Maximization of Data Return at X-band and Ka-band at DSN's 34m Beam-Waveguide Antennas[1]

Shervin Shambayati
Jet Propulsion Laboratory
4800 Oak Grove Dr. Ms 238-420
Pasadena, CA, 91109
Tel.: (818) 354-1280 FAX: (818) 354-6825
e-mail: *Shervin.Shambayati@jpl.nasa.gov*

Abstract—In this paper we offer a new approach to evaluating the performance advantage of Ka-band frequency over X-band frequency for receiving spacecraft downlink from deep space missions. For a given elevation profile for a pass, this approach uses atmospheric noise temperature statistics to select the optimum data rate that maximize the total data return volume over the pass. For illustration purposes, this approach is used to optimize the performance of a link for both X-band and Ka-band at a DSN 34m Beam Waveguide tracking station at both Madrid, Spain and Goldstone, California. Our calculations show that using such an approach an optimized Ka-band link offers between 5.9dB and 7.2dB more data volume over an optimized X-band link, and between 8.5dB and 10.3dB over an X-band link as currently operated by the DSN. This advantage, however, is gained through operating the link less reliably—

TABLE OF CONTENTS

1. INTRODUCTION

NASA's Deep Space Network (DSN) has spent large sums of money to make its 34m beam waveguide antennas (BWG) capable of receiving Ka-band signals. This is largely due to the fact that Ka-band 32GHz frequency has the potential of offering as much as 11.2dB more data than X-band, for the same spacecraft antenna size, spacecraft antenna efficiency and spacecraft transmitted power.. This advantage is wholly attributable to the ground system performance. However, since the Ka-band received signal to noise ratio (SNR) is more susceptible to large variations due to weather effects than is the X-band SNR and Ka-band receiver electronics have a higher noise figure than the X-band receiver electronics, not all of this advantage is realizable.

Previously, the analysis had focused on evaluating the advantage of Ka-band over X-band at fixed elevations (see [1] for example) or for a given link reliability (see [2]). However, as deep space missions have expressed interest in Ka-band, a more comprehensive approach is needed to evaluate the performance advantage of Ka-band over a whole pass. In this paper we will present one such approach based on the statistical gain to temperature ratio (G/T) performance of the ground system over a pass. We will show that using such an approach a Ka-band link offers between 5.9dB and 7.2dB more average data volume over an optimized X-band link, and between 8.5dB and 10.3dB over an X-band link designed according to current DSN practices.

The paper is organized in the following manner: In Section 2 we introduce the mathematical foundation of our study and our optimization methodology. In Section 3 we establish the current DSN baseline performance by evaluating the performance of the X-band link at the 34m BWG antennas under current DSN link design and operation practices for four typical passes. In Section 4, we apply our optimization method to these passes for both X-band and Ka-band and compare them to the baseline performance established in Section 3. In Section 5 we draw our conclusions and outline the limitations of our optimization approach.

2. THEORETICAL FOUNDATION

Consider a deep space telecommunication link. Ignoring the power that is put in the carrier portion of the downlink signal, the instantaneous supportable data rate, R, is directly proportional to the ground antenna's gain to system noise temperature ratio, Γ, so that

$$R = \alpha \cdot \Gamma \qquad (1)$$

where α is determined by a combination of the required bit signal to noise ratio, E_b / N_0, and the total received power at the antenna for the link. As α is a constant for the calculations in this paper it is assumed to be equal to 1. This assumption is equivalent to assuming that on a hypothetical spacecraft the combination of the spacecraft antenna gain and transmitter power for both X-band and Ka-band leads to reception of the same received Equivalent Isotropic Radiated Power (EIRP) at the ground antenna.

[1] The work described was funded by the IPN-ISD Technology Program and performed at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration.

As the tracking elevation changes, Γ is affected by three parameters: the atmospheric noise temperature, T_{atm}, which also affects the path loss through the atmosphere and thus the effective gain of the antenna, the receiver and ground equipment noise temperature, T_{vac}, and the change in gain of the antenna, G, due to change in the deformation of main antenna reflector. Dr. Stephen D. Slobin of Jet Propulsion Laboratory has developed mathematical models based on direct measurements that fully characterize G and T_{vac} as a function of the elevation for both X-band and Ka-band. Therefore, the only unknown in evaluating Γ is T_{atm}.

