UAS-Based P-Band Signals of Opportunity for Remote Sensing of Snow and Root Zone Soil Moisture

Simon Yueh*[a], Rashmi Shah[a], Xiaolan Xu[a], Kelly Elder[b], Steve Margulis[c], Glen Liston[d], Michael Durand[e], Chris Derksen[f], and Jack Elston[g]

[a]Jet Propulsion Laboratory, California Institute of Technology, California, USA

[b]United States Forest Service, Fort Collins, Colorado, USA

[c]University of California at Los Angeles, California, USA

[d]Colorado State University, Fort Collins, USA

[e]Ohio State University, Columbus, Ohio, USA

[f]Environment and Climate Change Canada, Canada

[g]Black Swift Technologies, Colorado

ABSTRACT

We have developed the P-band Signals of Opportunity (SoOp) sensor based on the Unmanned Aircraft System (UAS) to remotely sense Snow Water Equivalent (SWE) and Root Zone Soil Moisture (RZSM). The P-band UAS SoOp sensor for Hydrology (UASHydro) would operate on the S2 aircraft developed by Black Swift Technologies for sensing of SWE and RZSM with a spatial resolution of about 10m. Root-zone soil moisture and snow water storage in land are critical parameters of the water cycle. The long-term goal of our development would be to use small UAS to perform regional high resolution observation of two key hydrological measurements to improve the estimation of terrestrial water storage for water management, crop production and forecasts of natural hazard. The UASHydro concept utilizes passive receivers to detect the reflection of strong existing P-band radio signals at the 360-380 MHz band from geostationary Mobile Use Objective System (MUOS) communication satellites launched by the US Navy. The SWE remote sensing measurement principle using the P-band SoOp is based on the propagation delay (or phase change) of radio signals through the snowpack. The time delay of the reflected signal due to the snowpack with respect to snow-free conditions is directly proportional to the snowpack SWE, while the soil moisture can be retrieved from the reflectivity at the P-band frequencies for MUOS. We have been conducting ground-based campaigns to test the instrumentation and data processing methods at the Fraser Experimental Forest in Colorado since February 2016. The field campaign data has provided support to the measurement concept. To install the SoOp technologies on the UAS, a lightweight antenna has been built and interfaces with the S2 built by Black Swift Technologies have been completed. A set of flights have been planned starting April 2018 through the end of 2018 in Colorado.

Keywords: microwave remote sensing, snow, soil moisture

INTRODUCTION

Despite their importance, Snow Water Equivalent (SWE) and Root Zone Soil Moisture (RZSM) are arguably two of the least measured hydrologic states in the Earth System. Snow covered area can be relatively easily measured remotely using visible/near-infrared sensors (except for heavily forested areas which can mask underlying snow), but such measurements provide no direct information on the mass of snow on the ground. Methods using multi-frequency passive microwave measurement techniques (e.g. [1,2,3]) have a long heritage, but are known to suffer from many problems including, the many-to-one relationship between brightness temperature and SWE, sensitivity to grain size, signal saturation for deeper snow and the high-degree of sub-grid heterogeneity in mountainous environments [4]. With respect to soil moisture, the Soil Moisture Active Passive (SMAP) mission [5] or the airborne Passive/Active L-band system (PALS) [6] are already providing new insight into near-surface soil moisture storage, but does not provide direct information about RZSM, which plays a key role in the evapotranspiration/latent heat flux to the atmosphere and the modulation of recharge to near-surface groundwater aquifers.

The current state-of-the-art remote sensing method for RZSM is based on the multi-frequency P-/L-band synthetic aperture radar technique [7]; however, the US Department of Defense has recently worked with the International

Telecommunication Union (ITU) to designate the US Space Objects Tracking Radar (SOTR) as the primary user of the 435 MHz band. This change will prohibit spaceborne P-band earth remote sensing radars from operating over North America and most of Europe, severely limiting our ability to monitor RZSM. At this point, there are no clearly viable alternative remote sensing methods for RZSM and SWE under canopy.

The UASHydro concept based on the P-band SoOp technologies for remote sensing of SWE and RZSM will provide cost effective observations. P-band frequencies will have the capability to penetrate through heavy vegetation and snow, offering potential new capabilities not achievable by current GNSS-R and high frequency (>10 GHz) microwave technologies.

