# Operational Demonstration of Ka-Band Telecommunications for the Mars Reconnaissance Orbiter

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*Abstract*—The NASA Mars Reconnaissance Orbiter Project and the NASA Interplanetary Network Directorate are collaborating to establish the first operational use of Ka-band for telemetry and navigation in a deep space application. The objectives of the operational demonstration are to verify that the anticipated benefits of the higher carrier frequency can actually be realized under realistic operating conditions, and if possible to provide a significant enhancement to scientific data return. We anticipate being able to demonstrate Ka-band data rates in the range 0.5 to 4.0 Mbps depending on Earth-Mars distance. We also anticipate demonstration of significant improvements in the accuracy of round-trip Doppler, ranging, and differenced differential one-way range (delta-DOR). The major open issues to be addressed in the coming year of design activities are: further characterization of weather statistics; selection of the operational methods to manage weather-induced uncertainties of link performance; the ability to consistently point large ground antennas without residual carrier signals; the performance and pointing of a large spacecraft antenna on a dynamic spacecraft; the best methods of utilizing the ground and spacecraft data system resources for optimization of data return; and the construction of a Ka-band radio source catalog.

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## 1. INTRODUCTION

Since the late 1980s, NASA has been considering the use of Ka-band (32 GHz) for downlinks from deep space missions. There are two reasons for this:

— In communications systems, all things being equal, e.g., antenna sizes, transmit power, etc, a higher operating frequency results in better link performance. This gain is mainly from the increase in antenna gains on each end of the link as the square of the frequency. After accounting for other drawbacks such as lower efficiency in the antennas and transmitter, and higher system noise temperature at the ground-based receiving system, an improvement in the link by a factor of four can be expected in the transition from the currently used X-band (8.4 GHz) to Ka-band. [1].

— As NASA develops spacecraft with greater and greater capability to generate data, radio frequency spectrum usage becomes an issue. At X-band, 50 MHz of spectrum has been allocated for deep space communications downlinks. Under the rules of the Space Frequency Coordination Group

[1] 0-7803-7651-X/03/$17.00 © 2003 IEEE

(SFCG), a mission may not use more than 4 MHz of "essential bandwidth" which limits a mission to approximately 2 Megasymbols-per-second (Msps) (e.g., 2 Megabits-per-second (Mbps) uncoded BPSK, 4 Mbps uncoded QPSK, 1 Mbps rate-1/2 coded BPSK, etc.). Sending signals of 10-100 Msps in a bandwidth of 4 MHz using higher order modulations would require a substantially greater link energy-per-bit-to-noise-spectral-density (Eb/N0) ratio than with BPSK or QPSK and would be extremely difficult in the power starved deep space spacecraft. At Ka-band, deep space communications is allocated 500 MHz and there are currently no bandwidth usage requirements from the SFCG like there are at X-band. This allows one to use lower order modulations like BPSK and QPSK with coding, which reduces link signal-to-noise ratio requirements.

A few deep space spacecraft have been flown with onboard Ka-band equipment. The Ka-band Link Experiments (KaBLE) of Mars Observer and Mars Global Surveyor, in 1993 and 1997 respectively, characterized the downlink performance advantage of Ka-band versus X-band. These missions relied on an external frequency translator or a frequency multiplier for the generation of the Ka-band downlink and hence it was not independent of the X-band signal. [2] The Deep Space 1 (DS1) mission Ka-band technology demonstration repeated the objectives of the MGS experiment but was accomplished with the first Small Deep Space Transponder (SDST) developed by Motorola (now General Dynamics) and a solid-state power amplifier developed by Lockheed Martin. The SDST was specifically designed to have a Ka-band signal on which the modulation and data rates could be independent of X-band. [3] The DS1 technology demonstration also indirectly verified the operational readiness of the DSN Ka-band subnet. The Cassini mission has a Ka-band transponder (i.e., including both uplink and downlink at Ka-band) built by Alenia Spazio, which is currently being used as part of a radio science experiment for gravity wave detection. With these successful demonstrations, the feasibility of Ka-band operation has been established.

The Mars Reconnaissance Orbiter (MRO) spacecraft, being built by Lockheed Martin Astronautics (LMA) under contract to NASA, to be launched in 2005 will carry equipment and procedures to demonstrate the routine, operational use of Ka-band to transfer data to the Earth from the S/C at the highest possible data rates. Note that while there will be pre-defined, standard procedures that will work the first time, this demonstration will also contain an experimental part, which collects statistics of absolute Ka-band performance and relative Ka-band and X-band performance. The results will be fed back into the optimization of operational procedures. As an added incentive, the Ka-band link can provide an additional means to get science data to the ground in the later stages of the demonstration beyond what can be downlinked using X-band only. There are already future missions, e.g., Kepler, which are committed to using Ka-band as their primary science downlink and NASA must be ready for these missions.

It should be apparent from the foregoing that up until now Ka-band has been operated successfully in a preliminary fashion. The challenges remaining for full operational capability are:

— The completion of the planned complement of Ka-band stations in the Deep Space Network (DSN), with associated upgrades of antenna pointing, calibration and performance measurement; ground communications; and data management to accommodate the narrower beam widths and higher data rates planned

— Further characterization of weather statistics

— Selection of the operational methods to manage weather-induced uncertainties of link performance

— Development of the ability to consistently point large ground antennas without residual carrier signals

— Characterization of the performance and pointing of a large spacecraft antenna on a dynamic spacecraft

— Negotiation of the best methods for utilizing the ground and spacecraft data system resources for optimization of data return

— Construction of a Ka-band radio source catalog.

— Capitalization on the increased bandwidth available for delta-differential one-way ranging (delta-DOR)

— Extension of experience with X-band-up, Ka-band-down Doppler and ranging data

This paper will report our present understanding of these issues, with an emphasis on the operational characteristics to be managed for the Mars Reconnaissance Orbiter.

## 2. Ka-Band System Characteristics

*Weather Effects*

The single most important uncontrollable element in the performance of a Ka-band link is the effect of weather. The degradation caused by weather effects manifests itself in four ways: (a) reduced data return, (b) reduced link reliability, (c) disruption of data continuity, and (d) data incompleteness.

For deep space applications it is necessary to decide in advance what the link configuration will be during a particular communication session. The lead time for synchronizing information about the weather between the ground and spacecraft must be at least a round-trip light time and for practical reasons often a great deal longer. Therefore it is always necessary to make some assumption about future values of atmospheric noise temperature and absorption resulting from the weather. Usually this is spoken of as the atmospheric contributions to system noise temperature and gain. When the session occurs, the weather effect may be less than assumed (favorable condition) or may be more than assumed (adverse condition). A good approximation for links using error-control coding is that the link will work perfectly under favorable conditions and will not work at all under adverse conditions, on account of the very steep rise of uncorrected error with falling signal-to-noise ratio.

Note that we make a distinction between the concept of adverse and favorable link conditions, and the concept of good or poor weather. Both concepts evaluate the weather at some particular instant, but each compares the weather to a different standard. The concept of adverse and favorable link conditions makes the comparison to a particular assumption as to what the weather was expected to be at that instant, while the concept of good or poor weather makes a comparison to some historical distribution of weather. Both concepts are needed when discussing the optimization of link configuration. For example, it is quite possible to experience adverse conditions during good weather if one expected the weather to be better than it turned out to be.

With favorable conditions the link will perform well and exhibit some power margin representing a lost opportunity to send data. Under adverse conditions all the data will be lost. If it is expected that weather will be producing an increased system noise temperature, the session might still be saved but must be operated at substantially reduced data rates. This will reduce the total amount of data returned on the link. Clearly none of these situations are perfectly desirable. To fight this problem, either optimum data rates that maximize the average data return based on historical information could be selected [4] or forecast algorithms could be used to adjust predicted conditions in the hope of setting the data rates so as to maximize the data return per pass. There are also various operational strategies that can be applied to whatever link design is selected, as described later in this paper.

