National Aeronautics and Space Administration

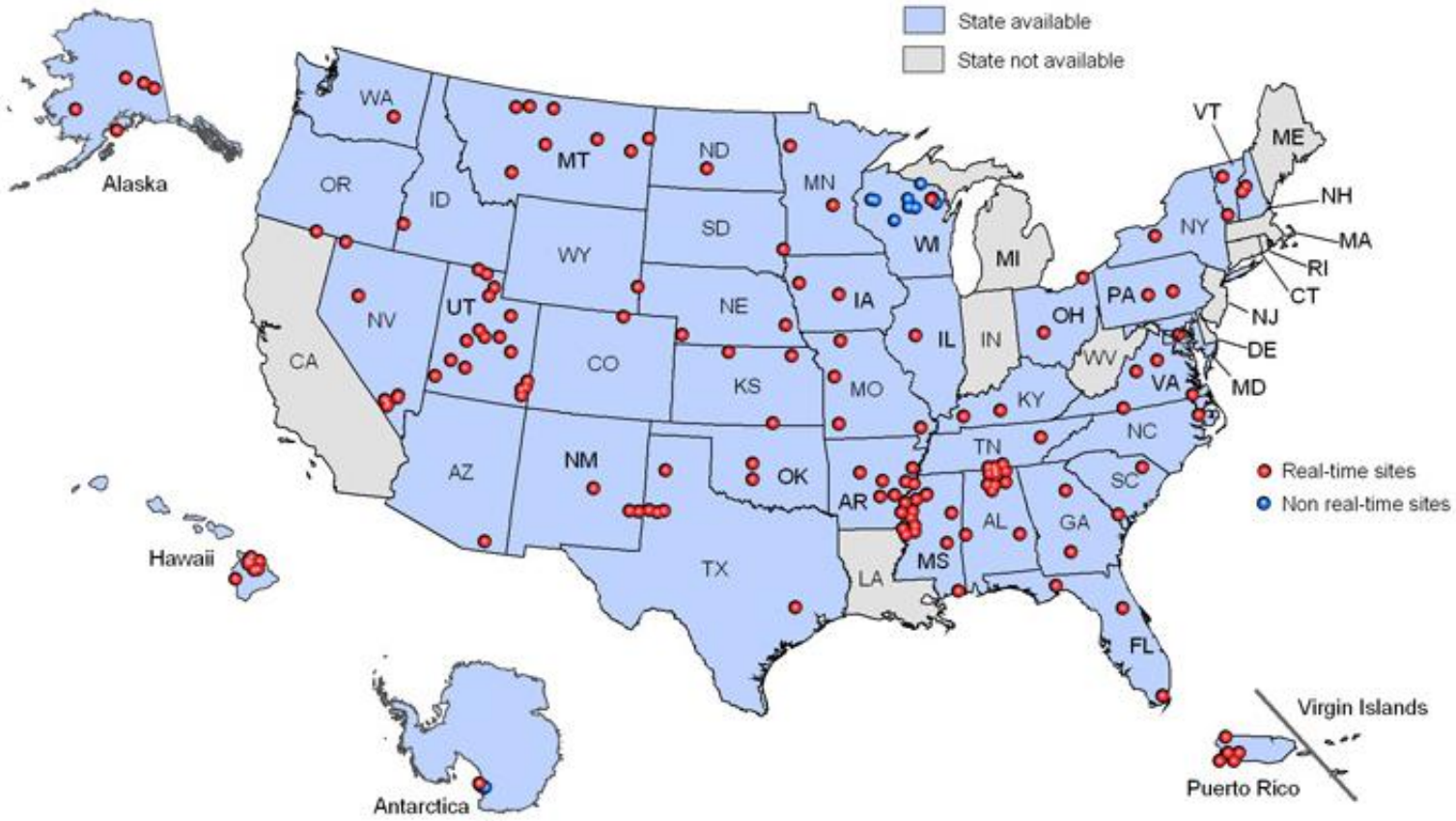


# Satellite Soil Moisture Products

Rajat Bindlish, NASA GSFC

Contributions from:
SMAP Team, SMOS

# Importance of Satellite Soil Moisture



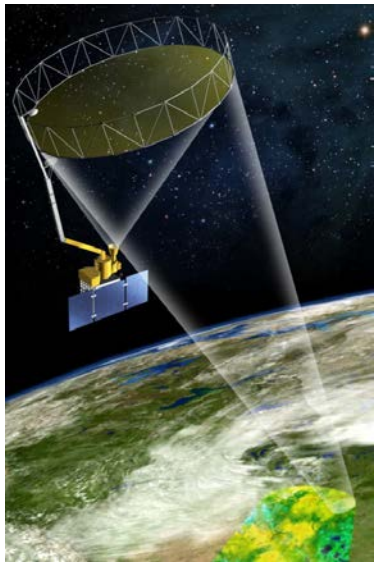

**Limitations in measuring global soil moisture:**

- Ground measurements of soil moisture are sparse and have limited coverage
- Higher frequency (X-band) Space-borne sensors have relatively low sensitivity and resolution



# Objectives of Satellite soil moisture missions

**Objective of a Soil Moisture mission is to provide high-resolution and frequent-revisit global maps of soil moisture.**



**Science and applications addressed by SMOS and SMAP:**

- 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, flood and drought prediction
- Other applications such as agricultural productivity and human health

# NASA Earth Observing Satellite Fleet

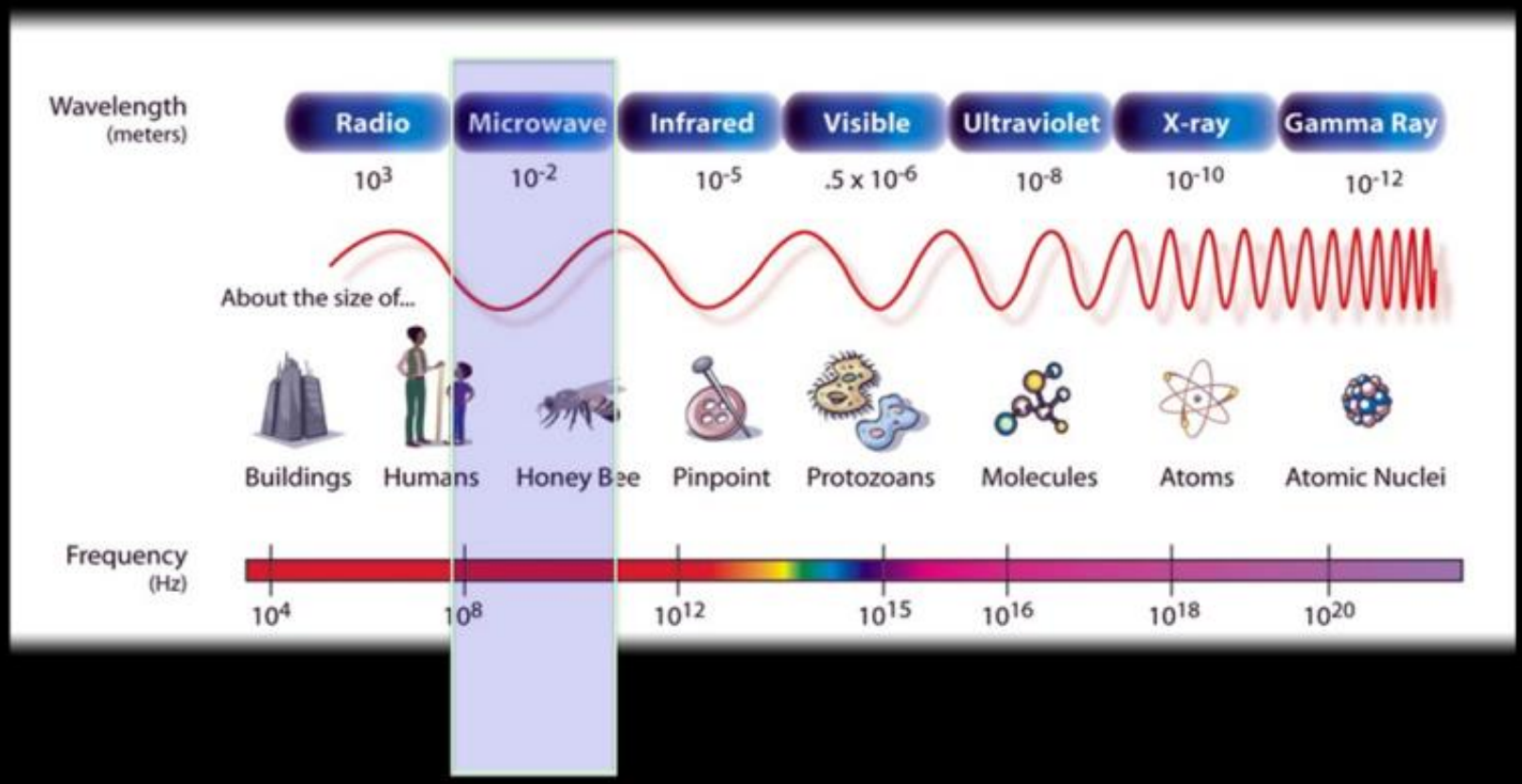
## International Satellites

- SMOS (ESA)
- ASCAT (ESA)
- GCOM-W (JAXA)



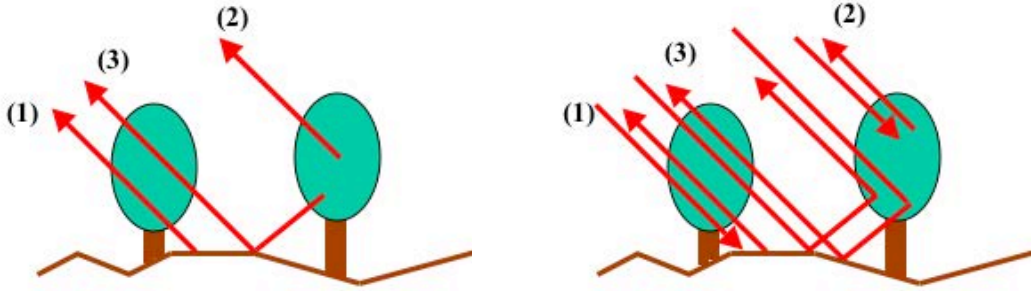

Courtesy of the Goddard Visualization Lab

# Microwave Sensing




- With Visible and Infrared sensors the soil is masked by clouds and vegetation. Optical sensors operate by measuring scattered sunlight and are “daytime only”.
- Microwaves can penetrate through clouds and vegetation, operate day and night, and are highly sensitive to the water in the soil due to the change in the soil microwave dielectric properties.

# Measurement Approach (Physical Basis)

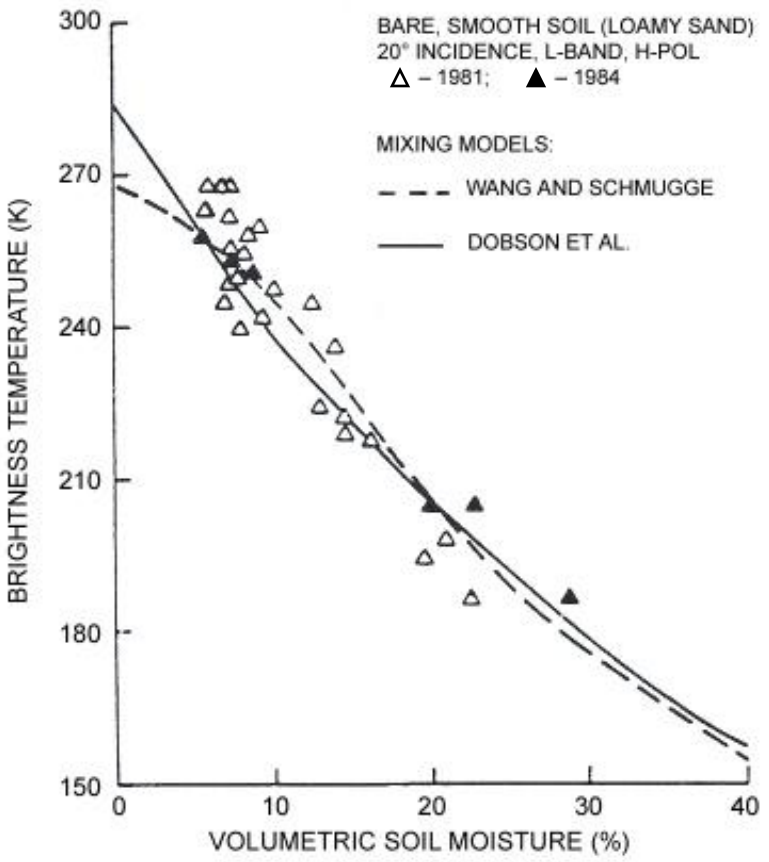



*Emission* *Backscatter*

$$T_{Bp}^{t} = T_{Bp}^{s} L_p + T_{Bp}^{v} + T_{Bp}^{sv} \qquad \text{(Emission)}$$

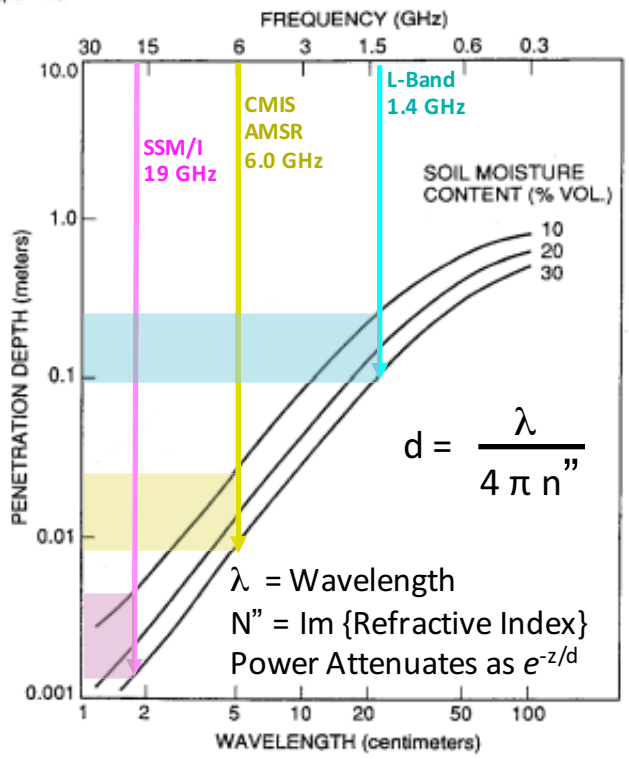
$$\sigma_{pq}^{t} = \sigma_{pq}^{s} L_{pq}^{2} + \sigma_{pq}^{v} + \sigma_{pq}^{sv} \qquad \text{(Backscatter)}$$

