Ka-band Estimated and Observed Frame Error Analysis

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ABSTRACT. — Given the Near-Earth Object Camera (NEOCam) Project's stringent data return requirement of having virtually no frame errors during a 100-minute tracking pass utilizing a K-band (26 GHz) link, an analysis was conducted to ensure that the link assumptions were sound in realizing this requirement. The link was designed with sufficient margin to ensure near 100 percent data return in the case of quiescent weather conditions. In this case, any lost data is expected to occur in isolated rare instances, where it can be easily retransmitted using a protocol such as Automatic Repeat Request (ARQ). For the case when significant fading occurs beyond 95 percent weather, widely scattered frame errors would necessitate all or almost all of the entire pass to be retransmitted, thus a link margin above 8 dB is used to alleviate this. A theoretical frame error rate (FER) of 10^{-8} will result in virtually no frames lost during a typical 100-minute pass. The change in threshold E_b/N_0 at FER = 10^{-8} relative to the Project's adopted threshold of E_b/N_0 at FER = 1.4×10^{-6} is only ~0.2 dB which lies well within the Project's adopted 8 dB margin, providing confidence in the link design.

Actual frame errors realized during operational Ka-band tracking passes were also examined in an attempt to provide observational evidence of the theoretical expectations. We used Kepler Ka-band (32 GHz) telemetry data from 66 tracking passes where specific criteria were satisfied. These criteria involved considering data where the minimum symbol signal-to-noise ratio (SSNR) exceeded 0 dB, which lies just above threshold for the coding/modulation configuration used. Out of the 66 passes examined, 60 had zero frame errors after removal of nonzero frame data with justified reasons for deletion. Out of ~388 million frames in the 66 passes examined, there were 6 tracking passes containing 14 time instances with 738 frame errors where no justification for deletion was apparent. Thus, after removing data points during periods of nonzero FERs with justified explanations, we have effectively found only 738 frame errors occurring in 14 discrete time instances that have yet to be fully explained.

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I. Introduction

The Near-Earth Object Camera (NEOCam) is a proposed mission which is planned to discover and characterize several potentially hazardous asteroids whose orbits lie close to Earth's orbit, as well as track them [1]. This mission makes use of a 50 cm diameter infrared telescope and will reside at the Sun-Earth L1 Lagrange point [1]. The mission is planned to perform infrared imaging of these potentially hazardous asteroids. Because of the nature of the compression algorithm used in the data to be transmitted, NEOCam requires a stringent data transmission and reception strategy that does not tolerate a high number of scattered frame errors over a tracking pass. A few frame errors in isolated spots can be tolerated, where the data would be later retransmitted using an Automatic Repeat Request (ARQ) protocol. This strategy only applies to quiescent weather. However, when significant fading occurs beyond ~95 percent weather, multiple frames would be lost, hence these widely scattered frame errors would necessitate all or almost the entire pass to be retransmitted.

The NEOCam mission plans to use a 26 GHz (K-band) link to return data back to Earth. The link design was examined to verify that virtually zero frame errors would occur during a nominal tracking pass. The first step involved estimating a theoretical number of frame errors expected, given the link design threshold and margin assumptions, to verify that the link design strategy is sound. The second step involved examining actual return of frame errors from an active Ka-band mission and comparing against expectations. Several years of Kepler received telemetry data at Ka-band (32 GHz) were examined to verify that near-zero frame errors were encountered when the link margin was sufficiently high. Both NEOCam and Kepler make use of the same coding scheme which consists of a [255,223] Reed-Solomon (RS) outer code concatenated with a (k = 7, r = 1/2) convolutional code with interleaver depth of 5. NEOCam will be transmitting suppressed carrier QPSK at 26 GHz, while Kepler transmitted residual carrier BPSK at 32 GHz. Thus, in addition to the frequency difference, NEOCam has a threshold symbol signal-to-noise ratio (SSNR or E_s/N_0) near 3 dB while Kepler has a SSNR near 0 dB.

II. Theoretical Frame Error Analysis

The NEOCam project makes use of a lossless Rice compression algorithm [2], where a high number of scattered frame errors over a pass cannot be tolerated. To support the exposure return requirements, the associated frame error rate (FER) is 1.4×10^{-6} for a 95 percent exposure return, and 2.9×10^{-7} for a 99 percent exposure return [3]. Thus, one would lose ~110 frames out of 80 million frames during a typical downlink session for 95 percent and lose 20 frames for 99 percent.[1] To estimate the theoretical number of frame errors encountered in a tracking pass, we assume a frame size of 1024 bytes, a tracking pass duration of 6000 s (100 min), and a data rate of 150 Mbps [3].

From the standpoint of the telecom system, the frames are considered to contain all information bits, although there may be project (science team) wrappers or overhead present. Using these assumptions, the number of frame errors encountered in a 100-minute tracking pass were calculated as a function of FER. Table 1 shows the number of frame errors encountered in a tracking pass of 100-minute duration lies at 1 at a FER of 10^{-8}.

[1] Mark Rokey, Jet Propulsion Laboratory, private communication.

Table 1. Number of frame errors in a 100-minute pass for selected FERs

Quantity	*Case 1*	*Case 2*	*Case 3*	*Case 4*	*Case 5*	*Case 6*	*Case 7*	*Case 8*	*Case 9*
Frame Error Rate	0.01	0.001	0.0001	0.00001	0.000001	1E-07	1E-08	1E-09	1E-10
Number of Frame Errors	1098633	109863	10986	1099	110	11	1	0.110	0.011

To obtain the bit energy-to-noise ratio (E_b/N_0) threshold as a function of FER, we first examine information from the DSN Telecom Link Design Handbook [4]. Reference [4] displays a set of curves for FER versus Energy per bit to noise Spectral Density Ratio (E_b/N_0) for the case of concatenated [255,223] RS and (k = 7, r = 1/2) convolutional code with interleaver depth of 5 using a residual carrier. The lowest FER shown in [4] is at 10^{-5} and will result in 1099 frame errors in a 100 m tracking pass (see Table 1). Given the desire to assess the link design to have virtually zero frame errors during the track, we need to consider a much lower FER. The FER of 10^{-5} corresponds to a threshold E_b/N_0 of 2.38 dB used in the baseline link budget.

