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Mars Reconnaissance Orbiter Ka-band (32 GHz) Demonstration: Cruise Phase Operations

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The X-band (8.41 GHz) frequency allocation currently used for deep space telecommunications is too narrow (50 MHz) to support future high rate missions. Because of this NASA has decided to transition to Ka-band (32 GHz) frequencies. As weather effects cause much larger fluctuations on Ka-band than on X-band, the traditional method of using a few dBs of margin to cover these fluctuations is wasteful of power for Ka-band; therefore, a different operations concept is needed for Ka-band links. As part of the development of the operations concept for Ka-band, NASA has implemented a fully functioning Ka-band communications suite on its Mars Reconnaissance Orbiter (MRO). This suite will be used during the primary science phase to develop and refine the Ka-band operations concept for deep space missions. In order to test the functional readiness of the spacecraft and the Deep Space Network's (DSN) readiness to support the demonstration activities a series of passes over DSN 34-m Beam Waveguide (BWG) antennas were scheduled during the cruise phase of the mission. MRO was launched on August 12, 2005 from Kennedy Space Center, Cape Canaveral, Florida, USA and went into Mars orbit on March 10, 2006. A total of ten telemetry demonstration and one high gain antenna (HGA) calibration passes were allocated to the Ka-band demonstration during cruise. Furthermore, a number of "shadow" passes were also scheduled where, during a regular MRO track over a Ka-band capable antenna, the Ka-band link was identically configured as the X-band and tracked by the station. In addition, nine Ka-band delta differential one way ranging (ΔDOR) passes were scheduled. During these passes, the spacecraft and the ground system were put through their respective paces. Among the highlights of these was setting a single day record for data return from a deep space spacecraft (116 Gbits) achieved during one 10-hour pass; achieving the highest data rate ever from a planetary mission (5.2 Mbps) and successfully demonstrating Ka-band ΔDOR. DSN performed well despit minor concerns with the active pointing of the Ka-band antennas as well as delivery of the monitor data from the stations. The spacecraft also presented challenges not normally associated with planetary missions mostly because of its very high equivalent isotropic radiated power (EIRP). This caused problems in accurately evaluating the in-flight EIRP of the spacecraft which led to difficulties evaluating the quality of the HGA calibration data. These led to the development of additional measurement techniques that could be used for future high-power deep space missions.

I. Introduction

NASA's Mars Reconnaissance Orbiter (MRO) is carrying a full suite of 32 GHz (Ka-band) telecommunications equipment in order to demonstrate the feasibility of Ka-band use for deep space telecommunications. This demonstration is necessary as the 50 MHz of bandwidth allocated at 8.41 GHz (X-band) is too small to handle the higher data rates expected from future deep space missions. (The frequency allocation at

32-GHz Ka-band is 500 MHz). The Ka-band link is more susceptible to severe weather events. Therefore, the operations concept that will be validated through this demonstration is based on maximizing the average data return on the Ka-band link subject to a minimum availability.[1–3]

It was decided that during the cruise period various ground and spacecraft functions will be verified through ten dedicated Ka-band demonstration passes. In addition to these, several Δ Differential One-Way Ranging (ΔDOR)passes as well as a number of "shadow" passes were scheduled. During the "shadoow" passes, the X-band and the Ka-band links on the spacecraft were identically configured and tracked by a ground antenna capable of receiving both X-band and Ka-band.

As a result of these passes, it was determined that MRO is fully capable of supporting the Ka-band demonstration activities during the two-year primary science phase (PSP). The Deep Space Network (DSN) also performed well despite some minor issues with the Ka-band monopulse active antenna pointing and receiving and archiving of monitor data. These issues are expected to be resolved before the start of the PSP activities.

The paper is organized in the following manner: In Section II an overview of the demonstration along with a brief description of the spacecraft and the ground system capabilities is given. In Section III, an overview of the Ka-band link telemetry and navigation performance during the ten dedicated passes and the "shadow" passes is provided. In addition, performance of the ground system in terms of antenna pointing and measuring of the signal-to-noise ratio is considered. In Section IV the issue of measuring the spacecraft EIRP is looked at in more detail. Section V covers the ΔDOR performance of the Ka-band during the cruise. Finally, in Section VI conclusions are reached.

II. Demonstration Overview

A. Demonstration Objectives

The objectives of this demonstration are to validate the proposed Ka-band operations concept for deep space missions and to modify this operations concept according to experience. Furthermore, this demonstration is to identify possible shortcomings in the ground systems for tracking of Ka-band and propose remedies for them.[4,5]

The objective of the passes assigned to the Ka-band demonstration during cruise are to verify that both the spacecraft and the ground systems have the necessary functionalities for the Ka-band demonstration activities during the PSP. In addition, the cruise passes will familiarize the Ka-band demonstration team with project procedures and interfaces. This will allow the Ka-band activities to be executed smoothly during the PSP.

B. MRO Spacecraft

The Mars Reconnaissance Orbiter was launched from Kennedy Space Center on August 12, 2005 and went into Mars Orbit on March 10, 2006. The spacecraft will finish its aerobraking maneuvers by September 2006 after which it will go through a series of calibration activities. From October 7, 2006 through November 7, 2006, the spacecraft will be in superior solar conjunction. During this time communications with the spacecraft will be limited and spacecraft operations will be kept to a minimum. From November 8, 2006 through November 18, 2008 the spacecraft will be in its PSP. During the PSP the spacecraft will gather more data on Mars than all the past missions to Mars combined. During the solar conjunctions period the Ka-band demonstration is allocated, on the average, one pass per day. During the PSP, the Ka-band demonstration is allocated two passes a week and one ΔDOR pass a month.[6] In addition, the project will use Ka-band to transmit low priority science data for mission enhancement.

The Ka-band suite on MRO consists of a 35-watt Traveling Wave Tube Amplifier (TWTA) and a 3-meter parabolic antenna which produces an Equivalent Isotropic Radiated Power (EIRP) of 101.3 dBm based on pre-launch measurements. By comparison, the X-band system has one primary 100-watt TWTA and one backup 100-watt TWTA with the same 3-meter dish producing an EIRP of 96.2 dBm based on pre-launch measurements. The reason that the Ka-band system has a larger EIRP is entirely due to the higher gain of the antenna at Ka-band.[7] The X-band signal could be transmitted on two low-gain antennas (LGAs) as well. There are two small deep space transponders (SDSTs) on the spacecraft (again, one as a back-up) for modulation of the data. A simplified block diagram is shown in Fig. 1.

Although the spacecraft is capable of using both turbo coding with block length 8920 bits and rates 1/2, 1/3 and 1/6 and Reed-Solomon (RS) coding (concatenation with (7,1/2) convolutional code is done by the SDST), there are limitations on simultaneous X-band and Ka-band operations. These limitations are:

1. If the data transmitted over the Ka-band link is different from that transmitted over the X-band link, one link has to use turbo coding; the other has to use RS or concatenated coding.
2. If the data transmitted over the Ka-band link is different from that transmitted over the X-band link, the combined channel symbol rate of the two bands should be no greater than 6 Msps. For concatenated codes this includes the symbol rate increase due to the use of (7,1/2) code.
3. If the same data is transmitted over both the X-band and the Ka-band links, then the symbol rate on each channel cannot exceed 6 Msps. For concatenated codes this includes the symbol rate increase due to the use of (7,1/2) code.
4. The turbo coding option can support a maximum of 1.5 Mbps with rate 1/2 code due to ground decoder hardware limitations.

The ranging modulation and data modulation index for each band are independently configurable. For symbol rates above 2 Msps QPSK modulation is used for X-band due to spectrum limitations. For Ka-band BPSK modulation is always used.

DOR tones can be modulated on both X-band and Ka-band. Ka-band uses wider DOR tones than X-band because of availability of more spectrum thus providing improved ΔDOR performance over X-band (see Section V).

The spacecraft is sequenced (programmed) primarily through two different procedures: background sequencing and mini-sequencing. Background sequencing programs the spacecraft for 28 days. Mini-sequencing programs the spacecraft for specific events such as calibrations of instruments and trajectory correction maneuvers. In addition, mini-sequencing is used to modify the background sequence according to the latest information available to the project. The background sequence usually takes 28 days to develop. Development time of mini-sequences vary depending on the nature of the sequence but they take at least a week. Real-time commands could also be used with the spacecraft. However, their use is very limited as all spacecraft sequences must be validated before their actual implementation. All Ka-band activities during the cruise were sequenced as part of the background sequence with the exception of some real-time commands for modulation index changes. We expect to use background sequences for practically all Ka-band demonstration activities during the PSP.

The basic requirements on spacecraft for the Ka-band demonstration are that:

1. The spacecraft must be capable of producing adequate EIRP for Ka-band (greater than 100 dBm).
2. The spacecraft's Ka-band link must be fully configurable in accordance to the *MRO Telecom Design Control Document*[7].
3. The link's data rate could be changed during a pass according to the background sequence.
4. The link's modulation index could be changed during a pass according to the background sequence and real-time commands.
5. The spacecraft must be capable of producing wideband DOR tones for Ka-band.

6. The spacecraft must be capable of modulating uplinked ranging tones on the Ka-band downlink.

The data rate change requirement is a necessity for the Ka-band as the link performance changes significantly as a function of elevation. Through modulation index changes in real time we try to emulate the signal-to-noise ratio (SNR) changes that would results from real-time data rate changes. In addition, modulation index changes allow us to change the SNR. This will allow us to obtain SNR thresholds for different coding types.

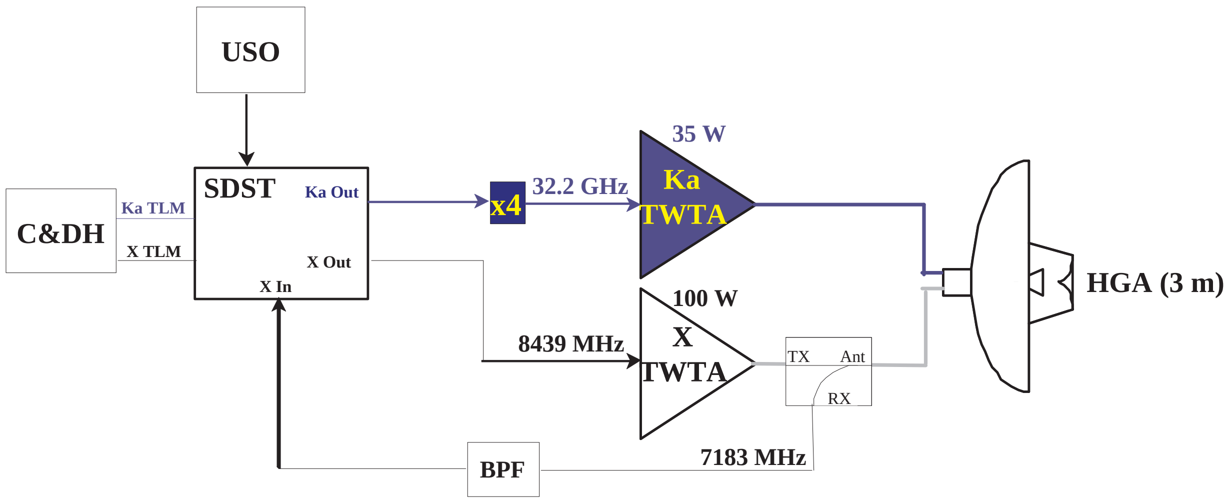

Figure 1. MRO telecommunications and commanding subsystem

C. Ground Systems

Part of the Ka-band demonstration is to assess the readiness of the Deep Space Network (DSN) to track Ka-band signals from deep space missions. It should be noted that the DSN has tracked Ka-band only sporadically for Cassini radio science activities on a best effort basis and that the MRO Ka-band demonstration will allow the DSN to track Ka-band telemetry regularly for the first time. Therefore, we expected that some challanges would arise with the DSN Ka-band tracking and that the passes during the cruise will be used to identify problems that may exist with the DSN Ka-band equipment and operations.

