Link Design and Planning for Mars Reconnaissance Orbiter (MRO) Ka-band (32 GHz) Telecom Demonstration

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Abstract—NASA is planning a Ka-band (32 GHz) engineering telemetry demonstration with Mars Reconnaissance Orbiter (MRO). Capabilities of Ka-band for use with deep space mission are demonstrated using the link optimization algorithms and weather forecasting. Furthermore, based on the performance of previous deep space missions with Ka-band downlink capabilities, experiment plans are developed for telemetry operations during superior solar conjunction. A general overview of the demonstration is given followed by a description of the experiment planning during cruise, the primary science mission and superior conjunction. As part of the primary science mission planning the expected data return for various data optimization methods is calculated. These results indicate that, given MRO's data rates, a link optimized to use of at most two data rates, subject to a minimum availability of 90%, performs almost as well as a link with no limits on the number of data rates with the same minimum availability requirement. Furthermore, the effects of forecasting on these link design algorithms are discussed.

TABLE OF CONTENTS

1. INTRODUCTION

NASA's deep-space missions with high data rate requirements are now forced to use the 32 GHz Ka-band frequency due to lack of spectrum at 8.41 GHz X-band frequency. Currently, X-band has only 50 MHz of heavily subscribed bandwidth for deep space use while Ka-band has 500 MHz of bandwidth allocated for deep-space missions. Plans are in place to equip all three of Deep Space Network's communication complexes in Goldstone, California; Madrid, Spain and Canberra Australia with Ka-band receiving capabilities with enhancements to the 34-m Beam waveguide (BWG) antenna subnet. While tests have been performed to evaluate the performance of the ground system, up to now no tests have been performed to evaluate the performance and operability of the end-to-end Ka-band link. With the launch of Mars Reconnaissance Orbiter (MRO) in 2005 there is an opportunity to do so. MRO has a fully functional independent Ka-band telemetry capability. This will allow the DSN to evaluate the end-to-end performance of the system as well as the operational methodologies that have been developed in various studies [1][2][3][4][10].

There are two parts to the MRO Ka-band demonstration: cruise phase and primary science phase. During the cruise phase the functionality of the Ka-band systems on the spacecraft and on the ground is verified. Furthermore, the experiment team's interfaces with the DSN operations and the MRO project are evaluated as to remedy any problems that may exist in this area before the primary science phase. During the primary science phase, three different operational scenarios will be evaluated: 1. Nominal link operations using link designs based on long-term monthly or weekly statistics. 2. Link operations using short-term forecasts. 3. Link operations during superior solar conjunction. This paper gives a detailed overview of the experiment plan both during the cruise and during the primary science phase of the mission.

This paper is divided in the following manner: In Section 2 a general overview of the Ka-band demonstration, including overviews of the spacecraft hardware and the ground tracking regime, is provided. In Section 3 plans for the cruise phase are discussed. The general link design approach using both long-term statistics and short-term forecasts is presented in Section 4. Plans for superior solar conjunction are presented in Section 5. Caveats are discussed in Section 6. In Section 7, conclusions are presented.

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2. AN OVERVIEW OF MRO KA-BAND DEMONSTRATION

NASA's Mars Reconnaissance Orbiter (MRO) is scheduled for launch in August, 2005. The Mars orbiting spacecraft will begin its primary mission in November, 2006, following its cruise, orbit insertion, and aerobraking phases. There are a number of sensors and a radar system onboard the spacecraft conducting high resolution imagery, atmospheric science investigations, sub-surface remote sensing, and other scientific observations. The primary mission is scheduled for two years, followed by a two-year period when the spacecraft will be used as a relay station between other Mars probes and Earth.

The MRO spacecraft will transmit at X and Ka bands, but it can only receive commands at X-band. The maximum aggregate downlink symbol rate that the spacecraft can support is 6 Msps. This rate is greater than that of any deep-space mission before it. In addition to the high-rate satellite-to-Earth link, the telecom system supports a host of radio metrics including Doppler, ranging, and very long baseline interferometry (VLBI). It uses a 3-meter parabolic, dual frequency, high gain antenna (HGA) with power amplifiers that provide 35 Watt of Ka-band RF power and 100 Watts of X-band RF power. The spacecraft is also equipped with a relay telecom system for relaying data between Mars probes and Earth. Figure 1 shows a high-level the block diagram of the telecommunications and command subsystem of the spacecraft.

The telecom downlink can be configured in several ways, including suppressed carrier and residual carrier signaling. For forward error correction coding, two options of turbo codes and Reed-Solomon codes exist. The Reed-Solomon code can be concatenated with (7,1/2) convolutional code, and turbo codes offer a range of code rates (1/2, 1/3, and 1/6) and block sizes. Due to a design peculiarity, Ka- and X-band links cannot select the same code format when transmitting different data -one will use turbo and the other Reed-Solomon. Although two options of QPSK and BPSK exist for data modulation, the Ka-band link will employ the BPSK option for the demonstration. Assuming all other parameters have been fixed, the data rate can be varied to increase or decrease the power margin of the link.

The standard method of commanding the spacecraft in deep-space applications is to perform "background sequencing." With this approach, the spacecraft is commanded once every four weeks to reconfigure its parameters -particularly the telecom parameters of interest in this paper. One of the key contributions of the MRO Ka-band demonstration will be to vary the link parameters in response to short-term weather forecasts via a commanding approach known as mini-sequencing. With mini-sequencing, telecom parameters of MRO, such as data rate profile and mod index, will be changed weekly rather than monthly.

