The SMAP Level 4 Surface and Root-Zone Soil Moisture (L4_SM) Product

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Rolf Reichle* NASA-GSFC
Wade Crow USDA-ARS
Randal Koster NASA-GSFC
John Kimball Univ. of MT

*Corresponding author: Rolf Reichle, 301-614-5693, Rolf.Reichle@nasa.gov
Motivation: SMAP sees only the top 5 cm of the soil, but many applications require knowledge of root-zone soil moisture (~top 1 m).

Assimilating SMAP data into a land model driven with observation-based forcings (incl. precipitation) yields:

1. a root zone moisture product (reflecting SMAP data)
2. an improved surface product
3. a complete and consistent estimate of soil moisture & related fields
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Key elements of the L4_SM algorithm:
- SMAP obs. (subject to error)
- Assimilation parameters
- Ensemble Kalman filter
- Assimilation
- Catchment model
  - Surface meteorology (subject to error)
  - Land surface parameters (subject to error)
- Land model (subject to error)
  - Surface and root-zone soil moisture, soil temperature, surface fluxes, … (subject to error)

Improved surface and root-zone soil moisture, surface fluxes, etc.
Soil moisture is determined by the equilibrium soil moisture profile from the surface to the water table ("catchment deficit") and by two additional variables that describe deviations from the equilibrium profile: the average deviation in a 1 m root zone layer ("root zone excess"), and the average deviation in a 5 cm surface layer ("surface excess"). The model outputs surface (top 5 cm), root zone (top 1 m), and total profile soil moisture as diagnostics.

The surface energy balance and surface runoff are computed separately for the saturated, transpiring, and wilting sub-areas of each catchment.

Different moisture levels (shown here as different water table depths) lead to different areal partitionings of the catchment into saturated, unstressed, and wilting regimes.

Implement for SMAP on a 9 km global grid (same as L3_SM_A/P product)

Koster et al. 2000; Ducharne et al. 2000; Bowling et al. 2003; Guo and Dirmeyer 2006; Guo et al. 2006
**Ensemble Kalman filter (EnKF)**

Nonlinear ensemble propagation approximates model errors.

Apply small perturbations to each ensemble member (model forcings and states) at every time step.

**Optional:** Adaptive estimation of error parameters

**Optional:** Dynamic bias estimation

Propagation $t_{k-1}$ to $t_k$:

$$x_k^i = f(x_{k-1}^i) + e_k^i$$

$e =$ model error

Update at $t_k$:

$$x_k^{i+} = x_k^i + K_k(y_k^i - x_k^i)$$

for each ensemble member $i=1...N$

$$K_k = P_k(P_k + R_k)^{-1}$$

with $P_k$ computed from ensemble spread

$x_k^i$ state vector (eg soil moisture)

$P_k$ state error covariance

$R_k$ observation error covariance

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Andreadis and Lettenmaier (2005); Durand and Margulis (2007); Kumar et al. (2008a, 2008b, 2009); Pan and Wood (2006); Reichle et al. (2002a, 2002b, 2007, 2008a, 2008b, 2009); Reichle and Koster (2003, 2004, 2005); De Lannoy et al. (2007); Crow and Reichle (2008); Zaitchik et al. (2008); Zhou et al. (2006)
L4_SM inputs and outputs

**SMAP inputs**
- **Baseline:**
  - L3_SM_A/P (9 km)
- **Option:**
  - L1C_S0_HiRes (3 km)
  - L1C_TB (40 km)
  - L3_F/T (3 km)

**L4_SM product**
- **Validated output (error < 0.04 m³/m³)**
  - surface soil moisture (≤ top 5 cm) (vol % & percentiles)
  - root zone soil moisture (≤ top 1 m) (vol % & percentiles)
- **Research output (not validated, exact list TBD)**
  - surface temperature (input to L4_C)
  - sensible, latent, and ground heat flux
  - fraction of saturated, wilting, and unsaturated area
  - snow water equivalent, snow depth, snow cover area
  - runoff, baseflow, snowmelt
  - surface meteorological forcings (air temperature, precipitation, …)
  - Catchment model parameters
  - error estimates (generated by assimilation system)