T_{atm} is a random variable and, therefore, so is Γ. We have complete probability distributions for T_{atm} based on actual measurements at both Madrid and Goldstone Deep Space Communications Complexes (MDSCC and GDSCC respectively) [1][3] at both X-band and Ka-band. Therefore, using these distributions along with Dr. Slobin's models for 34m BWG, we can calculate probability distributions for Γ at each complex for these frequencies at any given elevation. Based on this our optimization method is as follows: First we define

$$F(\gamma,\theta) = \Pr\{\Gamma > \gamma | eleavtion = \theta\} \quad (2).$$

This corresponds to the probability that a link designed with a required Γ of γ at elevation θ will successfully close. In other words, $F(\gamma,\theta)$ is the *reliability* of a link designed for a Γ of γ at elevation θ. Given this, the probabilistic data rate for the link design with required Γ of γ at elevation θ is given by

$$R_p(\gamma,\theta) = \alpha \cdot \gamma \cdot F(\gamma,\theta) \quad (3).$$

Let $\theta(t)$ define the elevation profile of a pass from its start time, t_s, to its end time, t_f. Assuming that the link is designed to close with a Γ of γ, then the expected returned data volume for the pass is given by:

$$\begin{aligned} V(\gamma) &= \int_{t_s}^{t_f} R_p(\gamma,\theta(t)) \cdot dt \\ &= \int_{t_s}^{t_f} \alpha \cdot \gamma \cdot F(\gamma,\theta(t)) \cdot dt \end{aligned} \quad (4).$$

Given (4) we can find an optimum value for γ, γ_{opt}, such that

$$V(\gamma_{opt}) \geq V(\gamma) \;\; \forall \;\; \gamma \quad (5).$$

Furthermore, we can define the average availability of the link over the pass as

$$A(\gamma) = \frac{1}{t_f - t_s} \int_{t_s}^{t_f} F(\gamma,\theta(t)) \cdot dt \quad (6).$$

We can, therefore, use (4), (5) and (6) to establish

a. The average returned data volume for any given pass for a given γ.
b. The optimum data rate in terms of average returned data volume.
c. The average availability of the link for any given γ.

In the next two sections we illustrate how these could be applied to evaluate the performance of both X-band and Ka-band links at a 34m BWG station at both GDSCC and MDSCC.

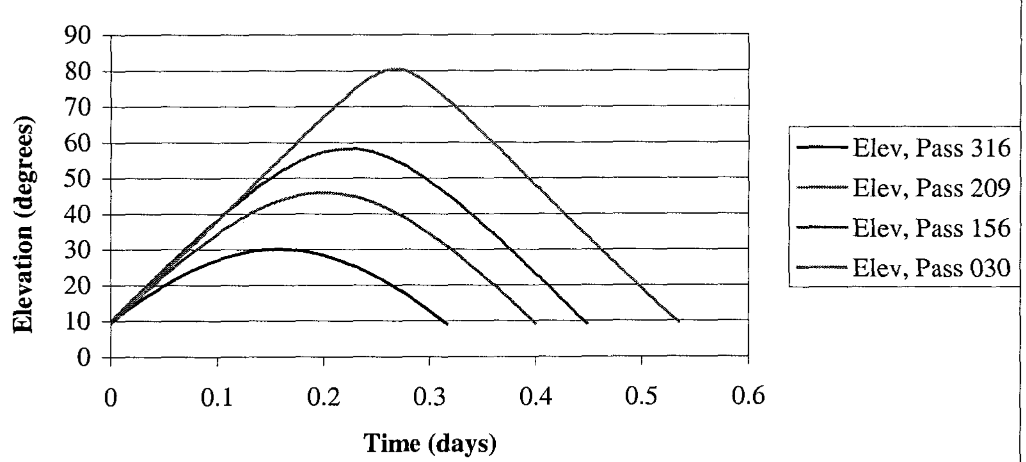

Figure 1. Elevation vs. Time, Passes 030, 156, 209 and 316

3. BASELINE PERFORMANCE

In this paper we consider four different elevation profiles with which we evaluate the performance of our optimization method. These profiles are shown in Figure 1 and are taken from actual passes that tracked Mars Global Surveyor. These passes cover a wide range of maximum elevations so that the variations in the performance advantage of a Ka-band link over an X-band link could be understood. As a first step to this we establish the performance of the X-band link as it is currently used for these four elevation profiles.