MRO will be tracked by NASAs Deep-Space Network (DSN). This network will command the spacecraft, receive telemetry from it, and provide navigation functions for MRO. The DSN consists of three sites Goldstone (U.S.), Madrid (Spain), and Canberra (Australia). These sites are spaced longitudinally about equally around the globe so that probes far from Earth are always in view of at least one complex. Each complex consists of a host of antennas with antenna diameter sizes of 70 m, 34 m, and 26 m. By the beginning of MRO operations, each site will have at least one 34-m beam waveguide (BWG) antennas with Ka-band capability.

During the primary science phase of the mission, there will be two passes per week scheduled over DSN's 34-m BWG subnet exclusively for Ka-band demonstration as the 34-m BWG antennas are the only antennas capable of receiving Ka-band in the DSN. Ka-band telemetry may also be received on a best-effort/non-interference basis during regular passes scheduled for science data return provided that the spacecraft is tracked over an antenna that is Ka-band capable. Any Ka-band data gathered during the science passes are considered a bonus and the success for this demonstration does not depend on the gathering of such data.

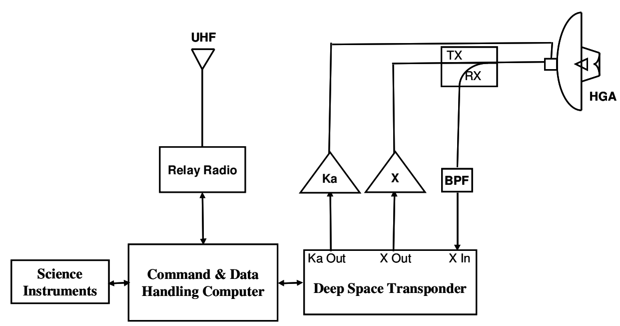

Figure 1. MRO telecommunications and commanding subsystem

3. KA-BAND OPERATIONS DURING THE CRUISE PHASE

The main objective of the cruise operation is to perform functional tests. These tests will validate end-to-end Ka-band data transmission and reception as well as confirm the appropriateness of the system operations. The ability to change telecom parameters and observe their impact on the link will be verified. Also the capability to perform background, mini, and real-time sequencing will be validated. In particular, the operations of weather forecasting tools will be functionally tested. Faults will be identified and corrected in time for the primary science phase.

During cruise, ten passes are allocated for Ka-band tests. The current plan will employ the first six passes to conduct functional tests. The last four passes are planned for quasi-performance tests where the link performance will be measured. Performance passes may be used as functional ones if the need arises during the cruise operations. A preliminary plan for cruise tests is given in Table 1. Note that the passes in Table 1 will be scheduled with one or two weeks separation between the passes to allow time for processing and analysis of the collected data.

4. NOMINAL KA-BAND LINK OPERATION DURING THE PRIMARY SCIENCE PHASE

The main goal of MRO Ka-band demonstrations is to illustrate that a Ka-band telemetry link designed according to the link design techniques developed previously [1][2][3][4] could be operated reliably. These link design techniques attempt to maximize the average link capacity with respect to a given atmospheric noise temperature distribution. The atmospheric noise temperature distribution could be based on either long-term statistics or short-term forecasts. Furthermore, because of limitations on the operational complexity and limited capabilities of the spacecraft and ground equipment, the number of data rate profiles over which the average capacity is maximized could be limited. For MRO, such limitations exist.

MRO has a limited number of channel symbol rates with a limited number of modulation indices. In addition, the ground decoders for the turbo codes used by the spacecraft have a limit on the maximum data rate at which they can decode. The limits on the channel symbol rate means that most of the time suboptimum data rates (in terms of maximum average capacity) are used in the link design. It also means that at higher data rates channel codes with higher rates and thus, lower performance (in terms of required E_b/N_0 for a given error rate) are used. The limit on the maximum data rate at which the ground decoders can decode the data also means that at higher data rates the best channel code is not used. Finally, the limited number of modulation indices means that for a given data rate/channel code combination the lowest possible P_t/N_0 (the total received power to noise ratio) value could not be used when designing the link [1].

Given these limitations, the set of data rates and their associated P_t/N_0 to be used for planning of the nominal operations during the primary science phase were selected in the following manner: First it was determined that the desired bit error rate (BER) for the link is 10^{-6}. Then for each data rate the best code (in terms of having the lowest required E_b/N_0 for the desired BER) that the equipment limitations allowed was selected. Then from the set of available modulation indices the index which provided the lowest required P_t/N_0 was selected. The results of this selection process are shown in Figure 2. As seen from this figure, with the available modulation indices the lowest required P_t/N_0 is nearly

[1] It should be noted that with residual carrier modulation the link optimization has to be performed with respect to P_t/N_0 as, ultimately, the optimization has to take place with respect to the total available spacecraft power and not just what is available on the data channel. The additional power in the carrier is needed to assure receiver lock on the ground.

