Performance Analysis of Operational Ka-band Link with Kepler

Timothy Pham, Jason Liao
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California, USA
e-mails: Timothy.Pham@jpl.nasa.gov Jason.Liao@jpl.nasa.gov

***Abstract* - This paper presents some observations on the signal behavior from an analysis of Kepler Ka-band link. The goal is to characterize the link performance with operational data obtained from the Deep Space Network (DSN) tracking of Kepler spacecraft. Kepler is the first mission supported by the DSN that uses Ka-band as a primary means to return science data. We examine how operational data may differ from the expectation. Operational data often show many surprises where data variations occur without an apparent cause. We try to quantify the signal power fluctuation so that future missions can adequately plan for the link design, especially for missions that operate with lower margin. We also attempt to quantify the effect of rains/heavy clouds and high winds.**

Keywords - DSN; performance analysis; weather statistics; Kepler; Ka-band operations

I. INTRODUCTION

The National Aeronautics and Space Administration (NASA) Deep Space Network (DSN) serves as a communications infrastructure to enable mission controllers communicate with their spacecraft exploring the outer space. The DSN currently comprises of 13 antennas operating at multi-frequency of 2 GHz S-band, 8 GHz X-band and 26 GHz & 32 GHz Ka-band. The majority of 30-plus missions supported by the DSN use X-band. A few still use the narrower S-band while some are moving to the new broader Ka-band. Compared to X-band operation, Ka-band offers missions greater bandwidth that better supports higher data rates. The International Telecommunications Union allocates about 500 MHz for deep space Ka-band (32 GHz) and 1.5 GHz for the near Earth Ka-band (26 GHz), compared to 45 MHz each for deep space and near Earth X-band. Ka-band operation also offers roughly 5.5 dB advantage in the signal-to-noise ratio (SNR) performance, compared to the X-band operation, assuming the same transmitting power [1]. The 5.5 dB advantage is a result of a higher antenna gain at Ka-band due to greater operating frequency, mitigated by the higher system noise temperature.

Kepler mission is the first deep space mission that uses the 32-GHz deep space Ka-band as an operational link for telemetry return. The higher link performance, afforded by a higher SNR compared to the X-band link, allows for faster data downlink and enables spacecraft to devote more time on the collection of science data. Although Ka-band downlink was also conducted on some earlier missions, such as the Mars Global Surveillance (MGS) and Mars Reconnaissance Orbiter (MRO), it was only for the purpose of technology demonstration - X-band was still the primary link for telemetry return. Two other ongoing missions - Cassini and Juno – has Ka-band signal, but it is a carrier only (without modulated telemetry) for the purpose of conducting radio science investigations. The received carrier's power, frequency and phase are used to infer the characteristics of planetary medium that the signal traverses.

Kepler mission has the advantage of operating at high SNR. Its healthy designed link margin, in the range of 4-5 dB, provides greater buffer to the impact of inclement weather. Other Ka-band missions to be launched in the near future, such as the Solar Probe Plus, will be operating at a much lower link margin. Thus, there is a strong interest in characterizing the link performance and signal fluctuation for better link design for future missions.

In this paper, we examine the data collected from Ka-band tracking of Kepler over yearlong period and try to provide the answer to these questions:

(1) What is the typical variation in the signal SNR from one tracking pass to the next?

(2) How often does rain negatively affect the link and cause data outage? How does the link behave in the presence of rains or heavy clouds?

(3) How often does high wind affect the antenna pointing and thus the link performance? How much degradation does the signal experience?

(4) What is the cumulative probability distribution of the signal fluctuation?

In Section II, we briefly describe the Ka-band operations of Kepler mission. General observations of the received signal characteristics, especially their variation from pass to pass, are discussed in Section III. Passes affected by the rain or cloud and high wind are discussed in Section IV and Section V, respectively. Section VI examines the statistics of signal power fluctuation. Conclusions are captured in Section VII.