- Equations for p = H, V (radiometer) and pq = VV, HH, HV (radar)
- Contributions include three terms: soil, vegetation, and soil-vegetation interaction
- Soil moisture is the dominant contributor to the signal
- $L$ is the vegetation attenuation factor, $\exp(-\tau_o / \cos\theta)$
- Retrievals invert these equations to obtain soil moisture, with corrections for vegetation, roughness and surface temperature

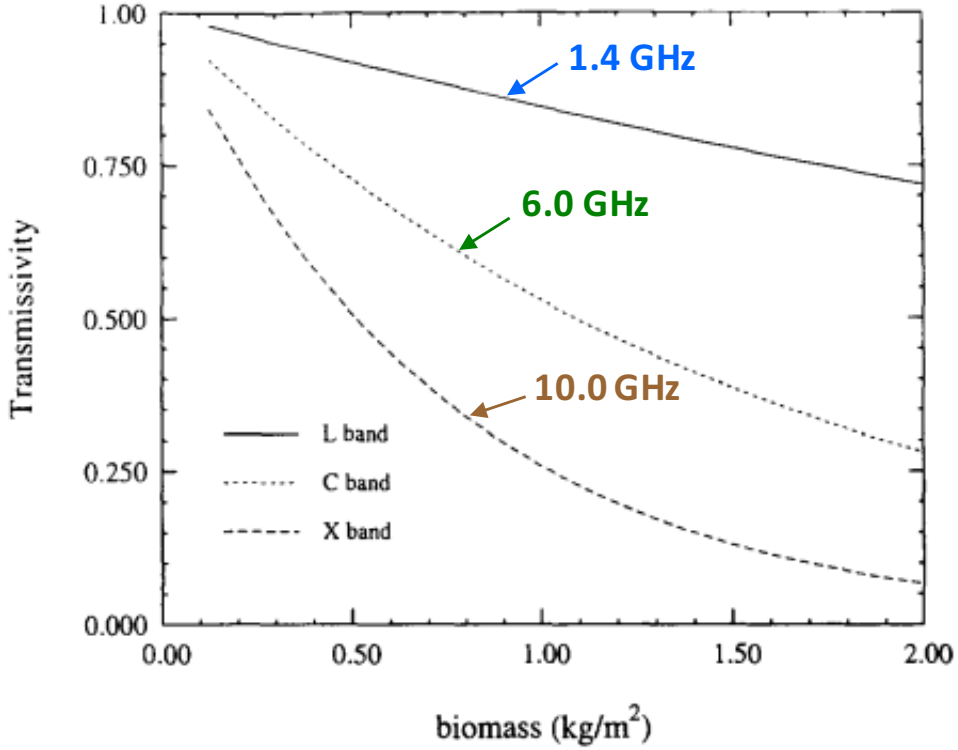



[Jackson and O'Neill, *IEEE TGARS, GE-25*, 1987.]

# Microwave Soil Moisture Sensing




Effective sensing depth decreases with increasing measurement frequency




Vegetation attenuation increases with increasing measurement frequency

***L-band provides significant improvements in soil moisture sensing capability over previous missions (e.g. AMSR-E at C-band)***



# Satellite Soil Moisture Data Characteristics

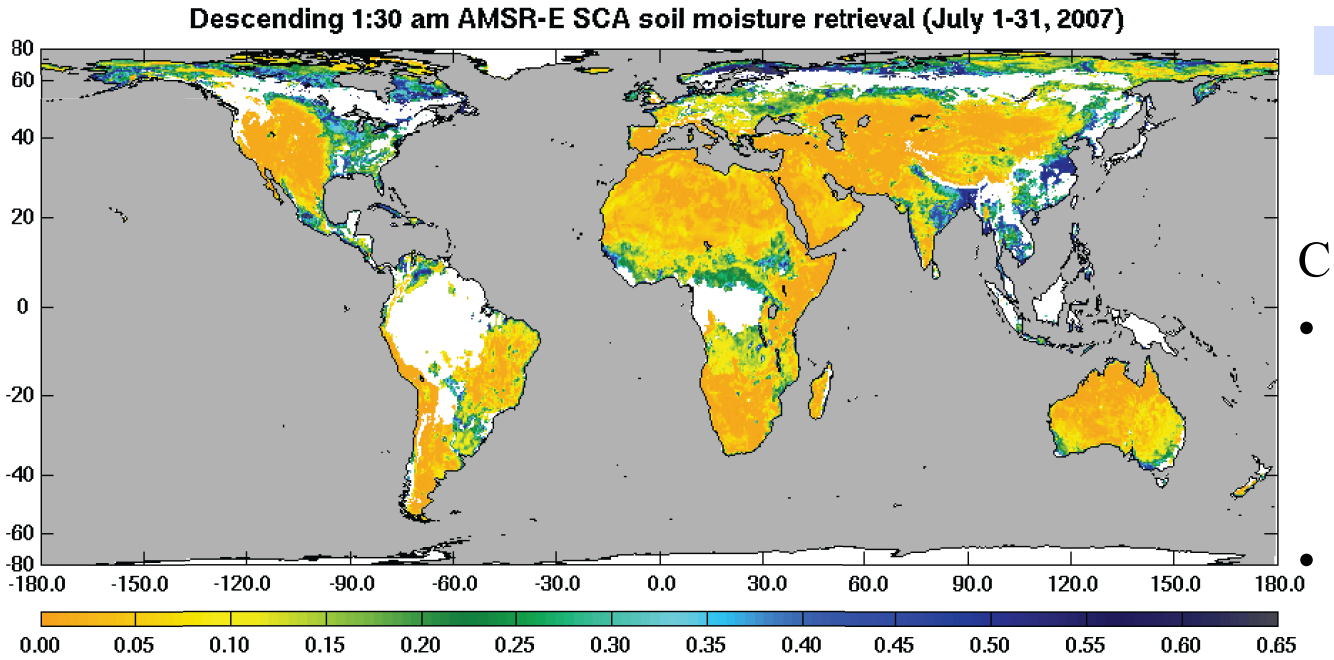
| | Mission Duration | SM Spatial Coverage[1] | Temporal Revisit | Orbit | Product Resolution |
|---|---|---|---|---|---|
| AMSR-E | 2002-2011 | Global land | 2-3 days | (1:30 pm asc / 1:30 am desc) | 25 km |
| GCOM-W(AMSR2) | 2012-Present | Global land | 2-3 days | (1:30 pm asc / 1:30 am desc) | 25 km |
| WindSat (DoD) | 2004-? | Global land | 2-3 days | Sun synch (6:00 am asc/ 6:00 desc) | 25 km |
| ASCAT | 2009-Present | Global land | | Sun synch (9:30pm asc / 9:30am desc) | 12.5 km/25 km |
| SMOS | 2009-Present | Global land | 2-3 days | Sun-synch (6am asc / 6pm desc) | 25 km |
| Aquarius | 2011-2015 | Global land | 8 days | Sun-synch (6pm asc / 6 am desc) | 100 km |
| SMAP | 2015-Present | Global land | 2-3 days | Sun-synch (6am desc / 6pm asc) | 3 km/9 km/36 km |
| SAOCOM | 2022-? | Argentina Pampas | ? | ? | 1 km |
| NISAR | 2021/2022-? | US and India land | 12 days | ? | 1 km |

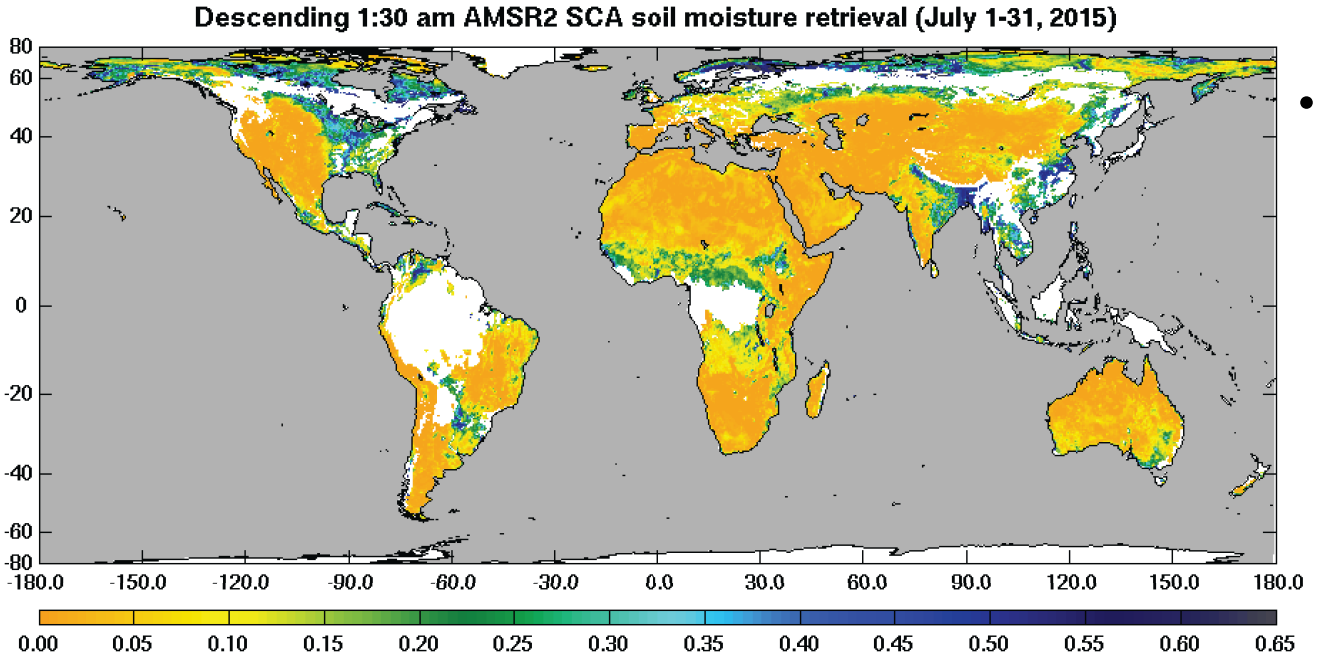


# AMSR Soil Moisture

- AMSR-E was the first satellite mission to develop a soil moisture product
- AMSR-E provided invaluable environmental data products (precipitation, cloud water, soil moisture, snow, sea ice) from 2002 to 2011
- AMSR2 was launched by JAXA in July 2012 and provides an opportunity to extend this data record
- AMSR2 products will be invaluable for a more complete understanding of the climate system
- AMSR-E and AMSR2 are both part of NASA's A-train satellites
- Goal Accuracy: 0.05 $m^3/m^3$ for regions with vegetation water contents (VWC) < 2 $kg/m^2$, 0.10 $m^3/m^3$ for VWC 2-5 $kg/m^2$.

# AMSR-E and AMSR2 SCA VSM

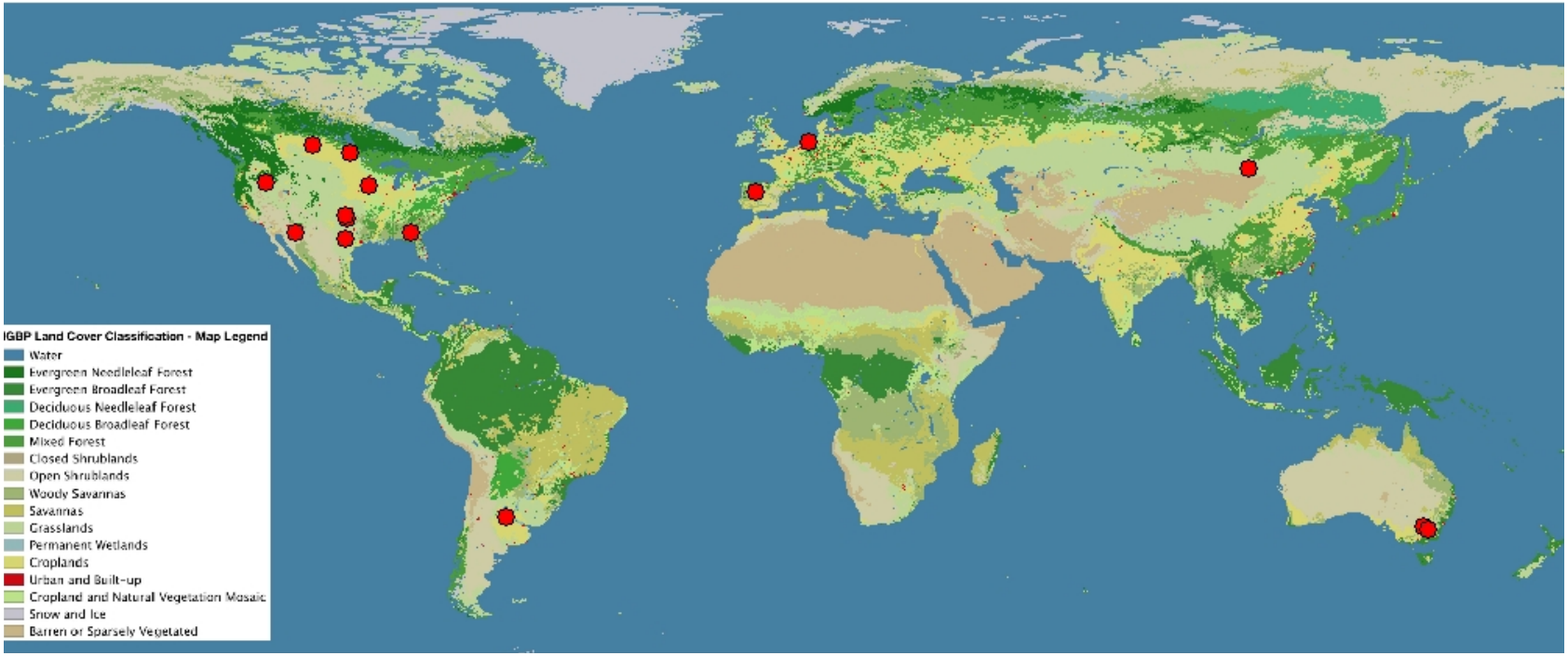



Comments

- Global soil moisture maps. Data represent long term averages for the month of July.
- Maps show similar spatial structure and consistency between the two SCA retrievals.
- Areas with dense vegetation masked out.

