Definition of a Technology Validation Mission for P-band Reflectometry using Signals of Opportunity

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INTRODUCTION

Root-Zone Soil Moisture (RZSM) (moisture profile in the top meter of soil) and Snow Water Equivalent (SWE) (total snow pack water content) are identified as priority target variables in the ESAS 2017 decadal survey [1] with critical roles in hydrology and water management. RZSM estimates are vital for understanding multiple Earth system processes and forecasting (for example, droughts [2]). Simultaneous knowledge of surface and RZSM could enable a breakthrough in estimating key unobserved hydrologic fluxes and reduce uncertainty in net ecosystem exchange (NEE), carbon balance [3] discharge estimates, and crop yield forecasts [4] .With the high albedo and insulating properties of snow, monitoring, SWE accumulation would provide a key constraint on the potential runoff during spring ablation while monitoring SWE disappearance rates would provide a key constraint on SWE partition into runoff vs. infiltration/recharge. [5] demonstrated that knowledge of early-spring SWE generally contributes most to streamflow forecast skill in the Western U.S. SWE is also a source of water storage that provides the water resources during spring snowmelt. Despite such potentially transformative contributions, accurate RZSM and SWE measurements are unattainable with current technology. While active/passive L-band methods (e.g. SMAP, SMOS) can reliably retrieve surface soil moisture in the top 5 cm of soil [6], [7]. RZSM estimates are only available through model assimilation of brightness temperatures with a radiative transfer and land surface models [8]. SWE estimation uses multi-frequency passive microwave techniques (e.g. [9]–[11]), which have significant problems with deeper snow and in forested and mountainous environments [12]. Signals of opportunity (SoOp) in P-band (200-400 MHz) is a new remote sensing technique with the capability of estimating both essential hydrologic variables, RZSM and SWE, circumventing many of the aforementioned limitations under all weather conditions day and night. SoOp is the re-utilization of existing powerful satellite transmissions within bands allocated for communications or navigation. P-band SoOp sensitivity to soil moisture has been demonstrated in an airborne experiment over Oklahoma in 2016 [13]. Recent theory [14] and experiments [15] have also confirmed that the reflection coefficient phase is proportional to SWE.

P-band SoOp has now reached a critical juncture in which further advancement of this technique requires in-space demonstration. Conditions of a relevant environment, required to advance to TRL6 and higher, are only met in orbit. A selection under NASA's In-Space Validation of Earth Science Technologies (InVEST) program, SigNals of Opportunity: P-band Investigation (SNOOPI) (depicted in Figure 1) will be the first demonstration of the P-band SoOp technique from orbit and will advance our prototype instrument to TRL-7. The objective of SNOOPI is to test assumptions about reflection coherence, robustness to the in-orbit RFI environment, and the instrument ability to capture and process the transmitted signal in space.

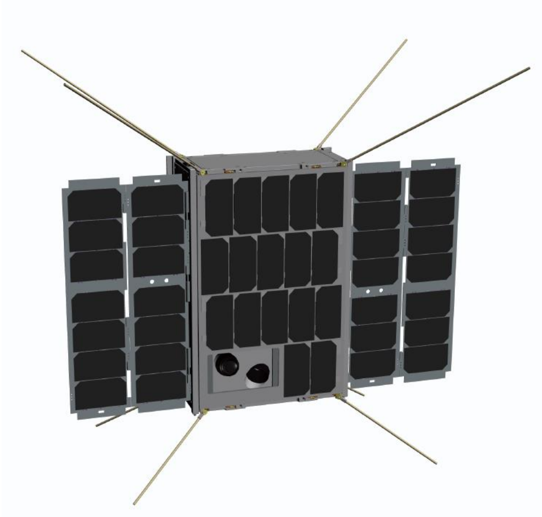

Fig. 1. SigNals Of Opportunity P-band Investigation (SNOOPI) spacecraft configuration

SIGNALS OF OPPORTUNITY: P-BAND INVESTIGATION (SNOOPI)

