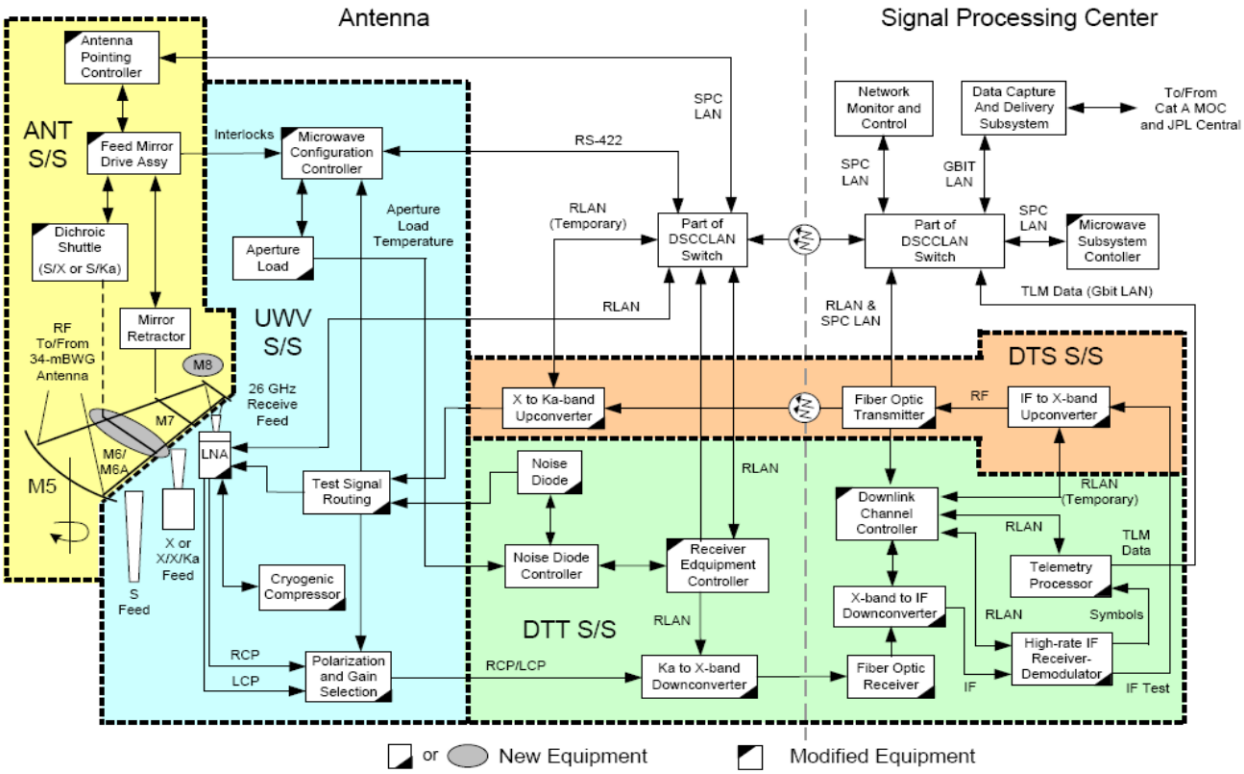


Figure 3. Ka-band Phase 2 System Block Diagram

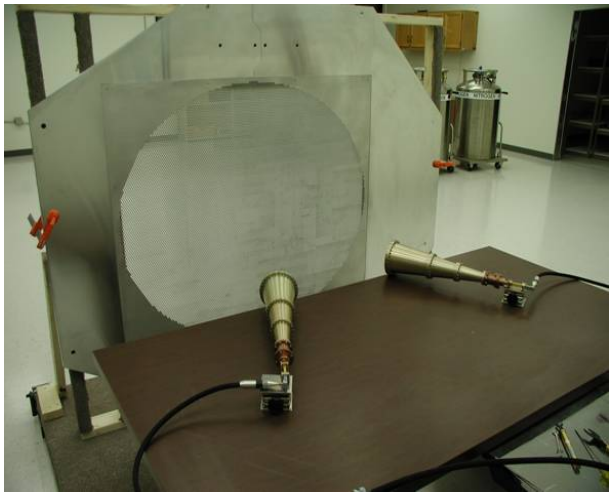


Figure 4. S/Ka Dichroic Plate (M6A) Test Setup

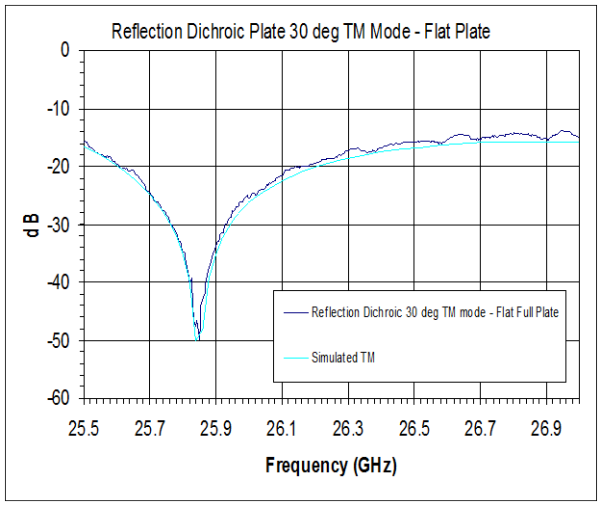


Figure 5. M6A Return Loss – Measured vs. Theory

b. Mechanical Design

In order to add a feed under the new M8 mirror, it was necessary to build a new (Ka2) platform above the existing X/Ka platform. Since it is high enough not to interfere with any equipment movement in the pedestal room, and in order to be useful as a staging area, the platform was extended from the shroud to the basement wall (see Figure 6). A modification was also made to the shroud, by replacing a flat panel with a "dog house" panel in the location where the new M6A mirror is withdrawn to "stow". The M6/M6A shuttle function was implemented by extending the trolley rails for the original M6 and suspending the new M6A mirror on a new frame sitting at the other end of the rail system. The M6A mirror movement does not require any new motors since it is moved by being latched and towed by the original M6 mirror. The existing Feed Mirror Drive (FMD) software was modified to enable the latching and towing required for the new S/Ka2 mirror configuration.

Figure 6 Ka2 Platform in Pedestal Room

c. Cryogenic Low-noise Amplifier (LNA) Subsystem

