NASA’s Soil Moisture Active Passive (SMAP) Mission: Project Overview and Status

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SMAP is one of four Tier-1 missions recommended by the U.S. NRC Earth Science Decadal Survey

“Earth Science and Applications from Space: National Imperatives for the next Decade and Beyond”
(National Research Council, 2007)
http://www.nap.edu

- SMAP was initiated by NASA as a new start mission in February 2008
- SMAP leverages work done under Hydros & Aquarius
- SMAP now in Phase B – PDR scheduled for Summer 2011
- The target launch date for SMAP is November 2014

<table>
<thead>
<tr>
<th>Tier 1:</th>
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<tbody>
<tr>
<td>Soil Moisture Active Passive (SMAP)</td>
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<th>Tier 2:</th>
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<tr>
<td>SWOT</td>
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<td>HYSPIRI</td>
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<td>ASCENDS</td>
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<td>GEO-CAFE</td>
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<th>Tier 3:</th>
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<tr>
<td>LIST</td>
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<tr>
<td>PATH</td>
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<td>GRACE-II</td>
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<td>SCLP</td>
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<td>GACM</td>
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<td>3D-WINDS</td>
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</table>
SMAP will provide high-resolution, frequent-revisit global mapping of soil moisture and freeze/thaw state to 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

SMAP data will also be used in applications of societal benefit that range from agriculture to human health.
# SMAP Science Drivers on Instrument

<table>
<thead>
<tr>
<th>Science Requirement</th>
<th>Primary Instrument Design Drivers/Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-3 day global coverage</td>
<td>Broad measurement swath</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>Antenna size, synthetic aperture radar</td>
</tr>
<tr>
<td>Measurement accuracy, including in presence of vegetation</td>
<td>Active, passive instrument combination, fixed measurement incidence angle, RFI mitigation features in radar and radiometer</td>
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<table>
<thead>
<tr>
<th>Instrument Requirements</th>
<th>Secondary Flight System Design Drivers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broad Swath, Antenna size, Fixed incidence angle</td>
<td>Rotating deployable reflector, Observatory Dynamics &amp; Control, Mass Properties</td>
</tr>
<tr>
<td>Compatibility with FAA navigation radars</td>
<td>Radar duty cycle, peak power, frequency adjustability</td>
</tr>
<tr>
<td>Synthetic aperture radar</td>
<td>Daily Data volume (up to 135 GB/day data return)</td>
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<td></td>
<td>Ground station coverage</td>
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</tbody>
</table>
Measurement Approach

• **Instruments:**
  - **Radiometer: L-band (1.4 GHz)**
    - V, H, 3rd & 4th Stokes parameters
    - 40 km resolution
    - Moderate resolution soil moisture (high accuracy)
  - **Radar: L-band (1.26 GHz)**
    - VV, HH, HV polarizations
    - 1-3 km resolution (SAR mode); 30 x 5 km resolution (real-aperture mode)
    - High resolution soil moisture (moderate accuracy) and Freeze/Thaw state detection
  - **Shared Antenna**
    - 6-m diameter deployable mesh antenna
    - Conical scan at 14.6 rpm
    - Constant incidence angle: 40 degrees
    -- 1000 km-wide swath
    -- Swath and orbit enable 2-3 day global revisit

• **Orbit:**
  -- Sun-synchronous, 6 am/pm, 680 km altitude
  -- 8-day exact repeat

• **Mission Operations:**
  -- 3-year baseline mission
  -- Launch in November 2014
SMAP RFI Mitigation

Strategy:

- **Survive** without damage
- **Detect** RFI-contaminated data
- **Avoid** RFI (radar only)
- **Remove** RFI effects in ground processing

Radar

- Ground-programmable operating frequency allows avoiding known regional RFI sources
- Filtering and dynamic range requirements assure that out-of-band RFI will avoid saturating receiver
- Residual RFI will be detected and removed during science data processing on the ground

Radiometer

- Digital spectral filtering enables RFI to be isolated within 16 radiometer subbands
- 4<sup>th</sup> Stokes is provided to further aid RFI identification
- Successfully demonstrated in Aircraft Tests
- Identification and removal is conducted in ground processing
# Top-Level Schedule

## Calendar Years

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<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
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<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
</tr>
</tbody>
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### PROJECT

- **KDP-A09/24**
- **Con Studies**
- **ASM**
- **KDP-B 01/21**
- **KDP-C**
- **PDP 05/21**
- **KDP-D 11/30**
- **KDP-E 11/30**
- **Launch 11/30**
- **IOC 02/28**
- **End of Mission 02/28**

### Science Definition Team (SDT)

- **Science Definition Team (SDT)**
- **SDT extended**

### ALGORITHMS

- **Algorithm Testbed Development**
- **Software Deliveries to SDS**
- **Del 1**
- **Del 2**
- **Del 3**
- **Del 4**
- **Del 5**
- **Alg Selection**
- **12/1**
- **09/30**

### CAL/VAL

- **Pre-launch Cal/Val Development & Data Acquisition**
- **ATBD Peer Review**
- **12/1**
- **SMAP campaign**

### Operations

- **Cal/Val 02/28**
- **Science Team (ST) 02/28**
- **SDT extended 02/28**

### Maintenance & Upgrades

- **L1-L4 Validation**
- **02/28**
- **End of Mission**
SMAP Level 1 Science Requirements