Table 1. Preliminary plan for Ka-band operations during the cruise phase

Pass Number	Activity
1	The first test to check out Ka-band functionality. X-band is disabled. No rate changes. Validate Ka-bad data reception, range and Doppler measurements, receive engineering data, radiometer observations -5th week after launch
2	Functionality test at Goldstone to verify X and Ka simultaneous operation and to verify mod index change during a pass. Ka-band ranging is off.
3	First Canberra functionality test. Also verify turbo code on Ka-band, change mod index in mid pass. This test may be used as a quasi-performance test using smaller mod index.
4	The first Madrid functionality test, and the first test to verify mid pass rate change. X-band is disabled.
5	The first functional test for mini sequencing and real-time commanding using mod index changes, Goldstone.
6	Functional test at Canberra using mini sequencing both on Ka- and X-band. Change data rate in both channels.
7	Performance test of real time commanding, changing Ka-band mod index in mid-pass. Non-interactive command is used, changing only the mod index, Madrid.
8	This performance test will generate frame errors to determine link threshold, Goldstone. Real-time commanding may be used.
9	This performance test will generate frame errors to determine link threshold, Canberra. Real-time commanding may be used.
10	This performance test will generate frame errors to determine link threshold, Madrid. Real-time commanding may be used.

achieved for all data rates. This figure indicates that for data rates of 800 kbps and below the (8920,1/6) turbo code could be used on the link while for data rates of 1 Mbps and 1.5 Mbps (8920,1/3) code is used. For data rates between 2 Mbps and 2.6 Mbps the channel code is the (8920,1/2) turbo code while for data rate above 2.6 Mbps the stand-alone (255,223) Reed-Solomon block code is used. This indicates that the limit on the output symbol rate of the transponder on the MRO requires the increase in the rate of the channel codes that are used. This increases the required link E_b/N_0 for the required BER leading to the jumps observed in Figure 2. It should be noted that there is a large gap in the available data rates between 2000 bps and 32000 bps. This is due to the fact that the data rates below 32000 bps are used primarily for data transmission over the spacecraft's low-gain antenna while data rates of 32000 bps and above are used for transmission of data on the high-gain antenna. Also note that at low data rates the required P_t/N_0 tends to flatten out. This is due to the fact that the ground receiver requires a minimum amount of power carrier power to noise ratio P_c/N_0 in order to lock. As the data rate is lowered, P_c/N_0 begins to dominate P_t/N_0, leading to the plateau observed in Figure 2.

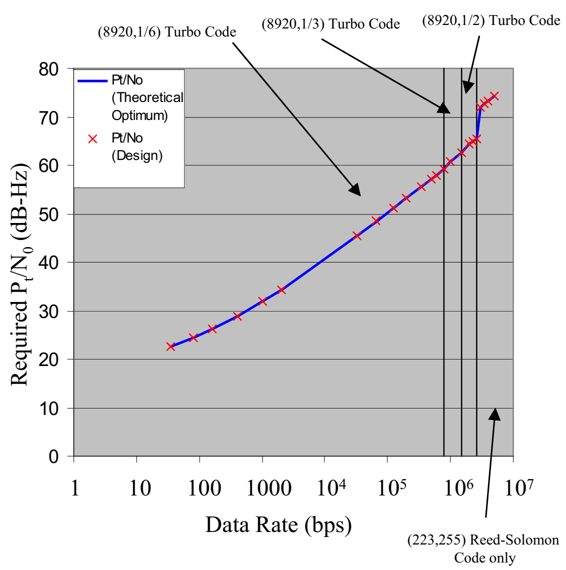

Figure 2. Required P_t/N_0 vs. Data Rate, MRO, Residual Carrier, PLL Loop BW=3Hz, BER= 10^{-6}

In order to evaluate the best way to operate the link, the data rates and their associated P_t/N_0 values were used to calculate the projected capacity of the MRO Ka-band link over the duration of the experiment using four different optimization methods. These methods, touched on briefly in [3] and [4], are:

1. Multi-rate, no constraints (MR-0): This method maximizes the average data rate at a given elevation regardless of the average availability of that data rate or the number of data rates that the spacecraft has used during a pass. Maximizing the average data rate at each elevation causes the average capacity to be maximized.
2. Multi-rate, 90% minimum availability (MR-90): This method is similar to MR-0 except that the data rate selected at any given elevation is subject to a minimum availability requirement of 90%. The spacecraft may use as many data rates as necessary during a pass.
3. Dual-rate, 90% minimum avaialability (DR-90): This method maximizes the average link capacity subject to the limit that at most only two data rates could be used during the pass. Furthermore, at any given point in time during a pass the spacecraft data rate has to have a minimum availability of 90%.
4. Single-rate, 90% minimum availability (SR-90): This method maximizes the average link capacity subject to the limit that only a single data rate could be used throughout the pass and that the said data rate has to have an availability of at least 90% at all times.

In order to use these optimization techniques the elevation profiles of passes throughout the experiment as well as the distance of the spacecraft to Earth during those passes are needed. As there are two Ka-band demonstration passes scheduled per week, the distance and the declination of Mars relative to Earth were obtained on a weekly basis from 12/1/2006 to 10/24/2008 using Jet Propulsion Laboratory's HORIZONS [5] System. Using the declinations obtained from HORIZONS along with the latitude of the antennas of the 34-m BWG subnet [6], elevation profiles of MRO during its view periods[2] for each 34-m antenna at each DSN communication complex were calculated on a weekly basis. As the station time allocation for MRO Ka-band demonstrations is not available at this time, it is assumed that if a station is allocated to the Ka-band demonstration then it is available during the whole view period of the spacecraft for that station. Using this assumption, the four optimization methods were applied on a weekly basis and the average link capacity for each site was calculated over the period under considerations.