II. KA-BAND OPERATIONS

The DSN has three tracking complexes spread evenly across the Earth longitudes in order to maintain a constant visibility with spacecraft in deep space. The three complexes are named the Goldstone, Canberra and Madrid Deep Space Communications Complexes, based on its location in the United States, Australia and Spain. The majority of the antennas are 34-m, with one 70-m at each site. Goldstone Complex currently has five operating antennas devoted to spacecraft tracking. Madrid and Canberra Complex each has four antennas. Within each complex, two 34-m antennas are equipped with 32-GHz Ka-band reception that can be used to support Kepler and other missions, such as Cassini and Juno. For a complete description, the DSN also supports the 26-GHz near-Earth Ka-band with one 34-m antenna at each complex. The near-Earth Ka-band is relevant to some near future missions, such as the Transiting Exoplanet Survey Satellite (TESS) in 2017 and the James Webb Space Telescope (JWST) in 2018. The analysis of this paper is done with the 32 GHz Kepler data; however, the findings should be applicable to the operations at 26-GHz near-Earth Ka-band due to spectral proximity.

The Kepler spacecraft uses two different frequencies, X- and Ka-band, for return telemetry data. The spacecraft relies on X-band for the return of low-rate spacecraft engineering data (up to 16 kbps) and for radiometric measurement (e.g., Doppler and ranging). X-band tracking occurs every three or four days, more often than Ka-band tracking. Once a month, when the science data buffer onboard spacecraft is nearly full, Kepler spacecraft would turn its Ka-band high gain antenna to Earth and downlink the high-rate science data (up to 4.3 Mbps) that are collected over the month-long observations. The Ka-band downlink sessions last several hours and typically take place over two DSN complexes. X-band data are also received concurrently with Ka-band. The dual-frequency links offer an opportunity to validate the observed signal fluctuation. If it is caused by common source of errors, such as bad weather or pointing problem on the ground or flight antenna, the effect would show up in both links, with a smaller effect expected on the lower X-band frequency link.

III. Signal Variations

In this section, we look at the performance characteristics of Kepler Ka-band passes. Figure 1 shows the link characteristics of all Ka-band passes in 2012. For each pass, the average telemetry symbol SNR (SSNR) and associated standard deviation, the observed SSNR minima and maxima are plotted. The label "DOYxx/DSS-xx" indicates the day of year (DOY) the pass took place and the antenna – Deep Space Station (DSS) – used for tracking (Goldstone: DSS-25 and -26; Canberra: DSS-34 and -35; Madrid: DSS-54 and -55).

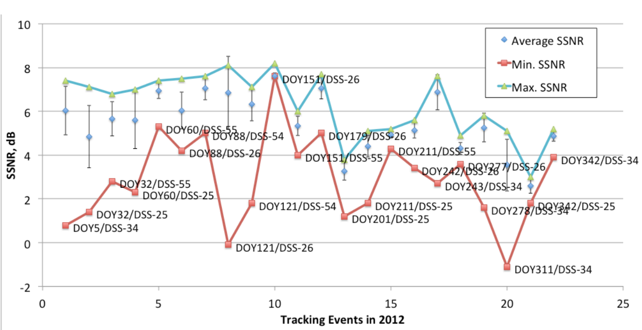

Figure 1. SNR characteristics of Kepler Ka-band passes

The data reflect the following observations:

1. The average SSNR varied quite significantly among the passes, as much as 4.8 dB (2.3 dB - 7.1 dB). Some factors affecting the variation are:
   (a) There is some performance difference among the DSN antennas used for the tracks.
   (b) Tracking passes are done at different elevation, as dictated by the selected antenna and the time of actual downlink within the pass. This results in different system noise temperature level.
   (c) Different data rates are used in the downlink, which affects the signal energy and thus, the symbol SNR.
   (d) Change in the spacecraft range from Earth.
   (e) Potential degradation from the rains/clouds or winds.