Weather also affects the reliability of the link and usually runs contrary to obtaining the maximum data return as greater link reliability is achieved as the data rate is reduced (see [4] for an example). The reason for this is that weather is constantly fluctuating, so that an attempt to obtain reliability inherently requires more power margin so as to maintain communication during the valleys of the fluctuation. All other things being equal, the only way to obtain more power margin is to reduce the data rate and therefore the total return.

Weather conditions at times can be so poor that no useful data could be obtained with Ka-band at any data rate. This is a far more likely event with Ka-band than it is with X-band because (a) the contribution of atmospheric noise temperature to the overall system noise temperature is much greater for Ka-band than it is for X-band, (b) the atmospheric contribution arises from water vapor, clouds, and rain all of which fluctuate strongly compared to other atmospheric sources, and (c) the amplitude of the fluctuations is large enough that it is inefficient in practical work to use risk-free design strategies. This lower reliability means that Ka-band is not a good choice for mission-critical events such as entry/descent/landing (EDL) or any other activities that require reliable transmission of data at a specific time, unless site diversity is available.

Weather variations during a pass also create discontinuities in the data stream as it is being received. Short-term fluctuations such as microbursts or similar weather phenomena greatly increase the system noise temperature thus causing outages for short periods of time. While the data that is lost during such events could be retransmitted, if a timely decision needs be made based on the received data such disruptions would greatly complicate mission operations.

Completeness of data is also worsened by weather outages. Even though retransmission of data is possible, because of practical data management concerns on the spacecraft, the data must usually be discarded after a certain period of time. This means that some permanent gaps within some data sets are possible. Therefore, the spacecraft needs to have enough storage space and the link needs to have enough capacity to reduce occurrence of such gaps to an acceptable level.

To quantify and combat each of these effects, several tasks are being performed by the DSN engineering staff:

In order to produce reliable atmospheric noise temperature statistics, the DSN has collected atmospheric noise temperature data at all three Deep Space Communication Complexes (DSCCs) using Water Vapor Radiometers (WVR) and Advanced Water Vapor Radiometers (AWVR). Currently, these data are used to obtain atmospheric noise temperature distributions for the three sites. These distributions have been used to calculate the potential advantage offered by Ka-band over X-band and to develop methods for maximizing data return for Ka-band links. In addition, this data has been used to validate and refine an atmospheric noise temperature prediction algorithm currently under development at JPL.

During fiscal year 2003, it is planned to use the WVR/AWVR data to produce time correlation statistics for the atmospheric noise temperature for the three DSCCs. Such statistics will be beneficial in evaluating different weather adaptation strategies discussed in a following section. In addition, this data will be used to produce gap statistics for Ka-band links optimized for maximum data return. Initial results indicate that optimized links will have good continuity most (between 75% and 97%) of the time. A sample of the continuity statistics appears in Figure 1, which shows the cumulative distribution function for longest period of good data per pass (longest "run" in the pass) and longest period of bad data per pass (longest "gap" in the pass) as a function of run or gap length, calculated for the month of February 2000 at the Canberra site. The runs and gaps were calculated from atmospheric noise temperature time series, assuming a hypothetical link design. The particular assumption of weather underlying the link design was a seasonal model, and the data rate was selected to optimize total data return over the month.

In addition, it is planned to study spacecraft data storage and link capacity requirements that different acknowledged retransmission schemes will impose. These requirements will be determined based upon required data completeness and timeliness. Preliminary results indicate that significant amount of storage will be needed on board the spacecraft in order meet the very stringent data completeness requirements that are typically imposed on deep space missions.

*Operations Strategies*

It is apparent from the preceding discussion that weather variability creates an inherent tradeoff of the desire for high data rate (and therefore data volume) against the desire for completeness and continuity of the Ka-band data stream. Previous S- or X-band missions have obtained good results in the face of qualitatively the same effects by assuming a constant weather condition for the telecom system design and primarily a "Just Send It" operational strategy. However, the weather challenge at Ka-band is quantitatively more pronounced and the operational technique of responding to variations in weather conditions can make a greater contribution to the aggregate data volume, completeness, and continuity. We have considered several different strategies for responding to the Ka-band weather challenge, as described below.

*Just Send It*—No attempt is made to adapt to changes in weather in the short term. Instead, a priori knowledge of weather statistics is used to determine the expected range of gain (G) and noise temperature (T), in advance of the operation. Decisions as to link configuration are made based on requirement that the link will operate correctly a certain fraction of the time even though the weather fluctuates, which in turn is usually expressed as a selected probability value on the cumulative distribution function for G/T. That is, if a 90% success rate is desired, values of G/T corresponding to the 90th-percentile of the cumulative distribution of G/T are assumed for link calculations. The G/T model may include a temporal variation based on past experience, for instance a seasonal model dependence in the weather and a diurnal dependence of G and T at a particular site for a particular spacecraft, but would exclude updates based on climate or weather forecasts. The link is then operated on a daily basis using this fixed policy. Some data will inevitably be lost when the actual weather is worse than assumed, and no particular effort is made to avoid such losses.

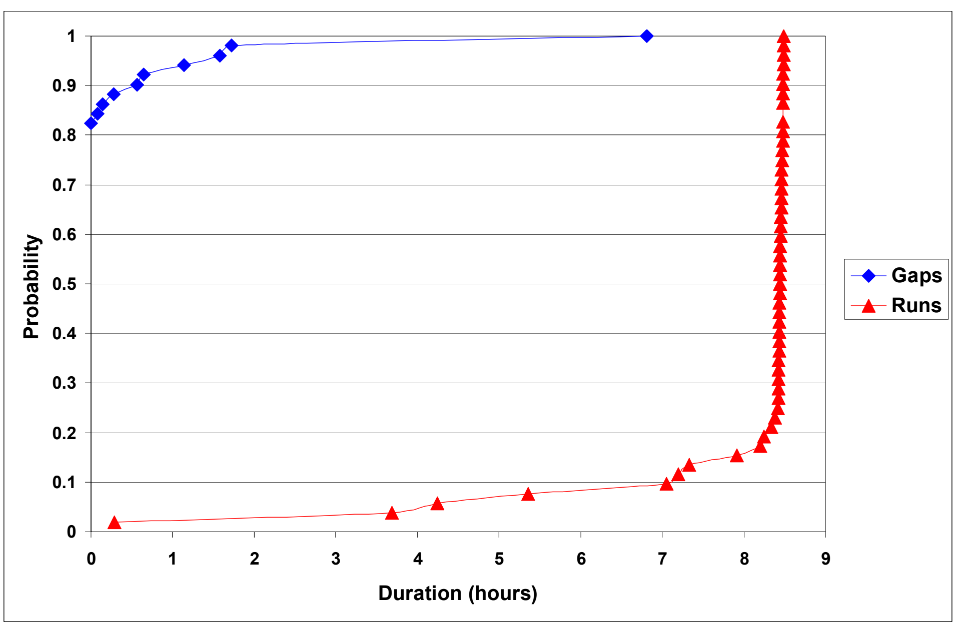


Figure 1. Cumulative Distribution of the Duration of Longest Runs and Gaps, Canberra, February 2000

*Pure Site Diversity*—If weather-induced losses are a concern, under the pure site diversity approach, the DSMS could construct extra Ka-band antennas. To be useful for weather adaptation, the extra antennas would need to be located in such a way that the view periods overlapped with the existing Deep Space Communications Complexes (DSCC), but far enough away that there is a small probability of weather being worse than expected at both sites simultaneously. A customer would request the use of two stations in advance, and whichever one has the better weather is used. In a simple form of site diversity the station with the worse weather goes unused; it is also conceivable to add the signals from both stations to either increase effective G/T when the weather permits, or to reduce the variance of the G/T distribution.

