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# The Soil Moisture Active and Passive (SMAP) Mission

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**ABSTRACT**: The Soil Moisture Active and 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 moisture present at 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 land and atmosphere. Soil moisture measurements are also of great importance in assessing flooding and monitoring drought. SMAP observations can help mitigate these natural hazards, resulting in potentially great economic and social benefits. SMAP soil moisture and freeze/thaw timing observations 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 would utilize an L-band radar and radiometer. These instruments will share a rotating 6-meter mesh reflector antenna to provide high-resolution and high-accuracy global maps of soil moisture and freeze/thaw state every two to three days. The SMAP instruments provide direct measurements of surface conditions. In addition, the SMAP project will use these observations with advanced modeling and data assimilation to provide deeper root-zone soil moisture and estimates of land surface-atmosphere exchanges of water, energy and carbon. SMAP is scheduled for a 2014 launch date

# 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 NASA, NOAA, and 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 were considered in the process. SMAP data has both high science value and high applications value. The high accuracy, resolution, and global coverage of SMAP soil moisture and freeze/thaw measurements are invaluable across many science and applications disciplines including hydrology, climate, carbon cycle, and the meteorological, environmental and ecology applications communities. Future water resources are 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. Current climate models' uncertainties result in disagreement on whether there will be more or less water regionally compared to today. SMAP data will enable 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. SMAP is one of four missions recommended by the NRC for launch in the first tier 2010 to 2013 period. Based on the report and follow-on activities, in early 2008 NASA announced that SMAP would be one of two new Earth science missions based on the recommendations of the Decadal Survey. SMAP launch is scheduled for 2014.

Significant heritage exists from design and risk-reduction work performed during Hydrosphere State (Hydros) mission formulation and other technology development activities [2]. Hydros was an Earth System Science Pathfinder satellite mission proposal that was submitted to NASA in 2001. It was successful through several down-selects in the competitive program and entered risk-reduction phase. It was cancelled in 2005 due to budget constraints at the agency. The science and applications community-building, algorithms work, field experimentation and engineering trade studies performed for Hydros are now used in the SMAP project to enhance the mission.



# 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 will 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;
- 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. Among the applications that drive soil moisture measurement requirements Numerical Weather Prediction (NWP) models and seasonal climate prediction figure prominently. For these applications, soil moisture retrievals are used in forecast initialization; in effect, 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.

### B. Applications

Equally important in the SMAP mission is the return of societal benefits, primarily through applications. SMAP measurements of soil moisture and freeze/thaw state, acquired globally and at high spatial and temporal resolutions, will have numerous applications that are described below.

*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 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, and fire, flood and drought hazards monitoring.

*Droughts*. Soil moisture strongly affects plant growth and hence agricultural productivity, especially during conditions of water shortage and drought. At present 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.

*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. Soil moisture in mountainous areas is one of the most important determinants of landslides. In cold land regions the timing of satellite radar derived thawing 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.

*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.

*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 lead to improved disaster preparation and response.

*National Security*. Information on surface soil moisture and freeze/thaw is critical to ground trafficability and mobility. Weather models need maps of the soil moisture and freeze/thaw variables to initialize forecasts for low-level fog, 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. DoD is partnering with NASA in launch services and will access the data to refine requirements and support national security applications.



## C. Science Measurement Requirements

The SMAP science and applications 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 of these groupings lead to the definition of science requirements and consequently flow to instrument requirements. The initial SMAP measurement requirements and instrument performance characteristics are summarized in Table 1. They are derived from the high level science requirements and specifications provided in [1], and follow those developed for Hydros [2]. Driving aspects of the SMAP measurement requirements include the need for simultaneous measurement of L-Band brightness temperature and backscatter with three day revisit and high spatial resolution (40 km and 3 km, respectively).