Typically, an X-band deep space mission is designed with a single data rate. This data rate is selected such that the link closes at 10 degrees elevation (nominal minimum tracking elevation used by the DSN) with a 3dB margin for 90% weather (for the rest of the paper this approach to the link design will be call the "standard" approach). This 3dB margin is usually carried in order to keep the link robust in the face of unforeseen variation in the signal to noise ratio. Looking at the tipping curves for the 34m BWG antenna at X-band (Figures 2a and 2b) we note that for Goldstone an X-band link designed in such a manner closes with a γ of 49.8dB and for Madrid, such link closes with a γ of 49.5dB. Looking at the same tipping curves we note that at 10 degrees elevation, these values correspond to lower than 99% weather γ for Goldstone and between 97.5% and 99% weather γ for Madrid. Furthermore, as the elevation increases, both values become much less than 99% weather γ. This means that through most of a typical pass, the reliability of a standard X-band link is better 99% as far as

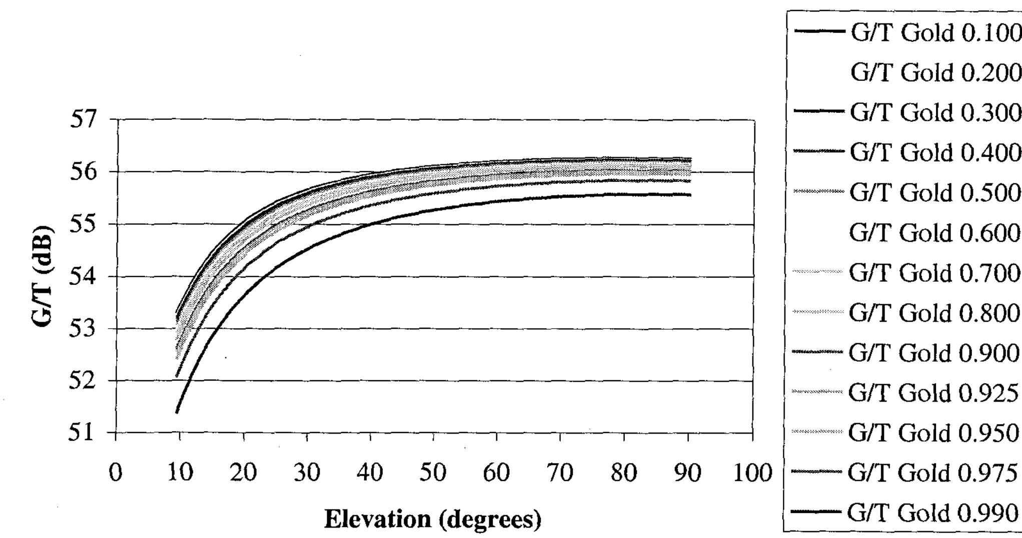

Figure 2a. X-band Tipping Curve, 34m BWG, Goldstone

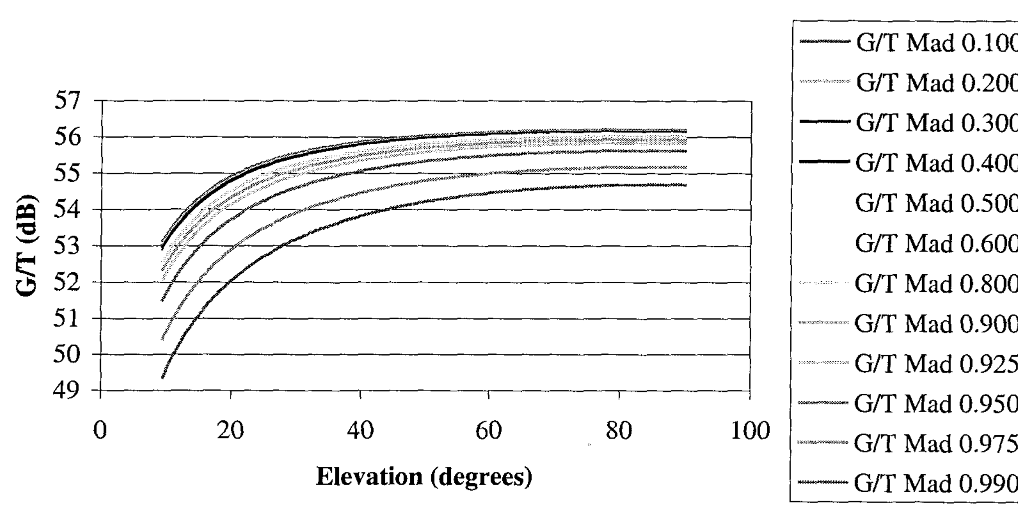

Figure 2b. X-band Tipping Curve, 34m BWG, Madrid

the weather is concerned.

If we apply the standard approach to a Ka-band link we observe that (figures 2c and 2d) the link closes with a γ of 53.4dB for Goldstone and 52.3dB for Madrid. Looking at figures 2c and 2d we note that at 10 degrees elevation, these values correspond to between 97.5% and 99% weather γ for Goldstone and between 95% and 97.5% weather γ for Madrid. This indicates that a Ka-band link designed in this fashion is less reliable than an X-band link.

Using the design γ values for the link at both X-band and Ka-band obtained through the standard approach, we can apply equations (4) and (6) from the previous section to establish the baseline performance of both X-band and Ka-band for each pass. These results are presented in Tables 1 through 4.

As we can see from these tables, the X-band link is extremely reliable. Ka-band link is also very reliable but not as reliable as the X-band link. Furthermore, the Ka-band data volume advantage is a constant 3.6dB for Goldstone and an almost constant 2.78dB for Madrid. Note that these values roughly correspond to the difference between the design γ for Ka-band and the design γ for X-band. This is due to the fact that at each site the reliabilities of both X-band and Ka-band for all the passes are near 100%. Therefore, the difference in data volume between the two bands is equal to the difference between the design γ values.

