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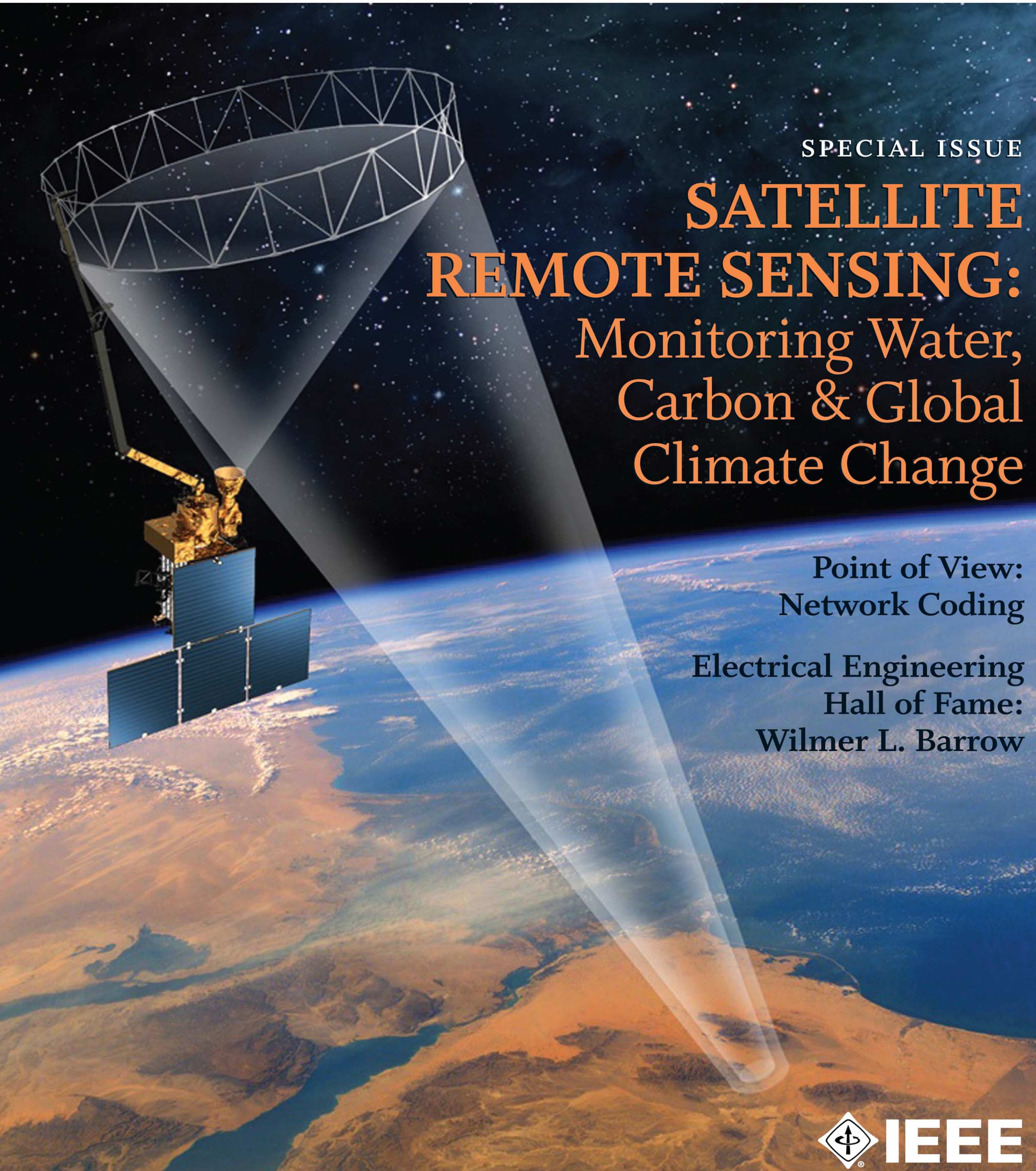

The Soil Moisture Active Passive (SMAP) Mission

This paper describes an instrument designed to distinguish frozen from thawed land surfaces from an Earth satellite by bouncing signals back to Earth from deployable mesh antennas.

By Dara Entekhabi, Eni G. Njoku, Peggy E. O'Neill, Kent H. Kellogg, Wade T. Crow, Wendy N. Edelstein, Jared K. Entin, Shawn D. Goodman, Thomas J. Jackson, Joel Johnson, John Kimball, Jeffrey R. Piepmeier, Randal D. Koster, Neil Martin, Kyle C. McDonald, Mahta Moghaddam, Susan Moran, Rolf Reichle, J. C. Shi, Michael W. Spencer, Samuel W. Thurman, Leung Tsang, and Jakob Van Zyl

ABSTRACT | The Soil Moisture Active Passive (SMAP) mission is one of the first Earth observation satellites being developed by NASA in response to the National Research Council's Decadal Survey. SMAP will make global measurements of the soil moisture present at the Earth's land surface and will distinguish frozen from thawed land surfaces. Direct observations of soil moisture and freeze/thaw state from space will allow significantly improved estimates of water, energy, and carbon transfers between the land and the atmosphere. The accuracy of numerical models of the atmosphere used in weather prediction and climate projections are critically dependent on the correct characterization of these transfers. Soil moisture measurements are also directly applicable to flood assessment and drought monitoring. SMAP observations can help monitor these natural hazards, resulting in potentially great economic and social benefits. SMAP observations of soil moisture and freeze/thaw timing will also reduce a major uncertainty in quantifying the global carbon balance by helping to resolve an apparent missing carbon sink on land over the boreal latitudes. The SMAP mission concept will utilize L-band radar and radiometer instruments sharing a rotating 6-m mesh reflector antenna to provide high-resolution and high-accuracy global maps of soil moisture and freeze/thaw state every two to three days. In addition, the SMAP project will use these observations with advanced modeling and data assimilation to provide deeper root-zone soil moisture and net ecosystem exchange of carbon. SMAP is scheduled for launch in the 2014–2015 time frame.

KEYWORDS | Freeze/thaw; geoscience; microwave; remote sensing; soil moisture

I. INTRODUCTION

The National Research Council's (NRC) Decadal Survey, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, was released in 2007 after a two year study commissioned by the National Aeronautics and Space Administration (NASA), the National