P-BAND SIGNALS OF OPPORTUNITY CONCEPT

Land and ocean remote sensing with Signals of Opportunity, such as Global Navigation Satellite System (GNSS) reflectometry (GNSS-R), has been developed substantially over the last 15 years, culminating in the selection of the CYGNSS tropical storm observation mission by NASA [8]. The use of GNSS signals at L-band (1.2 and 1.5 GHz) for surface soil moisture retrieval has been demonstrated by airborne measurements during the Soil Moisture Experiment 2002 [9] and a field campaign in Europe [10], and its theoretical principle is based on the response of L-band microwave reflectivity to surface soil moisture [11]. The sensitivity of GNSS-R data to soil moisture was also shown using CYGNSS precursor mission TechDemoSat-1 [12] and the SMAP data in Australia [13].

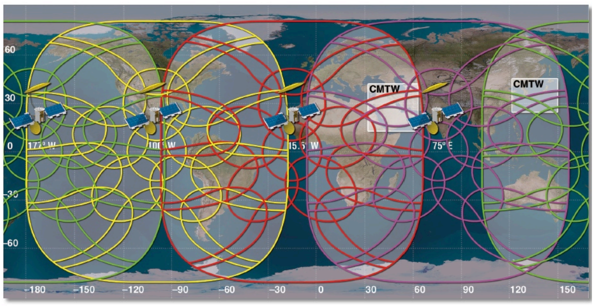


Figure 1. Global coverage of 4 MUOS satellites in geostationary orbits (top). The sampling coverage by three SoOp Cube-satellites operating at sun-synchronous orbits with 3-day repeat.

Navigation (GNSS) signals were well matched for reflectometry, due to their use of pseudorandom noise (PRN) codes for ranging. GNSS signals, however, have a few significant disadvantages, particularly for application to land remote sensing including: very low signal power, a spectrum allocation restricted to L-band, and limited penetration into soil and forest canopies.

The particular P-band communication satellites of interests to the UASHydro concept are the Navy's Mobile Users Objective System (MUOS) operating at P-band frequencies [14]. There are four MUOS satellites at geostationary altitudes, providing global coverage, except near the polar cap (Fig. 1). Each satellite broadcasts dual-frequency channels at P-band (360-380 MHz and 240 -270 MHz). The transmit power in terms of power density on the ground is significantly stronger than GNSS, thus allowing the airborne UASHydro SoOp receivers using small antennas to capture reflection with a high signal to noise ratio.

SOOP MEASRUEMENT PRINCIPLE FOR SNOW

Dry snow

The P-band SoOp measurement principle (Fig. 2) uses repeat pass data to exploit the change of coherent phase for radio propagation through dry snowpack [15,16]. For low incidence angles and small snow density, ϕ_s can be approximated by [17,18]

$$\phi_s = \frac{4\pi}{\lambda}\frac{0.8d\rho}{cos\theta} = \frac{4\pi}{\lambda}\frac{0.8SWE}{cos\theta} \qquad (1)$$

Therefore, the phase change is approximately linearly related to the SWE of dry snowpack.

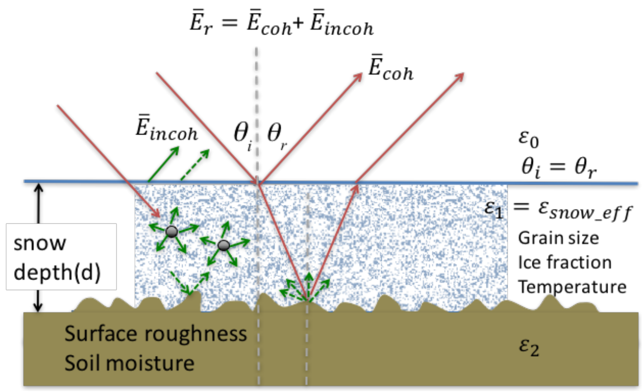


Figure 2. Physical principle of SoOp modeled by stratified medium. The reflected signal consists of coherent and incoherent electric fields, characterized by E_{coh} and E_{incoh}.