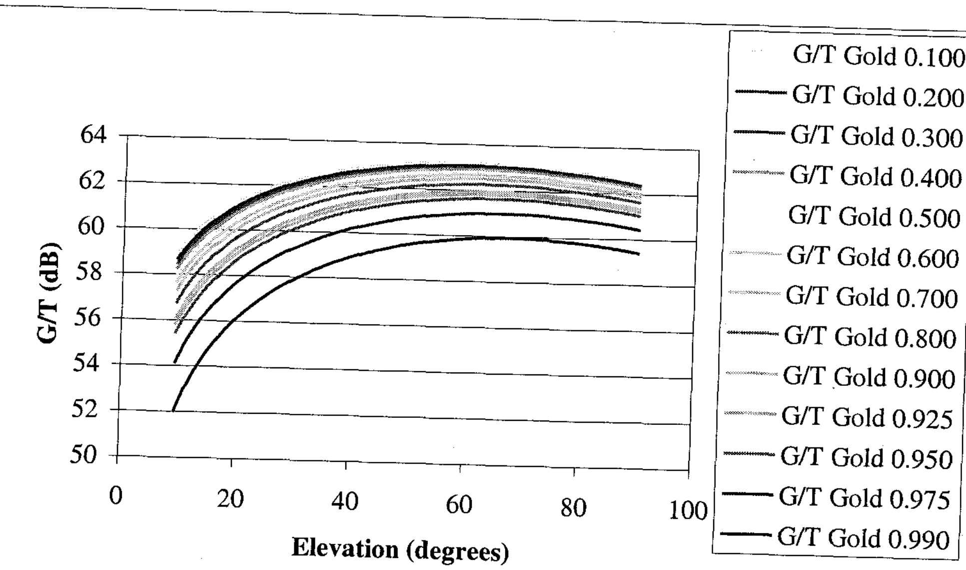

Figure 2c. Ka-band Tipping Curve, 34m BWG, Goldstone

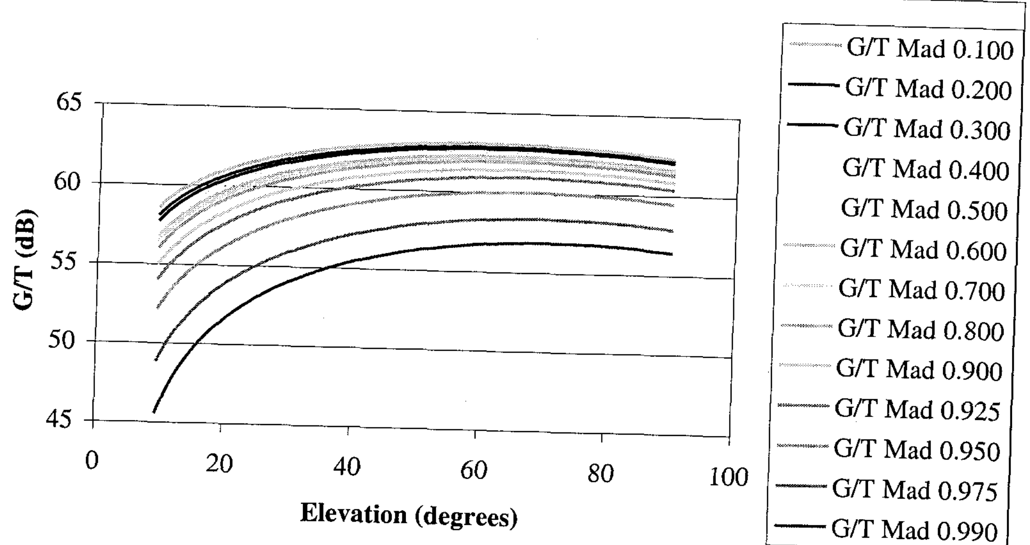

Figure 2d. Ka-band Tipping Curve, 34m BWG, Madrid

Obviously, compared to the potential 11.2dB performance advantage that Ka-band could offer over X-band, an advantage of 2.78dB to 3.6dB is disappointing. This is due to the fact that the standard approach is too conservative and sacrifices performance for reliability. In the next section we will show that by using the optimization method outlined in the previous section, this advantage could be increased by as much as 7dB.

TABLE 1. Ka-BAND AND X-BAND AVERAGE DATA RETURN, STANDARD LINK DESIGN, 34M BWG ANTENNA, GOLDSTONE

Pass	Ka-band (dB)	X-band (dB)	Ka-band Advantage (dB)
030	50.61	47.01	3.60
156	49.83	46.23	3.60
209	49.33	45.73	3.60
316	48.30	44.70	3.60

TABLE 2. Ka-BAND AND X-BAND AVERAGE DATA RETURN, STANDARD LINK DESIGN, 34M BWG ANTENNA, MADRID.

Pass	Ka-band (dB)	X-band (dB)	Ka-band Advantage (dB)
030	49.50	46.71	2.79
156	48.72	45.93	2.79
209	48.22	45.43	2.79
316	47.18	44.40	2.78

TABLE 3. Ka-BAND AND X-BAND AVAILABILITY, STANDARD LINK DESIGN, 34M BWG ANTENNA, GOLDSTONE.

Pass	Ka-band Availability	X-band Availability
030	>99%	>99%
156	>99%	>99%
209	>99%	>99%
316	>99%	99%

TABLE 4. Ka-BAND AND X-BAND AVAILABILITY, STANDARD LINK DESIGN, 34M BWG ANTENNA, MADRID.

Pass	Ka-band Availability	X-band Availability
030	>99%	>99%
156	>99%	>99%
209	>99%	>99%
316	>99%	99%

4. OPTIMIZED X-BAND AND Ka-BAND LINKS

As we saw in the previous section, the standard link design does not fully utilize, in terms of average data volume, the capabilities of the Ka-band link. In this section we apply the methodology developed in Section 2 to show the full advantage of a Ka-band link.