One could theoretically normalize these geometric and link variations among the data of different passes to remove the effect of factors (b), (c) and (d). That would have resulted in a smaller variation, leaving just the effect of factors (a) and (e) remained. As a note, we estimate that the variation due to the ground and spacecraft antenna pointing error was small (less than 0.2 dB) because of the active conical scanning tracking used in the ground antenna pointing and because of spacecraft pointing precision driven by stringent science objectives.

On the link robustness, we note that the average SSNR of all Ka-band passes is about 5.5 dB. That level provides a healthy 6.2 dB link margin relative to the -0.7 dB threshold required for successful decoding of the concatenated convolutional (7, ½) and Reed Solomon (255, 232) codes that is employed in Kepler link. With such a large margin, it is expected that Kepler link be well protected against potential outages.

2. The standard deviations also varied among the passes. Some passes had standard deviation as small as 0.25 dB while others had deviation up to 1.4 dB. The passes with small standard deviation demonstrate that the SSNR measurements are stable down to 0.25 dB level. The passes with large standard deviation prompt a greater interest because they reflect atypical conditions that can negatively affect the link design. Two of these passes - DOY121/DSS-26 & DOY243/DSS-34 – were exposed to high wind, up to 45 kph. One pass - DOY32/DSS-55 - experienced rain. Other passes, such as DOY211/DSS-25, had a large SSNR fluctuation but the cause was not well understood. More specific detailed analysis of these atypical passes is discussed later in Section VI.

3. The SSNR minima generally lie further away from the average SSNR. Some of them were in the 3-sigma range, such as the passes on DOY121, DOY247 and DOY311. This large difference indicates that the signal likely experienced some large SNR drops caused by short bursts of impact.

4. The SSNR maxima generally lie close to the average values, not too far from the upper 1-sigma point. This is due to a non-Gaussian distribution of the measurements, as later seen in Section VI, where most of the points are close

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to the maximum SNR level. They are not separated from the average values by 2 - 3 sigma.

There are a few observations about the data processing:

(1) Kepler occasionally changes the data rate in mid pass. So, the computation of representative metrics for the link performance – SSNR average, standard deviation, minima and maxima - need proper filtering to single data rate. Without such filter, the computed link metrics, especially the standard deviation, would be larger than what they actually are.

(2) Data on Ka-band link need to be separated from the X-band link. However, the positive benefit of having concurrent X-band data is that we can use it to validate the common impacts caused by environmental factors, such as winds and rains.

(3) Some of the passes were configured with dual receivers on Ka-band, for redundant processing. We expect that the measurements from both receivers would be within the 0.25 dB measurement noise indicated earlier. Such consistency can be seen in the upper plot of Figure 2 for DOY032/DSS-55 pass, where the difference between the two receivers was within 0.1 dB. Yet, there are passes where we observed a greater difference, as shown in the lower plot of Figure 2 for DOY342/DSS-25 pass. Here, the SSNR measurements reported by the two receivers differed on the average by 0.7 dB.

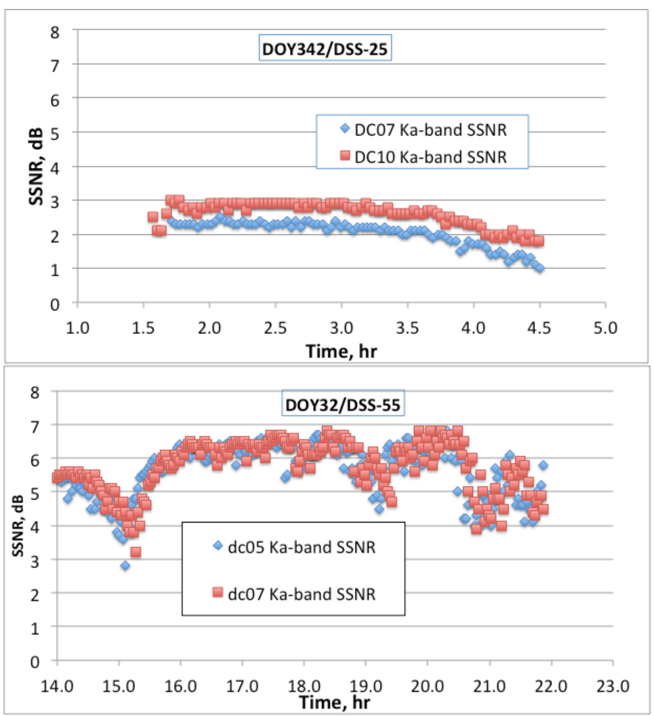

Figure 2. Variation of SSNR measurements from the two receivers on the same antenna in DOY32/DSS-55 and DOY342/DSS-25 passes

