

Deep-Space Ka-Band Flight Experience

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ABSTRACT. — Lower frequency bands have become more congested in allocated bandwidth as there is increased competition between flight projects and other entities. Going to higher frequency bands offers significantly more bandwidth, allowing for the use of much higher data rates. However, Ka-band is more susceptible to weather effects than lower frequency bands currently used for most standard downlink telemetry operations. Future or prospective flight projects considering deep-space Ka-band (32-GHz) telemetry data links have expressed an interest in understanding past flight experience with received Ka-band downlink performance. Especially important to these flight projects is gaining a better understanding of weather effects from the experience of current or past missions that operated Ka-band radio systems. We will discuss the historical flight experience of several Ka-band missions starting from Mars Observer in 1993 up to present-day deep-space missions such as Kepler. The study of historical Ka-band flight experience allows one to recommend margin policy for future missions. Of particular interest, we will review previously reported-on flight experience with the Cassini spacecraft Ka-band radio system that has been used for radio science investigations as well as engineering studies from 2004 to 2015, when Cassini was in orbit around the planet Saturn. In this article, we will focus primarily on the Kepler spacecraft Ka-band link, which has been used for operational telemetry downlink from an Earth trailing orbit where the spacecraft resides. We analyzed the received Ka-band signal level data in order to characterize link performance over a wide range of weather conditions and as a function of elevation angle. Based on this analysis of Kepler and Cassini flight data, we found that a 4-dB margin with respect to adverse conditions ensures that we achieve at least a 95 percent data return.

I. Introduction

Ka-band offers several advantages over lower frequency bands, such as wider spectrum allocation, higher antenna gain, and greater immunity to plasma effects. These make for possible increased telemetry performance and greater accuracy for navigation data types. Early deep-space Ka-band experiments and demonstration flights included Mars Observer, Mars Global Surveyor, Deep Space 1, and Mars Reconnaissance Orbiter. Mars Observer was the

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first demonstration of a deep-space communications link and had an active Ka-band campaign from 1993 to 1994 [1]. Mars Global Surveyor was launched in 1996 and had a comprehensive Ka-band campaign from 1997 to 1999 [2–5]. Mars Reconnaissance Orbiter (MRO) was launched in 2005 and had an active Ka-band campaign during cruise from late 2005 to early 2006 [6–10]. Among the highlights for MRO was achieving the highest Ka-band data rate ever from a planetary mission (6 Mbps). Deep Space 1 was launched in 1998 and was involved in very limited Ka-band studies, including acquiring Ka-band solar superior conjunction data at ~ 1 deg solar elongation [11].

More recently, a significant quantity of deep-space Ka-band observations from the Cassini and Kepler missions was analyzed to statistically infer atmospheric effects such as atmospheric attenuation and atmospheric noise temperature increase. A comprehensive study of the Cassini carrier signal strength data involved ~ 2 million closed-loop (1-s) observations acquired over ~ 10 years [12]. The Ka-band carrier level data were acquired at all three DSN tracking sites in order to characterize link performance over a wide range of weather conditions and as a function of elevation angle. Based on this analysis, we derived a baseline recommendation for a Ka-band link margin that flight projects may utilize in their preflight planning. Here we recommend a threshold assumption of 90 percent weather availability using statistics tabulated for the link budget weather parameters, and a margin of 4 dB to cover our perception of increased uncertainties at the 32-GHz Ka-band link frequency. We found that a 4-dB margin will ensure a ~ 95 percent data return at a minimum 20-deg elevation angle under 90 percent weather conditions at 32-GHz Ka-band.

The Kepler spacecraft makes use of a 0.85-m-diameter high-gain antenna (HGA) to transmit Ka-band signals to the ground at 32.166 GHz. The Ka-band transmitter provides 47.1 W of RF power through lumped circuit loss of 0.98 dB. The Deep Space Network (DSN) ground antennas make use of the Ka-band-capable 34-m-diameter beam-waveguide (BWG) subnet consisting of stations at Goldstone, California; Madrid, Spain; and Canberra, Australia. A telemetry modulation index of 72.3 deg was used in the link budget calculations. The spacecraft is in an Earth-trailing orbit where the range distance varied from 0.2 AU to 0.92 AU during the period the data were acquired that are reported on in this article.

We will discuss recommendations for projects with regard to Ka-band margin policy and thresholds. We focused on the adverse link curves providing a boundary from which we can inspect the number of P_c/N_0 measurements that lie below these curves. We considered various potential margins relative to the adverse link curves versus the respective fraction of the acquired data lying above the margin curves for each tracking site. This is with the intent of identifying which particular margin might provide an acceptable loss fraction as a baseline recommendation. Flight projects can then utilize margins that are larger or smaller depending upon on flight scenarios, defined threshold conditions, and uncertainties in link parameters.

II. Cassini Ka-Band Data Analysis

Over 2 million individual carrier signal-to-noise density (P_c/N_0) measurements from all three tracking sites were used to evaluate statistics due to atmospheric effects. From 187 tracking

passes (out of ~250), data were used in the statistical characterization discussed in [12]. The majority of the ~63 tracking passes removed from the statistical characterization were solar conjunction passes where charged-particle degradation was significant or dominant at low solar elongation angles.