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D. Entekhabi is with the Massachusetts Institute of Technology, Cambridge, MA 02139 USA (e-mail: darae@mit.edu).
E. G. Njoku, **K. H. Kellogg**, **W. N. Edelstein**, **S. D. Goodman**, **K. C. McDonald**, **M. W. Spencer**, **S. W. Thurman**, and **J. Van Zyl** are with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA (e-mail: eni.g.njoku@jpl.nasa.gov; kent.h.kellogg@jpl.nasa.gov; wendy.n.edelstein@jpl.nasa.gov; shawn.d.goodman@jpl.nasa.gov; kyle.c.mcdonald@jpl.nasa.gov; michael.w.spencer@jpl.nasa.gov; sam.w.thurman@jpl.nasa.gov; jakob.j.vanzyl@jpl.nasa.gov).
P. E. O'Neill, **J. R. Piepmeier**, **R. D. Koster**, **N. Martin**, and **R. Reichle** are with NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA (e-mail: peggy.e.oneill@nasa.gov; jeff.piepmeier@nasa.gov; randal.d.koster@nasa.gov; neil.f.martin@nasa.gov; rolf.reichle@nasa.gov).
W. T. Crow and **T. J. Jackson** are with USDA ARS Hydrology and Remote Sensing Lab, Beltsville, MD 20705 USA (e-mail: crow@hydrolab.arsusda.gov; tom.jackson@ars.usda.gov).
J. K. Entin is with NASA Headquarters, Washington, DC 20546 USA (e-mail: jared.k.entin@nasa.gov).
J. Johnson is with the Ohio State University, Columbus, OH 43210 USA (e-mail: johnson.1374@osu.edu).
J. Kimball is with The University of Montana, Polson, MT 59860-6815 USA (e-mail: johnk@ntsg.umt.edu).
M. Moghaddam is with the University of Michigan, Ann Arbor, MI 48109 USA (e-mail: mmoghadd@umich.edu).
S. Moran is with the USDA Southwest Watershed Research Center, Tucson, AZ 85719 USA (e-mail: susan.moran@ars.usda.gov).
J. C. Shi is with the University of California, Santa Barbara, CA 93106 USA (e-mail: shi@icess.ucsb.edu).
L. Tsang is with the University of Washington, Seattle, WA 98195 USA (e-mail: leung@ee.washington.edu).

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Oceanic and Atmospheric Administration (NOAA), and the U.S. Geological Survey (USGS) to provide consensus recommendations to guide the agencies' space-based Earth observation programs in the coming decade [1]. Many factors involving both scientific advances and societal benefit of potential missions were considered as part of this process. As articulated in the Decadal Survey, Soil Moisture Active Passive (SMAP) data would have both high-science and high-applications value. The accuracy, resolution, and global coverage of SMAP soil moisture and freeze/thaw measurements would be invaluable across many science and applications discipline including hydrology, climate, carbon cycle, and the meteorological, environmental and ecology applications communities. Change in future water resources is a critical societal impact of climate change, and scientific understanding of how such change may affect water supply and food production is crucial for policy makers. Uncertainties in current climate models result in disagreement on whether there will be more or less water regionally compared to today. SMAP data will help climate models to be brought into agreement on future trends in water resource availability. For these reasons, the NRC Decadal Survey's Water Resources Panel gave SMAP the highest mission priority within its field of interest. Furthermore, other NRC Decadal Survey panels dealing with weather, climate, ecosystems, and human health cited uses for the SMAP data. The broad uses of soil moisture and freeze/thaw information in Earth system science and applications resulted in the recommendation that SMAP be considered a high-priority mission in the Decadal Survey. SMAP is one of four missions recommended by the NRC for launch in the first tier 2010–2013 period. Based on the NRC Decadal Survey report and follow-on activities, NASA announced in early 2008 that SMAP would be one of its two new Earth science missions. The SMAP project is currently in Phase B and launch is scheduled for the 2014–2015 time frame.

Significant heritage exists from design and risk-reduction work performed during the Hydrosphere State (Hydros) mission formulation phase, and other technology development activities [2]. Hydros was an Earth System Science Pathfinder satellite mission proposed to NASA in 2001. It passed through a selective approval process in the competitive program and entered risk-reduction phase. However, it was subsequently canceled in 2005 due to NASA budget constraints. The Hydros science and applications community building, algorithm developments, field experiments, and engineering trade studies are directly relevant to SMAP and are now being used by the SMAP project to enhance the mission. The SMAP measurement approach with the conically scanning L-band radar and radiometer that share a rotating large antenna are directly derived from Hydros design. The SMAP design enhances the Hydros radiometer design to include radio frequency interference (RFI) detection and mitigation features. The SMAP observatory has additional enhancements over Hydros with selective redundancies and design improvements that allow for better accuracy measurements and more data acquisitions. The ground data systems, science processing, and algorithms are also significantly improved since the Hydros project.

II. SCIENCE AND APPLICATIONS

A. Soil Moisture and Freeze/Thaw

The SMAP project will implement a spaceborne Earth observation mission designed to collect measurements of surface soil moisture and freeze/thaw state, together termed the hydrosphere state. SMAP hydrosphere state measurements will yield a critical data set that enable science and applications users to:

- understand processes that link the terrestrial water, energy, and carbon cycles;
- estimate global water and energy fluxes at the land surface;
- quantify net carbon flux in boreal landscapes;
- enhance weather and climate forecast skill; and
- develop improved flood prediction and drought monitoring capability.

Soil moisture controls the partitioning of available energy into sensible and latent heat fluxes across regions where the evaporation regime is, at least intermittently, water-limited (as opposed to energy-limited). Since the fluxes of sensible heat and moisture at the base of the atmosphere influence the evolution of weather, soil moisture is often a significant factor in the performance of atmospheric models, both in weather and in climate applications. Numerical weather prediction (NWP) models and seasonal climate prediction figure prominently among the applications that drive soil moisture measurement requirements. For these applications, soil moisture retrievals are used in forecast initialization. Given the persistence of soil moisture anomalies, the initialized soil moisture can influence land fluxes, and thus simulated weather or climate, for days to months into the forecast. In this context, the metric that is used to define soil moisture measurement requirements is influenced by the need to capture soil moisture's control over land–atmosphere interactions in atmospheric models.

Equally important are the likely societal benefits to be derived from SMAP measurements. Many of these application areas and the approach to their improvement and modernization are also present in Global Earth Observation System of Systems (GEOSS[1]). The application areas directly addressed by SMAP measurements of soil moisture and freeze/thaw state, acquired globally and at high spatial and temporal resolutions, are as follows:

1) *Weather and Climate Forecasting*. Soil moisture variations affect the evolution of weather and climate over continental regions. Initialization of numerical weather prediction and seasonal climate models

[1] http://www.earthobservations.org/.

with accurate soil moisture information enhances their prediction skills and extends their skillful lead times. Improved seasonal climate predictions will benefit climate-sensitive socioeconomic activities, including water management, agriculture, fire, flood, and drought hazards monitoring.

