Weather-Impacting Link Analysis for New Horizons Data Return

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***Abstract* - This paper describes a recent effort in characterizing the weather conditions at the Canberra Deep Space Communications Complex of the National Aeronautics and Space Administration (NASA) Deep Space Network (DSN) to assess how they could impact the data return of the New Horizons mission during the Pluto encounter period. The frequency of rain occurrence is quantified based on recent 2014 statistics. The cumulative distribution of the precipitation rate during the rain events and the corresponding signal degradation are studied. The result is then evaluated against the anticipated link margin for two possible tracking configurations: one with a single 70m antenna, the other with an array of a 70m and three 34m antennas. The array offers a more robust link with greater margin, thus, a better protection against possible rain degradation; however, it would negatively impact other missions that require DSN support over the same period. The determination of possible improvement in terms of increased probability of data return offered by the antenna arraying helps selecting a strategy that best balances the benefit to the New Horizons mission and the impact to other missions concurrently supported by the DSN.**

Keywords - DSN; performance analysis; weather statistics; New Horizons

I. INTRODUCTION

The National Aeronautics and Space Administration (NASA) New Horizons mission is preparing for a historic encounter with the dwarf planet Pluto in July 2015. Since this is a once in a lifetime event, the mission design team wants to maximize the success probability of data return. A few weeks prior to the actual encounter on July 14, 2015, there will be several tracking passes that are critical to mission planning. These passes return the optical navigation data on possible hazardous objects around Pluto that are critical to the trajectory design of the flyby. There are also a few tracking passes immediately after the flyby that return the important scientific observation data.

To maximize the probability of data return over the scheduled passes to ensure the timeliness of trajectory design, the New Horizons mission is interested in quantifying if there is sufficient link margin to cover the adverse weather conditions. Rains – particularly the heavy ones – would reduce the received signal quality. In rainy condition, the signal to noise ratio is reduced by simultaneous effects of signal attenuation caused by the absorption and scattering of the raindrops, and of the increase in the ground system noise temperature.

In the previous baseline operation, the New Horizons mission plans to use the 70m antenna for the return of data. To get additional link margin, the mission could request for other 34m antennas to be added for arraying with the 70m. Doing so however would take away the tracking antennas needed by other missions. It is important then to understand if there is significant advantage with the array that would justify the negative impact to other missions.

In this paper, we will address the following questions:

(1) What is the probability of encountering the rain?
(2) In the event of rain, what is the likelihood that the signal degradation would exceed the available link margin?
(3) Would the extra gain from the array significantly improve the probability of a successful data return?

In Section II, we will discuss the available link margin for single antenna and the extra gain provided by the array. We will examine the statistics of events where rains affect the data return and quantify the probability that a pass may encounter rains in Section III. Section IV discusses the relationship between the precipitation rate (which is an indication on the intensity of the rain) and the signal degradation. Section V considers the statistics of precipitation rate observed in past rain events, assesses the probability where the link margin can sustain the signal degradation, and reflects the resulting operational planning under consideration. Conclusions are captured in Section VI.

II. AVAILABLE LINK MARGIN

The DSN has three tracking complexes spread evenly across the Earth longitudes in order to maintain a constant visibility to spacecraft in deep space. The three complexes are known as Goldstone, Canberra and Madrid Deep Space Communications Complexes, based on the its location in the United States, Australia and Spain. Each complex has a 70m antenna, one 34m high efficiency (HEF) antenna and at least two 34m beam-waveguide (BWG) antennas (Goldstone complex has one additional 34m BWG antenna). The distinction of the HEF vs. BWG antennas is due to their design and performance since the two sets of antennas were constructed at different time and with different technology and operations considerations. The HEF antenna offers a better signal performance because its design is optimized at X-band, but its support is limited to S- and X-band. The BWG design focuses mainly on X- and Ka-band, and offers other operational advantages such as the ease of maintenance and addition of other frequency bands as needed.

For the Pluto flyby operation, the New Horizons mission plans to have a reserved 1.5 dB link margin with the 70m antenna tracking. Arraying the 70m with other 34m antennas would add additional margin. Each 34m antenna has a slightly less than half of the antenna aperture and a higher zenith system noise temperature than that of the 70m antenna. Since the system noise temperature changes as a function of elevation – due to different amount of atmospheric noise contribution resulted from different path length that the signal travels through the Earth atmosphere – the relative performance metric of Gain over Noise Temperature (G/T) between the 34m and the 70m antennas varies over the elevation range of the pass. Table 1 shows the G/T of the 70m, 34m HEF and 34m BWG at some key elevation points.