| Table 1. SMAP Preliminary Mission Requirements | |
|---|---|
| **Scientific Measurement Requirements** | **Instrument Functional Requirements** |
| Soil Moisture:<br>~±0.04 $m^3m^{-3}$ volumetric accuracy in top 2-5 cm for vegetation water content < 5 kg $m^{-2}$;<br>Hydrometeorology at ~10 km;<br>Hydroclimatology at ~40 km | L-Band Radiometer (1.41 GHz):<br>Polarization: V, H, U<br>Resolution: 40 km<br>Radiometric Uncertainty*: 1.3 K<br>L-Band Radar (1.26 GHz):<br>Polarization: VV, HH, HV (or VH)<br>Resolution: 10 km<br>Relative accuracy*: 0.5 dB (VV and HH)<br>Constant incidence angle** between 35° and 50° |
| Freeze/Thaw State:<br>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):<br>Polarization: HH<br>Resolution: 3 km<br>Relative accuracy*: 0.7 dB (1 dB per channel if 2 channels are used)<br>Constant incidence angle** between 35° and 50° |
| Sample diurnal cycle at consistent time of day (6am/6pm);<br>Global, ~3 day revisit;<br>Boreal, ~2 day revisit | Swath Width: ~1000 km<br><br>Minimize Faraday rotation (degradation factor at L-band) |
| Observation over minimum of three annual cycles | Minimum three-year mission life |
| * Includes precision and calibration stability<br>** Defined without regard to local topographic variation | |



## III. PHYSICS OF MEASUREMENT

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 soil minerals and in changes of surface dielectric properties that occur as water transitions between solid and liquid phases. The sensitivity of radar and 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.

In long wave-length and low frequency L-band (1.20-1.42 GHz) microwave region the atmosphere is mostly transparent. Furthermore the attenuation due to vegetation cover is less in this section of the microwave relative to higher frequencies. These factors in addition to the sensitivity to soil moisture and freeze-thaw make L-band a preferred region for microwave remote sensing of land surfaces.

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

$$T_{Bp} = T_s \, e_p \exp(-\tau_p \sec\theta) + T_c (1 - \omega_p) [1 - \exp(-\tau_p \sec\theta)] [1 + r_p \exp(-\tau_p \sec\theta)] \qquad (1)$$

This so-called tau-omega model has subscripts $p$ that refers to polarization ($V$ or $H$). $T_s$ is the soil effective temperature, $T_c$ is the vegetation temperature, $\tau_p$ is the nadir vegetation opacity, $\omega_p$ is the vegetation single scattering albedo, and $r_p$ is the soil reflectivity. The reflectivity is related to the emissivity by $e_p = (1 - r_p)$, and $\omega_p$. The surface emissivity at L-band is sensitive to soil moisture because of the large contrast in the dielectric constant properties of water and soil (minerals). The 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 degrees Kelvin. For these reasons radiometry in the L-band is well suited for surface soil moisture detection. The SMAP measurement approach with constant look angle of $\theta = 40°$ is advantageous to the retrieval of soil moisture based on the tau-omega model.

Radar remote sensing of the total co-polarized backscatter from the landscape at polarization $p$ is the sum of three components:

$$\sigma_{pp}^{t} = \sigma_{pp}^{s} \exp(-2\tau_c) + \sigma_{\mathrm{pp}}^{\mathrm{vol}} + \sigma_{pp}^{\mathrm{int}} \qquad (2)$$

The first term is the surface backscatter, $\sigma_{pp}^{s}$, modified by the two-way attenuation through a vegetation layer of opacity $\tau_c$ along the slant path. The second term represents the backscatter from the vegetation volume, $\sigma_{pp}^{vol}$. The third term represents interactions between vegetation and the surface, $\sigma_{pp}^{int}$.