The low system temperature requirement of 36K (in vacuum) was derived from the link budget required to support the relatively high data rates (up to 28 Mbps) for science missions at the edge of deep space, such as JWST at the Lagrange 2 (L2) point. In order to achieve the low system temperature, it was necessary to employ a cryogenic system, cooled to about 10K. The resulting LNA/feed effective temperature (Te) is therefore about 13K. The waveguide configuration inside the vacuum dewar (shown upside down), with the cryogenic coldhead attached, is shown in Figure 7. This assembly includes the septum polarizer, couplers for noise and test signal injection and the LNA's for both RCP and LCP polarizations.

An RF plate assembly, mounted externally to the cryostat, is used for a post amplifier, polarization selection, test signal configuration and high/low gain selection. The low gain mode is 20 dB lower than the nominal 57 dB RF system gain and is used to support very strong signals during early post-launch mission phase. The existing front end controller software was modified to incorporate control of the new Ka2 equipment. A LAN interface was also added to remotely monitor the cryostat temperatures and pressures in the SPC.

The LNA module itself is a 4-stage amplifier, based on an InP high electron mobility transistor (HEMT) device and is shown in Figure 8. The device is a legacy DSN design that is used for the Ka1 32 GHz band, but has been fine tuned to the Ka2 26 GHz band for this application.