As Ka-band system noise temperature is very sensitive to changes in the atmospheric noise temperature, it was decided to use different atmospheric noise temperature distributions at different times of year in order to reflect the effects of seasonal changes on the capacity of the link. At first it was decided to use monthly distributions. However, because the monthly distributions tend to change abruptly from month to month it was decided to generate a series of "sliding window" distributions from the observations of the atmospheric noise by Water Vapor Radiometers (WVRs) and Advanced Water Vapor Radiometers (AWVR). These distributions were generated in the following manner: The year was divided into 52 periods with the first period starting on January 1st. All these periods except for the period starting on February 26th

[2] A view period for a station is defined as the period from when the spacecraft rises above 10 degrees elevation from the station's point of view to the time that the spacecraft sets below 10 degrees elevation.

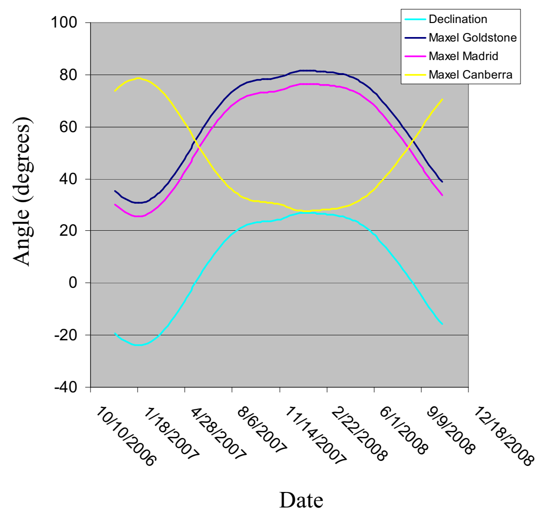

Figure 3. Mars Declination and Maximum Elevation for Different Sites vs. Time

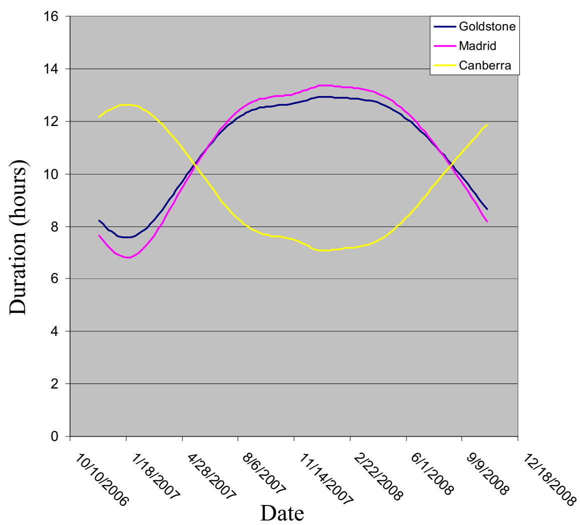

Figure 4. Mars View Period Durations vs. Time for Different DSN Sites

(because it may include a leap day) and the period starting on August 27th (selected arbitrarily to include an extra day to cover the whole year) are 7 days long. For each period a distribution was calculated using the WVR/AWVR data corresponding to that period over the years as well as those corresponding to the periods immediately before and after it. Such a distribution was then used with the optimization algorithms discussed above for any day that fell in the distribution's corresponding period of the year.

The results of these optimizations as well as original data about geometry of the spacecraft are shown in Figures 3 to 14.

As seen from figures 3 and 4, at southerly declinations (declination less than zero) the view periods are longer for Canberra than those for Madrid and Goldstone and at northerly declinations the northern sites of Goldstone and Madrid have longer view periods. Furthermore, these figures show that as the view periods for a site get longer so does the maximum elevation of the spacecraft relative to the site. This is to be expected for objects that stay more-or-less in the plain of ecliptic.

Figure 5 shows Mars-Earth distance as a function of time. This figure along with figures 3 and 4 indicates that the Mars-Earth distance is at its maximum when Mars is at its most southerly declination. This occurs roughly around end of December/beginning of January in years 2006/2007 and 2008/2009. The bad weather for Madrid and Goldstone for this time of the year along with short view period durations and low maximum elevations for these sites combine to reduce the average link capacity during these times significantly. This is shown in figures 6 and 7. As seen from these figures, there is a significant change in the average capacity of the link for Goldstone and Madrid during MRO Ka-band demonstration period. As Mars gets nearer to Earth its northerly declination combined with the shorter Mars-Earth distance causes an increase in the average capacity of between 8 to 10 dB for Goldstone and between 11 and 13 dB for Madrid, depending on the optimization method. By contrast, for Canberra, the shorter Mars-Earth distance effect is canceled out by the shorter view period durations and lower maximum elevations caused by the northerly declination of Mars. This causes only a 3 to 4 dB swing in the average capacity of the link at Canberra (see Figure 8).