The DSN consists of three Deep Space Communication Complexes (DSCCs) located at Goldstone, California; near Canberra, Australia and near Madrid, Spain. These sites were selected by NASA in order to provide both round the clock coverage for missions that need them and to provide north-south coverage for the DSN.

There are four Deep Space Stations (DSSs, as the DSN antennas are called) in the DSN that are capable of receiving Ka-band. All these antennas are part of the DSN 34-meter beam waveguide (BWG) subnet. These are DSS-25 and DSS-26 at Goldstone, DSS-34 at Canberra and DSS-55 at Madrid. During the Ka-band demonstration we expect to use all the stations with roughly equal number of passes divided among the three complexes (not the stations). The gain and noise temperature characteristics of these antennas are listed in JPL document 810-005, Rev. E.[8]

There are two sets of capabilities that are required for the ground systems: those related to individual antenna performance and those related to the complex's signal and data processing capabilities. The basic antenna functions required for Ka-band demonstration are as follows:

1. The stations' Ka-band low-noise amplifiers (LNA) must meet the performance specifications in[8] .
2. The blind pointing of the station for Ka-band must be better than 10 mdeg so that the active pointing (monopulse system) will be able to operate.
3. The monopulse must be operational at all the stations for all the passes.

It should be noted that, as the 34-m BWG Ka-band beamwidth is rather narrow (less than 18 mdeg). Therefore, the ground antenna pointing needs to be very good. Without the active antenna pointing there could be 4 or 5 dB loss in the link performance due to pointing errors.

The required signal and data processing functions are as follows:

1. DSCCs must be able to demodulate and decode Ka-band telemetry.
2. The ground receivers must accurately measure the system noise temperature (SNT).
3. The ground receivers must accurately measure signal-to-noise ratio (SNR), especially symbol SNR (SSNR).
4. DSCCs must be able to measure Doppler and perform 2-way ranging with the Ka-band signal.
5. DSCCs must be able to receive Ka-band DOR tones and perform ΔDOR measurements at Ka-band.
6. Monitor data from each pass should be delivered to the MRO query servers for each pass from the DSCCs with the proper sampling rate (once every five seconds).

It should be noted that for normal spacecraft operations only demodulation and decoding of the data, Doppler and ranging measurements and ΔDOR measurements are required. The reason for the additional requirements is that the MRO Ka-band demonstration needs to identify those data outages that are caused by weather events and separate them from outages caused by other phenomena such as errors in the ground antenna pointing. For this purpose, the analysis will consist of correlating decoding errors with drops in the SNR and increases in the SNT. Therefore, accurate reporting of the SNR and the SNT as well as proper delivery and archiving of the monitor data are needed for this demonstration.

III. Ka-band Telemetry Passes During Cruise

In this section an exposition of Ka-band activities during those passes over which Ka-band telemetry was received is discussed. These passes fall into three categories: 1) Dedicated Ka-band passes, 2) Ka-band shadow passes around trajectory correction maneuver 2 (TCM-2), and 3) Ka-band shadow passes around gravity science calibration 2. Each of these categories is treated separately.

A. Dedicated Ka-band Passes

There were ten passes dedicated to Ka-band demonstration during which both the ground system and spacecraft were put through their respective paces. While a pass-by-pass description is beyond the scope of this paper, a general account of the performance of the spacecraft and the ground system is given here.

Of the ten passes, DSS-25, DSS-34 and DSS-55 had three passes each and DSS-26 had one. During these passes the spacecraft data rate, coding and modulation index on Ka-band were changed during a pass using the background sequence. Also the modulation index on Ka-band was changed using real time commands. In addition, the Ka-band signal was turned off and on during a pass to simulate occultations around Mars forcing the DSN to reacquire the Ka-band signal from the spacecraft repeatedly. Overall, the spacecraft performed flawlessly and all its required functions with the exception of the spacecraft Ka-band EIRP (see Section IV below) were readily verified. On the Ka-band pass on day 05-304 (October 31, 2005) over DSS-55, MRO set a planetary mission record for largest amount of data received in a day (116 Gbits) and also for the highest data rate ever (5.2 Mbps) from a planetary spacecraft using the Ka-band link. Also, on the Ka-band pass on day 05-280 (October 7, 2005) over DSS-25, MRO became the first JPL mission to transmit turbo coded data, again on Ka-band. Table 1 shows that all required spacecraft functions have been validated through these passes.

Ground systems functions, as indicated by Table 2, however, have not been fully validated. As mentioned before, this was not unexpected as the DSN had not tracked Ka-band on a regular basis and that one of the objectives of the cruise activities was to identify potential problems with the DSN so they could be fixed before the start of the PSP.

One of the early problems that was encountered was the fact that due to high spacecraft received power at both X-band and Ka-band, very high signal-to-noise (SNR) ratios on both the X-band and the Ka-band and interference from the ranging tones, the symbol SNR (SSNR) and the carrier SNR (P_c/N_0) values were not reported accurately. The errors in the SNR measurements along with high received signal power caused the SNT to be reported erroneously. This is because of the fact that the SNT measurements are based on a total in-band power measurement and in order to calculate the SNT, signal-to-noise ratio needs be known very accurately in cases where the signal power greater than or equal to noise power in the band over which the SNT is estimated. As expected, as the spacecraft moved farther away, the problems with the SNR and the SNT reporting became less pronounced.

The monopulse active pointing system has functioned properly for all four antennas but not for all of the passes (monopulse was operational for 7 of the 10 dedicated Ka-band passes). Hardware problems at DSS-55 and lack of operational experience by DSN personnel contributed to this. The hardware problems at DSS-55 has now been fixed. However, operational experience is necessary to validate this fix. In addition, a performance anomaly at DSS-34 on day 05-319. As Fig. 2 shows, there were drops in the measured SSNR (E_s/N_0) that correlated very closely with large pointing offsets by monopulse. This was only the second time that DSS-34 was tracking the MRO Ka-band signa. Therefore, the monopulse equipment may have not been properly calibrated. Further analysis of this problem is required.

While the monopulse may have not worked perfectly at all times, based on the results obtained when monopulse was working, DSS-34 seems to have had the best blind pointing performance for the parts of the sky where MRO was tracked with pointing offsets of roughly 4 or 5 mdeg most of the time. Other stations do not have as good a blind pointing as DSS-34; however, their performance seems to be adequate for monopulse operations most of the time.

There have also been problems with the monitor data being delivered fully to JPL and to MRO query servers. There were two passes at DSS-55 (day 05-325 and day 05-339) and one pass at DSS-34 (day 05-353) for which the monitor data was sampled rather slowly (several minutes between monitor updates compared to five seconds between updates under normal conditions, see Fig. 3). The reason for this slowness has not been determined yet.

DSN has been notified of problems with the monopulse and the monitor data updates and is working towards solving them. Based on the progress that has been made up to now, it is expected that by the beginning of the PSP these issues will be fully resolved.

The DSN processed Ka-band telemetry as expected. However, it should be noted that the link was never stressed as it would be under nominal operating conditions during the PSP. In addition, some peculiar behaviors were observed on a few of the passes. First, on the pass on day 05-315 (November 11, 2005) over DSS-25, the Ka-band link was operating at 3 Mbps data rate with concatenated codes (6 Msps, 2.61 Mbps information data rate) with a modulation index of 31.4 degrees and ranging turned off. During this time some frame errors were observed even though according to the DSN's Viterbi decoder (MCD) the link had at least 6 dB of margin. This could have been caused by a combination of low modulation index and high received uplink power on the spacecraft. The second problem was observed when the link was operating with 35 degree ranging modulation index and low data modulation indices (30 to 40 deg). In this case periodic frame errors on the link were observed with the periodicity of the errors corresponding to the ranging tone periodicity even though the link had more than 6 dB of margin. Until these two observations are fully

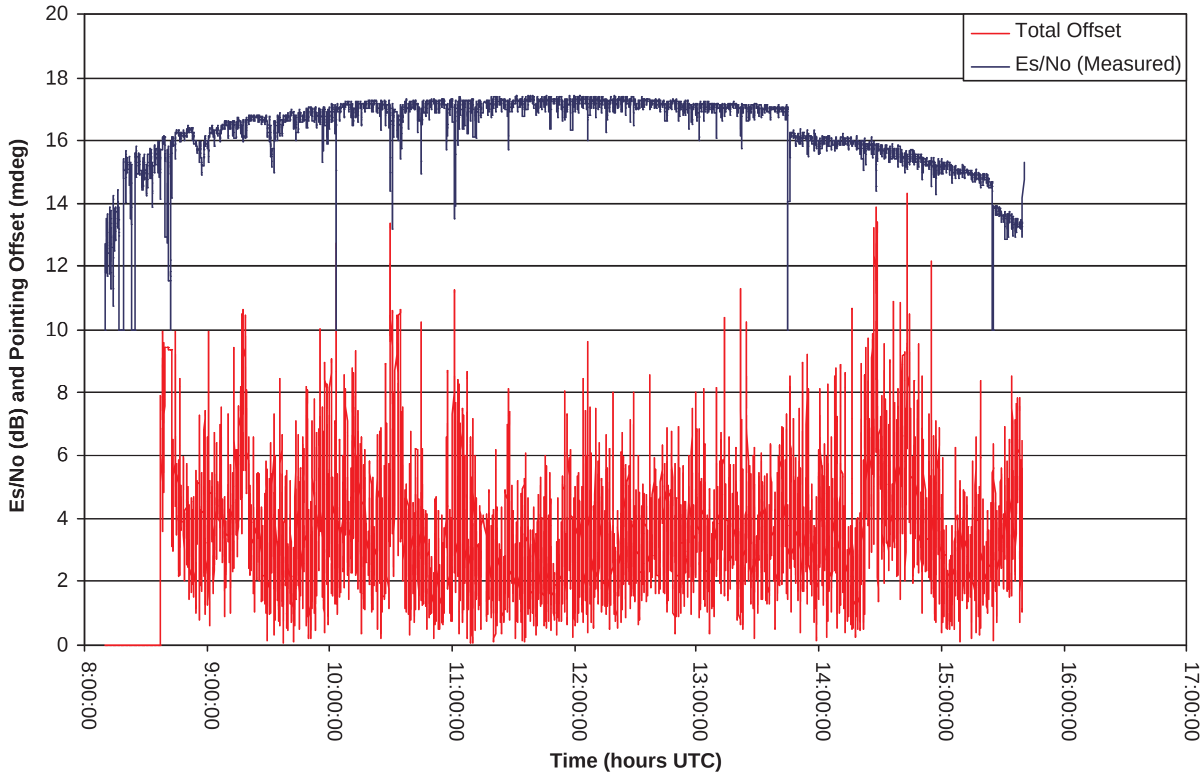

Figure 2. Day 05-319 Ka-band E_s/N_0 and monopulse pointing offsets.

explained, we are reluctant to use low modulation indices and high ranging modulation indices during the PSP.

