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Enabling Big Science in a Small Satellite - The Global L-band Observatory for Water Cycle Studies (GLOWS) Mission

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ABSTRACT

The SMOS and SMAP radiometers have demonstrated the ability to monitor soil moisture and sea surface salinity. It is important to maintain data continuity for these science measurements. The proposed instrument concept (Global L-band active/passive Observatory for Water cycle Studies - GLOWS) will enable low-cost L-band data continuity (that includes both L-band radar and radiometer measurements). The objective of this project is to develop key instrument technology to enable L-band observations using an Earth Venture class satellite. Specifically, a new deployable *meta*-lens antenna is being developed that will enable a smaller EELV Secondary Payload Adapter (ESPA) Grande-class satellite mission to continue the L-band observations at SMAP and SMOS resolution and accuracy at substantially lower cost, size, and weight. The key to maintaining the scientific value of the observations is the retention of the full 6-meter antenna aperture, while packaging that aperture on a small ESPA Grande satellite platform. The *meta-lens antenna* is lightweight, has a simplified flat deployed surface geometry, and stows in a compact form facto*r*. This *dramatic aperture packaging reduction* enables the GLOWS sensor to fit on an Earth Venture class satellite.

1. INTRODUCTION

Small satellites have repeatedly demonstrated the ability to perform critical science and data gathering missions. Often, aperture sizes are compromised to support the reduced satellite format or multiple satellites are used in tandem to create a sparse aperture of sufficient size to support the data collection requirements. New deployable antenna technologies are enabling larger, more capable apertures on small satellite platforms, potentially replicating large-satellite capabilities in small-satellite missions at dramatically reduced mission cost.

L-band observations have been shown as the optimum technique for estimating soil moisture and ocean salinity variables to study the land surface and ocean. The European Space Agency (ESA) Soil Moisture and Ocean Salinity (SMOS) mission was the first spaceborne L-band radiometer. This was followed by two L-band missions flown by the National Aeronautics and Space Administration (NASA) to measure sea surface salinity (Aquarius) and soil moisture (SMAP). It is critical to continue the time series of L-band observations and have long-term L-band soil moisture and ocean salinity data records. To address this need we propose a new low-cost instrument concept known as the Global L-band active/passive Observatory for Water cycle Studies (GLOWS) that will include an L-band radiometer and radar to provide data continuity. GLOWS will continue the science observations of SMAP and SMOS at the same resolution and accuracy at substantially lower cost, size, and weight.

In this presentation we describe the GLOWS mission concept and system design. It has been long been assumed that the large antenna aperture required for high resolution L-band measurements requires a large spacecraft, with a correspondingly large cost. However, the new proposed reflectarray antenna configuration enables L-band radar and radiometer observations with the required performance that can be flown on a small satellite. Key to the new concept is new deployable 6-meter diameter meta-lens antenna with a compact feed. We present our progress in demonstrating key hardware elements and antenna design. The science goals of the GLOWS mission for continuing the L-band climate series mission will be presented. These goals are synergistic with the goals of the ESA Copernicus Imaging Microwave Radiometer (CIMR) mission, which will collect radiometer data across L, C, X, Ku, and Ka bands, and NASA's NISAR which will collect radar data at both L and S bands.

The proposed instrument concept (Global L-band active/passive Observatory for Water cycle Studies - GLOWS) enables low-cost L-band data continuity that includes radar and radiometer data. The objective of this project is to develop key instrument technologies to enable L-band observations within an Earth Venture class mission (total cost <$200M USD). Specifically, a new deployable meta-lens antenna is being developed by MMA Design, combined with current advances in electronics packaging, that enables a smaller, EELV Secondary Payload Adapter (ESPA) Grande-class satellite mission.

2. SOIL MOISTURE MEASUREMENT AND APERTURE NEEDS

Knowledge of global soil moisture is fundamental to the advancement of our understanding of Earth as one integrated system. The climate dynamics of such a system, along with the associated economic and societal impacts, are heavily influenced by the global water and energy cycles reflected by the spatio-temporal variability of soil moisture over land. In addition, long-term patterns of soil moisture variability are particularly desirable, as they offer a unique time window to trace the formation and evolution of terrestrial hydrological trends on regional and continental spatial scales. These trends are often indicators of slow but persistent hydrological threats such as drought, deforestation, and flood/landslide risk that carry significant economic, societal, and environmental impacts. Soil moisture observations have also been shown to be important for other applications including agricultural productivity forecast, terrain mobility, weather, wildfire risk, and water resources.