<table>
<thead>
<tr>
<th>Science Discipline Measurement Need</th>
<th>Level 1 Science Measurement Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydro-Meteorology</td>
<td></td>
</tr>
<tr>
<td>Hydro-Climatology</td>
<td></td>
</tr>
<tr>
<td>Carbon Cycle</td>
<td></td>
</tr>
<tr>
<td>Resolution</td>
<td>4–15 km</td>
</tr>
<tr>
<td></td>
<td>50–100 km</td>
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<tr>
<td></td>
<td>1–10 km</td>
</tr>
<tr>
<td>Refresh Rate</td>
<td>2–3 days</td>
</tr>
<tr>
<td></td>
<td>3–4 days</td>
</tr>
<tr>
<td>Accuracy(1)</td>
<td>.04–.06 cm³/cm³</td>
</tr>
<tr>
<td></td>
<td>.04–.06 cm³/cm³</td>
</tr>
<tr>
<td>Range</td>
<td>80–70%</td>
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<tr>
<td></td>
<td>80%</td>
</tr>
<tr>
<td></td>
<td>.06 cm³/cm³</td>
</tr>
<tr>
<td></td>
<td>70%</td>
</tr>
<tr>
<td>Soil Moisture</td>
<td>10 km</td>
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<tr>
<td></td>
<td>3 km</td>
</tr>
<tr>
<td>Freeze/Thaw(2)</td>
<td>10 km</td>
</tr>
<tr>
<td></td>
<td>10 km</td>
</tr>
<tr>
<td>Soil Moisture</td>
<td>3 days</td>
</tr>
<tr>
<td></td>
<td>2 days</td>
</tr>
<tr>
<td>Freeze/Thaw(2)</td>
<td>3 days</td>
</tr>
<tr>
<td></td>
<td>3 days</td>
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</tbody>
</table>

Mission Duration Requirement:
3 Years Baseline; 18 Months Threshold

(1) volumetric soil moisture content (1-sigma) ; % classification accuracy (binary Freeze/Thaw)
(2) North of 45° N latitude

Derived from models and decision-support tools used in areas of application identified by decadal survey for SMAP

Table: Science Requirement

<table>
<thead>
<tr>
<th>DS Objective</th>
<th>Application/Discipline</th>
<th>Science Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weather Forecast</td>
<td>Initialization of Numerical Weather Prediction (NWP)</td>
<td>Hydrometeorology</td>
</tr>
<tr>
<td>Climate Prediction</td>
<td>Boundary and Initial Conditions for Climate Models</td>
<td>Hydroclimatology</td>
</tr>
<tr>
<td></td>
<td>Testing Land Surface Models in General Circulation Models</td>
<td></td>
</tr>
<tr>
<td>Drought and</td>
<td>Seasonal Precipitation Prediction</td>
<td>Hydroclimatology</td>
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<tr>
<td>Agriculture</td>
<td>Regional Drought Monitoring</td>
<td></td>
</tr>
<tr>
<td>Monitoring</td>
<td>Crop Outlook</td>
<td></td>
</tr>
<tr>
<td>Flood Forecast</td>
<td>River Forecast Model Initialization</td>
<td>Hydrometeorology</td>
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<tr>
<td></td>
<td>Flash Flood Guidance (FFG)</td>
<td></td>
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<tr>
<td></td>
<td>NWP Initialization for Precipitation Forecast</td>
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<tr>
<td>Human Health</td>
<td>Seasonal Heat Stress Outlook</td>
<td>Hydroclimatology</td>
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<tr>
<td></td>
<td>Near-Term Air Temperature and Heat Stress Forecast</td>
<td>Hydrometeorology</td>
</tr>
<tr>
<td></td>
<td>Disease Vector Seasonal Outlook</td>
<td>Hydroclimatology</td>
</tr>
<tr>
<td></td>
<td>Disease Vector Near-Term Forecast (NWP)</td>
<td>Hydrometeorology</td>
</tr>
<tr>
<td>Boreal Carbon</td>
<td>Freeze/Thaw Date</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Freeze/Thaw State</td>
<td></td>
</tr>
</tbody>
</table>

Peggy O'Neill, NASA GSFC
## SMAP Data Products

<table>
<thead>
<tr>
<th>Data Product Short Name</th>
<th>Description</th>
<th>Data Resolution</th>
<th>Grid Spacing</th>
<th>Mean Latency*</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1B_S0_LoRes</td>
<td>Low Resolution Radar $\sigma_o$ in Time Order</td>
<td>5x30 km (10 slices)</td>
<td>-</td>
<td>12 hrs</td>
</tr>
<tr>
<td>L1C_S0_HiRes</td>
<td>High Resolution Radar $\sigma_o$ on Swath Grid</td>
<td>1x1 km to 1x30 km</td>
<td>1 km</td>
<td>12 hrs</td>
</tr>
<tr>
<td>L1B_TB</td>
<td>Radiometer $T_B$ in Time Order</td>
<td>36x47 km</td>
<td>-</td>
<td>12 hrs</td>
</tr>
<tr>
<td>L1C_TB</td>
<td>Radiometer $T_B$</td>
<td>40 km</td>
<td>36 km</td>
<td>12 hrs</td>
</tr>
<tr>
<td>L2_SM_A</td>
<td>Radar Soil Moisture</td>
<td>1-3 km</td>
<td>3 km</td>
<td>24 hrs</td>
</tr>
<tr>
<td>L2_SM_P</td>
<td>Radiometer Soil Moisture</td>
<td>40 km</td>
<td>36 km</td>
<td>24 hrs</td>
</tr>
<tr>
<td>L2_SM_A/P</td>
<td>Active-Passive Soil Moisture</td>
<td>9 km</td>
<td>9 km</td>
<td>24 hrs</td>
</tr>
<tr>
<td>L3_F/T_A</td>
<td>Daily Global Composite Freeze/Thaw State</td>
<td>1-3 km</td>
<td>3 km</td>
<td>50 hrs</td>
</tr>
<tr>
<td>L3_SM_A</td>
<td>Daily Global Composite Radar Soil Moisture</td>
<td>1-3 km</td>
<td>3 km</td>
<td>50 hrs</td>
</tr>
<tr>
<td>L3_SM_P</td>
<td>Daily Global Composite Radiometer Soil Moisture</td>
<td>40 km</td>
<td>36 km</td>
<td>50 hrs</td>
</tr>
<tr>
<td>L3_SM_A/P</td>
<td>Daily Global Composite Active-Passive Soil Moisture</td>
<td>9 km</td>
<td>9 km</td>
<td>50 hrs</td>
</tr>
<tr>
<td>L4_SM</td>
<td>Surface and Root Zone Soil Moisture</td>
<td>9 km</td>
<td>9 km</td>
<td>7 days</td>
</tr>
<tr>
<td>L4_C</td>
<td>Carbon Net Ecosystem Exchange</td>
<td>9 km</td>
<td>9 km</td>
<td>14 days</td>
</tr>
</tbody>
</table>