As for the optimization methods, figures 6 through 14 indicate that:

- As expected, MR-0 optimization method has the highest average capacity while SR-90 method has the lowest. Conversely, MR-0 has the lowest average availability and SR-90 has the highest.
- DR-90 has almost as high an average capacity as MR-90 and in some cases equaling it.
- While MR-0's average capacity is generally higher than that for the other optimization methods, at very short Mars-Earth distances MR-0's average capacity is equal to the others. This is due to the limitations on the spacecraft data rates.
- While MR-0 and MR-90 use the whole view period, SR-90 and DR-90 do not necessarily do so. This is due to the fact that these optimization algorithms consider all possible passes starting above 10 degrees elevation and centered at the meridian crossing in order to maximize the average capacity. Therefore, these algorithms may indicate that the pass should start and end at some elevation higher than 10 degrees so that the average capacity could be maximized.
- While at times DR-90 and SR-90 have roughly the same average capacity, in many cases DR-90's average capacity is greater than SR-90's by approximately 1 dB.

• MR-0 has no constraints on the link's minimum availability; therefore, its average availability fluctuates wildly. However, the other optimization methods are better behaved with their average availability hovering well above 90%.

Given these observations it was decided that the best optimization method for the MRO Ka-band demonstration was DR-90. DR-90 offers high reliability with near maximum average capacity and slight increase in the operational complexity of the mission. It is expected that during the actual mission, DR-90 method will be used to determine the data rate profile for the passes at the beginning of each 28-day sequencing period and that these data rate profiles will be programmed onboard the spacecraft as part of its background sequence for the two MRO Ka-band demonstration passes per week.

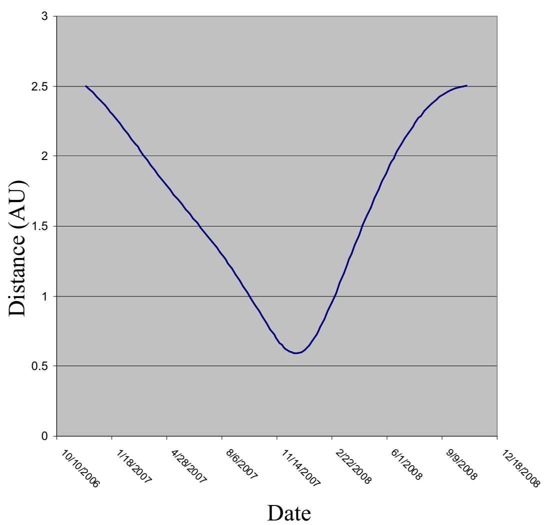

Figure 5. Mars-Earth Distance

Weather Forecasting

As mentioned above the optimization methods that are considered for Ka-band link design during the primary science phase operations optimize the pass data rate selection according to a given zenith atmospheric noise temperature distribution. Figures 6 through 11 were generated using long-term distributions obtained from previous observations of atmospheric noise. With forecasting, these distributions are generated according to the forecast. The mathematical formulation of this concept was presented in [4]. Currently JPL is working on an algorithm to convert meteorological forecasts into atmospheric noise temperature distribution. The meteorological forecasts are generated by the Spaceflight Meteorology Group (SMG) of the National Weather Service located at Johnson Space Center in Houston, Texas [11]. If the development of forecasting algorithm is successful, it is expected that the capacity of the pass will increase during periods of good weather and its availability will increase during bad weather.

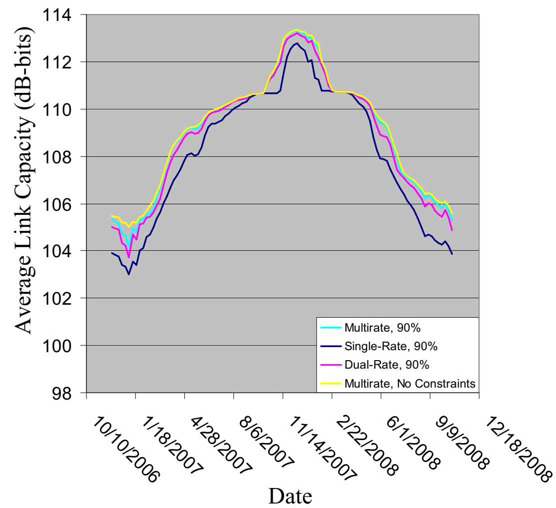

Figure 6. Goldstone Average Link Capacity vs. Time for Different Optimization Methods

Initial results of the algorithms under consideration have been promising. Figure 15 shows two distributions obtained from the forecasting algorithm for Goldstone along with the aggregate distributions based on long term observations for Goldstone. As seen from this figure, the "good weather" distribution has a very narrow range consisting of low noise temperature values (less than 10 K). The "bad weather" distribution has a wider range than the "good weather" forecast but its range is still narrower than that for the aggregate distribution. This indicates that the forecasting algorithm reduces the uncertainty in the link. Furthermore, the lower noise temperature values for the "good weather" distribution indicate that when " good weather" is forecasted the link capacity could be increased significantly. Note that the "bad weather" distribution is almost identical to the aggregate distribution for noise temperature values above 90 percentile level. This means that with "bad weather" the performance of a link designed for a minimum of 90% availability for the "bad weather" distribution is going to be nearly identical to the performance of a link designed for the aggregate distribution. These points are illustrated in Table 2.