# IV. INSTRUMENT AND MISSION DESIGN

## A. Measurement Approach

The instrument design is driven by key measurement requirements outlined in Table 1: 1) Polarimetric L-Band radiometer measurements at 40 km resolution, 2) Linear HH, VV and HV (or VH) L-Band radar measurements at 3 km resolution or better, and 3) A wide swath to insure global three-day refresh time for these measurements (1000 km swath at the selected orbit altitude of 670 km). As a solution to this set of requirements, a 6-meter, conically-scanning reflector antenna architecture was selected for the instrument design. The deployable mesh antenna is shared by both the radiometer and radar instruments by using a single L-Band feed. This solution leverages the light-weight, inherently wide-bide, and low-loss characteristics of deployable mesh technology which has extensive heritage in spaceborne communication applications. The reflector rotates about the nadir axis at 14.6 rpm, produces a conically scanning antenna beam at a surface incidence angle of approximately 40° (Fig. 1).

**Fig. 1** The SMAP observatory is a dedicated space-craft with a rotating 6-m light-weight deployable mesh reflector. The radar and radiometer share a common feed.

The baseline feed assembly design employs a single horn, capable of dual-polarization and dual frequency (radiometer frequency at 1.41 GHz, and the radar frequencies centered on 1.26 GHz). The radar and radiometer frequencies will be separated by diplexers and routed to the appropriate electronics for detection. In the baseline design, the radiometer electronics are located on the spun side of the interface. Slip rings provide a signal interface to the S/C. The more massive and more thermally dissipative radar electronics are on the despun side, and the transmit/receive pulses are routed to the spun side via a two channel RF rotary joint.

The SMAP radiometer utilizes a real-aperture resolution approach, where 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 the first three modified Stokes parameters, V, H and U, at 1.41 GHz. The U-channel measurement is included to provide correction of Faraday rotation caused by the ionosphere.

To obtain the required 3 km and 10 km resolution for the freeze/thaw and soil moisture products, the radar will employ pulse compression in range and Doppler discrimination in azimuth to sub-divide the antenna footprint. This is equivalent to the application of synthetic aperture radar (SAR) techniques to the conically scanning radar case. Due to squint angle effects, the high-resolution products will be somewhat degraded within the 300-km band of the swath centered on the nadir track (see Fig. 2) with azimuth resolution capability decreasing over this region as the target area approaches the nadir track. The baseline system has both V- and H-pol channels. An additional channel measures the HV cross-pol return.

