IPN Progress Report 42-223 • November 15, 2020

Demonstration of Advanced Ranging Instrument

James S. Border,* Meegyeong Paik,† Clement Lee,† Dong K. Shin,* Christopher P. Volk*

ABSTRACT. — For more than half a century, ranging measurements in the Deep Space Network (DSN) have contributed to spacecraft navigation and radio science investigations. Due to solar plasma noise conditions and systematic instrumental effect limitations, performance over the past three decades has remained near the 1 m level. To meet the goal of 10 cm ranging, JPL invested in the design and development of the Advanced Ranging Instrument (ARI) that will improve the accuracy of ranging measurements by one order-of-magnitude. The current ranging uses a single frequency uplink, 7.1 GHz (X-band). By using dual-frequency uplinks, X and 34 GHz (Ka-band), and generating three coherent downlinks (X-up/X-down, X-up/Ka-down, Ka-up/Ka-down), solar plasma noise can be removed completely and station delay can be measured continuously to obtain a precise calibration. Implementing wide-band pseudo noise (PN) code ranging further reduces system noise. The ARI has made these techniques available at Deep Space Station (DSS) 25 and initial tests were carried out with the European Space Agency (ESA) BepiColombo spacecraft in May and August 2019. The Ka-band range at 24 Mcps PN code has demonstrated a level of precision of ~1 cm.

I. Introduction

Radio science techniques linking spacecraft and Deep Space Network (DSN) antennas have advanced solar system exploration for the past five decades. These techniques provide unique information about solar system bodies, solar wind, and fundamental physics. As described at the recent NASA Planetary Sciences Vision 2050 Workshop [1], a number of new technologies that offer the possibility of significantly enhanced or qualitatively new measurements are becoming available.

The DSN recently developed the Advanced Ranging Instrument (ARI) [2] to enable an order-of-magnitude improvement in spacecraft ranging (from the current 1 m standard to 10 cm precision). The key enabling DSN element is Ka-band uplink pseudo-noise (PN) ranging at a high chip rate. The DSN added ranging capability to the Ka uplink at DSS-25. The uplink ranging assembly and the block 6 exciter [3] provide PN chip rates as high as

* Tracking Systems and Application Section.

† Communications Architectures and Research Section.

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

24 Mcps. Additionally, an advanced spacecraft transponder that regenerates the PN uplink is necessary for the highest accuracy. The European Space Agency's (ESA) BepiColombo spacecraft [4] regenerates a PN-code ranging uplink on three radio frequency links: X-up/X-down at ~3 Mcps, X-up/Ka-down at ~3 Mcps, and Ka-up/Ka-down at ~24 Mcps.

The Mercury Orbiter Radioscience Experiment (MORE) [4] on the BepiColombo mission uses high-accuracy Doppler and range to generate a high-resolution gravity map of Mercury, allowing inference of the interior structure of the planet. MORE will also enable significant improvements in fundamental physics measurements, such as 10 times greater determination of the post-Newtonian parameter gamma and 20 times greater dynamical determination of the solar oblateness. Previously, only Doppler were available for these types of investigations with Cassini. The Cassini measurement of the deflection parameter gamma was a significant advance in measuring post-Newtonian parameters. The new DSN ranging capability will further enhance fundamental physics measurements.

The new DSN ranging capability has been demonstrated with BepiColombo passes at Deep Space Station (DSS) 25 in 2019. This article describes the DSN enhancements and presents the results of the measurements from the initial tests with BepiColombo.

II. DSN Upgrades

Ka-band uplink capability was added at DSS-25 (a 34 m beam-waveguide station at the Goldstone DSN complex) in the late 1990s to support the Cassini Gravity Wave Experiment. At that time, only a carrier signal could be transmitted in the 34 GHz band. Modifications were required to add a ranging uplink capability. While some new assemblies were needed for ranging uplink capability, most of the modifications were phased in during regular DSN upgrade cycles. Figure 1 shows the principle components in the Ka-up/Ka-down ranging system.