# AMSR2 Cal/Val Sites




- **USA (7)**
- Canada (2)
- Argentina (1)
- Spain (1)
- Netherlands (1)
- Mongolia (1)
- Australia (2)



# Summary Statistics for AMSR2 Soil Moisture

| | JAXA | | | | SCA | | | | LPRM | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ubRMSE ($m^3/m^3$) | Bias ($m^3/m^3$) | RMSE ($m^3/m^3$) | R | ubRMSE ($m^3/m^3$) | Bias ($m^3/m^3$) | RMSE ($m^3/m^3$) | R | ubRMSE ($m^3/m^3$) | Bias ($m^3/m^3$) | RMSE ($m^3/m^3$) | R |
| Avg. AMSR2 All | 0.059 | -0.089 | 0.111 | 0.502 | 0.055 | -0.047 | 0.080 | 0.569 | 0.088 | 0.100 | 0.137 | 0.601 |
| AMSR2 (VWC < 2 kg/m2) | 0.049 | -0.068 | 0.085 | 0.533 | 0.048 | -0.035 | 0.069 | 0.593 | 0.083 | 0.077 | 0.115 | 0.655 |

- Not much difference between A and D for a specific AMSR2 algorithm
- Each AMSR soil moisture product has different performance assessment (compared to in situ observations)
- SCA and JAXA meet the ubRMSE accuracy mission goal
- LPRM has high bias but good correlation



# The SMOS Mission

SMOS is the second Earth Explorer opportunity mission (1st round)

An ESA/CNES/CDTI project

Selected in 1999, initiated in 2000

Launched in November 2009

A **new technique** (2D interferometry) to provide **global measurements** from space of **key variables** (SSS and SM) for the **first time**.

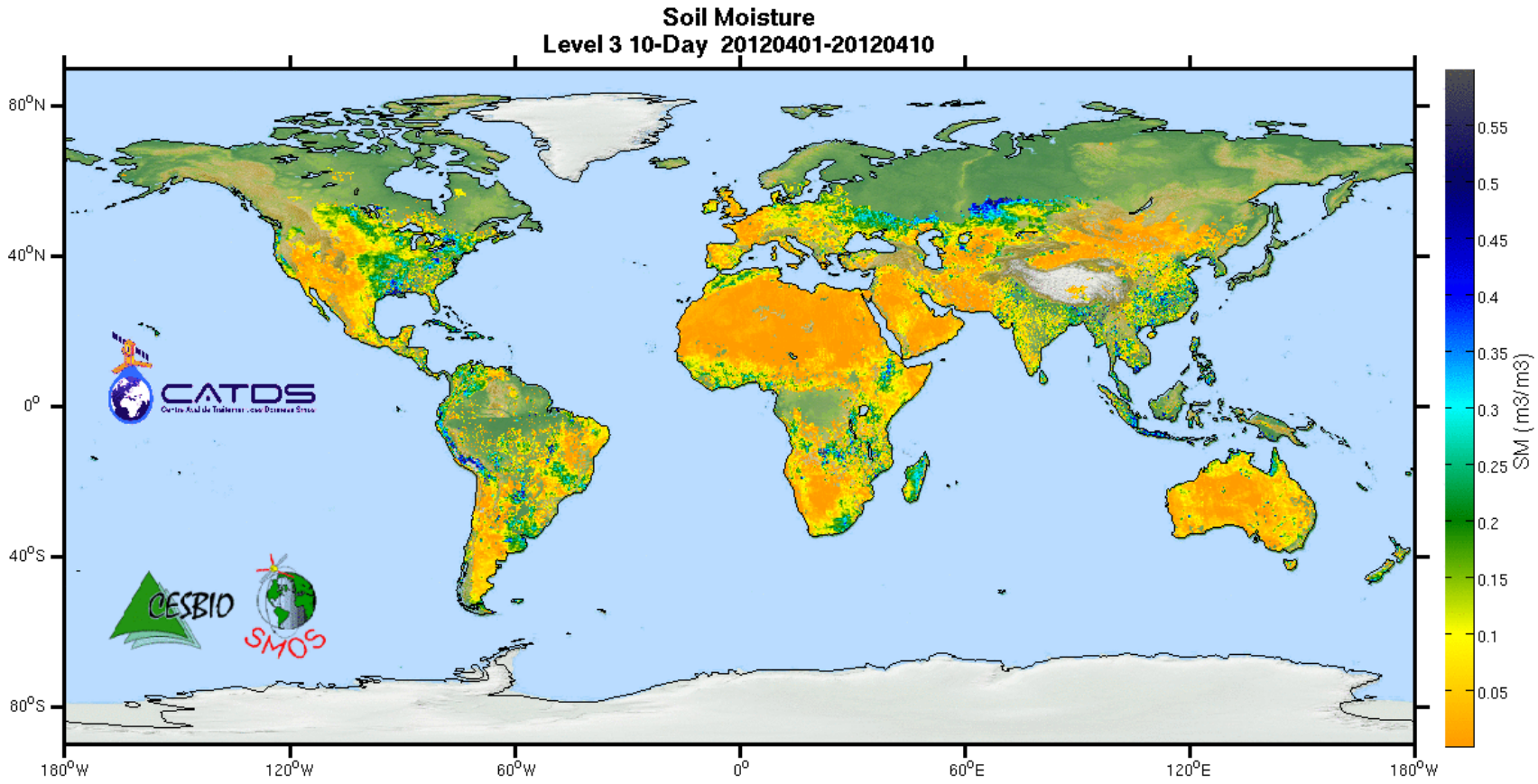
## SMOS : 2010-Present

- Need for soil moisture and sea surface salinity fields
- Only passive L band suitable
- Real aperture systems currently not adequate (antenna size) ==>Synthetic antenna



Yann et al.

# SMOS

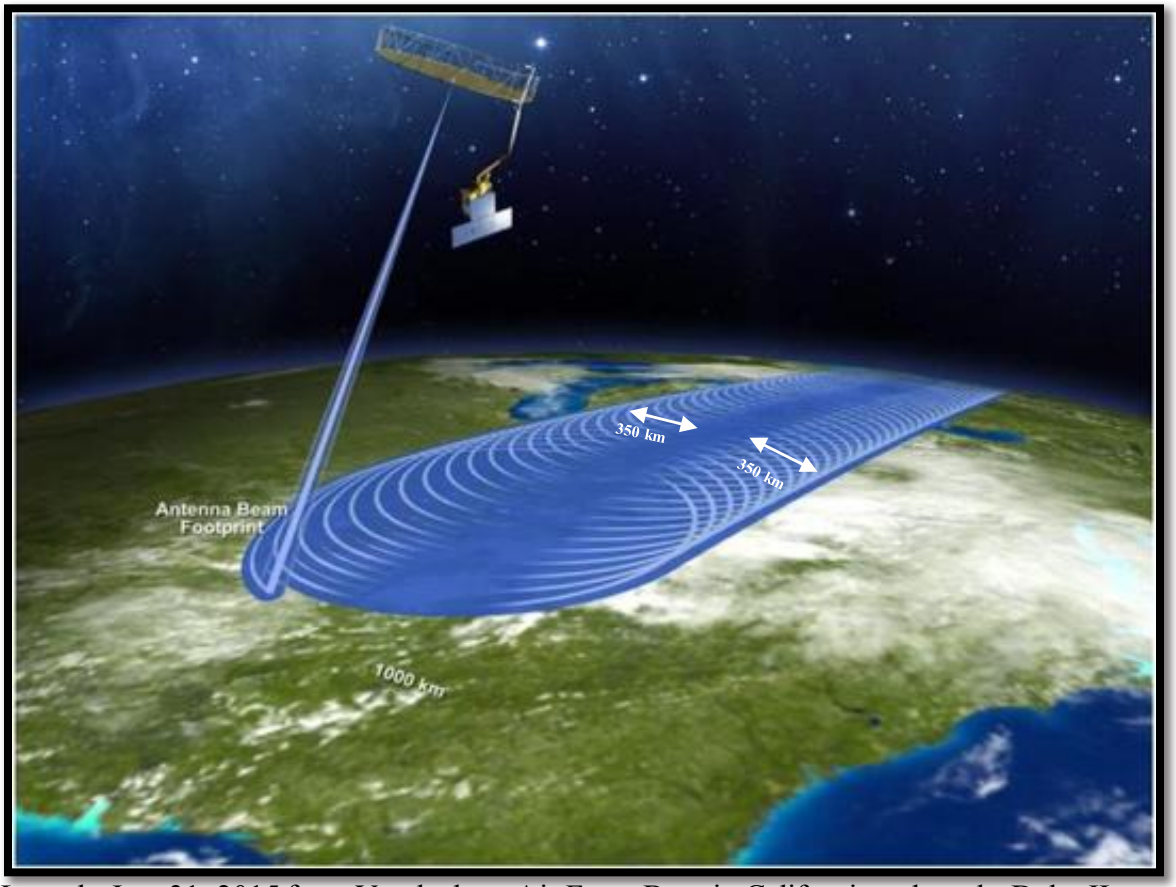



- SMOS was the first dedicated soil moisture L-band mission in space
- SMOS is performing great but is impacted by RFI



# SMAP Overview

SMAP objective is to provide high-resolution and frequent-revisit global mappings of soil moisture and landscape freeze/thaw state




Launch: Jan. 31, 2015 from Vandenberg Air Force Base in California onboard a Delta II.

- ***Radar*** - High spatial resolution (1-3 km) but more sensitive to surface roughness and vegetation
- ***Radiometer*** - High accuracy (less influenced by roughness and vegetation) but coarser spatial resolution (40 km)
- **Combined Radar-Radiometer** product provides optimal blend of resolution and accuracy to meet science requirements

- Uniqueness: Continuous observations every 2-3 days

## SMAP Instrument Configuration

**Radar**
Frequency: 1.26 GHz
Polarizations: VV, HH, HV
Resolution: 3 km
Relative Accuracy: 1.0 dB (HH and VV), 1.5 dB (HV)

**Radiometer**
Frequency: 1.41 GHz
Polarizations: H, V, 3rd & 4th Stokes
Resolution: 40 km
Relative Accuracy: 1.3 K

**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 orbit, **685 km** altitude

**Mission Operations**
3-year baseline mission

# SMAP Level 1 Science Requirements



| Requirement | Soil Moisture | Freeze/ Thaw |
|---|---|---|
| Resolution | **9 and 36 km** | 3 km |
| Refresh Rate | 3 days | 2 days(1) |
| Accuracy | **0.04** [$cm^3/cm^3$] (2) | 80% (3) |
| Duration | 36 months | |

(1) North of 45° N Latitude
(2) % volumetric water content, 1-sigma
(3) % classification accuracy (binary: Freeze or Thaw)

| Product Short Name | Description | Data Resolution |
|---|---|---|
| **L3_FT_HiRes** | Daily Global Composite Freeze/Thaw State | 1-3 km |
| **L3_SM_P** | Daily Global Composite Radiometer Soil Moisture | 36 km |
| **L3_SM_AP** | **Daily Global Composite Active-Passive Soil Moisture** | **9 km** |
| **L4_SM** | Surface & Root Zone Soil Moisture | 9 km |
| **L4_C** | Carbon Net Ecosystem Exchange | 9 km |