Fortunately, in this study, since we are less concerned with the absolute SSNR level between passes and more interested in the signal fluctuation within the pass, this measurement difference does not negatively affect the analysis. If our analysis objective were to evaluate the loss in the ground system, this difference would have some impact.

IV. IMPACT OF RAINS/CLOUDS

In 2012, there was one Ka-band passes affected by rain or heavy clouds. The water content in the air column reduced the SSNR by as much as 3 dB. Figure 3 shows the SSNR variation in DOY32/DSS-55 pass over Madrid. The Ka-band SSNR measured by both receivers reflected a 3 dB, 2.5 dB and 3 dB drop near the time15:00 hr, 19:00 hr and 21:00 hr, respectively. The X-band SSNR showed a similar degradation but with smaller impact, in the order of 1 dB, as expected. The drops in SSNR matched with the increases in the system noise temperature (SNT) around the same time. This correlation implies an impact from the external environment.

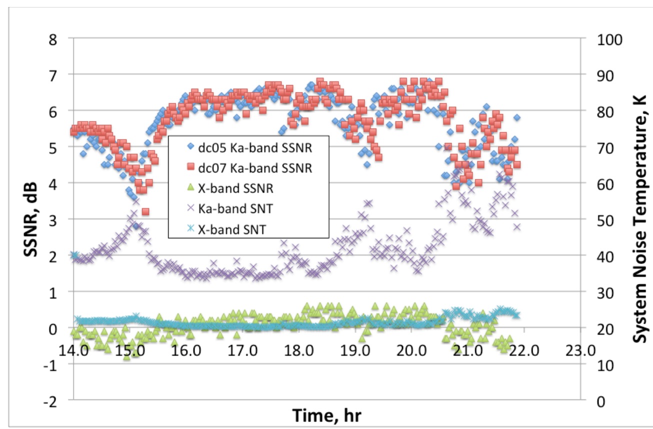

Figure 3. Variation of symbol SNR and system noise temperature at Ka- and X-band on DOY32/DSS-55

Each DSN Complex has a weather station that measures the wind speed/direction, humidity and precipitation. The precipitation data reflects the rainfall as measured by a rain gauge. The weather station however does not provide measurement on cloudiness where the water content in the air column would affect the system noise temperature and causing signal degradation. For the DOY32/DSS-55 data set, despite the presence of the SSNR variation, there was no indication of rainfall from the precipitation measurement. The absence of rain would make it hard to pinpoint the link between the SSNR degradation and weather. The only available collaborating evidence is the increase in the measured system noise temperature. Fortunately, we are able to independently confirm the system noise temperature measurement with the data from special research equipment called the Advanced Water Vapor Radiometer (AWVR) that independently measures the water content in the air. The AWVR is available at Goldstone and Madrid complex, but not Canberra, and has been in operations for over two decades. The AWVR measures the sky brightness temperature at 31.4 GHz [2]. The water vapor radiometer data are collected continuously throughout the day, one sample every 10 minutes. The measurements are done at zenith but the data can be translated to any elevation of interest so that they can be compared with the measured system noise temperature of the pass (which is done by a different set of equipment, using the Y-factor method with a small injected noise-diode) [3]. This AWVR elevation translation however produces a uniform estimated noise temperature in all azimuth directions. In contrast, the SNT measurement is azimuth specific because the measurement is done along the line of sight of antenna tracking spacecraft. So, there may be some difference in the absolute measurements between the two data sets. Nevertheless, we found the data with reasonable consistency. Figure 4 shows the AWVR-derived noise temperature on DOY32 at 40-deg elevation, approximately the same elevation of Kepler tracking at 21:00 hr [4].