Previously, ranging uplink was only available at S-band and X-band. Pseudo-noise ranging was available at low chip rates (about 2 Mcps) using a code, known as the DSN code, developed by Robert Tausworthe [5]. The uplink control software was modified to enable ranging on a Ka-band uplink. The uplink signal generator was modified to provide a PN ranging signal using either the Consultative Committee for Space Data Systems (CCSDS) T2B or T4B code [6] with a chip rate up to 24 Mchip/s. The high chip rate improves precision and is needed to meet radio science requirements. The block 6 exciter was modified to provide modulation on a Ka-band uplink signal. A zero-delay device for the Ka-up/Ka-down link was built to calibrate the test translator for this link.

Ranging signals are recorded in wide channels on the open loop receiver (OLR) for each of the six links. There are RF links for X-up/X-down, X-up/Ka-down, and Ka-up/Ka-down from both the spacecraft and the station uplinks routed back through the test translators. Data are transferred from the OLR to the Advanced Ranging Processor (ARP) at Goldstone in near real-time. ARP uses software to extract Doppler and ranging for all six signal links. The processed data are output in tracking data message (TDM) format [7] for use by radio science or navigation.

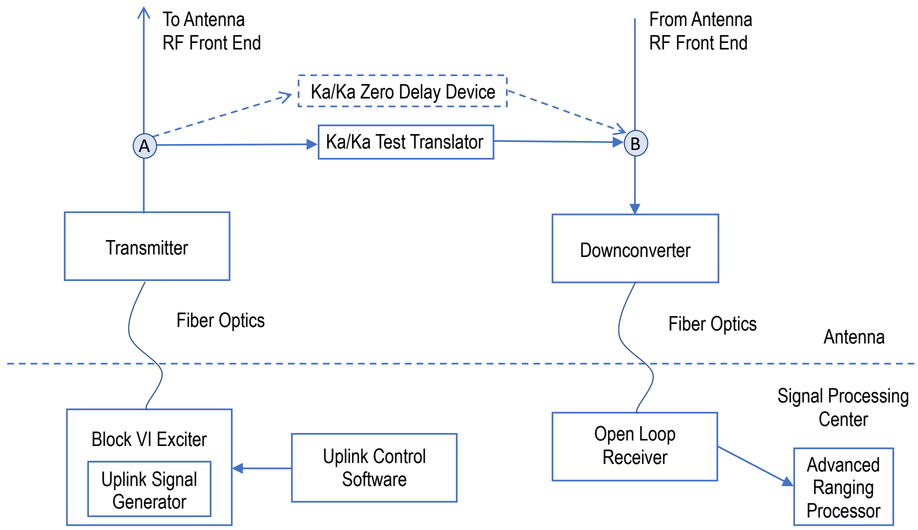

Figure 1. Principle components of the DSN ranging system for Ka-band uplink and downlink.

III. Open-Loop Ranging

Normally in the DSN, Doppler and range data are provided in real-time by a closed-loop receiver [8]. However, open-loop techniques have advantages in some situations. The DSN open-loop ranging technique was developed to provide high-accuracy data for radio science experiments [2]. The uplink signal is continuously looped through the test translator and measured at the OLR at the same time as the spacecraft signal. A turnaround ratio for the test translator is chosen so that the spacecraft and test translator signals are at about the same frequency, assuming telemetry is not required during the radio science passes. The frequency alignment provides better cancellation of instrumental phase errors. The continuous measurement of the test translator signal throughout the pass calibrates temporal drifts in station instrumental delays.

The open-loop ranging observable is defined as

$$R_{OL}(t) = \phi_{TT}(t) - \phi_{SC}(t)\,, \tag{1}$$

where $\phi_{TT}(t)$ is the phase of the test translator range code measured at the OLR and $\phi_{SC}(t)$ is the phase of the range code received from the spacecraft and measured at the OLR. Referring to Figure 1, note that the station delay calibration required for closed-loop ranging is implicitly included in Equation (1). Measuring the two signals in the same assembly, with respect to the same station timing signal, eliminates the timing jitter found in closed-loop tracking where the uplink signal is measured in one assembly while the downlink signal is measured in a different assembly. Also, the closed-loop system uses carrier aiding to freeze the ranging signal at the beginning of the averaging interval and uses the beginning of the averaging interval as the time-tag. This causes some distortion in a measurement during solar conjunction experiments since the effect of charged particles has the opposite sign for phase delay and group delay. The open-loop technique eliminates this error by measuring variations in the range code phase over time within the averaging interval and by using the center of the averaging interval as the time-tag.