*Site-Time Diversity*—The expense of pure site diversity may be a deterrent to many applications. However, the existing architecture already includes DSCCs at three widely separated longitudes to provide continuous view from deep space. This architecture inherently provides some protection against weather outages at one site, if the customers and the provider have enough flexibility to wait for the Earth to rotate another site into view.

The architecture can be used in the following way to obtain site-time diversity. A customer would schedule a single station (call it the "planned" session). If the weather is better than assumed, data is gathered without incident. If weather turns out to be worse than assumed, an extra session is scheduled on short notice (call this pass the "makeup" session) at the next available station with satisfactory weather. At the earliest opportunity, the customer informs their spacecraft to "retain the data and resend", or alternatively refrains from sending a "data received, okay to discard data" message. When the makeup session is completed, the data can be released onboard the spacecraft.

*Selective Retransmission*—The short term scheduling challenges of site-time diversity may be difficult to overcome in practical situations. Another alternative is to retransmit data that is lost due to weather. In a planned series of sessions, if the weather turns out to be better than assumed the data can be gathered without incident. If weather turns out to be worse than assumed, lost data is detected and the spacecraft is informed to "retain the lost data and resend it." The detection of lost data and the resend decision can be made manually or automatically, by either the customer or the provider.

*Forecast-Driven Weather Adaptation*—A key opportunity is the possibility of obtaining significantly more data during good weather, and a key risk is the possibility of short-term climatic fluctuations such as the El Nino phenomenon in the Eastern Pacific Ocean creating unusually adverse weather at one or more of the sites for a period of time. For this reason it may be beneficial in some situations to tailor the predicted G/T based on forecasts of weather.

To effectively use a forecast, it is necessary to refrain from deciding the best link configuration until a point in time "close" to the time of operation. This does not preclude using a provisional data rate in the spacecraft sequence for safety. The term "close" is a subjective issue depending on a particular customer's sensitivity to weather fluctuation; we are aware of very useful forecasts with lead times in the range 0-72 hours, though there is a lower limit on information transfer imposed by the round-trip light time to the spacecraft. However it could be argued that longer-lead forecasts are helpful to reduce the risks associated with climatic variation, and it could reasonably be said that even the "Just Send It" method is a kind of forecast with a lead time of a few years using a simple forecast model in which the future is assumed to be the same as the past.

The following steps are needed to apply a forecast in actual operation, assuming the provider will be the one initiating the process (call this "provider-driven weather adaptation"). The provider observes the weather conditions surrounding the site, and gathers forecasts and meteorological data from other weather services in advance. When the chosen lead-time arrives, the provider makes a prediction as to the expected G and T as a function of time during the pass. This prediction is provided to the customer, who then decides the link configuration to use during the session. This can be done by the customer either at their operations center, or the function can be delegated to the spacecraft if the forecast is sent there instead. During the session, the provider compares the actual conditions to predicted during the pass. If the weather is close to the prediction, then data is gathered without incident. If the weather is significantly better or worse than predicted, a new prediction is made and sent to the customer for iteration.

It is also possible for the customer to be the one initiating the process (call this "customer-driven weather adaptation"), with some differences of the operational transactions.

*Error-Control Coded Operations*—A very attractive solution that will be useful for some customers is to use an error control code that is capable of error-free transmission through comparatively long gaps associated with weather, provided that at least some minimum fraction of the total data is captured with a characteristic time window. A very simple example of such a code is an interleaved repeat-N code, although we speculate that there are better codes available. During flight operations, data can be scheduled and collected without regard to weather losses, relying on the code to fill in gaps. One difficulty with the error-control code approach is that the data inherently must be sent multiple times and so may be less efficient. However, other error-control codes also have the same characteristic in order overcome very short gaps and yet achieve higher overall efficiency than an uncoded approach. We believe this is an important area for further investigation.

The operational strategies we considered each have different characteristics with respect to several figures of merit such as data volume, completeness, cost, etc. Table 1 summarizes our evaluation of the strategies with respect to these figures of merit. Since customers differ in their preferences, or since even a single customer may have different preferences depending on time or type of data, it is not in general possible to select a single strategy as being the best. The key factors in deciding among the possibilities are:
—Whether the customer needs completeness of data greater than approximately 90% (a value for which total data return is optimized for weather experience at DSN sites)
—Whether there is a small fraction of the data, e.g., 5-10% requiring high completeness
—Whether the customer's mission system is capable of selective retransmission
—Whether the customer has partners who are willing to share sessions with a small, approximately 10%, risk of loss of the session for makeup work
—Whether the customer's data is of very high value compared to other missions, and how often high value data occurs
—Whether the customer needs the maximum link efficiency, or can be satisfied with a factor of two less than the maximum,
—How fast the customer can respond to updated weather information, and how constrained the customer is with respect to operations staff.

We offer in Figure 2 a possible arrangement of the decision process for selecting the best strategy given particular conditions, which takes into account the various factors above.

*Changes in DSN Support for MRO*

The major changes in DSN support for MRO arise from its higher data rates and volume, and the addition of a Ka-band channel expressly for telemetry. The impacts of these changes are elaborated below.

*High Data Rates and Volume* —MRO will have higher data rates and volumes than any previous deep space mission. Previously the Space Infrared Telescope Facility (SIRTF), which is currently scheduled to be launched in the spring of 2003, held the record with downlinks at 2.2 Mbps for one hour twice a day. MRO has the potential for downlinking at 4 Mbps (possibly up to 6 Mbps) for 24 hours per day, an increase by a factor of approximately two in data rate and 24 in data volume.

Investigation of the current capabilities of the DSN showed that all components could handle 4 Mbps except the format-

Table 1. Comparison of Operational Strategies

| Operational Strategy | Data Volume | Completeness | Continuity | Sequence change rate* | delta-Impl. Cost | delta-Operating Cost | Risk | Network Utilization |
|---|---|---|---|---|---|---|---|---|
| Just Send It | med | 90% | poor-good | 0/0/0 | $0 | $0 | low | good |
| Pure Site Diversity | hi | 99% | excellent | 0/0/0 | $100M | $3M/yr | hi | poor |
| Site-Time Diversity | hi | 99% | good | 0/3/0 | $0 | $25K/yr | low | good |
| Retransmission | hi | 99.9% | excellent | 28/0/0 | $3M | $0 | low | excellent |
| DSMS-Driven Weather Adaptation | hi | 90% | good | 0/9/0 | $280K | $250K/yr | low | good |
| Customer-Driven Weather Adaptation | hi | 90% | good | 0/9/0 | $280K | $250K/y | low | good |
| Error-Control Coded Operations | low | 99.9% | excellent | 0/0/0 | $1M | $0 | med | poor |

* Number of changes per 28 days, with lead-time near/mid/far (0-12hr/12hr-3d/3-28d)

Note: All evaluations assume link designed for 90% weather availability, with lead-time of weather forecast 2yr except for weather adaptation lead time 12 hr-3d.