# SMAP Data Product Status

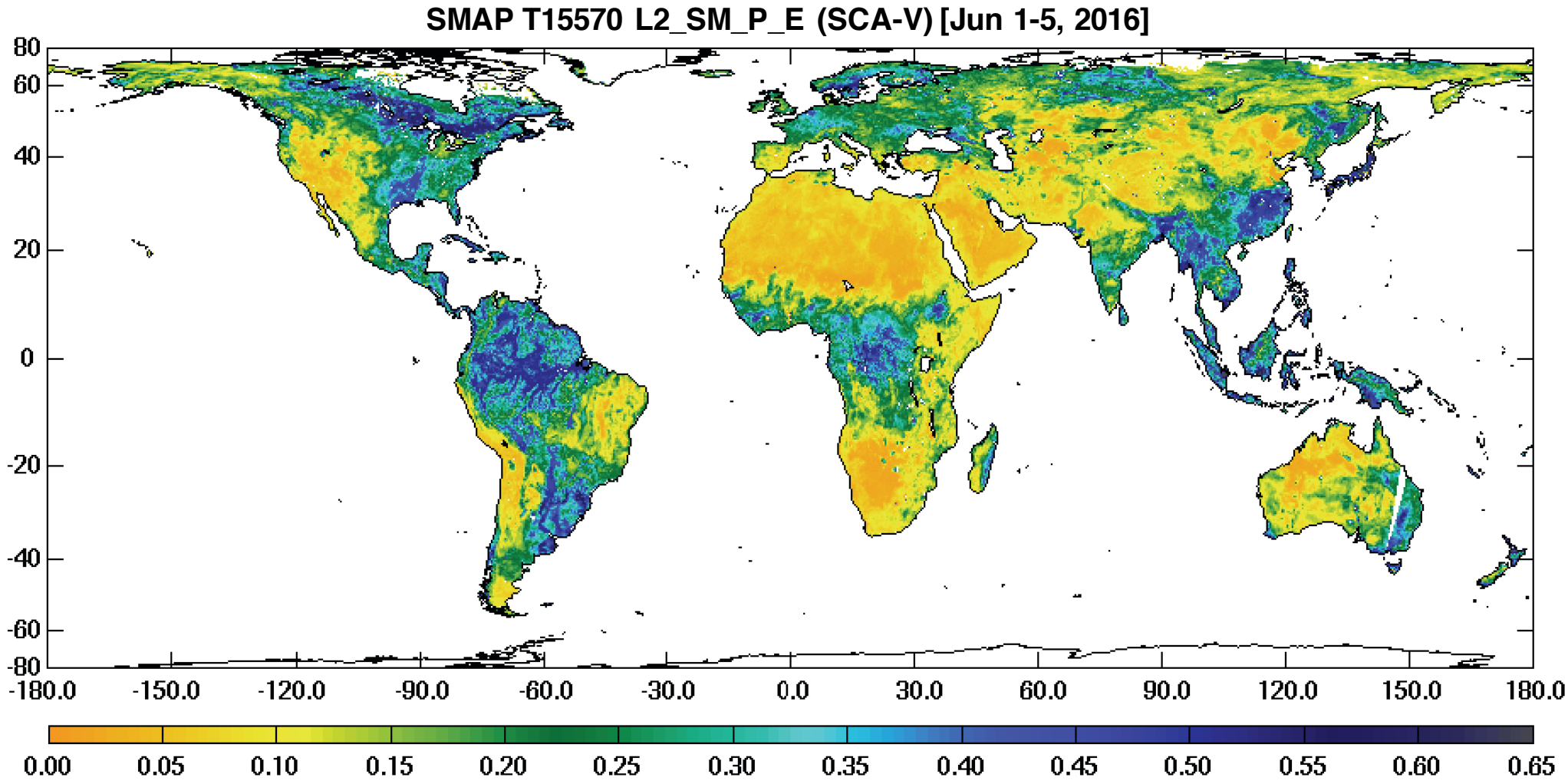
Products in **boldface** are in routine operational production

| Product | Description | Gridding (Resolution) | Latency | Data Type |
|---|---|---|---|---|
| **L1A_Radiometer** | **Radiometer Data in Time Order** | **-** | **12 hrs** | Instrument Data |
| L1A_Radar | Radar Data in Time Order | - | 12 hrs | |
| **L1B_TB** | **Radiometer $T_B$ in Time Order** | **(36 x 47 km)** | **12 hrs** | |
| L1B_S0_LoRes | Low Resolution Radar $\sigma_o$ in Time Order | (5 x 30 km) | 12 hrs | |
| L1C_S0_HiRes | High Resolution Radar $\sigma_o$ on EASE Grid 2.0 | 1 km (1 – 3 km) | 12 hrs | |
| **L1C_TB** | **Radiometer $T_B$ on EASE Grid 2.0** | **36 km** | **12 hrs** | |
| **L1C_TB_E (★)** | **Radiometer $T_B$ on EASE Grid 2.0 (Enhanced)** | **9 km** | **12 hrs** | |
| L2_SM_A | Soil Moisture (Radar) | 3 km | 24 hrs | Science Data (Half-Orbit) |
| **L2_SM_P** | **Soil Moisture (Radiometer)** | **36 km** | **24 hrs** | |
| **L2_SM_P_E (★)** | **Soil Moisture (Radiometer, Enhanced)** | **9 km** | **24 hrs** | |
| L2_SM_AP | Soil Moisture (Radar + Radiometer) | 9 km | 24 hrs | |
| **L2_SM_SP (★)** | **Soil Moisture (Sentinel Radar + Radiometer)** | **3 km** | **Best effort** | |
| L3_FT_A | Freeze/Thaw State (Radar) | 3 km | 50 hrs | Science Data (Daily Composite) |
| **L3_FT_P** | **Freeze/Thaw State (Radiometer)** | **36 km** | **50 hrs** | |
| **L3_FT_P_E (★)** | **Freeze/Thaw State (Radiometer, Enhanced)** | **9 km** | **50 hrs** | |
| L3_SM_A | Soil Moisture (Radar) | 3 km | 50 hrs | |
| **L3_SM_P** | **Soil Moisture (Radiometer)** | **36 km** | **50 hrs** | |
| **L3_SM_P_E (★)** | **Soil Moisture (Radiometer, Enhanced)** | **9 km** | **50 hrs** | |
| L3_SM_AP | Soil Moisture (Radar + Radiometer) | 9 km | 50 hrs | |
| **L4_SM** | **Soil Moisture (Surface and Root Zone)** | **9 km** | **7 days** | Science Value-Added |
| **L4_C** | **Carbon Net Ecosystem Exchange (NEE)** | **9 km** | **14 days** | |

★ New SMAP products post-radar failure



# SMAP Radiometer Soil Moisture

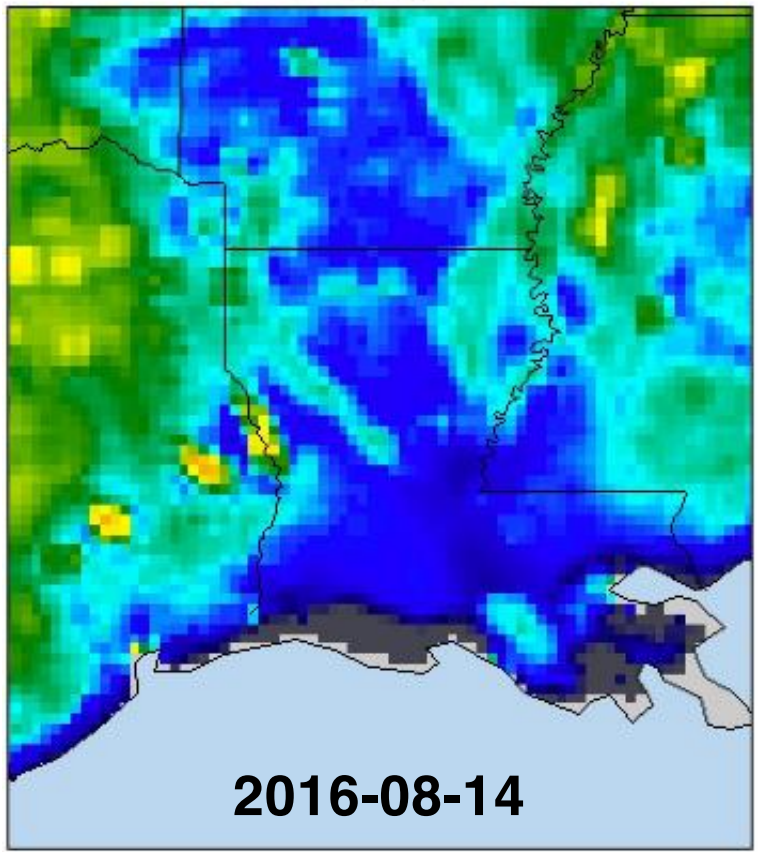



The regions that are expected to be very dry (i.e., the Sahara desert) and wet (i.e., the Amazon Basin) reflect the expected levels of retrieved soil moisture.

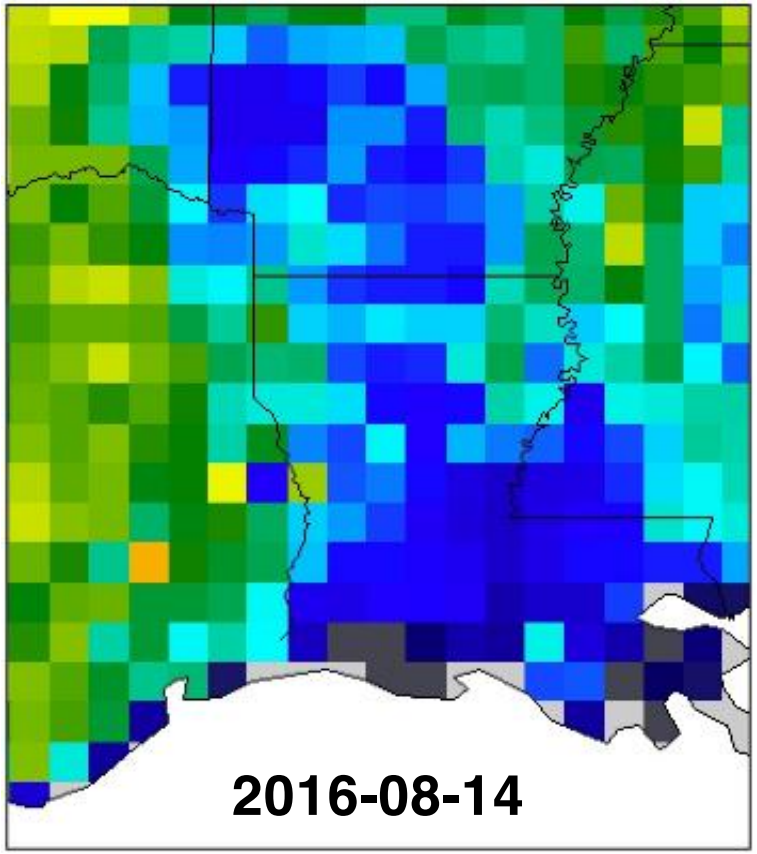
# Enhanced Passive Soil Moisture Product

soil moisture mapping during the 2016 Louisiana flood

**Enhanced SMAP**
**Passive Soil Moisture Product**
**(9 km grid resolution)**




**Standard SMAP**
**Passive Soil Moisture Product**
**(36 km grid resolution)**

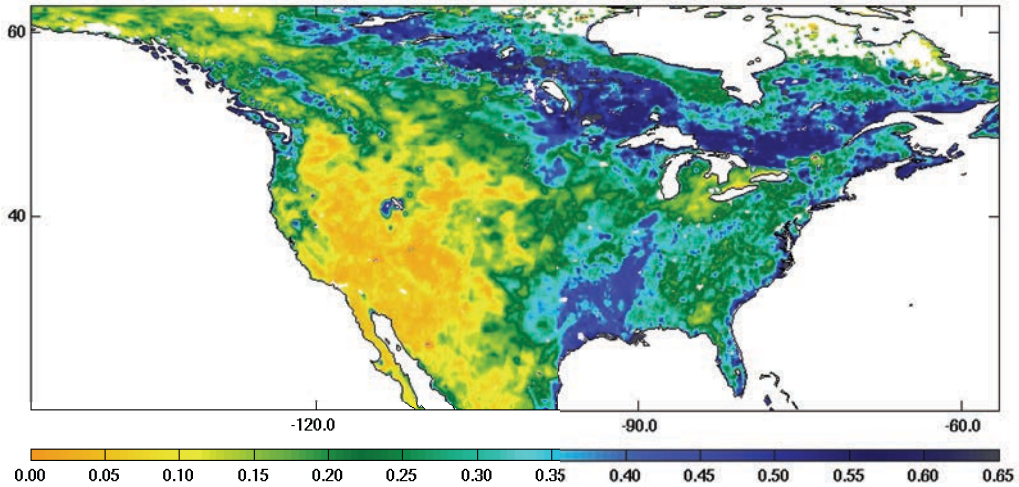




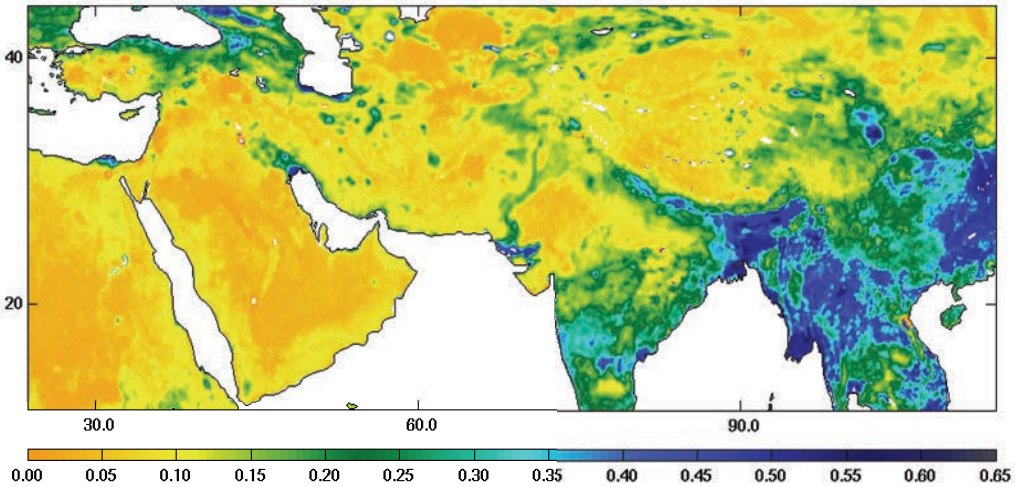



# SMAP Radiometer Soil Moisture

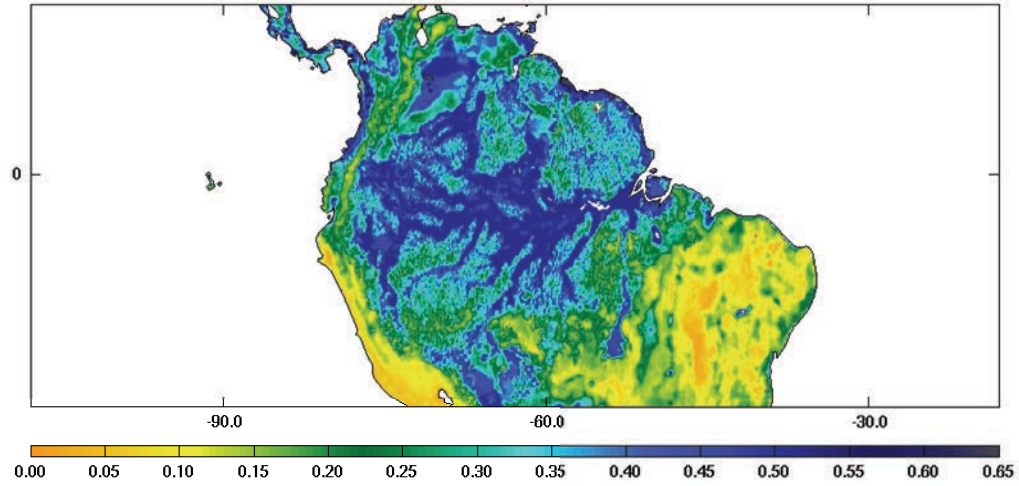
SMAP T15570 L2_SM_P_E (SCA-V) [Jun 1-5, 2016]