To assess threshold E_b/N_0 values for lower FERs (than was in shown in [4]), we regenerated the curve over a wider range of FERs using the equation and coefficients provided in Appendix A of [4]. From Eqs. A-5 and A-6 in [4], the following was used to generate the curve shown in Figure 1:

$$FER(x) = \min\left\{1, \exp\left(a_0 - a_1 x\right)\right\} \tag{1}$$

where $a_0 = 105.0019$ and $a_1 = 67.4242$ are coefficients applicable for concatenated RS and Viterbi (7,1/2) codes from Table A-2 in [4], and $x = 10^{((E_b/N_0)/10)}$ where E_b/N_0 is the dB equivalent of the linear ratio (x) of bit energy-to-noise spectral density.

Note in Figure 1, the threshold E_b/N_0 is ~2.6 dB at an FER of 10^{-8} results in one frame error per pass. For the purpose of the link budget exercise, we adopt this as threshold which effectively results in ~0 errors during a 100-minute tracking pass.

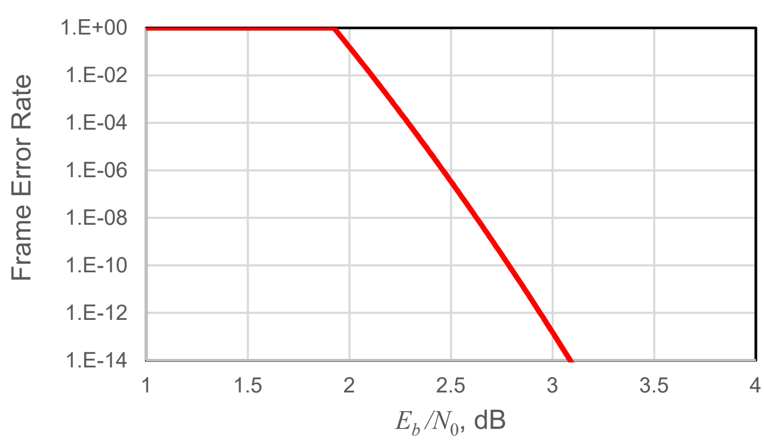

Figure 1. Baseline FER versus threshold E_b/N_0 for FER values of 10^{-14} to 1 pertaining to the case of concatenated (7,1/2) convolutional inner code with RS outer code.[2]

[2] The definition of inner and outer codes means that the information bits at the transmitter are first subject to Reed-Solomon encoding (outer code), interleaving, and then convolutional encoding (inner code).

Finally, we have taken the NEOCam Ka-band science downlink link budget from [3] with an E_b/N_0 threshold of 2.38 dB and link margin of 8.94 dB. The threshold E_b/N_0 of 2.38 dB was then replaced with the value of 2.6 dB corresponding to a FER of 10^{-8}. This results in a margin of 8.7 dB. Thus, given that the threshold E_b/N_0 increases by only about 0.2 dB to yield near zero frame errors, the margin of 8.7 dB is more than adequate to realize this. Thus, the project's link design is sound.

III. Analysis of Operational FER Results

Given that the above FER estimates apply to the ideal theoretical case, it is instructive to examine achieved results with actual flight data. The Kepler project makes use of a deep-space Ka-band link at 32 GHz. An earlier report examined the performance of the Kepler Ka-band carrier (P_c/N_0) measurements from over 100 tracking passes conducted from 2010 to 2017 [5]. In this article, the performance of the telemetry channel data is examined in terms of frame counts and actually achieved FER for each tracking pass.

A. Initial Analysis

Given that the Kepler spacecraft operated with very high margins for many of its earlier passes when it was close to Earth, it is expected that Kepler should have achieved virtually no frame errors during those high margin passes. We have characterized the achieved FER over a total of 256 Kepler Ka-band passes conducted between 2009-072[3] and 2018-131. The data were generated using the Service Quality Assessment (SQA)[4] portal of Jet Propulsion Laboratory (JPL) where frame counts for each pass were tabulated and characterized. These included number of good frames, bad frames and total frames. The FER for each pass was calculated as the ratio of the total number of bad frames over the total number of frames. Twenty-two of the tracking passes were removed from consideration as they were classified as commissioning passes, in which the project conducts tests with several mode changes as well as exercise changes in operational procedures, prior to the start of a series of passes. In all cases, only data were considered where the carrier loop, the symbol loop, the frame synchronizer and the convolutional decoder were all in lock.

Figure 2 displays the FER versus year for each of the 234 tracking passes, which initial set of statistics were extracted using tools from the SQA portal. Some of the higher FER values in Figure 2 could be attributed to the significant number of bad frames encountered during portions of a pass where the SSNR was near or below threshold. Therefore, we wanted to consider only those passes where the minimum SSNR exceeded 0 dB, as shown in Figure 3, where there is now a set of 67 passes to be analyzed in detail.

Examining the FER against minimum SSNR over a pass facilitates the analysis avoiding the problem of arduously and selectively removing data points at unusually low SSNRs caused by an antenna not being fully on-point. Figure 3 shows most of the FERs passes from 2012 to 2018 were closer to zero, whereas passes prior to 2012 appear to have higher FERs with the largest occurring at a FER of 0.011 (see point inside red circle in Figure 3).

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[3] The notation "2009-072" corresponds to year 2009 and day of year 72.

[4] SQA (Service Quality Assessment) is a DSN subsystem with CI No. 317 (as listed in the DSN Configuration Items Management Software). It is defined by Functional Requirements Document (FRD) #834-151 in PDMS.