SNOOPI will utilize transmissions from geosynchronous communication satellites. These transmissions, occupying bands allocated for government use, consist of a number of 5 KHz and 25 KHz data channels within the 244-270 MHz spectrum and four (4) 5 MHz wideband spread-spectrum channels between 360-380 MHz. The complex reflection coefficient will be estimated from the autocorrelation function of a single channel formed from the interference of the direct and reflected signals. In contrast to a cross-correlation approach previously applied to airborne and tower experiments, the auto-correlation requires only one antenna without a ground plane. Signal coherence will be evaluated by statistical tests applied to the differential phase between data channels and by varying the coherent integration time in post-process. The nominal mission design will generate a complex delay-Doppler map using 1 msec coherent integration onboard for five (5) data channels in the lower band and one wideband channel in the upper band. Reflection coefficient retrievals will be compared against predictions from a forward model using in-situ observations at SMAP cal/val sites. The working baseline mission requirements call for 100 cumulative match-ups with SMAP sites. A SMAP site overpass occurs approximately once per day. A wide range of orbital parameters (350-600 km and 45-98 deg. inclination) are expected to meet the mission requirements, providing flexibility in selection of a launch opportunity.

INSTRUMENT DESIGN

The SNOOPI instrument design builds upon the heritage of a low noise front end (LNFE), developed from an airborne demonstrator, and a digital back end (DBE) evolved from the Cion, TriG and Blackjack GPS receivers [16]. Success with SNOOPI will retire the critical risks associated with a P-band SoOp satellite instrument and exit at TRL-7.

Evolution of the LNFE is shown in figure 2. This single-board front-end in the CubeSat form factor (90 x 96 mm) will provide 4 channels internal calibration paths, and gain needed to interface with the digital backend. The DBE, shown in figure 3, will digitize, channelize, and perform auto-correlation on the recorded signal to create delay-Doppler Maps (DDMs) from which phase and reflectivity can be extracted. The antenna will be a single COTS cross-dipole design for each of the two frequency bands. Direct and reflected signals are separated by polarization and time delay through auto-correlation.

SPACECRAFT BUS DESIGN

The SNOOPI spacecraft will be based upon a 6U (3X2) cubesat bus structure compatible with Nanosatellite Launch Adapter System (NLAS) 6U deployer on the International Space Station (ISS). This will be a 3-axis stabilized spacecraft with deployable arrays. SNOOPI will operate in two primary mission modes: (1) Sun pointing with solar arrays ±15 deg of the sunline to stay power positive, (2) Science mode to reorient the spacecraft for optimal antenna signal strength during measurement collection.

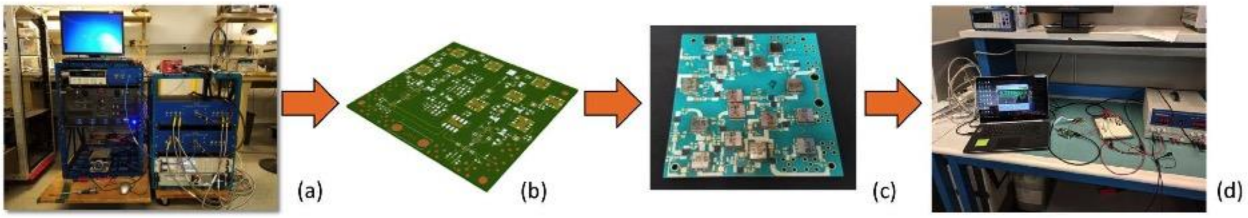

Fig. 2. Development of the SNOOPI Low Noise Front End (LNFE). (a) SoOp-AD airborne instrument integration and testing at NASA GSFC. (b) GSFC CAD model (c) Miniaturized Prototype version 1 (d) Telemetry testing of LNFE prototype.

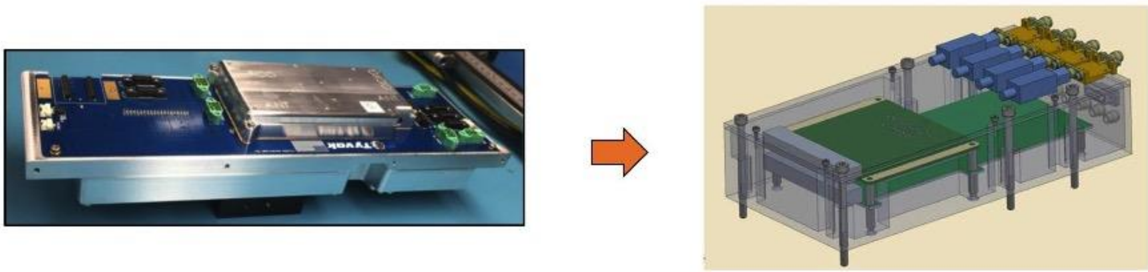

Fig. 3. Digital Back End (DBE)

