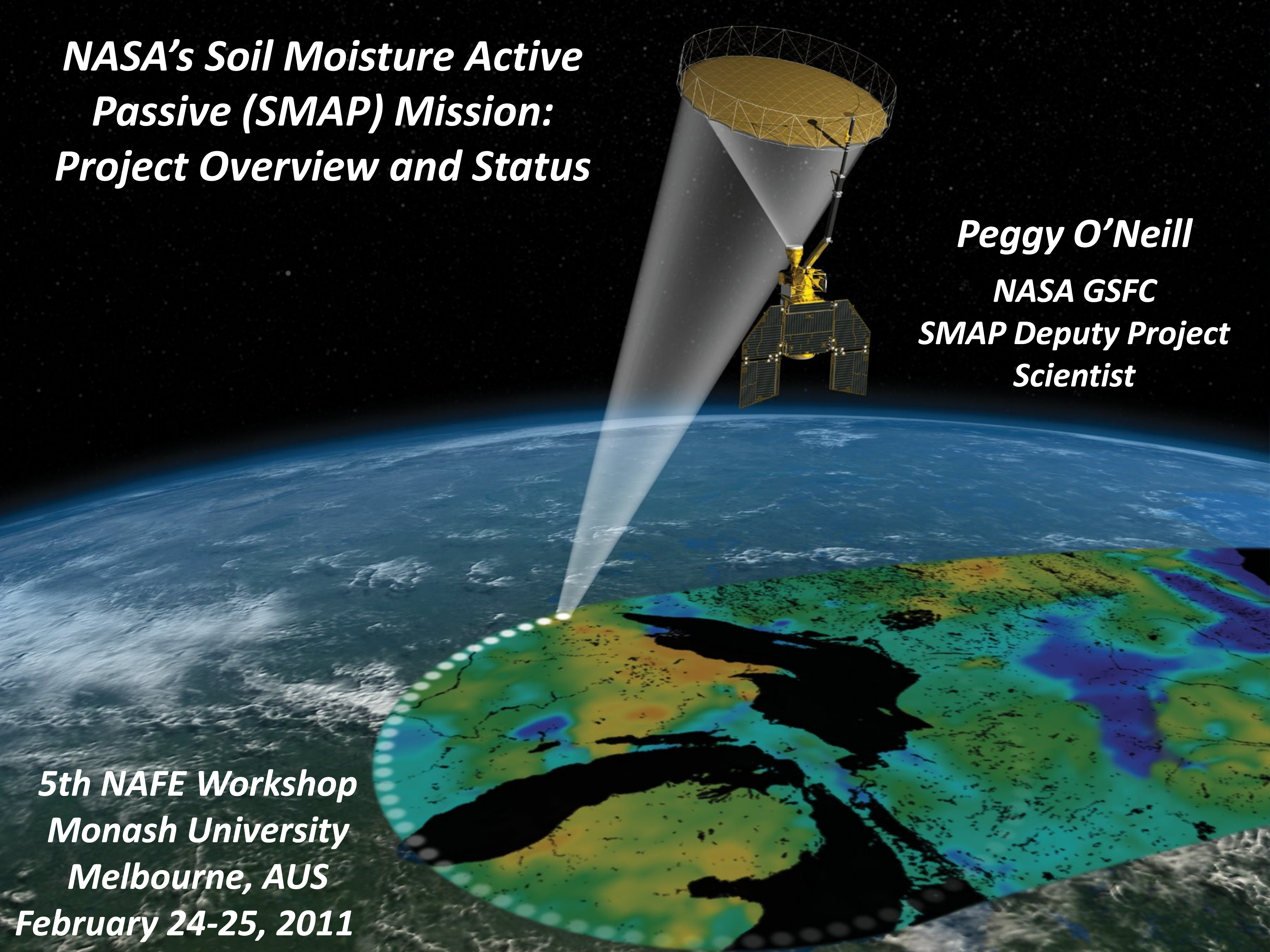
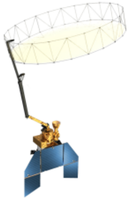
NASA's Soil Moisture Active Passive (SMAP) Mission: Project Overview and Status