In addition to the telemetry demonstration, the MRO team also evaluated the performance of the Ka-band (and X-band) radiometric data types used for navigation and radio science during the cruise. These radiometric data types included Doppler and ranging. The downlink Doppler for both the X-band and the Ka-band (coherent with an X-band uplink signal) performed better than the specified navigation requirements. The scatters on the residuals of the two downlink Doppler signals were comparable between the bands suggesting that the dominant error sources were either non-dispersive or due to charged particle effects on the common X-band uplink signal. The performance on the X-band and Ka-band downlink ranging signals (both coherent with an X-band uplink) were also characterized and found to be comparable between the two bands, with the residual scatter and bias not exceeding the specified navigation requirements. In addition to the coherent data types, one-way Doppler performance using the Ultra-Stable Oscillator (USO) and the Auxiliary Oscillator (AUX OSC) onboard the spacecraft was also characterized and found to be consistent with expectations based on specifications or pre-flight measurements. In addition to analyzing performance of the individual X-band and Ka-band frequency bands, the difference between simultaneous X-band and Ka-band downlink frequency data was examined for the purpose of identifying band specific or dispersive error sources. Application of media calibration techniques on the data is currently being investigated for the

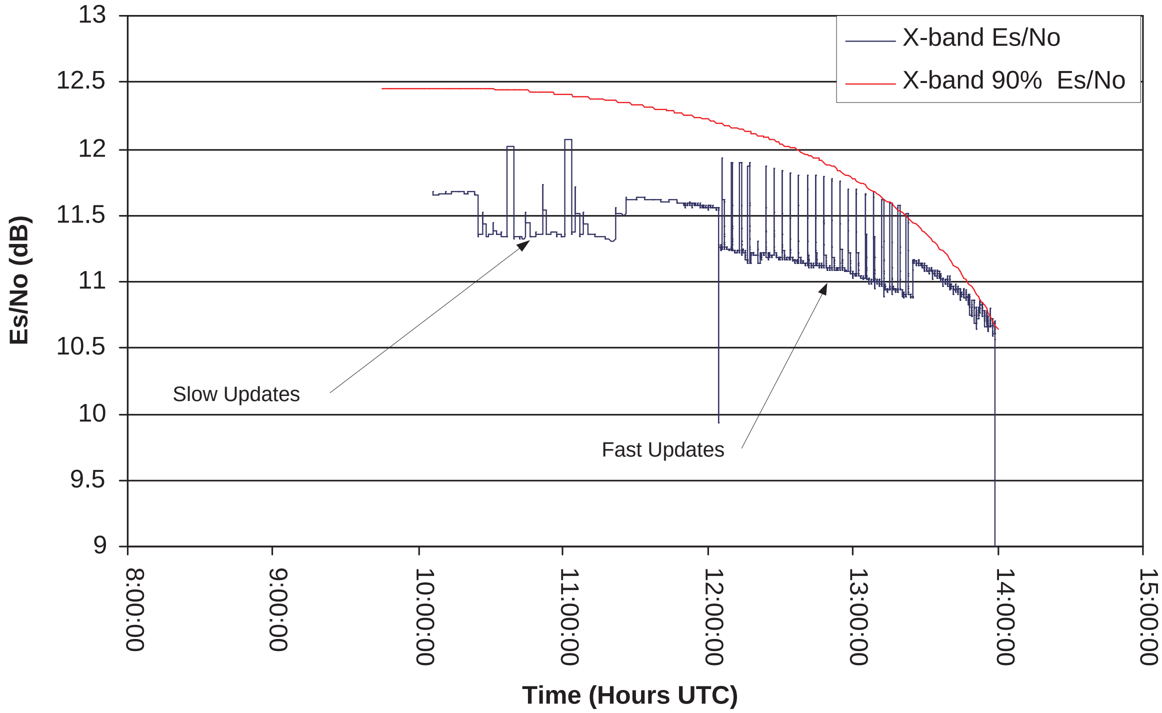

Figure 3. Day 05-353 X-band E_s/N_0.

purpose of realizing any improved performance.

Finally, these passes helped the Ka-band demonstration team and the spacecraft sequencing team to fully understand each other's *modus operandi*. For example, bit rate that the sequencing team uses is referenced to the input to the SDST. As the turbo encoding of the data occurs before SDST, this means that the sequencing team specifies the data rate for turbo codes in terms of encoded symbol rate. The Ka-band team, however, had initially thought that the turbo code data rates were specified in terms of the information bit rate. During the cruise passes this issue was clarified.

B. TCM-2 "Shadow" Passes

For these passes, the Ka-band team used the opportunity that the spacecraft was being continuously tracked from November 14 through November 20, 2005 to have the spacecraft send down telemetry on the Ka-band link whenever the spacecraft was being tracked by a Ka-band capable antenna. The Ka-band configuration for these passes were identical to X-band configuration,*i.e.*, 550 Kbps concatenated coded data (1.1 Msps, 480 Kbps information data rate) with 72 degrees modulation index. The ranging was turned off for Ka-band but was turned on for X-band with a ranging modulation index of 17.5 degrees. The monopulse was not used for these passes.

These passes afforded us the opportunity to observe the Ka-band performance over several passes under nearly identical conditions with the weather as the only variation. We could not do this with our dedicated

Ka-band passes as consecutive passes over the same station were several weeks apart. Furthermore, we needed to verify many different functions with the dedicated Ka-band passes; thus the link configuration changed from pass to pass.

The "shadow" passes also allowed the Gravity Mapping team to obtain simultaneous X-band and Ka-band Doppler data to see whether or not Ka-band could be used to enhance gravity mapping of Mars. The SSNR data obtained during these passes were the first data from operational DSN stations which indicated that the spacecraft is producing adequate Ka-band EIRP. The data from DSS-34 were especially indicative of this (see Fig. 4 for example).

During some of these passes slow downs in the monitor data similar to those described in the previous section were also observed.

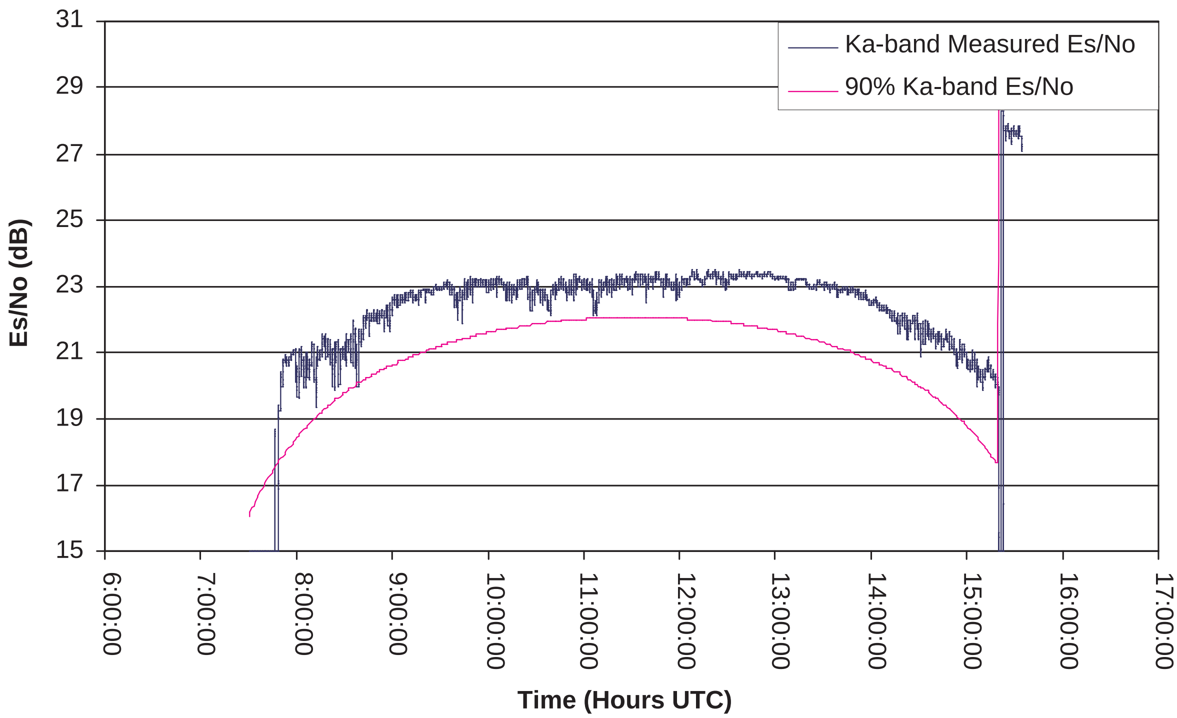

Figure 4. Day 05-321 DSS-34 Ka-band E_s/N_0.

C. "Shadow" Passes around Gravity Calibration 2

For these passes, the Ka-band team used the opportunity that the spacecraft was being continuously tracked from December 26, 2005 through January 4, 2006 to have the spacecraft transmit telemetry on the Ka-band link whenever the spacecraft was being tracked by a Ka-band capable antenna. The Ka-band configuration for these passes were identical to X-band configuration,*i.e.*, 550 Kbps concatenated coded data (1.1 Msps, 480 Kbps information data rate) with 72 degrees modulation index and ranging modulation index set to 17.5 degrees. These passes were also important in that the distance from the spacecraft to Earth for these passes was approximately the same as the distance from Mars to Earth at their closest approach (approximately 0.6 AU). Therefore, the results from these passes are directly relevant for performance of end-to-end Ka-band link during the PSP.