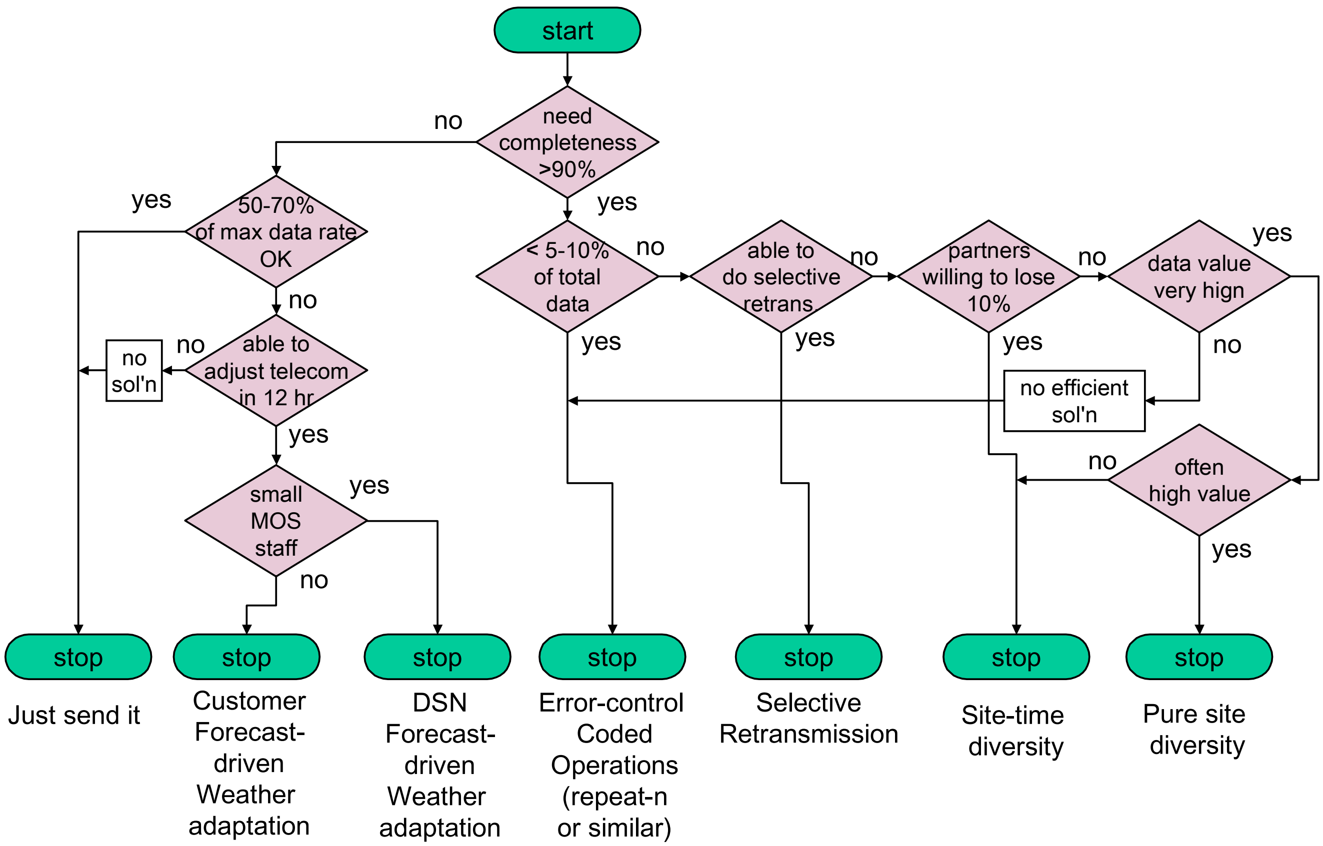


Figure 2. Decision Tree for Operational Strategies.

ter, which creates CCSDS Standard Format Data Units (SFDU) for transmission from the DSCC to JPL, and the decoders for the Turbo codes planned for use with MRO. The formatter will be upgraded to at least 4 Mbps in time for MRO. The turbo decoders will be upgraded from the current 700 kbps capability to approximately 1.6 Mbps for MRO launch, with a possible increase during the MRO Primary Science Phase.

Data lines from the DSCCs to JPL are being upgraded so that the data from a 12-hour track with a 70-meter station can be completely delivered within 24 hours of beginning of track. This guideline was chosen to make sure that data from one track is not still waiting to be delivered when the next day's track begins

High priority data, such as real-time engineering, will be delivered with a nominal latency of less than 5 minutes. CCSDS-defined Virtual Channels created onboard the spacecraft will be used for prioritizing data delivery from the spacecraft to the DSN and from the DSN to JPL.

The MRO spacecraft has limits to on-board memory, that preclude being able to hold data for retransmission of missing data at the high rates with the committed latency for data delivery. Various techniques are being investigated to allow for lower latency accountability. These include increasing the DSCC-JPL data line capacity to allow for real-time delivery of all data; the use of the CCSDS File Delivery Protocol with the extraction of the accounting information at the station; or use of the Advanced Orbiting System Transfer Frame, with a longer Frame Counter, allowing retransmit by Frame Number based on accounting at the station.

Various decisions were made by the MRO Project to support these high data rates. The high data rates selected in turn create regulatory issues as to the range of spectrum used. The Space Frequency Coordination Group (SFCG) has mandated that missions using X-band must stay within a 4 MHz spectrum band unless a specified filter is used. This corresponds in the ideal to 4 Megasymbols-per-second (Msps) and practically to a 2 Msps limit on the data that may be downlinked at X-band.

Because MRO has a high-resolution camera capable of taking 16 Gbit images very frequently, the amount of data returned from MRO will be completely determined by the capacity provided from the spacecraft to the ground.

The MRO spacecraft is carrying a 3-meter High Gain Antenna (HGA) and 100 watt X-band transmitter. Its link margin is such that it could reach the spacecraft limit of 6 Msps when Mars is close to Earth. There is a study going on as to whether MRO can exceed the spectrum limitation without affecting other users. Also, the ability of other components of the ground system to support the higher data rates is being investigated. In addition, the possibility of using more tracking time during the period when Mars is far from Earth is being evaluated.

Various coding techniques use a different number of symbols for each information bit. The codes used by MRO included turbo code with two or three symbols per bit, concatenated convolutional and Reed-Solomon with slightly more than two symbols per bit and stand-alone Reed-Solomon, with 1.14 symbols per bit.

The MRO Project decided to implement quadrature-phase-shift-keyed (QPSK) modulation, which uses only one transmitted channel symbol per coded symbol. This contrasts to the customary modulation technique, bi-phase-shift-keyed (BPSK) modulation in which two transmitted channel symbols are required for each coded symbol. This fact would have limited even the stand-alone Reed-Solomon code to 4 Msps coded, or a maximum of 2 Mbps raw data unless filtering was used.

Use of QPSK poses a challenge, in that QPSK inherently has a completely suppressed carrier. Because the conventional DSN ranging technique requires some residual carrier to be modulated with the ranging code, there is no capability to do ranging while using QPSK for telemetry. Even if there were some residual carrier, there would still be some interference between the high rate telemetry and the ranging code due to overlapping spectrum. Previous, lower-rate missions avoided this interference by taking advantage of the DSN's ability to keep the ranging code farther from the carrier than telemetry, but within the limit imposed by spectrum regulators. To circumvent this difficulty the Project is looking for ways to conduct ranging for its primary orbital use, Gravity Science, without significantly affecting the telemetry data return.

Another challenging characteristic of QPSK is that it has an ambiguity, which has to be resolved. The DSN has already implemented the ambiguity resolution in its turbo decoder and convolutional decoder. However, since MRO is also using stand-alone Reed-Solomon decoding, the capability to do the ambiguity resolution will be added for that case.

*Addition of Ka-band*—Various missions in the past have carried a Ka-band transmitter for limited experimental use. In contrast MRO will be carrying a Ka-band transmitter in order to perform a demonstration of operational use of Ka-band for returning a substantial volume of data, and perhaps to enhance the overall science data return as a goal. The results of this demonstration will be used to provide guidance for the use of Ka-band by missions such as Kepler.

Currently the DSN has only one tracking station capable of receiving Ka-band telemetry, namely DSS-25 at Goldstone. By the time MRO will start returning science data, there will be three Ka-band-capable stations at Goldstone, two at Madrid and one at Canberra.