This suggests we can use SoOp (bistatic) repeat pass phase detection to detect the phase change caused by the change of SWE (accumulation or depletion). This measurement principle has been demonstrated using field campaign data acquired in 2016 at Fraser Colorado [19]. The test site from which data was acquired in early 2016 has no tree cover, just natural ground with rough surface and residual vegetation debris. The unwrapped phase time series was computed from data collected daily between 5 AM and 6 AM MST between Jan. 16, 2016 and March 11, 2016. There was a high correlation between phase change and SWE (0.94), covering several snowfall and melt/refreeze cycles, while a lower correlation was found between phase change and snow depth (0.69). The root mean square error (RMSE) of the linear regression of retrieved SWE and *in situ* SWE was found to be 7.5 mm [19].

Wet Snow

We have applied the stratified medium model [20] to examine the effects of wet snow. The dielectric constant of wet snow is characterized by wetness as well as temperature and density [21]. We find that the dielectric constant of wet snow essentially does not change in the frequency range of 260 MHz-1GHz, indicating that the snowpack is essentially non-dispersive in this range of frequencies. The imaginary parts remain quite small from moist to very wet (3-15%). As the snow wetness increases, the dielectric contrast between ground and snow reduces, leading to a reduction in reflection between the snow and ground interface. In contrast, the dielectric contrast between air and snow increases with wetness. When the wetness reaches above 5%, the total reflection will be dominated by the reflection from the air-snow interface.

The changing dominance of air-snow and snow-ground interfaces leads to the changing correlation of reflected signal with SWE or snow depth [16]. When the snow becomes considerably wet (>5%), the phase change of reflected signal will reduce with increasing snow depth because the air-snow interface will move toward the receiver, thus reducing the path delay (Fig. 3). In this case, the phase angle is related to the snow depth or SWE by

$$\phi_s = -\frac{4\pi}{\lambda} d\cos\theta = -\frac{24}{\rho} f\cos\theta \cdot SWE \qquad (2)$$

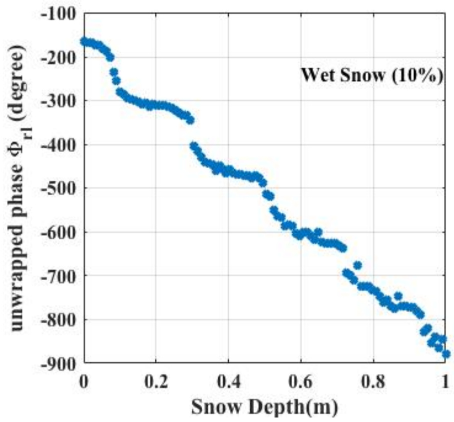


Figure 3. Phase change is related to snow depth for very wet snow where the air-snow interface dominates the coherent reflection. MEMLS snow dielectric model [21] is used for the dielectric constant of snow with wetness. Results correspond to frozen ground and random snow density between 200-300 kg/m^3.

where "*f*" is in GHz. Hence, for wet snow, the SoOp reflectometer will perform like an altimeter, being most sensitive to the depth of snowpack for wet snow.

SoOp Measurement Principle for RZSM

The P-band MUOS frequencies allow a penetration of ~0.5-1 m into the soil to sense the change of moisture in the root zone. The P-band frequencies complement the L-band frequencies for the Soil Moisture Active Passive (SMAP) and CYGNSS missions, which are primarily sensitive to the soil moisture in the top few centimeters of soil. We have carried out a modeling analysis based on the stratified medium model. The dielectric constant of the soil is evaluated using the Mironov model [22]. The reflectivity at the MUOS and GNSS frequencies show varying degrees of sensitivity to the soil moisture at the depth of 50 cm. Through theoretical modeling analysis, we find that the dual-band MUOS signals together with the CYGNSS L-band reflectivity data can allow estimation of soil moisture profile.

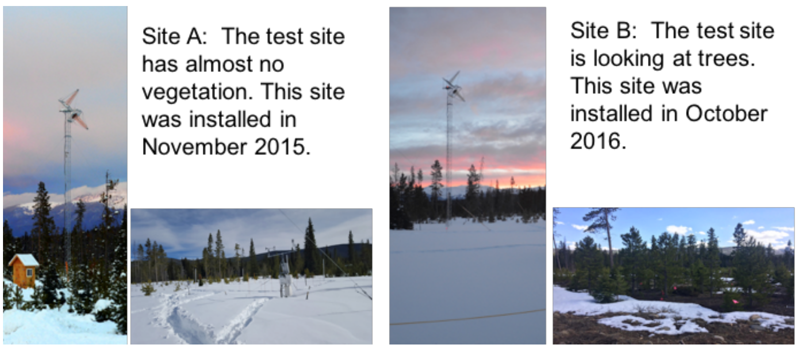


Figure 4. Experimental setup at USFS FEF located at Fraser Colorado: Site A (no vegetation) and Site B (vegetation). Dual-frequency P-band SoOp receivers at each site for data acquisition every three hours.