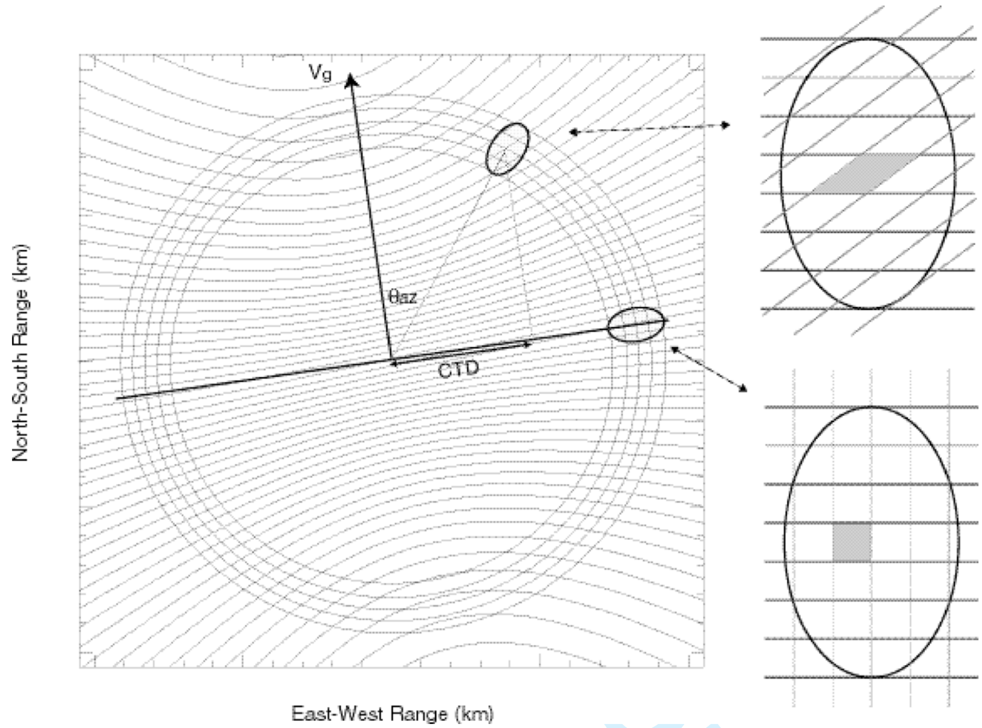



**Fig. 2:** Synthetic Aperture Processing (SAR) will be used to produce high-resolution radar data.

At L-band, radio-frequency interference (RFI) can contaminate both radar and radiometer measurements. Both the radar and radiometer electronics and algorithms include features to mitigate the effects of RFI on the science return. Interference into the SMAP radar largely comes from terrestrial air surveillance radars, which share the spectrum with Earth science radars. To combat this, the SMAP radar will utilize selective filters and an adjustable carrier frequency in order to tune to pre-determined RFI-free portions of the spectrum while on orbit. The radiometer, however, suffers interference primarily due to out-of-band and spurious emissions from active services such as radars and communications systems. Thus, the radiometer will implement a combination of time and frequency diversity and kurtosis 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 [3]. These techniques have been demonstrated in airborne remote sensing [4, 5, 6].

## V. MEASUREMENTS AND ALGORITHMS HERITAGE

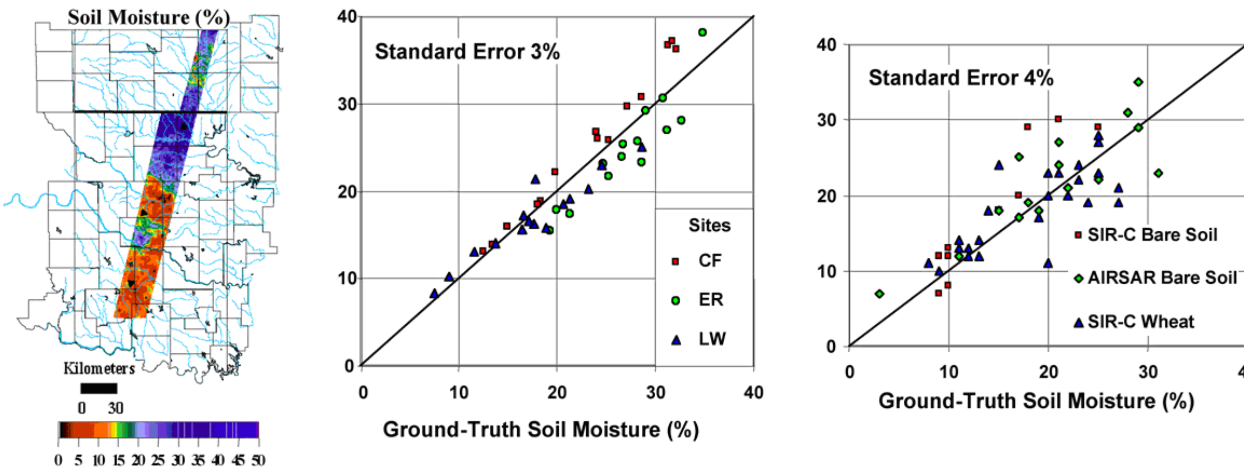
The passive and active soil moisture retrieval algorithms under consideration for SMAP have been developed and validated over an extensive period (~three decades) of microwave modeling and field experiments using ground-based, airborne and space shuttle instruments. A few of the most relevant are summarized here. For passive microwave approaches, early ground-based experiments such as those reported by Wang et al. [7] provided key datasets for a wide range of conditions, which are still used in today's algorithms and models. Figure 3 shows this instrument configuration. The studies summarized in [8] established a description of vegetation effects and provided a comprehensive approach to correcting for it in retrievals. Other important early studies are summarized in Ulaby et al. [9]. In more recent years, the Soil Moisture Ocean Salinity (SMOS) mission has supported numerous L-band ground-based investigations that have contributed to its unique multiangle retrieval algorithm approach [10].