Satellite remote sensing of soil moisture has advanced significantly over the last decade due to the success of the SMOS [1] and SMAP [2] missions, both of which provide global soil moisture retrievals on approximate 3-day repeat intervals at an accuracy of approximately 0.04 m^3/m^3. It is critical to extend this dataset beyond the life of the current missions in order to study the impact of soil moisture at climatologically relevant time scales on weather prediction, energy and carbon cycles and climate change. L-band observations also provide estimates of ocean salinity, sea ice thickness, vegetation water content, and ocean surface winds [3].

The major challenge of future low frequency microwave mission is to strike the correct balance between antenna size/design (what is technically possible), performance (swath coverage, resolution, instrument noise), and cost/efficiency of operation. As these trade-offs are driven by the need for a large antenna (previously implying a large cost), new strategies for low-cost rotating antennas are needed.

3. THE GLOWS MISSION

Knowledge of long-term patterns of soil moisture variability offers a critical window for tracking the formation and evolution of terrestrial hydrological trends over a variety of regional and continental spatial scales. We note that the usefulness of an Earth Science Data Record (ESDR) is heavily dependent on its continuity. Any discontinuity in data level within the combined time series, whether due to discrepancies among satellites in calibration, viewing geometry, orbital parameters, or sensing frequency, could lead to overestimation or underestimation of trends and increase the number of years of observations required to detect a trend of a given magnitude. The construction of a long record of available observations can only be accomplished by merging observations in a consistent manner from multiple satellites over a multi-decadal period. Extending the current L-band record is what we aspire to with the GLOWS mission concept.

The GLOWS payload performance requirements are based on, and justified by, the original SMAP mission performance requirements [4]. The goal of GLOWS is to provide L-band data continuity at SMAP-level of performance at lower cost and in a smaller package. This is achieved by employing an innovative membrane meta-lens antenna that is lightweight and, more importantly, can be deployed from a very small package. The meta-lens design is flat and radially symmetric. The meta-lens packaging and design greatly simplify the bus and spinning mass requirements compared to SMAP.

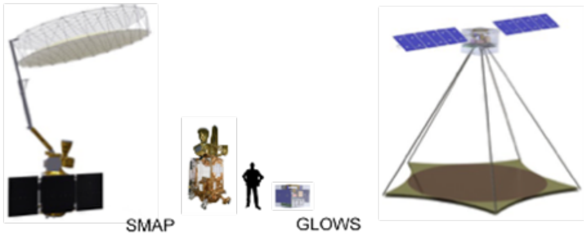

Figure 1: Comparison of SMAP and GLOWS and integrated in an ESPA-class spacecraft.

NOTE: the similarity of deployed configurations and the contrast of launch configurations. A human is added for scale.

Table 1: Comparison of SMAP and GLOWS

Parameter	SMAP	GLOWS
Mission Stowed Volume	15.5 m^3	1.54 m^3
Mission Power beginning of life (BOL)	1.5 kW	1.5 kW
Average Power	448 W	< 500 W
Mission Mass	1122 Kg	403 Kg
Instrument Mass	356 Kg	199 Kg

We also exploit improvements in radar and radiometer electronics to minimize the size, weight, and power (SWaP) of the of active/passive GLOWS instrument system. Figure 1 compares SMAP and GLOWS integrated onto an ESPA-class spacecraft.

Deployable RF apertures have been available for decades, but these systems have limitations on packaging factors and require significant mission budgets. Membrane reflectarray antennas have demonstrated smaller packaging and lower cost than traditional deployable mesh antennas. The GLOWS concept of operations, orbit, and data set are intended to match that of the SMAP mission. Figure 1 and Table 1 compare SMAP and GLOWS projected mass and stowed volumes.

GLOWS payload performance requirements are based on, and justified by, the original SMAP mission performance requirements [4]. The GLOWS mission approaches these requirements by emulating many aspects of the mission CONOPS. The similarities, as well as a description of GLOWS differences, is summarized in Table 2.