*Mean latency under normal operating conditions. Latency defined as time from data acquisition by instrument to availability to designated data archive. The SMAP project will make a best effort to reduce these latencies.
Simulated products generated with prototype algorithms on the SDS Testbed

**L1C_S0_Hi-Res Radar Backscatter Product (1-3 km)**

**L1C_TB Radiometer Brightness Temperature Product (36km)**

**L3_SM_A Radar Soil Moisture Product (3 km)**

**L2_SM_P Radiometer Soil Moisture Product (36 km)**

**L2_SM_AP Combined Soil Moisture Product (9 km)**
Several candidate radiometer retrieval approaches based on the tau-omega model are being evaluated now, with varying requirements for ancillary data:

- **Single-Channel (SCA):** uses H-pol brightness temperature which is corrected sequentially for surface temperature, vegetation water content, and surface roughness using ancillary data [can also use V-pol single channel; both implemented in algorithm testbed now]

- **Iterative (2CA):** adjusts soil moisture and vegetation water content iteratively to minimize the difference between computed and observed $T_{BV}$ and $T_{BH}$; both SM and another parameter (such as VWC) can be retrieved [implemented in algorithm testbed now]

- **Land Parameter Retrieval Model (LPRM):** 2-channel iterative approach which uses a microwave polarization difference index and emissivity to parameterize $\tau_c$; assumes $\tau_c$ and $\omega$ are the same for H and V polarization; assumes a constant $\omega$ [implemented in algorithm testbed now]

- **Reflectivity Ratio (RR):** uses both $T_{BV}$ and $T_{BH}$ and vegetation & roughness correction factors for SM retrieval; algorithm proposes to use SMAP radar data to determine vegetation correction factor needed in the passive retrieval

**One candidate algorithm will be selected as the one SMAP baseline algorithm for this product prior to launch.**
The L2_SM_P processor converts a half-orbit L1B_TB swath into L1C_TB and L2_SM_P products:

**L2_SM_P Algorithm Flow**

1. **L1B_TB** (TB’s, lat/lon, time, azimuth)
2. **Earth grid registration**
   - Drop-in-bucket
   - Nearest neighbor
3. **L1C_TB** (Fore/aft-look TB’s, time)
4. **Water TB Correction**
   - Combine fore/aft-look TB’s
   - Perform correction everywhere except 100% open water
5. **L2_SM_P Retrieval**
   - Single channel using TBH
   - Single channel using TBV
   - Dual channel using TBH and TBV
   - LPRM using TBH and TBV

Retrieve soil moisture everywhere except (1) 100% open water, (2) frozen soil, (3) urban area, and (4) permanent snow/ice. Freeze/thaw state will be determined by L3_F/T with soil temperature data as a backup.

Program control parameters

I/O and ancillary data paths

Simulation control parameters

Read in control parameters

Read in data paths

Earth grid registration

Water fraction

Freeze/thaw state

Soil temperature

Soil texture

Surface roughness

Land classification

NDVI / veg info

To DAAC

L2_SM_P (Soil moisture, QC)
### DATA INPUT:
- Grid cell location on fixed Earth grid (lat, lon)
- Time tag (date and time of day)
- Calibrated water-corrected L1C_TB*
- Static ancillary data: permanent masks (land/water, urban, etc.), soil type, DEM info, % land cover types
- Dynamic ancillary data:
  - Soil temperature
  - Vegetation water content
  - Vegetation parameters ($b$, $\tau$, $\omega$)
  - % open water in pixel [from HiRes radar]
  - Temperature of open water from $T_s$ at 6 am
- Frozen ground flag [from L3_F/T]
- Precipitation flag (if set)
- Snow/ice flag (if set)
- RFI flag [from L1_TB]
- Quality flag [from L1_TB]

* L1B_TB have been water-corrected and gridded prior to being input to the soil moisture retrieval part of the L2_SM_P algorithm.