- **9 km global grid with 5-day latency** (after 1-year cal/val phase)
- **3-hourly averages**
- **Snapshots** at/near SMAP overpass times (EnKF updates at 0z, 3z, …, 21z)

**Ancillary data inputs**
- **GMAO GEOS-x**: (~1/8° resolution by 2013)
- **Land model parameters**
  - Land cover, albedo, porosity, soil hydraulic and topographic parameters, LAI, greenness
- **Surface meteorology**
  - Precipitation – corrected with observational product (e.g. pentad CMAP)
  - Downward longwave and shortwave radiation, air temperature and humidity, surface pressure and wind
- **Land assimilation parameters**
  - Observation and model error standard deviations; temporal, spatial, and cross-correlation parameters

*GEOS-x = Land and atmospheric modeling and assimilation system at the NASA Global Modeling and Assimilation Office (GMAO)

* adjusted for consistency with parameters used by other SMAP products

**Data volume:**
- ~4 MB/field
- ~45 GB/month

**Output format:**
- netcdf4/hdf5
**L4_SM assimilation parameters**

Perturbations to model forcing and prognostic variables approximate "model errors".

<table>
<thead>
<tr>
<th>Perturbation</th>
<th>Additive (A) or Multiplicative (M)?</th>
<th>Standard deviation</th>
<th>AR(1) time series correlation scale</th>
<th>Spatial correlation scale</th>
<th>Cross-correlation with perturbations in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td>M</td>
<td>0.5</td>
<td>1 day</td>
<td>50 km</td>
<td>-0.8</td>
</tr>
<tr>
<td>Downward shortwave (SW)</td>
<td>M</td>
<td>0.3</td>
<td>1 day</td>
<td>50 km</td>
<td>n/a</td>
</tr>
<tr>
<td>Downward longwave (LW)</td>
<td>A</td>
<td>50 W m$^{-2}$</td>
<td>1 day</td>
<td>50 km</td>
<td>n/a</td>
</tr>
<tr>
<td>Catchment deficit</td>
<td>A</td>
<td>0.05 mm</td>
<td>3 h</td>
<td>25 km</td>
<td>n/a</td>
</tr>
<tr>
<td>Surface excess</td>
<td>A</td>
<td>0.02 mm</td>
<td>3 h</td>
<td>25 km</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Values are based on experience with AMSR-E assimilation (Reichle et al. 2007) and synthetic experiments (Reichle et al. 2002b; Reichle and Koster 2003).

Will be tuned with SMOS observations.

Optional adaptive filtering module may help determine optimal values.
Figure shows typical bias between satellite and model surface soil moisture that must be addressed in the assimilation system.

Scaling is based only on data from a single year.

**Baseline algorithm:** A priori scaling (cdf-matching) of L3_SM_A/P into Catchment model climatology (Reichle and Koster 2004, Drusch et al. 2005).

**Optional algorithm:** Dynamic bias estimation (De Lannoy et al. 2007).

Will be tuned with SMOS observations.
### L4_SM cal/val

<table>
<thead>
<tr>
<th>Pre-launch</th>
</tr>
</thead>
<tbody>
<tr>
<td>– Use L4_SM system with SMOS obs &amp; apply cal/val to the extent possible.</td>
</tr>
<tr>
<td>– Conduct OSSE’s (calibration of assimilation parameters).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Post-launch</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Calibration within 1(^{st}) year:</strong></td>
</tr>
<tr>
<td>Bias correction param’s (“cdf matching”), assimilation param’s (thru innovations).</td>
</tr>
</tbody>
</table>

**Validation with in situ observations:**

- **Surface soil moisture:**
  - Apply L3_SM_A/P cal/val procedures.