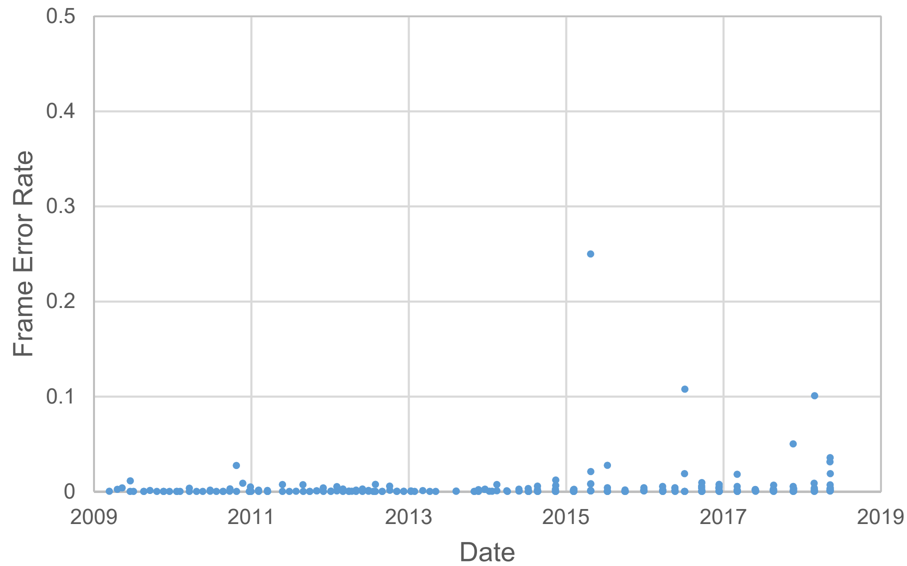

Figure 2. Kepler Ka-band FER versus date for 234 tracking passes.

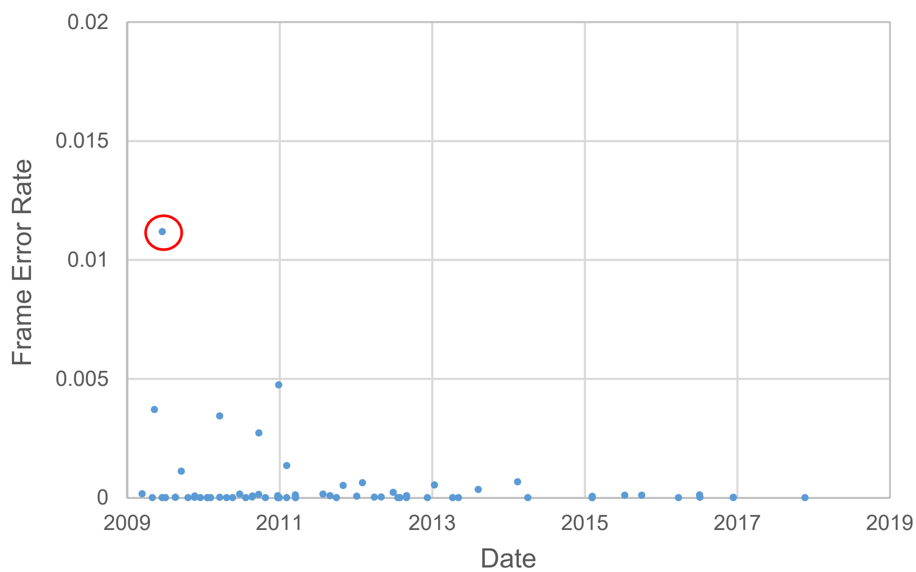

Figure 3. Kepler Ka-band FER versus Date for 67 tracking passes where minimum SSNR exceeds 0 dB.

We plotted the FER versus minimum SSNR for several of the Kepler Ka-band tracking passes as shown in Figure 4, where FER is plotted on a logarithmic scale for easier visualization. The points for 25 passes had zero frame errors so they do not show up in this plot as they lie below the minimum FER displayed of 10^{-8}. In practice, all FERs should be effectively zero for minimum SSNRs > 0 dB[5] (E_b/N_0 ~> 3 dB). Passes with minimum SSNRs < 0 dB are not plotted. Figure 4 shows there are appreciable FERs for minimum SSNRs exceeding 0 dB,

[5] For a discussion of the rationale using a 0 dB threshold for SSNR, see discussion in Section III.B.

with the highest valued one (FER = 0.011) occurring at a minimum SSNR of 13.24 dB (blue point inside red circle).

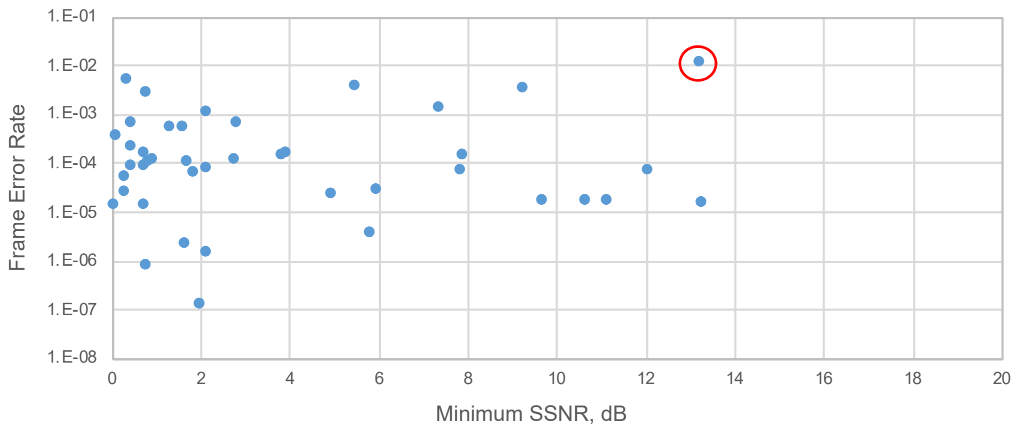

Figure 4. FER as a function of minimum SSNR over each tracking pass.

In the quest to identify why the FERs exceeded what was expected for Kepler Ka-band passes with high SSNRs, we examine the individual frame errors versus time for selected passes with high minimum SSNR. The pass chosen first was conducted on 2009-06-17/18 (2009-168/169) at DSS-25 where a high FER of 0.011 was observed when none of the SSNR measurements exceeded 13.24 dB (see point inside red circle in Figure 4).