OPERATIONS

As a technology demonstration mission, SNOOPI operations are defined to achieve coverage of a sufficient number of match-ups with ground in-situ observations to validate the reflection coefficient retrievals. Cal/Val sites defined for the SMAP mission will be used to test the ground reference points for evaluating observations related to soil moisture retrieval. SWE retrieval will require a coherent phase observation, so the mission will be planned to collect long arcs (5-10 min) of data over snow-covered regions.

The Science Operations Center (SOC), shown in Figure 4 is located in Armstrong Hall at Purdue University. The SOC will be responsible for science mission planning, science data processing, storage, and distribution, including:

- Propagation of SNOOPI orbit elements (two weeks) to predict orbit ground track and specular point locations.
- Maintaining a database of P-band sources and SMAP cal/val sites.
- Developing and using planning software to predict P-band specular point match-ups with SMAP Cal/Val sites.
- Producing weekly science observation plans and with timelines for uplink to the satellite.
- Collecting and distributing data including auto-correlation, reflection coefficient, and statistical tests of coherence.
- Graphically displaying orbit ground-track, source P-band locations, and surface target locations.
- Maintaining a map of global snow coverage.

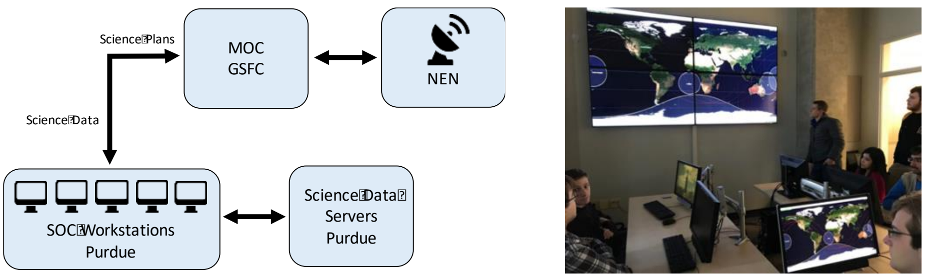

Fig. 4. Science Operations Center, Purdue University

Command of SNOOPI operations will be handled by the Mission Operations Center (MOC) at NASA Goddard Space Flight Center, which will receive the weekly operations plans from the SOC and will relay the science data back to the SOC, as shown in Figure 4.

The operations plan for SNOOPI is shown in Figure 5. Following deployment from the ISS, and bus checkout planned for a total of 2 weeks, there will be a 2-month period of engineering check-out of the instrument. This will be followed by 9 months of planned science operations in which the SMAP Cal/Val match-up and snow arc data will be collected.

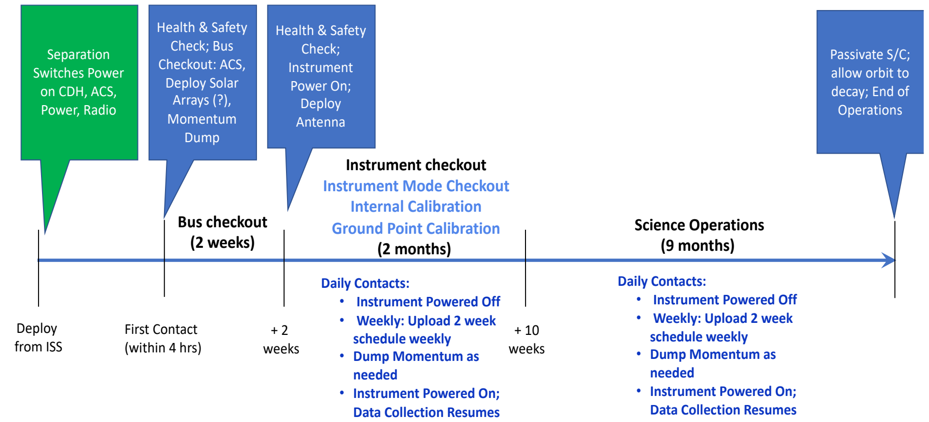

Fig. 5. Operations plan for SNOOPI Mission

ACKNOWLEDGEMENT

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