- **Root-zone soil moisture:**
  - In principle, cal/val is identical to surface soil moisture, but
  - have fewer in situ obs. (e.g. from USDA/SCAN, NCDC/CRN)
  - rarely/never have multiple in situ obs. within single grid cell

**Additional evaluation:**

- Examine “obs-minus-model” residuals for internal consistency of the L4_SM algorithm (Reichle et al. 2008; Crow and Reichle 2008).
- Evaluate with high-quality, independent precipitation obs (Crow 2007).
- Evaluate research product components (e.g. fluxes) to the extent possible.

**Requirement:** Need as many **root-zone** soil moisture obs. as possible.
Assimilate AMSR-E surface soil moisture (2002-09) into NASA Catchment model

Validate with USDA SCAN stations (only 36 of 103 suitable for validation)

### Anomaly RMSE

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>AMSR-E</th>
<th>Model</th>
<th>Assim.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface s.m.</td>
<td>36</td>
<td>0.049</td>
<td>0.051</td>
<td>0.048</td>
</tr>
<tr>
<td>Root zone s.m.</td>
<td>32</td>
<td>n/a</td>
<td>0.039</td>
<td>0.036</td>
</tr>
</tbody>
</table>

### Anomaly R

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>AMSR-E</th>
<th>Model</th>
<th>Assim.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface s.m.</td>
<td>36</td>
<td>.42±.01</td>
<td>.38±.01</td>
<td>.47±.01</td>
</tr>
<tr>
<td>Root zone s.m.</td>
<td>32</td>
<td>n/a</td>
<td>.37±.01</td>
<td>.45±.01</td>
</tr>
</tbody>
</table>

Anomalies ≡ Daily data with mean seasonal cycle removed

Higher quality of SMAP obs. will provide better improvements (see next slides).

**Uncertainty estimates: OSSE approach**

**Key error sources:**
1. Errors in land model ("model error"), incl. errors in
   a) Surface meteorological forcing
   b) Land model parameterizations and parameters
2. Errors in input SMAP products ("obs error")
3. Errors in assimilation parameters

**Soil moisture assimilation OSSE (Observing System Simulation Experiment)**
Investigate range of obs and model errors by assimilating synthetic SMAP retrievals from a TOPLATS “truth” model integration into the Catchment model.

**Example: Skill of anomalies in terms of R (=anom. time series correlation coeff. v. synthetic truth).**
Each plus sign indicates result of one 19-year assimilation integration over Red-Arkansas domain.
Contour surface shows skill improvement of assimilation estimates over model estimates.

Anomalies ≡ Daily data with mean seasonal cycle removed

OSSE is consistent with results from AMSR-E and SMMR assimilation.

AMSRE-E (Δ):
ΔR=0.06

SMMR (○):
ΔR=0.03

Uncertainty estimates: OSSE approach

**anomaly RMSE [m³/m³]**

<table>
<thead>
<tr>
<th>surface soil moisture</th>
<th>root zone soil moisture</th>
</tr>
</thead>
</table>

Skill *improvement* of assimilation over model (ΔRMSE)

(surface soil moisture)

Skill *improvement* of assimilation over model (ΔRMSE)

(root zone soil moisture)

Symbols indicate (actual or estimated) skill for satellite observations and land modeling systems.

Anomalies ≡ Daily data with mean seasonal cycle removed

- ○ = L4_SM (high skill)
- x = L4_SM (low skill)
- Δ = AMSR–E
**L4_SM uncertainty estimates**