**Fig. 3** The NASA Goddard Space Flight radiometer system used in the Beltsville Agricultural Research Center experiments in the 1970s and 1980s (T. J. Jackson and J. R. Wang).

A tremendous amount of ground-based active microwave remote sensing research was conducted in the 1970s and 1980s that examined soil and vegetation effects. Most of this work is presented in [10]. Only a few radar studies have been conducted since then. These included SIR-C supporting investigations [11].

There have been very few combined active/passive L-band ground-based experiments. At the present time there is only one such system in operation the ComRAD.

Ground-based studies have been extremely important in formulating and validating models and algorithms, however, they 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 radiometer experiments summarized in Schmugge et al. [12] established the sensitivity and linearity of the L-band radiometer responses to soil moisture with single fixed beam instruments. In the 1980s and early 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 [13]. 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. It was also a prototype of the technology that would later be implemented in SMOS. Some of the key contributions of ESTAR were the Monsoon'91 [14], Washita'92 [15], and SGP97 [16] experiments. Figure 4a shows an example of a map product from SGP97. Figure 4b 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) have focused on other regions of the U.S. and have utilized a new version of ESTAR that operated in two-dimensions [17].




(a) (b) (c)

**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), and (c) comparison of ground based soil moisture observations and radar estimates for study sites in Washita'94.

Airborne and Spaceborne imaging L-band radars have been available for many years. These have been capable of providing very high resolution observations. Perhaps the most significant investigation was conducted as part of Washita'94 and involved both the AIRSAR and SIR-C instruments. These datasets provided the basis for the baseline radar-based retrieval algorithm that will be used in SMAP [18]. Figure 4c shows the Washita'94 comparison of the observed and estimated soil moisture.