TABLE I. G/T PERFORMANCE OF VARIOUS DSN ANTENNAS AND CONTRIBUTION OF 3X34M ARRAY TO THE 70M ANTENNA

Elevation	G/T_70-m, dB	G/T_34-m HEF, dB	G/T_34-m BWG, dB	Contribution of 34-m HEF to 70-m	Contribution of 34-m BWG to 70-m	Array Gain with 3x34-m added to 70-m, dB
10	57.6	52.0	51.5	0.28	0.24	2.37
20	60.1	53.6	53.3	0.23	0.21	2.08
30	61.0	54.3	53.9	0.21	0.20	1.96
45	61.3	54.5	54.2	0.21	0.20	1.95
80	61.2	54.8	54.5	0.23	0.21	2.07

At the referenced 45 deg elevation, the 34m antenna G/T is about 20% of the G/T of the 70m antenna. An array of the 70m and three 34m antennas (one HEF and two BWGs) would yield 61% improvement in G/T compared to that of the 70m antenna alone. Allowing for 0.1 dB loss due to imperfect estimation and thus compensation of the relative delays among the input signals to be combined, the array would add 1.95 dB gain to the original 1.5 dB link margin of the 70m antenna. At other elevations, the array gain is higher, extending up to 2.4 dB at the lower elevation of 10 deg. Thus, with the array configuration, the link would have a minimum of 3.4 dB margin.

III. RAIN STATISTICS

In this section, we examine the rain statistics observed at the DSN sites. Among the three sites, Canberra typically has more rain [1]. Thus, assessment on the rain impact is based on Canberra data.

Records of Canberra tracking passes during January – November 2014 indicated that there were 37 events of rain that affect the data return. The majority was associated with data loss; however, some just resulted in signal degradation without data loss. The total data affected was 6871 minutes over a 10-month period, equated to 1.6% of the time. The probability of a tracking pass affected by the rain is thus only 1.6%.

Since the Pluto Flyby will occur on July 14, 2015 and the critical passes under consideration take place in June – July 2015, there is a concern on whether the weather conditions during these two months are different from, or worse than, the average statistics. Table 2 shows the long-term averaged precipitation measured at the nearby Tidbinbilla Reserve [2]. July is typically considered as one of the rainier months.

TABLE II. TYPICAL PRECIPITATION AT TIDBINDILLA NEARBY CANBERRA TRACKING COMPLEX

Tidbinbilla Long-term Averages	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Mean Max (°C)	26.9	26.1	23.5	19.1	15.2	11.7	10.8	12.6	15.5	18.7	22.0	24.7	***18.7***
Mean Min (°C)	12.1	12.3	10.0	6.7	3.7	1.3	0.1	1.0	3.5	5.8	8.8	10.6	***6.2***
Mean Rain (mm)	83.2	75.3	69.1	65.7	67.7	66.9	83.8	95.8	92.6	89.9	91.7	65.1	***946.1***
Median Rain (mm)	62.9	48.1	43.3	38.2	59.7	54.4	69.5	89.5	86.8	81.2	81.2	54.0	***874.9***
Mean Rain Days	7.9	7.5	7.7	7.8	9.9	12.2	12.1	12.6	11.8	10.6	10.6	8.2	***115.6***

Next we examine at the rain statistics specifically in the past year of 2014 to further validate the long-term averages. Figure 1 shows the actual the day of year when the 37 rain events occurred and their duration in January – November 2014. The rain impact lasted from a few minutes to up to 10 hours, with an average duration of about 3 hours (185 minutes). The data also indicated that June and July were not particularly rainier compared to other months. Instead, the rains seemed to occur throughout the year, although with less rain in March and May.

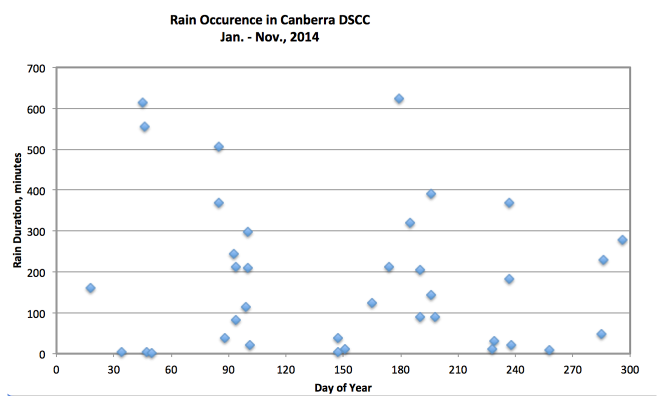

Figure 1. Rain Occurrence at Canberra Complex, January-November 2014

The recent rain observations in 2014 for the month of July is different from the long-term average shown in Table 2. We attribute the difference to be a variation of one specific year from the long-term average.