Figure 7. Cryo LNA Assembly

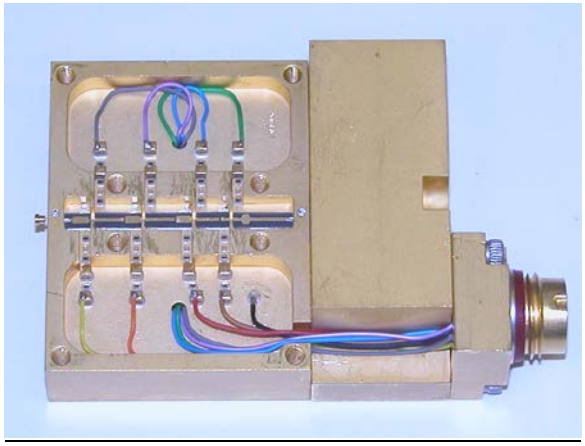


Figure 8. Ka2 LNA Module

d. RF Subsystem

The RF design is driven by both the high dynamic range and broad bandwidth requirements. The dynamic range requirement is achieved with a low-noise fiber optic link, to transport the X-band IF signals from the antennas to the Signal Processing Centers (SPC), which are up to 20 km apart. In order to minimize equipment in the antennas, a block Ka-to-X band downconverter is used in the antennas. Bringing the full 1.5 GHz bandwidth to the Signal Processing Center (SPC) also allows easy addition of more receiver channels, in the event that a requirement is added for multiple spacecraft per antenna. This scenario is possible if there are multiple lunar missions operating simultaneously, for example. Further downconversion and channel selection, with an X-to-IF downconverter, is then done in the Signal Processing Center (SPC). An industry standard IF frequency of 720 MHz is used for compatibility with commercial telemetry receivers. A dual downconversion architecture is used in the synthesized downconverter to maintain a high spurious-free dynamic range in the presence of possible radio frequency interference (RFI).

System noise temperature (SNT) measurement is done remotely (via a LAN interface), using a synchronous detector circuit within the Ka-X block downconverter. The measurement approach is basically that of a noise adding radiometer, using a modulated noise source and a synchronous Y-factor measurement. An ambient aperture load, mounted over the Ka2 feed, is used to periodically calibrate the noise source.

Test signal generation is done using the internal test source of the RT Logic digital receiver. The 720 MHz IF test output is upconverted and tuned to the desired channel using basically the inverse architecture of the downconversion chain. Flexibility for fault isolation is accomplished by having 3 different test injection loops: short loop for injection back into the digital receiver assembly, medium loop for injection at the LNA/post amplifier output and long loop for injection at the LNA input.

The physical arrangement of the RF subsystem "front end" boxes and the feed/LNA assembly at the shroud interface is shown in Figure 9.

Figure 9. Ka2 Feed/LNA Package

e. Digital Receiver Subsystem

Demodulation and telemetry processing is done using a "2-box" commercial telemetry subsystem from RT Logic, consisting of a receiver (demodulator/decoder) assembly and a telemetry processor assembly. The demodulation, convolutional (Viterbi) decoding and differential decoding is done in the receiver, while the frame synchronization, Reed Solomon decoding and PN decoding is done in the telemetry processor. Software development was limited to modifications to the existing DSN monitor and control programs, to reduce development time and cost. The operator interfaces remain basically the same as the existing DSN receiver subsystem, to allow a quick transition from development to transferred operations. This has reduced the required software "soak" period and the required operations personnel training.

The arrangement of the redundant receiver and telemetry processor assemblies in the SPC rack is shown in Figure 10. The synthesized downconverter that provides the 720 MHz IF signal to both receivers can be seen in the bottom of the Receiver rack.

Figure 10. Receiver and Test Generator Racks

IV. SYSTEM TEST RESULTS

a. Antenna calibration

Since the 34 meter BWG antennas had not been previously tested at the 26 GHz band, it was necessary to do extensive calibration measurements for each of the 3 antennas. Most of the Ka2 antenna calibration data was taken using a DSN operational system called the Antenna Calibration Measurement

Equipment (ACME). This system is used for all of the DSN operational bands (S, X, Ka1 and Ka2) and is described in detail in the Deep Space Communication and Navigation Systems Center of Excellence (DESCANSO) series [3].

The summary of the principle antenna parameters measured for the Ka2 band is given in Table 1. An example of one of the tipping curves, showing the strong dependence of sky temperature (Tsky) and system operating temperature (Top) with elevation angle for the Ka2 band is shown in Figure 11. The so-called T (antenna microwave), or Tamw, is the Top with atmospheric effects and cosmic background noise taken out. The Top for dry atmospheric conditions, at zenith, is about 45K. A continuous sweep of system temperature (Tamw, in vacuum) over the Ka2 band was also measured and is shown in Figure 12 for all 3 antennas. The noise contribution of the M6A dichroic plate, for both RCP and LCP, is shown in Figure 13.