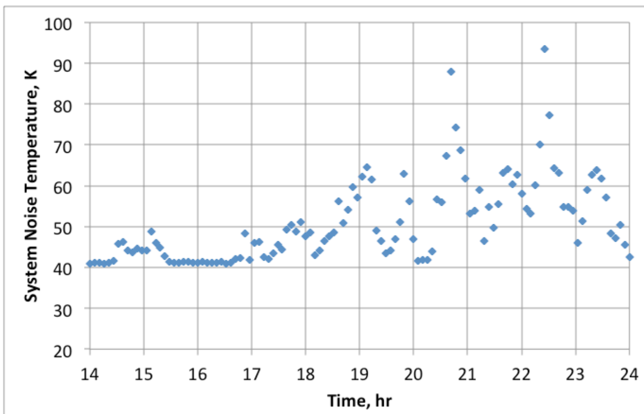

Figure 4. AWVR system noise temperature for DOY32/DSS-55

The temperature is observed to vary significantly at 18:00 hr, with big bursts of 30 K or more near 21:00 hr, which is consistent with the variation seen in the SNT measurement in Figure 3.

V. IMPACT OF WINDS

There are two tracking passes - DOY121/DSS-26 at Goldstone and DOY243/DSS-34 at Canberra - with high wind condition, up to 45 km/hr. The impact of wind on the SNR degradation is quite apparent on DOY243 while it is more ambiguous on DOY121.

We first look at the DOY243 data. Figure 5 shows the measurements of symbol SNR and carrier SNR (Pc/No), as well as the system noise temperature and wind speed on DOY243. Both the SSNR and Pc/No showed high level of fluctuation during the first hour of the pass. Several big drops in SNR occurred at the same time for both measurements, indicating the phenomenon was real rather than just a measurement error. The relatively constant system noise temperature implied that the variation in the SNR was in the signal power reduction rather than in the increased noise (as caused by rains or clouds). There were high winds, up to 45 kph, in the earlier part of the track. Some of the highest peaks of wind speed aligned with the drops in the SSNR and Pc/No, as much as 4 dB. These sudden SNR drops are what cause the SNR minima of the pass to be much lower than the one-sigma point below the average SSNR, as mentioned earlier in Section III.

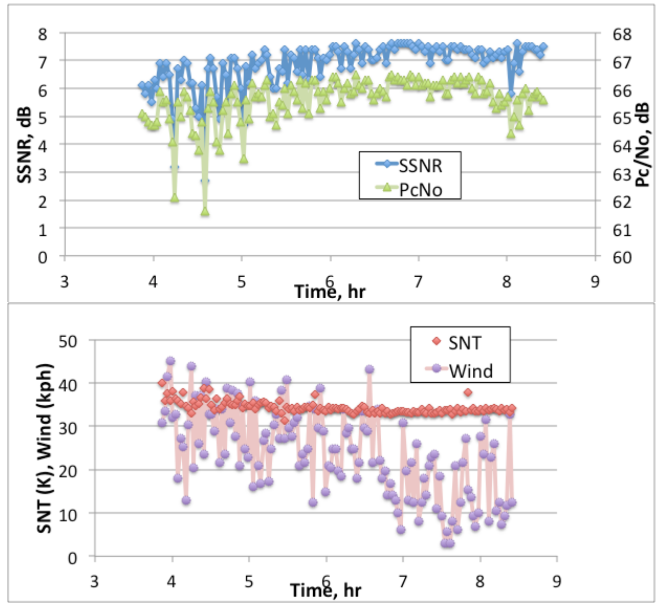

Figure 5. Variation of SNR, system noise temperature and wind speed on DOY243/DSS-34

Figure 6 shows a correlation between the SNR degradation and the wind speed. Here, the SNR degradation is defined as the difference between the SSNR maxima of a given pass (which is considered as the best possible SSNR without degradation) and the measured SSNR within the pass. A second order polynomial curve fit, with a forcing constraint of having zero degradation at zero wind speed, is also included. At 45-kph winds, the fitted degradation can be as much as 2 dB; however, we should note that the r-squared value is low at 0.29, indicating a large uncertainty with the fitting.