IV. SIGNAL DEGRADATION MODEL

As indicated in Section III, the chance of having a track coincides with a rain event is rather small (1.6%). However, if the track happens to be on a rainy day, we want to know the probability that the link margin can buffer the negative effect of the rain.

As signal travels through the rain, two effects occur. First, signal is attenuated because of scattering and absorption of signal power by the raindrops. The scattering diffuses the signal power. The absorption - due to a

 ISBN: 978-1-61208-397-1

resonance between the signal waveform and the vibration of water molecules - also draws the power away from the signal and transfers it to the increased motion of the water molecules. These effects become greater as there are more raindrops in heavier rains. Based on the Recommendation ITU-R P.838-3, Specific Attenuation Model for Rain for Use in Prediction Methods [3], the signal specific attenuation – attenuation per unit distance (dB/km) – can be modeled as a power function of the precipitation rate:

$$\gamma(R) = kR^{\alpha} \quad (1)$$

where:

γ is the specific attenuation (dB/km)

R is the precipitation rate (mm/h)

k = 0.0037825 (for circular polarization at X-band)

α = 1.38557 (for circular polarization at X-band)

The total attenuation is equal to the specific attenuation multiplied by the path length that the signal traverses through the rain. Assuming a height of rain cloud of h and a spacecraft line of sight at θ elevation, the signal attenuation path length L can be approximated as:

$$L(R) = \frac{\gamma(R).h}{\sin\theta} \quad (2)$$

In addition to the signal attenuation, the rain also causes an increase in the system noise temperature. This is due to the fact that the temperature of the rain (~300K) is much higher than that of typical cold sky (~25K) and the rain also acts as a lossy waveguide. As shown in [4], the increase in atmospheric noise temperature is:

$$\Delta T = (T_r - T_a)(L-1)/L \quad (3)$$

where:

ΔT is the increase in atmospheric noise temperature, K.

T_r is the rain physical temperature, ~300K.

T_a is the typical cold sky temperature, ~25K.

L is the rain attenuation.

Figure 2 shows a sample of the rain impact for the case of cloud height $h = 7.5\,km\ and$ spacecraft elevation $\theta = 45$ deg. This elevation is chosen as an example because it is almost the midpoint in the 10-80 deg elevation range expected with New Horizons tracking at Canberra. Individual effects of signal attenuation (given by (2)) and degradation in system noise temperature (given by (3)) are included, as well as the total degradation.

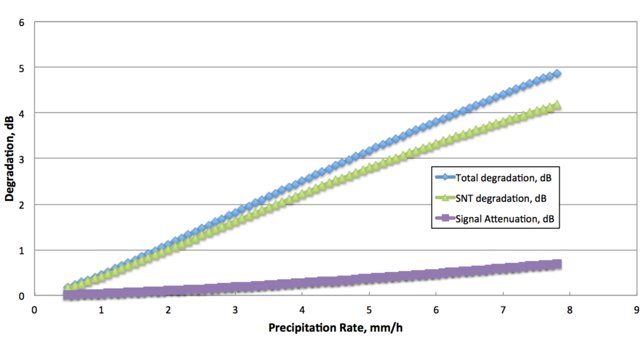

Figure 2. Modeled signal attenuation, system noise temperature degradation and total degradation for various precipitation rates at 45-deg elevation and 7.5 km rain height

V. ASESSMENT

For the particular case of 45-deg elevation and an assumed 7.5 km rain height, the single 70m antenna tracking with a 1.5 dB link margin could tolerate any rain with precipitation rate up to 1.5 mm/h. In contrast, with a 3.4 dB margin from an array of 70m and three 34m antennas, the link can sustain the rains up to 3.1 mm/h.

To determine the probability of occurrence of rain with precipitation rates of 1.5 mm/h and 3.1 mm/h, we examined the precipitation rate of each of the 37 rain events in 2014. The average precipitation rates are plotted in Figure 3. Twenty-five rain events (68%) were found to have precipitation rate below 1.5 mm/h, and 32 events (86%) below 3.1 mm/h.