### DATA OUTPUT:
- Grid cell location on fixed Earth grid (lat, lon)
- Time tag (date and time of day)
- Calibrated water-corrected L1C_TB
- Retrieved soil moisture for 6 am overpass
- Dynamic ancillary data:
  - Soil temperature
  - Vegetation water content
  - Vegetation parameters ($b$, $\tau$, $\omega$)
  - % open water in pixel
  - Temperature of open water
- Frozen ground flag [from L3_F/T]
- Precipitation flag (if set)
- Snow/ice flag (if set)
- RFI flag
- Quality flag
L2_SM_A Algorithm Concept

**Snapshot methods** for low-vegetation surfaces (VWC < 0.5 kg/m²) has a pair of HH and VV input.

--- **Data-cube algorithm – current baseline**: inversion by searching a two-dimensional (soil moisture and roughness) lookup table generated by a radar scattering model; 0.046 cm³/cm³ retrieval accuracy.

**Time-Series methods** for vegetated surfaces has time-series pairs of HH and/or VV; HV will be used to estimate the vegetation level. Exploit time-series information during the period when the roughness and/or vegetation remains time-invariant.

--- **Data-cube algorithm - current baseline**: assumes time-invariant roughness. Minimum-distance (D) inversion by searching 3-dimensional ‘data cube’ using N time-series data (soil moisture, roughness, vegetation) generated by a radar scattering model. 7 vegetation classes are being modeled by the SDT. The classes are grass, corn, soybean, shrub, tundra, broadleaf and conifer trees (representing up to 75-85% of land surfaces). In the future, more classes will be added. 0.052 cm³/cm³ retrieval accuracy.

\[
d(t) = \sum_{ch}^{H,H',H''} \left( \sigma_{ch,measured}^0 - \sigma_{ch,\text{datacube}}^0(m_v,\text{retrieve},\text{rough}_\text{retrieve},\text{vegetation}) \right)^2 & D = \sum_t t
\]
L2_SM_A Algorithm Flow

Key
- SMAP Data Product
- Ancillary data
- Other data / files
- Processing step
- Data flow
- Control

Static Ancillary data (global)
- Permanent water body
- Urban area
- Mountain area
- Dense vegetation area
- Permanent frozen ground
- Vegetation classes
- Soil texture(*)

Dynamic Ancillary data (global)
- Snow and ice
- Precipitation
- NDVI, Vegetation
- Soil temperature(*)

Swath-grid
$\sigma_{vv}, \sigma_{hh}, \sigma_{hv}$ from L1C_S0 (1 km)

- Average to 3km s0
- Determine quality flags

Detect transient waterbody

Compute radar vegetation index

Define F/T state

L2_FT Pass File (Internal product)

Extract over a granule (static)

Extract over a granule (dynamic)

Quality flags $\rightarrow$ perform retrieval?

Yes

Low vegetation area?

Yes & No

Time-series retrieval of dielectric constant

Data cube

Snapshot retrieval of dielectric constant

Yes

Assign a default

Convert dielectric constant to soil moisture

Conversion table from dielectric constant to soil moisture.

Ancillary data in (*)

L2_SM_A output

Research product with $\sim 0.06$ cm$^3$/cm$^3$ accuracy target
L2_SM_AP Algorithm Concept

Temporal changes in $T_B$ and $\sigma_{pp}$ are related. Parameters $\alpha$ and $\beta$ are estimated at scale-$C$ using successive overpasses.

$$T_{B_p} = \tau C_p + 3 \sigma \cdot \tau \cdot C_p$$

Heterogeneity in vegetation and roughness conditions within scale-$C$ are evaluated by estimating sensitivities in radar cross-pol:

$$\sigma \cdot \left[ \frac{\partial}{\partial r_p} \left( M_j \right) \right] + \left( \frac{\partial}{\partial r_q} \left( M_j \right) \right) \cdot \sigma \cdot \left( M_j - r_q \cdot C_p \right)$$

$T_B$-disaggregation algorithm now becomes:

$$T_{B_p} = T_{B_p} \cdot C_p + 3 \sigma \cdot \tau \cdot \sigma \cdot ( M_j - r_q \cdot C_p )$$

$T_B(M_j)$ is used to retrieve soil moisture at 9 km (consistent algorithm and ancillary data as radiometer algorithm)
L2_SM_AP Algorithm Flow

Static Ancillary Data
- Retrieval Masks (9 km)

Config File
- Get date and time
- Read in config file parms
- Read in static ancillary files

L3_SM_A
- Read in $n$ days of L3_SM_A

L3_SM_P
- Read in $n$ days of L3_SM_P (water-body corrected)

Prior Parameters $(\beta, \Gamma)$ Files
- Read $\beta$ parameter file
- Read $\Gamma$ parameter file

$\beta$ prior Parameter file exists? [Yes/No]

- Bayesian update of $\beta$

Dynamic Ancillary Data
- Precipitation flag (9 km)
- Snow flag (9 km)
- Frozen soil (9 km)
- Land temperature (9 km)
- Vegetation water content (9 km)
- Land classification (9 km)
- Soil sand, clay fraction (9 km)

L2_SM_A
- Read in $\sigma$, $\sigma_p$, $\sigma_B$, and flags from L2_SM_A
- Read in water corrected $T_{B_p}$ and flags from L2_SM_P
- Read in dynamic ancillary data
- Implement Active-Passive algorithm
- Write algorithm disaggregated $T_{B_p}$ to L2_SM_A/P files
- Apply L2_SM_P retrieval algorithm with 9 km ancillary data

L2_SM_P
- Read in $\sigma$, $\sigma_p$, $\sigma_B$, and flags from L2_SM_P

Write Soil Moisture (9 km), Brightness Temperature (9 km), and Flags (9 km) in L2_SM_AP
**L3_FT_A   Algorithm Concept**