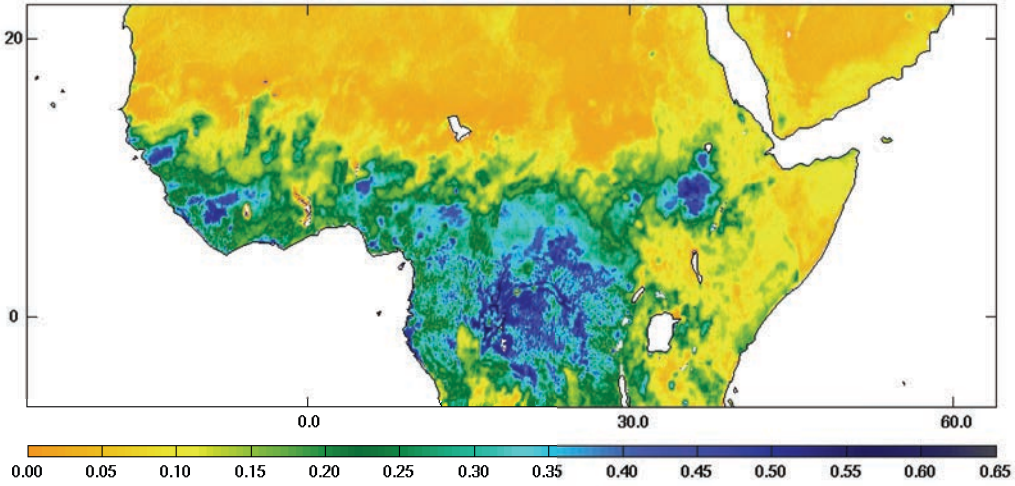

SMAP T15570 L2_SM_P_E (SCA-V) [Jun 1-5, 2016]




SMAP T15570 L2_SM_P_E (SCA-V) [Jun 1-5, 2016]




SMAP T15570 L2_SM_P_E (SCA-V) [Jun 1-5, 2016]

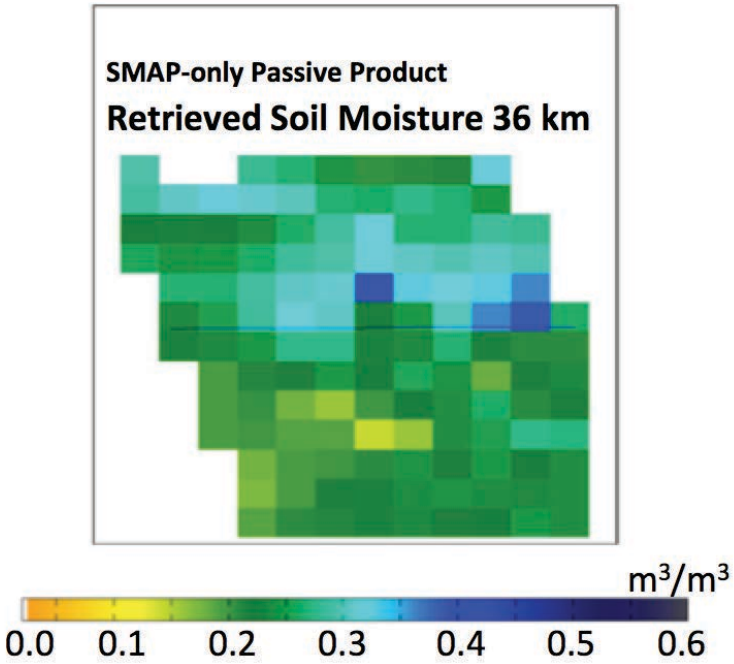


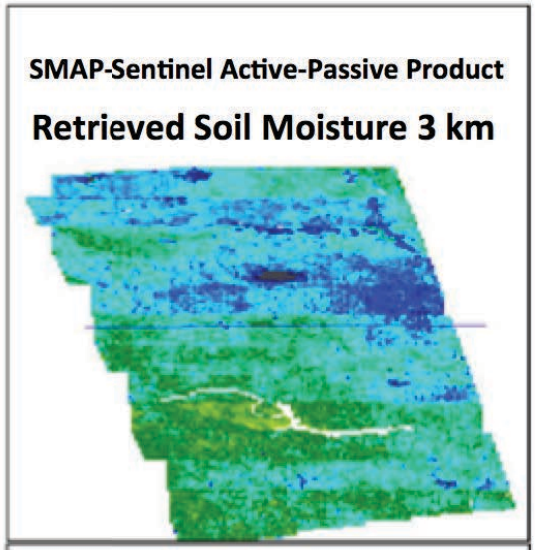


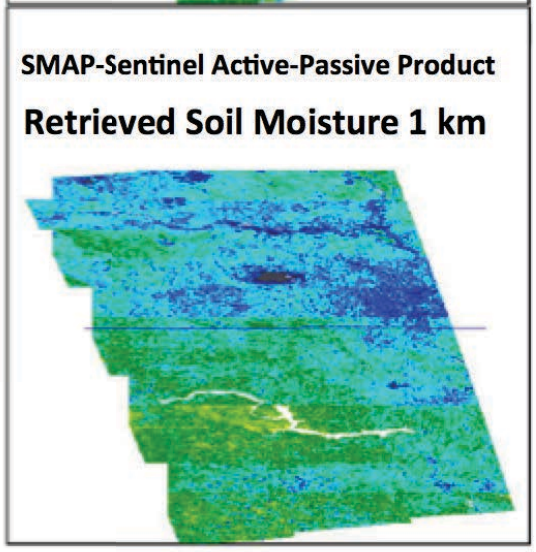
# SMAP-Sentinel Active-Passive Product

## SMAP Active-Passive Algorithm

$$T_{B_p}(M) = T_{B_p}(C) + \beta(C) \cdot \{ [\sigma_{pp}(M) - \sigma_{pp}(C)] - \Gamma(C) \cdot [\sigma_{pq}(M) - \sigma_{pq}(C)] \}$$



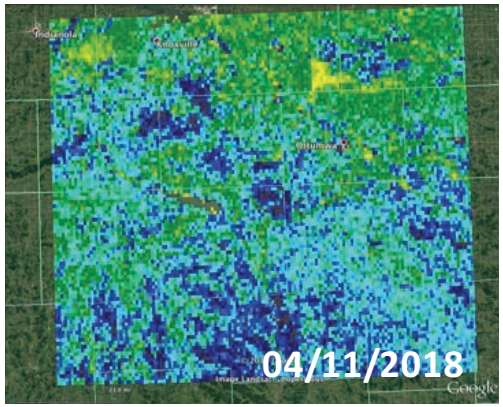

**Soil Moisture at Different Resolutions**
**Retrieved for May 17th, 2015**
**Over Manitoba region Canada**

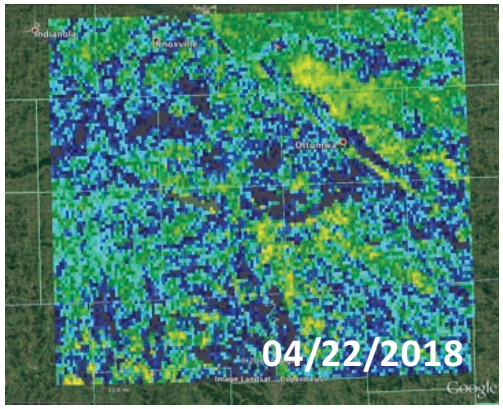
Das et al.

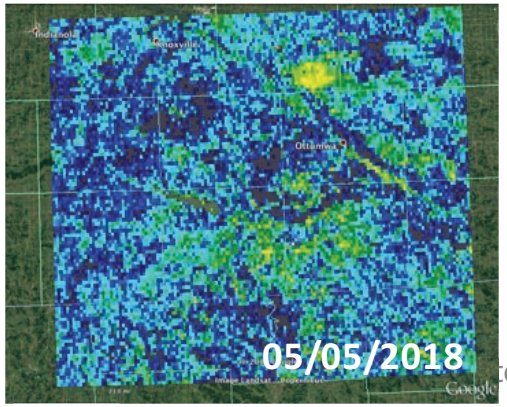


# High Resolution
# SMAP-Sentinel Soil Moisture Product

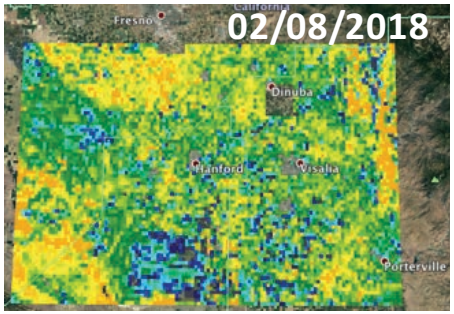
Southeast Iowa

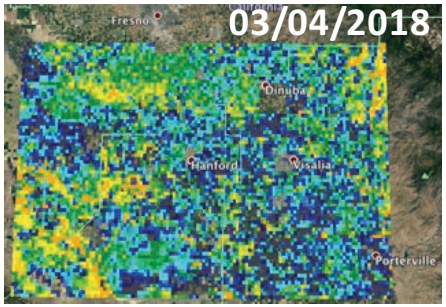


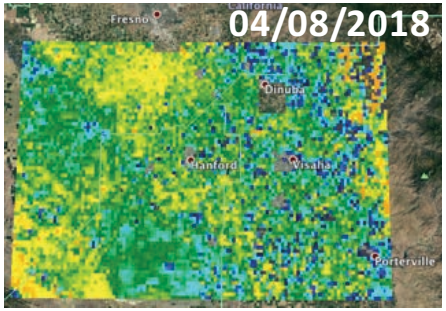



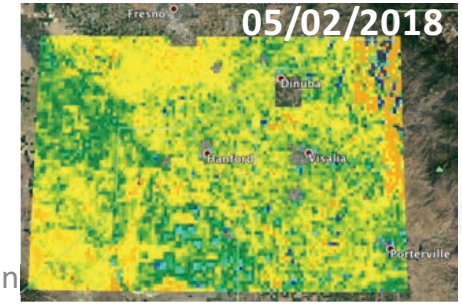




San Joaquin Valley, California




The time series over two different regions clearly demonstrate how the L2_SM_SP product captures the evolution (wetting and drying) of soil moisture at fine resolution.




ternal use on

Das et al.



# SMAP Level-4 Soil Moisture Product

Surface and root-zone soil moisture

National Aeronautics and Space Administration

## Algorithm Overview

Precipitation observations

NWP surface meteorology

**SMAP observations**
**36-km brightness temperatures**

*Multi-layer soil water and energy balance modeling*

***Land Model***
***9-km***

***Data assimilation***

***Ensemble Kalman Filter (EnKF):***

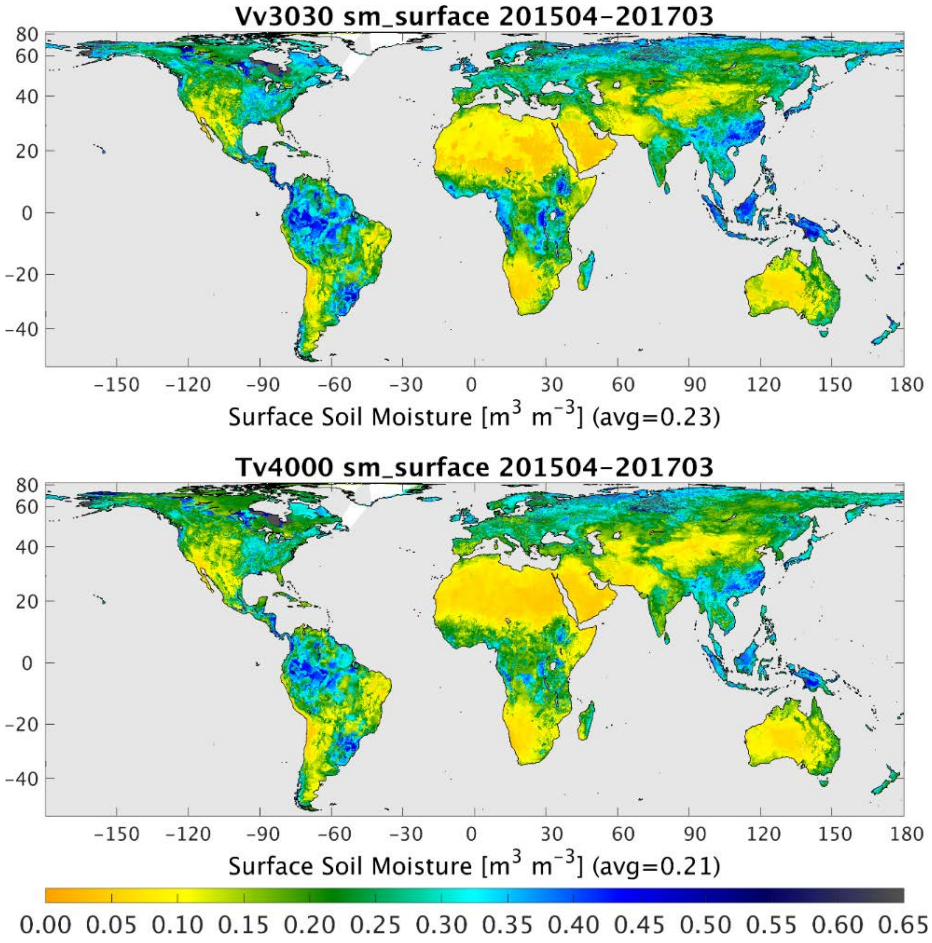
*Optimal update of land model's soil moisture states using error covariance statistics sampled from a 24-member ensemble.*

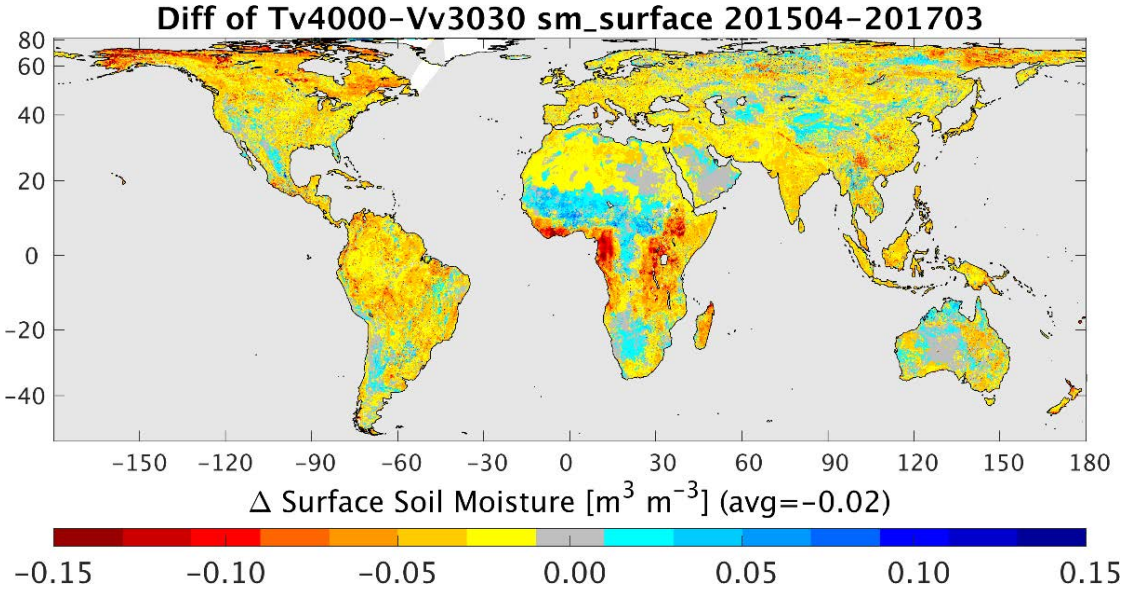
**L4_SM Product:**
**9-km, 3-hourly, global, 2.5-day latency**



Reichle et al.