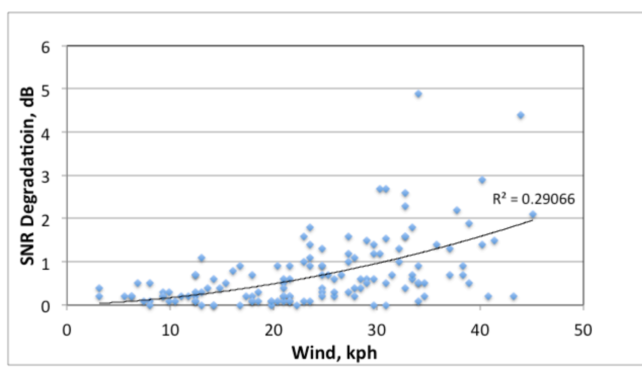

Figure 6. Correlation of SSNR degradation and wind speed on DOY243/DSS-34

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Next we examine the other data set with high winds on DOY121/DSS-26. Figure 7 plots the SSNR, Pc/No, system noise temperature and wind speed for that pass. Both SSNR and Pc/No showed a drop around the time of 23.8 hr. The characteristics are however different. While the SSNR drop was prominent and abrupt, as much as an 8 dB in less than 6 minutes, the Pc/No drop was more gradual, just about 1 dB over 20 minutes. This raises an uncertainty on the SSNR measurement over this period of impact. Although the symbol tracking was reported to be in lock, we suspect it might be in error and thus, affected the reported SSNR.

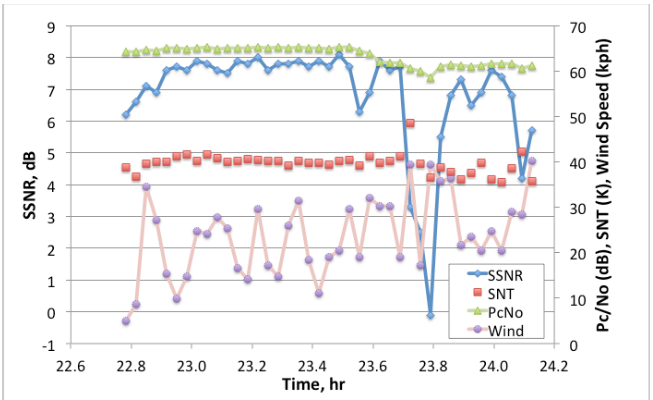

Figure 7. Variation of SNR, system noise temperature and wind speed on DOY121/DSS-26

Figure 8 reflects a possible correlation between the SNR degradation and the wind speed. The polynomial fit indicates a degradation of 3.1 dB at 40 kph; however, it is a relatively low-confidence fit, with an r-squared value of 0.19. One reason for the poor fit is the presence of some data points that are out of normal expectation. For example, the first two data points where the wind is below 10 kph seem to be erroneous. These are the same measurements right after successful signal acquisition, as indicated in the previous Figure 7 around the time 22.8 hr. There are also other data points with anomalous large degradation. Because the receiver reported the signal was in lock and there was no other indication that invalidate the measurements, we decide to keep these out-of-the-norm data points in the analysis, rather than rejecting them.