**Concept:**
-- use a temporal change detection scheme to classify the binary frozen / non-frozen landscape state
-- algorithm has heritage based on contemporary & archived satellite radar and radiometer time-series data
-- algorithm will be applied separately to AM and PM orbital passes

**Baseline Algorithm:**  Seasonal Threshold Approach

• **Approach:** classify landscape AM and PM freeze/thaw state based on time series radar backscatter relative to seasonal reference frozen and unfrozen states
  -- AM and PM states are combined to provide the combined state as (1) frozen (frozen AM, frozen PM), (2) thawed (thawed AM, thawed PM), (3) transitional (frozen AM, thawed PM) and (4) inverse transitional (thawed AM, frozen PM) states

• **Inputs:** Time series radar backscatter (L1C_S0_HiRes), both AM and PM

• **Outputs:** Landscape freeze/thaw state for AM, PM, and combined. 3x3 km resolution, daily product

• **Domain:** Vegetated areas encompassing (1) boreal/arctic latitudes (≥45°N) and (2) global regions where temperature is a significant constraint to vegetation productivity
L3_FT_A Algorithm Flow

Key
- SMAP Data Product
- Ancillary data
- Other data/files
- Processing step
- Data flow
- Control

Gridded $\sigma_{hh}$, $\sigma_{vv}$ from L2_SM_A processor (3 km)

FT algorithm parameters
- VV, HH frozen, thawed $\theta$, reference states
- VV, HH threshold $\Delta$ (may be seasonally dependent)
- 3km grids

Loop over grid cells with valid data:

Compute $\Delta = [\sigma_{vv} - \sigma_{froz ref}] / [\sigma_{thaw ref} - \sigma_{froz ref}]$

at either/both VV and/or HH polarizations

Select Threshold based on time, location (and TBD ancillary data) from parameter grid

Yes

$\Delta < \text{Threshold}$?

Set frozen soil flag for L2_SM_A (frozen)

Clear frozen soil flag for L2_SM_A (thawed)

No

Write Frozen Soil Flags (3 km) to L2_SM_A

Write temporary "L2_FT" half-orbit data for input to L3

Static/Dynamic Ancillary data
- Precipitation flag (3 km)
- Snow flag (3 km)
- Soil temperature (3 km)
- Vegetation water content (3 km)
- Land cover classification (3 km)

80% frozen/thawed classification accuracy target
Main objectives:

• Provide estimates of root zone soil moisture (top 1 m) based on SMAP observations
• Provide global, 3-hourly, 9 km surface and root zone soil moisture

Baseline algorithm:

• Customized version of existing NASA/GEOS-5 Land Data Assimilation System
  – 3d Ensemble Kalman filter
  – Catchment land surface model

Optional algorithm extensions:

• Dynamic bias estimation and correction
• Adaptive filtering for dynamic estimation of input error parameters
• Ensemble smoothing
L4_SM Algorithm Flow

GEOS-DAS products
Land parameters
Meteorological data
Source: NASA/GMAO

GPCP precipitation
Source: NOAA/CPC

L4_SM(x,t-1)

Catchment model
Forecast: t-1 → t

FCST(x,t)

Disagree?

no

Thawed?

no

yes

L3_F/T_A

Freeze-thaw analysis:
Update soil and snow heat content

L1C_TB

L2_SM_A

L1C_TB

Soil moisture analysis:
Update soil moisture and temperature

No analysis:
L4_SM(x,t) = FCST(x,t)

L4_SM(x,t)
**L4_SM Input/Output**

**SMAP inputs**

- **Brightness temperature**
  (L1C_TB, 36 km)
- **Radar soil moisture**
  (L2_SM_A, 3 km)
- **Freeze-thaw state**
  (L3_F/T_A, 3 km)

**Ancillary data inputs**

- Land model parameters
- Surface meteorology (incl. observation-corrected precip)
- Land assimilation parameters

**L4_SM product**

9 km, 3-hourly global output with 7-day latency

- **Surface soil moisture** (≡ top 5 cm)
- **Root zone soil moisture** (≡ top 1 m)

**Research output**

- surface and soil temperatures (**input to L4_C**)
- sensible, latent, and ground heat flux
- runoff, baseflow, snowmelt
- surface meteorological forcings (air temperature, precipitation, ...)
- **error estimates** (generated by assimilation system)

*In units of cm$^3$ cm$^{-3}$ and percentiles*
Baseline: Land-atmosphere CO₂ exchange

Motivation/Objectives: Quantify net C flux in boreal landscapes; reduce uncertainty regarding missing C sink on land

Approach: Apply a soil decomposition algorithm driven by SMAP L4_SM and GPP (e.g. MOD17) inputs to compute land-atmosphere CO₂ exchange (NEE)

Inputs: Daily surface (<10cm) soil moisture & temperature (L4_SM) & GPP (MODIS)

Outputs: NEE (primary/validated); R_{eco} & SOC (research/optional)

Domain: Vegetated areas encompassing boreal/arctic latitudes (≥45°N)

Resolution: 9x9 km

Temporal fidelity: Daily (g C m⁻² d⁻¹)

Latency: 14-day

Accuracy: Commensurate with tower based CO₂ obs. (RMSE ≤ 30 g C m⁻² yr⁻¹ and 1.6 g C m⁻² d⁻¹)
L4_C Algorithm Flow

Static Ancillary Data
- Land cover map (9 km)
- Open water mask (9 km)

Config File

- Get date and time
- Read in config file parms
- Read in L4_C para file
- Read in static ancillary files

L4_C para file

Read in L4_SM soil moisture and temperature (SFMC_PRCNTL, TSOIL1, ...)