2) *Droughts*. Soil moisture strongly affects plant growth and hence agricultural productivity, especially during conditions of water shortage and drought. Currently, there is no global *in situ* network for soil moisture monitoring. Global estimates of soil moisture and plant water stress must be derived from models. These model predictions (and hence drought monitoring) can be greatly enhanced through assimilation of space-based soil moisture observations.
3) *Floods*. Soil moisture is a key variable in water-related natural hazards including floods and landslides. High-resolution observations of soil moisture and landscape freeze/thaw status will lead to improved flood forecasts, especially for intermediate to large watersheds where most flood damage occurs. The surface soil moisture state is key to the partitioning of precipitation into infiltration and runoff, and thus is one of the major pieces of information which drives flood prediction modeling. Similarly, soil moisture in mountainous areas is one of the most important determinants of landslides. In cold land regions, the timing of thawing (which can be derived from satellite radar measurements) is coincident with the onset of seasonal snowmelt, soil thaw, and ice breakup on large rivers and lakes. Hydrologic forecast systems initialized with mapped high-resolution soil moisture and freeze/thaw fields will therefore open up new capabilities in operational flood forecasting.
4) *Agricultural Productivity*. SMAP will provide information on water availability and environmental stress for estimating plant productivity and potential yield. The availability of direct observations of soil moisture status and the timing and extent of potential frost damage from SMAP will enable significant improvements in operational crop productivity and water stress information systems, by providing realistic soil moisture and freeze/thaw observations as inputs for agricultural prediction models.
5) *Human Health*. Improved seasonal soil moisture forecasts using SMAP data will directly benefit famine early warning systems particularly in sub-Saharan Africa and South Asia, where hunger remains a major human health factor and the population harvests its food from rain-fed agriculture in highly monsoonal (seasonal) conditions. In the temperate and extra-tropical latitudes, freeze/thaw measurements from SMAP will benefit environmental risk models and early warning systems related to the potential expansion of many disease vectors that are constrained by the timing and duration of seasonal frozen temperatures. SMAP will also benefit the emerging field of landscape epidemiology (aimed at identifying and mapping vector habitats for human diseases such as malaria) where direct observations of soil moisture and freeze/thaw status can provide valuable information on vector population dynamics. Indirect benefits will also be realized as SMAP data will enable better weather forecasts that lead to improved predictions of heat stress and virus spreading rates. Better flood forecasts will also lead to improved disaster preparation and response.
6) *National Security*. Information on surface soil moisture and freeze/thaw is critical to ground trafficability and mobility. Weather models also need maps of the soil moisture and freeze/thaw variables to initialize forecasts for low-level fog, aviation density altitude, and dust generation. SMAP soil moisture and freeze/thaw information exceed current capability in terms of resolution, sensitivity, coverage, and sensing depth. Furthermore, radar observations over oceans and water bodies yield information on ice cover at high resolution and regardless of illumination.

B. Science Measurement Requirements

The large number of SMAP science and application objectives cover a range of resolutions and have different data refresh rate, sensing depth, and accuracy requirements. Not all requirements can be met with a single satellite mission and a given measurement approach. Nonetheless, three major groupings of data products can be defined: soil moisture hydroclimatology, soil moisture hydrometeorology, and carbon science. The resolution, refresh-rate, and accuracy requirements of these groupings have led to definition of the SMAP science requirements and consequently flow to the instrument requirements. In the following section, the heritage of microwave remote sensing for soil moisture mapping is reviewed. The spaceborne, airborne, and ground-based experimental heritage led directly to development of the SMAP measurement approach.

C. Comparison With Other Approaches

There is significant heritage from both observations and theory showing the relative advantages of lower frequency microwave radiometry over that from higher frequencies for mapping soil moisture content at the land surface. At lower frequencies, the atmosphere is less opaque, the intervening vegetation biomass is more transparent, and the effective emission profile is more representative of the soil below the surface skin layer.

The limited duration SkyLab mission in the 1970s was the earliest demonstration of soil moisture retrieval from orbit based on L-band radiometry [3]. Currently, the

European Soil Moisture and Ocean Salinity (SMOS) mission is in orbit (successfully launched in early November 2009) and is preparing to provide global L-band radiometric observations for soil moisture and ocean salinity [4], [5]. The SMOS radiometer measures at L-band for optimum sensitivity to soil moisture and ocean salinity. The wide swath provides two to three day global revisit for adequate sampling of dry down and storm wetting episodes. The SMOS instrument uses a synthetic aperture antenna that yields multiangular brightness temperature mapping at about 40-km resolution [4], [5].

Higher frequency microwave radiometers such as those at C-band ($\sim$6 GHz; AMSR-E, Windsat, and MIS) or X-band ($\sim$10 GHz; TMI) have to contend with a lower penetration depth for soil moisture retrievals and higher attenuation in the presence of vegetation. At L-band, the brightness temperature emission originates from the top $\sim$5 cm of soil, and the measurements are sensitive to soil moisture through vegetation of up to $\sim$5 kg m^{-2} water content. This corresponds to about 65% of the nonfrozen global land regions and excludes dense forests. In tropical forests, which comprise much of the land region with vegetation water content larger than 5 kg m^{-2}, exchanges of heat and moisture between the land and the atmosphere are principally limited by available energy rather than soil moisture. Thus, for regions where soil moisture is a control on land–atmosphere exchanges (important for climate modeling, numerical weather prediction, and water and energy cycles science), L-band retrievals can be performed and meet the science requirements. In contrast, C- and X-band measurements are representative of the top 1 cm or less of soil. Moderate vegetation (greater than $\sim$3 kg m^{-2}) attenuates the signal sufficiently at these frequencies to make the measurements relatively insensitive to soil moisture. At even higher microwave frequencies (e.g., 37 GHz), the utility of measurements for surface wetting detection is limited to essentially bare soil or flooded regions.

L-band radiometry at 1.4 GHz has an added advantage because it includes a region of the spectrum that is allocated exclusively for radio astronomy and passive Earth sensing. Measurements at C-band are vulnerable to RFI. Even though the L-band spectrum is legally protected, there are still transmissions and leakages of man-made microwave signals within this band. Both the SMAP radiometer and radar have adopted RFI detection and mitigation measures that are described in Section IV.

Synthetic aperture radars (SARs) provide observations at much higher spatial resolution than radiometers. The heritage of spaceborne L-band SARs includes SIR-C, JERS, and PALSAR (currently operating). SARs provide high-resolution measurements, but typically operate with narrow swaths and do not provide the frequent temporal coverage needed for global land hydrology applications. The high-resolution advantage of radar is mitigated for soil moisture sensing by the higher sensitivity of radar to surface roughness and vegetation scattering.

The SMAP measurement approach is to integrate an L-band radar and an L-band radiometer as a single observation system combining the relative strengths of active and passive remote sensing for enhanced soil moisture mapping. The radar and radiometer measurements can be effectively combined to derive soil moisture maps that approach the accuracy of radiometer-only retrievals, but with a resolution intermediate between the radar and radiometer resolutions (and that can approach the radar resolution under some conditions). The SMAP mission requirements include simultaneous L-band brightness temperature and backscatter data products, with three-day (or better) global revisit at spatial resolutions of about 40 and 3 km, respectively. The combined radar–radiometer-based soil moisture product is generated at about an intermediate 9-km resolution (see Section VI-B). Because the effects of vegetation and surface roughness are dependent on incidence angle, the SMAP mission adopted a conical scan, constant incidence angle approach. This reduces the retrieval complexity and also facilitates the use of time-series retrieval algorithms. To maximize the independent information obtainable from the polarized V and H brightness temperature channels, a single incidence angle in the range between 35° and 50° is desired. A 40° incidence angle was adopted for SMAP as a suitable angle for both the radiometer and radar designs. The wide swath that results from this approach enables SMAP observations to provide global coverage in two to three days. Table 1 is a summary of the SMAP instrument functional requirements derived from the science measurement needs.