Parameter	Requirement	Measured	Notes
Pointing Error	< 5.5 mdeg	4.0 mdeg	MRE
G/T @ 26.0 GHz	> 61.5 dB/K	62.2 dB/K	@ 45 deg.
G/T, 25.5-27.0 GHz	> 60.7 dB/K	61.4 dB/K	@ 45 deg.
Efficiency	N/A	61.20%	@ 55 deg.

Table 1 Antenna Calibration Data – DSS-24

b. Passband Flatness

The overall system passband flatness over the nominal 400 MHz telemetry bandwidth was measured using the aperture load as a "flat" noise source. The resulting noise output at the 720 MHz IF, with the input channel set to the Ka2 band center, is given in Figure 14.

c. Phase Stability

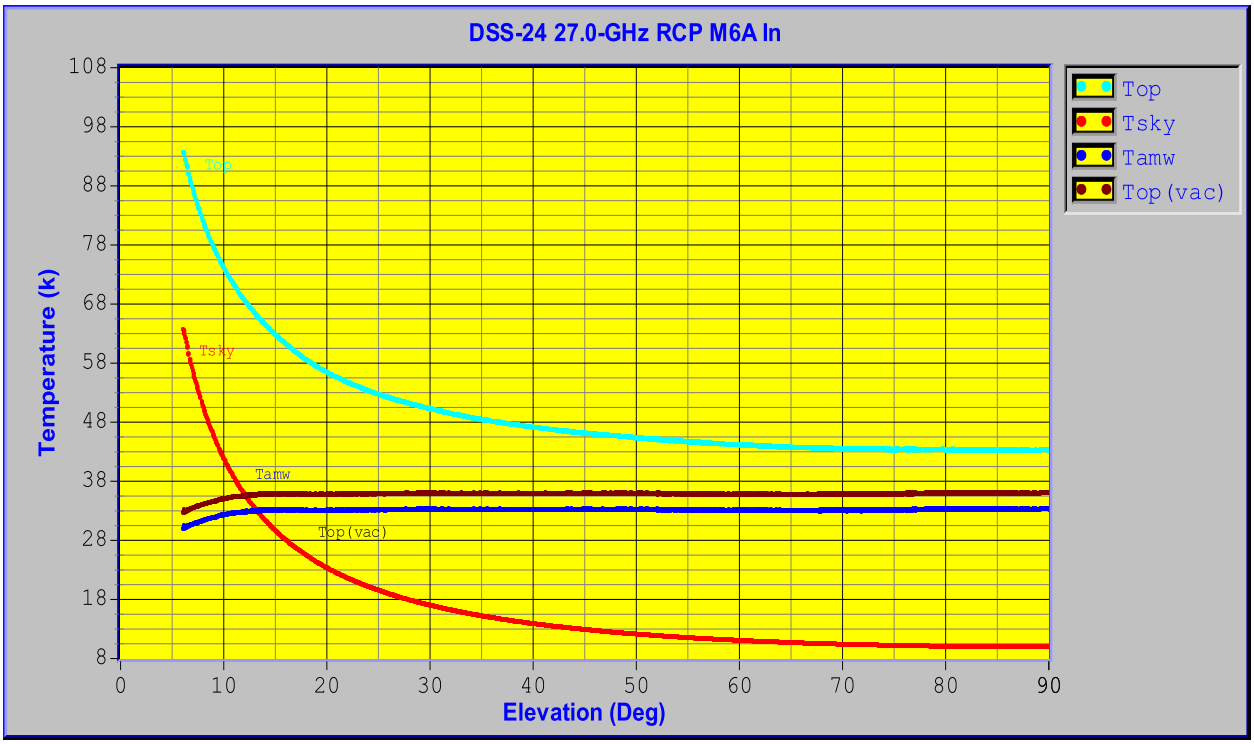
Although the Ka2 system is not intended to be used for radio science applications, there is a short-term phase stability requirement imposed in order to meet the future Doppler measurement accuracy requirement. This requirement translates to an Allen Deviation requirement of 1.7E-13 for a 60 second integration time. The system performance is about an order of magnitude lower than the requirement, as seen in the plot in Figure 15.