The higher gain of the DSN antennas at Ka-band arises from their higher directivity, in other words, a narrower beamwidth. The beamwidth is sufficiently narrow at Ka-band (3 mdeg to 0.5 dB, or 8.5 mdeg to 3.0 dB gain reduction), and the structure sufficiently large that a host of effects such as wind, structural deformation, and thermal gradients interfere with pointing. It has already been demonstrated that blind pointing can be achieved to 4 mdeg, 6 mdeg, or 11 mdeg mean radial error in winds up to 10, 20, and 30 mph respectively, which is somewhat less accurate than desirable for telemetry purposes, or for navigational tasks involving radio source observations such as delta-DOR, clock synchronization, Earth rotation and polar motion studies, crustal dynamics, radio reference frame, or radio source catalog development.

To improve antenna pointing to the desired level, one measure has already been applied and several others are under investigation. The DSN has already implemented monopulse pointing for Ka-band, including the feed, low-noise amplifiers, receivers, and computation. The monopulse system is capable of better than 1.5 mdeg (0.1 dB) mean radial error for spacecraft signals possessing residual carriers with greater than 17 dB-Hz signal-to-noise ratio [5].

However, the monopulse as presently constituted cannot address suppressed carrier signals that arise from BPSK or QPSK signaling, nor can it address broadband noise from radio sources. Therefore we are actively studying improved blind pointing based on laser metrology, squaring strategies to reconstruct carriers from suppressed carrier signals, and monopulse for broadband signals including both quasars and the telemetry modulation itself.

Also, weather affects Ka-band more than it does X-band, as discussed elsewhere in this paper. Presently the DSN has basic meteorological sensors, water vapor radiometers, and microwave temperature profilers deployed at each DSCC that are operating for research purposes. We are advocating the extension of these capabilities to a minimum operational status sufficient to support real time decisions regarding Ka-band data and to record sufficient data to fully account for the role of weather in system performance after the fact. We are also advocating the development of gain and noise temperature prediction capabilities to facilitate customer decisions regarding their link configuration. For MRO we consider it likely that we will succeed to at least provide historically-based seasonal models of performance; in the long run we believe it will be possible to provide useful predictions based on weather forecasts with lead times of 12-72 hours or more.

Although there is no commitment on the part of the Project or DSMS to deliver science data using Ka-band, it is likely that the Ka-band will in fact be used to increase the science data return. This is especially the case since the Project is making modifications to their on-board telemetry handling to allow different data to be sent on X-band and Ka-band. It is likely that Ka-band will be assigned a Virtual Channel to be used for lower priority data that does not have high completeness and continuity requirements. Although it will be received concurrently with higher priority data X-band data, it will be delivered to JPL with lower priority.

In addition, since QPSK is not required on Ka-band to avoid spectrum limitations, Ka-band could be used for supplementing the minimum amount of X-band Gravity Science ranging data during the times when QPSK is used on the X-band.

There are frequently more spacecraft requiring tracking from Mars than can be handled by the existing stations. Therefore, a capability has been developed for doing Multiple Spacecraft per Antenna (MSPA). The antenna is pointed at the center of Mars. For all except the most elliptical orbits, spacecraft in Mars orbit or on the surface of Mars will be in the X-band beam. However, this will probably not be the case for Ka-band. The capability to do MSPA with one or more of the spacecraft using Ka-band will have to be investigated.

*Radio Metric Performance*—The ground equipment accuracy for range rate as measured by Doppler frequency X-up/Ka-down is expected to be better than 0.5, 0.1, and 0.1 mm/s one-sigma at integration times of 5, 60, and 1000 seconds respectively. The ground equipment accuracy for range as measured by round-trip light time X-up/Ka-down is expected to be 17, 7, and 5.6 ns one-sigma at integration times of 5, 30, and 60 minutes respectively. It should be understood that these are committed values based on analysis of system components. Characterization of the ground system using actual spacecraft signals remains to be accomplished and may yield better performance.

During cruise, delta-DOR measurements will be made at X-band to support navigation. The MRO transponder will emit DOR tones at X-band with a spacing of 38.4 MHz. These measurements will provide angular position accuracy of 5 nrad, comparable to the performance that was achieved during Odyssey cruise [6]. A demonstration of delta-DOR measurements at Ka-band is being planned. Taking advantage of the wider spectrum allocation at Ka-band for deep space tracking, the MRO transponder will emit DOR tones with a spacing of 153.6 MHz at Ka-band. Spanned bandwidth is a significant factor in the delta-DOR error budget, since the precision of the group delay observable is inversely proportional to bandwidth. Measurement performance at Ka-band is potentially better than at X-band due to the increase in the spanned bandwidth of the downlink signal and also due to the reduced effects of charged particles on signal propagation.

*Radio Source Catalog*—Astrometric observations of distant active galactic nuclei have been used to construct quasi-inertial global reference frames, most notably the International Celestial Reference Frame (ICRF) which now forms the basis for all astrometry including deep space navigation. This work has been done at S-band (2.3 GHz) and X-band (8.4 GHz) and needs to be extended to Ka-band (32 GHz.) Until antennas are equipped at Ka-band, the NRAO VLBA facility will be used for preliminary work at K-band (22 GHz) and Q-band (43 GHz) because these frequencies bracket the desired Ka-band. By interpolating K- and Q-band measurements we obtain an estimate of source flux and structure variability at Ka-band. While we await long baseline Ka-band capability, VLBI measurements are being made on a short baseline using the Ka-band receivers at the DSN DSS-13 and DSS-25 in Goldstone, California. Once the first intercontinental DSN baseline is available in November 2003, regular catalog measurements will begin at Ka-band.

## 3. APPLICATION TO MRO

The MRO Ka-band operational demonstration will demonstrate standard downlink telemetry functions and ranging, Doppler, and delta-DOR navigation functions at Ka-band. Coherent turn-around functions for Doppler and ranging measurements will be done with an X-band uplink and Ka-band downlink. Two 8-hour passes per week at any of the three Deep Space Communications Complexes (Goldstone, CA, Madrid, Spain, or Canberra, Australia) have been allocated to the Ka-band demonstration. The most important aspect of these passes is that standard Deep Space Network (DSN) and MRO planning, prediction and sequencing processes will be used to validate the operational procedures for using Ka-band. Careful data archiving and after-the-fact analysis will evaluate these standard procedures for any updating needed. During these passes, there are a number of options for operation:

- Ka-band only passes during which predictions and procedures will be evaluated
- Ka-band and X-band simultaneously for relative evaluation of the two bands

Note that it is possible that there could be additional Ka-band transmissions during standard MRO X-band downlink passes if these passes are scheduled at a Deep Space Station (DSS) that is capable of receiving Ka-band and on a non-interference basis.

*Telecommunications Hardware*

The MRO telecommunications hardware is shown in Figure 3. One important feature to notice in this figure is that the Ka-band hardware is not redundant. The Ka-band hardware was not requested by NASA nor included in the original spacecraft design proposed by Lockheed Martin Astronautics. After the original design, it was decided to include Ka-band in the forward-looking effort by the Mars Exploration Program to continue to develop Ka-band for the reasons mentioned in the introduction of this paper. Due to limited funds for this add-on, the decision was made not to make it a redundant system.

The heart of the telecommunications system is the aforementioned SDST. The SDST provides both X-band and Ka-band outputs. The data rates, subcarriers, error-correction coding, BPSK or QPSK, and tones for delta-DOR are independent for each band. The only dependence is that the Ka-band downlink frequency must be related to the X-band downlink frequency by 42/11. The QPSK function is new for the MRO SDST and the delta-DOR tones have increased frequency span relative to X-band (153.6 MHz at Ka and 38.4 MHz at X). The error correction coding included in the SDST are the CCSDS standard (7,1/2), (14, 1/4) and (15, 1/6) convolutional codes although only the (7,1/2) code is intended to be used in this mission—from the SDST.