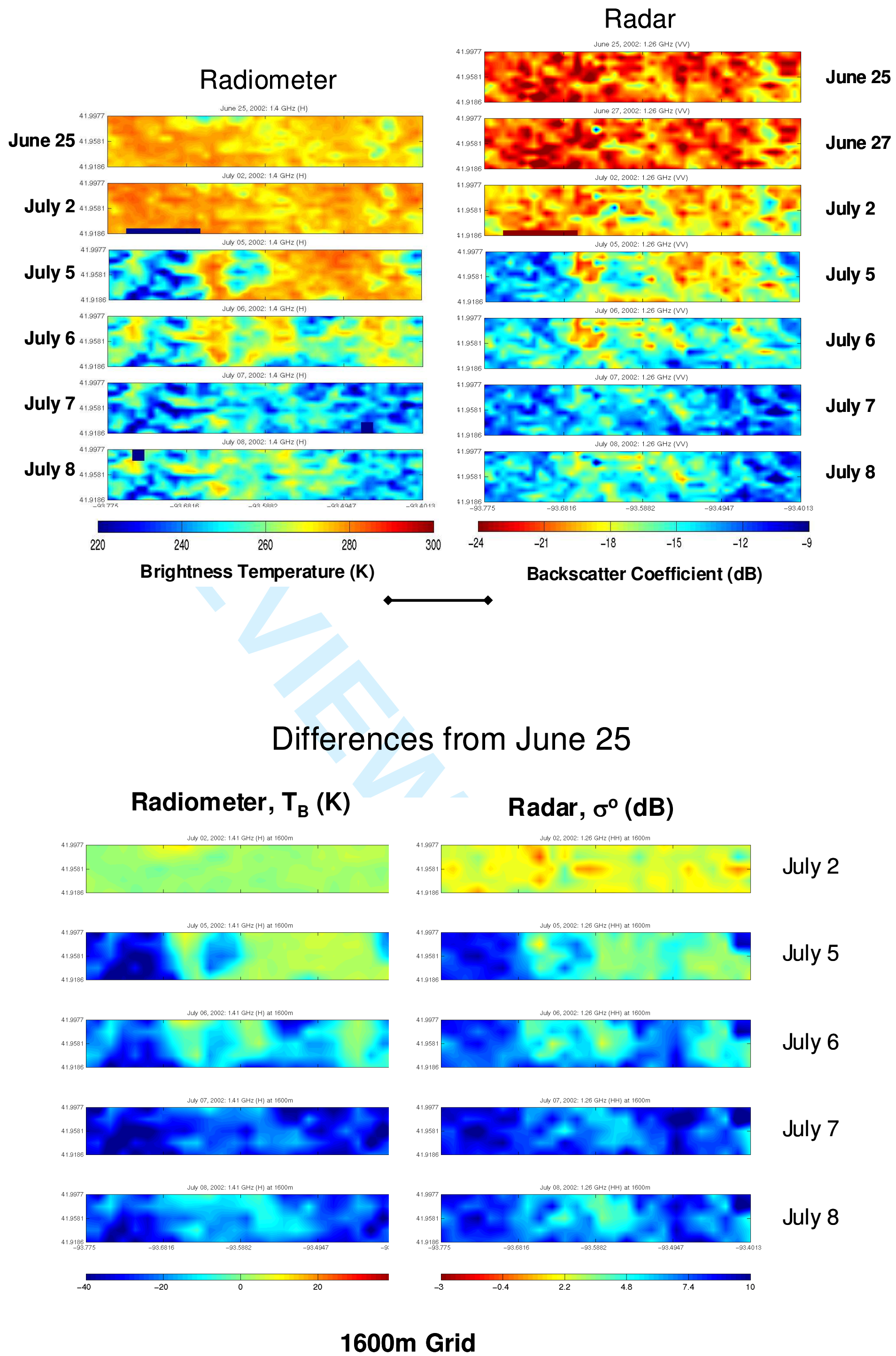



**Fig. 5** PALS results from SMEX02; (a) temporal sequences of brightness temperature (left) and backscatter (right), (b) the change in brightness temperature (left) and backscatter (right) from the first day of observation (June 25).

Recognizing the potential of combined active/passive observations for soil moisture, several aircraft-based field campaigns have been conducted utilizing a prototype of SMAP called the Passive Active L-band System (PALS) [19]. These include SGP99 [19], SMEX02 [20], CLASIC [21], and SMAPVEX08. One of the challenges that we have faced is understanding the relative importance of scene feature and instrument parameters in radiometer and radar observations. These concurrent observations have helped to clarify these issues. A highly relevant example was obtained in SMEX02 over cropland in Iowa. Temporal sequences of radiometer and radar data revealed consistently similar patterns of brightness temperature and backscatter (Fig. 5a).These patterns were even clearer when the daily changes were compared (Fig. 5b). 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.

## VI. GEOPHYSICAL DATA PRODUCTS

SMAP products defined by level are listed in Table 1. Level 1 data products are calibrated and corrected instrument measurements of surface radar backscatter cross-section and brightness temperature. Level 3 products are geophysical retrievals of soil moisture based on level 1 products and ancillary information. Level 4 products are modeling value-added data products that support key SMAP applications and address the driving science questions.

| Data Product | Description |
|---|---|
| L1B_S0_LoRes | Low Resolution Radar Backscatter Cross-Section in Time Order |
| L1C_S0_HiRes | High Resolution Radar Radar Backscatter Cross-Section on Earth Grid |
| L1B_TB | Radiometer Brightness Temperature in Time Order |
| L1C_TB | Radiometer Brightness Temperature on Earth Grid |
| L3_F/T_HiRes | Freeze/Thaw State on Earth Grid (3 km) |
| L3_SM_40km | Radiometer Soil Moisture on Earth Grid (40 km) |
| L3_SM_A/P | Radar/Radiometer Soil Moisture on Earth Grid (10 km) |
| L4_C | Net Ecosystem Exchange (NEE) of Carbon on Earth Grid (10 km) |
| L4_SM | Surface and Root-Zone Soil Moisture on Earth Grid (10 km) |