We have completed a proof-of-concept experiment alongside an intensive system of *in situ* sensors to validate the SoOp concept at the Fraser Experimental Forest (FEF) Headquarters, near Fraser, Colorado (39.847°N, 105.912°W) during 2015-2017. FEF is a 93 km^2 research watershed in the heart of the central Rocky Mountains approximately 80 km west of Denver. The FEF Headquarters is operated by the US Forest Service (USFS) with the intent to study watershed hydrology in the subalpine zone. This site maintains long-term records on hydrology, climate, forest structure and growth, and responses to forest management. FEF's favorable location, network of other instrumentation, and long record of climate monitoring made it a well-suited site for this research.

A flat location at FEF with little forest vegetation was selected in 2015-2016. A 15.2 m tower was erected with P-band antennas, LNAs, and filters installed at the top. One additional tower was deployed in summer 2016 to make observations at two locations with different background roughness and vegetation cover. Both of these sites recorded data at MUOS frequencies. The data was recorded every three hours. The new site has some lodgepole pine with trees up to 3 meters in height (Fig. 4). So, a study on the effect of vegetation on the under-canopy snow measurement can be done with this site.

During the experiments, *in situ* measurements of snow depth and other snowpack properties were performed every one to two weeks for comparison with the remotely sensed data. Snowpack measurements were taken next to the tower site in a location that would not compromise the satellite signal. A network of soil moisture sensors, time-lapse cameras, acoustic depth sensors, and meteorological instruments were installed next to the site to collect *in situ* measurements of snow, weather, and soil conditions. The camera recorded images three times a day (during daytime) and the soil moisture probes, located at 5 cm, 10 cm, 27 cm, and 40 cm, recorded soil moisture and soil temperature at the same interval as that of the reflection data i.e. every three hours.

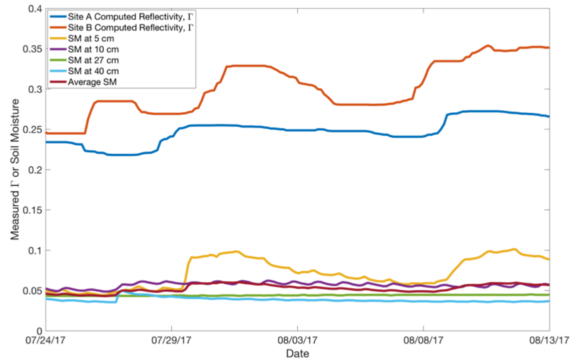


Figure 5. The measured reflection coefficient from two sites (not vegetated and vegetated) in summer 2017. A similar trend is observed from both sites. The in situ soil moisture

The SoOp receivers also collect data during the summer (i.e. snow free conditions) which is being used to develop the algorithm for extraction of reflectivity from the data for the purposes of RZSM retrieval. For examination of reflectivity, the power (as opposed to phase) of the reflected signal data with reference to the direct signal data is being examined. Figure 5 shows the time series of reflectivity measurements from 367 MHz signal during July – August 2017 and the *in-situ* measurement from soil moisture probes at the depth of 5, 10, 27, and 40 cm, daily. Figure 6 shows the reflection coefficient magnitude versus soil moisture at both sites. It can be seen that the reflectivity correlates with in situ soil moisture very well.