The power amplifier is a 35 watt traveling wave tube amplifier (TWTA) developed under the Interplanetary Network Directorate Technology Program by Thales. For efficiency reasons, the TWTA will be mounted on the back of the high gain antenna (HGA).

The HGA is a 3-meter diameter offset fed dual frequency design. Since this demonstration is on a non-interference, minimal cost basis, there are two issues that may be non-

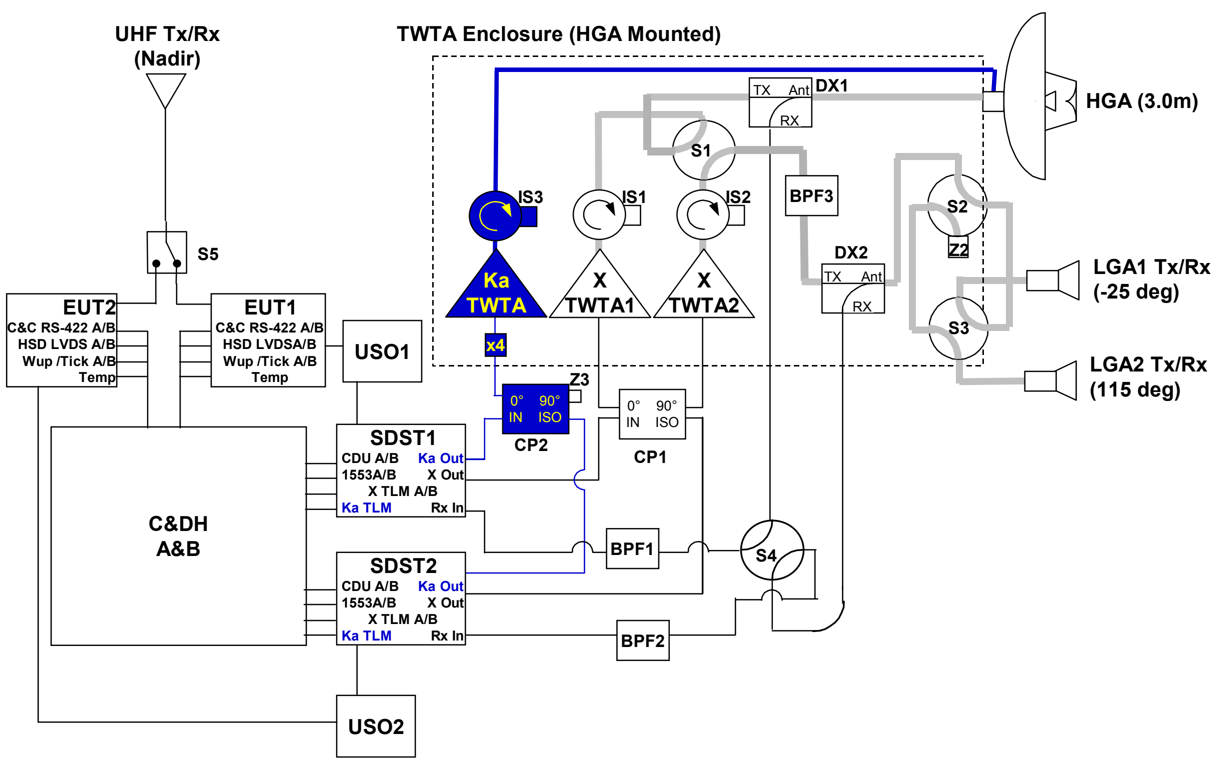


Figure 3. MRO Telecommunications Hardware.

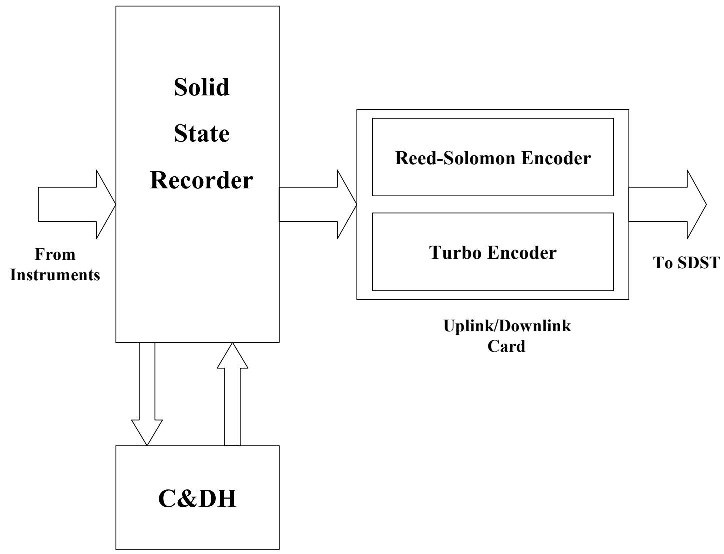


Figure 4. Avionics Preprocessing.

optimal from a Ka-band perspective. The antenna pointing accuracy on the spacecraft was originally specified for X-band. Due to the narrower beamwidth at Ka-band, the pointing loss will be worse at Ka-band than at X-band. Currently the specification for the antenna pointing accuracy is 1.6 mrad CEP that will translate into a 2.7 dB loss. The second issue is the surface accuracy of the main reflector, which is currently under negotiation. It is hoped that the losses due to surface "roughness" can be kept to a tolerable minimum.

*Telecomm Related Avionics Hardware*

Figure 4 notionally shows the "preprocessing" performed by the avionics prior to the SDST. Data from the instruments is stored in the solid-state recorder (SSR) along with on-board engineering data. This data is formatted by the Command and Data handling (C&DH) computer, into CCSDS standard frame formats for downlinking to Earth and then stored in the SSR again. Once it is ready to be transmitted the data passes through the uplink/downlink card (UL/DL) where error correction coding is added. The choices for encoding are CCSDS standard (255,223) Reed-Solomon (RS) or rate 1/2 or 1/3 turbo codes. These are two separate encoding paths that can be used to encode only one stream of data at a time. Since data can be sent over X-band or Ka-band, there are a number of options of encoding and transmitting. If identical data is to be sent over X and Ka, simultaneously, the possibilities are

—RS encoding in the UL/DL and sending over X and Ka simultaneously followed by rate 1/2 convolutional encoding in the SDST

—Turbo encoding in the UL/DL and sending over X and Ka

—RS encoding in the UL/DL followed by rate 1/2 convolutional encoding in the SDST over X and Turbo encoding (rate 1/2 or 1/3) over Ka (no encoding in the SDST)

—RS encoding followed by rate 1/2 convolutional encoding over Ka and Turbo encoding (rate 1/2 or 1/3) over X

If independent data is to be sent over X and Ka simultaneously, the possibilities are

—RS encoding in the UL/DL card followed by rate 1/2 convolutional coding in the SDST for X and turbo encoding in the UL/DL card for Ka

—RS encoding in the UL/DL card followed by rate 1/2 convolutional coding in the SDST for Ka and turbo encoding in the UL/DL card for X

Note that the UL/DL has a limitation of 6 Msps output total that must be shared across the two possible channels—RS or turbo.