For Cassini, we found that 99.6 percent of the data lie above the 4-dB margin curve (with respect to adverse link assumptions) for Goldstone, 98.6 percent for Canberra, and near 95 percent for Madrid. We believe the majority of the data points that lie below the 4-dB margin curves are due to weather-related degradation. Weather-related degradation to the P_c/N_0 measurements usually includes atmospheric attenuation and atmospheric noise temperature increase. However, other sources of weather-related degradation include those due to wind and thermal gradient radiation effects on the antenna structure. The thermal degradation causes differential structural distortion that gives rise to additional pointing errors in which proposed solutions are currently being evaluated.¹ A smaller percentage of these data lying below the 4-dB margin curve could be attributable to spacecraft pointing issues. As there are over 10 years of data from the various stations, we speculate that bad weather occurrences may have been undersampled for Goldstone and Canberra, given the high percentages of data lying above 4-dB margin. This would be relative to Madrid, which has a lower percentage of data points above the 4-dB margin curves where bad weather may have been oversampled. However, for all three sites, 95 percent or better of the data lie above the 4-dB curve, suggesting that this is a reasonable margin for preflight planning for projects or programs that may consider using Ka-band telecommunication links. We stress the point that this recommended margin was based on the analyses involving Cassini-specific flight experience [12]. Projects may then opt to adjust this margin up or down as they define their threshold conditions, gain more understanding of their requirements as their design evolves, and their link parameter uncertainties tighten.

If we normalize all the data discussed in the Cassini study to a common range distance, we find that the dispersion bands of the data are reduced somewhat [12]. Once we redraw the favorable and adverse link curves and perform the same analysis, we find that the percentages of the data lying above the 4-dB curves are a little lower but similar: 98 percent for Goldstone, 97 percent for Canberra, and 94 percent for Madrid. Here we believe that these results are somewhat more conservative than the results without range adjustments as they may include some additional data points hindered more by mispointing than by atmosphere.

III. Kepler Ka-Band Data Analysis

The data reported here include closed-loop data acquired from 102 DSN tracking passes that accommodate Ka-band downlink; DSS-25 at Goldstone, California (20 passes), DSS-26 at Goldstone, California (24 passes), DSS-54 at Madrid, Spain (13 passes), DSS-55 at Madrid, Spain (21 passes), DSS-34 at Canberra, Australia (15 passes), DSS-35 at Canberra, Australia (6 passes), and DSS-36 at Canberra, Australia (3 passes) at 5-s sampling resolution. The

¹ David Rochblatt, personal communication, Jet Propulsion Laboratory, Pasadena, California, November 9, 2017.

data set spans from 2010-356² to 2017-149 excluding data acquired from September 2013 through all of 2015, when the spacecraft was on thrusters during Ka-band data downlink operations. The thrusters induce huge variations (>10 dB) into the received Ka-band signal data from the induced attitude disturbances, thus making characterization of any atmospheric effects very difficult and time consuming if not impossible. For data acquired prior to 2010-356, the Kepler project had archived the high-resolution data (sampled every 5 s). However, these data were not assessable for this study. A previous study on a limited Kepler Ka-band data set (2012 data only) was conducted by others [13].

The range distance over the observations varied from 0.19 AU near the beginning of the data sets used (2010) to about 0.93 AU in 2016, resulting in a spread of 13.7 dB in space loss between the observations. Accordingly, we adjusted all Kepler P_c/N_0 measurements to a common range distance of 0.7895 AU to allow for an equitable comparison between observations. This is in contrast to the 2.8-dB spread in observations due to differences in space loss for Cassini due to the Earth–Saturn distance extremities experienced from a maximum range distance of ~11 AU to the minimum of ~8 AU. Consequently, the adverse and favorable link curves for the Cassini analysis took into account these extremities in range distance when plotted against the raw P_c/N_0 measurements [12]. The statistics for the Cassini data adjusted to a common range distance was also discussed in that study [12].

In addition to the P_c/N_0 observations that were examined as a function of elevation angle, we also compared these against link budget predictions based on the best available spacecraft parameters and ground station parameters [14,15]. We maintained the same Kepler spacecraft parameters throughout for the link budgets such as transmit power, passive losses, antenna gain, and pointing loss. The pointing loss used in the link budgets for the Kepler HGA was derived based on a pointing error of 0.02 deg, which utilized a pointing strategy that employed two working reaction wheels.³

A. Goldstone Ka-Band Data Analysis

There were at 131108 observations of Ka-band downlink P_c/N_0 acquired over 44 tracking passes acquired from the two Goldstone Ka-band stations DSS-25 and DSS-26 (see Table 1).

Figure 1 displays P_c/N_0 versus elevation angle for all the DSS-25 observations (colored data points; see legend). Also shown are the curves based on the favorable link budget assumptions (solid black) (nominal atmosphere and monopulse tracking at the ground station), adverse link budget assumptions (solid red) (90 percent weather and non-monopulse ground station tracking), and that based on a 4-dB margin lying below adverse link assumptions (dashed yellow).

The favorable link budget curve (solid black line) in Figure 1 hugs the top of the envelope of the observations, suggesting confidence in the link assumptions during the most favorable conditions (minimal weather effects and monopulse enabled pointing). The adverse link (solid red curve) assumes 90 percent weather and the use of blind pointing at the ground station. Note that many points still lie below this curve, consistent with instances

² The designation “2010-356” refers to the year 2010 and day of year 356.

³ Marcie Smith, personal communication, NASA Ames Research Center, Moffett Field, California, July 18, 2017.

Table 1. Kepler and Cassini P_c/N_0 statistics.

Goldstone			
Spacecraft	Number of Observations	Number of Observations >4 dB Curve	Percent >4 dB Curve
Cassini [1]	730922	715738	97.92
Kepler [2]	131108	124889	95.26
Total	862030	840627	97.52
Madrid			
Cassini [1]	832745	785738	94.36
Kepler [2]	142101	139751	98.35
Total	974846	925489	94.94
Canberra			
Cassini [1]	527328	512100	97.11
Kepler [2]	86793	83362	96.05
Total	614121	595462	96.96

[1] From Cassini study with observations normalized to common range distance [12].
 [2] Usable Kepler data from 2010 to 2017 normalized to common range distance.