While monopulse was not required for these passes, the stations used this opportunity to activate the monopulse to track Ka-band with varying degrees of success. For example, DSS-34 and DSS-55 successfully operated the monopulse on every one of their passes whereas the only time DSS-25 used its monopulse, the system seems to have malfunctioned.

There were two important observations made during these passes. The first observation is that the SNT measurements for Ka-band seem to be accurate even at the shortest possible Mars-Earth distance provided that the monopulse is working properly. This is indicated by the fact that when the monopulse is not working the reported SNT values have larger fluctuations (see Figs. 5 and 6). The second observation is that under good weather conditions, the Ka-band link could outperform the X-band link (see Fig. 7). This means that Ka-band has the potential to return as much data as X-band for MRO and could be considered a viable back up for the X-band system with about a third of the X-band's transmitted power.

Again during some of these passes, a slowdown in the monitor data updates was observed. This indicates that there is a recurring problem in the DSN with regards to delivery of the monitor data from the DSN complexes to JPL.

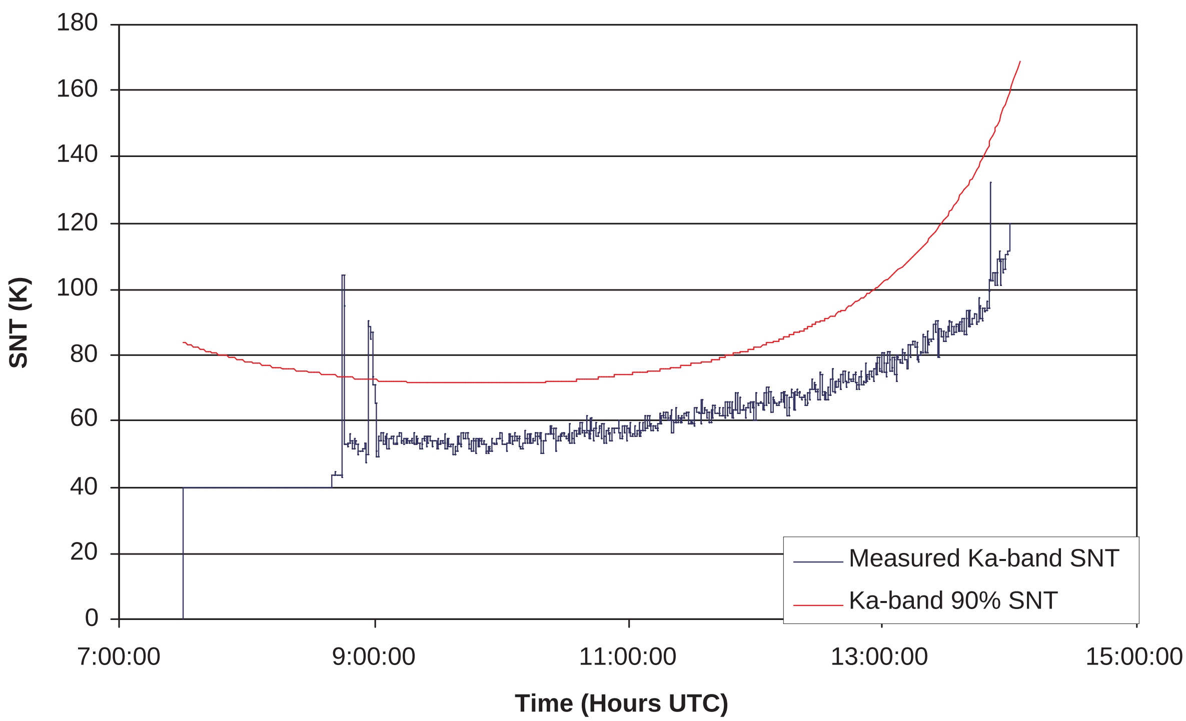

Figure 5. Day 05-360, DSS-34 SNT (monopulse operational).

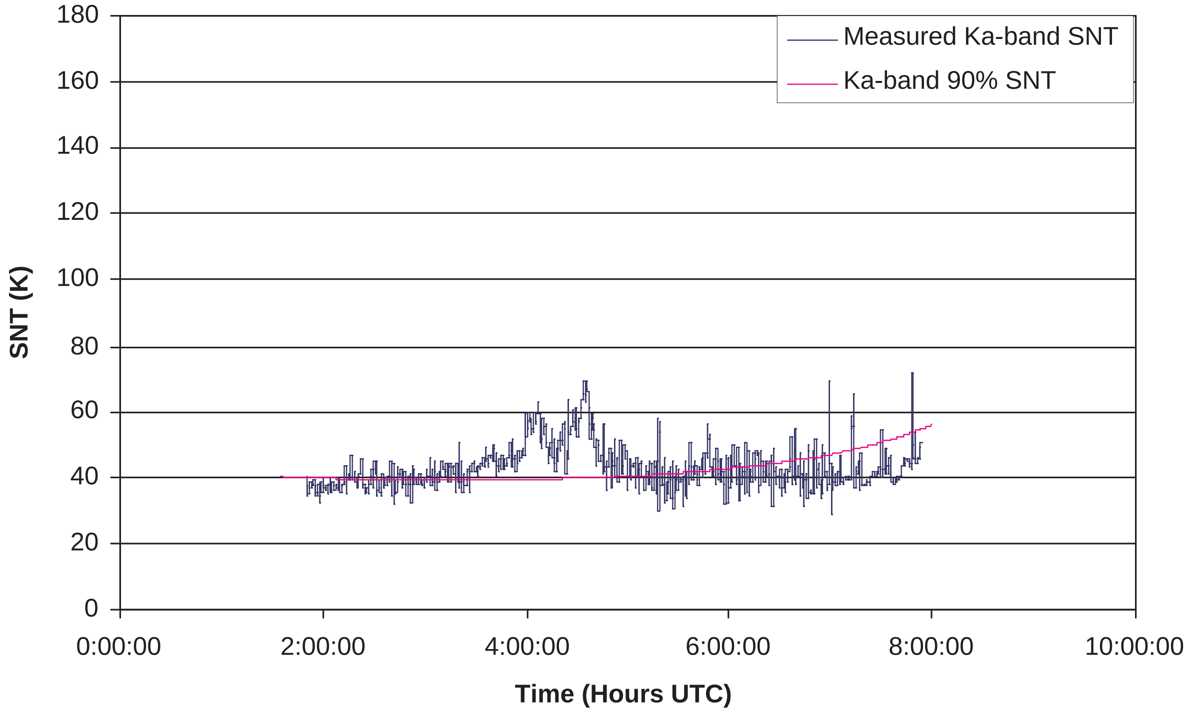

Figure 6. Day 06-003, DSS-26 SNT (monopulse not used).

IV. Evaluating the Spacecraft EIRP

During the cruise phase, MRO presented challenges not normally associated with planetary missions because of its very high received downlink signal power. Because the high received downlink power caused errors in SNR and SNT estimates, it was not clear whether or not the HGA calibration was successful. This also pointed to the fact that the DSN does not have a standard procedure for directly measuring the spacecraft received power. For power measurements DSN relies on calculations based on SNR and SNT measurements. Because the SNR and the SNT estimates were affected by the high received downlink signal power, the DSN could not make an accurate estimate of spacecraft received power and the spacecraft Ka-band EIRP at the beginning of the cruise.

Since the initial SNR measurements during the first Ka-band pass were lower than expected and initial measurements at DSS-13 indicated that the spacecraft EIRP was 5 dB below pre-launch measurements, a Mission Change Request (MCR) was affected to leave the MRO Ka-band on in carrier-only mode for most of the cruise. This allowed us to develop methods for measuring the spacecraft EIRP directly without relying on a ground receiver. In the following we discuss the original HGA calibration and activities at DSS-13 and at the 6-m array breadboard antennas at JPL Mesa.

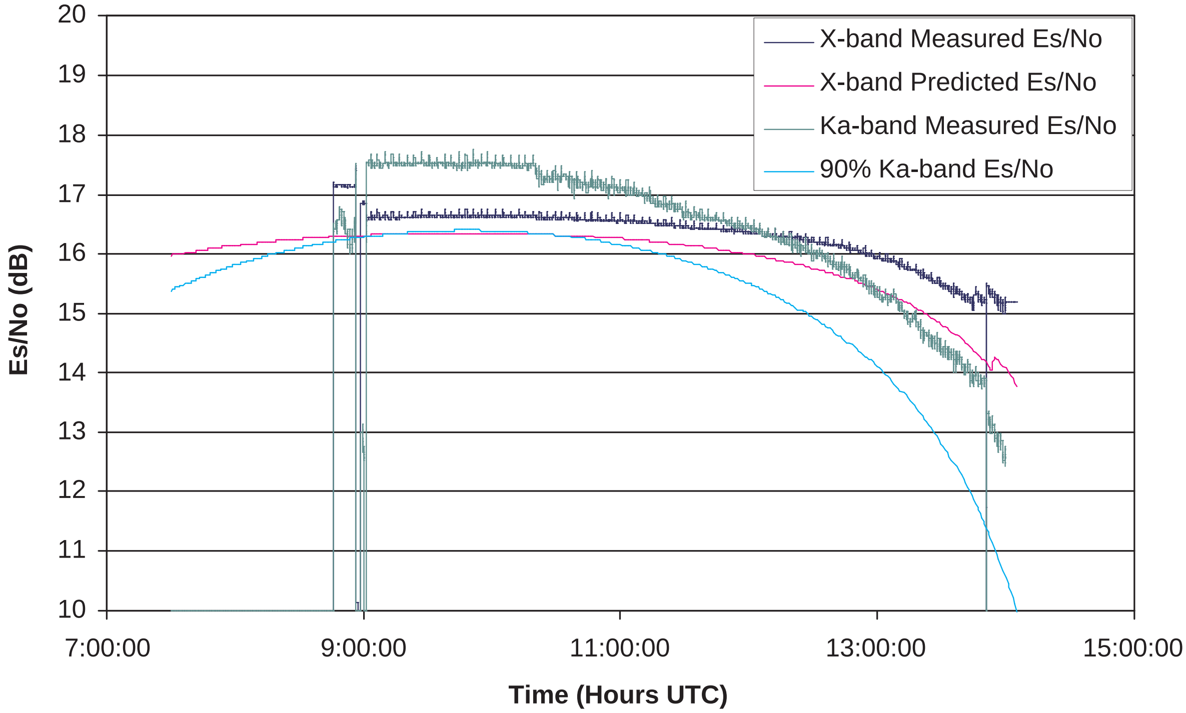

Figure 7. Day 05-360 DSS-34 Ka-band and X-band E_s/N_0.