Table 2 compares the performance of a link designed according to MR-90 method for the aggregate distributions with those designed according to MR-90 method for the forecasted distributions under the conditions when the forecasted distribution applied for a spacecraft with MRO's Ka-band capabilities at 2.4 au distance and zero declination. As seen from this table, when the "good weather " distribution applies, by using the forecasted distribution instead of the aggregate distribution the average link capacity is increased by 0.67 dB while the link availability is only slightly decreased. Conversely, when the "bad weather" distribution applies, by using the forecasted distribution instead of the aggregate distribu-

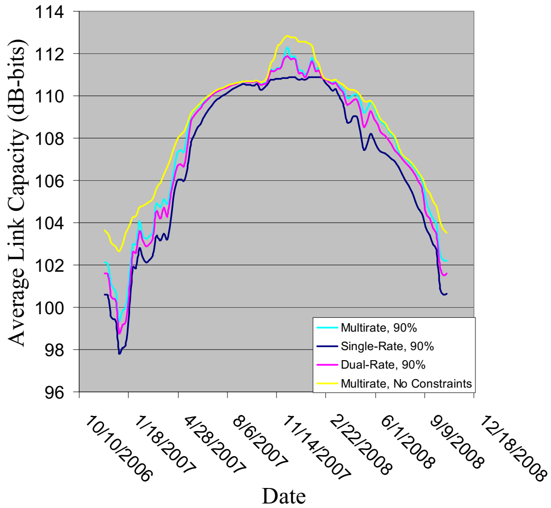

Figure 7. Madrid Average Link Capacity vs. Time for Different Optimization Methods

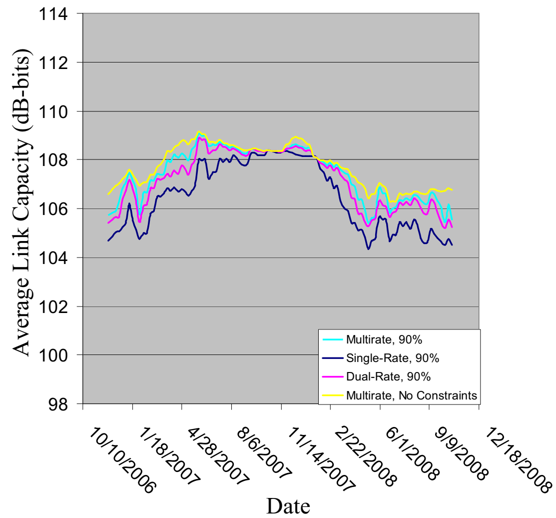

Figure 8. Canberra Average Link Capacity vs. Time for Different Optimization Methods

Table 2. Data Return and Average Availability for Different Forecast Distributions and Data Rate Profiles, MR-90 Link Design Method

Dist.	Avg. Cap., Forecast	Avg. Avail. Forecast	Avg. Cap., Aggregate	Avg. Avail. Aggregate
"Good"	107.51 db-bits	0.980	106.84 dB-bits	1.000
"Bad"	106.65 db-bits	0.968	106.63 dB-bits	0.952

tion both the average capacity and the availability are slightly increased.

It is expected that at least an engineering version of the forecasting algorithm to be available during MRO Ka-band demonstration for all three DSN sites. It is expected that for a period of time forecasts generated by these algorithms will be used to generated mini-sequences for at least one pass a week to validate the effectiveness of these algorithms.

5. Solar Conjunction Experiments

The objectives of the solar conjunction experiment are 1) to evaluate Ka-band performance as a function of solar elongation angle by comparing against the concurrent X-band performance, and 2) to measure any degradation to the link that may occur during solar coronal transient activity such as coronal mass ejections. The Solar Conjunction Experiment will characterize solar charged-particle effects on the Ka and X-band signal links (carrier and telemetry), as well as evaluate relative performance between Ka-band and X-band as a function of SEP angle[3]. Since solar effects are much smaller at Ka-band, the advantage of using Ka-band over X-band has been demonstrated by past missions using carrier signals [7][8][9]. During the MRO solar conjunction experiments, the use of carrier signals will be further demonstrated, but it will also be the first time that solar charged particle effects to spacecraft telemetry is expected to be comprehensively measured at Ka-band. An X-band telemetry link using BPSK begins to degrade near 2 degrees SEP angle. At Ka-band, it is predicted that the link would start to degrade somewhere near 1 degree, where solar effects are comparable to that of X-band at 2 degrees [10].

There are two solar conjunction experiments for which Ka-band experiments are planned. The first solar conjunction experiment will be conducted during October and November in 2006 during which the SEP angle will lie below 5 degrees. During this experiment, the spacecraft will be configured in a quiet operational mode, during which no formal science data downlink is planned. The planned mode for both frequency bands will be one-way or non-coherent, that is to use the onboard Ultra-Stable Oscillator (USO) as the signal reference. The prime DSN station preferred for these experiments is DSS-25 at Goldstone California, whose desert climate presents a minimum of weather-induced troposphere effects on the Ka-band signal. The first solar conjunction Ka-band experiment will consist of one pass per day between Oc-

[3] SEP angle is the Sun-Earth-Probe angle which is the angle subtended by the spacecraft to the center of the solar disk as seen by the observer on Earth.