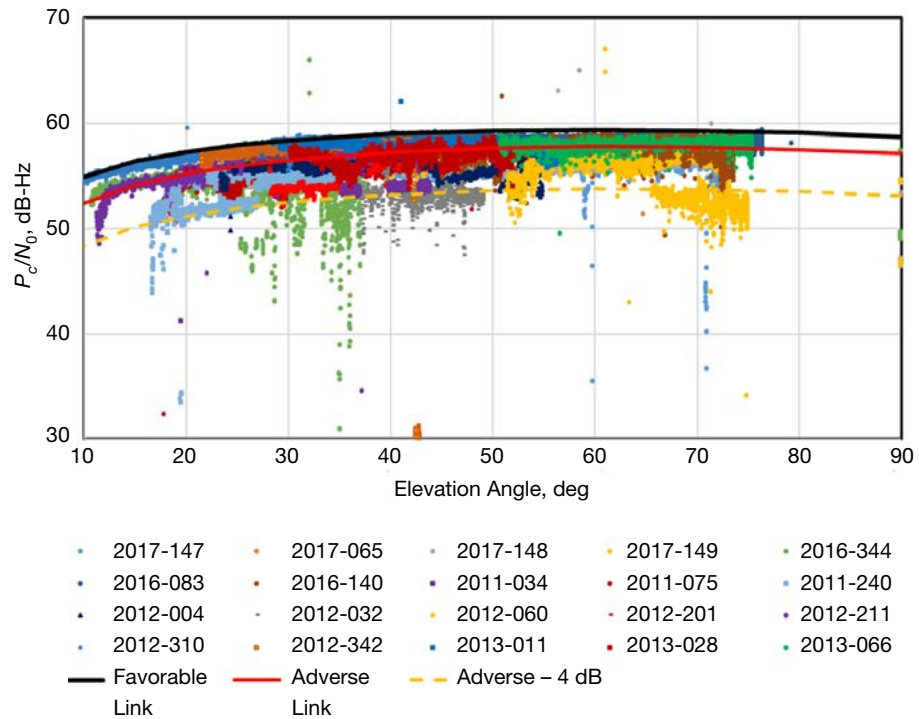


Figure 1. P_c/N_0 versus elevation angle for DSS-25 observations (individual data points) along with Favorable, Adverse, and “Adverse - 4 dB” link curves (solid and dashed curves) — see legend.

of station (or spacecraft) mispointing or equipment issues beyond that specified in the link assumptions, as well as instances when weather effects exceed 90 percent.

The 4-dB curve lying below the adverse curve (dashed yellow curve in Figure 1) was plotted in a similar manner as was done in the Cassini Ka-band study [12]. It is believed that most of the data dominated by non-atmospheric effects lie above the 4-dB margin curve in Figure 1. The vast majority of the data points lying below the 4-dB curve are believed to be mostly due to degradation due to weather (with possible contribution due to non-weather effects). About 95 percent of the data points lie above the 4-dB margin curve. We can compare this with the 97.5 percent of the data points that were found to lie above the 4-dB curve for the Cassini analysis for DSS-25 [12].

Pass 2016-344 (scattered green data points lying below the dashed yellow curve in Figure 1) was characterized by high wind speeds and monopulse being alternatively enabled and disabled. This pass had a high percentage of data points lying below the 4-dB margin curve (see Figure 1 between 25 and 38 deg elevation).

Figure 2 displays the received P_c/N_0 signal level data of the Kepler closed-loop Ka-band data from DSS-26 as a function of elevation angle for 24 tracking passes (see legend). Also shown