A. High Gain Antenna Calibration

The MRO Project conducted a High Gain Antenna (HGA) calibration on September 9, 2005 (day 05-252) over Madrid, Spain. This calibration was intended to obtain the boresight of both the X-band and the Ka-band for the spacecraft HGA. For this purpose, point-and-slew patterns at two different attitudes were used with a line separation of 0.1 degrees. The Ka-band 3 dB beamwidth is only 0.18 degrees; therefore no beam pattern could be obtained from these scans. Instead a centroid approach was used to obtain the Ka-band boresight of the antenna. Unfortunately during this pass, the weather was bad; therefore, the SNR measurements fluctuated. In addition, not all the spacecraft high rate gimbal position data were transmitted after the calibration activity; therefore, the gimbal position commands rather than gimbal position knowledge were used for centroid calculations. Even though the boresight calculations that were performed proved highly accurate, because of the coarseness of the calibration pattern and the SNR and the SNT measurements, these calculations were deemed unreliable. Therefore, methods to validate them through direct measurements of the received downlink power were sought.

B. DSS-13 Activities

As previously mentioned, because of the high spacecraft received power, the coarseness of the HGA calibration pattern, and errors in SNR estimates from the receivers, there were concerns as to whether or not the spacecraft was providing adequate Ka-band EIRP and whether or not the spacecraft antenna was on Earth-point. These concerns led to the development and exercise of measurement techniques that could be used for future high-power deep space missions. These techniques were exercised at DSS-13, an R&D 34-m beam waveguide antenna located in Goldstone, California during several passes that spanned MROs cruise phase.

Among the early activities performed at Ka-band (and X-band) at DSS-13 from September through October 2005 were several that involved checkout and calibration of various subsystems. These activities included characterization and measurement of system operating noise temperature (SNT), measurement of system gain and linearity, measurement of the ground antenna efficiency using natural calibrator radio sources, exercising pointing techniques, measurement of MRO X-band signal strength, measurement of Cassini's X-band and Ka-band signal strength, Y-factor and follow-on noise temperature measurements, and attenuator adjustments. The initial calibration data and measurements of MRO Ka-band EIRP indicated that the DSS-13 Ka-band system was not fully optimal. This led to the need for further calibration and installation of additional equipment. A specialized filter was obtained in order to accept MROs Ka-band 522 MHz IF signal within a reasonably small bandpass (13 MHz noise-equivalent bandwidth) in the Ka-band chain. The center frequency and bandwidth of this filter was such that it could accept all of the power in MROs Ka-band signal including carrier and telemetry. A series of additional activities and tests were performed in December at the station, including optimizing system response and linearity, adding amplification prior to the TPR and adjusting attenuation elsewhere in the system, and configuring the system to measure signal strength at RF on day 05-350. IF measurements were performed with the TPR and the spectrum analyzer on Day 05-350 as well as on other days.

Gain and linearity measurements were performed at the beginning of each session or when configuration changes were made. Calibrations were also performed periodically throughout each track in combination with the TPR or spectrum analyzer measurements. A detailed discussion of the system calibration methodology is provided in.[9] Antenna efficiency measurements using natural calibrator radio sources[10] were performed at both X-band and Ka-band in order to evaluate the ground station gain correction in the estimation of the spacecraft EIRP.

A set of procedures were employed in order to measure signal strength using the TPR, and the station spectrum analyzers. The latter entailed measurement of carrier peak minus noise floor, or the carrier peak strength referenced to the LNA input using system gain calibrations.

The TPR method involves using the Total Power Radiometer (TPR) at DSS-13 which accepts two independent IF signal paths, one from X-band RCP and the other from Ka-band RCP for the case of the MRO spacecraft. By peaking the antenna beam onto the signal using the boresight algorithm, the on-source system noise temperature is measured. Then, by moving off-source sufficiently, the background system noise temperature on the cold sky is measured. The difference between these two values results in the system noise temperature increase due to the spacecraft signal. On day 05-350, from about 7:00 to 10:00 UTC, the MRO spacecraft was tracked at X-band and Ka-band while measurements were being made at RF (in pedestal room) and IF (control room). The system noise temperature increase due to the MRO Ka-band signal varied from 350K to about 100K during the pass. This is attributed to elevation dependence of both the atmosphere and the antenna efficiency at Ka-band. This system noise temperature increase was then converted to received signal power over the equivalent noise bandwidth (see Fig. 9). Removed from these figures are data that occurred during calibrations and boresight observations. In Fig. 9, the measured received signal power using the TPR method is displayed in blue, the red dots are spot checks using the spectrum analyzer method at IF, and the purple dots were taken from concurrent measurements at the JPL Mesa using the 6-m prototype array breadboard antennas.

The received signal power in Fig. 9 was then converted to EIRP by using the link equation accounting for space loss, atmospheric attenuation, ground station gain, ground antenna mispointing, etc. The EIRP is referenced at the plane of the HGA and is displayed in Fig. 10 for day 05-350. The red line denotes the predicted EIRP assuming the spacecraft HGA is perfectly on-point. The EIRP can be compared with prediction and provide an indication of how well the spacecraft is performing or of any problem such as spacecraft mis-pointing. The gain of the receiving antenna utilized curves derived from the antenna efficiency

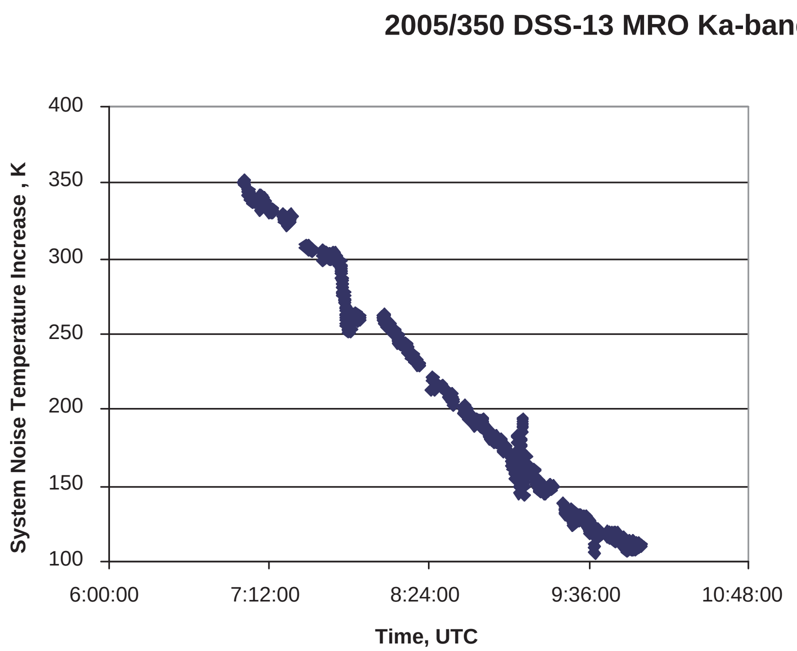

Figure 8. System Noise Temperature Increase due to MRO Ka-band Signal at DSS-13 on Day 05-350.

measurements of natural radio source calibrators as a function of station elevation angle. The atmospheric attenuation was calculated using a tip curve of off-source system temperature measurements or from surface meteorological parameters input into a weather model [a].

Upon inspection of Fig. 10 , note that the measured EIRP is usually within 1 dB of the predicted and displays some interesting signatures that are not yet understood, but may be possibly attributed to some deficiency in the ground antenna efficiency model or possibly spacecraft motion. The uncertainty in Ka-band efficiency is anticipated to lie within 0.6 dB. Other error contributions such as those due to atmospheric attenuation are small.

In addition to the day 05-350 track, there were several other tracks that were conducted to measure the spacecraft's Ka-band EIRP (see Fig. 11). In this figure, the red diamonds were measurements performed at the 6-m prototype array antennas located on the Mesa at JPL. All of the DSS-13 measurements utilized the Total Power Radiometer (TPR) or station spectrum analyzers (SA). Note that between days 05-325 and 05-360, there is good agreement between the measurements with all measurements indicating that the MRO spacecraft is on-point for Ka-band. The measurements conducted on January 10, 2006 (day number 375 on the graph, 06-010) was found to be about 4 dB low. This was due to a known spacecraft pointing offset related to a spacecraft safing event that occurred on January 4, 2006. As a result, a correction for spacecraft pointing using the known off-point angle was applied.

The measurements depicted in Fig. 11 confirm that the MRO Ka-band EIRP measured at DSS-13 is consistent with the HGA being on-point, and lies within about 1 dB of predict. The error bars on the DSS-13 TPR measurements represent the standard deviation of the measurements about the mean value

[a] The weather model is developed by Dr. Stephen Slobin of JPL

over each pass, except for one pass for which the measurement was a spot check, in which case the error bar was assigned a value of 0.5 dB to conservatively account for unknown effects. Error bars were not available for the JPL Mesa measurements but are expected to be relatively small.

The same procedures were exercised for the simultaneous X-band signal emitted by MRO, and the X-band EIRP was found to be consistent with pre-launch measurements.

C. 6-meter Antennas

The two 6-meter array breadboard antennas at JPL's mesa are intended as testbeds for the DSN large antenna array project. These antennas have a gain of 65.5 dB at Ka-band and have a cryogenically cooled feed producing a very low noise system. As of this writing, these antenna do not have any receiving equipment, but they do have a heterodyne mixer for downconverting the Ka-band RF signal to 1 GHz IF.

At these 6-m antennas a spectrum analyzer attached to a laptop was used to measure the spacecraft EIRP. These measurements were based on an initial calculation of received carrier power (P_c) and using geometry and knowledge about the gain of the antenna to obtain the EIRP measurements. The carrier power is obtained in the following manner: first the antenna is off pointed and SNT is measured while the spectrum analyzer is connected to the IF. Matching the noise floor on the spectrum analyzer to the SNT calibrates the spectrum analyzer. Then the spacecraft signal is tracked and the relative P_c power is measured on the spectrum analyzer. From the calibration of the spectrum analyzer absolute value of P_c is calculated. Fig. 12 shows a spectrum plot from day 05-333 (November 29, 2005) from breadbaord antenna 1 and how the P_c was calculated from this spectrum.

When the spectrum analyzer is connected to a computer, P_c measurements could be made regularly from which the spacecraft EIRP could be calculated. Figs. 13 and 14 show the difference between the measured EIRP and pre-launch EIRP for day 05-337 (December 3, 2005) and day 05-347 (December 13, 2005), respectively obtained in this manner. As these figures indicate, the EIRP measurements match the pre-launch EIRP measurements very closely.

This method of measuring the spacecraft EIRP could be easily adopted by the DSN for making direct power measurement by connecting a spectrum analyzer to the IF patch panel at each complex.