# SMAP L4 – Surface Soil Moisture

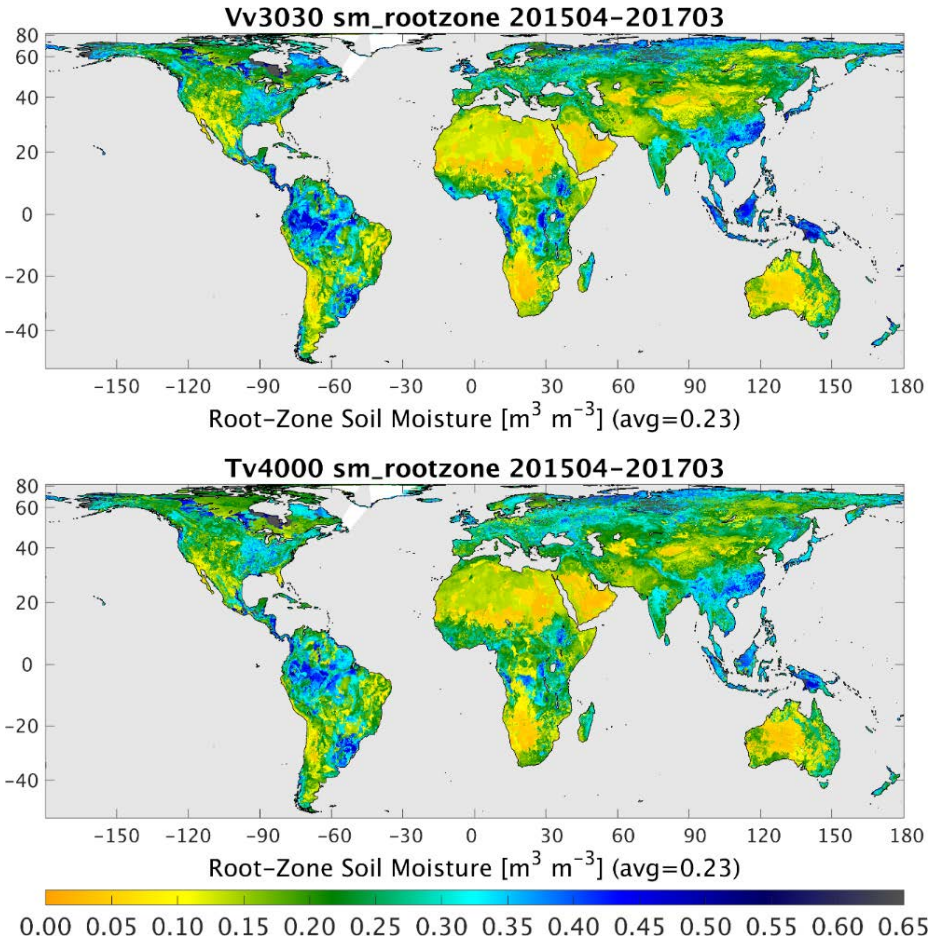


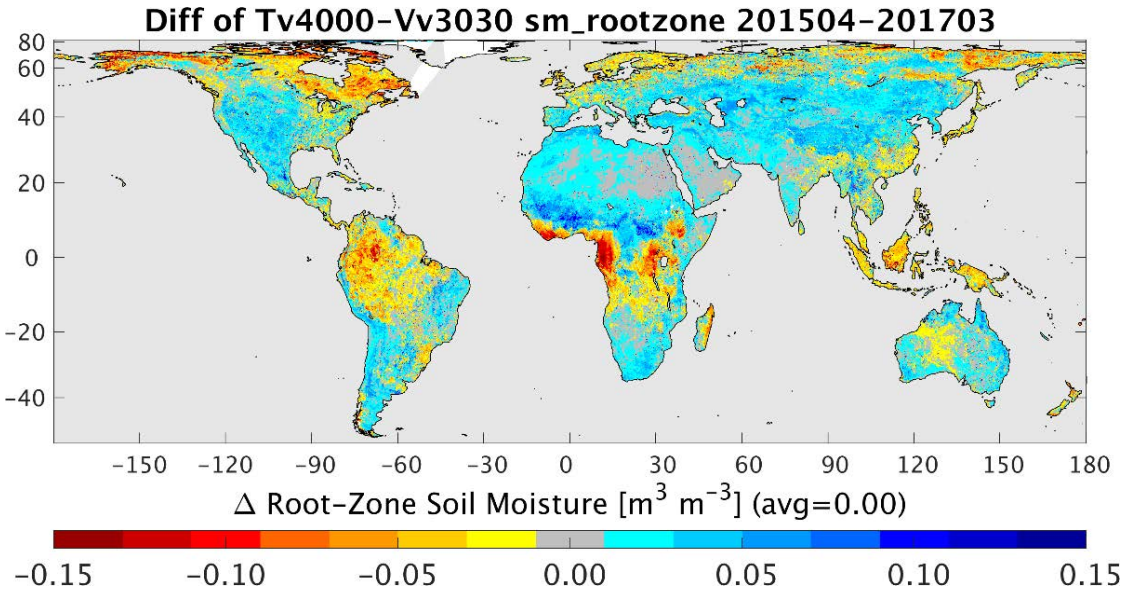




- Tv4000 surface slightly drier in most regions.
- Less impact of soil texture patterns in very dry regions.
- Changes in Africa and at very high latitudes owing to rescaling of GEOS-5 precip to GPCPv2.2 climatology.

Reichle et al.

# SMAP L4 – Root-Zone Soil Moisture



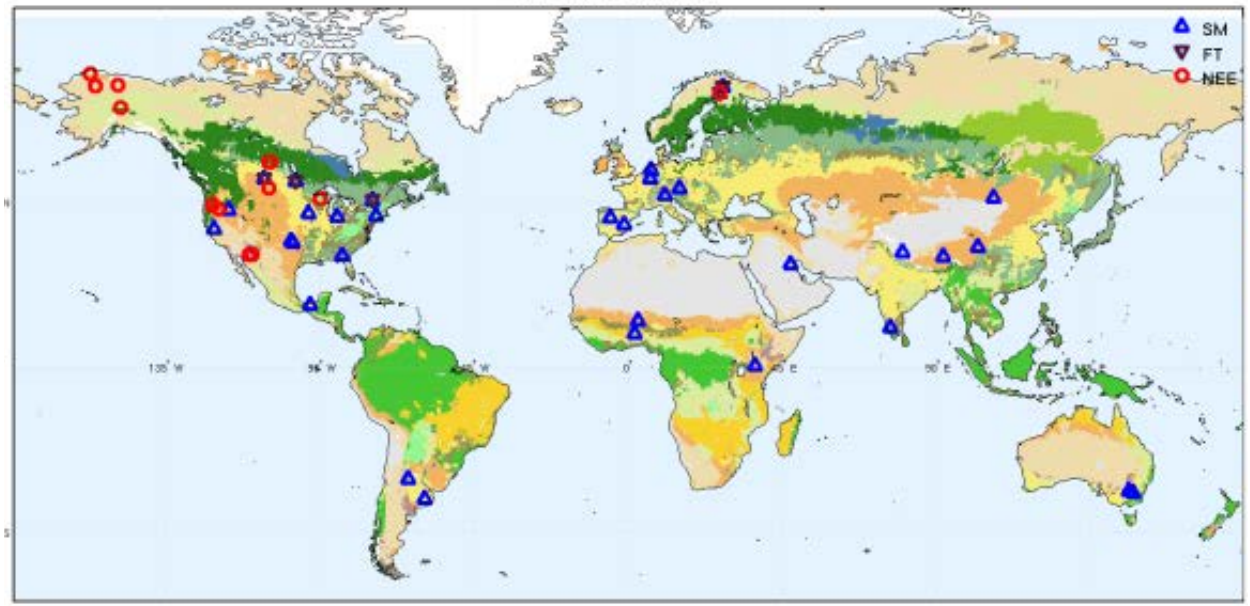



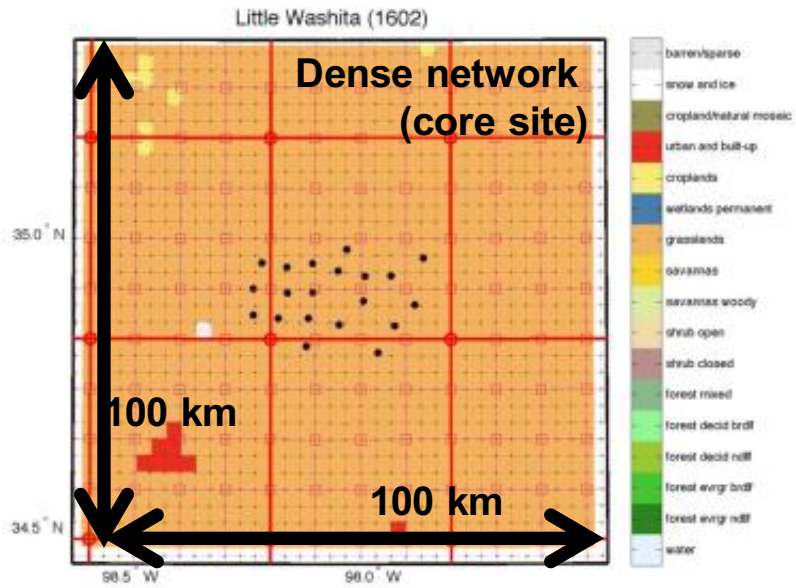

- Tv4000 root-zone slightly wetter in most regions.
- Changes in Africa and at very high latitudes owing to rescaling of GEOS-5 precip to GPCPv2.2 climatology.

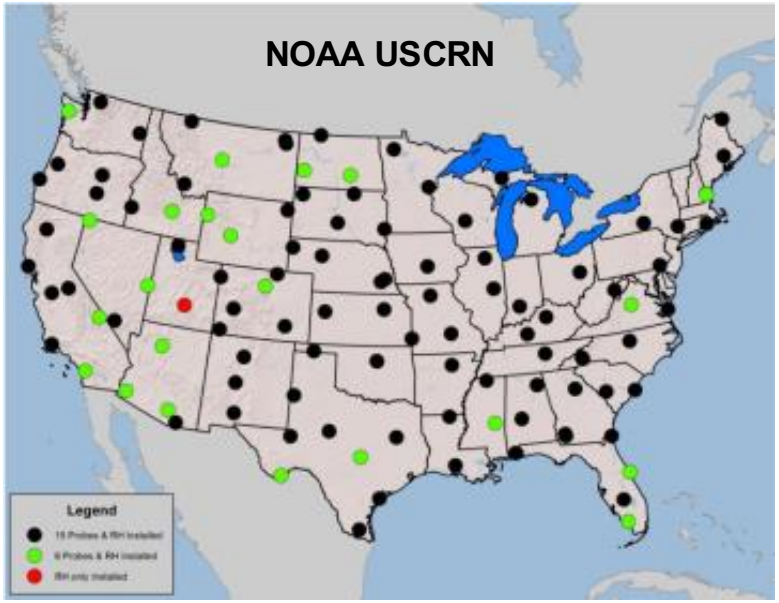
Reichle et al.