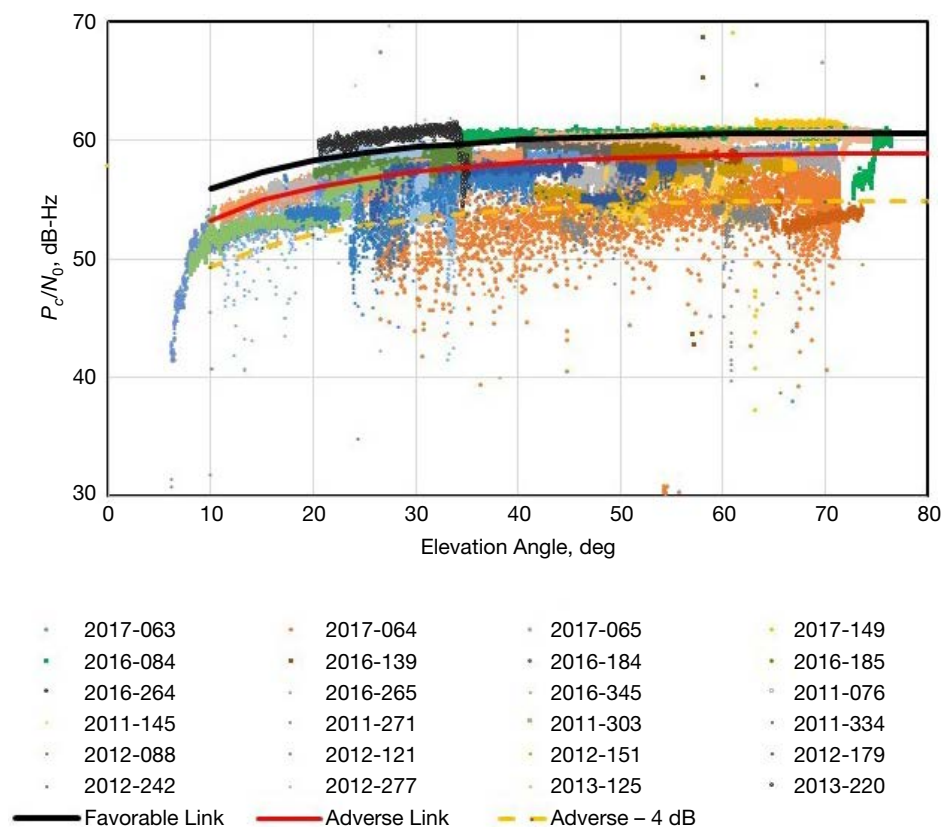


Figure 2. P_c/N_0 versus elevation angle for DSS-26 observations (individual data points) along with Favorable, Adverse, and “Adverse - 4 dB” link curves (solid and dashed curves) — see legend.

are the curves based on the favorable link budget (solid black) parameters (nominal atmosphere and monopulse tracking at the ground station), and adverse link budget (solid red) parameters (90 percent weather and non-monopulse tracking). Also shown is the curve corresponding to a 4-dB margin lying below the adverse link curve (dashed yellow).

The favorable link budget curve (solid black line) hugs the top of the envelope of most of the observations, suggesting confidence in the link assumptions during the most favorable conditions (minimal weather effects and monopulse enabled pointing at the ground station). However, there are some data points that lie ~1 to 2 dB above the favorable curve, such as from pass 2013-220, suggesting some change somewhere in the flight or ground configuration differing from the link assumptions. The adverse link (solid red curve) assumes 90 percent weather and the use of blind pointing at the ground station. Note that many points still lie below this curve; however, there may be issues with station (or spacecraft) pointing or equipment as well as instances when weather effects exceed 90 percent. Most notably, there were significant wind speeds experienced during pass 2017-064 (orange data points in Figure 2) where the wind speeds were close to the limit for stowing the antenna. The 4-dB curve lying below the adverse curve (dashed yellow) was derived in a similar manner as was done in the Cassini study [12]. Most of the data points lying below the 4-dB margin curve (see Figure 2) are possibly due to atmospheric degradation, with perhaps a smaller contribution of unknown pointing loss not covered in the link assumptions.

About 95 percent of the Goldstone Ka-band data points lie above the 4-dB margin curve (compare with 98 percent for the Cassini analysis stations [12]; see Table 1).

B. Madrid Ka-Band Data Analysis

There were 142101 observations of P_c/N_0 acquired over 34 tracking passes acquired from the two Madrid Ka-band stations DSS-54 and DSS-55 (see Table 1).

Figure 3 displays the received closed-loop Ka-band P_c/N_0 data from DSS-54 as a function of elevation angle. Also shown are the curves based on the favorable link budget assumptions (solid black) (nominal atmosphere and monopulse tracking at the ground station), adverse link budget assumptions (solid red) (90 percent weather and non-monopulse tracking), and the curve based on 4-dB margin below adverse link assumptions (dashed yellow). About 98 percent of the P_c/N_0 measurements lie above the 4-dB margin curve.

One pass in particular displays significant rain fade features in Figure 3 (2016-186 purple points). As seen in the P_c/N_0 versus time signature for this pass (see Figure 4), the fades in P_c/N_0 (blue points) are clearly anti-correlated with large excursions in system noise temperature (SNT) (brown points), reminiscent of atmosphere. In addition, fades seen in P_c/N_0 for another pass 2017-148 (orange points in Figure 3 near ~65-deg elevation angle) are also atmospheric in nature.

Similar results were observed for the other Madrid Ka-band-capable downlink station, DSS-55 (see Figure 5).

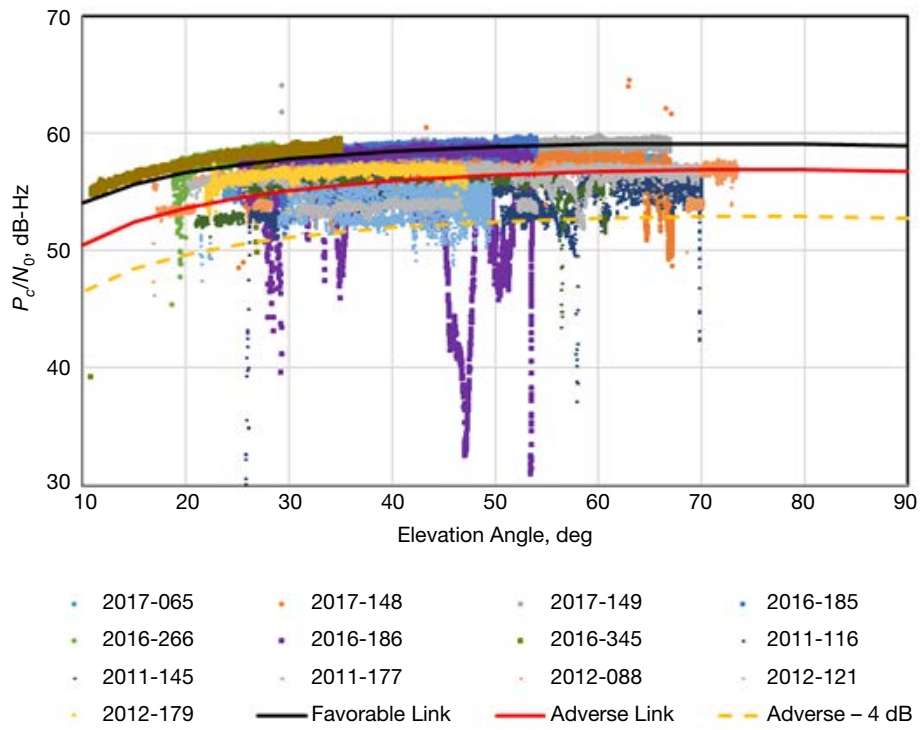


Figure 3. P_c/N_0 versus elevation angle for DSS-54 observations (individual data points) along with Favorable, Adverse, and “Adverse – 4 dB” link curves (solid and dashed curves) — see legend.

