# Soil Moisture Active/Passive (SMAP) Mission Concept

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## ABSTRACT

Soil Moisture Active/Passive (SMAP) Mission is one of the first 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 better estimates of water and energy transfers between Earth's surface and atmosphere, which are primary driving factors for weather and climate. Soil moisture measurements are also of great importance in assessing flooding potential and as input to flood prediction models. Conversely, observations of widespread low soil moisture levels can provide early warning of drought conditions, reduced water supply and crop loss. SMAP observations can help mitigate these natural hazards, resulting in potentially great economic and social benefits. SMAP freeze/thaw timing observations will also reduce a major uncertainty in quantifying the global carbon balance and will help resolve the problem of the missing carbon sink. The SMAP mission concept would utilize L-band radar and radiometry. These instruments will share a rotating 6-meter mesh antenna to provide high-resolution and high-accuracy global maps of soil moisture and freeze/thaw state every two to three days.

Keywords: Soil moisture, freeze thaw, microwave, climate

## 1. INTRODUCTION

The National Research Council's (NRC) (2007) 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. Many factors involving both scientific advance and societal benefit were considered in the process. In the end, the NRC report recommended the Soil Moisture Active/Passive (SMAP) mission to observe soil moisture and freeze/thaw for weather and water cycle processes for implementation in the first of three phases (2010-2013). Later in 2007, NASA convened a series of workshops to further investigate each of the missions recommended for near-term implementation and initiated further review of the mission concepts that had been recommended. Several key conclusions resulted from the SMAP workshop:

- There is a stable set of instrument measurement requirements for SMAP that are traceable to science requirements for soil moisture/freeze-thaw.
- The baseline SMAP instrument design is capable of satisfying the science measurement requirements.
- Significant heritage exists from design and risk-reduction work performed during Hydrosphere State (Hydros) mission formulation and other technology development activities (Entekhabi et al., 2004). This heritage includes studies addressing science applications and algorithms, antenna rotation dynamics, antenna RF performance, and RFI mitigation techniques.
- Heritage and lessons learned can be leveraged from the Aquarius project. This includes both the L-Band radiometer and radar electronics.
- There are no technology "show-stoppers," and SMAP formulation is positioned to begin where Hydros left off.

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 is currently in pre-Phase A and the

mission concept is under development. Launch is anticipated in 2013. In the following sections some aspects of SMAP are described in more detail.

## 2. SMAP MISSION CONCEPT

SMAP will provide global observations of soil moisture and freeze/thaw state, together termed the hydrosphere state. SMAP hydrosphere state measurements will be used to enhance our understanding of the processes that link the water, energy and carbon cycles, and to extend the capability of weather and climate prediction models. SMAP data will be used to quantify net carbon flux in boreal landscapes and to develop improved flood and drought prediction capabilities.

SMAP employs a dedicated spacecraft with an instrument suite that will be launched on an expendable launch vehicle into a near-polar, sun-synchronous orbit, with equator crossings at 6 am and 6 pm local time. The instruments include a radiometer and synthetic aperture radar operating in the L-band range (1.20-1.41 GHz) designed to make coincident measurements of surface emission and backscatter and sense the soil surface through moderate vegetation cover. These measurements will be analyzed to yield estimates of soil moisture and freeze/thaw state. The swath width of 1000 km provides global coverage within 3 days at the equator and 2 days at boreal latitudes (>50°N). SMAP science measurements will be acquired for a period of three years, and a comprehensive validation program will be used to assess the accuracies of the soil moisture and freeze/thaw estimates. All data products from the SMAP mission will be made publicly available through the NASA distributed active archive centers.

## 3. INSTRUMENT DESCRIPTION

The SMAP instrument incorporates an L-band radar and an L-band radiometer that share a single feedhorn and parabolic mesh reflector. The reflector is offset from nadir and rotates about the nadir axis at 14.6 rpm, providing a conically scanning antenna beam with a surface incidence angle of approximately 40°. The reflector has a diameter of 6 m, providing a radiometer footprint of 40 km. The real-aperture radar footprint is 30 km, defined by the two-way antenna beamwidth. To obtain the desired high spatial resolution the radar employs range and Doppler discrimination. The radar data can be processed to yield resolution enhancement to 1-3 km spatial resolution. The provision of constant incidence angle across the swath simplifies the data processing and enables accurate repeat-pass estimation of soil moisture and freeze/thaw change.

The science goal is to combine the attributes of the radar and radiometer observations (in terms of their spatial resolution and sensitivity to soil moisture, surface roughness, and vegetation) to estimate soil moisture optimally at a resolution of 10 km, and freeze-thaw state at a resolution of 1-3 km.