d. System Linearity

The system linearity was measured, using the ACME system, to be about 0.2% at the -90 dBm noise input level. The compression characteristic was also measured using a spectrum analyzer and is plotted in Figure 16. The 1 dB input compression point for the high gain mode, at the LNA input, is approximately -63 dBm.

e. Bit Error Rate (BER)

The most fundamental performance of the Ka2 system was characterized by measuring the bit error rate performance. The theoretical reference for rate ½ Viterbi coding is documented in [4]. A summary of measured versus theoretical performance for 100 Mbps data rates is given in Fig.ure 17, showing good agreement. Based on the measured BER values, the demodulator/decoder loss of the Ka2 system is less than 1 dB.



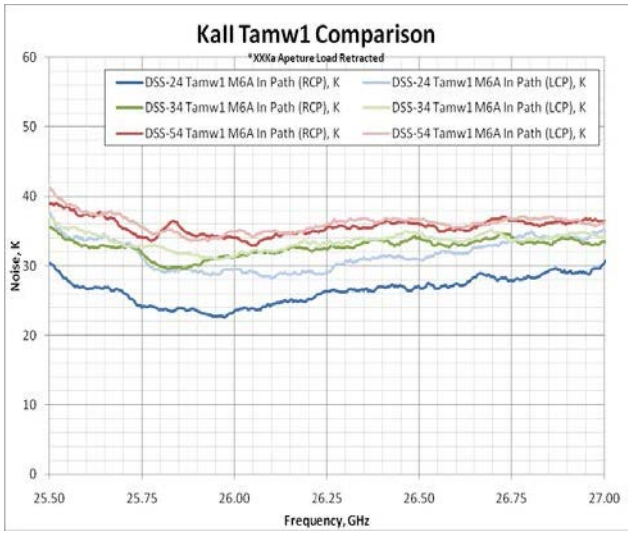


Figure 12. System Noise Temperature vs Frequency (vacuum)

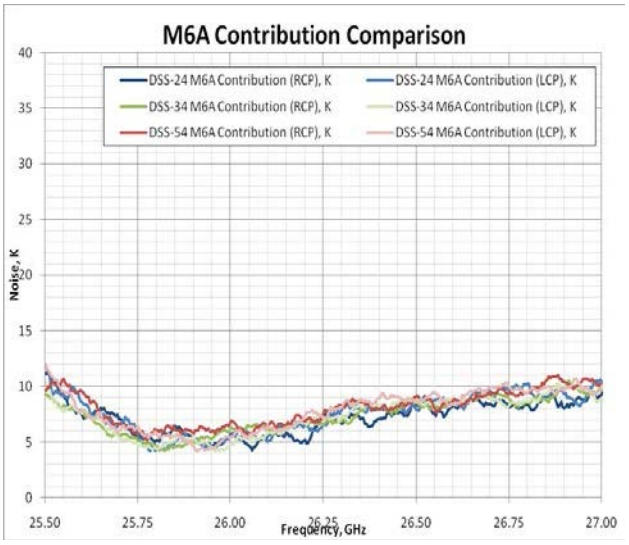


Figure 13. M6A Noise Contribution vs Frequency

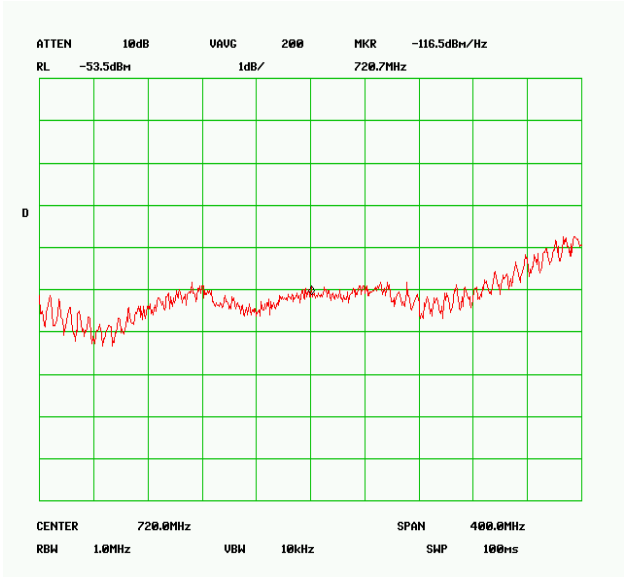


Figure 14. System Passband Flatness - 400 MHz Span (DSS-54)