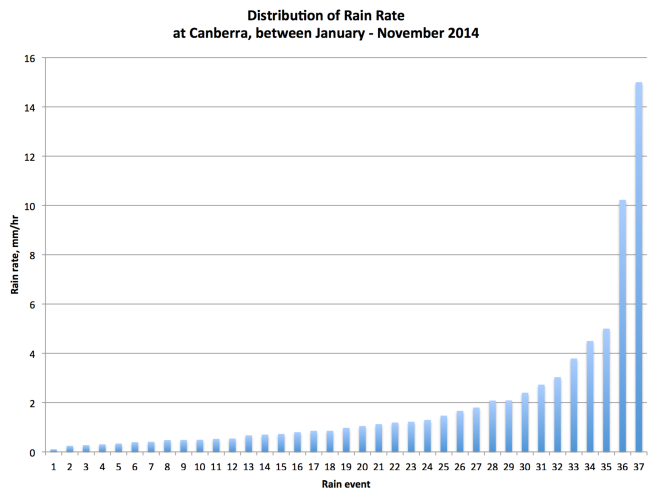

Figure 3. Distribution of precipitation rate from rain events in 2014 at Canberra.

Thus, the probability of sustaining the rain impact with a single 70m antenna tracking is 68%. With an array, that probability increases to 86%.

More general, the probability of successful data return at other elevations (10, 20, 30, 45 and 80 deg) is presented in Figure 4. At lower elevations, the single 70m antenna configuration has lower probability of success because the signal suffers more loss as it travels on a longer path through the rain. In those cases, the benefit of having extra gain provided via the array is more significant. At higher elevations, the single 70m antenna has greater chance to succeed due to smaller impact of the rain over shorter path. Correspondingly, there is a smaller improvement with the arraying.

Note that the New Horizons spacecraft does not spend equal amount of time across the elevation range. Because the spacecraft changes its elevation at a much faster rate during rise and set, the time spent at low elevations (10 – 30 deg) is much less than the time at high elevations (30 – 80 deg). In a typical New Horizons track at Canberra, 75% of the track time is above 30-deg elevation. Thus, in Figure 4, the region of high elevations above 30 degrees is more relevant to the assessment of improvement in the probability of success between the single 70m antenna and the array

 ISBN: 978-1-61208-397-1

configuration. At 30-deg elevation, the array would increase the probability of success from 73% to 89%. At highest elevation, the success probability increases from 86% to 95%.

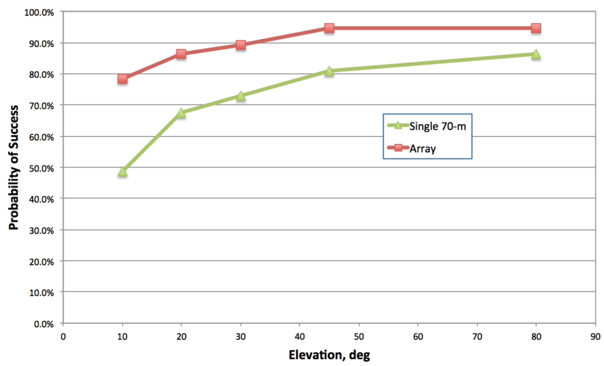

Figure 4. Probability of successful data return in the event of rain for single 70m antenna and array configuration

Given that the probability of success with the single 70m antenna at high elevation is already above 70% and the array only increases the chance by 9% – 16%, the New Horizons mission operations team, at the time of this report, is considering a hybrid approach (subject to the final decision). The mission would stay with the single 70m antenna configuration for these critical passes. That would allow other missions continue to be supported by other 34m antennas in the DSN. In the event of forecasted rain or encountering actual rain during the pass, the New Horizons mission would then request the 34m antennas, if available, to be added to the array to increase the probability of successful data return.

VI. CONCLUSION

In summary, our analysis indicates that the probability that a New Horizons' tracking pass could encounter rain is about 1.6%. When subjected to rain, there is a 73% chance that a New Horizons pass with a single 70m antenna would be able to sustain the rain's impact. If an array of one 70m and three 34m antennas is used, the link margin would increase by 1.95 dB and the success probability of weathering the rain would improve by an additional 9% – 16% at various tracking elevations. This analysis has aided the New Horizons mission planners to design a strategy that would maximize the probability of data return within various operational constraints.

ACKNOWLEDGMENT

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

REFERENCES

[1] DSN Telecommunications Link Design Handbook, Document No. 810-005, Rev. E, Jet Propulsion Laboratory, Pasadena, California, http://eis.jpl.nasa.gov/deepspace/dsndocs/810-005/, accessed December 20, 2014

[2] Weatherzone, http://www.weatherzone.com.au/climate/station.jsp?lt=site&lc=7031, accessed December 20, 2014

[3] Recommendation ITU-R P.838-3, Specific Attenuation Model for Rain for Use in Prediction Methods, http://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.838-3-200503-I!!PDF-E.pdf, accessed December 20, 2014

[4] R. A. Nelson, "Rain – How it affects the communications link", Via Satellite 2000, http://www.aticourses.com/sampler/Rain_Affect_Communicatons_Link.pdf, accessed Dec. 20, 2014