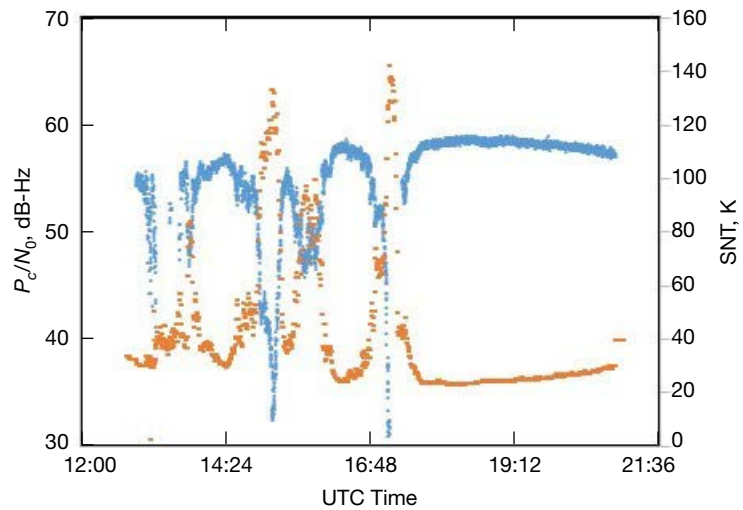


Figure 4. Individual pass P_c/N_0 and SNT versus time for DSS-54 conducted on 2016-186 clearly showing strong anti-correlation between P_c/N_0 and SNT.

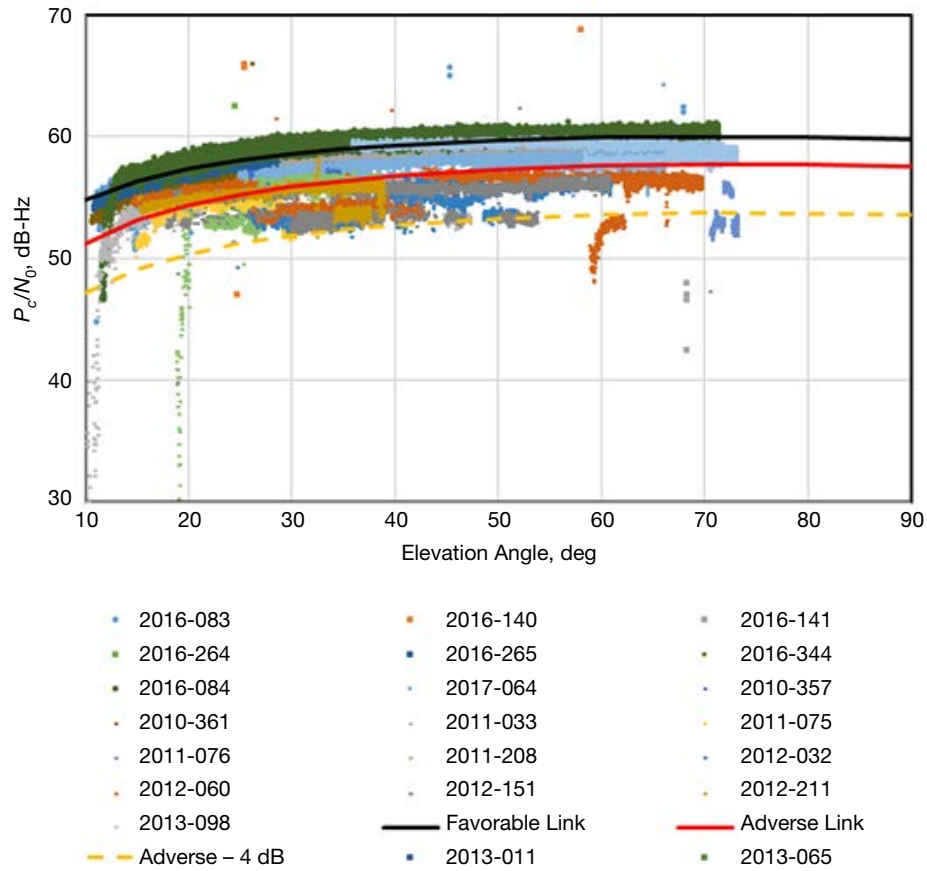


Figure 5. P_c/N_0 versus elevation angle for DSS-55 observations (individual data points) along with Favorable, Adverse, and “Adverse – 4 dB” link curves (solid and dashed curves) — see legend.

The favorable link budget curves for DSS-54 and DSS-55 hug the top of their envelopes for most of the observations, suggesting confidence in the link assumptions during the most favorable conditions (minimal weather effects and monopulse enabled pointing at the ground station). However, there are some data points that lie about 1 to 2 dB above the favorable curve for about three of the tracking passes deviating from the favorable link assumptions. The adverse link (solid red curve) assumes 90 percent weather and the use of blind pointing at the ground station. Many data points lie below these curves; however, there may be issues with station (or spacecraft) pointing or equipment as well as instances when weather effects exceed 90 percent. The 4-dB curve lying below the adverse curve was generated in a similar manner as was done for the Cassini study [12]. It is believed that most of the data dominated by non-atmospheric effects lie above the 4-dB margin curves. The vast majority of the data points lying below the 4-dB curve are believed degraded by weather effects.