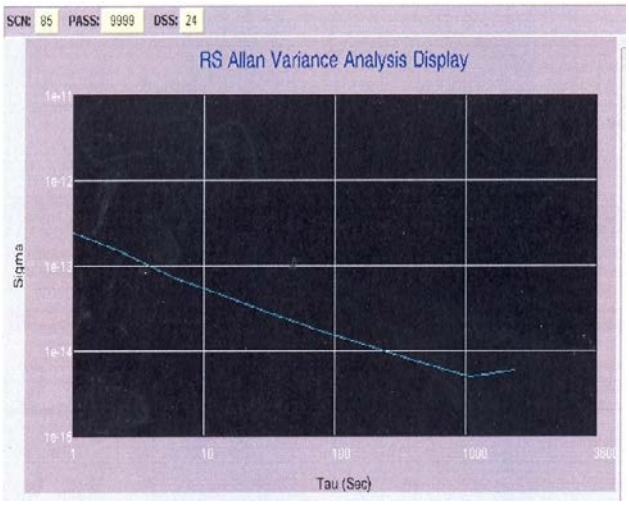


Figure 15. System Phase Stability (Allen Deviation, DSS-24)

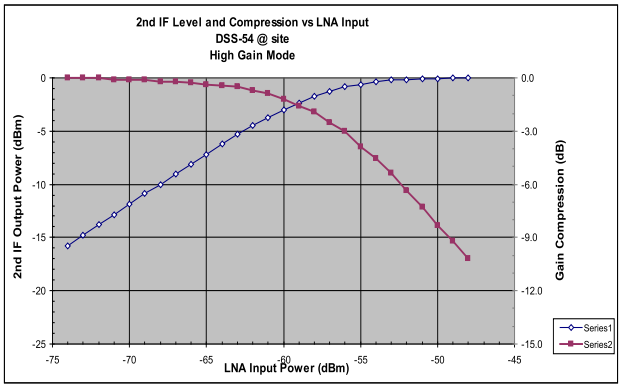


Figure 16. System Linearity – High Gain Mode

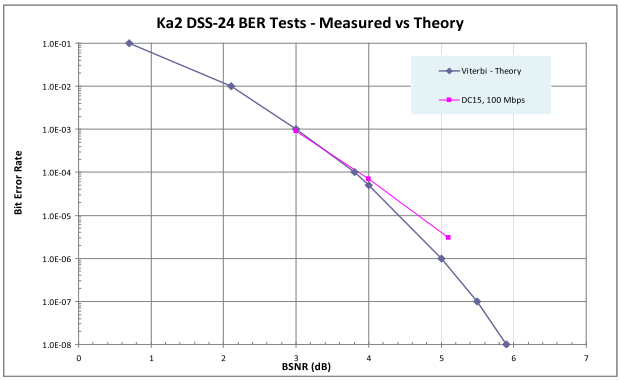


Figure 17. Bit Error Rate (100 Mbps) – Measured vs Theory (DSS-24)

V. CONCLUSION

The Ka-band Phase 2 upgrade is a major addition to the capability of the DSN, allowing the network to support a new mission set with much higher data rates than the traditional deep-space missions. The RF front-end architecture is designed to allow economical addition of multiple back-end receivers to support multiple spacecraft within the same antenna beam. The Ka-band Phase 2 upgrade has been recently implemented into 3 different 34-meter BWG antennas in the DSN, one at each of the complexes in Canberra (Australia), Goldstone (California) and Madrid (Spain), and is ready to support Category A Ka-band missions.

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