Table 1: GLOWS CONOPS – Comparing GLOWS and SMAP

Similarities	Differences
Active (Radar) and passive	Flat multi-layer membrane meta-lens vs. Canted mesh reflector
(Radiometer) share a common aperture	Nadir deployed aperture with 5 symmetrical supports vs. Zenith deployed hoop on single deployed boom support
Same orbit (685 km 6am/6pm)	Instrument aperture obscuration of data downlink window vs. Solar illumination and GPS
6-meter aperture	Electrical Disconnect after deployment vs slip rings/rotary joints
Same L-band frequencies for both radar and radiometer	Lens temperature sensors vs. no sensors
14.6 rpm rotation motor that creates a rotational swath pattern on the earth	Fixed Multi-element Patch Feed vs. Spinning Horn
Same on-orbit calibration plans/maneuvers	GLOWS 199 kg. vs SMAP 359 kg (45% instrument mass reduction)
3-year mission objective	ESPA Grande (1.54 m3) ride-share mission launch volume vs. Delta II Payload Volume (15.5 m3) (90% Reduction)
	~80% cost reduction (without inflation)

4. GLOWS SYSTEM

4.1 GLOWS Concept of Operations

GLOWS collects L-band radar and radiometric measurements over a wide swath using a rotating meta-lens antenna system illustrated in Figure 2. The 6 m diameter flat antenna spins at 14.6 rpm about the nadir axis. The antenna feed looks downward and illuminates the antenna membrane, which is covered with thin metal resonant elements. These steer the beam to the side so that as the antenna rotates (and the spacecraft moves along its orbit), a helical scan pattern on the Earth results. The antenna beam width and rotation rate provide overlap between consecutive scans that enable us to grid the data at a fine grid resolution consistent with the radar resolution [5].

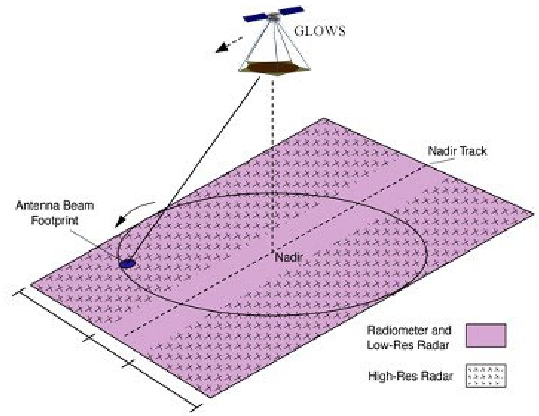

Figure 2: GLOWS Observation Swath

Radar measurements are collected by transmitting a linear frequency modulated (LFM) signal and receiving the echo (see Figure 2). Radar and radiometer measurements are collected over the full swath. Like SMAP, coherent processing of the radar data enables fine resolution over most of the swath [2], [6]. from the surface. The return echo power is coherently processed to infer the normalized radar cross-section of the Earth's surface on a fine grid over most of the swath [6]. The processing accounts for rotation of the antenna during the long time (~10 ms) between transmit and receive. Receive-only radiometer measurements are collected between radar transmit cycles and have spatial resolution dictated by the footprint size on the surface. Finer resolution requires a larger aperture, hence the desire for a large aperture antenna.

The radar and radiometer electronics are state-of-the-art that exploit recent developments in flight hardware.

4.2 Antenna System

The key innovation of GLOWS is the flat rotating meta-lens antenna rather than the offset fed, asymmetrically rotating reflector used by SMAP. Because is it rotationally symmetric and low mass, the GLOWS antenna is much easier to balance and rotate than traditional offset fed, asymmetrically rotated, large-aperture reflectors. Further, the meta-lens antenna can be densely packed into a small volume for launch. The radiometric performance of a meta-lens reflectarray antenna has not been previously studied. We are in the midst of a detailed study of this, but preliminary results are very encouraging. Validation of this technology opens the possibilities of further use of scalable, large-aperture meta-lens antennas for other missions. The SMAP mission incorporated a spinning 6-meter diameter deployable Northrop Grumman Astromesh parabolic reflector deployed at a 35.5° angle on the end of a reflector support mast. This configuration required significant stowed volume and complex balancing of an asymmetric rotating antenna. The deployable reflector was paired with a large horn feed and the antenna was jointly shared by a radar and radiometer.

The proposed GLOWS instrument incorporates a tensioned aperture of flat membranes that shape and direct the RF energy of the instruments through passive phase-shifting elements on the membrane. The phase shifting steers the beam to a 40° angle from the flat membrane. This results in the same ground incidence angle as SMAP. Like SMAP, the flat GLOWS meta-lens is rotated at 14.6 rpm to sweep out a wide observation swath. The membrane design is combined with a patch array feed dramatically improving the packing factor of the antenna system.

Figure 1: Illustration of the GLOWS antenna beam steering provided by its phase-shifting meta-lens antenna.