**Interpreting the OSSE for SMAP yields:**

|                          | Skill scenario | L3_SM<sup>1,3</sup> (A/P) | Model<sup>2,3</sup> | L4_SM<sup>3</sup> | |Δ| |
|--------------------------|----------------|---------------------------|--------------------|-------------------|-------|
| **Expected anomaly RMSE [m<sup>3</sup>/m<sup>3</sup>]** |                |                           |                    |                   |       |
| Surface soil moisture    | High           | 0.028                     | 0.046              | 0.035*            | 0.012 |
|                          | Low            | 0.037                     | 0.051              | 0.038*            | 0.012 |
| Root zone soil moisture  | High           | n/a                       | 0.036              | 0.031             | 0.005 |
|                          | Low            | n/a                       | 0.038              | 0.031             | 0.007 |
| **Expected anomaly R**   |                |                           |                    |                   |       |
| Surface soil moisture    | High           | 0.78                      | 0.63               | 0.71              | 0.08  |
|                          | Low            | 0.70                      | 0.41               | 0.54              | 0.13  |
| Root zone soil moisture  | High           | n/a                       | 0.55               | 0.63              | 0.08  |
|                          | Low            | n/a                       | 0.46               | 0.59              | 0.13  |

<sup>1</sup>Source: SMAP measurement requirements.
<sup>2</sup>Source: USDA/SCAN results.
<sup>3</sup>Source: OSSE results.

Assimilation of SMAP obs will provide improvements (over model) of ~0.01 m<sup>3</sup>/m<sup>3</sup> for surface and ~0.005 m<sup>3</sup>/m<sup>3</sup> for root-zone soil moisture.

L4_SM is expected to meet the 0.04 m<sup>3</sup>/m<sup>3</sup> error requirement.
Next steps and time line

- External review *(in progress – more later)*
- Finalize L4_SM ATBD *(by Jan 2010)*
  - Error budget
  - Root-zone soil moisture cal/val
  - Refine specification of L4_SM product
- L4_SM development and implementation
  - Catchment model customization for SMAP *(start ASAP)*
    - 9 km global grid and 5 cm surface layer
  - Assimilation system development
    - L3_F/T assimilation development *(start ASAP)*
    - Decide between baseline and option algorithm *(start 2010)*
    - Operational implementation *(start Oct 2010)*
  - Exercise L4_SM with SMOS obs. and apply cal/val
External review

Input on L4_SM algorithm requested from select commentators.

To date received 7 (of 8) responses – THANKS!!!

[proposed] system […] is state-of-the-art

most important contribution […] is […] root-zone soil moisture

extremely beneficial; looks quite okay to me
great asset to the SMAP mission

very useful for a large range of applications

emphasis should […] be put on a flexible bias correction

assimilate Tbs and S0s [as opposed to L3 products]

Catchment land surface model is one of the best […]

Consider using an ensemble of models. I DO NOT believe the Catchment model is […] best

[for validation] need as a minimum […] 5 stations in a ‘grid’ cell

What do you think? Let us know!
**Discussion**

*Suggested topics (feedback from external review, project needs):*

- **Algorithm specifications**
  - baseline v. option algorithm (estimation of bias & assim. parameters)
  - choice of land model
  - smoother
  - F/T assimilation

- **Output product specifications**
  - fields
  - units
  - space-time resolution

- **Validation**
  - metric and bias
  - special case of root-zone soil moisture

- **Applications**
  - any specific requirements?
THANK YOU FOR YOUR ATTENTION!
BACKUP SLIDES
**Science objectives**

- Global land surface water, energy, and carbon fluxes.
- Enhance weather and climate forecast skill.
- Improve flood prediction and drought monitoring.

**Platform and instruments**

L-band (1.4 GHz) synthetic aperture radar (active) and radiometer (passive) with 6-m rotating antenna

- **Orbit:** Sun-synchronous
  - ~680km altitude
  - 6am/7pm overpass
- **Swath width:** 1,000 km
- **Resolution:**
  - 1-3 km (radar)
  - 40 km (radiometer)
- **Revisit:** 2-3 days
- **Duration:** 2013-16
- **Sensing depth:** ~5 cm