**Table 1.** SMAP Data Products

### A. Radiometer Soil Moisture Data Product

Retrieval of soil moisture from 1.4 GHz SMAP brightness temperatures is based on the inversion of the tau-omega model (1). The tau-omega model assumes that vegetation multiple scattering and reflection at the vegetation-air interface are negligible. Corrections for surface roughness are performed as $r_{p\ smooth} = r_{p\ rough} / \exp(-h)$ where the parameter $h$ is assumed to be linearly related to the root mean square surface height. Nadir vegetation opacity is related to the total columnar vegetation water content (VWC) $W$ (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 in-land water bodies, topography, and vegetation characteristics at the sub-radiometer resolution. The radar-derived information is a key feature of the SMAP approach to surface soil moisture estimation with L-band radiometer brightness temperature.

If the air, vegetation, and near surface soil can be assumed to be in thermal equilibrium, as is the case near 6 am local time, then $T_C$ is approx. equal to $T_S$ and they can be replaced in the equation by a single effective temperature for the scene ($T_{eff}$). Soil moisture can be estimated from $r_p$ using Fresnel and dielectric-soil moisture relationships. Retrieval of soil moisture with the L3_SM_40km algorithm will focus on the data from the 6 am 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 in this period of the day.

The SMAP mission requirement is to produce soil moisture to an RMS (root mean square) error of 4% or better absolute volumetric soil moisture for those areas of the Earth's land surface where vegetation *W* does not exceed ~ 5 kg $m^{-2}$. This level of performance will enable SMAP to meet the needs of the hydroclimatology and hydrometeorology applications identified in the NRC report [1].

Radiometer based soil moisture retrieval has a substantial ground, aircraft, and satellite heritage. Tower and aircraft based experiments have been used to establish and parameterize the basic retrieval techniques, clearly demonstrating that L-band is optimal for soil moisture retrieval. A series of aircraft-based field experiments have shown that point scale modeling and tower relationships scale to satellite footprint scale and the potential of the spatial and temporal soil moisture information. Although it operates at higher frequencies and it limited to very low vegetation covers, the AMSR-E soil moisture products have demonstrated that a useful soil moisture product can be retrieved at the 40 km scale and that it is of value in hydroclimatology.

### B. Combined Radar and Radiometer Soil Moisture Product

Mapping radars are capable of a very high spatial resolution but, since radar backscatter is highly influenced by surface roughness, vegetation canopy structure and water content, they have a low sensitivity to soil moisture. Various algorithms for retrieval of soil moisture from radar backscattering have been developed, but they are only valid in low-vegetation water content conditions [18]. In contrast, the spatial resolution of radiometers is typically low, the retrieval of soil moisture from radiometers is well established and radiometers have a high sensitivity to soil moisture. To overcome the individual limitations of the passive and active approaches, the Soil Moisture Active and Passive (SMAP) mission is combining the two technologies. The accurate retrievals of soil moisture at the coarse resolution of the radiometer need to be combined with the relatively less accurate soil moisture information from the high resolution radar measurements in order to yield an intermediate scale soil moisture data product.

In the case of SMAP the radiometer-based soil moisture data product is the 40 km resolution L3_40km_SM data product (also called the Hydroclimatology Data Product) . This data product is posted over 30 km Earth grid. The higher resolution radar data are used in the generation of this product principally through detection of inland water bodies, urban areas and other within-radiometer footprint features. The radar backscatter cross-section is gridded over a 3 km Earth grid in the L1C_S0_HiRes product. The resolution of this product ranges from 1 km at the edge of the swath to 10 km near the nadir track.

The merging of radar and radiometer measurements and retrieved information yields the Hydrometeorology Product at intermediate scale called L3_SM_A/P. This data product uses both active and passive sensing. It is required to be at 10 km scale which is intermediate to the radar and radiometer resolutions. This allows some aggregation of the radar data which reduces noise and speckle in the measurements. For both the Hydroclimatology and Hydrometeorology data products, the baseline SMAP mission is required to provide estimates of soil moisture in the top 5 cm of soil with an error of no greater than 4% volumetric (one sigma) and 3-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).