V. ΔDOR Passes

The technique of Delta Differential One-way Ranging (ΔDOR) has proved to be valuable for supporting spacecraft cruise navigation, especially for missions with tight targeting requirements at Mars. Spacecraft transmit tones, referred to as DOR tones, with a wide spacing from the carrier to enable these measurements. Today, measurements are made operationally in the DSN at X-band frequencies and provide an angular position accuracy of about 2.5 nrad. The deep space spectrum allocation and the restricted bandwidth of spacecraft transmitters at X-band limit the accuracy that can be achieved. The wider spectrum allocation for deep space tracking at Ka-band will enable an advance in ΔDOR measurement accuracy. Higher accuracy is needed to support future navigation challenges such as Mars landings or encounters with outer planet moons.

In a ΔDOR measurement, VLBI systems are used at two stations to make high rate recordings of signals from spacecraft and angularly nearby radio sources. Antennas alternate between spacecraft and radio sources about ten times in one hour. Radio source observations calibrate the system. For each source, the difference in signal arrival time between stations is measured and delivered to the navigation team. The MRO spacecraft emits DOR tones at both X-band and Ka-band. The DOR tone frequency is 19 MHz at X-band, yielding a spanned bandwidth of 38 MHz. The MRO transponder was designed for a DOR tone frequency of 76 MHz at Ka-band, providing a factor of four increase in spanned bandwidth. About 50 ΔDOR measurements were scheduled during cruise to support navigation. Of these, nine were selected to have dual band X/Ka downlinks to demonstrate performance at Ka-band. Measurements were completed using the DSN 34m BWG antennas that have X/Ka feeds. These measurements were the first ΔDOR measurements to be attempted at 32 GHz.

To prepare for these measurements, surveys were made of radio source flux, using NRAOs Very Large Baseline Array, at 24 GHz and 43 GHz. Information from this survey was used to select radio sources to observe at 32 GHz. In the DSN, models for antenna pointing were improved to allow blind pointing to the coordinates of faint radio sources. The receiver used for VLBI data recording was modified to have a larger front end bandwidth that allowed reception of the entire Ka-band spectrum allocation for deep space, including the received frequencies of the MRO DOR tones.

Data were successfully acquired at X-band and Ka-band for seven of the nine scheduled measurements. The measured data at Ka-band are in general agreement with the measured data at X-band and the precision of the Ka-band measurements is within expectations. The DSN receiving system worked well at 32 GHz. Antenna pointing was generally good, but some loss of signal power occurred due to errors in pointing that exceeded the very tight 4 mdeg requirement. One of the selected radio sources was found to have insufficient flux for use in these measurements, given the recording bandwidth that was used. Otherwise data acquisition was nominal.

Eventually, an operational system at Ka-band is expected to provide better accuracy than the current X-band system. The wider span of DOR tones improves group delay precision and reduces error due to dispersive instrumental phase. Both of these effects scale with spanned bandwidth. A higher data recording rate has been used at Ka-band, improving the precision of radio source delays. But higher system temperature and lower quasar flux at Ka-band reduce the benefits of the above mentioned effects. Ionospheric path delay is reduced by a factor of 15 at Ka-band relative to X-band. Radio source cores are more compact at higher frequencies, implying that, given sufficient source survey effort, an improved astrometric reference catalog could be defined using X/Ka data compared to that available today using S/X data.

The expected ΔDOR measurement accuracy is shown in Fig. 15 for three cases: MRO X-band data, MRO Ka-band data, and proposed future Ka-band data. Except for effects that depend on recording bandwidth, spanned bandwidth, and ionospheric path delay, all assumptions are the same for the three cases. For MRO, the quasar system noise error is reduced by $\sqrt{2}$ at Ka-band. This is the net effect of system temperature x2 higher at Ka, quasar flux x2 lower at Ka, spanned bandwidth x4 higher at Ka, and record rate x2 higher at Ka. For a future Ka-band system, the record rate could be further increased by x4 and the spanned bandwidth could be further increased by x2. Dispersive instrumental phase is x4 smaller at Ka for MRO and would be x8 smaller for the future system. Ionospheric path delay is x15 smaller at Ka since charged particle delay is inversely proportional to the square of the frequency.

Fig. 15 shows expected one sigma accuracy for typical observing conditions for the three cases. Some improvement is seen at Ka-band for MRO, and further improvement in some error components is seen for the proposed higher bandwidth system at Ka-band. But to take advantage of the reduction in the error components that is provided by transitioning to Ka-band frequencies, other work will be needed to realize a significant improvement in end-to-end system performance. An improvement in troposphere calibration will be needed. This could be achieved by making use of high performance water vapor radiometers at each tracking station. Improvements in real-time knowledge of earth orientation will be needed. This could be achieved by using a system similar to the ΔDOR system for making quick turnaround VLBI measurements of UT1. Finally, improvements in the global reference frame, including station coordinates and quasar coordinates, will be needed. This will require a measurement and analysis campaign, over several years, using radio source data at X-band and Ka-band. If development work is completed in these areas, then end-to-end system performance at Ka-band could improve to the 1-nrad level or better.

VI. Conclusion

As the results from the Ka-band activities during MRO cruise indicate, the spacecraft is fully capable of supporting the Ka-band demonstration during the PSP. Furthermore, while some minor issues with the monopulse antenna pointing and delivery of the monitor data still remain, these issues are expected to be resolved before the start of the PSP and the DSN is expected to be completely ready for support of the Ka-band demonstration during the PSP. As a result of Ka-band cruise activities MRO has set several milestones for planetary missions including most amount of data returned in a single day (116 Gbits) and highest data rate (5.2 Mbps) ever. In addition, MRO has successfully demonstrated Ka-band Δ DOR operations during the cruise. Furthermore, as a result of Ka-band cruise activities, techniques for direct measurement of spacecraft received power have been developed.

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Function to Validate	Status	Comments
Transmission of Ka-band Telemetry	Validated	Tested first on DOY 267 at DSS-25
Simultaneous transmission on Ka-band and X-band, same data on both bands	Validated	Tested first on DOY 267 at DSS-25
Simultaneous transmission on Ka-band and X-band, different data on each band	Validated	Tested first on DOY 280 at DSS-25
Changing data ratesduring a Pass	Validated	Tested first on DOY 267 at DSS-25
Changing mod index during a pass, background sequence	Validated	Tested first on DOY 280 at DSS-25
Changing mod index during a pass, real time command	Validated	Tested first on DOY 325 at DSS-55
Changing coding during a pass: RS only to concatenated	Validated	Tested on DOY 267 at DSS-25
Changing coding during a pass: turbo to concatenated	Validated	Tested on DOY 319 at DSS-34
Transmission of RS only encoded data	Validated	Test first on DOY 267 at DSS-25
Transmission of concatenated coding encoded data	Validated	Tested first on DOY 267 at DSS-25
Transmission of turbo Encoded data	Validated	Validated on DOY 280 at DSS-25
Transmission of subcarrier modulated, 32 Kbps data in 1-way mode using the USO	Validated	Tested on DOY 315 at DSS-25
Transmission of direct carrier modulated data in 1-way mode using the AUX OSC	Validated	Tested on DOY 325 at DSS-55
Transmission range tones	Validated	Tested first on DOY 267 at DSS-25
Transmission of DDOR tones	Valdiated	Tested for the first time on DOY315, Goldstone, DSS-25/Canberra, DSS-34 baseline
Boresighting of the antenna/HGA calibration	Validated	SNR measurements along with EIRP measurements at DSS-13 and the 6-m antennas have validated the boresighting of the antenna and Ka-band EIRP
Obtaining the spacecraft EIRP	Validated	See comments for Boresighting

Table 1. Spacecraft Functional Validation Matrix.

Function	DSS-25	DSS-26	DSS-34	DSS-55	Comments
Receive simultaneous X-band and Ka-band telemetry	Validated	Validated	Validated	Validated	
Receive RS only data	Validated	Validated	Not tested	Validated	DSS-34 Not tested
Receive concatenated coded data	Validated	Not tested	Validated	Not tested	DSS-26 and DSS-55 are not tested
Receive turbo encoded data	Validated	Not tested	Validated	Vlidated	On DOY 319 Pass at DSS-34 no errors were observed at High SNRs with turbo 1/3 code
Receive 1.5 Mbps turbo encoded data	Not tested	Not tested	Not tested	Validated	
Receive undecoded RS only data from AMMOS	Not tested	Validated	Not tested	Not tested	Undecoded data from DOY 336 has been queried and verified.
Receive ranging tones	Validated	Validated	Validated	Validated	
Receive monitor data	Analysis Not Complete	Analysis Not Complete	Analysis Not Complete	Analysis Not Complete	There has been occassional slow down in the updating of the monitor data at the MSA and for the query servers. The DSN has seen this problem mostly at Madrid and is currently investigating it.
Measure SNT	Validated	Validated	Validated	Validated	The SNT reporting for passes around Gravity calibration 2 indicates that SNT reporting at minimum Mars distance is reliable provided that the monopulse is working.
Measure SNR	Validated	Validated	Validated	Validated	SNR measurements during Gravity Cal-2 period have been accurate. As these passes were performed at distances equal to the minimum Mars to Earth distance, SNR measurements functionallity requirement is considered fulfilled.
Active Ka-band pointing (Monopulse)	See Comment	See Comment	See Comment	See Comment	A careful analysis of the monopulse indicates that during one pass at DSS-34 monopulse made erroneous estimates of the pointing offset causing the antenna to go off point. No correlation with wind has been found. Recent calibration of DSS-55 monopulse have been consistent. The reason for the instability of the monopulse at DSS-55 was a faulty LNA vacuum window. More operational experience is needed.
Blindpointing	Validated	Validated	Validated	Validated	Cassini Blind pointing model has been used for now.
Perform Ka-band DDOR measurements	Validated	Validated	Validated	Validated	

Table 2. Ground System Functional Validation Matrix.