The SMAP orbit is still under review; however, the baseline was chosen to optimize the revisit and temporal sampling characteristics of the chosen instrument architecture, while still ensuring that the spatial resolution requirements can be met with a 6 meter diameter antenna. The baseline orbit parameters are:

- Orbit Altitude: 670 km
- Inclination: 98 degrees, sun-synchronous
- Local Time of Ascending Node: 6 pm

## 4. SMAP SCIENCE

SMAP will provide a capability for global mapping of soil moisture and freeze/thaw state with unprecedented accuracy, resolution, and coverage. The scientific objective of SMAP is to acquire space-based hydrosphere state measurements over a three-year period to:

- Link terrestrial water, energy and carbon cycle processes
- Extend weather and climate forecast skill
- Develop improved flood and drought prediction capabilities
- Quantify net carbon flux in boreal landscapes

Soil moisture, as the state variable of the water cycle over land, determines water flux between the atmosphere, the surface and subsurface. Because a large amount of heat is exchanged when water changes phase, the water cycle is also fundamental to the dynamics of the Earth's energy cycle. Furthermore, since water is the universal solvent in the Earth system, biogeochemical cycles (e.g., carbon, nitrogen, and methane) are embedded in the water cycle. SMAP soil moisture information will be transformational for elements of Earth system science, for water resource assessment, and for natural hazards mitigation.

Soil moisture is a key control on evaporation and transpiration at the land-atmosphere boundary. Since large amounts of energy are required to vaporize water, soil moisture control also has a significant impact on the surface energy flux. Thus, soil moisture variations affect the evolution of weather and climate particularly over continental regions. Initialization of numerical weather prediction (NWP) models and seasonal climate models with accurate soil moisture information enhances their prediction skill and extends their skillful lead-times.

Soil moisture and its freeze/thaw state are also key determinants of the global carbon cycle. Carbon uptake and release in boreal landscapes is one of the major sources of uncertainty in assessing the carbon budget of the Earth system (the so-called missing carbon sink). The SMAP mission will quantify the nature, extent, timing and duration of landscape seasonal freeze/thaw state transitions that are key to the estimation of terrestrial carbon sources and sinks. SMAP freeze/thaw state measurements will also contribute to understanding how ecosystems respond to and affect global environmental change, improving regional mapping and prediction of boreal-arctic ecosystem processes.

## 5. 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 & 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.

*Drought.* 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 & Landslides.* Soil moisture is a key variable in water related natural hazards such as floods and landslides. High-resolution observations of soil moisture 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 partitioning of precipitation into infiltration and runoff. Soil moisture in mountainous areas is one of the most important determinants of landslides. Hydrologic forecast systems initialized with mapped high-resolution soil moisture fields will therefore open up new capabilities in operational flood forecasting.

*Agricultural Productivity.* SMAP will provide information on water availability for estimating plant productivity and potential yield. The availability of direct observations of soil moisture from SMAP will enable significant improvements in operational crop productivity and water stress information systems, by providing realistic soil moisture 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. 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. 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 can provide valuable information on vector population dynamics.

## 6. SMAP MEASUREMENT 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 the NRC(2007) report, and follow those developed for Hydros. These will be refined as the mission progresses. 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>Relative accuracy*: 1.5 K<br>L-Band Radar (1.26 GHz):<br>Polarization: VV, HH, HV<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
** Defined without regard to local topographic variation

## 7. SMAP DATA PRODUCTS AND ALGORITHMS

The primary science data products for SMAP are listed in **Error! Reference source not found.**. These products include calibrated sensor data (backscatter cross-section, $\sigma^o$, and brightness temperature, $T_B$), geophysical products of soil moisture and freeze/thaw, and higher-level products using model assimilation. The geophysical products are derived at

spatial resolutions appropriate to the resolutions of the sensor data from which they are obtained. SMAP product specifications were developed from Hydros heritage and science team inputs.

Software to generate the SMAP geophysical data products will be implemented based on algorithms developed by the SMAP science team. These algorithms will be described by Algorithm Theoretical Basis Documents (ATBDs) developed by the science team. Each SMAP science data product has a target accuracy, spatial resolution, spatial gridding (posting), global repeat, and latency requirement. .

**Table 2. SMAP Data Products**

| Data Product | Description |
|---|---|
| L1B_S0_LoRes | Low Resolution Radar $\sigma^o$ in Time Order |
| L1C_S0_HiRes | High Resolution Radar $\sigma^o$ on Earth Grid |
| L1B_TB | Radiometer $T_B$ in Time Order |
| L1C_TB | Radiometer $T_B$ on Earth Grid |
| L3_SM_HiRes | Radar Soil Moisture on Earth Grid |
| L3_F/T_HiRes | Freeze/Thaw State on Earth Grid |
| L3_SM_40km | Radiometer Soil Moisture on Earth Grid |
| L3_SM_A/P | Radar/Radiometer Soil Moisture on Earth Grid (10km) |
| L4_GPP | Gross Primary Productivity on Earth Grid |
| L4_4DDA | Soil Moisture Model Assimilation on Earth Grid |

### 7.1. Soil Moisture Algorithms

SMAP soil moisture retrieval algorithms are based on physical models of microwave emission and backscatter from the surface. These models range from simplified first-order models to sophisticated electromagnetic scattering models that take into account details of the soil substructure, surface roughness and topography, and vegetation structure including stem and leaf dimensions, orientations, and dielectric properties. Such rigorous models are useful for understanding the sensitivity of microwave sensor response to the many surface variables, but simplified models are necessary in the development of retrieval algorithms for sensors with a limited number of observation channels.