Measurement precision is improved when using spacecraft transponders that regenerate the uplink PN ranging signal. Using a higher PN chip rate, such as 24 Mcps, also improves measurement precision. Further, the higher chip rate reduces instrumental errors caused by phase non-linearities in the station signal chain. Finally, charged particle errors can be eliminated by using multiple frequency links. All of these advantages are needed to reach the 10 cm accuracy in the error budget presented in Reference [2]. Table 1 contrasts current DSN ranging at X-band with the Advanced Ranging Instrument using multiple frequency links.

Table 1. Comparison of current X/X ranging with advanced Ka/Ka ranging.

Comparison	ARI	Current Ranging
One-way Range Accuracy	0.1 m unconditionally	1 m conditionally
Restriction	Independent of Sun-Earth-Probe (SEP) angle	SEP > 30°
Frequency Links Uplink and Downlink	Simultaneous multi-frequency ranging X/X, X/Ka, Ka/Ka	Single X/X
Plasma Calibration	Completely calibrate plasma noise	N/A
Station Delay Calibration	Continuously measure for X/X, X/Ka, Ka/Ka	Pre-cal or Post-cal
Tracking Mode	Open-loop	Closed-loop
Signal Processing	Post-processing	During a track
Spacecraft Transponder	Regenerative	Non-regenerative
DSN Uplink Ranging System	X and Ka	X
Ranging Scheme	T2B, T4B PN Code (CCSDS)	Sequential, DSN PN
PN Code Chip Rate	~3 Mcps for X, ~24 Mcps for Ka	~2 Mcps for X

IV. Demonstration with BepiColombo

Two time-intervals, between arcs of ion thrusting, were identified in 2019 for commissioning of the MORE instrument on BepiColombo. A tracking campaign was organized to obtain Doppler and range and verify data performance against the MORE requirements. BepiColombo uses a deep space transponder for its primary communications. The X-band uplink is coherently transponded at X and Ka downlinks, with the uplink 3 Mcps PN range code regenerated onboard the spacecraft. BepiColombo also has a transponder for Ka-up and Ka-down, and the uplink 24 Mcps PN range code is also regenerated onboard the spacecraft.

Data were acquired at both the DSS-25 and the ESA tracking station at Malargüe, Argentina. ESA has also implemented Ka-band uplink and advanced water vapor radiometry in its tracking network to support radio science investigations. Joint analysis of data from the two networks is ongoing and will be necessary to validate the data to the level of accuracy required for MORE and other radio science investigations. This article reports on the internal consistency and precision of the ranging data acquired at DSS-25.

Data were acquired during 12 tracking passes at DSS-25 in May 2019 and six tracking passes in August–September 2019. The uplink was from DSS-25 for some passes providing two-way data. For other passes, the uplink was provided by Malargüe and three-way data were acquired at DSS-25. The tracking passes are summarized in Table 2. TDM files with Doppler and range observables were written for all passes and links with successful acquisition shown in Table 2. Some opportunities were lost early in the campaign until we were able to verify the polarization of the Ka-band uplink from DSS-25 and the polarity of the PN codes expected by the spacecraft for the two uplinks. They differ!

Table 2. Summary of BEPI ranging passes in 2019.

Year-DOY	Date	Duration	Mode	X/X Range	X/Ka Range	Ka/Ka Range	X Chip Rate	Ka Chip Rate
2019-122	May 2, 2019	1.3 Hrs	3-way			Y		~24 Mcps
2019-126	May 6, 2019	2.1 Hrs	2-way	Y	Y		~2 Mcps	
2019-131	May 11, 2019	2.3 Hrs	2-way	Y			~2 Mcps	
2019-132	May 12, 2019	1.7 Hrs	2-way	Y			~2 Mcps	
2019-133	May 13, 2019	2.3 Hrs	3-way			Y		~24 Mcps
2019-136	May 16, 2019	1.4 Hrs	3-way			Y		~24 Mcps
2019-137	May 17, 2019	2.5 Hrs	3-way			Y		~24 Mcps
2019-140	May 20, 2019	3.1 Hrs	3-way			Y		~24 Mcps
2019-141	May 21, 2019	2.3 Hrs	3-way			Y		~24 Mcps
2019-143	May 23, 2019	1.5 Hrs	3-way			Y		~24 Mcps
2019-147	May 27, 2019	2.7 Hrs	2-way	Y			~3 Mcps	
2019-149	May 29, 2019	2.7 Hrs	3-way			Y		~24 Mcps
2019-223	Aug 11, 2019	2.5 Hrs	2-way			Y		~24 Mcps
2019-231	Aug 19, 2019	1.5 Hrs	2-way			Y		~24 Mcps
2019-236	Aug 24, 2019	1.4 Hrs	2-way	Y		Y	~3 Mcps	~24 Mcps
2019-237	Aug 25, 2019	1.5 Hrs	2-way	Y		Y	~3 Mcps	~24 Mcps
2019-243	Aug 31, 2019	2.5 Hrs	2-way	Y		Y	~3 Mcps	~24 Mcps
2019-244	Sep 1, 2019	1.5 Hrs	2-way	Y		Y	~3 Mcps	~24 Mcps