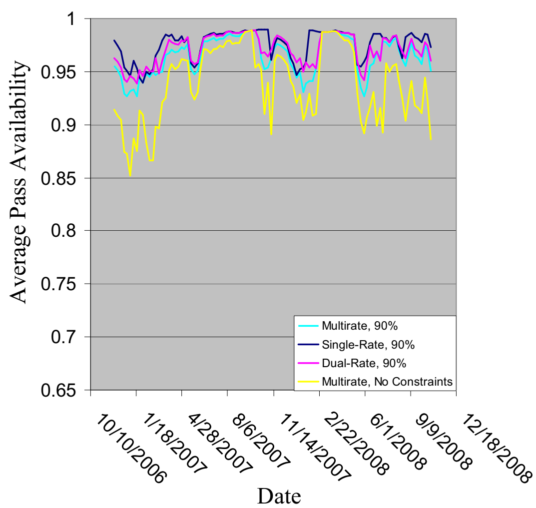

Figure 9. Goldstone Average Pass Availability vs. Time for Different Optimization Methods

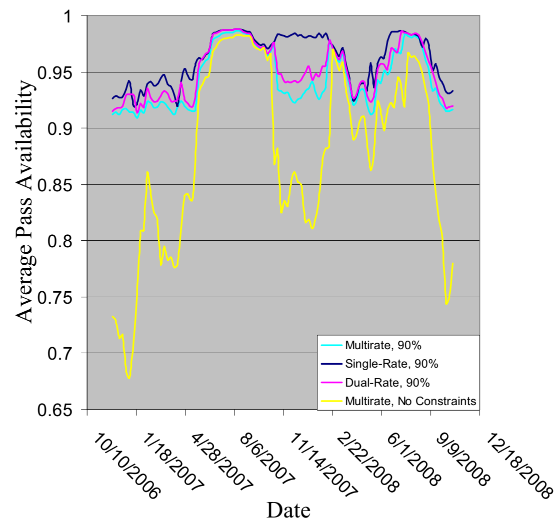

Figure 10. Madrid Average Pass Availability vs. Time for Different Optimization Methods

tober 8, 2006 and November 7, 2006, a span of one month, where the SEP angle will lie below 5 degree. The minimum SEP angle for the 2006 solar conjunction is expected to be approximately 0.39 degrees on October 23, 2006. For SEP angles below 1 degree, the Ka-band link using conventional BPSK is expected to begin to degrade. Planned tests for SEP angles of 1 degree and below include testing simulated FSK using the carrier. Demonstrating information flow through the solar corona using simulated FSK (even at very low rates such as 1 bps) will be useful for future solar conjunctions with similar minimal SEP angles. In addition, dual-frequency (differenced Ka-band and X-band) Doppler and possibly ranging data will be analyzed. Solar plasma effects are expected to be small for the signal path lying above the solar polar regions during this period of solar minimum. We will use high margins in order to adequately characterize and capture solar effects to the data. A similar set of experiments is expected to be conducted during the solar conjunction of November 18 to December 24, 2008.

The closed-loop receiver will be configured appropriately for solar conjunction signal conditions, including widening the loop bandwidth as needed to accommodate signal fluctuations. The telemetry modulation index and receiver loop bandwidth parameters will be carefully chosen to obtain adequate carrier margin to overcome increased thermal noise and spectral broadening of the signal, and to allow for reasonable data rates in the telemetry channel with sufficient margin. One goal of this experiment is to see how low in SEP angle we can go to maintain carrier lock and achieve reasonably reliable telemetry. The signal will experience significant degradation due to solar charged particles such as scintillation and spectral broadening as the SEP angle falls below 1 deg. for Ka-band. The use of open-loop receiver carrier data will allow signal fluctuations to be carefully measured which can be correlated against telemetry frame error rates.

6. CAVEATS

While the initial analysis presented here has provided a guideline as to how the Ka-band link will be operated during MRO Ka-band demonstration. However, as of this writing, certain factors that should be considered during the actual demonstration remain unknown. First of all, it is not clear if the forecasting algorithm will be fully functional (or for that matter fully funded) during the experiment. In addition, updates and upgrades to NASA's Deep Space Network require that the models that were used for optimization in Section 4 to be updated. It should also be noted at this time the maximum decoding rate for DSN's turbo decoder is not clear. This could reduce the maximum data rate at which turbo code could be used, thus changing the results presented in Figure 2. Furthermore, the models presented in Section 4 assume that the whole view period is allocated to the experiment. In reality, only a portion of the view period is allocated to the pass. This means that during the primary science phase optimization algorithms should be run to optimized the capacity of the link according to the allocated pass time and not view period duration. Furthermore, the optimization algorithms presented here do not take into account outages due to occultations that occur as the spacecraft orbits Mars and changes in the link performance due to ranging and uplink activities. During the planning it is OK to ignore such changes on the link. However, during the actual operations these changes should be characterized accurately and be considered in the link design. Finally, operational limitations that the MRO mission may impose on the experiment is still in a state of flux. However,