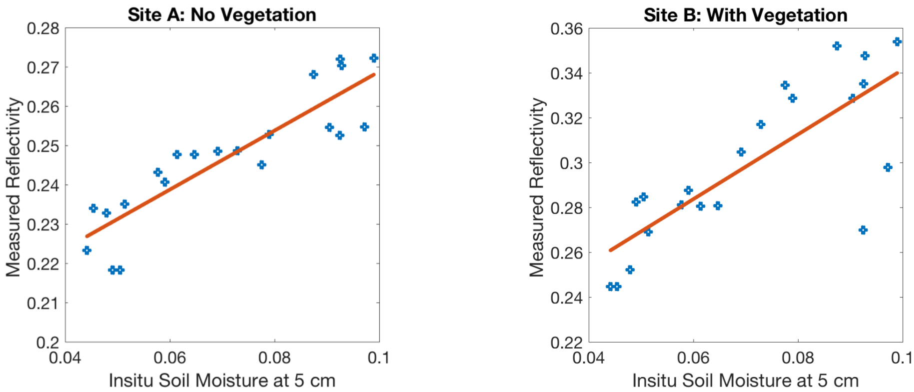


Figure 6. The measured reflection coefficient from two sites (not vegetated and vegetated) in summer 2017 versus the soil moisture observations.

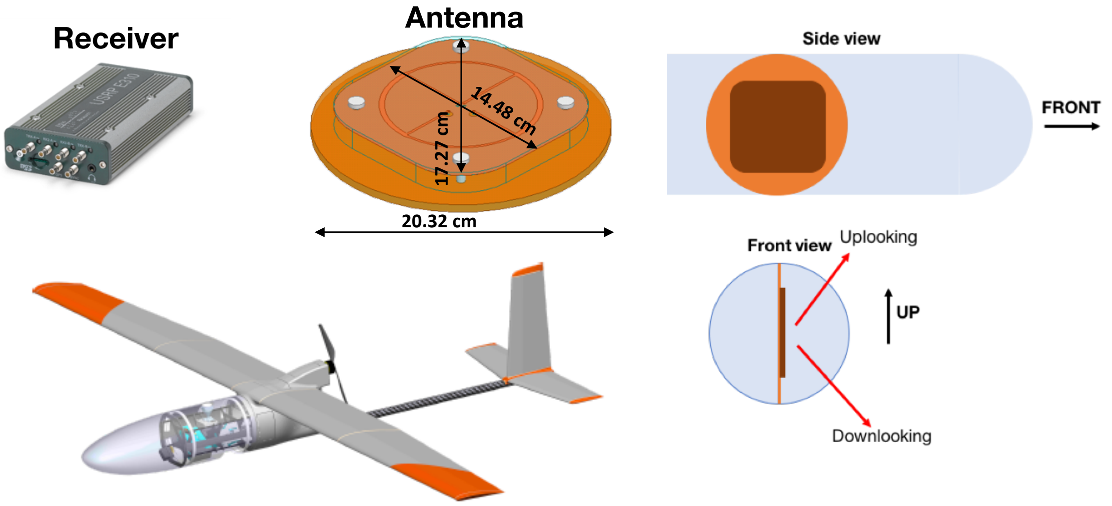


Figure 7. The components of UASHydro and its flight configuration. The antenna and receiver are mounted in the nose cone near the wing. The antenna is mounted vertically to allow reception of both direct and reflected signals.

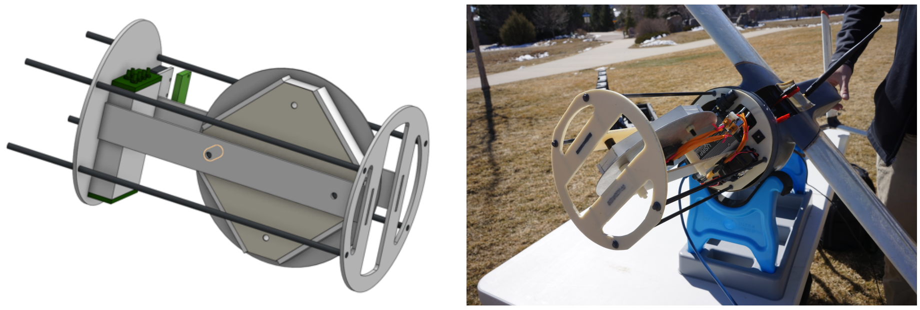


Figure 8. Left panel illustrates the antenna and receiver mounted on a support structure, which is then attached to the aircraft near the wing (right panel).