For each scheduled DSN pass, a recording script was developed for the OLR. Wide channels were recorded for each of the three RF downlinks that captured both the spacecraft ranging signal and the test translator ranging signal. Signals are separated at the ARP by their Doppler profile differences. Standard antenna, exciter, and receiver predicts were provided to the station.

New operational procedures were developed for (1) configuring the PN ranging code to CCSDS T2B; (2) setting a new chip rate for each band; (3) enabling the test translator to convert the uplink signal to a downlink signal and inject the downlink signal into the downlink path for the entire pass time; (4) configuring the test translator attenuator to set the translated downlink signal to noise spectral density ratio to 60 dB-Hz. Additionally, a new ranging table was developed to configure the ranging system. A new uplink table was developed for the uplink acquisition that includes calibration frequency, tuning parameters, test translator turn-round ratio, and transmit power.

During the track, data are streamed from the OLR to the ARP for real-time data processing using Linux tail and piping to secure shell (ssh). When the streaming data transfer is buffered enough, real-time processing goes uninterrupted. ARP first tracks the carrier, modeling carrier phase, phase rate, and phase acceleration with a phase locked loop (PLL). The resulting estimated phase rate is scaled to the code clock rate, allowing the code clocks to be tracked similarly and separately via two more PLLs. The PN code has a separate acquisition to determine the initial code delay prior to the delay lock loop (DLL), which then tracks the code model (phase, phase rate, phase acceleration). The DLL uses a chip rate scaled from the carrier phase rate, similar to that of the code clock loops. Since the larger dynamics are removed in the carrier tracking loop, the resulting dynamics in the following loops are much smaller, allowing for longer integration times, which improves the signal-to-noise ratio (SNR) in the phase estimates of the code clocks and PN code.

Spacecraft and test translator range estimates are created by combining the model phase and loop residual estimates from the PN code and code clocks. The code clocks offer the best range precision but have ambiguity beyond one code clock cycle. The PN code phase corrects this ambiguity error. The range observable is the difference between the test translator range clock phase and the spacecraft range clock phase. Doppler observables are created using a polynomial fit to 1-second intervals of the accumulated phase from the carrier tracking loop.

V. Results

During the time period reported on here, BepiColombo was tracked by both the European Space Tracking (ESTRACK) network and DSS-25. Ka-band uplink and Ka-band downlink were used at DSS-25 and at the ESTRACK station at Malargüe to acquire Doppler and ranging data. Tracking data were also acquired at X-band. The DSN data were provided to the European Space Operations Center (ESOC) for comparison with ESTRACK data. It was reported that the ESTRACK and DSN data were in good agreement [9] [Frank Budnik, ESOC, private communication 2019].

For the geometry of these passes, the spacecraft was no more than 0.3 AU from Earth and solar plasma effects are very small at Ka-band. Only Ka-band data are analyzed in this article.

The data were examined by the project navigation team and found to be in general agreement with standard ESA tracking data. In this article, a single range bias is estimated for each station and for each data arc. Thus, we are not determining the absolute accuracy of the ranging data, but rather the precision and internal consistency. This strategy also eliminates the problem of calibration between uplink and downlink for three-way range. On some tracks where Malargüe had the uplink, DSS-25 acquired data in the three-way mode. Figure 2 shows ranging residuals for both two-way (Malargüe) and three-way (DSS-25) data on May 17, 2019. Each data set has a root mean square (RMS) below 1 cm. The two data sets show similar trends at the 1 cm level, likely due to media effects on the uplink.