III. GEOPHYSICAL CONTRIBUTIONS TO THE MEASUREMENTS

The ability of microwave remote sensing instruments to sense soil moisture and its freeze/thaw state has its origin in the distinct contrast between dielectric properties of water and dry soils, and in changes of surface dielectric properties that occur as water transitions between solid and liquid phases. The early foundations of soil moisture remote sensing can be found in [6]–[10]. The sensitivity of radar backscatter and radiometer brightness temperature signatures to these landscape features is affected strongly by the sensing wavelength, as well as landscape structure and moisture conditions. The composite remote sensing signature represents a sampling of the aggregate landscape dielectric and structural characteristics, with sensor wavelength having a strong influence on the sensitivity of the remotely sensed signature to the various landscape constituents.

Components from the soil and the vegetation canopy contribute to the L-band brightness temperature as

$$T_{Bp} = T_s e_p \exp(-\tau_p \sec\theta) + T_c(1-\omega_p)\left[1-\exp(-\tau_p \sec\theta)\right] \times \left[1 + r_p \exp(-\tau_p \sec\theta)\right]. \quad (1)$$

Table 1 SMAP Mission Requirements

Scientific Measurement Requirements	Instrument Functional Requirements
Soil Moisture: ~±0.04 m^3m^{-3} volumetric accuracy in the top 5 cm for vegetation water content ≤ 5 kg m^{-2}; Hydrometeorology at ~10 km resolution; Hydroclimatology at ~40 km resolution	L-Band Radiometer (1.41 GHz): Polarization: V, H, U Resolution: 40 km Radiometric Uncertainty*: 1.3 K L-Band Radar (1.26 GHz): Polarization: VV, HH, HV (or VH) Resolution: 10 km Relative accuracy*: 0.5 dB (VV and HH) Constant incidence angle** between 35° and 50°
Freeze/Thaw State: Capture freeze/thaw state transitions in integrated vegetation-soil continuum with two-day precision, at the spatial scale of land-scape variability (~3 km).	L-Band Radar (1.26 GHz): Polarization: HH Resolution: 3 km Relative accuracy*: 0.7 dB (1 dB per channel if 2 channels are used) Constant incidence angle** between 35° and 50°
Sample diurnal cycle at consistent time of day (6am/6pm Equator crossing); Global, ~3 day (or better) revisit; Boreal, ~2 day (or better) revisit	Swath Width: ~1000 km Minimize Faraday rotation (degradation factor at L-band)
Observation over minimum of three annual cycles	Baseline three-year mission life
* Includes precision and calibration stability ** Defined without regard to local topographic variation	

This simplification of the radiative transfer process is referred to as the tau–omega model where subscript p refers to polarization (V or H), T_s is the soil effective temperature, T_c is the vegetation temperature, τ_p is the nadir vegetation opacity, ω_p is the vegetation single scattering albedo, and r_p is the soil reflectivity [6], [9], [10]. The soil reflectivity is related to the soil emissivity by $e_p = (1 - r_p)$. The surface emissivity at L-band is sensitive to soil moisture because of the large contrast in the dielectric constant properties of water and dry soil. Values of e_p can range from 0.6 for moist soils to close to unity for dry soils. The resulting dynamic range of brightness temperature can be up to 100 K. For these reasons, radiometry in the L-band is well suited for surface soil moisture detection.

Radar remote sensing of the total copolarized backscatter from the landscape at polarization p is the sum of three components [7], [8], [11]

$$\sigma_{pp}^{t} = \sigma_{pp}^{s}\exp(-2\tau_p \sec\theta) + \sigma_{pp}^{\text{vol}} + \sigma_{pp}^{\text{int}}. \tag{2}$$

The first term is the surface backscatter σ_{pp}^{s} modified by the two-way attenuation through a vegetation layer of nadir opacity τ_p. The second term represents the backscatter from the vegetation volume σ_{pp}^{vol}. The third term represents interactions between vegetation and the soil surface σ_{pp}^{int}. Expressions for each of these components depend on characteristics of the soil dielectric properties, surface roughness, and the vegetation dielectric and structural properties.

IV. INSTRUMENT AND MISSION DESIGN

A. Measurement Approach

The SMAP instrument design is driven by the key measurement requirements outlined in Table 1. The optimized instrument design includes a 6-m diameter, conically scanning, deployable mesh reflector antenna. The antenna is shared by both the radiometer and the radar, using a single L-band feed. The reflector rotates about the nadir axis at 14.6 rpm, producing a conically scanned antenna beam with a surface incidence angle of approximately 40° (Fig. 1).

The feed assembly design employs a single horn, with dual-polarization and dual-frequency capability (radiometer at 1.41 GHz and radar at 1.26 GHz). The radar and radiometer frequencies are separated by diplexers and routed to the appropriate electronics for detection. The radiometer electronics are located with the feedhorn on the spun side of the reflector boom assembly and spacecraft interface. Slip rings provide a signal interface to the spacecraft. The more massive and thermally dissipative radar electronics are on the despun side, and the transmit/receive pulses are routed to the spun side via an RF rotary joint.

The SMAP radiometer provides a real aperture resolution in which the dimensions of the 3-dB antenna footprint projected on the surface meet the 40-km spatial resolution requirement (calculated as the root ellipsoidal area). The radiometer measures four Stokes parameters at 1.41 GHz. The U-channel measurement is included to provide a capability to correct for possible Faraday rotation

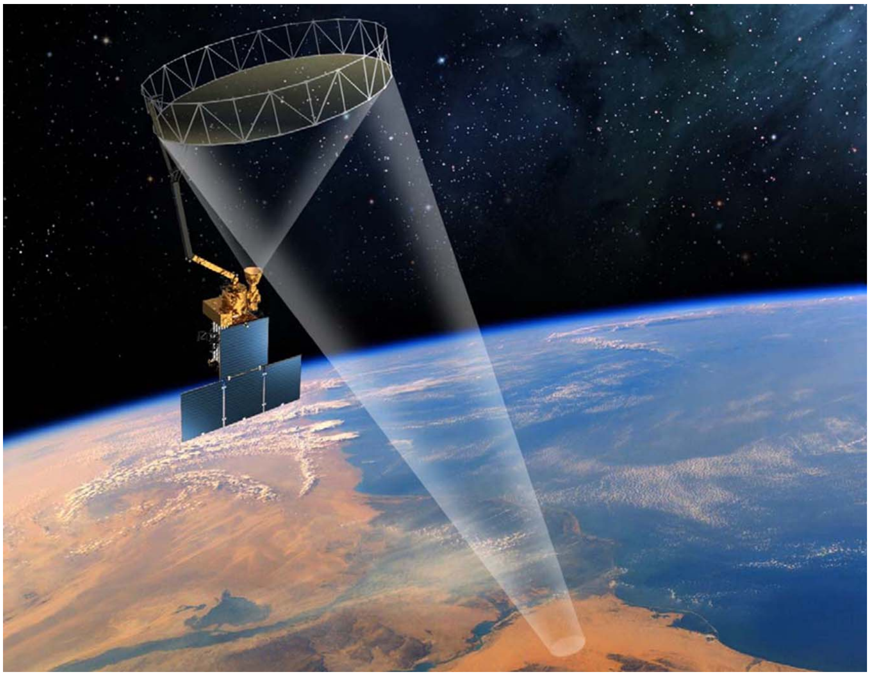


Fig. 1. ***SMAP observatory is a dedicated spacecraft with a rotating 6-m lightweight deployable mesh reflector. The radar and the radiometer share a common feed.***

caused by the ionosphere, although such Faraday rotation is minimized by the selection of the 6 A.M./6 P.M. sun-synchronous SMAP orbit. Correction in the presence of ionospheric inhomogeneities and the use of the first Stokes parameter are under investigation in the Faraday rotation and retrieval algorithm enhancements.