*Only surface soil moisture!*
### SMAP Baseline Science Data Products

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
<th>Resolution</th>
<th>Latency</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1B_S0_LoRes</td>
<td>Low Resolution Radar Backscatter ($\sigma^0$)</td>
<td>~ 30 km</td>
<td>12 hours</td>
</tr>
<tr>
<td>L1C_S0_HiRes</td>
<td>High Resolution Radar Backscatter ($\sigma^0$)</td>
<td>~ 1-3 km</td>
<td>12 hours</td>
</tr>
<tr>
<td>L1B_TB</td>
<td>Radiometer Brightness Temperature ($T_B$)</td>
<td>~ 40 km</td>
<td>12 hours</td>
</tr>
<tr>
<td>L1C_TB</td>
<td>Radiometer Brightness Temperature ($T_B$)</td>
<td>~ 40 km</td>
<td>12 hours</td>
</tr>
<tr>
<td>L3_F/T_HiRes</td>
<td>Freeze/Thaw State</td>
<td>~ 3 km</td>
<td>24 hours</td>
</tr>
<tr>
<td>L3_SM_HiRes</td>
<td>Radar Soil Moisture (internal product)</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>L3_SM_40km</td>
<td>Radiometer Soil Moisture</td>
<td>~ 40 km</td>
<td>24 hours</td>
</tr>
<tr>
<td>L3_SM_A/P</td>
<td>Radar/Radiometer Soil Moisture</td>
<td>~ 10 km</td>
<td>24 hours</td>
</tr>
<tr>
<td>L4_SM</td>
<td>Surface &amp; <strong>Root-zone</strong> Soil Moisture</td>
<td>~ 10 km</td>
<td>7 days</td>
</tr>
<tr>
<td>L4_C</td>
<td>Carbon Net Ecosystem Exchange</td>
<td>~ 10 km</td>
<td>14 days</td>
</tr>
</tbody>
</table>
The L4_SM algorithm will be
– based on the existing NASA GMAO land assimilation system,
– developed and implemented within the NASA GEOS modeling and assimilation framework,
– written primarily in Fortran90 and an object-oriented extension (ESMF), and
– executed on Linux-based cluster computing facilities at NASA.

<table>
<thead>
<tr>
<th>Estimated computational requirements:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Catchment model time step</td>
<td>20 min</td>
</tr>
<tr>
<td>EnKF update time step</td>
<td>3 h</td>
</tr>
<tr>
<td>Model/assimilation grid spacing</td>
<td>10 km</td>
</tr>
<tr>
<td>Number of model grid cells</td>
<td>1e6</td>
</tr>
<tr>
<td>Number of ensemble members</td>
<td>~24</td>
</tr>
<tr>
<td>CPU requirement per simulated month</td>
<td>18 h</td>
</tr>
<tr>
<td>Total memory requirement</td>
<td>23 GB</td>
</tr>
<tr>
<td>Online (hard-drive) storage requirement (1 data month)</td>
<td>90 GB</td>
</tr>
<tr>
<td>Long-term (tape) storage requirement (for entire 3-year mission)</td>
<td>3 TB</td>
</tr>
</tbody>
</table>
A number of scientists in national and international agencies were identified who envision using the SMAP L4_SM product, primarily for reanalysis and/or research/validation w.r.t. their operations and products:

<table>
<thead>
<tr>
<th>Institution</th>
<th>POC</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOAA/NCEP, NOAA/NESDIS</td>
<td>Zhan</td>
</tr>
<tr>
<td>ECMWF</td>
<td>De Rosnay</td>
</tr>
<tr>
<td>Environment Canada</td>
<td>Belair</td>
</tr>
<tr>
<td>Air Force Weather Agency</td>
<td>Eylander</td>
</tr>
<tr>
<td>NOAA Climate Prediction Center</td>
<td>Mo, Xie</td>
</tr>
<tr>
<td>US Army</td>
<td>Davis</td>
</tr>
<tr>
<td>US Army</td>
<td>McWilliams</td>
</tr>
<tr>
<td>USGS Famine Early Warning System</td>
<td>Verdin</td>
</tr>
</tbody>
</table>