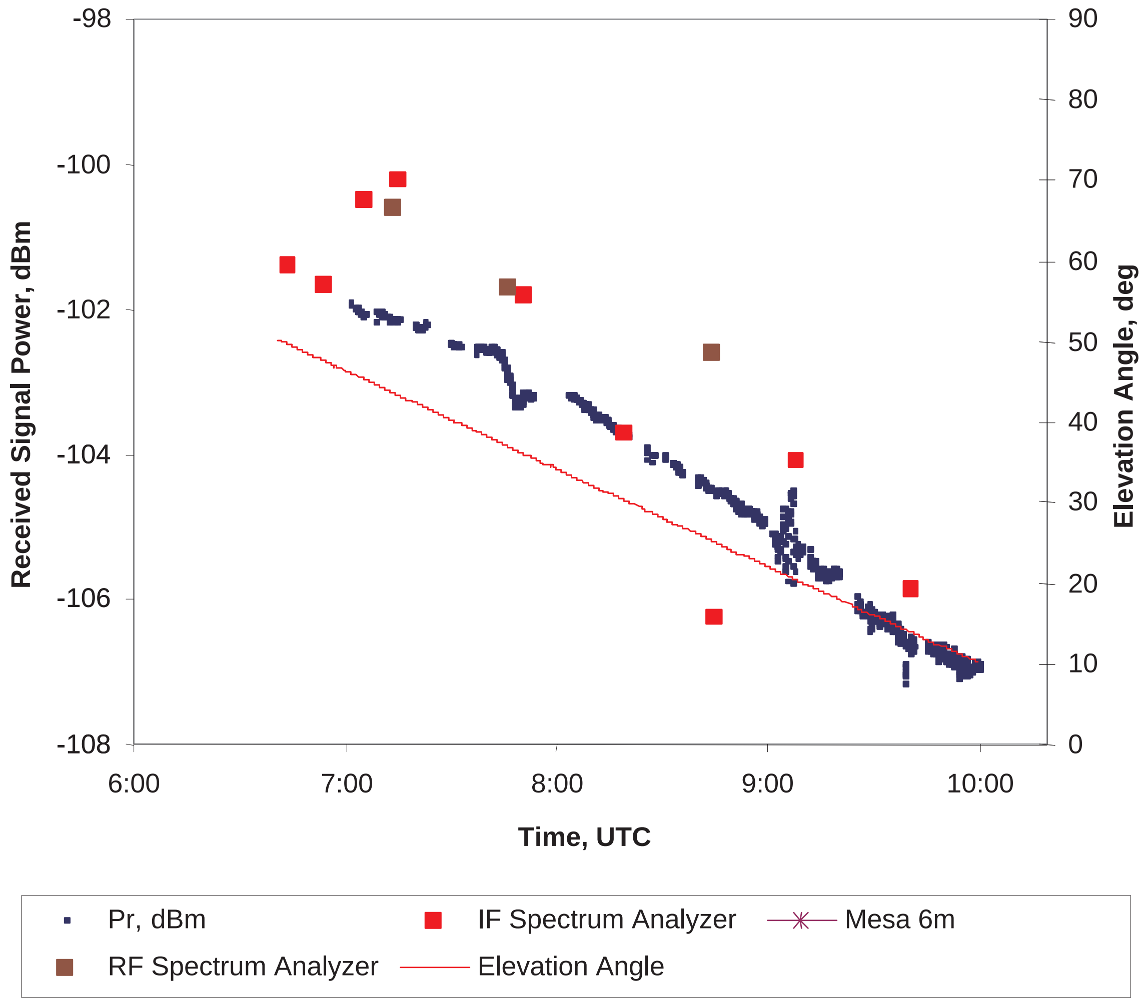


Figure 9. Measured Ka-band Signal Strength received at DSS-13 on Day 05-350 (blue dots TPR method, red dots spectrum analyzer method, purple Mesa 6-m (corrected to 34-m) - red curve elevation angle)

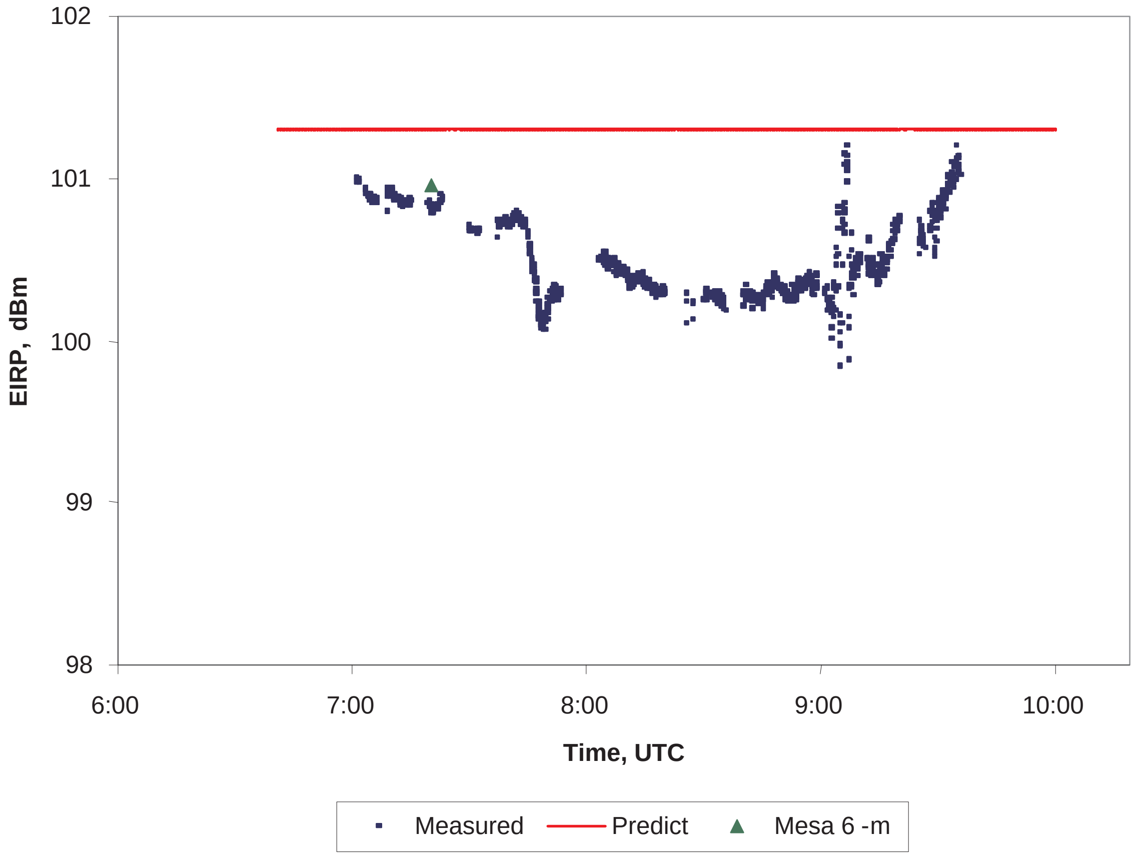


Figure 10. MRO Ka-band EIRP on Day 05-350 Referenced at the Spacecraft

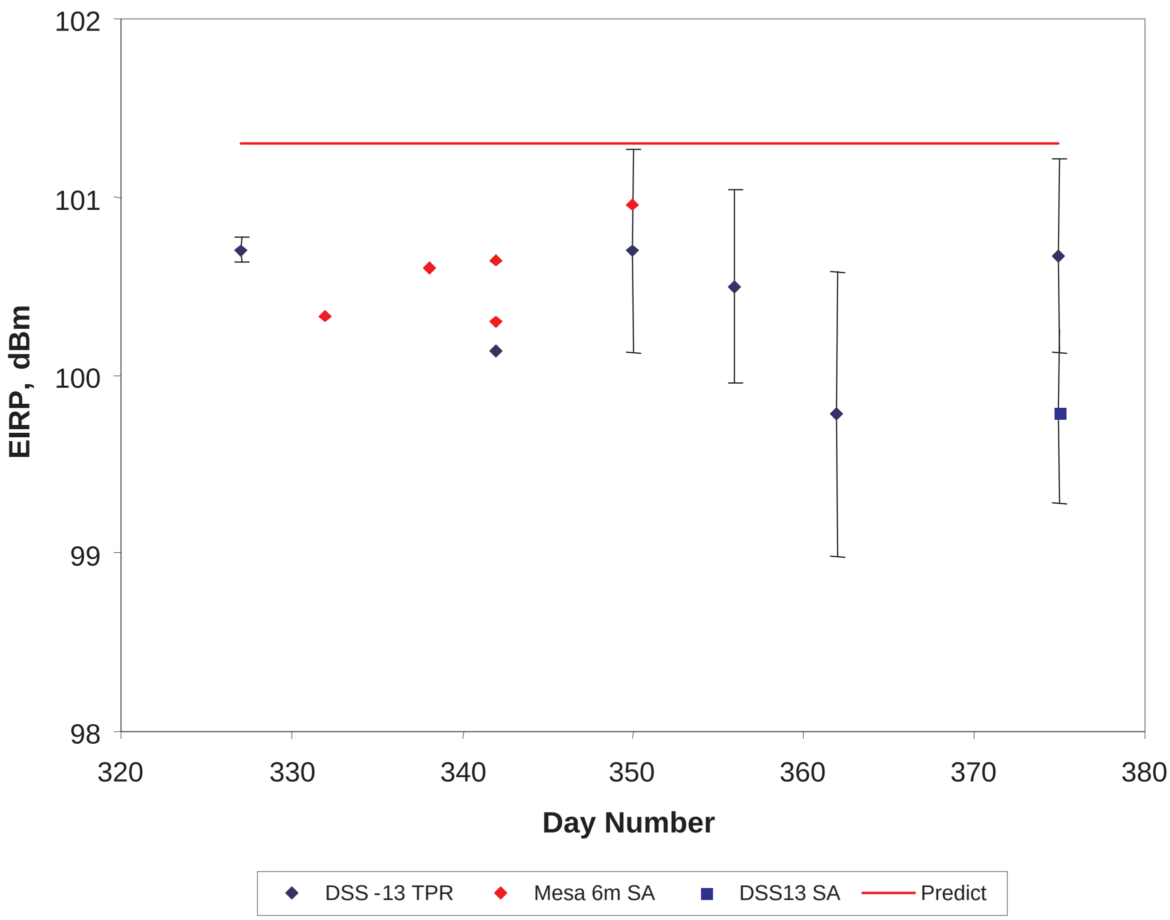
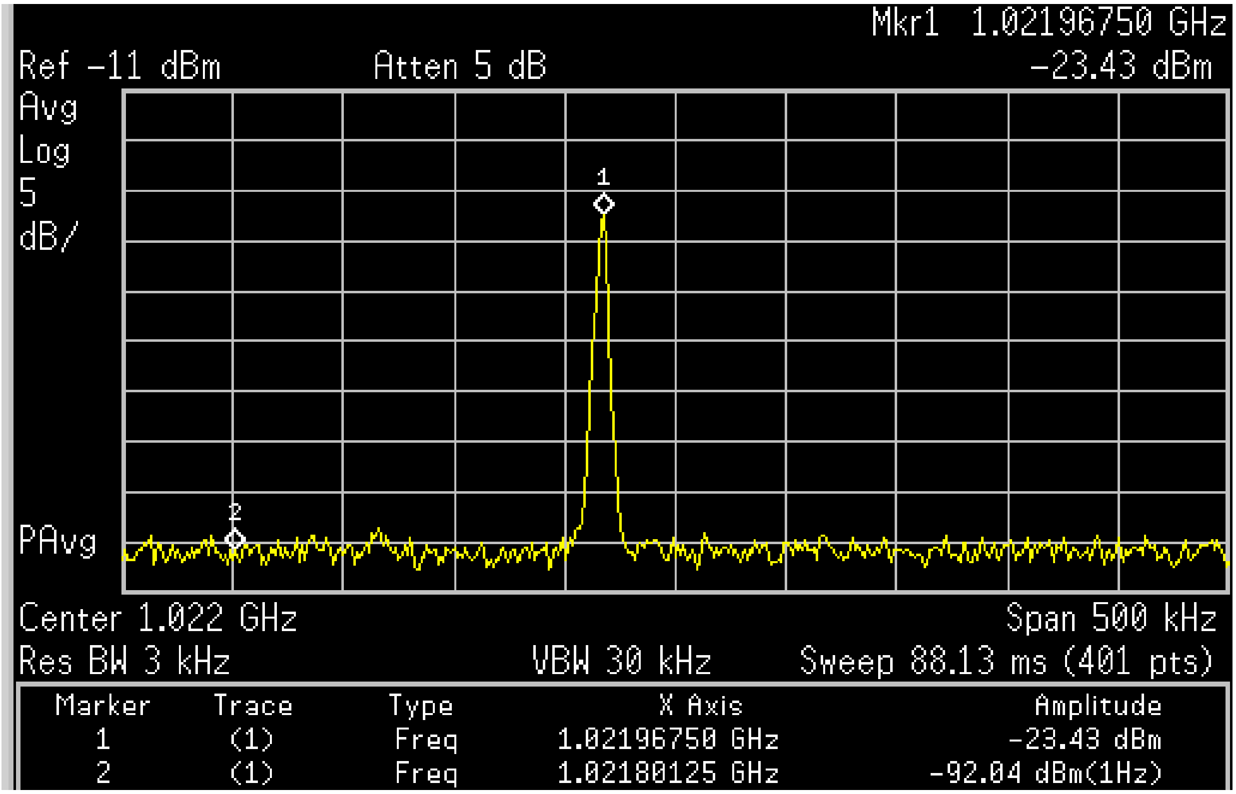