For pass 2009-168/169, there were a total of 9598068 good frames and 108551 bad frames, which resulted in the 0.011 FER. According to the data for this pass, huge numbers of total frames were reported in the 5-s monitor data period from 23:59:58 to 00:00:03 UTC that crossed the day number boundary. However, the number of possible frames per 5 s should not be any greater than ~2548.[6] Both total frame and bad frame counts were found to be excessive for a 5-s reporting period. It was subsequently discovered that the high number of frame errors for the day-crossing data point were due to a software book-keeping issue,[7] and thus this point can be removed from the statistical analysis. If we exclude this one 5-s data point, then the total number of bad frames is now 551, a much smaller number.

Figure 5 displays the number of nonzero frame error points (bad frames, blue points) and SSNR (orange points) versus time reported in five second intervals during this pass. The 551 bad frames for this pass occur at two distinct 5 s data points. At 01:57:38 UTC (just before 26.0 in Figure 5), 169 of these occur just after a long outage period that started just after 00:18:29 UTC (near 24.3 hours UTC). After subtracting out 169 from the remaining 551 bad frame count, we are left with 384 bad frames, which can be traced to a remaining 5-s reporting period that occurred at 23:50:42 UTC (just before 24 h in Figure 5). This was also an end-point of a data segment, which was the first point after an 8 min 40 s outage period that started at 23:42:02 UTC.

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[6] The nominal bit rate for Kepler Ka-band for this pass was about 4.3 Mbps with ~10,000 bit frame sizes.

[7] Ara Kassabian, Jet Propulsion Laboratory, private communication, August 20, 2018.

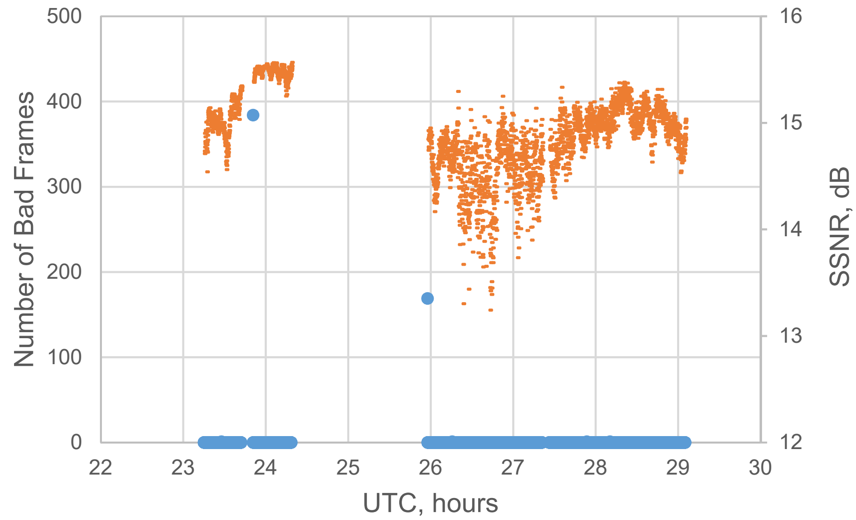

Figure 5. Number of bad frames (blue) and SSNR (orange) for pass 2009-168/169 conducted at DSS-25.

If these three reporting periods containing nonzero frame errors are removed from the overall 2801 samples each of 5-s duration from the FER statistical determination, then we achieve a FER of 0 frames out of 6,150,116 total frames for the remaining 2798 reporting periods, in line with expectations for the minimum SSNR of 13.24 dB. Thus, points with nonzero frame errors just before or after a gap in tracking coverage) can be removed from the statistical analysis with justification. The gaps in tracking coverage within a pass are due to mission directed activities.

In summary, additional filters were identified that were necessary to assess FERs as a function of measurable SSNR for each pass. These filters include examining frame counts when carrier, symbol, frame sync and decoder loops are locked. After the first iteration of examining pass-by-pass frame statistics described above, we found that one cause of abnormally large frame errors occurred at the end and start of data segments separated by tracking gaps or at monitor points that crossed a day boundary.

B. Evaluation of Threshold for Kepler Frame Error Analysis

We initiated a second iteration of data inspection using additional filters (removing most first and last points of long tracking segments and removing most day-crossing data points). The results of this second run is shown in Figure 6, where FERs (blue data points) are plotted as a function of minimum symbol SNR (SSNR) over each tracking pass. This time passes were included where minimum SSNRs lie below the chosen threshold of 0 dB. In addition, Figure 6 plots the FER versus SSNR model curve for the case of concatenated coding used by Kepler (red curve). There are now fewer points with nonzero FERs at high SSNR, and the points remaining have generally lower values than in the previous iteration (Section III.A). The model curve was also adjusted for the 0.5 dB implementation loss provided in the Kepler Ka-band link budgets.[8] The adjusted model curve (red) aligns

[8] D. Hansen, Jet Propulsion Laboratory, private communication.

reasonably well with the steep increase in FER (blue) near SSNR~ –1.3 dB, providing confidence in the link assumptions.

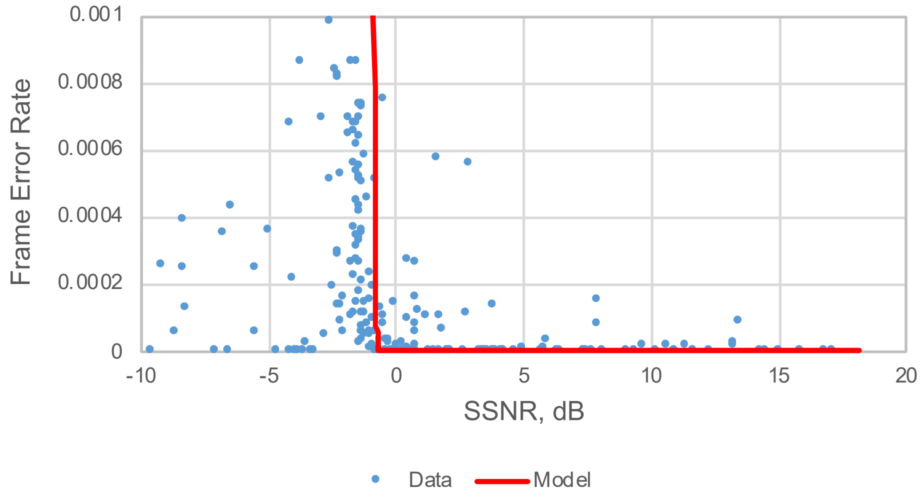

Figure 6. FER versus minimum SSNR over pass for Kepler Ka-band tracking passes: measurements (blue points), model (red curve).