To obtain the required 3- and 9-km resolution for the freeze/thaw and soil moisture products, the radar employs pulse compression in range and Doppler discrimination in azimuth to subdivide the antenna footprint. This is equivalent to the application of SAR techniques to the conically scanning radar case. Due to squint angle effects, the azimuthal resolution of the pixels degrades towards the center of the swath (see Fig. 2). The SAR-processed pixels will be multilooked and posted on a 1-km grid in swath coordinates, but the single-look resolution varies from about 360-m at the swath edge to about 1.2-km at a distance of 150 kilometers from the center track. When the data are averaged to the required 3-km measurement cells, the accuracy requirement is met over the outer 70% of the 1000-km swath. The radar instrument provides VV, HH, and HV channels, but is not a fully polarimetric system.

At L-band, RFI can contaminate both radar and radiometer measurements. Early measurements and results from the SMOS mission indicate that in some regions RFI is present and detectable. The SMAP radar and radiometer electronics and algorithms have been designed to include features to mitigate the effects of RFI. Interference for the SMAP radar comes largely from terrestrial air surveillance radars that share the spectrum with Earth science radars. To combat this, the SMAP radar utilizes selective filters and an adjustable carrier frequency in order to tune to predetermined RFI-free portions of the spectrum while on orbit. The radiometer suffers interference primarily from out-of-band and spurious emissions by numerous active services (including radars, communications systems, and others). The SMAP radiometer will implement a combination of time and frequency diversity and kurtosis

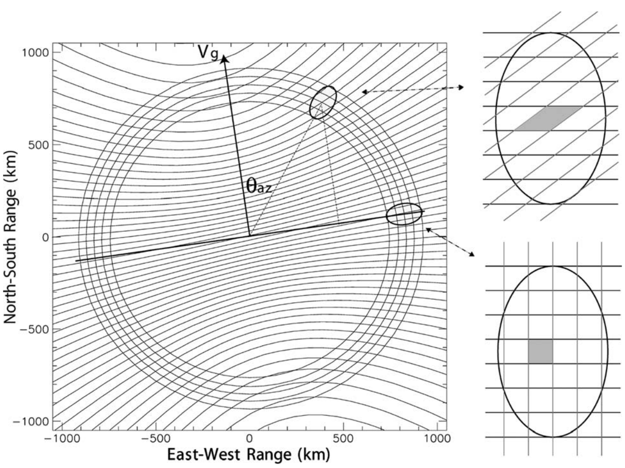


Fig. 2. ***Due to conical scan configuration the spatial resolution varies across the swath, with single look resolution ranging from 360-m at the swath edge to approximately 1.2-km at a point in the swath 150-km from the ground track.***

detection, to mitigate RFI. Mitigation of RFI using time-domain detection and removal was part of the original Hydros design and is being used on Aquarius [12]. These techniques have been demonstrated in airborne remote sensing [13]–[15].

The SMAP radar and radiometer also derive some heritage from the NASA Aquarius/SAC-D mission which also carries L-band active and passive microwave instruments. Aquarius/SAC-D is designed to make high-accuracy radiometer measurements for retrieval of surface sea salinity. The Aquarius/SAC-D radiometer makes push-broom coarse-resolution but accurate measurements. The L-band scatterometer provides data to correct for sea surface roughness. The SMAP conically scanning radiometer derives some heritage from Aquarius/SAC-D in its RF assembly, solid-state phased array, and loop-back/switch. The SMAP radar RF electronics have considerable heritage from the Aquarius/SAC-D design. The Aquarius/SAC-D heritage reduces risk and allows for cost savings. A distinguishing feature of SMAP radar and radiometer measurements, when compared with Aquarius/SAC-D, is the approach to measurements. SMAP makes conical scans of the surface with a rotating reflector that result in wide-swath mapping of the surface. This measurement approach allows for the frequent revisit times and data refresh that are required for soil moisture and freeze/thaw monitoring. Synthetic aperture processing of radar measurements allows for high-resolution surface mapping which is also required given the heterogeneity of land surface conditions.

Fig. 3. ***NASA radiometer system used in the Beltsville Agricultural Research Center experiments in the 1970s and 1980s.***