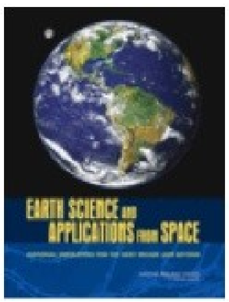
Peggy O'Neill
NASA GSFC
SMAP Deputy Project Scientist

5th NAFE Workshop
Monash University
Melbourne, AUS
February 24-25, 2011



Mission Context

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

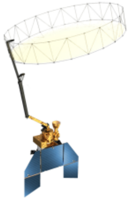


"Earth Science and Applications from Space: National Imperatives for the next Decade and Beyond"

(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

Tier 1:	
	Soil Moisture Active Passive (SMAP)
	ICESAT II
	DESDynI
	CLARREO
Tier 2:	
	SWOT
	HYSPIRI
	ASCENDS
	GEO-CAFE
	ACE
Tier 3:	
	LIST
	PATH
	GRACE-II
	SCLP
	GACM
	3D-WINDS

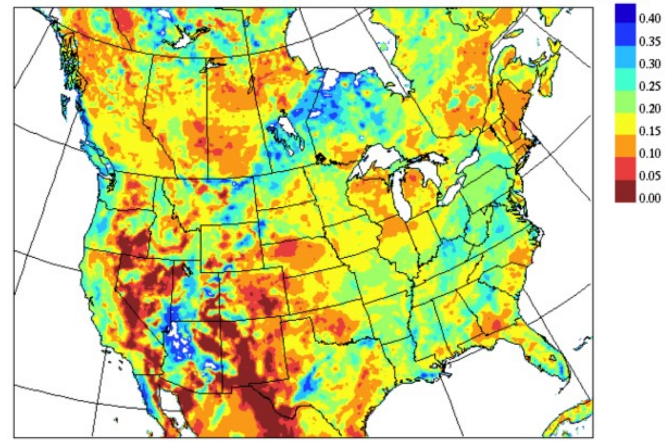


Science Objectives

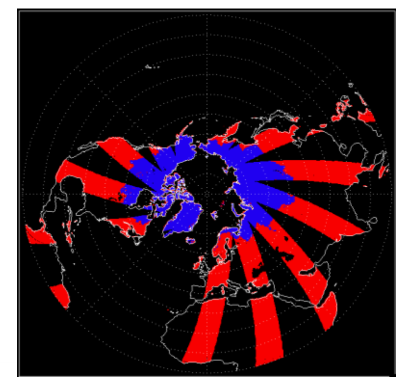
SMAP will provide high-resolution, frequent-revisit global mapping of soil moisture and freeze/thaw state to enable science and applications users to:

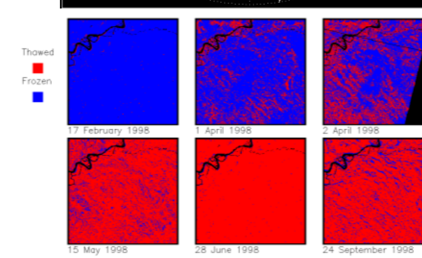
- **Understand processes that link the terrestrial water, energy and carbon cycles**
- **Estimate global water and energy fluxes at the land surface**
- **Quantify net carbon flux in boreal landscapes**
- **Enhance weather and climate forecast skill**
- **Develop improved flood prediction and drought monitoring capability**