We anticipate that the SMAP L4_SM product will be widely used in academic and government research
– because it includes root-zone soil moisture and related land surface fields,
– because of its complete coverage, and
– because of the availability of consistent and comprehensive estimates of land surface hydrologic conditions.
## Baseline v. option algorithm

<table>
<thead>
<tr>
<th>Baseline: Assimilate L3_SM_A/P + L3_F/T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option: Assimilate L1C_S0_HiRes + L1C_TB + L3_F/T</td>
</tr>
</tbody>
</table>

**Advantages of option algorithm:**
- Consistent handling of surface soil temperature.
- L4_SM processing independent of L3 algorithms.

**Disadvantages of option algorithm:**
- Option algorithm requires implementation of forward radiative and backscatter transfer model within L4_SM processing system.
- May not be as sophisticated as the corresponding inverse algorithms.

For now, focus on baseline algorithm.

Test option algorithm when permitted by L3 algorithm development, L4 implementation, and availability of SMOS data.
A generic land data assimilation system

Land surface OBSERVATIONS
(Satellite and conventional)

- Forcings
  Precipitation, radiation, air temperature, …

- Parameters
  Soil, vegetation, albedo, …

- States
  Soil moisture, snow, terrestrial water storage, …

Analysis

"Model" estimates

Weights based on uncertainties.

"Optimal" land surface estimates

Land data assimilation system

ESMF
Connections through the Earth System Modeling Framework

Atmosphere-ocean modeling & analysis system

APPLICATIONS
What is special about land assimilation?

**Land model:**
“Local” and “damped” physics; (mostly) non-differentiable equations.

**Modest improvements from assimilation of “state” obs.**

**Ensemble-based analysis system most appropriate.**

**Focus on errors in model forcing (as opposed to initial condition).**

**Land obs:**
Satellite obs. typically no better than land “model” estimates.
Uncertainty estimates: OSSE approach

<table>
<thead>
<tr>
<th>anomaly R</th>
<th>surface soil moisture</th>
<th>root zone soil moisture</th>
</tr>
</thead>
</table>

Skill improvement of assimilation over model (ΔR)
(surface soil moisture)

Skill improvement of assimilation over model (ΔR)
(root zone soil moisture)

Symbols indicate (actual or estimated) skill for satellite observations and land modeling systems.

○ = L4_SM (high skill)
× = L4_SM (low skill)
△ = AMSR–E
□ = SMMR

Anomalies ≡ Daily data with mean seasonal cycle removed
**Multi-model soil moisture assimilation**

How does land model formulation impact assimilation estimates of root zone soil moisture?

---

**Normalized ROOT ZONE soil moisture improvement from assimilation of surface soil moisture**

<table>
<thead>
<tr>
<th>Model</th>
<th>Synthetic observations from</th>
<th>Avg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Catch</td>
<td>Mos</td>
</tr>
<tr>
<td>Catch</td>
<td>0.71</td>
<td>0.54</td>
</tr>
<tr>
<td>Mos</td>
<td>0.55</td>
<td>0.69</td>
</tr>
<tr>
<td>Noa</td>
<td>0.43</td>
<td>0.43</td>
</tr>
<tr>
<td>CLM</td>
<td>0.11</td>
<td>0.21</td>
</tr>
<tr>
<td>Avg</td>
<td><strong>0.45</strong></td>
<td><strong>0.47</strong></td>
</tr>
</tbody>
</table>

Catchment and Mosaic work better for assimilation than Noah or CLM.

Catchment or MOSAIC “truth” easier to estimate than Noah or CLM “truth”.

**Stronger coupling between surface and root zone provides more “efficient” assimilation of surface observations.**

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Soil moisture

Snow model (3 layers)

Sensible heat flux

Latent heat flux

Ground-water

Heat diffusion model (7 layers)