

SNOOPI: DEMONSTRATING P-BAND REFLECTOMETRY FROM ORBIT

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ABSTRACT

SigNals Of Opportunity: P-band Investigation (SNOOPI) will be the first on-orbit demonstration of remote sensing using Signals of Opportunity (SoOp) in P-band (240-380 MHz). P-band is needed to penetrate through dense vegetation and into the root zone. The longer wavelength of P-band also increases the unwrapping interval for phase observations. These observations hold the potential for spaceborne remote sensing of root-zone soil moisture (RZSM) and snow water equivalent (SWE), two variables identified as priorities in the 2017-2027 Decadal Survey for Earth Science and Applications from Space. SNOOPI will provide in-space validation of both the P-band SoOp technique and a science instrument prototype. SNOOPI technology validation goals will be met by targeting observations within 9 km of the SMAP calibration/validation sites in the continental United States. A secondary priority is collection of continuous phase data over snow-covered regions. These goals are evaluated under constraints of a limited data budget and mission lifetime, with a launch readiness in early 2022. Updates on the development of measurement models and mission planning to support SNOOPI are provided. A ground-based station will be deployed to monitor the non-cooperative sources, in order to reduce risk due to uncertainty in knowledge of the broadcast power, spectrum shape, and orbital position.

Index Terms—Soil Moisture, bistatic radar, hydrology

I. INTRODUCTION

Root-Zone Soil Moisture (RZSM) and Snow Water Equivalent (SWE) are identified as priority target variables in the ESAS 2017 decadal survey [1] with critical roles in hydrology and water management.

Whereas active/passive L-band methods (e.g. SMAP, SMOS) can reliably retrieve surface soil moisture in the top 5 cm of soil [2], [3], a lower sensing depth will require use of lower frequencies. P-band (280-440 MHz) airborne SAR has been used to measure RZSM in regional campaigns [4], [5]. There are significant technical challenges in P-band spaceborne remote sensing, however. ESA-BIOMASS, for example, uses an active radar operating at 435 MHz. That radar requires a 15-m antenna to meet resolution requirements and will be prohibited from operating over North America and Europe due to operation of the Space Object Tracking Radar in the same band [6].

SoOp is an alternative approach to microwave remote sensing, re-utilising existing satellite broadcasts within bands allocated for communications or navigation. Experiments with P-band signals have been conducted from airborne and tower-based platforms [7]–[9].

SNOOPI was selected by NASA under the 2017 InVEST program of the Earth Science Technology Office ¹ to advance the P-band SoOp technique to Technology Readiness Level 7 (TRL7). Three objectives were identified for the in-orbit validation experiments.

- 1) Verify the forward model, based upon the radar equation, under a variety of surface conditions and terrain. In particular, it has been assumed that the reflected signal is coherent in the wavelengths being studied (0.8 to 1.2 m).
- 2) Assess the effect of Radio frequency Interference (RFI) on SoOp measurements. RFI is a significant problem for P-band radar and radiometry. SoOp makes use of powerful signals already exiting outside of the bands protected for science (which, themselves would be potential sources of RFI in other bands). The forward-scattered geometry presents a higher signal-to-noise ratio than backscatter. It has been assumed that these features would provide a robustness to RFI. This assumption, however, has not been tested in the space environment in which there may be many terrestrial sources within the wide antenna beam. Suspected RFI has been observed in airborne experiments [10].
- 3) Validate the function of a prototype SoOp instrument given the expected uncertainty in source orbital position, transmitted power, and prediction of the reflected signal delay and Doppler. In orbit, delay and Doppler vary over a much larger range than on an airborne experiment. Model prediction requires knowledge of both transmitter and receiver orbits and integration with a surface topography model. In-space demonstration of this tracking will be critical to validate the end-to-end instrument engineering and quantify the system error budget.

II. SNOOPI SYSTEM DESIGN

SNOOPI is planned for deployment from the International Space Station into a 400 km altitude orbit at 51.6 deg. inclination

¹<https://esto.nasa.gov/invest/>

The SNOOPI spacecraft design is shown in figure 1. It uses a standard 3X2U configuration with a single antenna for each frequency (255 MHz and 370 MHz). The instrument payload consists of three (3) subsystems; Low Noise Front End (LNFE), Digital Back-End (DBE) and antennas, described in the following subsections.