Near surface soil moisture



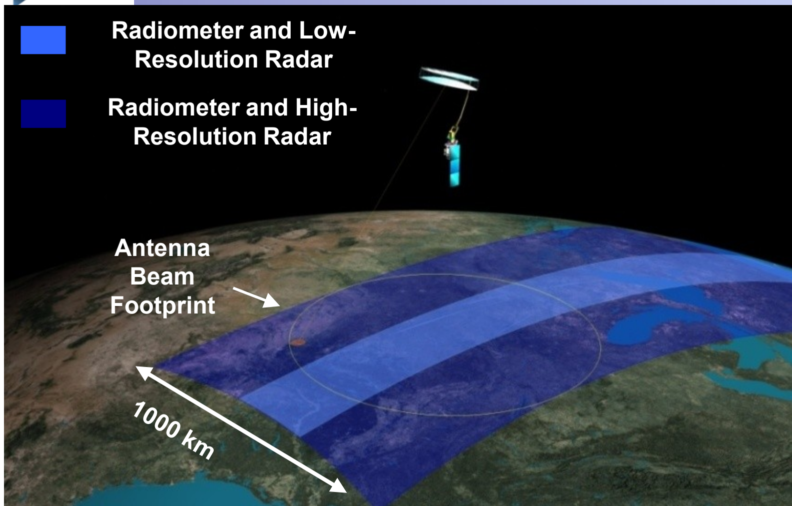
Freeze/thaw state

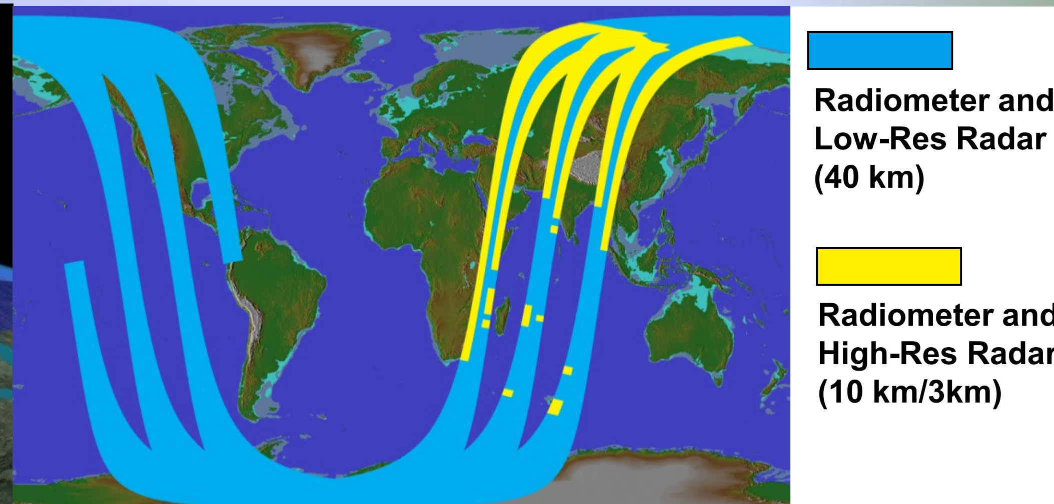




SMAP data will also be used in applications of societal benefit that range from agriculture to human health.

SMAP Science Drivers on Instrument

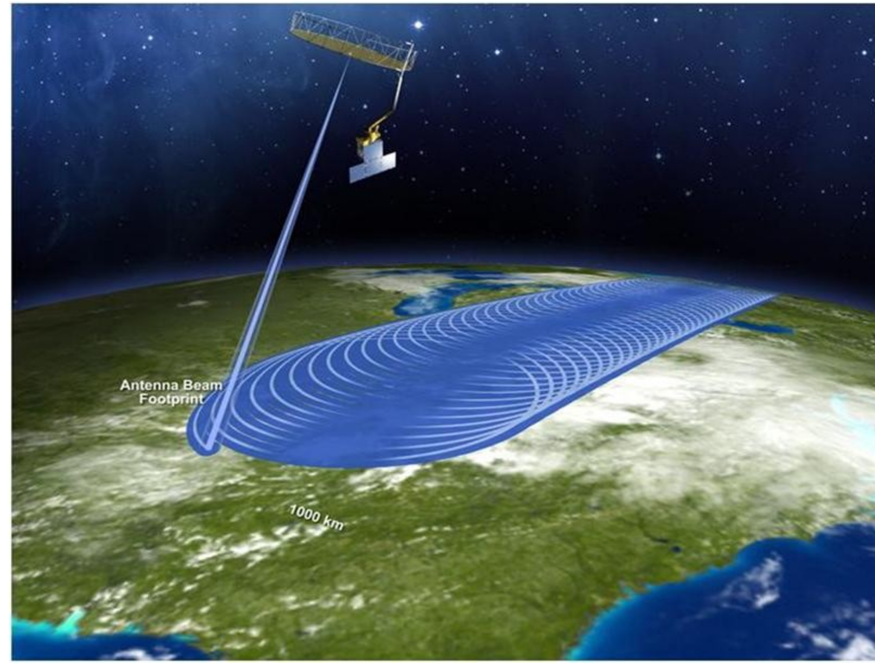




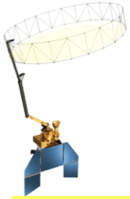
Science Requirement	Primary Instrument Design Drivers/Requirements
2-3 day global coverage	Broad measurement swath
Spatial resolution	Antenna size, synthetic aperture radar
Measurement accuracy, including in presence of vegetation	Active, passive instrument combination Fixed measurement incidence angle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