About 99 percent of the measured P_c/N_0 data lie above the 4-dB margin curve for DSS-55 versus the 97.6 percent for DSS-54. About 98 percent of the Madrid data points lie above the 4-dB margin curve (compare with 94 percent for the Cassini analysis for the Madrid Ka-band stations [12]; see Table 1).

C. Canberra Ka-Band Data Analysis

Figure 6 displays the received P_c/N_0 closed-loop Ka-band data from DSS-34 as a function of elevation angle for 15 tracking passes. All the measurements were adjusted to a common range distance of 0.7895 AU, to allow for equitable comparison. We also maintained the same Kepler spacecraft parameters throughout for the link budgets such as transmit power, passive losses, antenna gain, pointing loss, etc. Also shown are the curves based on the favorable link budget assumptions (solid black) (nominal atmosphere and monopulse tracking at the ground station), adverse link budget assumptions (solid red) (90 percent weather and non-monopulse tracking), and the curve denoting 4-dB margin lying below that of adverse link assumptions (dashed yellow). About 98 percent of the DSS-34 P_c/N_0 measurements lie above the 4-dB margin curve.

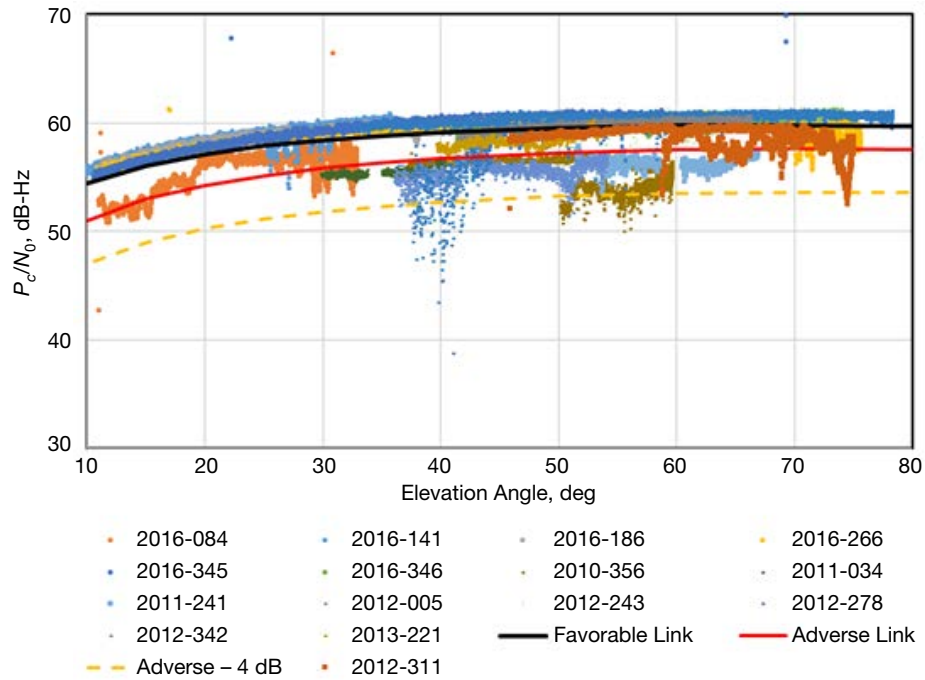


Figure 6. P_c/N_0 versus elevation angle for DSS-34 observations (individual data points) along with Favorable, Adverse, and “Adverse – 4 dB” link curves (solid and dashed curves) — see legend.

The favorable link budget curve (solid black line) hugs the top of the envelope for many of the observations, suggesting confidence in the link assumptions during the most favorable conditions (minimal weather effects and monopulse enabled pointing at the ground station). However, there are some data points that lie about 1 to 2 dB above the favorable curve, such as from passes 2012-078, 2016-141, 2016-186, 2016-266, and 2016-345. The fact that these passes lie in succession to each other in time (2016-141 to 2016-345) seems to suggest a possible change somewhere in the ground or spacecraft configuration deviating from the link assumptions in the favorable direction.

The adverse link (solid red curve) assumes 90 percent weather and the use of blind pointing at the ground station. Many data points still lie below this curve; however, there may be

issues with station (or spacecraft) pointing or equipment as well as instances when weather effects exceed 90 percent.

The 4-dB curve lying below the adverse curve (dashed yellow curve) was plotted in a similar manner as was done in the Cassini Ka-band study [12].

Data acquired from Canberra Ka-band stations DSS-35 (Figure 7) and DSS-36 (Figure 8) show similar results. Pass 2016-265 for DSS-35 showed significant P_c/N_0 signal level variations (see Figure 9), which were strongly anti-correlated with the SNT measurement variations, suggesting atmospheric effects. Measurements from other DSS-35 and DSS-36 passes that lie below the -4 dB curves are likely due to atmospheric degradation, as suggested from SNT and concurrent weather data from the site (see Figure 10 for pass 2017-064 conducted at DSS-36).

About 96 percent of the data points from all three Canberra stations (DSS-34, DSS-35 and DSS-36) lie above the 4-dB margin curve (see Table 1). We can compare this with 97 percent for the Canberra Ka-band stations from the Cassini analysis [12] (see Table 1).

IV. Combined Cassini and Kepler Ka-Band Analysis Results

The statistics from all of the applicable delivered data sets from both Cassini and Kepler are summarized in Table 1. The Cassini results obtained from the previous study [12] were converted to a common range distance to allow for an equitable comparison. We see that the statistics are reasonably comparable. We expect to add to this database as more Ka-band observations are gathered and processed from other missions such as Juno and Mars Reconnaissance Orbiter.