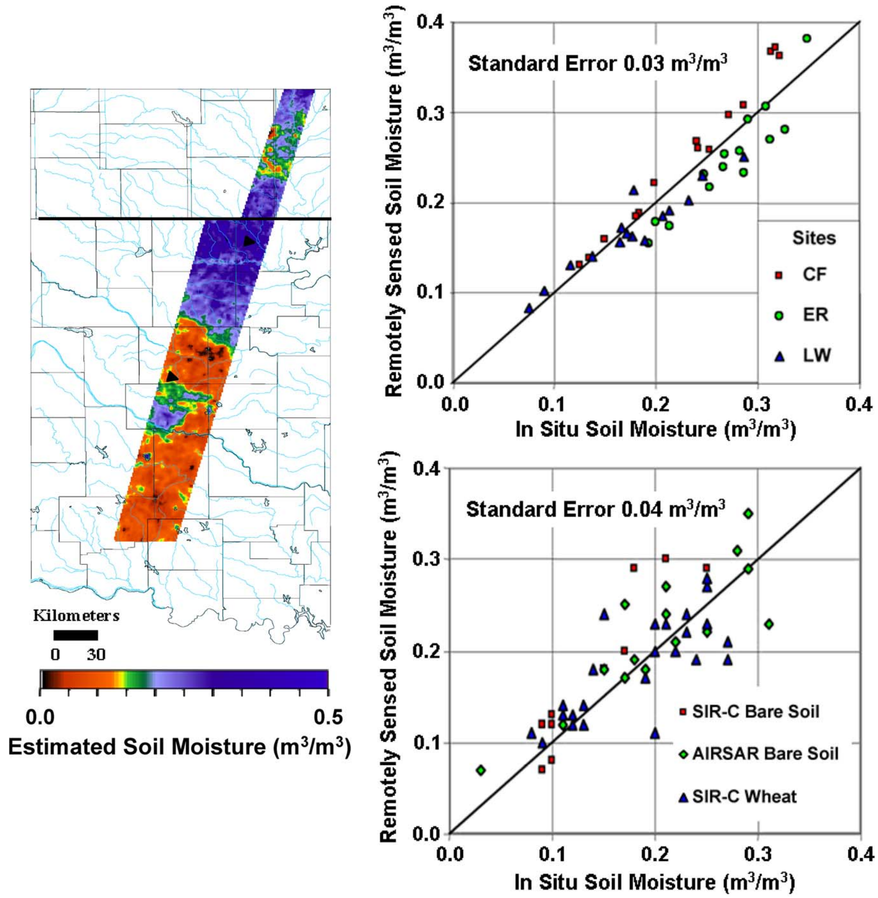
V. MEASUREMENTS AND ALGORITHMS HERITAGE

The L-band passive and active soil moisture retrieval algorithms under consideration for SMAP have been developed over an extensive period (~three decades) of microwave modeling and field experiments using ground-based, airborne, and space shuttle instruments. Only a few of the most relevant heritage studies are summarized here. For passive microwave approaches, early ground-based experiments such as those reported by [16] provided key data sets for a wide range of measurement and field conditions. Fig. 3 shows an instrument system used in these early experiments. The studies summarized in [17] established a description of vegetation effects and provided a comprehensive approach to correcting for vegetation in soil moisture retrievals. Other important early studies are summarized in [7] and [8]. In more recent years, the SMOS mission has supported numerous L-band ground-based investigations that have contributed to its unique multiangle retrieval algorithm approach [18]. In addition to the references cited here, there is a rich heritage of soil moisture research that has been generated as part of the SMOS mission. Detailed descriptions of the SMOS mission and its scientific approach to measurements, retrievals, and applications are included in this issue of the IEEE Proceedings.

An intensive period of ground-based active microwave remote sensing research took place in the 1970s and 1980s with research conducted to examine soil and vegetation effects on radar backscatter. Much of this work is presented in [7] and [8]. Fewer radar studies have been conducted since then. These have included SIR-C supporting investigations [19] and other supporting studies for the JERS, Radarsat, PALSAR, and other spaceborne SARs.

There have been very few combined active/passive L-band ground-based experiments. Currently, there is only one such system in operation: the NASA GSFC/GWU's Combined Radar/Radiometer (ComRAD) system [20]. However, there have been a number of airborne combined active/passive L-band deployments which have provided valuable data sets to develop and test SMAP algorithms (see Fig. 5 and associated references). These airborne experiments are described in more detail below.

Though data from ground-based field experiments have been extremely important in formulating and validating models and algorithms, ground-based systems are not amenable to observing a wide range of soil and vegetation conditions or resolving critical issues of implementation such as point to footprint scaling. Early airborne radiometer experiments summarized in [21] established the sensitivity and linearity of L-band radiometer responses to soil moisture with single fixed beam instruments. In the 1980s and early



(a) (b)

Fig. 4. ***Examples of supporting large scale field experiment results: (a) L-band-radiometer-based soil moisture map for one day during SGP97 (10 000 km^2 at a resolution of 800 m); (b) comparison of ground-based soil moisture observations and L-band radiometer estimates for three study sites in SGP97 (top), and comparison of ground-based soil moisture observations and radar estimates for study sites in Washita'94 (bottom).***

1990s, an instrument called the Push Broom Microwave Radiometer (PBMR) provided the capability to map larger domains, which facilitated the observation of a wider range of conditions [20]. A milestone in L-band aircraft remote sensing was the development of the Electronically Scanned Thinned Array Radiometer (ESTAR). This instrument was capable of mapping large domains at high resolution very efficiently, and demonstrated the concept of aperture synthesis microwave radiometry, on which the MIRAS instrument aboard the SMOS mission is based [4]. Some of the key contributions of ESTAR were the Monsoon'91 [23], Washita'92 [24], and SGP97 [25] experiments. Fig. 4(a) shows an example of a map product from SGP97. Fig. 4(b) shows a comparison between ground observations and ESTAR estimates for intensive study sites that contributed to establishing the expected performance of SMAP. Additional experiments (SMEX03 and SMEX04) focused on other regions of the United States and utilized a new version of ESTAR that operated in 2-D [26].

Airborne and spaceborne imaging L-band radars have been available for many years. These instruments have been capable of providing very high-resolution observations. Perhaps the most significant investigation was conducted as part of the Washita'94 field campaign and involved both the AIRSAR and SIR-C radars. These data sets have supported development of radar-based soil moisture retrieval algorithms such as [28]. Fig. 4(b) (bottom) shows the Washita'94 comparison of observed and estimated soil moisture.

Recognizing the potential of combined active/passive observations for soil moisture, several aircraft field campaigns have been conducted utilizing a prototype of SMAP called the Passive and Active L-band System (PALS) [28]. These field campaigns include SGP99 [28], SMEX02 [29], CLASIC, and SMAPVEX08. A significant challenge has been to understand the relative importance of scene feature and instrument parameters in simultaneous radiometer and radar observations. The concurrent active and passive measurements by PALS have helped to clarify these issues.