Measurement Approach

- **Instruments:**
  - **Radiometer: L-band (1.4 GHz)**
    - V, H, 3^{rd} & 4^{th} 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



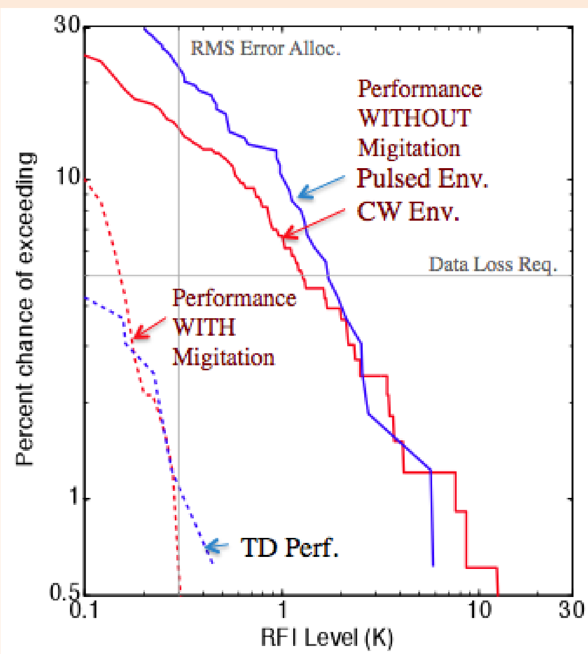
- **Orbit:**
  - -- Sun-synchronous, 6 am/pm, 680 km altitude
  - -- 8-day exact repeat
- **Mission Operations:**
  - -- 3-year baseline mission
  - -- Launch in November 2014



SMAP RFI Mitigation

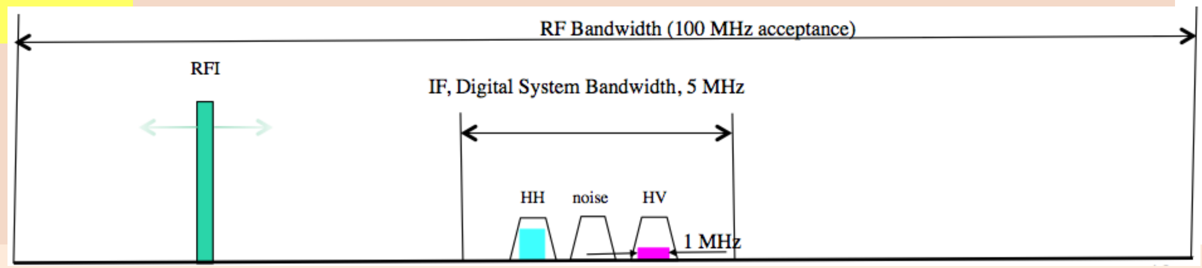
Strategy:

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



Radar

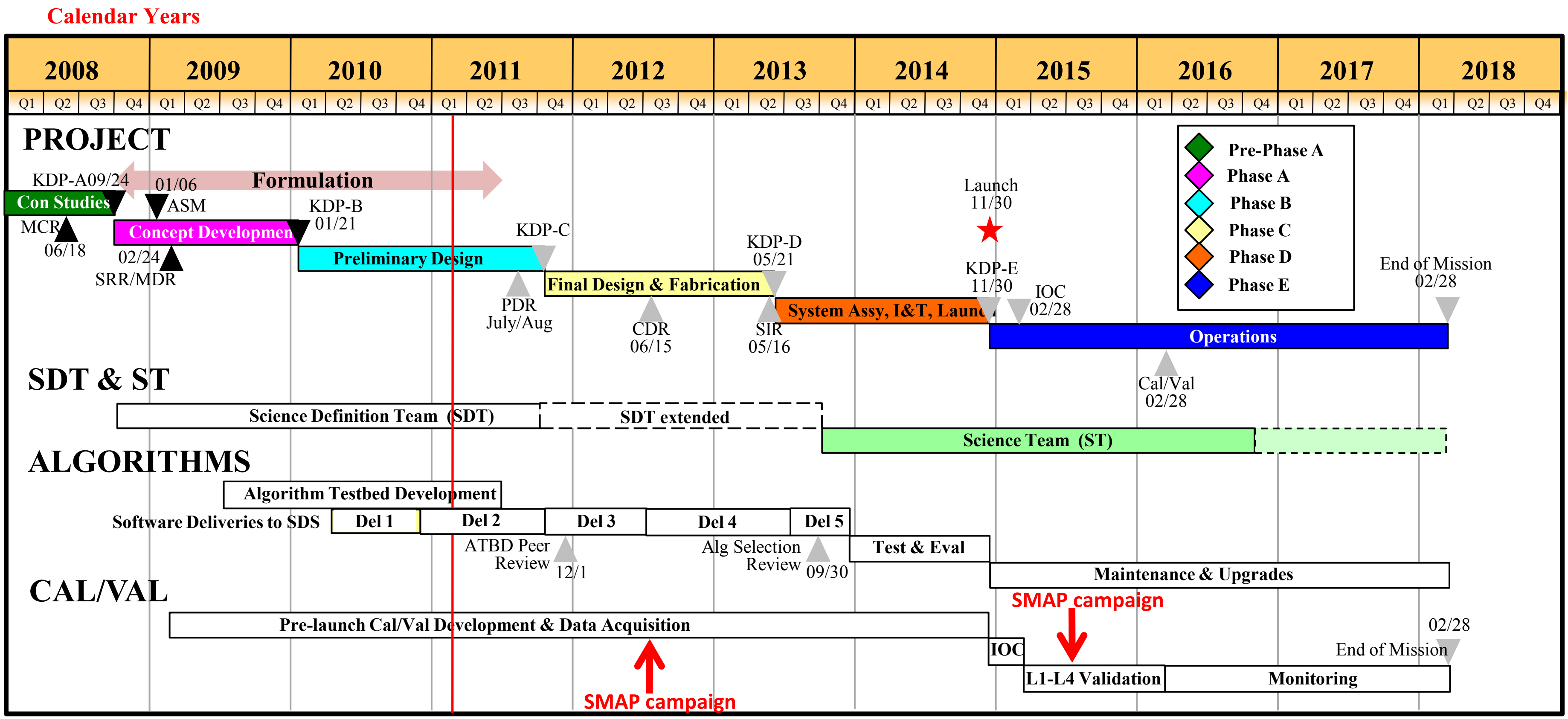
- Ground-programmable operating frequency allows avoiding known regional RFI sources
- Filtering and dynamic range requirements assure that out-of-band RFI will avoid saturating receiver
- Residual RFI will be detected and removed during science data processing on the ground

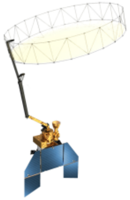


Radiometer

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

Top-Level Schedule





SMAP Level 1 Science Requirements

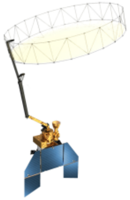
	Science Discipline Measurement Need			Level 1 Science Measurement Requirements			
				Baseline Mission		Threshold Mission	
	Hydro-Meteorology	Hydro-Climatology	Carbon Cycle	Soil Moisture	Freeze/Thaw[2]	Soil Moisture	Freeze/Thaw[2]
Resolution	4–15 km	50–100 km	1–10 km	10 km	3 km	10 km	10 km
Refresh Rate	2–3 days	3–4 days	2–3 days	3 days	2 days	3 days	3 days
Accuracy[1]	.04–.06 cm^3/cm^3	.04–.06 cm^3/cm^3	80–70%	.04 cm^3/cm^3	80%	.06 cm^3/cm^3	70%

Mission Duration Requirement:
3 Years Baseline; 18 Months Threshold

(1) volumetric soil moisture content (1-sigma) ; % classification accuracy (binary Freeze/Thaw)
(2) North of 45^0 N latitude