To further assess the assumption of the threshold crossover point for Kepler Ka-band SSNR, we elected to examine a pass that included huge fades due to weather (rain fades), as was seen for pass 2016-186 involving Madrid (DSS-54) [5]. This pass is not part of the sample used for assessing frame errors, but only used here to assess the threshold assumption used in our criteria for valid data selection. Figure 7 displays SSNR (orange) and FER (blue) as a function of time for this pass. Clearly, the frame errors become nonzero and significant during periods where the SSNR drops below ~0 dB. It should be noted that only the carrier in-lock filter is applicable here. No filters were used for symbol lock, frame-synchronization lock and decoder lock in the selection of data. Therefore, data points where the carrier was not in lock do not show up in Figure 7.

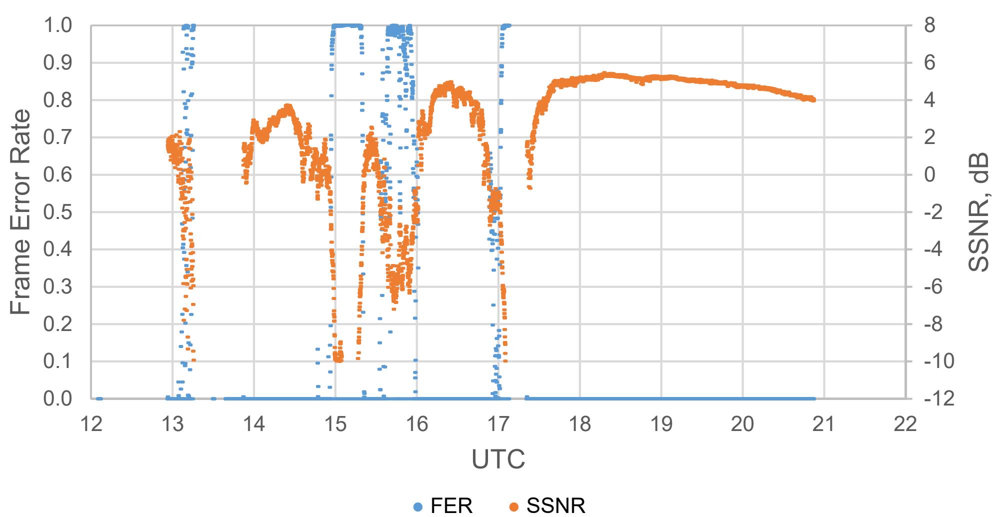

Figure 7. FER (blue) and SSNR (brown) versus UTC for pass 2016-186 with DSS-54 (Madrid).

An improved visualization of the FER performance for this pass is achieved by displaying FER versus SSNR (see Figure 8), where 100 point averages were taken to reduce scatter. The frame errors are virtually zero for SSNRs greater than 0 dB. The FER begins to increase between 0 and –1 dB SSNR, and reaches ~100% for SSNR < –6 dB.

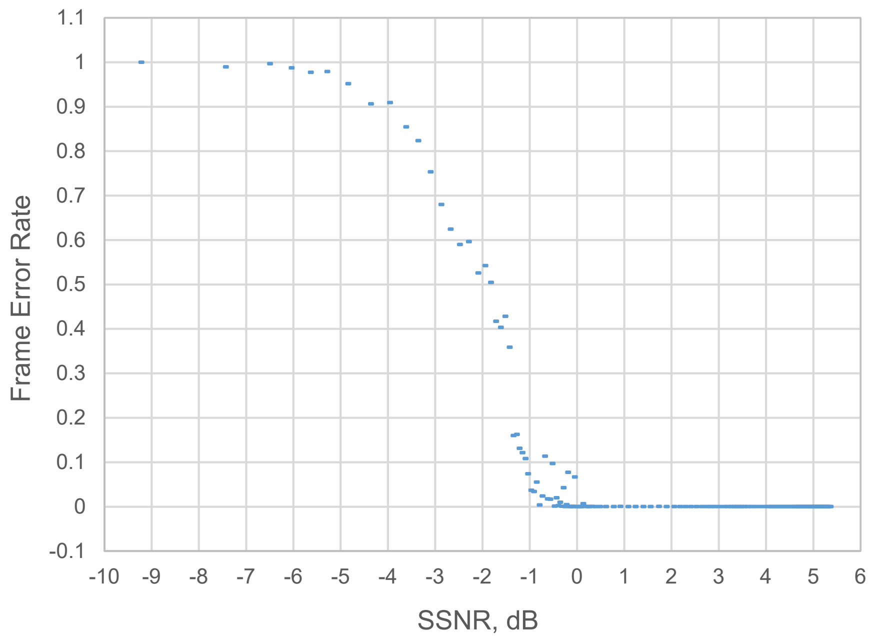

Figure 8. FER versus SSNR for pass on 2016-186 involving DSS-54 at Madrid.

To further validate the apparent threshold crossover in FER between –1 and 0 dB SSNR in Figure 8, we chose to examine the Kepler link budget design point for Ka-band. Kepler assumes a 2.38 dB theoretical threshold for E_b/N_0 at a FER of 10^{-5}, which is applicable to a concatenated (7, 1/2) convolutional RS code. When we factor in the link budget implementation loss of 0.5 dB, one expects an effective threshold E_b/N_0 of 2.88 dB for Kepler. Given the rate ½ convolutional code and the 1.14 overhead due to the [255,223] RS outer code, the effective E_s/N_0 (SSNR) threshold becomes –0.72 dB. This is in good agreement to within a few tenths of a dB with the visual crossover inferred from Figure 8, which suffices given the resolution of the data.