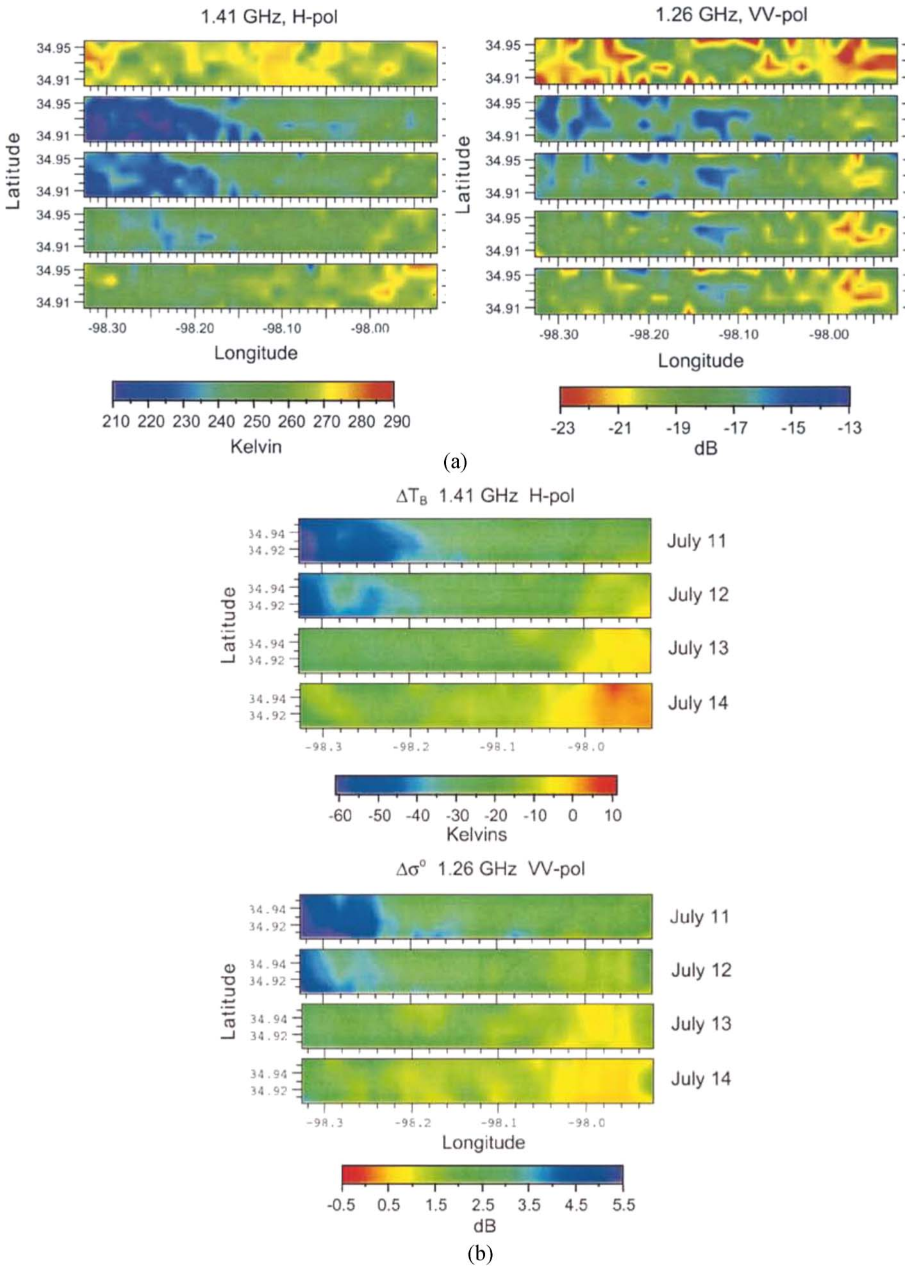


Fig. 5. ***PALS results from SGP99: (a) daily image sequences (July 9 and 11–14) of brightness temperature (T_B—H-pol) and radar backscatter cross section (σ^t—VV co-pol) across Little Washita watershed area in Oklahoma. A rain event occurred on July 10. (b) Sensor change responses, $\triangle T_B$ and $\triangle\sigma^t$, to soil moisture change from initial dry conditions on July 9, showing the similar spatial patterns of wetting and drying in the passive and active data, independent of the relatively time-invariant spatial landscape patterns (influenced by vegetation, roughness, and topography) [28].***

A relevant example is derived from SGP99 PALS data over Oklahoma. Temporal sequences of radiometer and radar data revealed patterns of brightness temperature and backscatter contributed by roughness, vegetation, and soil moisture variations [Fig. 5(a)]. The contributions of soil moisture changes to these patterns were made clearer when daily changes were compared [Fig. 5(b)]. This result contributed to establishing the basis for the combined active/passive approach that will be utilized in SMAP that optimizes the retrieval accuracy of the passive instrument with the higher resolution of the radar (see Section VI-B).

VI. GEOPHYSICAL DATA PRODUCTS

The SMAP planned data products are listed in Table 2. Level 1B and 1C data products are calibrated and geolocated

Table 2 SMAP Data Products Table

Product Name	Short Description	Spatial Resolution
L1A_S0	Radar raw data in time order	–
L1A_TB	Radiometer raw data in time order	–
L1B_S0_LoRes	Low resolution radar σ_o in time order	5x30 km
L1B_TB	Radiometer T_B in time order	36x47 km
L1C_S0_HiRes	High resolution radar σ_o (half orbit, gridded)	1-3 km
L1C_TB	Radiometer T_B (half orbit, gridded)	36 km
L2_SM_P	Soil moisture (radiometer, half orbit)	36 km
L2_SM_A/P	Soil moisture (radar/radiometer, half orbit)	9 km
L3_F/T_A	Freeze/thaw state (radar, daily composite)	3 km
L3_SM_P	Soil moisture (radiometer, daily composite)	36 km
L3_SM_A/P	Soil moisture (radar/radiometer, daily composite)	9 km
L4_SM	Soil moisture (surface & root zone)	9 km
L4_C	Carbon net ecosystem exchange (NEE)	9 km

instrument measurements of surface radar backscatter cross section and brightness temperatures derived from antenna temperatures. Level 2 products are geophysical retrievals of soil moisture on a fixed Earth grid based on Level 1 products and ancillary information; the Level 2 products are output on half-orbit basis. Level 3 products are daily composites of Level 2 surface soil moisture and freeze/thaw state data. Level 4 products are model-derived value-added data products that support key SMAP applications and more directly address the driving science questions.

For both the hydroclimatology (L2_SM_P) and hydrometeorology (L2_SM_A/P) data products, the baseline mission requirement is to provide estimates of soil moisture in the top 5 cm of soil with an error of no greater than 4% volumetric (one sigma) at three-day average intervals over the global land area excluding regions of snow and ice, frozen ground, mountainous topography, open water, urban areas, and vegetation with water content greater than 5 kg m^{-2} (averaged over the spatial resolution scale). This level of performance will enable SMAP to meet the needs of the hydroclimatology and hydrometeorology applications identified in the NRC report [1].

A. Radiometer Soil Moisture Data Product

The SMAP radiometer-based soil moisture product (L2_SM_P, also called the hydroclimatology data product) has a spatial resolution of 40 km and is posted on a 36-km grid.

Retrieval of soil moisture from the SMAP radiometer data is based on inversion of the tau–omega model (1) which assumes that vegetation multiple scattering and reflection at the vegetation–air interface are negligible. Corrections for surface roughness are performed as $r_{p\ \mathrm{smooth}} = r_{p\ \mathrm{rough}}/\exp(-h)$ where the parameter h is a function of the root mean square (rms) surface heights [31]. Nadir vegetation opacity is related to the total columnar vegetation water content W (kg/m^2) by $\tau_p = b_p W$ with the coefficient b_p dependent on vegetation type. The high-resolution radar data will be used to identify inland water bodies, and vegetation characteristics at the subradiometer resolution. The contribution of radar-derived information is a key feature of the SMAP approach to surface soil moisture estimation using L-band radiometry.

The SMAP passive microwave algorithm relies on vegetation information that are derived from the SMAP radar cross-pol and co-pol high-resolution measurements (radar vegetation index) augmented with ancillary data from high-resolution optical and infrared measurements and databases. During the period leading to the SMAP launch and data acquisitions, the utility of SMOS retrievals of vegetation microwave properties will be analyzed in the context of the SMAP retrieval approach. SMOS multiangular measurements allow retrieval of both soil moisture and microwave properties of vegetation over the radiometer footprint.

If the air, vegetation, and near surface soil can be assumed to be in thermal equilibrium, as is the case near the SMAP overpass time of 6 am, then T_C is approximately equal to T_S and these temperatures can be replaced in the radiative transfer equation by a single effective temperature for the scene (T_{eff}). Information on T_{eff} will be obtained from ancillary data sources. Soil moisture can be estimated from r_p using Fresnel and dielectric-soil moisture relationships. Retrieval of soil moisture will focus on the data from the 6 A.M. SMAP overpass since the assumptions of thermal equilibrium and near uniformity of conditions in the near surface soil layers and overlying vegetation are more likely to be true at this time of day than at 6 P.M.