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

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



SMAP Data Products

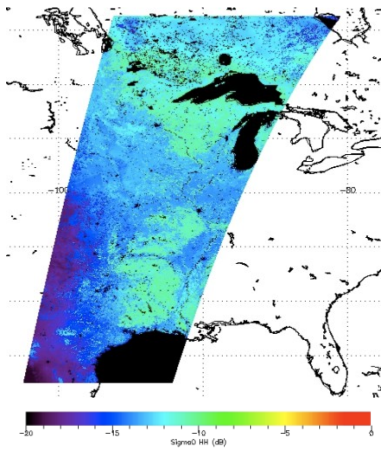
Data Product Short Name	Description	Data Resolution	Grid Spacing	Mean Latency*
L1B_S0_LoRes	Low Resolution Radar σ_o in Time Order	5x30 km (10 slices)	-	12 hrs
L1C_S0_HiRes	High Resolution Radar σ_o on Swath Grid	1x1 km to 1x30 km	1 km	12 hrs
L1B_TB	Radiometer T_B in Time Order	36x47 km	-	12 hrs
L1C_TB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

*** 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.**

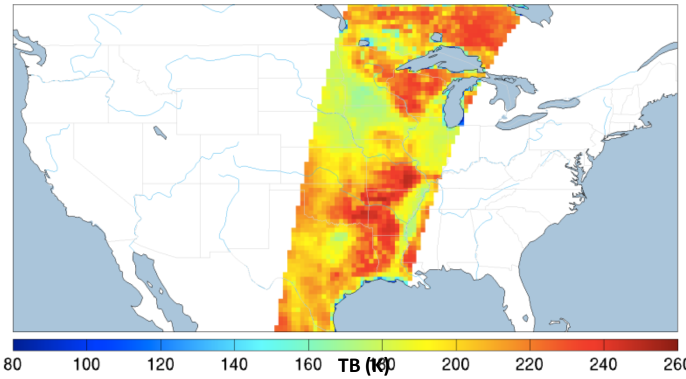
SMAP Algorithm Testbed

Simulated products generated with prototype algorithms on the SDS Testbed

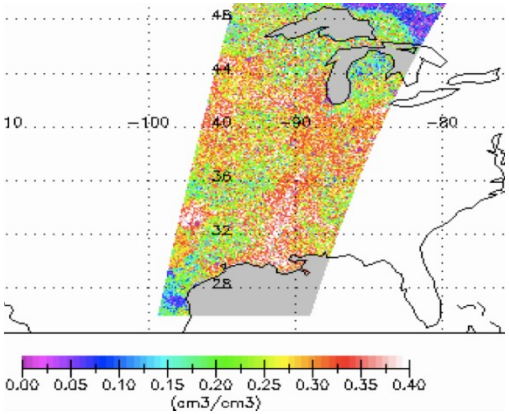
L1C_S0_Hi-Res Radar Backscatter Product (1-3 km)



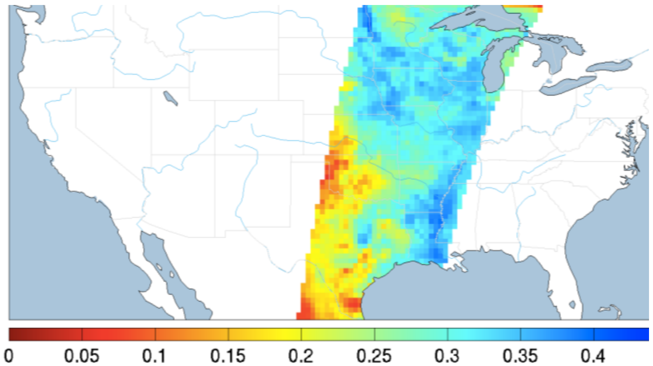
L1C_TB Radiometer Brightness Temperature Product (36km)