Normally we would assume that a 4-dB margin below 90 percent weather conditions would result in a much higher than 95 percent data return based on statistics characterizing atmospheric attenuation and atmospheric noise temperature increase for the deep-space case [14]. However, we hypothesize that some of the data points may have been reduced due to pointing errors or equipment issues beyond that of raw atmospheric effects covered in the link budget assumptions. We also do not want to exclude the possibility that some of this degradation was due to pointing errors induced by differential thermal radiation on the antenna structure.⁴ This additional weather-related effect is not accounted for in the link budget assumptions. This effect is another focus for future study where the data sets will be analyzed to assess day/night correlations. Wind loss may also play a role; however, many of the Lunar Reconnaissance Orbiter (LRO) data sets were also plagued by wind effects at White Sands, but that data set still yielded a 99 percent return below its 3-dB margin curve [16]. We expect that the LRO pointing accuracy for both the LRO spacecraft and White Sands ground station antennas was consistent with link budget assumptions based on that study [16]. We suspect that the Cassini and Kepler data sets were sometimes plagued by higher than nominal pointing errors either at the spacecraft or ground station,

⁴ David Rochblatt, personal communication, Jet Propulsion Laboratory, Pasadena, California, November 9, 2017.

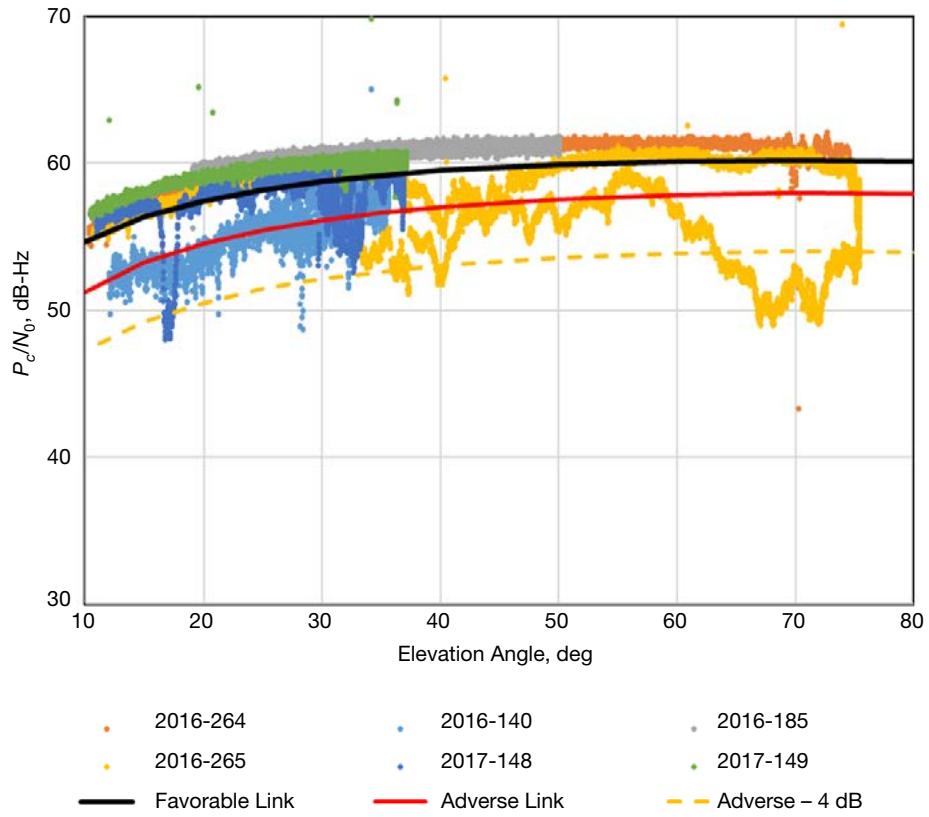


Figure 7. P_c/N_0 versus elevation angle for DSS-35 observations (individual data points) along with Favorable, Adverse, and “Adverse - 4 dB” link curves (solid and dashed curves) — see legend.