*Data Return at Ka-band*

Figure 5 displays the maximum achievable Ka-band telemetry data rate the link can support for MRO for two cases: conventional convolutional (7,1/2) coding with an outer Reed-Solomon (255,223) code (RS), and a rate 1/3 Turbo code with a 8920 bit frame size. The time axis of Figure 5 spans the period from September 15, 2005 shortly after launch, to December 15 2008. The cruise phase extends from just after launch (2005/09/15) to orbit insertion (2006/03/11). The aero-braking phase extends from orbit insertion (2006/07/13) to the start of MRO operations (2006/07/13) and is denoted by a thin line devoid of points in Figure 5, as trajectory information was not available for this phase, since the aerobraking has not yet

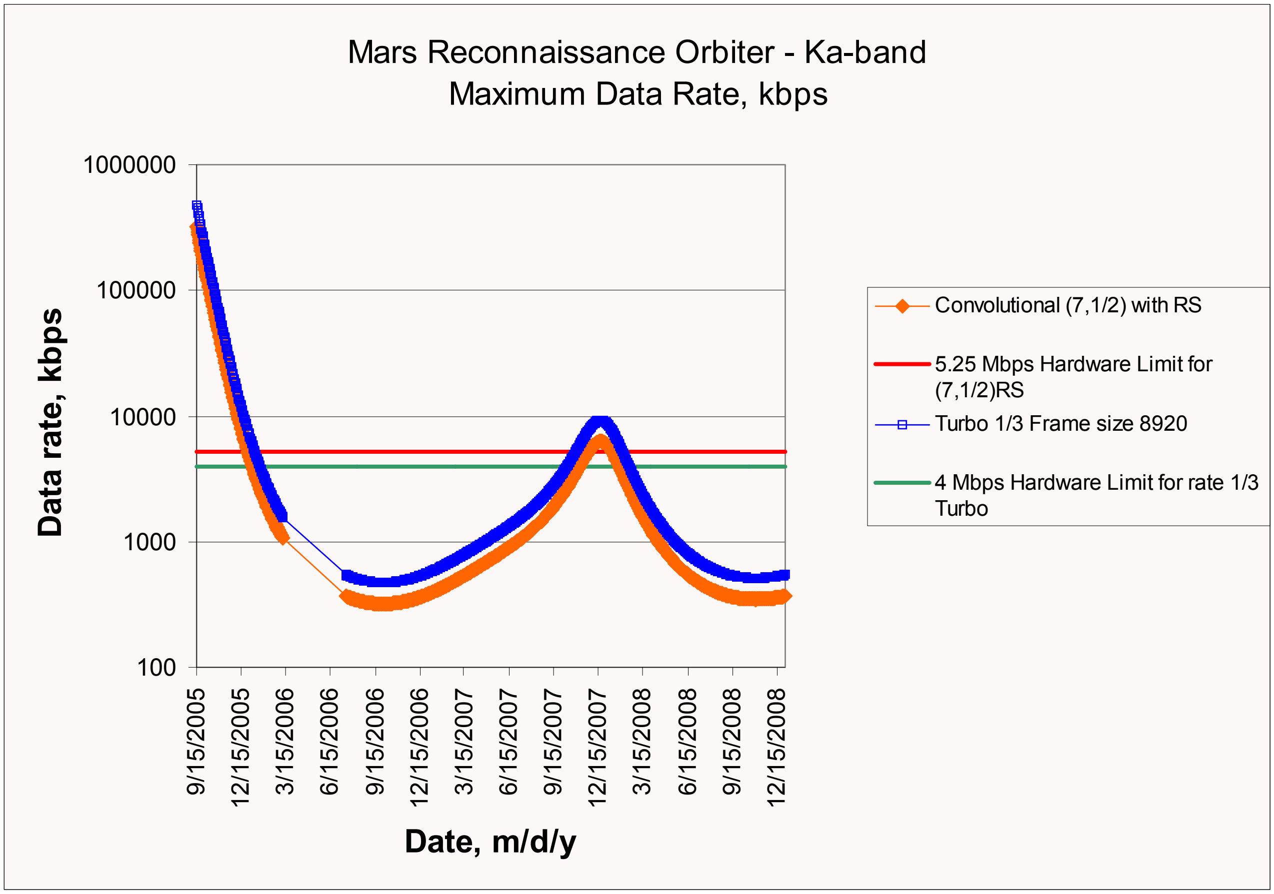


Figure 5.  MRO Data Rates.

been designed. The thin blue line is approximate, and the actual data rate segment in this period will be somewhat curved. The nominal MRO operations period extends from 2006/07/13 to 2008/12/31.  The solid red line in Figure 5 denotes the 5.25 Mbit/s hardware limit of telemetry system for the (7,1/2)+RS case.

Given that the uplink/downlink card inside the spacecraft computer has a 6 Msps limitation, and that RS has a 14% overhead, the (7,1/2) convolutional code of the SDST will result in an effective 5.25 Mbps maximum data rate limit for the Ka-band link. The rate 1/3 Turbo code maximum date rate limited by the hardware is 2 Mbps and is designated by the thick green line in Figure 5. No overhead is assumed for this limit.

The link design is conservative. The spacecraft Ka-band system parameters include 35-W of RF output power, 0.78 dB of circuit losses, and a 3-m diameter HGA with 61% efficiency (57.9 dBi gain on axis). The propagation losses for atmospheric attenuation and system operating noise temperature assume 90% weather at Goldstone, California, and were obtained from the DSN 810-05 document assuming an elevation angle of 20°. The ground station is a 34-m diameter beam waveguide (BWG) antenna designed as DSS-25, which is currently operational and is expected to be available during MRO operations.

A 3-dB loss due to mispointing of the HGA by about 1.6 milli-radians (0.092°) is assumed in the link. The pointing requirement of 1.2 milli-radians (0.06875°) would result in a 1.6 dB pointing loss, and the data rates in the curves of Figure 5 would thus improve by 1.4 dB.  Figure 6 displays the numerically calculated Ka-band antenna pattern for the HGA using theoretical equations assuming a 3.0-meter diameter parabolic dish and a 32.0 GHz frequency. The actual antenna pattern will deviate from this somewhat and will not be known explicitly until it is measured on the antenna range and in flight.

The link assumes residual carrier tracking with significant amount of carrier suppression using a modulation index of 80°. However, even at the worst-case range distance of 2.67 au, the residual carrier has 23 dB of margin using a loop bandwidth of 10 Hz.