UASHYDRO DEVELOPMENT

We have been working with Black Swift Technologies to develop the UAS-based P-band SoOp technology on UAS. Figure 7 illustrates the components of the system, including the P-band receiver and antenna. The total weight of the payload is under 5 lbs to allow operation inside the nose cone of the S2 aircraft.

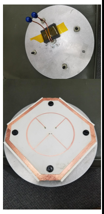
The S2 sUAS is a commercial-of-the-shelf (COTS), fixed-wing UAS built and sold by Black Swift Technologies. The S2 was designed and developed by BST for use in NASA science missions under the SBIR program. The S2 was designed to be a highly efficient, robust, rapidly and easily deployable airframe. It is optimized for carrying payloads up to 5 lbs. It was specifically built with scientific payloads in mind providing easy access and rapid integration of new payloads. The S2 is a fully composite aircraft that utilizes electric propulsion.

No modifications were made to the airframe itself for the P-band UASHydro payload. However, a payload tray was designed around the sensor. The S2 sUAS was specifically designed with a modular and swappable payload section that is separate from the rest of the sUAS. This includes a clearly defined mechanical and electrical interface. The new payload tray was designed and built by BST to accommodate the P-Band SoOp sensor developed by Jet Propulsion Laboratory (JPL). For maintenance, the aircraft will be inspected prior to each flight. This pre-flight includes an inspection and testing.

Parts of the aircraft (i.e. control horns, servos, wire connections, etc.) that either do not function or begin showing wear and tear will be replaced.

The development of every payload components (Table 1) and system integration has been completed at Black Swift Technologies' facilities (Fig. 8). We have also conducted compatibility tests to ensure that there will be no interference between the P-band receiver and S2.

Table 1: typical payload items and their specifications

Payload Item	**Picture**	**Sensor Characteristic**	**Dimensions**	**Weight**	**Max Power Consumption**	**Effects on CG**
P-Band Antenna		Passive Antenna to receive direct and reflected P-band signals	20.32 cm diameter and 3.05 cm thickness	1.35 kg	N/A	Located forward of the CG, required to balance the aircraft.
P-Band SoOp receiver	 	Embedded Software Defined Radio and Amplifier to record the directed and reflected P-band signals	Receiver: 133 X 68.2 X 26.4 mm Amplifier Dimension for each is 18.8 X 30.0 X 11.7 mm	0.64 kg	~7W	Located forward of the CG, required to balance the aircraft.

We are planning the flight campaign at the Fraser Experiment Forest from April through the end of 2018. Aircraft will be operated under standard VFR conditions, during daytime, during safe weather.

Figure 9 shows the flight area and hazard area based on the maximum glide of the S2 from the edge of the boundary. The flight lines are setup to perform a mapping mission using the onboard sensors. The flight box is 272x1667 meters. Access in the area allows for us to operate from the center of the box, ensuring that the plane will not be further than 1km away.

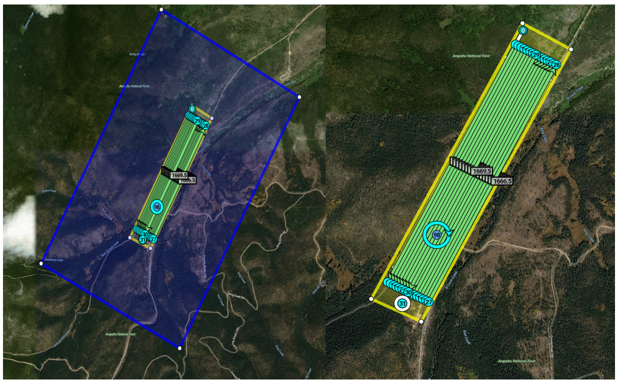


Figure 9. (Left) Flight operations location and sampling site / pattern along with hazard area (yellow box) and maximum glide area (blue box). (Right) Zoomed in view of the flight plan and hazard area.

SUMMARY

We have developed the UASHydro instrument based on the P-band SoOp to provide cost-effective regional high resolution sampling of RZSM and SWE to provide critical datasets for weather and climate forecasting, runoff prediction and water resource management, and prediction of flooding. The achievable spatial resolution is about 10m and thus would allow the observation over complex topography. Because the spatial resolution is achieved by the coherent Fresnel reflection, the baseline antenna size is very small, about 20cm, allowing the installation on a small UAS.

ACKNOWLEDGEMENT

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. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

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