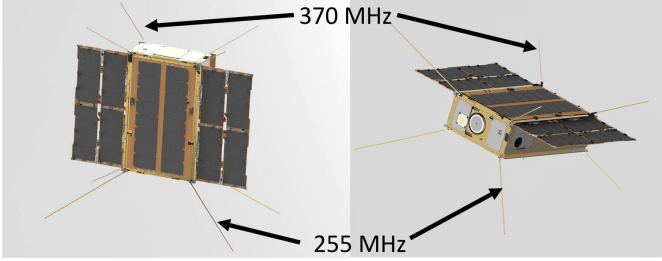


Fig. 1. SNOOPI satellite configuration illustrating instrument antennas.

A. Low Noise Front-End (LNFE)

The purpose of the LNFE is to provide the first stages of filtering and amplification of signals from the antenna subsystem as well as two calibration references that can be switched into the signal path for gain and offset corrections. These are implemented using temperature monitored loads plus a common noise diode split and coupled into the four receiver inputs for inter-channel gain and phase calibration. This architecture is inherited from SoOp-AD [11] and re-designed for the U-Class (CubeSat) form factor.

B. Digital Back-End (DBE)

The SNOOPI DBE builds upon extensive heritage of past JPL missions. Main components of the DBE include a Novatel OEM 729 GNSS receiver, a SpaceMicro CubeSat Space Processor (CSP) with a custom-designed RF/Clock/Host board and a Zynq 7020 (which combines two ARM processors and a re-programmable FPGA in a “system on a chip” (SOC) package). Four (4) P-band downconverters with eight 14-bit ADCs and a high-performance clock are used for sampling.

Five (5) 25 KHz data channels will be tracked in the 255 MHz band and a single 5 MHz channel will be tracked in the 370 MHz band. The default coherent integration time is $T_I = 1$ ms with the data budget sized to allow the downlink of complex samples at this rate. A short T_I was selected due to the uncertainty in the coherence time of the reflected signal and the desire to evaluate retrievals with longer T_I in post-process. Measurement simulations (presented next) were performed at both 1 and 5 ms.

The delay-Doppler mapping configuration was driven by uncertainty in source and receiver location, combined with the expected terrain variation at the SMAP cal/val sites. These analyses determined the requirement for a delay window of 3000 m around the predicted specular point. Table I gives the key specifications for the delay-Doppler mapping.

TABLE I
DELAY-DOPPLER MAPPING SPECIFICATIONS.

	370 MHz	255 MHz
Mod. Bandwidth	5 MHz	25 KHz
Coh. Int. Time	1 ms	1 ms
Chip Length	60 m	12 km
Delay Resolution	0.25 chip	0.05 chip
Doppler Resolution	500 Hz	500 Hz
Delay Bins	200	5
Doppler Bins	3	3
No. Channels	1	5
Bits/DDM	1.92E+04	2400

C. Antennas

High gain directional antennas are not required, due to the high radiated power (EIRP) of the transmissions (designed for communications with portable receivers). Path delay is used for separation of direct and reflected signals. A single commercial off-the-shelf (COTS) deployable turnstile antenna is used for each frequency.

Each antenna is sensitive to both right (RHCP) and left (LHCP) hand circular polarised electromagnetic waves, depending on the direction of arrival. A single antenna is, therefore, capable of receiving both direct and reflected signals. (See figure 2.) We have determined that it is possible to generate observations, using a method similar to that demonstrated on SoOp-AD, from auto-correlation of the signal received through a single antenna.

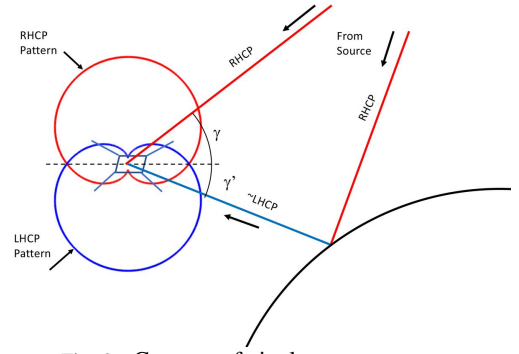


Fig. 2. Concept of single antenna use

D. Communications

The NASA Near-Earth network (NEN) will be used for communications. The total daily contact time was estimated to be approximately 34 min. Combined with the data budget generated from the information in table I, this would allow a collection of 6 min. of data per 24 hour period.