Both passive and active microwave modeling of the surface can be represented as the sum of three basic terms: emission or backscatter from the soil surface, emission or backscatter from the vegetation volume, and soil-vegetation interaction terms involving emission and/or scattering from both the soil and vegetation. Radar backscatter is influenced more than radiometric brightness temperature by soil topography, roughness, and vegetation characteristics, but radar observations can achieve much higher spatial resolution due to synthetic aperture processing. Since the information contained in the active and passive signals is complementary, the retrieval algorithms seek to optimally combine the active and passive observations in a joint retrieval approach, taking advantage of the enhanced spatial resolution afforded by the active measurements.

The passive and active soil moisture retrieval algorithms have been developed and validated over an extensive period (nearly three decades) of microwave modeling and field experiments using ground-based, airborne and space shuttle instruments. Recent field experiments include MacHydro'90, Monsoon'91, Washita'92, FIFE, HAPEX, SGP'97, '99, SMEX'02, '03, '04, '05, and CLASIC.

Current research in SMAP soil moisture algorithm development focuses on methods for optimizing the trade-off between the higher accuracy but lower spatial resolution of passive soil moisture retrievals and the lower accuracy but higher spatial resolution of active soil moisture retrievals. There are presently three algorithm development streams for SMAP soil moisture retrievals: (1) passive-only at 40 km resolution, (2) active-only at 1-3 km resolution, and (3) combined active/passive at an intermediate resolution, e.g., 10 km. The active-only and combined active/passive algorithms are less mature than the passive-only algorithms.

The development of the combined active/passive algorithm is being pursued via both field experiments using the aircraft simulator instruments and theoretical simulation studies known as Observing System Simulation Experiments (OSSEs)

that use synthetic observational data sets that can incorporate geophysical variability, sensor modeling, and both geophysics and sensor modeling error and observational error. OSSEs are essential for conducting sensitivity studies, evaluating instrument design trades, and for algorithm development, however they do not fully represent realistic soil and vegetation conditions, and are therefore a supplement and not a replacement for observational field campaigns that acquire experimental data for microwave model and algorithm development.

### 7.2. Freeze/Thaw Algorithm

SMAP freeze/thaw retrieval algorithms operate on the basis of detecting the transition from unfrozen to frozen water in the soil and vegetation biomass as expressed through the change in the microwave dielectric constant of water on freezing/thawing. The radar signal is used primarily in SMAP data processing for detecting the change in dielectric constant, since the high resolution of the radar is necessary to detect the freeze/thaw signal against the background clutter of landscape heterogeneity in the boreal regions where freeze/thaw transition data are most needed. Currently, the freeze/thaw radar-based algorithms have been developed independently from the soil moisture retrieval algorithms; however a more integrated retrieval algorithm approach will be pursued in future studies.

The SMAP soil moisture and freeze/thaw retrieval algorithms are robust and have been demonstrated using both field campaign and synthetic model-generated data. Algorithm maturity has been established through the heritage of studies conducted during the past three decades and has evolved significantly during the Hydros risk-reduction and Phase A studies, particularly in the understanding of vegetation effects, landscape heterogeneity, and incorporating time-history information (relative change) as a means for improved retrievals.

### 7.3. L4 Data Assimilation Products

To generate Level 4 SMAP products, SMAP microwave data or Level 3 retrievals will need to be combined with ancillary data in the framework of a data assimilation system. The required ancillary data consist of diurnally varying standard meteorological forcing fields (e.g., precipitation, downwelling shortwave/longwave radiation, wind speed, near surface air temperature, near surface specific humidity, and air pressure), seasonally-varying information on vegetation state, and fixed fields containing soils and topography information, which are also required in the lower level products. The production of Level 4 products requires estimates of the measurement errors in the SMAP brightness and backscatter data (or for the errors in the Level 3 retrievals), which will come directly from the SMAP teams responsible for generating these data.

## 8. SUMMARY AND PLANS

Direct measurement of soil moisture and freeze/thaw state by SMAP will improve our understanding of weather and water cycle processes, ecosystem productivity, and the linkages between water, energy, and carbon cycles enabling 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 2013. Science requirements and success criteria are being defined. Near term activities include spacecraft/instrument/science trade studies, baseline algorithm selection, field campaigns, validation planning, and the selection of the science team.

## REFERENCES


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