We have obtained the optimum values of γ for both X-band and Ka-band for both Goldstone and Madrid for each pass. The optimum Ka-band average data return was then compared to both the standard X-band link average data return and the optimized X-band link average data return. The results of this analysis are presented in Tables 5 through 8.

TABLE 5. γ_{opt} IN dB FOR GOLDSTONE AND MADRID, X-BAND AND Ka-BAND

Pass	γ_{opt}, Ka-band Goldstone	γ_{opt}, X-band Goldstone	γ_{opt}, Ka-band Madrid	γ_{opt}, X-band Madrid
030	61.4	53.5	61.2	53.4
156	61.2	53.4	60.9	53.3
209	60.8	53.3	60.5	53.1
316	59.9	52.8	59.4	52.6

TABLE 6. AVAILABILITY OF OPTIMIZED LINK, GOLDSTONE AND MADRID, X-BAND AND Ka-BAND

Pass	%Avail. Ka-band, Goldstone	%Avail. X-band, Goldstone	%Avail. Ka-band, Madrid	%Avail. X-band, Madrid
030	72.68%	85.42%	66.93%	83.83%
156	72.35%	85.68%	67.94%	83.77%
209	72.86%	84.57%	67.98%	84.28%
316	74.60%	88.68%	71.70%	87.66%

TABLE 7. OPTIMUM AVERAGE DATA RETURN FOR Ka-BAND AND X-BAND AND OPTIMUM Ka-BAND ADVANTAGE OVER OPTIMUM X-BAND AND STANDARD X-BAND IN dB, GOLDSTONE.

Pass	Optimum Ka-band	Optimum X-band	Ka-band Adv. over Opt. X-band	Ka-band Adv. over Std. X-band
030	57.27	50.07	7.20	10.26
156	56.27	49.21	7.07	10.04
209	55.40	48.55	6.85	9.67
316	53.58	47.23	6.35	8.88

TABLE 8. OPTIMUM AVERAGE DATA RETURN FOR Ka-BAND AND X-BAND AND OPTIMUM Ka-BAND ADVANTAGE OVER OPTIMUM X-BAND AND STANDARD X-BAND IN dB, MADRID.

Pass	Optimum Ka-band	Optimum X-band	Ka-band Adv. over Opt. X-band	Ka-band Adv. over Std. X-band
030	56.71	49.89	6.82	10.00
156	55.70	49.01	6.69	9.77
209	54.80	48.33	6.47	9.37
316	52.90	46.98	5.93	8.50

As we can see from these tables, for Goldstone, γ_{opt} for the Ka-band link is between 6.5dB and 8dB higher than the γ obtained by the standard link design approach. For Madrid, γ_{opt} is greater than standard design γ by between 7.1dB and 8.9dB. For X-band, γ_{opt} is greater than standard design γ by between 3dB to 3.7dB at Goldstone and between 3.1dB to 3.9dB at Madrid. We also note that link's average availability is much less under our optimization approach than it is under standard link design approach. For the same elevation profile the optimized link is less reliable at Madrid than it is at Goldstone. This is due to the fact that Madrid has worse weather than does Goldstone. Therefore, the weather is subject to greater variations, thus, making the Ka-band link less reliable than at Goldstone.

In return for this decrease in average availability, the average data return is increased over the standard link. For Ka-band, this increase is between 5.2dB and 6.7dB for Goldstone and between 5.7dB and 7.2dB for Madrid. For X-band, the increase in average data return is less. For Goldstone, this increase is between 2.5dB and 3dB and for Madrid this increase is between 2.5dB and 3dB. This indicates that a single rate optimized Ka-band link not only has an advantage over the standard X-band link in terms of average data return (between 8.5dB and 10.26dB), but it also is approximately 4 to 5 times (6dB to 7dB) better than a single rate optimized X-band link.