# SMAP Soil Moisture Cal/Val Approach

- Primary calibration and validation approach is utilization of dense in situ soil moisture measurements (multiple soil moisture measurement within the 3-km to 36-km SMAP footprint)




- Supplemental approach will utilize large-scale sparse networks (one measurement within footprint), and global remote sensing and model-based soil moisture data products



# SMAP Radiometer soil moisture CVS Assessment

| CVS | ubRMSE ($m^3/m^3$) | | | Bias ($m^3/m^3$) | | | RMSE ($m^3/m^3$) | | | R | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SCA-H | SCA-V | DCA | SCA-H | SCA-V | DCA | SCA-H | SCA-V | DCA | SCA-H | SCA-V | DCA |
| AM SMAP L2SMP_E Average V2 (2018) | 0.046 | **0.038** | 0.049 | -0.029 | **-0.001** | 0.039 | 0.062 | **0.047** | 0.072 | 0.780 | **0.814** | 0.728 |
| AM SMOS Average V2 (2018) | 0.053 | | | -0.022 | | | 0.067 | | | 0.665 | | |
| PM SMAP L2SMP_E Average V2 (2018) | 0.045 | **0.036** | 0.047 | -0.024 | **-0.002** | 0.031 | 0.061 | **0.045** | 0.066 | 0.780 | **0.818** | 0.712 |
| PM SMOS Average V2 (2018) | 0.055 | | | -0.026 | | | 0.068 | | | 0.677 | | |

- SMAP radiometer-only soil moisture products meet the level 1 accuracy requirement
- SMAP soil moisture estimates outperform other satellite soil moisture products
- AM and PM retrieval assessment is consistent



# SMAP Radiometer Soil Moisture

## Sparse Network Assessment

| IGBP Class | ubRMSD (m3/m3) | | Bias (m3/m3) | | RMSD (m3/m3) | | R | | N |
|---|---|---|---|---|---|---|---|---|---|
| | SCA-V | SMOS | SCA-V | SMOS | SCA-V | SMOS | SCA-V | SMOS | |
| AM SMAP L2SMP_E Average V2 (2018) | **0.045** | 0.068 | **0.003** | −0.043 | **0.065** | 0.099 | **0.668** | 0.511 | 399 |
| PM SMAP L2SMP_E Average V2 (2018) | **0.046** | 0.067 | **0.008** | −0.039 | **0.067** | 0.097 | **0.635** | 0.497 | 399 |
| Average is based upon all sets of observations, not the average of the land cover category results. | | | | | | | | | |

- Sparse results are similar to CVS results and verify the assessments

Fan et al.



# Summary Statistics for AMSR2 Soil Moisture

| | JAXA | | | | SCA | | | | LPRM | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ubRMSE ($m^3/m^3$) | Bias ($m^3/m^3$) | RMSE ($m^3/m^3$) | R | ubRMSE ($m^3/m^3$) | Bias ($m^3/m^3$) | RMSE ($m^3/m^3$) | R | ubRMSE ($m^3/m^3$) | Bias ($m^3/m^3$) | RMSE ($m^3/m^3$) | R |
| Avg. AMSR2 All | 0.059 | -0.089 | 0.111 | 0.502 | 0.055 | -0.047 | 0.080 | 0.569 | 0.088 | 0.100 | 0.137 | 0.601 |
| AMSR2 (VWC < 2 kg/m2) | 0.049 | -0.068 | 0.085 | 0.533 | 0.048 | -0.035 | 0.069 | 0.593 | 0.083 | 0.077 | 0.115 | 0.655 |
| SMAP | - | - | - | - | 0.038 | -0.001 | 0.047 | 0.820 | - | - | - | - |

- Not much difference between A and D for a specific AMSR2 algorithm
- Each AMSR soil moisture product has different performance assessment (compared to in situ observations)
- SCA and JAXA meet the ubRMSE accuracy mission goal
- LPRM has high bias but good correlation
- The one metric to note is the much improved correlation.
- Expected improvement due to lower observation frequency

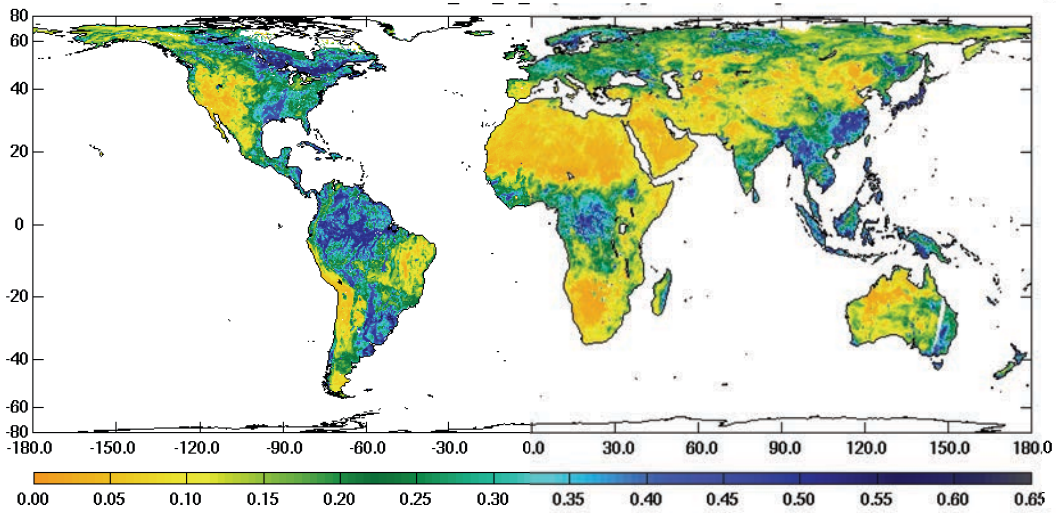


# Satellite Soil Moisture Products

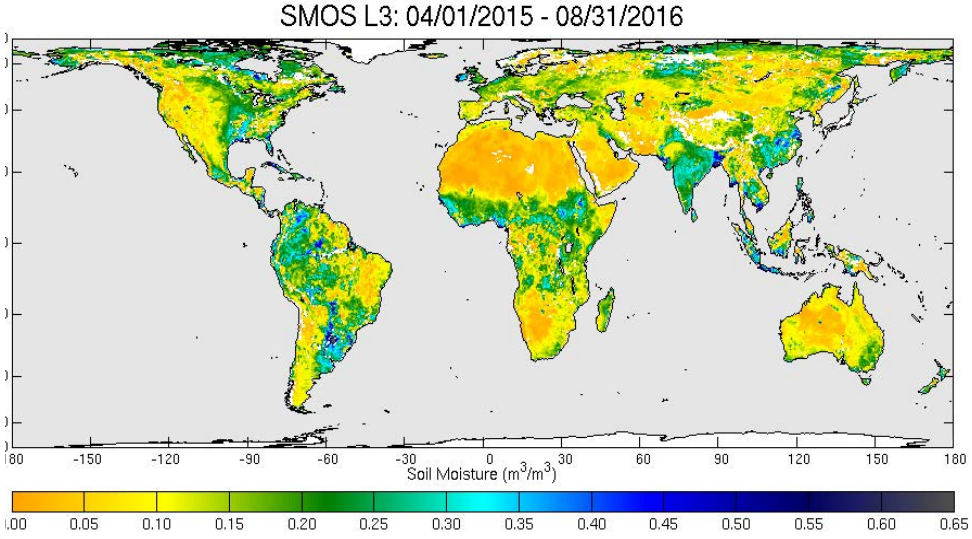
- SMAP, SMOS, AMSR2 and ASCAT are microwave satellites with soil moisture products
- Use different technologies
  - SMOS – L-band synthetic aperture radiometer
  - SMAP – L-band conically scanning radiometer
  - AMSR2 – C,X band conically scanning radiometer
  - EUMETSAT ASCAT – C-band scatterometer
- SMAP, SMOS, ASCAT and AMSR2 use different soil moisture retrieval algorithms
- The satellite missions use different ancillary datasets
- Irrespective of these differences – All missions provide a surface soil moisture product