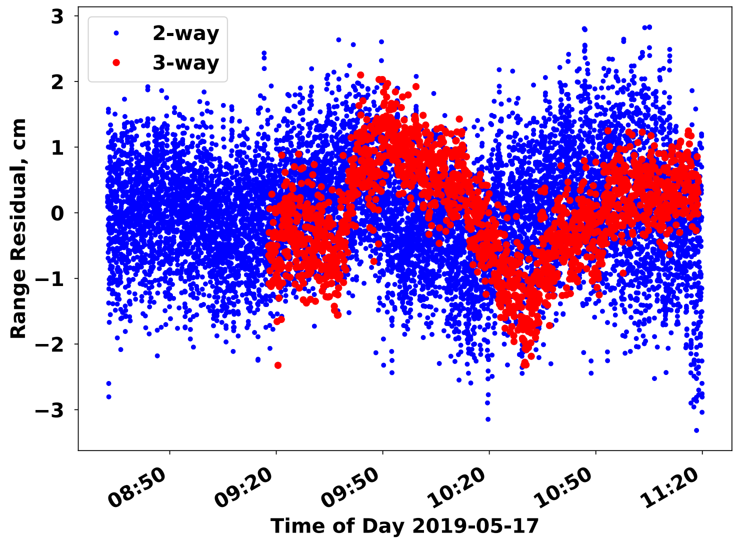

Figure 2. Comparison of two-way range from Malargüe and three-way range from DSS-25 (Malargüe data courtesy of Virginia Notaro, Sapienza University of Rome).

The DSS-25 data were calibrated point-by-point for variations in station delay, as discussed in the Open-Loop Ranging section. Figure 3 shows a plot of the variations in station delay during the August 31 pass. These variations were evidently removed from the ranging observables using the formulation of Equation (1). The RMS of the calibration signal residuals is 1.43 cm.

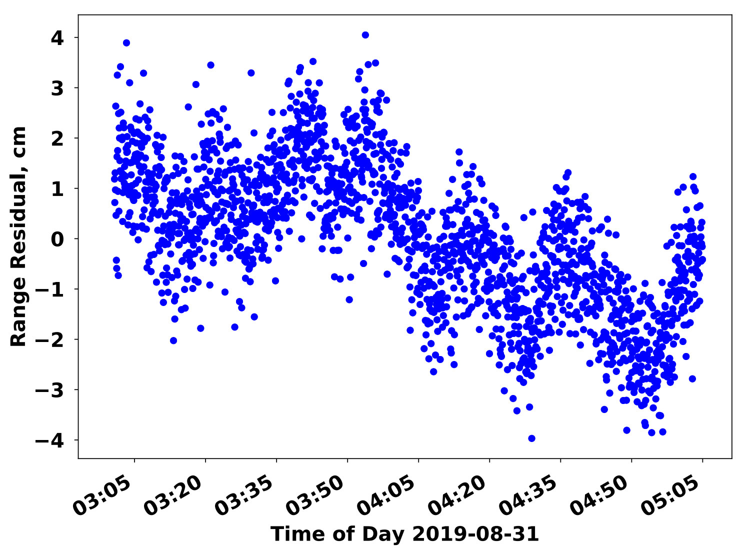

Figure 3. Variations in station delay from test translator signal loop measurements during the August 31 pass.

To assess the quality of the DSN two-way ranging data, two data arcs of several days' duration were selected. For each arc, a solution was done fitting to the Ka-up/Ka-down Doppler and range. A 1 sec count time was used for Doppler and a 4 sec integration time was used for range. Only spacecraft epoch state and a single range bias were estimated for each arc. Figure 4 shows ranging residuals for August 19–24. Doppler and range were fit flat for the two days separated by five days. The range RMS is 0.54 cm. Figure 5 shows ranging residuals for August 25 to September 1. Again, Doppler and range were fit flat over the three days and the range RMS is 0.69 cm. Doppler data were also fit very well giving further confidence in the internal consistency. There was an apparent spacecraft thrusting event between August 24 and August 25. Without knowledge of the event, we are unable to get a high-quality fit spanning the event.