Ka-band Availability Revisited

As mentioned above in exchange for the increase in the average data return, the average availability of the link is substantially decreased for Ka-band. However, by looking at how the availability of a pass changes as the elevation changes, we notice that this decrease in availability is not as serious as one might think. Figures 3a and 3b show plots of $F(\gamma_{opt}, \theta(t))$ (defined by equation (2) above) vs. time for the four passes for Goldstone and Madrid, respectively. As these plots indicate, the reliability of an optimized Ka-band increases as the elevation increases and that a large fraction of each pass has a reliability of 90% or better. Since, statistically, most of the data return is received during the high reliability period of a pass, the link could be operated only at high reliability periods associated with high elevations without too much loss of data. Therefore, the Ka-band advantage could still be realized without too much decrease in the reliability of the link. Under such a scenario, instead of starting a pass at 10 degrees elevation, the pass starts at a higher elevation depending on instantaneous reliability requirements.

Note that such an approach requires calculation of a new γ_{opt} based on the instantaneous reliability requirements of the pass. Limiting the pass to the time that, for a given γ, the reliability of the pass is greater than a minimum required reliability, $p_{\min}$, makes the start time and the finish time of a pass into functions of γ and $p_{\min}$. Thus equation (4) has to be rewritten as:

$$V(\gamma) = \int_{t_s(\gamma, p_{\min})}^{t_f(\gamma, p_{\min})} \alpha \cdot \gamma \cdot F(\gamma, \theta(t)) \cdot dt \qquad (7)$$

and then optimized. (We have started the analysis of such an optimization, however, as of this writing the results are incomplete and thus, are not presented here.)

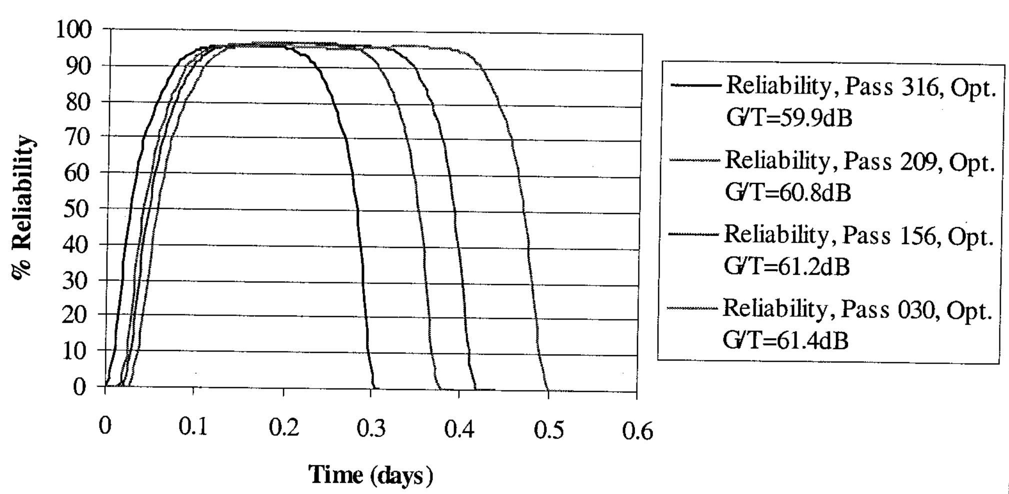

Figure 3a. Ka-band Link Reliability vs. Time, Optimized Link, 34m BWG Antenna, Goldstone