B. Combined Radar and Radiometer Soil Moisture Product

Radars are capable of high spatial resolution. However, since radar backscatter is highly influenced by surface roughness and vegetation structure and water content, they have reduced sensitivity to soil moisture as compared to radiometers. Various algorithms for retrieval of soil moisture from radar backscatter have been developed, but they perform adequately only in low-vegetation water content conditions [27]. In contrast, although the spatial resolution of L-band radiometers is relatively coarse, the retrieval of soil moisture from radiometers is well established, and L-band radiometers have a high sensitivity to soil moisture even in the presence of moderate vegetation. To overcome the individual limitations of the passive and active techniques, the SMAP approach combines both measurements to yield an intermediate resolution soil moisture data product while maintaining the required retrieval accuracy.

The merging of radar and radiometer measurements in a combined retrieval yields the SMAP L2_SM_A/P hydrometeorology product. This product is required at about the 10-km scale which is intermediate between the individual radar and the radiometer resolutions. This allows some aggregation of the radar data with associated reduction in speckle and other random error contributions.

Brightness temperature disaggregation techniques as well as time-series methods have been developed to combine the more accurate, but lower spatial resolution radiometer measurements with higher resolution but lower accuracy radar measurements in order to form an intermediate-resolution soil moisture product [30], [32]–[34]. The current SMAP baseline approach uses a time-series approach to establish a relationship between changes in brightness temperature and changes in radar backscatter using sequential measurements at a fixed location for a season and at the same look angle. The relationship is taken to be linear based on experimental data as well as theoretical analysis. The established relationship is then used to disaggregate brightness temperature over the terrain using the higher resolution radar backscatter measurement anomalies (from the spatial average). The brightness temperature retrieval algorithms developed for the L2_SM_P product are then applied to the disaggregated brightness temperatures to retrieve soil moisture at about 10-km resolution for the L2_SM_A/P product. Ancillary data at the equivalent resolution are used in the algorithm. The feasibility of brightness temperature disaggregation and time-series change analysis have been demonstrated using PALS airborne radar and radiometer data obtained during field campaigns [28].

C. Radar-Based Freeze/Thaw Detection Products

Derivation of the SMAP freeze/thaw L3_F/T_A product will employ a time-series change detection approach that has been previously developed and successfully applied using satellite remote sensing radar backscatter and radiometric brightness temperature data from a variety of sensors and spectral wavelengths [35]. The general approach of these techniques is to identify landscape freeze/thaw transition sequences by exploiting the dynamic temporal response of backscatter or brightness temperature to differences in the aggregate landscape dielectric constant that occur as the landscape transitions between predominantly frozen and nonfrozen conditions. These techniques assume that the large changes in dielectric constant occurring between frozen and nonfrozen conditions dominate the corresponding backscatter and brightness temperature temporal dynamics, rather than other potential sources of temporal variability such as changes in canopy structure and biomass or large precipitation events. This assumption is valid during periods of seasonal freeze/thaw transitions for most areas of the cryosphere.

Temporal change detection classifies and maps landscape freeze/thaw state using SMAP time-series L-band radar data. The freeze/thaw algorithms include a seasonal threshold approach representing the baseline algorithm, as well as optional moving window and temporal edge detection algorithms that may eventually augment the current baseline algorithm. These algorithms require only time-series radar backscatter data to derive landscape freeze/thaw state information. However, the use of ancillary data to enhance algorithm performance is being investigated, including the use of land cover and open water classification maps to refine algorithm parameters and mask open water and permanent ice areas during operational data processing.

D. Model Value-Added Products

SMAP measurements provide direct sensing of surface soil moisture in the top 5 cm of the soil column. However, several of the key applications targeted by SMAP require knowledge of root zone soil moisture in the top 1 m of the soil column, which is not directly measured by SMAP. As part of its baseline mission, the SMAP project will produce model-derived value-added (Level 4) data products to fill this gap and provide estimates of root zone soil moisture that are informed by and consistent with SMAP surface observations. Such estimates are obtained by merging SMAP observations with estimates from a land surface model in a soil moisture data assimilation system [36]. During the SMAP preflight period when SMOS radiometer measurements will be available, the SMAP project will develop and test its land data assimilation system with these available measurements.

The land surface model component of the assimilation system is driven with observations-based meteorological forcing data, including precipitation, which is the most important driver for soil moisture. The model also encapsulates knowledge of key land surface processes, including the vertical transfer of soil moisture between the surface and root zone reservoirs. Finally, the model interpolates and extrapolates SMAP observations in time and in space. The SMAP L4_SM product thus provides a comprehensive and consistent picture of land surface hydrological conditions based on SMAP observations and complementary information from a variety of sources. The assimilation algorithm considers the respective uncertainties of each component and yields a product that is superior to satellite or model data alone. Error estimates for the L4_SM product are generated as a by-product of the data assimilation system.

The L4_C algorithms utilize daily soil moisture and temperature inputs with ancillary land cover classification and vegetation gross primary productivity (GPP) inputs to compute the net ecosystem exchange (NEE) of carbon dioxide with the atmosphere over northern ($> 45°$ latitude) vegetated land areas. The NEE of carbon dioxide with the atmosphere is a fundamental measure of the balance between carbon uptake by vegetation GPP and carbon losses through autotrophic and heterotrophic respiration. The total ecosystem respiration rate encompasses most of the annual terrestrial carbon dioxide efflux to the atmosphere and more than 70% of total carbon uptake by GPP.

The SMAP L4_C product will provide regional mapped measures of NEE and component carbon fluxes that are within the accuracy range of point tower carbon dioxide eddy covariance measurement approaches. The computation of NEE, its constituent carbon fluxes, and associated soil moisture and temperature controls to respiration will enable mechanistic understanding of spatial and temporal variations in NEE. NEE represents the primary measure of carbon exchange between the land and the atmosphere and the L4_C product will be directly relevant to a range of applications including regional mapping and monitoring of terrestrial carbon stocks and atmospheric transport model inversions of terrestrial source-sink activity for atmospheric CO_2. The SMAP L4_C product will also satisfy carbon cycle science objectives of the NRC Decadal Survey [1], and advance understanding of the way in which northern ecosystems respond to climate anomalies and their capacity to reinforce or mitigate global warming.

VII. SUMMARY

Global monitoring of soil moisture and freeze/thaw state with SMAP will improve our understanding of the linkages between the water, energy, and carbon cycles. It will also lead to improvements in estimation of global water and energy fluxes at the land surface, weather and climate forecasts, flood and drought monitoring, predictions of agricultural productivity, and quantification of net carbon flux in boreal landscapes. Additional science and applications cover a wide range of disciplines. The SMAP radar and radiometer measurements support estimation of sea ice cover, ocean salinity, and high ocean surface winds. There are also applications in human health and national security. SMAP will demonstrate the potential benefits obtainable from combined active and passive L-band sensing for hydrologic applications. SMAP will also demonstrate the technology of large rotating deployable-mesh antennas in space for remote sensing. For these reasons, the SMAP mission will provide a unique new capability for Earth observations from space. ■

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ABOUT THE AUTHOR

Authors' photographs and biographies not available at the time of publication.