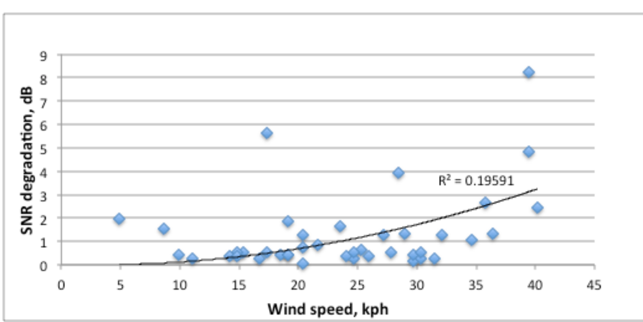

Figure 8. Correlation of SSNR and wind speed on DOY121

The above example reflects some of the challenges with data processing, e.g., what to include vs. exclude in the data analysis in order to arrive at the right model. Some operational measurements are not as consistent as we like them to be.

VI. Signal Fluctuation Statistics

We are interested in characterizing the probability distribution of the signal variations to aid with the link design in future missions. In an ideal case, if there were accurate prediction on the signal SNR, any operational degradation would be reflected as a deviation of the measurement from the prediction since the prediction are model-based and have no knowledge of real-time weather impact. Unfortunately, predictions are not available with Kepler Ka-band passes.

To compensate for the lack of SNR prediction, we calculate the fluctuation by a degradation against the maximum SSNR of the pass, as discussed in Section V. Additional adjustment is also needed since both the antenna gain and system noise temperature change as a function of antenna elevation [5]. The antenna gain is affected by the gravity distortion of the antenna structure. The system noise temperature varies due to different path length through the Earth atmosphere that the signal traverses at different elevation. Lower elevation results in a higher noise temperature because of the longer atmospheric path.

For each pass, the measured SSNR's are subtracted from the SSNR maxima of the pass. Fluctuation data of all Ka-band passes in 2012 are then combined to generate the cumulative distribution function of SNR variation, as shown in Figure 9.

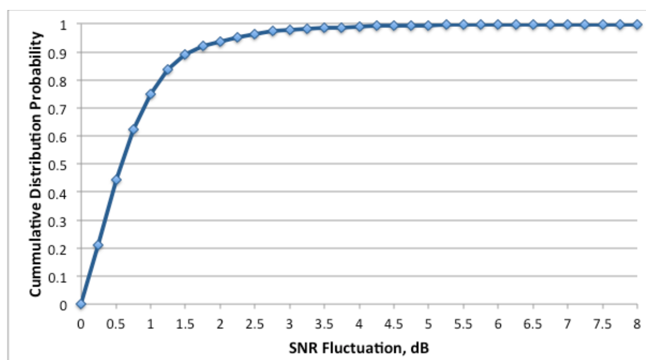

Figure 9. Cumulative distribution of SNR fluctuation

The distribution shows that 50% of the fluctuations are less than 0.6 dB, 90% are within 1.6 dB, and 95% being less than 2.2 dB.

VII. Conclusion

In summary, this paper examines the variation of Kepler Ka-band signal observed from the DSN tracking. In a benign condition, the SSNR measurements within a pass are stable within 0.25 dB. In adverse weather of heavy clouds or winds, the SSNR within the pass can vary as much as 1.5

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dB (1-sigma). Out of 22 Ka-band passes in 2012, only one pass was affected by the heavy clouds (no rains) and two passes impacted by high winds. Both of these effects could result in an instantaneous change of SNR by up to 3 dB. Kepler mission, however, has a robust link with an average 6.2 dB margin, which helps minimizing the telemetry data outage. The cumulative distribution of the SSNR variation shows that 50% of the variation are within 0.6 dB of the maximum SSNR within the tracking pass, 90% are within 1.6 dB and 95% within 2.2 dB.

Through this analysis, we learned that one has to be careful with the data selection. Since a track could involve multiple receivers at multiple frequency (X- and Ka-band) and multiple data rates (spacecraft can change data rate within the pass to preserve link margin), proper filtering of data is essential for valid data compilation and analysis. Compensation for the changing elevations in the signal SNR is required to normalize the data to the same conditions. We also learned that while measurements from two different receivers of the same received Ka-band signal are generally the same to within 0.25 dB, at times they could differ by as much as 0.75 dB. This difference would have greater impact on future studies, such as system loss, that are dependent on the absolute, rather than relative, accuracy of the SSNR measurements.

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