The FER should still be zero for effectively any SSNR above ~–1 dB, as should be the case since we are plotting against minimum SSNR over each tracking pass. The fact that we see some higher than expected FERs was cause for concern and further examination (see Section III.A). Thus, the above exercise illustrates why only passes where the minimum SSNR exceeded 0 dB were chosen for the analysis. This allowed for a reasonable threshold in which to expect zero frame errors, as well as to minimize issues with not having to hand-remove data points from passes with lower minimum SSNRs from the analysis data set (as addressed in Section III.A).

C. Second Iteration and Detailed Analysis of Individual Passes

A second iteration of obtaining frame error statistics for each pass was conducted after performing additional filtering in order to simplify the process of identifying justification for removal of nonzero frame error occurrences for the applicable 42 passes shown in Figure 4. We included filters to address data where carrier, symbol, decoder and frame-sync equipment were in lock, as well as removing some initial and final points in data arcs, and some day-crossing points. We also considered only passes where the minimum SSNR over the pass exceeded 0 dB. Thus, there were 67 passes meeting the stated criteria, 25 of which had zero frame errors throughout the entire pass (zeros not shown in Figure 4) and 42 of which with nonzero frame errors (shown in Figure 4).

The next step was to examine the frame error versus time behavior for individual passes in order to infer whether we could identify issues that required additional filtering or provide reasonable explanations to allow justification for deleting points with nonzero frame counts. This would allow us to verify if the expected zero FER was realized when the minimum SSNR exceeded 0 dB.

Additional work involved analyzing the individual pass FER behavior for other passes with nonzero FERs at high minimum SSNR shown in Figure 4. This was done to infer whether additional instances of nonzero frame errors could be explained by any of the previous categories of justified point deletion, or whether there were any new categories. After identifying passes that had nonzero frame errors due to the known issues of uplink transfers or mode changes, first or last points in a pass (or data arc), and day crossing points (software book-keeping issue), we removed these data points and found that the FER went to zero for 28 additional passes shown in Figure 4. This left 14 passes with nonzero frame errors with minimum SSNR > 0 dB that required further scrutiny.

Of these 14 passes, four were further identified with justification for removal of all nonzero frame error points. Pass 2009-072 DSS 55 was removed because it was actually a commissioning pass (very first data downlink after launch), and was not identified as such during the initial analysis. Since commissioning passes were automatically removed from consideration in the analysis, this pass was also removed, since numerous telemetry mode changes were tested. Pass 2009-131 at DSS-55 was subsequently adjusted to zero FER after close inspection of the Network Monitor Control (NMC) logs showing mode changes and elevation brake issues during known instances of nonzero frame errors. Pass 2013-011 at DSS-25 was set to zero FER after identifying issues described in DSN post-pass documentation. Pass 2013-221 conducted at DSS-34 had its FER set to zero after identifying a nonzero frame error point occurring at the start of a pass.

The next pass selected for individual analysis had a minimum SSNR of 13.449 dB and a FER of 8.65×10^{-5}. The time history of the frame errors and SSNR is displayed in Figure 9 for this pass which was conducted on 2009-324 (November 20) and involved DSS-34 as the receiving station. Upon examination of the frame errors, we note that one monitor point located at the end of the pass has a large number of nonzero frame errors, which, as an end-point, is justified for removal from statistical consideration. The cluster of five data points with nonzero frame errors lying between 5:28:51 and 5:30:09 UTC (near 5.5 hours in Figure 9) was found to have occurred during an overlap (or handover) between DSS-25 and

DSS-34 uplinks. The carrier power was noisy over DSS-34 (~3 dB variation and there was a sharp ~3 dB or more drop in carrier power at this time). The project was aware that at this time they had bad frames in the form of RS decoder failures, and reported this as a known problem when operating two-way. This problem became worse as the range distance increased, where it became a real issue in 2011.[9] After removal of the last data point and the five data points with high FERs near the handover, a zero FER was achieved at the minimum SSNR of 13.449 dB, consistent with expectations.

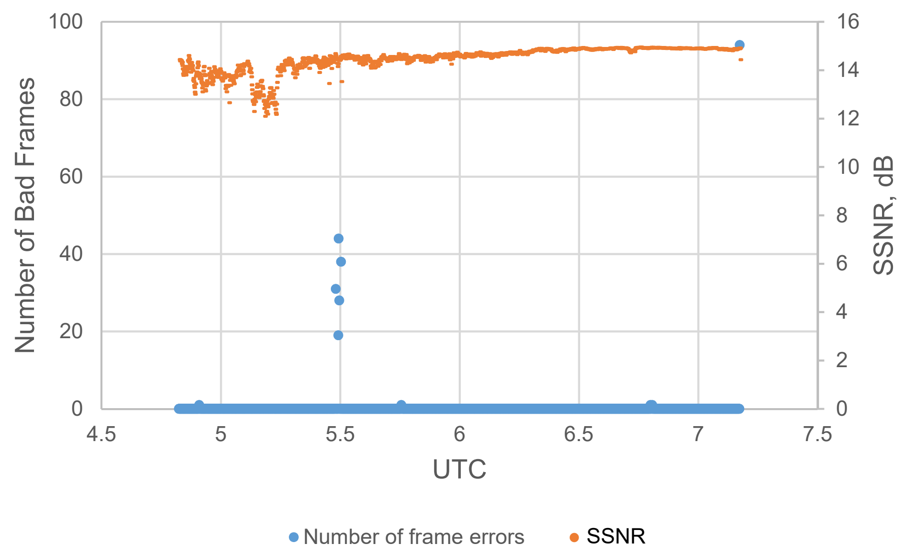

Figure 9. Number of bad frames (blue) and SSNR (orange) versus time for pass 2009-324 at DSS-34.

The pass conducted on 2015-192 at DSS-26 (see Figure 10), had a total of 289 instances of bad frames. There were 70 instances of bad frames occurring at the first data point resulting in justified deletion. There were 8 bad frames that occurred at 00:49:10 UTC after a several minute gap where a known telemetry mode change had occurred at 00:43:29 UTC resulting in a justified deletion. There were 211 bad frames that occurred at 01:52:58 UTC (~25.9 in Figure 10) where there were several instances of "LOCK STATUS CHANGED" messages in the NMC logs, which also showed the decoder fell out of lock and the SSNR went very low during portion of the 5-s reporting period. Given that the reported SSNRs used in the above analysis were snapshots during the 5-s period monitor point in question, it is conceivable that the SSNR could lie below this value during some portion of the 5-s duration. Since we know that the SSNR went low, we are justified in deleting these bad frames from consideration of the statistics. Thus, this pass had zero frame errors after removing all bad frames with known issues and low SSNR.