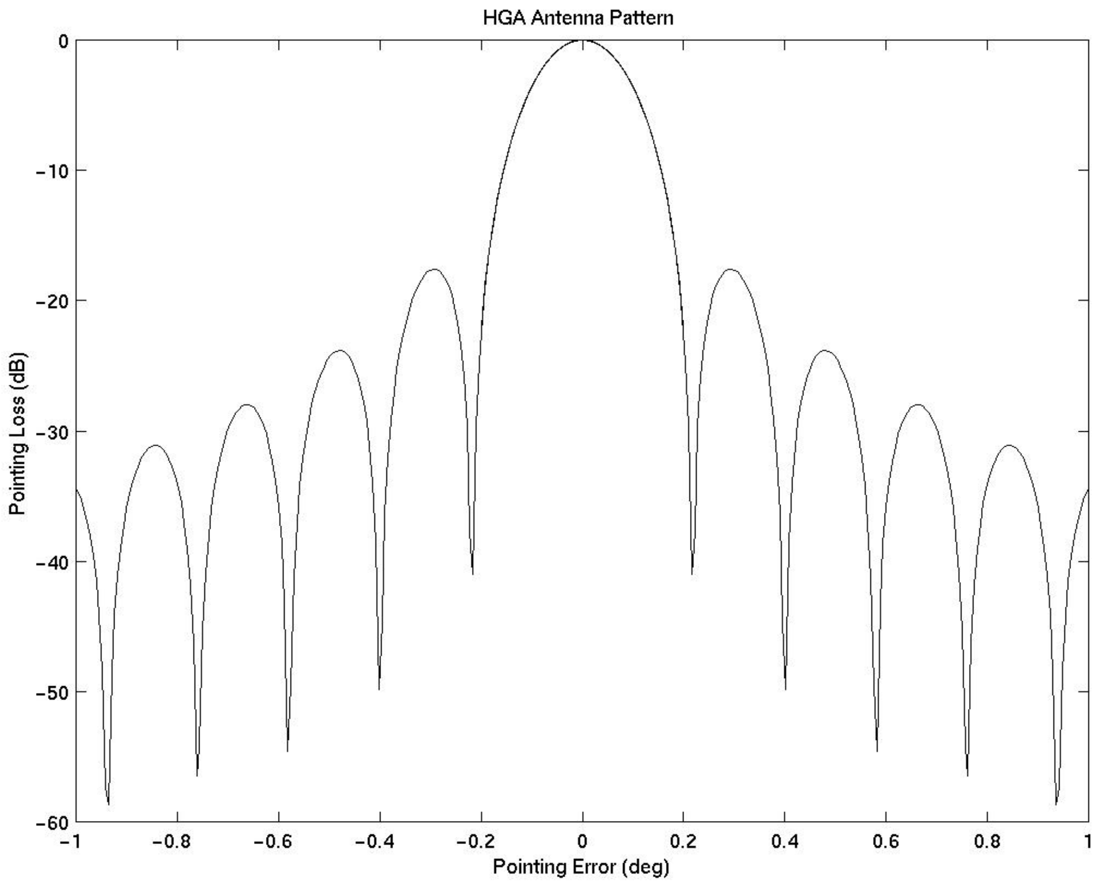


Figure 6. Theoretical Beam Pattern for MRO HGA

*Operational Considerations and Constraints*

As pointed out in Section 2, there are many possible modes of operation that are being considered to handle the vagaries of propagation at Ka-band. Unfortunately, as a non-interference basis, add-on to MRO, there is a limitation to what can actually be implemented. In addition, much of the operations plans for MRO are still being developed, so, for example, what retransmission scheme to be used, if any and whether the CCSDS File Delivery Protocol (CFDP) will be implemented are still open issues. At a minimum, a "Just Send It" standard procedure for defining links based upon 90% weather, either yearly or more likely monthly, will be developed and the results of gaps during passes and bad weather days will be evaluated. Experiments will be carried out with variations around the 90% weather parameter and with simultaneous X-band transmission. Simultaneous "site diversity" will probably not be possible due to a lack of Ka-band capable deep space stations at sites near enough to the DSN complexes in the MRO time frame. Future opportunities in this area will continue to be explored. As can be negotiated with the MRO Project and the DSN, "site-time diversity," "selective retransmission" "forecast-driven weather adaptation" and simple "error-control coded" strategies will be tested.

## 4. SUMMARY

NASA is developing the use of Ka-band (32 GHz) for downlinks from deep space missions to obtain better link performance and to manage radio frequency spectrum usage issues.

The Mars Reconnaissance Orbiter (MRO) spacecraft, to be launched in 2005, will carry equipment and procedures to demonstrate the routine, operational use of Ka-band to transfer data to the Earth from the S/C at the highest possible data rates. This is a forward-looking effort by the Mars Exploration Program to continue to develop Ka-band from the preliminary capabilities demonstrated on previous missions. MRO will carry the Small Deep Space Transponder, providing both X-band and Ka-band outputs. The Ka-band power amplifier is a 35,watt traveling wave tube amplifier, and the high-gain antenna is a 3-meter diameter offset fed dual frequency design. The MRO Ka-band telecommunication link will be capable of an effective

5.25 Mbps maximum data rate using Reed-Solomon concatenated with convolutional (7,1/2) coding, and a 2 Mbps maximum data rate with the rate 1/3 Turbo code.

The DSN is undergoing upgrades for MRO for its higher data rates and volume, for its QPSK signaling, and for the addition of a Ka-band channel expressly for telemetry. The ground system will be capable of at least 4 Mbps for the Reed-Solomon + convolutional coded data, and approximately 1.6 Mbps for Turbo codes by MRO launch, with a possible increase during the MRO Primary Science Phase. The DSN has already demonstrated a monopulse pointing system capable of better than 1.5 mdeg (0.1 dB) mean radial error for spacecraft signals possessing residual carriers with greater than 17 dB-Hz signal-to-noise ratio, and is investigating several methods to handle BPSK, QPSK, and quasar pointing.

The single most important uncontrollable element in the performance of a Ka-band link is the effect of weather. The degradation caused by weather effects manifests itself in four ways: (a) reduced data return, (b) reduced link reliability, (c) disruption of data continuity, and (d) data incompleteness. Generally the weather effects create an adverse tradeoff between the desire for maximum data return and for reliability, continuity, and completeness. This tradeoff can be managed by a combination of link optimization techniques (either maximization of the average data return based on historical information, or forecasts to maximize the data return per pass) and various operational strategies. We examined six strategies, namely

—Just Send It
—Pure Site Diversity
—Site-Time Diversity
—Selective Retransmission
—Forecast-Driven Weather Adaptation
—Error-Control Coded Operations

and evaluated their characteristics with respect to several figures of merit. Since customers differ in their preferences, or since even a single customer may have different preferences depending on time or type of data, we devised a decision process for selecting the best strategy given particular conditions.

To aid in the intelligent selection among strategies, the DSN has collected atmospheric noise temperature data at all three Deep Space Communication Complexes (DSCCs). Currently, this data is used to obtain atmospheric noise temperature distributions for the three sites. These distributions have been used to calculate the potential advantage offered by Ka-band over X-band and to develop methods for maximizing data return for Ka-band links. In addition, this data has been used to validate and refine an atmospheric noise temperature prediction algorithm currently under development at JPL. In the near future we expect to produce time correlation statistics for the atmospheric noise temperature for the three DSCCs, and to study spacecraft data storage and link capacity requirements that different acknowledged retransmission schemes will impose.

We are advocating the extension of research-level weather measurement capabilities to a minimum operational status sufficient to support real time decisions regarding Ka-band data, and to record sufficient data to fully account for the role of weather in system performance after the fact. We are also advocating the development of gain and noise temperature prediction capabilities to facilitate customer decisions regarding their link configuration.

The ground equipment accuracy X-up/Ka-down Doppler is expected to be better than 0.5, 0.1, and 0.1 mm/s one-sigma at integration times of 5, 60, and 1000 seconds respectively, and for ranging to be better than 17, 7, and 5.6 ns one-sigma at integration times of 5, 30, and 60 minutes respectively. A demonstration of delta-DOR measurements at Ka-band is being planned, to take advantage of the wider spectrum allocation at Ka-band. The MRO transponder will emit DOR tones with a spacing of 153.6 MHz at Ka-band, which is expected to enable a significant improvement in delta-DOR accuracy.

At present the DSN has not yet achieved long baseline Ka-band VLBI capability, which is needed both for delta-DOR and the development of a supporting radio source catalog. In the interim, VLBI measurements are being made on a short baseline using the Ka-band receivers at the DSN DSS-13 and DSS-25 in Goldstone, California. Once the first intercontinental DSN baseline is available in November 2003, regular catalog measurements will begin at Ka-band.

While many of the operations plans for MRO are still being developed, we expect that a standard procedure for defining links based upon 90% weather, either yearly or more likely monthly, will be developed and the results of gaps during passes and bad weather days will be evaluated. There may also be a retransmission mechanism based on the CCSDS File Delivery Protocol, and to the extent that can be negotiated with the MRO Project and the DSN, "site-time diversity," "selective retransmission" "forecast-driven weather adaptation" and simple "error-control coded" strategies will be tested.

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## ACKNOWLEDGEMENT

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

The authors wish to thank Allan Halsell for the trajectory files for the cruise and orbital operations, and Michael Britcliffe for the estimates of ground antenna pointing performance.

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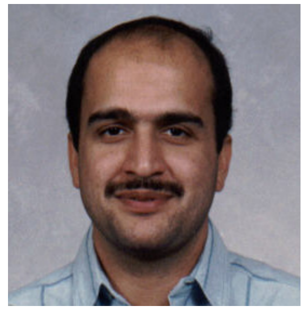

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