III. DESCRIPTION OF OBSERVATION

Source transmissions are RHCP and the reflected signal is expected to be predominantly LHCP at reasonable incidence angles. The gain patterns for the antennas in these two orthogonal polarisations are almost opposite of each other. The collected signal is thus a sum of the direct signal reaching the antenna at an elevation of γ and the corresponding reflected signal reaching the antenna at an elevation of $-\gamma'$. (For a source at infinity and a planar surface, $\gamma = \gamma'$.) This is illustrated in figure 2.

We have developed an observable, based upon the autocorrelation of this combined signal, allowing the estimate of the complex reflection coefficient (magnitude and phase) at the surface. The basic idea is illustrated in figure 3. A

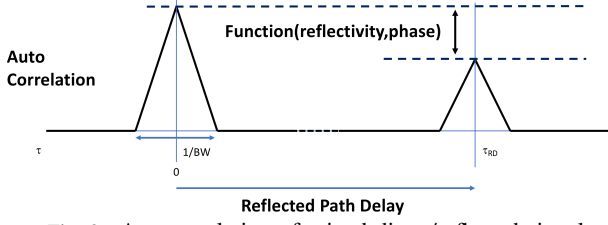


Fig. 3. Autocorrelation of mixed direct/reflected signal

theoretical signal model (in a forthcoming publication) and a signal simulator have been compared and shown to produce similar predictions of the retrieval error. Results are shown in figure 4 for reflectivity and figure 5 for phase.

Numerical values used for these simulations are: $T_I=5$ ms, direct and reflected antenna gains of $G_D=0$ dB and $G_R=-3$ dB, Effective Isotropic Radiated Power (EIRP) of 37 dBW and total system noise temperature of 1100 K. These results are for a single 5 MHz bandwidth channel at a 370 MHz center frequency. The angle of incidence was 60 deg. Errors are shown for a single observation, which can be reduced by averaging.

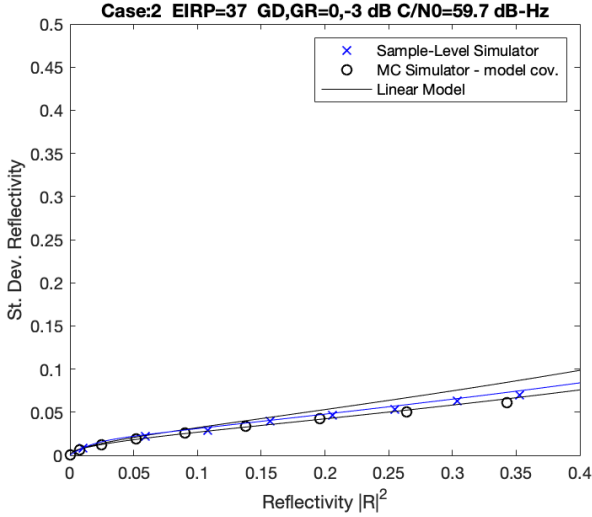


Fig. 4. Model comparison for surface reflectivity retrieval using autocorrelation

IV. MEASUREMENT VALIDATION PLAN

A measurement validation plan is being developed, constrained by the 9 month science mission duration and the data budget limited by contacts with the NEN. The latter will allow an estimated 6 min of data collection per day.

Experimental sites will be prioritized as follows:

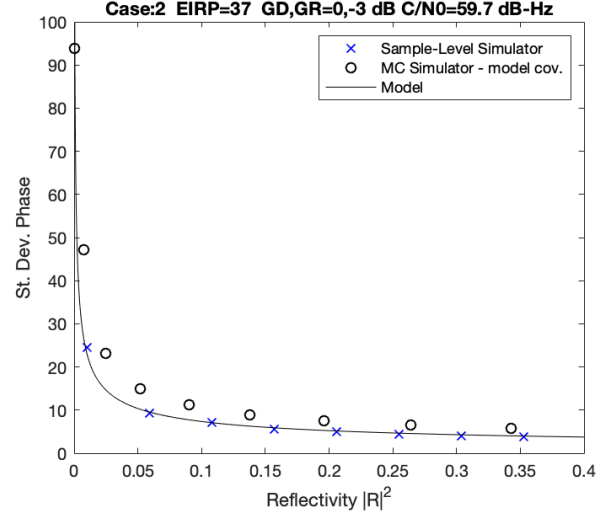


Fig. 5. Model comparison for phase retrieval using autocorrelation

- 1) SMAP cal/val sites in the Continental United States (CONUS), with RZSM measurements, and non-frozen ground.
- 2) Snow covered regions, with an arc length of 6 min.
- 3) Transects of CONUS