After examination of these 14 remaining passes with yet unexplained nonzero frame errors, reasons were found for justified deletions of nonzero frame error points for eight of these passes, some of which were explained in detail above.

[9] The Kepler Project stated that they incurred significant Reed-Solomon decoder issues starting in 2011 when the SSNR was still high (well above 0) when they were two-way. This changed after going non-coherent during Ka downlinks. Marcie Smith, NASA Ames Research Center, private communication.

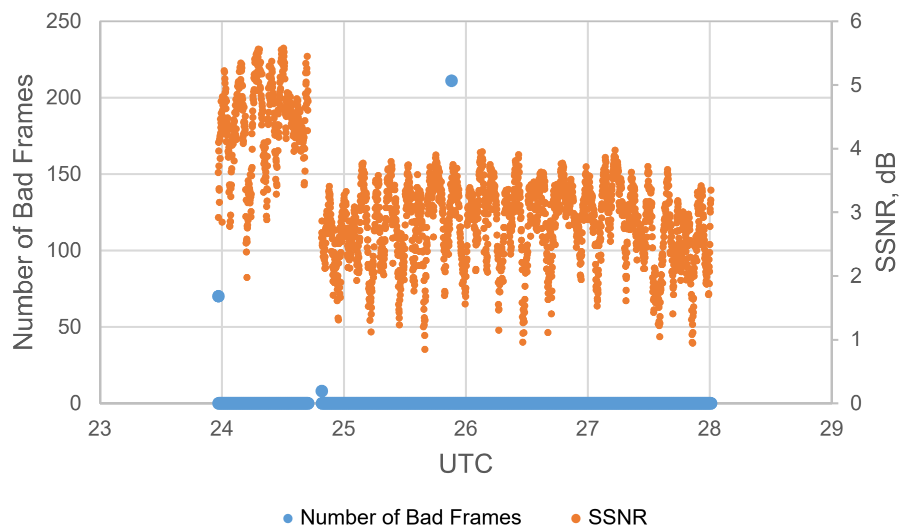

Figure 10. Number of bad frames (blue) and SSNR (brown) versus time on 2015-192 at DSS-26.

The remaining six passes where nonzero frame errors required resolution are listed in Table 2 with unaccounted for number of bad frames (no justification for deletion) and number of good frames (zero errors). It is possible that the project may have initiated uplink transfers or mode changes via real-time commands that do not show up in the DSN documentation, SQA products or in the schedule for some passes. We performed a closer examination of the frame error occurrences in these passes by examining the post-pass products. We discuss these six remaining passes in detail below.

Table 2. Passes remaining with unresolved frame errors.

Pass ID	*Station*	*Number of Bad Frames*	*Number of Good Frames*
2010-078	DSS-26	11	9319007
2010-265	DSS-26	311	8066294
2012-121	DSS-54	4	11958463
2012-211	DSS-55	23	10427819
2012-243	DSS-34	294	5765270
2014-044	DSS-26	95	6424717

Pass 2010-078 at DSS-26 had a total of 160 bad frames (see Figure 11), 149 occurred between 23:20:40 to 23:28:29 UTC with an associated gap. According to the post-pass report there was a failed uplink transfer that occurred at 23:20 UTC with DSS-55, allowing for a justified deletion. The 11 bad frames that occurred at 3:11:15 UTC (27.2 UTC in Figure 11) were of unknown nature at this time, but coincided with instances of LOCK STATUS CHANGED messages reported in the NMC logs. Thus, these frames are likely to be accounted for pending future confirmation, and thus removed from statistical consideration.

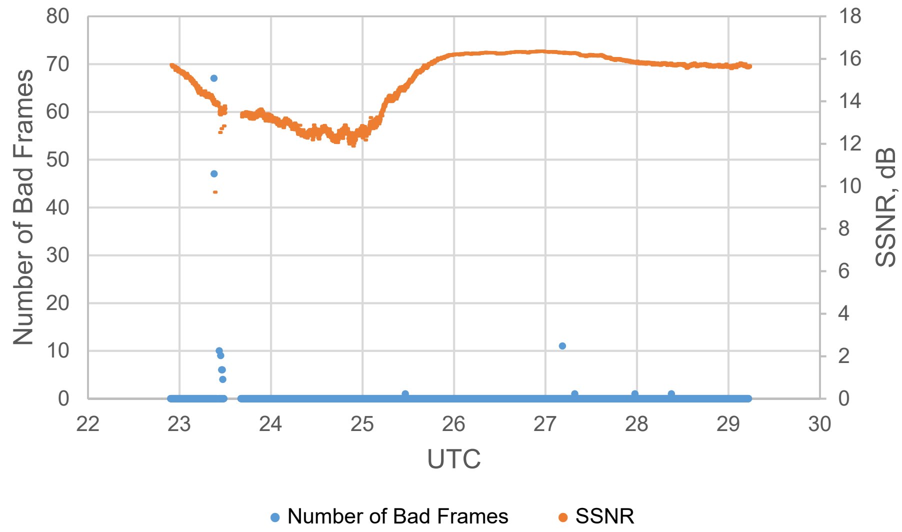

Figure 11. Number of bad frames (blue) and SSNR (brown) versus time on 2010-078 at DSS-26.

Pass 2010-265 at DSS-26 had a total of 1117 bad frames, 290 occurred during a 10 s period where there were several instances of elevation track errors listed in the NMC logs. At the last data point, 806 bad frames occurred allowing for a justified deletion. Thus, approximately 311 bad frames were yet to be resolved for justified deletion for this pass.

Pass 2012-121 at DSS-54 had a total of 296 bad frames in which 4 are currently unaccounted for. The unaccounted four bad frames occur at 20:20:40 UTC where instances of LOCK STATUS CHANGED messages were seen to occur in the NMC log, but no other information was found. The remaining 292 bad frames occurred during a known uplink transfer, allowing for justified deletion.