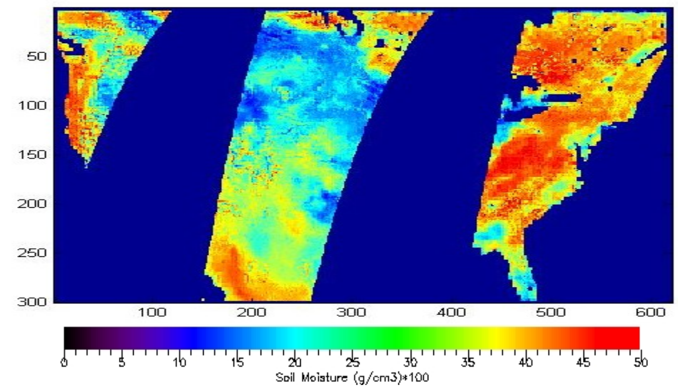
L3_SM_A Radar Soil Moisture Product (3 km)



L2_SM_P Radiometer Soil Moisture Product (36 km)



L2_SM_AP Combined Soil Moisture Product (9 km)



L2_SM_P   Algorithm Concept

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 τ_c ; assumes τ_c and ω are the same for H and V polarization; assumes a constant ω **[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.

L2_SM_P Algorithm Flow

L1B_TB (TB's, lat/lon, time, azimuth)

Program control parameters

I/O and ancillary data paths

Simulation control parameters

Read in control parameters

Read in data paths

Earth grid registration

1. **Drop-in-bucket**
2. **Nearest neighbor**

To DAAC ✓ **L1C_TB** (Fore/aft-look TB's, time)

The L2_SM_P processor converts a half-orbit L1B_TB swath into L1C_TB and L2_SM_P products:

Water fraction

Water TB Correction

1. **Combine fore/aft-look TB's**
2. **Perform correction everywhere except 100% open water**

Freeze/thaw state

Soil temperature

Soil texture

Surface roughness

Land classification

NDVI / veg info

L2_SM_P Retrieval

1. **Single channel using TBH**
2. **Single channel using TBV**
3. **Dual channel using TBH and TBV**
4. **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.

To DAAC ✓ **L2_SM_P** (Soil moisture, QC)

L2_SM_P Input/Output

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

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

L2_SM_A   Algorithm Concept

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

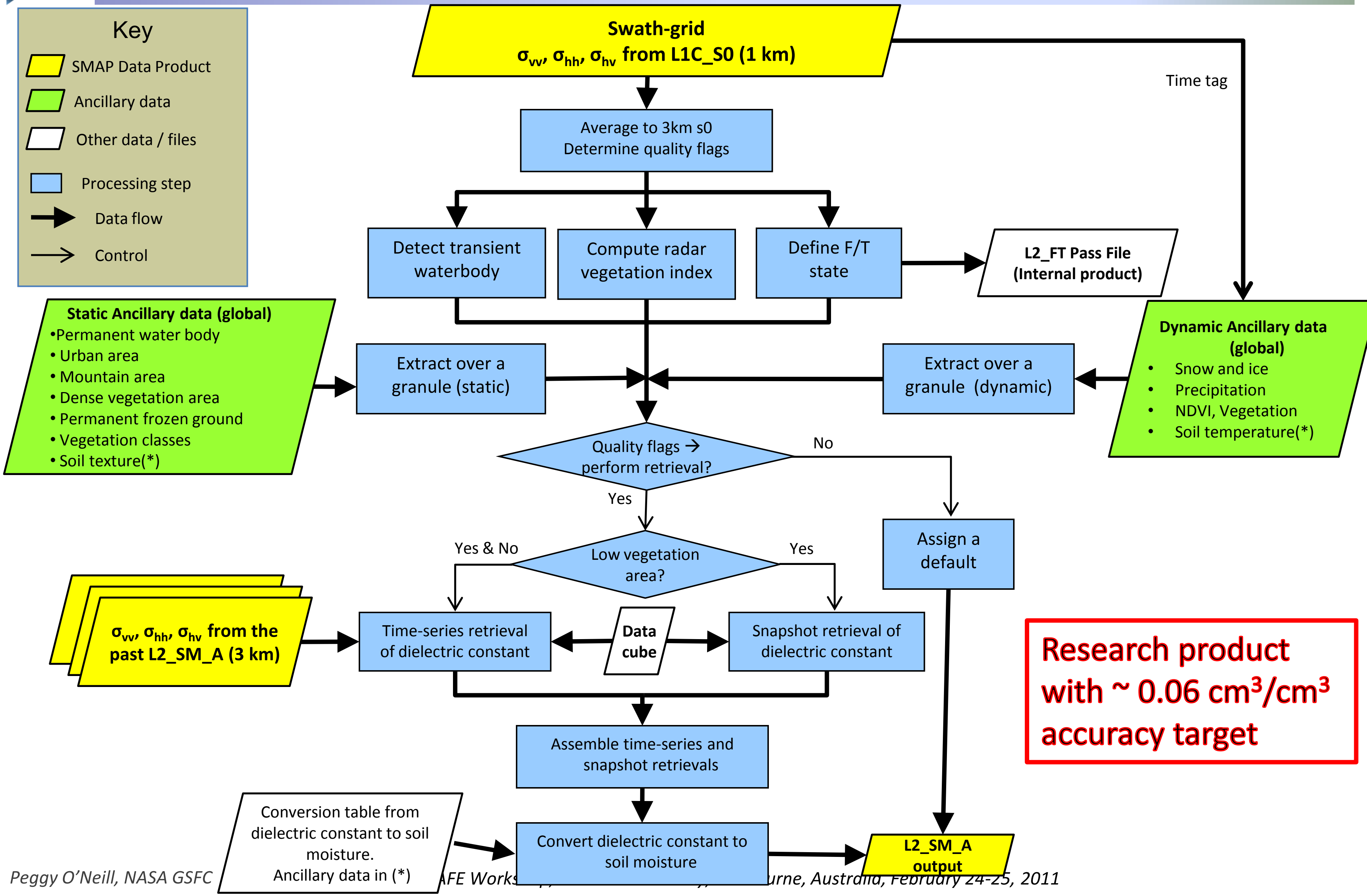
  -- **Data-cube algorithm – current baseline**:   inversion by searching a two-dimensional (soil moisture and roughness) lookup table generated by a radar scattering model; 0.046 cm^3/cm^3 retrieval accuracy.