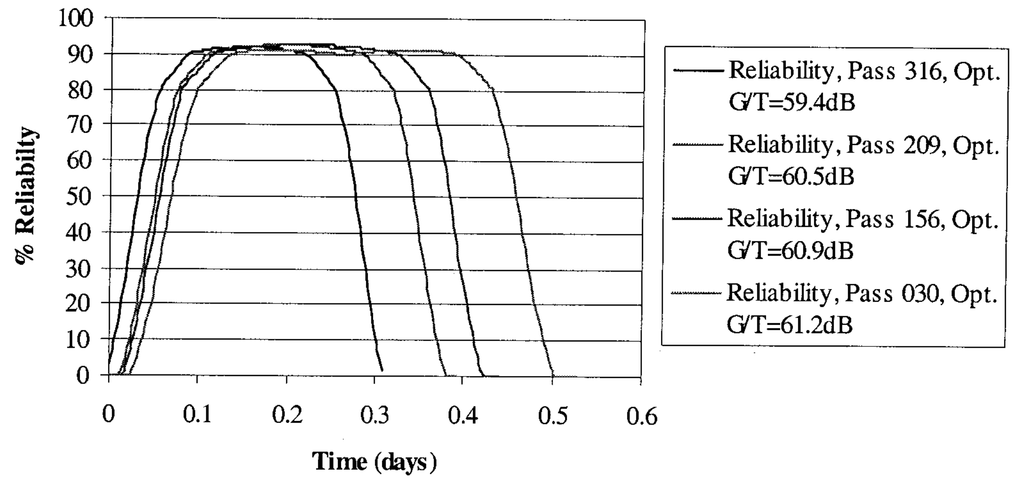

Figure 3b. Ka-band Link Reliability vs. Time, Optimized Link, 34m BWG Antenna, Madrid

5. CONCLUSIONS AND CAVEATS

Conclusions

In this paper we have introduced a method to optimize a single data rate Ka-band link to maximize the average data return over the link. Applying this method to four typical passes we have shown that an optimized Ka-band link on the average provides between 8.5dB and 10.3dB more data than a standard X-band link and between 5.9dB and 7.2dB more data than a similarly optimized X-band link. Our results also indicate that the optimized Ka-band link is much less reliable than either the standard or the optimized X-band link. However, this unreliability is limited to the beginning and the end of passes where the elevation is too low and the effects of atmosphere most severe on the Ka-band link.

Caveats

It should be noted that one reason that the standard X-band link does not offer as much data return as either of the optimized links (both X-band and Ka-band) is that in standard link design, 3dB of margin at 10 degrees elevation is allocated to keep the link robust and reliable. This 3dB not only guards against variations in the weather but also against such things as antenna mispointing and ground equipment malfunction. Our optimization method does not take into account such variations.

Furthermore, throughout this paper we have assumed that the received equivalent isotropic radiated power (EIRP) is the same for both frequencies. Therefore, all the analysis presented here is the result of the Ka-band ground system advantage over X-band. However, currently Ka-band amplifiers are less powerful and less efficient than X-band amplifiers, and due to the narrower antenna beam at Ka-band, the spacecraft antenna pointing losses are greater at Ka-band than they are at X-band. All these factors cut into the Ka-band advantage that is reported in this paper.

Finally, our optimization increases average data return at the expense of the reliability of the link. While not always stated, most links have a requirement for the continuity in the data. Because our optimized link is not very reliable, it will have a hard time meeting most data continuity requirements.

REFERENCES

[1] Shervin Shambayati, "Optimization of a Deep Space Ka-band Link Using Atmospheric-Noise-Temperature Statistics," *TMO Progress Report 42-139,* Jet Propulsion Laboratory, Pasadena, CA, November 15, 1999

[2] Koerner, M. A., "Relative Performance of 8.5-GHz and 32-GHz Telemetry Links on the Basis of Total Data Return per Pass," *TDA Progress Report 42-87,* Jet Propulsion Laboratory, Pasadena, CA, pp. 65-80, November 15, 1986.

[3] R. W. Sniffin, Ed., *DSMS Telecommunications Link Design Handbook (810-005, Rev. E),* Jet Propulsion Laboratory, Pasadena, CA, November 30, 2000

Shervin Shambayati obtained his Bachelors of Science degree in Applied Mathematics and Engineering in 1989 from California State University, Northridge. Subsequently, he obtained his MSEE and Engineer's Degree from University of California, Los Angeles in 1991 and 1993, respectively. In 1993, Mr. Shambayati joined Deep Space Communications Systems Group at Jet Propulsion Laboratory where he took part in development and testing of Deep Space Network's Galileo Telemetry receiver (DGT). In 1997, Mr. Shambayati joined the Information Processing Group at JPL where he has been working ever since. With

that group Mr. Shambayati has been involved in various projects including Mars Global Surveyor's Ka-Band Link Experiment II, Deep Space 1 Ka-band testing and 70m antenna Ka-band Task. Mr. Shambayati's current research interests are the effects of demodulation synchronization error on channel codes, Deep Space Network availability models, evaluation of Ka-band performance for Deep Space missions and optimization of modulation parameters for Deep Space missions.