Pass 2012-211 at DSS-55 had 23 instances of bad frames, coinciding with LOCK STATUS CHANGE messages in the NMC log. The NMC log shows that the operator set the carrier loop bandwidth to 30 Hz from 250 Hz for Ka-band a few seconds earlier, and the system noise temperature increased. Thus, the 23 bad frames may be related to this, but, for now, we consider these occurrences not yet justified for deletion.

Pass 2012-243 at DSS-34 had a total of 486 bad frames, 192 bad frames occurred near a known uplink transfer allowing for justified removal of these points. The remaining 294 bad frames are yet unaccounted for lacking reasons for justification for deletion.

Pass 2014-044 at DSS-26 had a total of 4285 bad frames, 3031 bad frames occurred at the day crossing point allowing for a justified deletion due to the known day-crosser book-keeping issue, 145 bad frames occurred after a 20-sec outage coinciding with a telemetry data rate change allowing for a justified deletion, and 1014 bad frames occurred at the single monitor point that occurred after a 10-min gap. An out of lock condition was noted in the NMC log along with a message that the symbol tracking loop was turned off. This configuration change allowed for a justified deletion for these bad frames. Ninety-five bad frames occurred at a time point that coincided with several LOCK STATUS CHANGED messages in the NMC log, but no other information was found to be readily available. Thus, only the 95 bad frames occurring at a single 5 s monitor point were not yet removed from the statistics as no definitive justification for deletion was yet identified.

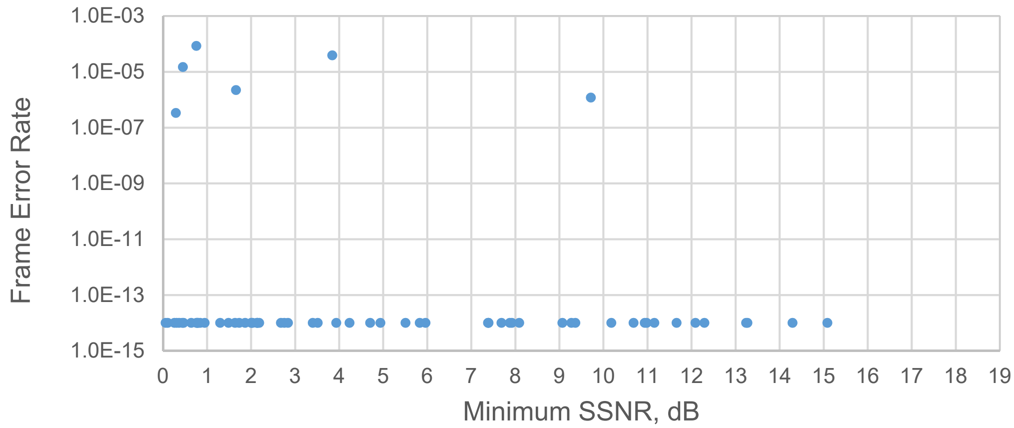

Figure 12. FER versus minimum SSNR for 66 passes after removing nonzero frame errors due to acceptable criteria. Here, zero FERs were set to 10^{-14} in allow for easy visualization.

IV. Summary and Implications for NEOCam

There were a total of 256 Kepler Ka-band passes conducted between 2009-072 and 2018-131, in which 67 met conditions of having minimum SSNR exceeding 0 dB (over the pass), and where we implemented filters on carrier, symbol, frame-synchronization and decoder loops. We removed from consideration passes where the project was testing new configurations (denoted as commissioning passes). Of the 67 passes, 25 had 0 frame errors over the entire time series duration, 28 had 0 frame errors after identifying and removing lost frame points from the statistical consideration with justified reasons, and 14 remaining passes had nonzero frame errors, due to unknown or yet unidentified reasons.

The next stage of analysis involved more closely inspecting these 14 passes with unaccounted-for nonzero bad frame counts. Of the 14 passes, it was found that one was a commissioning pass (which was labeled with a different code in the delivered pass summary file). This brought the count of our pass sample to 66. Of the remaining 13 passes, 7 were subsequently resolved with all occurrences of nonzero frame counts being justified for removal, and 6 passes left with unresolved bad frame counts (Table 2), where specific detail was provided in Section III.C.

The resulting plot of FER versus minimum SSNR is shown in Figure 12 where points with zero frame error are plotted at FER = 10^{-14} (to allow visualization of zero on a log plot). Sixty of these passes have zero FERs (after removing nonzero frame error points with justification) and six remaining passes had nonzero FERs unaccounted for (pending further investigation). Out of ~388 million frames in the 66 passes examined, there were 6 passes containing 14 time instances (5-s monitor points) with 738 frame errors where no justification for deletion was readily identified.

Thus, at a minimum, a project such as NEOCam operating a link free of mode changes and uplink transfers with sufficient SSNR will expect to encounter few if any nonzero frame errors, and any occurrences should be constrained to isolated time instances (as shown for the cases discussed in Section III.C) allowing for easy retransmission via ARQ protocols. At best, one should expect effectively zero frame errors operating with sufficient margin, if such issues such as noted in Table 2 for Kepler are later confirmed to have explanations yielding justification for removal. It is understood that the link for NEOCam is designed for 95 percent availability so one should expect some pass-wide outages due to excessive rain fades, but even these will be reduced given the 8 dB margin assumed. The technique of ARQ can be used during instances of extreme rain fade conditions.

Kepler's link design makes use of a threshold of SSNR (E_s/N_0) > 0 dB for the case of BPSK with concatenated coding. This approximates the link performance of NEOCam's QPSK design with concatenated coding threshold $E_s/N_0 \sim E_b/N_0$ [10] which should be of order 2.7 dB. The link is assuming about 2.5 dB of implementation loss and 8.6 dB of margin, which should help realize the NEOCam project's desire to have virtually zero frame errors during their tracking passes.

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[10] The equivalence of E_s/N_0 and E_b/N_0 for QPSK deals with the fact that QPSK employs 2 bits per symbol, whereas BPSK employs one bit per symbol (given the same rate ½ coding scheme).

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