Change detection techniques have been demonstrated to be able to potentially monitor temporal evolution of soil moisture. The changes backscatter cross-section aggregated to the scale of the radiometer and changes in the radiometer brightness temperature are statistically related together using a linear in the combined algorithm. The statistical model is then used on finer resolution radar data disaggregate the 40 km brightness temperature to the resolution of the radar data. The brightness temperature retrieval algorithms are then applied to the disaggregated brightness temperatures to retrieve soil moisture at 10 km resolution. Ancillary data at this resolution is used alongside the algorithm.

The feasibility of a brightness temperature disaggregation and change detection have been demonstrated using the Passive and Active L- and S-band airborne sensor (PALS) radar and radiometer data obtained during field campaigns.

### A. Radar-Based Freeze-Thaw Detection Products

Derivation of the SMAP L3_F/T_HiRes product will employ a temporal change detection approach that has been previously developed and successfully applied using time-series satellite remote sensing radar backscatter and radiometric brightness temperature data from a variety of sensors and spectral wavelengths. The general approach of these techniques is to identify landscape F/T 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 non-frozen conditions. These techniques assume that the large changes in dielectric constant occurring between frozen and non-frozen 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 our baseline algorithm, as well as optional moving window and temporal edge detection algorithms that may eventually augment the current baseline algorithm. These algorithms are described in detail below. All of them currently require only time-series radar backscatter information to derive landscape freeze-thaw state information. However, we will investigate the use of ancillary data to enhance algorithm performance, including the use of digital terrain, land cover and open water classification maps to refine algorithm parameters and mask open water and permanent ice areas during operational L3_F/T_HiRes data processing.

### B. Model Value-Added Products

SMAP measurements provide direct sensing of surface soil moisture (in the top 5 cm of the soil column). Several of the key applications targeted by SMAP, however, require knowledge of root zone soil moisture (~top 1 m of the soil column), which is not directly measured by SMAP. The project will produce model value-added products to fill this gap and provide estimates of root zone soil moisture that are informed by and consistent with SMAP observations. Such estimates are obtained by merging SMAP observations with estimates from a land surface model in a soil moisture data assimilation system [22].

The land surface model component of the assimilation system is driven with observations-based surface 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 Level 4 Soil Moisture 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 Level 4 Soil Moisture product are generated as a by-product of the data assimilation system.

The SMAP L4 Carbon (L4_C) product. The L4_C algorithms utilize daily surface (≤5 cm depth) soil moisture and temperature inputs with ancillary land cover classification and daily vegetation gross primary productivity (GPP) inputs to compute the net ecosystem exchange of carbon dioxide (CO2) with the atmosphere over northern (>45° latitude) vegetated land areas. The net ecosystem exchange (NEE) of CO2 with the atmosphere is a fundamental measure of the balance between carbon uptake by vegetation gross primary production (GPP) and carbon losses through autotrophic (Ra) and heterotrophic (Rh) respiration. The sum of Ra and Rh define the total ecosystem respiration rate (Rtot), which encompasses most of the annual terrestrial CO2 efflux to the atmosphere and more than 70 percent of total carbon uptake by GPP.

The SMAP L4_C product will provide regional measures of NEE and component carbon fluxes (GPP, Rtot) that are within the accuracy range of tower CO2 eddy covariance measurement approaches. The computation of NEE, it's constituent carbon fluxes, and associated soil moisture and temperature controls to Rtot will enable mechanistic understanding of spatial and temporal variations in NEE. NEE represents the primary measure of carbon exchange between the land and atmosphere and the L4_C products 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 CO2. The SMAP L4_C product will also satisfy carbon cycle science objectives of the NRC Decadal Survey [1], and advance our 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 weather forecasts, flood and drought forecasts, and predictions of agricultural productivity.  Additional enabled science and applications could include climate prediction, sea ice, salinity, surface winds, human health, and defense applications. SMAP is currently under going mission development with an expected launch in 2014.

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