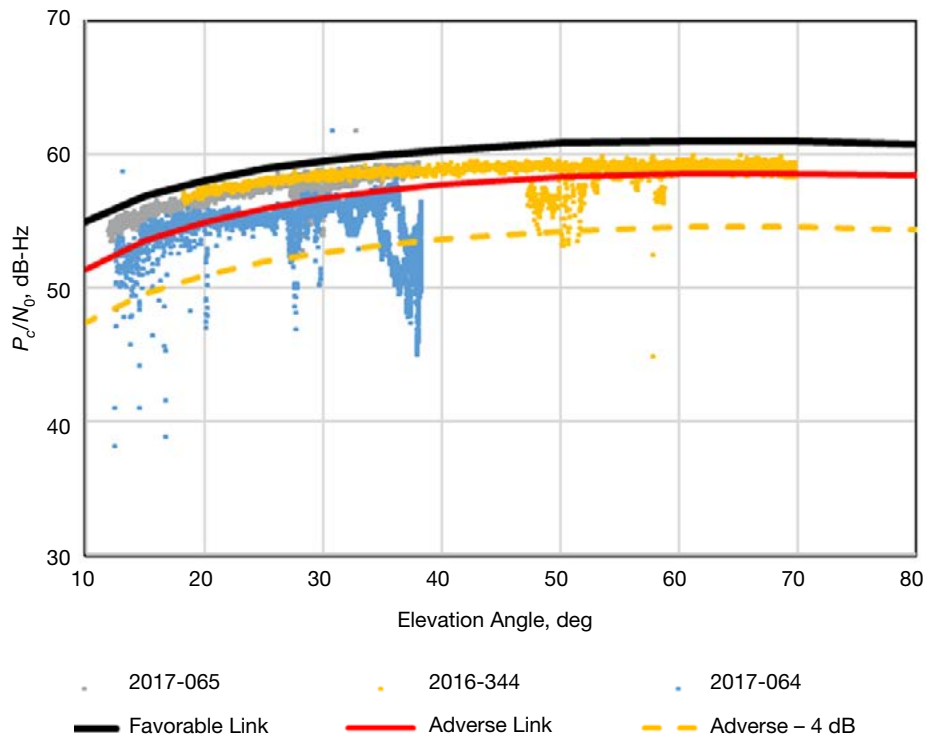


Figure 8. P_c/N_0 versus elevation angle for DSS-36 observations (individual data points) along with Favorable, Adverse, and “Adverse - 4 dB” link curves (solid and dashed curves) — see legend.

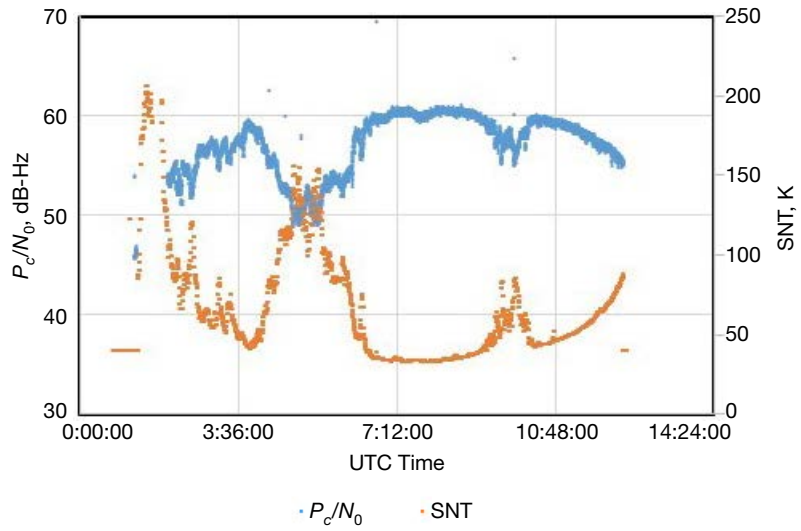


Figure 9. Individual pass P_c/N_0 and SNT versus time for DSS-35 conducted on 2016-265 clearly showing anti-correlation between P_c/N_0 and SNT.

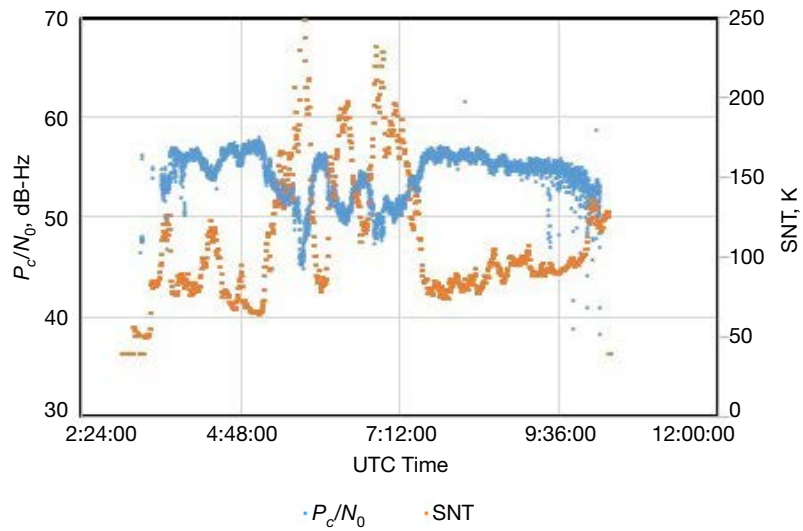


Figure 10. Individual pass P_c/N_0 and SNT versus time for DSS-36 conducted on 2017-064 clearly showing anti-correlation between P_c/N_0 and SNT.

except for those instances where we found some passes having better than 1 to 2 dB signal P_c/N_0 beyond favorable link assumptions. For those few tracks, the cause of the favorable discrepancy remains unknown.

V. Conclusion

This article reports on the analysis findings of received signal strength from the Kepler mission collected between 2010 and 2017 from all three DSN complexes. We analyzed these data to characterize link performance over a wide range of weather conditions, season, and as a function of elevation angle. These results, together with the previously analyzed Cassini results, show that a 4-dB margin with respect to adverse link budget assumptions will ensure at least 95 percent data return under 90 percent weather conditions at 32 GHz (Ka-band). Upon examination of the data, one finds that this 4-dB margin is applicable over all elevation angles from 10 deg and above. Most prospective deep-space missions considering Ka-band links may use a minimum 20-deg elevation angle in their design. However, missions that may have more power margin, perform data rate stepping versus elevation angle, or are considering other nonstandard techniques may opt to go down to 10 deg as their minimum elevation angle. Although this is just a baseline recommendation, flight projects might opt to consider other link margins in their design as more information becomes available, as uncertainties of non-atmospheric link parameters are reduced, or as a function of mission phase.

The results of a companion article in this volume showed that for LRO, a 3-dB margin will ensure a ~99 percent data return under 95 percent weather conditions at 26 GHz (K-band) over all elevation angles above 10 deg for the White Sands, New Mexico, near-Earth network tracking site [16].

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