Table 2: Key GLOWS Instrument Requirements (Similar to SMAP)

Parameter	Radiometer	Radar
Measurement bandwidth	1400-1427 MHz	MHz IBW* within 1217-1298 MHz
Polarization	HH, VV, T3, T4	HH, HV, VV (not polarimetric)
Swath width	Km	Km
Ground resolution	30km, 39 × 47 km footprint	× 400 m
Antenna efficiency	90%	shared aperture and feed
PRF	N/A	2.85 kHz
Transmit peak power	N/A	W
Relative accuracy	<1.5 K on 40 km grid	1-1.5 dB on 3 km grid
Antenna beam rotation rate	14.6 rpm	14.6 rpm

*Instantaneous bandwidth

The flat membrane aperture is deployed symmetrically with the instrument/satellite centered and orthogonal to the rotating membrane, greatly simplifying the balancing of the rotating aperture. The meta-lens aperture in operation is illustrated in Figure 3. This architecture eliminates the concerns of shadowing of the solar arrays as well as blockage of signal reception from the GPS satellite constellation.

As noted, the antenna system is based on a unique spinning membrane meta-lens mentioned. First introduced in 1949 as an artificial dielectric [7], the implementation as a phase shifting surface (very similar to reflectarrays) has proven a viable implementation approach [8]. The method allows a meta-lens antenna to be optimized over a small bandwidth with few layers. For GLOWS, the operation within 1.2 to 1.4 GHz for both the radar and radiometer, means the bandwidth (~15%) and relative electrical size (D/λ ~28) are small, simplifying the design problem. The GLOWS meta-lens will consist of flexible substrate layers with an array of thin metallic elements that electrically "form" the RF shape of the meta-lens system [8] [9].

The baseline antenna feed implementation is a 50 cm diameter microstrip patch array containing two beamformers – one for vertical polarization and one for horizontal polarization. Each radiating element connects to the beamformer with short lengths of low-loss coaxial cable. The assembly easily supports the peak and average power handling with low loss and no multipaction. The feed provides an approximate 10 dB edge taper illumination of the meta-lens/aperture. This is chosen to achieve high beam and aperture efficiency; however, this parameter will be traded to optimize the radiometer performance.

4.3 Radiometer Subsystem

The GLOWS radiometer electronics follows the design of the successful SMAP radiometer. At L-band the total power gain architecture offers significant advantages over any alternative, and it is employed here. However, the need to detect in-band RFI prevents the use of the simplest direct RF detection approach. The signal from each of the two beamformer/diplexer networks is fed to a coupler and then to a cascaded radiometer front end (RFE), radiometer back end (RBE), and radiometer digital electronics (RDE) chain.

Couplers allow the injection of signal from an external noise source (NS); this noise source is redundant to the internal noise source, which will be used for calibration. Some filtering, to prevent or reduce RFI from the radar to enter the radiometer chain, will be added to the coupler assembly. The RFE contains the primary internal calibration switches and noise source, RF amplification, and additional filtering. The calibration switches are used to give the RF chain an RFI-free signal, to which the internal noise source signal is added, providing an RFI-free gain calibration.

4.4 Radar Subsystem

The GLOWS radar design is based on existing/maturing DoD/commercial radar flight hardware. This approach is proposed to exploit the rapidly advancing improvements in radar technology. The architecture reflects a design based on existing flight hardware developed by our partners. The radar consists of five primary subsystems. The radar receiver/exciter (REX) contains a software defined radio (SDR) that provides up/down frequency conversion, A/D and D/A conversion, and waveform generation. The Radar Processor (RP) handles pulse / receive scheduling and processes and formats the raw samples from the REX. The RP also serves as the data interface between the payload and the host bus.

The Frequency Reference Unit (FRU) generates all required local oscillator signals and sample clocks for the Radar Processor and REX. The High-Power Amplifier (HPA) consists of multiple GaN amplifier stages providing over 500 W output power. A switch, under REX control, selects transmit polarization. Circulators are used at the interface to the antenna assembly to isolate transmit and receive paths. The antenna assembly contains high isolation diplexers that multiplex the radiometer spectrum (1400 to 1427 MHz) with the radar band (1217 to 1298 MHz). The radar data is processed on the ground using both a low-resolution scatterometer mode over the full swath and coherent synthetic aperture processing over the outer swath, see Figure 2.

5. CONCLUSION

As technologies and innovations advance, small satellites truly can perform missions that were previously exclusive to larger satellites. The GLOWS mission is designed to be a follow-on to SMAP with extremely similar capabilities in a fraction of the size and cost. It will provide both active and passive L-band observations of the Earth with a 6-meter aperture to continue the ESDR started by SMOS and SMAP. The mission will allow a continuance of data collection to support the measurement and scientific study of soil moisture, ocean salinity, and sea ice thickness.

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