V. MISSION OPERATIONS

The SNOOPI mission will be supported by a science operations center (SOC) located at Purdue University. The SOC will be capable of performing the following tasks:

- 1) Orbit determination for SNOOPI
- 2) Orbit prediction for SNOOPI and P-band transmitter sources
- 3) Prediction of the location of the specular point for the reflected signal
- 4) Generation of activity plans for SNOOPI
- 5) Visualization of SNOOPI's orbit and attitude
- 6) Storing and processing science data from the mission

Figure 6 shows the relationships between the SOC at Purdue and the Mission Operations Center (MOC) at NASA Goddard Space Flight Center.

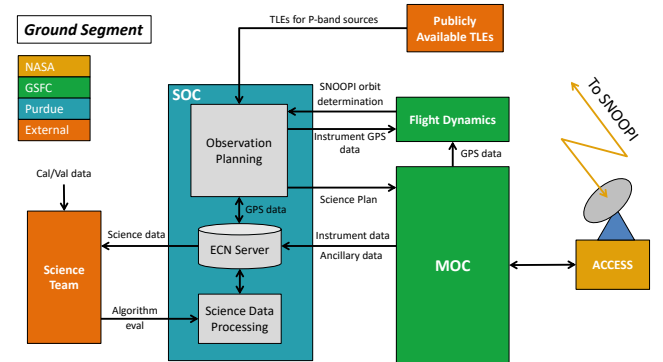


Fig. 6. Interfaces between the SOC and the MOC

Orbit determination will use GPS position data downlinked from SNOOPI and a least squares estimator to determine the

orbit state and covariance. The orbit will then be propagated for 14 days using NASA's General Mission Analysis Tool [12]. Testing on GPS data from CYGNSS has shown that a total prediction error of less than 10 km in position over 14 days, mostly in the along-track direction, is attainable.

Orbits for the MUOS P-band sources will be propagated based on publicly available two-line elements. The propagated positions of SNOOPI and each MUOS transmitter are used to compute the location of the specular point on a digital elevation map of the Earth using the unit difference method [13].

The specular point trajectories are then searched for arcs that meet the prioritised criteria described in Section IV. For each of these arcs, the delay and Doppler for both the reflected and direct signals are computed. Vectors to the MUOS transmitter and the corresponding specular point are used to compute the attitude that maximises antenna gain. The spacecraft attitude, delay, Doppler, start and stop times for each arc, along with additional instrument settings constitute the science activity plans that will be delivered to a mission operations center (MOC) at NASA GSFC for conversion into uplink commands. Although each science plan will cover the full 14 day orbit prediction, updated plans will be delivered to the MOC on a weekly basis. Performing orbit determination through to science plan generation takes only a few hours.

Finally, the SOC will maintain a server for storing raw data from the mission and processing it into level 1 data products such as the complex reflection coefficients for each instrument channel.

VI. EIRP MONITOR

A receiver has been designed to monitor the SoOp source EIRP, spectrum and ambiguity functions over time. As shown in Figure 7, two (2) antenna pairs, covering RHCP and LHCP at 255 and 370 MHz will be mounted on an azimuth and elevation actuator pedestal for full sky scanning capability. The system is designed with a microwave calibration network for estimating system gain and noise. The microwave front end is placed in a temperature-controlled enclosure for radiometric stability. This system will be installed at in a rural environment at Purdue University to reduce the likelihood of RFI.

VII. ACKNOWLEDGEMENT

This work was supported by NASA Grant 80NSSC18K1524.

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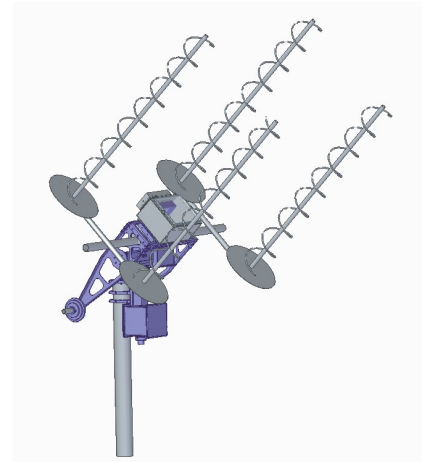


Fig. 7. CAD drawing of the EIRP monitor

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