Dynamic Ancillary data
- MODIS GPP (9 km)

Dynamic Ancillary Data
- Read in dynamic ancillary data
- Implement L4 carbon algorithm

L4_SM

- Update soil carbon stock
- Write NEE (9 km), ecosystem respiration (9 km) and soil carbon stock (9 km) in L4_C

L4_C
Summary

- SMAP provides high-resolution and frequent-revisit global mapping of soil moisture and freeze/thaw state that has:
  - Science value for Water, Carbon and Energy Cycles
  - Applications benefits in Operational Weather, Flood & Drought Monitoring, other areas
  - Addresses priority questions on Climate and Climate Change
  - NOAA, DoD, USDA, others are actively engaged with SMAP to develop an Applications Plan for using SMAP data after launch
  - Science Definition Team has international participation: Canadian, British, Australian, French & Italian representatives

- SMAP will take advantage of precursor data from ESA’s SMOS mission
  - SMOS data will aid in SMAP algorithm development and global RFI assessment and mitigation; SMAP will also strive to be consistent with SMOS’ choice of ancillary data

- SMAP will hold its Preliminary Design Review and proceed into Phase C this summer
BACKUP
Synergistic Data and Experience from SMOS and Aquarius

- SMAP complements SMOS and Aquarius:
  - Extends global L-band radiometry beyond these missions (yields long-duration land hydroclimate soil moisture datasets)
  - Significantly increases the spatial resolution of soil moisture data
  - Adds characterization of freeze thaw state for carbon cycle science
  - Adds substantial instrument and processing mitigations to reduce science degradation and loss from terrestrial RFI

- SMAP benefits from strong mutual science team members’ engagements in missions
  - SMOS & Aquarius data are important for SMAP’s algorithm development
  - SMAP will collaborate in and extend SMOS & Aquarius Cal-Val campaigns
  - SMOS and Aquarius will provide valuable data on the global terrestrial RFI environment which is useful to SMAP

<table>
<thead>
<tr>
<th>Mission</th>
<th>LRD</th>
<th>Measurement</th>
<th>Instrument Complement</th>
<th>Resolution / Revisit</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMOS</td>
<td>Nov ’09</td>
<td>Soil Moisture Ocean Salinity</td>
<td>L-band Radiometer</td>
<td>50 km / 3 days</td>
</tr>
<tr>
<td>Aquarius</td>
<td>June ’11</td>
<td>Ocean Salinity Soil Moisture (experimental)</td>
<td>L-band Radiometer, Scatterometer</td>
<td>100 km / 7 days</td>
</tr>
<tr>
<td>SMAP</td>
<td>Nov ’14</td>
<td>Soil Moisture Freeze/Thaw State</td>
<td>L-band Radiometer, SAR (unfocused)</td>
<td>10 km / 2-3 days</td>
</tr>
</tbody>
</table>
Instrument Overview

- **Radiometer**
  - Provided by GSFC
  - Leverages off Aquarius radiometer design
  - Includes RFI mitigation (spectral filtering)

- **Common 6 m spinning reflector**
  - Enables global coverage in 2-3 days
  - Spin Assembly (provided by Boeing) and Reflector Boom Assembly (provided by NGST-Astro) have extensive heritage

- **Radar**
  - Provided by JPL
  - Leverages off past JPL L-band science radar designs
  - RFI mitigation through tunable frequencies & ground processing

Radiometer is spun-side mounted to reduce losses

Radar is fixed-mounted to reduce spun inertia
Mission Design Overview

Instrument

- L-band (1.26 GHz) Radar (JPL)
- L-band (1.41 GHz) Radiometer (GSFC)
- Shared Antenna (6m diameter)
- Conical scan: 14.6 rpm; 40° incidence
- Contiguous 1,000 km swath width

Spacecraft

- JPL-Developed & Built
- JPL's Multi-mission System Architecture Platform Avionics
- Commercial Space Components

SMAP Flight System (Observatory)

- 680 km polar orbit (sun-sync)
- 8-day repeat ground-track
- Continuous instrument operation
- 2-3 day global coverage
- 3-year mission duration

Near Earth Network

- SMAP is compatible with a number of potential launch vehicle options
- Target Launch: Nov 2014

SMAP Mission Operations & Data Processing (JPL, GSFC)

Data Center (Location: TBD)
Microwave Emission Model for L2_SM_P

Surface Brightness Temperature given by Zero-Order Tau-Omega Model:

\[ T_{Bp} = T_s (1 - r_p) \exp(-\tau_c) + T_c (1 - \omega) [1 - \exp(-\tau_c)] [1 + r_p \exp(-\tau_c)] \]

where

- \( T_s \) and \( T_c \) are physical temperatures of the soil and vegetation canopy (K)
- \( r_p \) is the soil reflectivity [related to the emissivity by \( e_p = (1 - r_p) \)]
- \( \tau_c \) is the vegetation opacity along the slant path where \( \tau_c = b \ W_c \ sec \ \theta \)
  - \( W_c \) is the vegetation water content (kg/m^2) and \( b \) is a vegetation parameter
- \( \omega \) is the vegetation single scattering albedo
- soil roughness can be corrected as \( r_p^{\text{smooth}} = r_p^{\text{rough}} / \exp (-h) \)
- \( r_p^{\text{smooth}} \) is then related to the soil dielectric constant \( \varepsilon \) by the Fresnel equations
- soil moisture content \( m_v \) (% volumetric) is then estimated from the dielectric constant using dielectric models