Figure 11. MRO Ka-band Measurement Set at DSS-13 with JPL Mesa Measurements and prediction.



- Tsys 36K
- Relative No (Marker 2) -92 dBm
- Relative Pc (Marker 1) -23.4 dBm
- Pc/No 68.6 dB -Hz
- Pc received (LNA) -114.4 dBm
- Pc predicted -114.16 dBm

Figure 12. Spectrum Plot and P_c Calculation for 6-m Antenna 2, Day 05-333

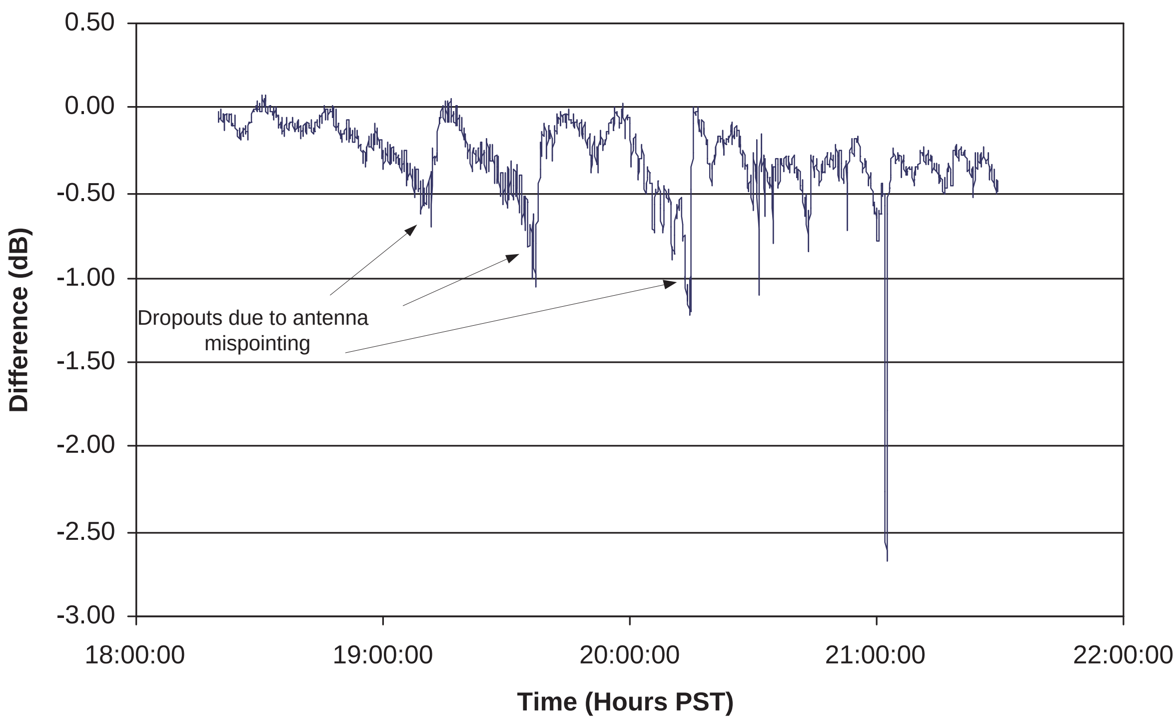


Figure 13. Difference between Measured Ka-band EIRP at the 6-m Antenna and pre-launch Ka-band EIRP, Day 05-337.

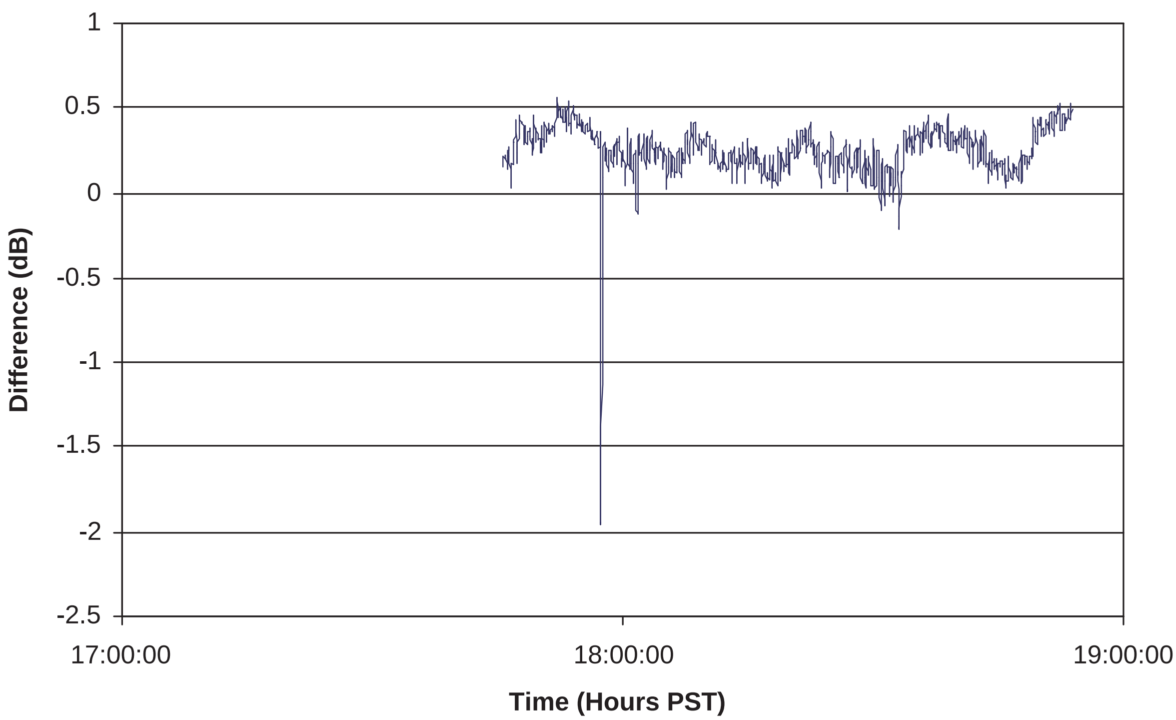


Figure 14. Difference between Measured Ka-band EIRP at the 6-m Antenna and pre-launch Ka-band EIRP, Day 05-347.

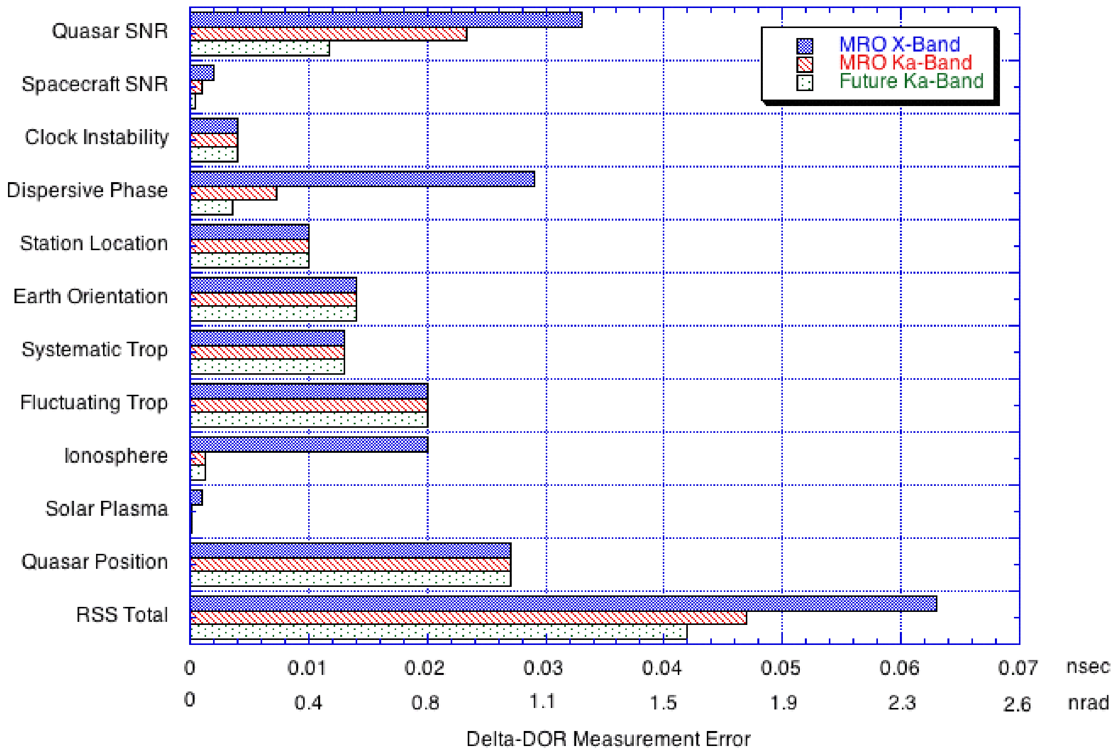


Figure 15. Expected ΔDOR Measurement Accuracy for Three Cases