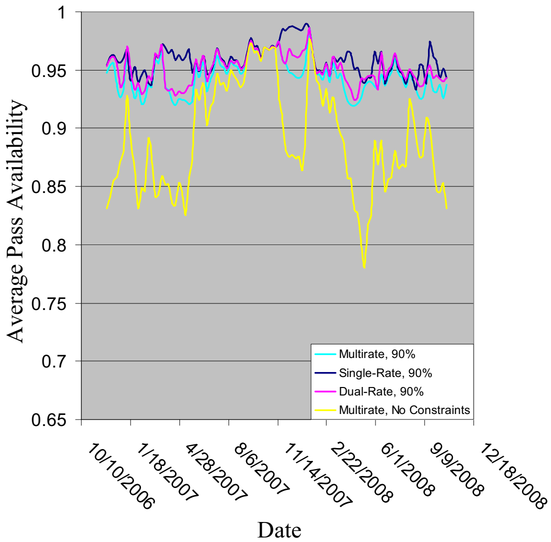

Figure 11. Canberra Average Pass Availability vs. Time for Different Optimization Methods

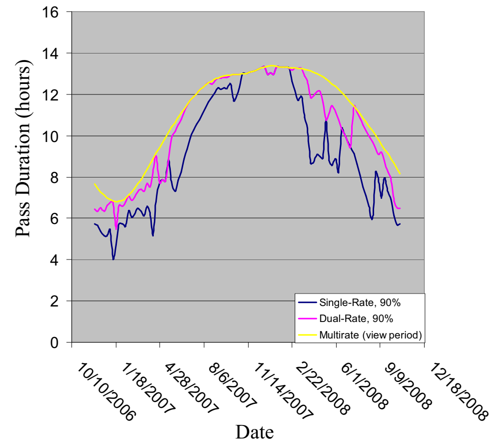

Figure 13. Madrid Pass Duration vs. Time for Different Optimization Methods

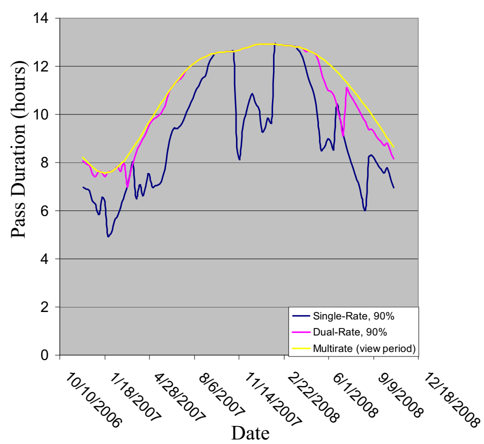

Figure 12. Goldstone Pass Duration vs. Time for Different Optimization Methods

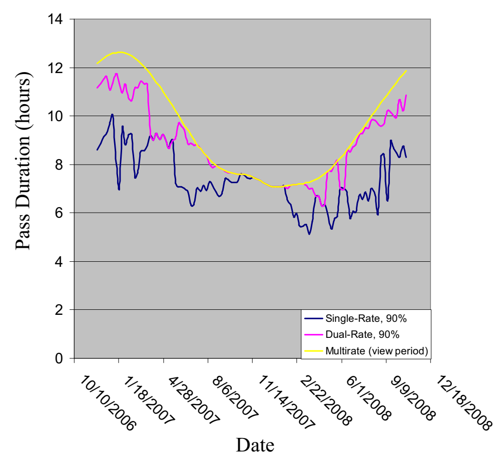

Figure 14. Canberra Pass Duration vs. Time for Different Optimization Methods

as the launch date for MRO approaches these limitations will become better defined and will be considered during the link design.

7. Conclusions

In this paper plans for Ka-band operations during Mars Reconnaissance Orbiter Ka-band demonstration in order to illustrate the operational feasibility of Ka-band for receiving telemetry from deep space missions were presented. Plans during the cruise phase are designed to validate the functionality of the Ka-band equipment onboard the spacecraft as well as validating the proposed methods of link operation for the primary science phase. Analysis is also presented regarding the expected link performance under various link optimization methods. Based on the results of this analysis, during the primary science phase a link design according to an optimization method that uses at most two data rates with a minimum availability of 90% is deemed satisfactory. Furthermore, it is expected that during the primary science phase the benefits of short-term weather forecasting algorithms will be demonstrated. During superior solar conjunction, MRO Ka-band demonstration is expected to document the Ka-band telemetry link performance as a function of solar elongation angle and to measure the performance degradations that may occur due to transient solar event.

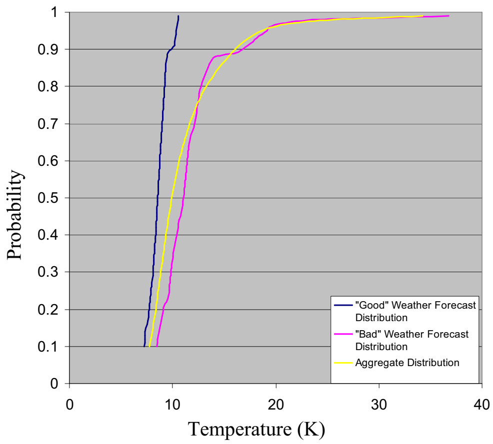

Figure 15. Zenith Atmospheric Noise Temperature Distributions, Aggregate and Forecast, Goldstone

8. ACKNOWLEDGMENTS

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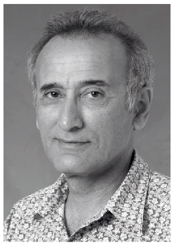

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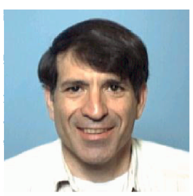

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