# Global L2SMP inter-comparison (SMAP, SMOS, AMSR2, ASCAT)

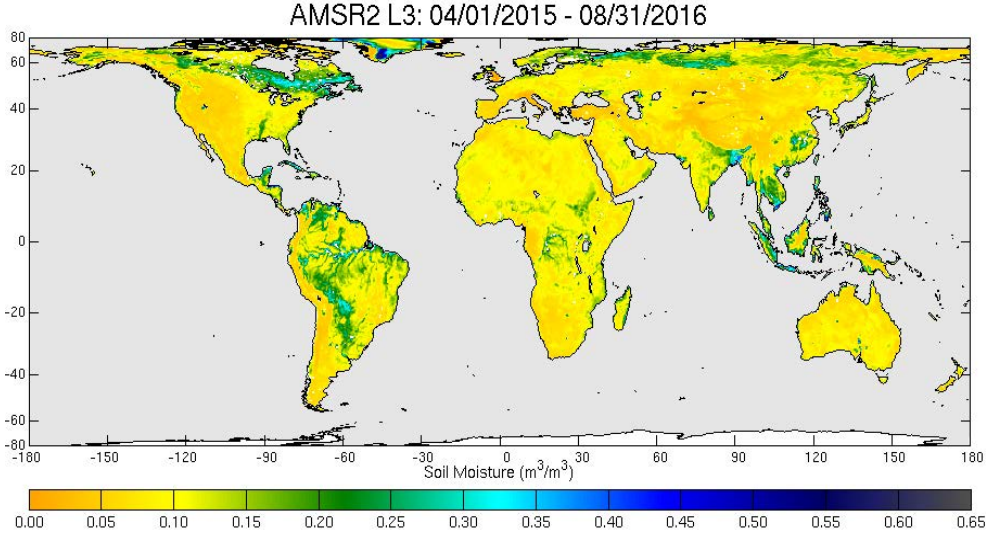
## SMAP



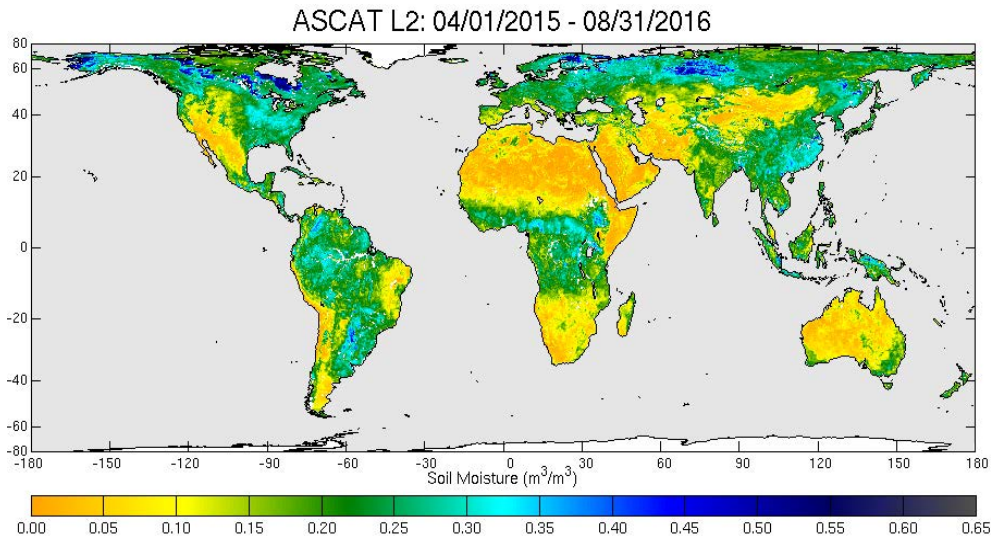

## SMOS



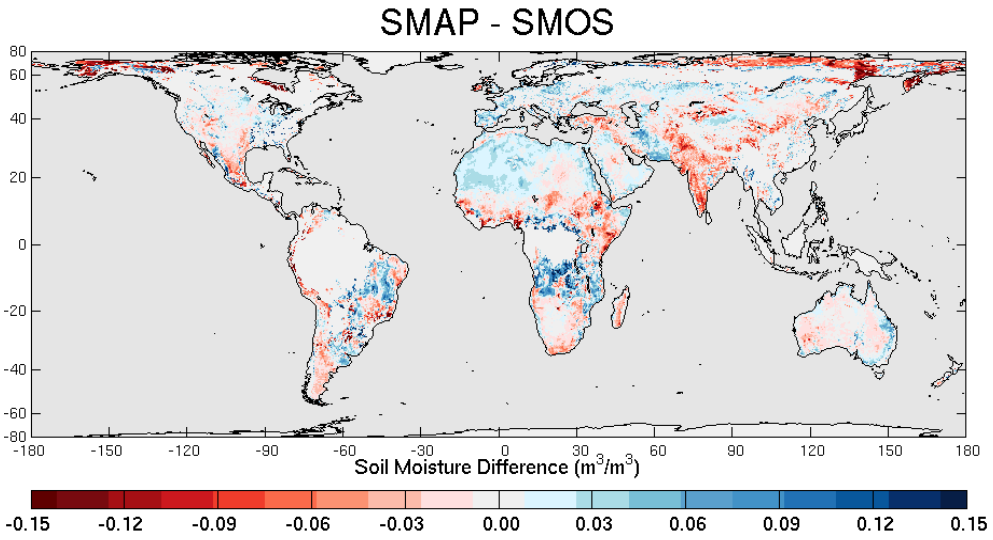

## AMSR2

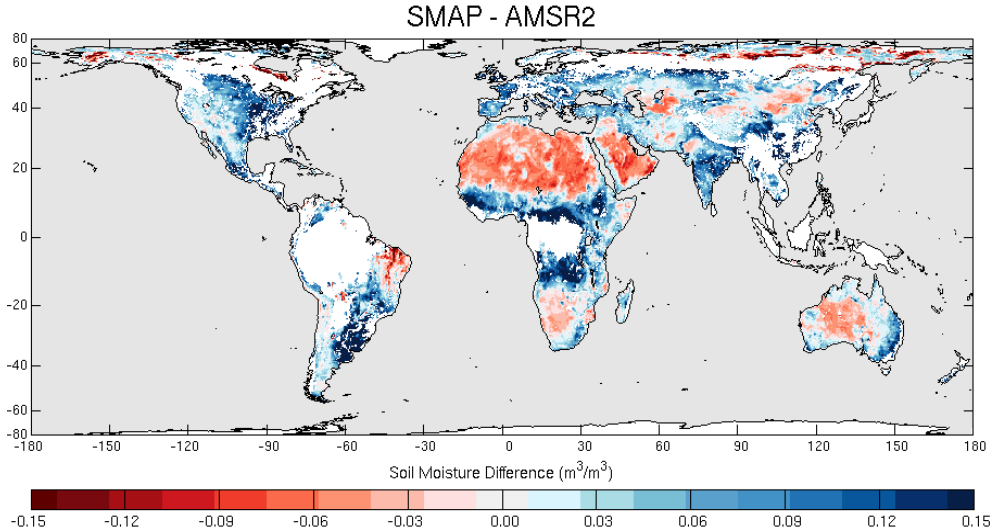


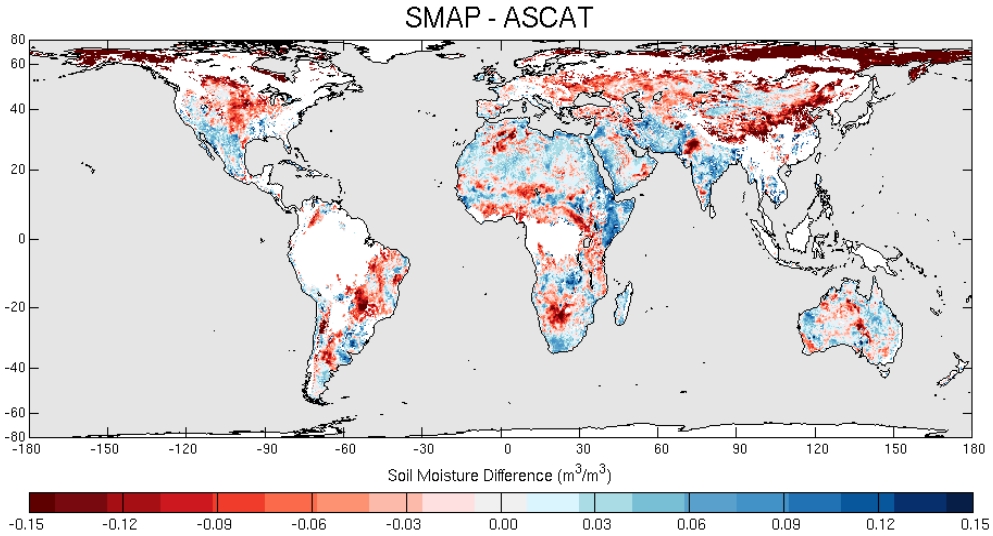

## ASCAT



# Global L2SMP inter-comparison
## (Bias wrt SMAP)

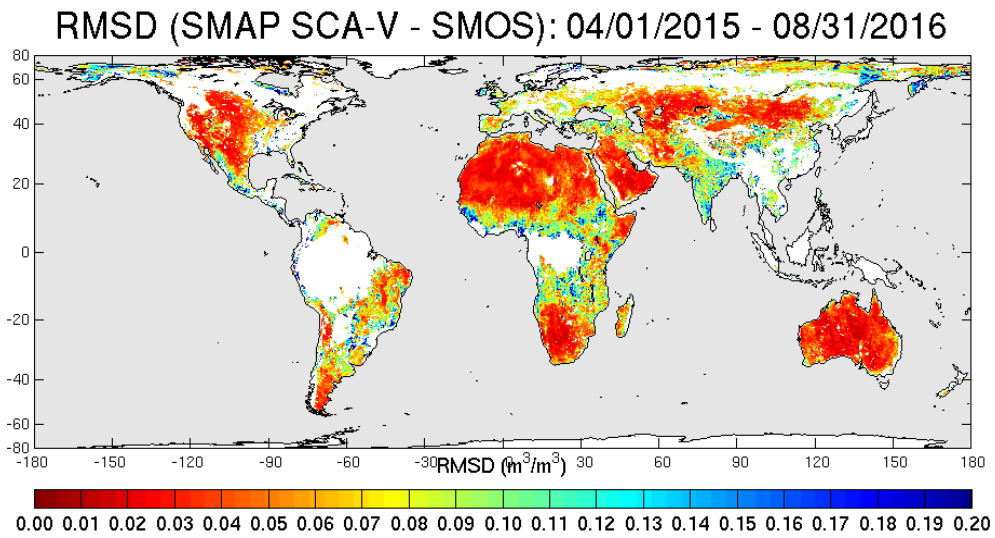


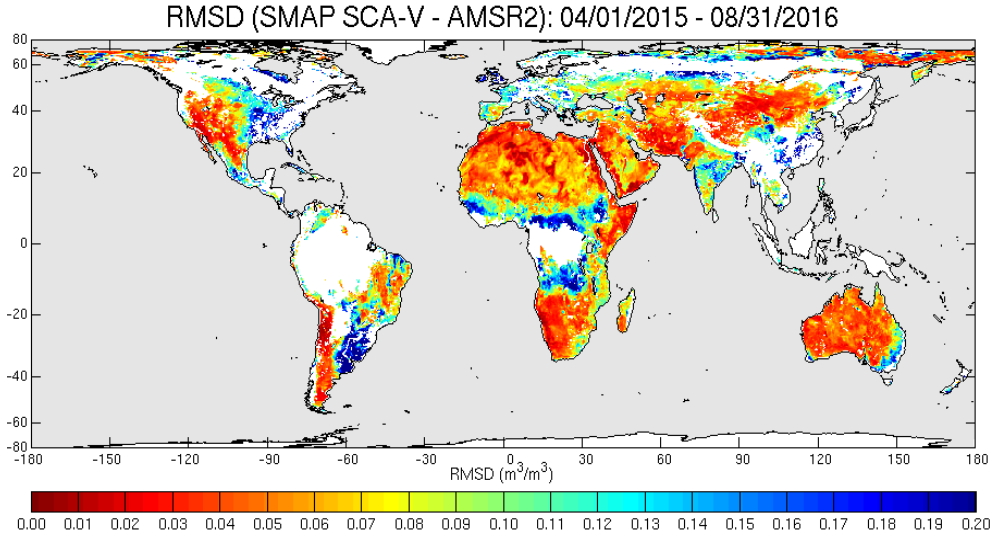



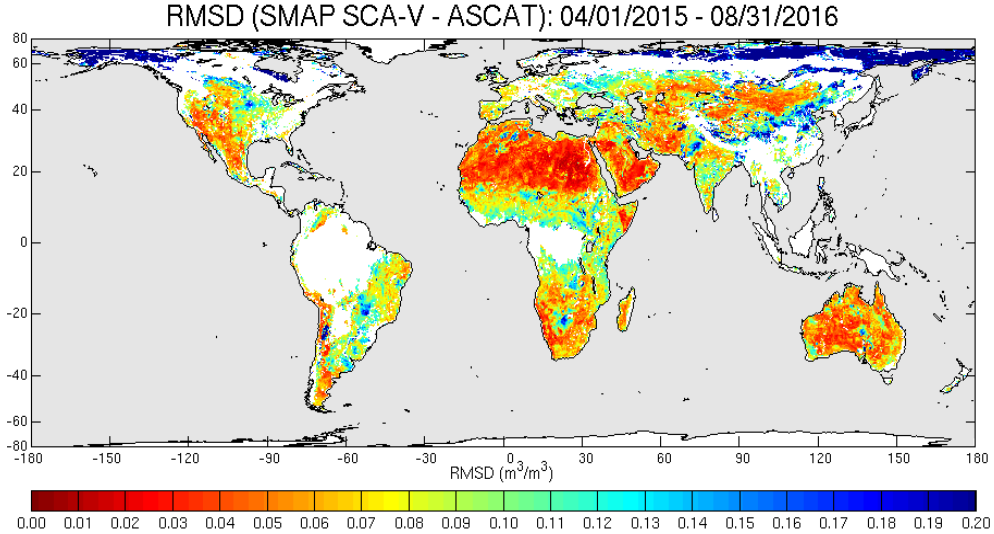




- SMAP and SMOS have low bias over most of the globe
- SMAP and AMSR2 have greater biases (SMAP-drier over arid areas, wetter over other biomes)
- SMAP and ASCAT have higher bias (ASCAT is wetter than SMAP over most domains)

# Global L2SMP inter-comparison
## (RMSD wrt SMAP)

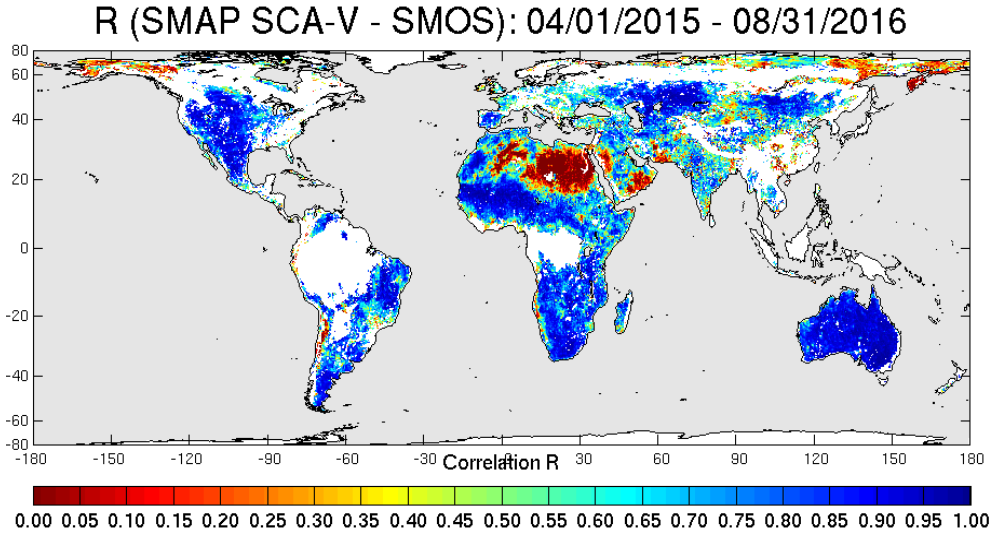


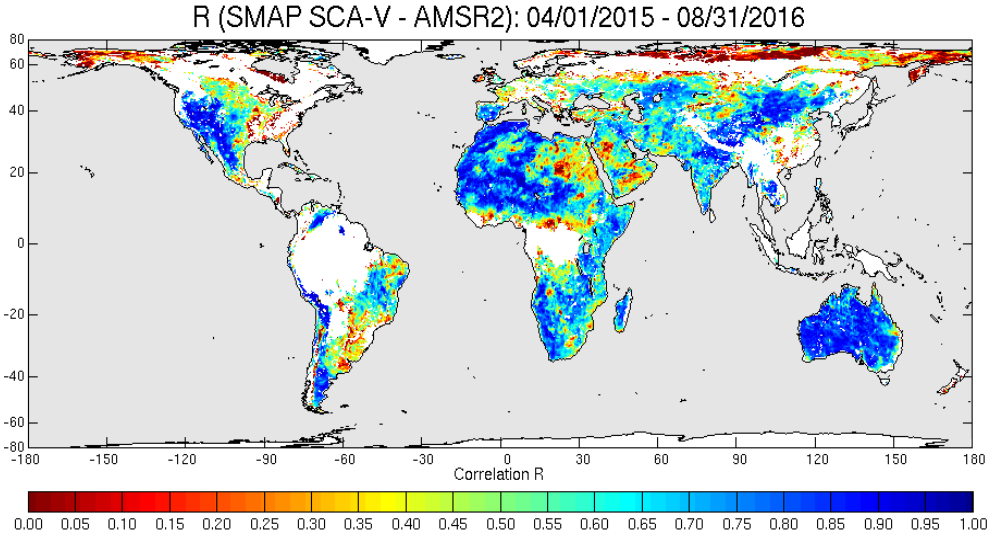



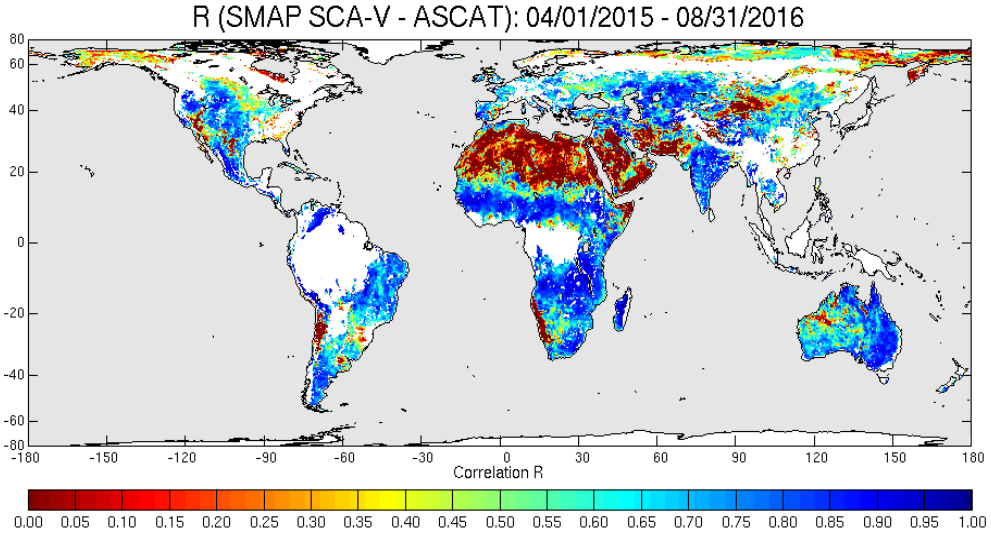




- SMAP and SMOS have low RMSD (greater differences over Sahel, India)
- SMAP and AMSR2 have greater differences over most biomes

# Global L2SMP inter-comparison
## (R wrt SMAP)




- SMAP has high correlation with other satellite soil moisture products
- Lower correlation over arid/desert areas (low dynamic range)
- Highest correlation observed with SMOS



# Conclusion

- AMSR2 is healthy and providing good soil moisture estimates over areas with low vegetation.
- Plans for AMSR3 are currently being developed.
- SMOS is healthy is performing well. New SMOS product will be released later this year. SMOS is impacted by RFI.
- SMAP radiometer is in good health. SMAP radiometer-only soil moisture products meet the level 1 accuracy requirement
- SMAP project has developed additional products after the radar failure. Radiometer-only enhanced products and SMAP-Sentinel enhanced product provide additional information and added benefit to the community.
- Next version (end of prime mission) products will be publically released in June 2018 (Next Week). SMAP mission was approved for extended mission
- L-Band passive satellite provides the most reliable soil moisture estimates
- Currently there are no plans for a follow-on soil moisture mission beyond SMOS and SMAP (Takes 5-7 years before the mission is launched)