**note:** if the air, vegetation, and near surface soil can be assumed to be in thermal equilibrium, then \( T_c \approx T_s = T_{\text{eff}} \), the effective temperature over the microwave sampling depth
L2_SM_P Error Analysis

Single-Channel Algorithm*:

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Estimated $T_B$ Error (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Temperature (2°C error)</td>
<td>1.7</td>
</tr>
<tr>
<td>Vegetation Water Content (10%)</td>
<td>1.6</td>
</tr>
<tr>
<td>Model Parameterization (h, $\omega$, b, all at 5% error, classification, etc.)</td>
<td>1.4</td>
</tr>
<tr>
<td>Surface Heterogeneity</td>
<td>0.9</td>
</tr>
<tr>
<td>Total RSS of Geophysical Errors</td>
<td>2.87</td>
</tr>
<tr>
<td>Radiometer Precision &amp; Calibration Stability</td>
<td>1.3</td>
</tr>
<tr>
<td>Total RSS Error</td>
<td>3.15</td>
</tr>
</tbody>
</table>

[* Error budget to be generated and updated for each candidate algorithm using SMAP simulations and analysis of SMOS data *]
**L2_SM_A  Algorithm Concept**

**Snapshot methods** for low-vegetation surfaces (VWC < 0.5 kg/m\(^2\)) has a pair of HH and VV input.

1. **Data-cube algorithm – current baseline:** inversion by searching the two-dimensional (soil moisture and roughness) lookup table generated by a radar scattering model. 0.046 cm\(^3\)/cm\(^3\) retrieval accuracy.

2. **Dubois/van Zyl empirical algorithm:** analytical inversion of an empirical scattering model. 0.04 cm\(^3\)/cm\(^3\) retrieval accuracy.

3. **Shi’s algorithm:** reduction of Kp error through combination of co-pol channels. 0.037 cm\(^3\)/cm\(^3\) retrieval accuracy.

**Time-Series methods** for vegetated surfaces has time-series pairs of HH and/or VV; HV will be used to estimate the vegetation level. Exploit time-series information during the period when the roughness and/or vegetation remains time-invariant.

1. **Data-cube algorithm - current baseline:** assumes time-invariant roughness. Minimum-distance \((D)\) inversion by searching 3-dimensional ‘data cube’ using \(N\) time-series data (soil moisture, roughness, vegetation) generated by a radar scattering model. 7 vegetation classes are being modeled by the SDT. The classes are grass, corn, soybean, shrub, tundra, broadleaf and conifer trees (representing up to 75-85% of land surfaces). In the future, more classes will be added. 0.052 cm\(^3\)/cm\(^3\) retrieval accuracy.

\[
d(t) = \sum_{ch} \chi \left( \sigma_{ch,measured}^0 - \sigma_{ch,datab}^0 \left( m_{\text{v,retrieve}}, rough_{\text{retrieve}}, \text{vegetation} \right) \right)^2 & D = \sum_t t
\]

2. **Kim/van Zyl algorithm:** assumes time-invariant roughness and vegetation. 0.05 cm\(^3\)/cm\(^3\) retrieval accuracy.

\[
m_v = A \times \sigma^0 + B
\]

3. **Wagner change detection algorithm:** assumes time-invariant roughness and vegetation. Provides indexes of soil moisture change. 6 levels of change were detected.

\[
M_S = \left( 0(t) - \sigma_{\text{dry}}^0 \right) / \left( 0_{\text{wet}} - \sigma_{\text{dry}}^0 \right)
\]
## L2_SM_A Error Analysis

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of the pair of HH and VV radar backscatter used as time-series input</td>
<td>24 (~2 months)</td>
</tr>
<tr>
<td>Kp noise (dB, 1σ)</td>
<td>0.5</td>
</tr>
<tr>
<td>Vegetation water content error (1σ)</td>
<td>10%</td>
</tr>
<tr>
<td>Data cube error (physics modeling &amp; grid resolution)</td>
<td>TBD</td>
</tr>
<tr>
<td>Conversion error from dielectric constant to soil moisture</td>
<td>TBD</td>
</tr>
<tr>
<td>Effect of scaling and scene heterogeneity</td>
<td>TBD</td>
</tr>
<tr>
<td>Soil moisture retrieval error (cm³/cm³) at VWC of 3 kg/m²</td>
<td>0.065</td>
</tr>
</tbody>
</table>

Baseline data-cube time-series retrieval performed on the Hydros OSSE domain using the Dubois/Oh/Ulaby data cube. \( N \) = Number of passes in time-series data.

Baseline data-cube snapshot retrieval for Michigan bare surface data.

Baseline data-cube time-series for SGP99 grass (VWC of 0.5 to 1 kg/m²). \( N \) = 6. (Data cubes from Dr. Leung Tsang.