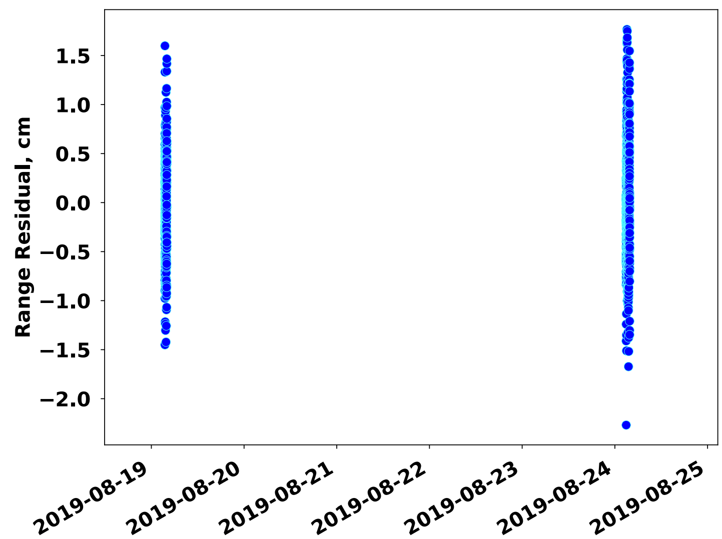

Figure 4. Two-way range residuals for DSS-25 data acquired from August 19 to August 24.

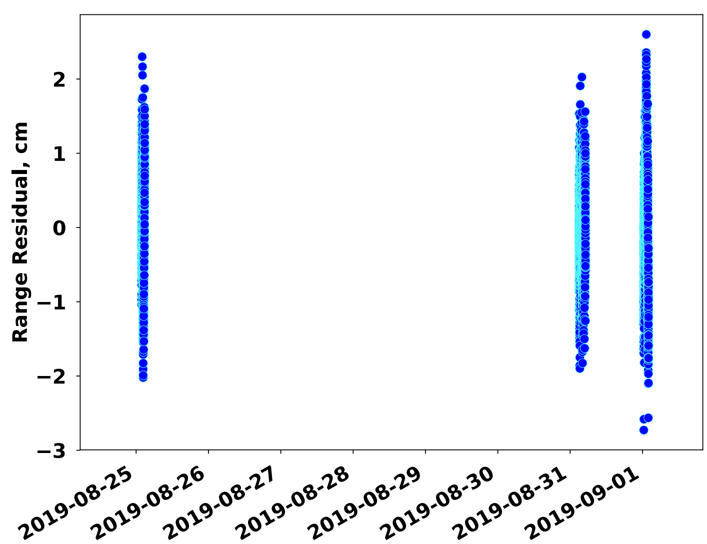

Figure 5. Two-way range residuals for DSS-25 data acquired from August 25 to September 1.

These solutions demonstrate that the precision of the ranging measurements is well within the error budget predicted in Reference [2]. The solutions also show data consistency over several days. However, there is not enough data at this time to verify the absolute accuracy of the ranging measurements to the predicted level of 10 cm. An independent orbit solution with accuracy of order 10 cm is not available. More data is required, preferably from two stations, for this purpose. A larger data campaign will be needed to accomplish this goal.

VI. Summary

Uplink ranging capability in the 34 GHz band has been implemented at DSS-25 for support of radio science experiments. PN chip rates as high as 24 Mcps are available to achieve high accuracy. Station procedures were developed to acquire ranging data at three RF links with continuous calibration of station delay using the signal loop through the test translator. Also, capability was developed to process data recorded on the OLR into Doppler and range observables in standard format for use in radio science and navigation.

Data were acquired during two tracking campaigns in 2019 to commission the MORE instrument for ESA's BepiColombo mission. Data fits have validated the precision and internal consistency of DSS-25 two-way ranging data at the sub-centimeter level. Further tracking data campaigns and joint analysis with data from the ESA station at Malargüe will be required to validate the absolute accuracy of the data to the 10 cm level.

Acknowledgments

This DSN upgrade was made possible by the JPL system engineers and implementers who contributed through the course of their work. We thank Virginia Notaro of Sapienza University of Rome and Tomas Martin-Mur of JPL for their valuable feedback on our preliminary data processing. We are also grateful to Tomas for the setup of the navigation software used for the final data fitting and evaluation. This work has been carried out with funding from the JPL Research and Technology Development Program.

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