Both analyses suggest ~0.06 cm³/cm³ error target is feasible (up to 1-3 kg/m² VWC at 0.5 dB Kp)
## L2_SM_AP Error Analysis

<table>
<thead>
<tr>
<th>Error Sources</th>
<th>Estimated Error</th>
<th>Nominal Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Radiometer precision and calibration</td>
<td>1.30 [K]</td>
<td>1.30 [K]</td>
</tr>
<tr>
<td>2 Faraday rotation</td>
<td>0.20 [K]</td>
<td>0.20 [K]</td>
</tr>
<tr>
<td>3 Atmospheric gases</td>
<td>0.10 [K]</td>
<td>0.10 [K]</td>
</tr>
<tr>
<td>4 Non-Precipitating clouds</td>
<td>0.10 [K]</td>
<td>0.10 [K]</td>
</tr>
<tr>
<td>5 Tb RSS error (L1_TB) RSS</td>
<td>1.32 [K]</td>
<td>1.32 [K]</td>
</tr>
<tr>
<td>6 Gridding error</td>
<td>0.20 [K]</td>
<td>0.20 [K]</td>
</tr>
<tr>
<td>7 Waterbody fraction (3%, 5%, 10%)</td>
<td>0.16</td>
<td>0.45</td>
</tr>
<tr>
<td>8 Adjusted Corrected Tb RSS</td>
<td>1.35</td>
<td>1.41</td>
</tr>
<tr>
<td>9 Radar S0(pp) and S0(pq) errors*</td>
<td>2.00 [K]</td>
<td>2.00 [K]</td>
</tr>
<tr>
<td>10 Disaggregated Tb (9 km) RSS</td>
<td>2.41</td>
<td>2.45</td>
</tr>
<tr>
<td>11 VWC** (0-1, 1-2, 2-3, 3-4, 4-5 [kg/m2]) 10% error</td>
<td>0.003</td>
<td>0.010</td>
</tr>
<tr>
<td>12 Soil temperature (2 [K])</td>
<td>0.010</td>
<td>0.013</td>
</tr>
<tr>
<td>13 Soil dielectric model (5% error in sand &amp; clay fraction)</td>
<td>0.002</td>
<td>0.003</td>
</tr>
<tr>
<td>14 Parameters (h, ω, and b) 5% error each</td>
<td>0.003</td>
<td>0.004</td>
</tr>
<tr>
<td>15 Soil moisture retrieval at 9 km RSS</td>
<td>0.011</td>
<td>0.017</td>
</tr>
</tbody>
</table>

* Calibration and contamination errors
**Vegetation Water Content
Underlined values are used as nominal
# L4_C Error Analysis

## Estimated uncertainty (RMSE) for L4_C based NEE

<table>
<thead>
<tr>
<th>Type of Error</th>
<th>Error Source</th>
<th>Source Units</th>
<th>Range</th>
<th>Value</th>
<th>NEE Contribution (g C m(^{-2}) yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Data</td>
<td>Temperature</td>
<td>°C</td>
<td>1.5-4</td>
<td>3.5</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>Moisture</td>
<td>vol. cm(^3) cm(^{-3})</td>
<td>0.04-0.10</td>
<td>0.05</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>GPP</td>
<td>g C m(^{-2}) d(^{-1})</td>
<td>1.0-2.0</td>
<td>1.5</td>
<td>4.4</td>
</tr>
<tr>
<td>Model Parameterization</td>
<td>Optimal Decomp. Rates/Response Curves</td>
<td>d(^{-1})</td>
<td>0.001-0.01</td>
<td>0.0015</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>Pool Representation/Steady State</td>
<td>g m(^{-2})</td>
<td>100-1000</td>
<td>500</td>
<td>12.0</td>
</tr>
<tr>
<td></td>
<td>Autotrophic Respiration fraction</td>
<td>dim.</td>
<td>0.05-0.15</td>
<td>0.1</td>
<td>1.5</td>
</tr>
<tr>
<td>Heterogeneity</td>
<td>Land Cover Heterogeneity (Soil Respiration)</td>
<td>g C m(^{-2}) yr(^{-1})</td>
<td>10-95</td>
<td>95</td>
<td>25.0</td>
</tr>
<tr>
<td>Total NEE Error</td>
<td>Inputs Only</td>
<td>g C m(^{-2}) yr(^{-1})</td>
<td></td>
<td></td>
<td>5.2</td>
</tr>
<tr>
<td></td>
<td>Model Only</td>
<td>g C m(^{-2}) yr(^{-1})</td>
<td></td>
<td></td>
<td>12.1</td>
</tr>
<tr>
<td></td>
<td>Inputs + Model</td>
<td>g C m(^{-2}) yr(^{-1})</td>
<td></td>
<td></td>
<td>13.2</td>
</tr>
<tr>
<td></td>
<td>Inputs + Model + Het.</td>
<td>g C m(^{-2}) yr(^{-1})</td>
<td></td>
<td></td>
<td>28.7</td>
</tr>
</tbody>
</table>

**NEE accuracy commensurate with tower based CO\(_2\) flux measurements:** RMSE ≤ 30 g C m\(^{-2}\) yr\(^{-1}\) and 1.6 g C m\(^{-2}\) d\(^{-1}\).
Formulation Highlights

• Finalized science mapping orbit to achieve global coverage requirements

• Developed cost effective approach to dramatically increase science data volume (45 Gb/day to 130 Gb/day) to mitigate/improve science measurement margins

• Developed prototype science data testbed system has been provided to Science and is being actively used for algorithm development and testing

• Formulated RFI mitigation strategies and incorporated design features in radiometer and radar to enable detection and removal/correction to substantially reduce associated data loss
  • Conducted extensive surveys and simulations to understand RFI environment and assess effectiveness of mitigation strategies
  • Completed preliminary signal processing design for radiometer spectral filtering, conducted two signal processing focused reviews to vet approach

• Redesigned radar to minimize interference to FAA radars; conducted tests with FAA & GPS; dynamic analyses characterized interactions considering orbit and RBA motions

• Developed 128Gb on-board science data storage card to provide robust capacity (nearly one full day of storage) and simultaneous high rate data storage & stored data downlink