- **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.**

  -- **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.

$$d(t) = \sum_{ch}^{HH,VV} {}'_{ch}(\sigma^0_{ch,measured} - \sigma^0_{ch,datacube}(m_{v,retrieve}, rough_{retrieve}, vegetation))^2 \ \& \ D = \sum_{t}^{N} \quad t)$$

L2_SM_A Algorithm Flow



L2_SM_AP Algorithm Concept

Temporal changes in T_B and σ_{pp} are related. Parameters α and β are estimated at scale-*C* using successive overpasses.

$$T_{B_p}(C) = \alpha(C) + \beta(C)\cdot\sigma_{pp}(C)$$

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

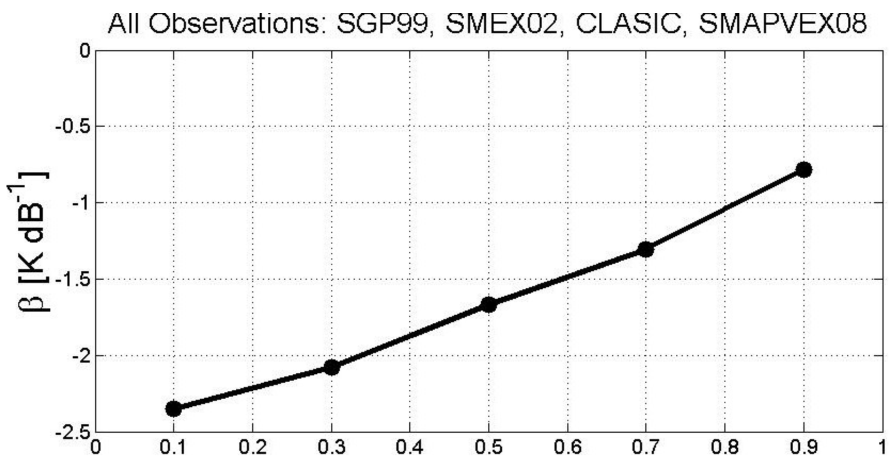
$$\sigma_{pp}(M_j) \approx \sigma_{pp}(M_j) + \left[\frac{\partial\sigma_{pp}(M_j)}{\partial\sigma_{pq}(M_j)}\right]_C \left(\sigma_{pq}(M_j) - \sigma_{pq}(C)\right)$$

T_B-disaggregation algorithm now becomes:

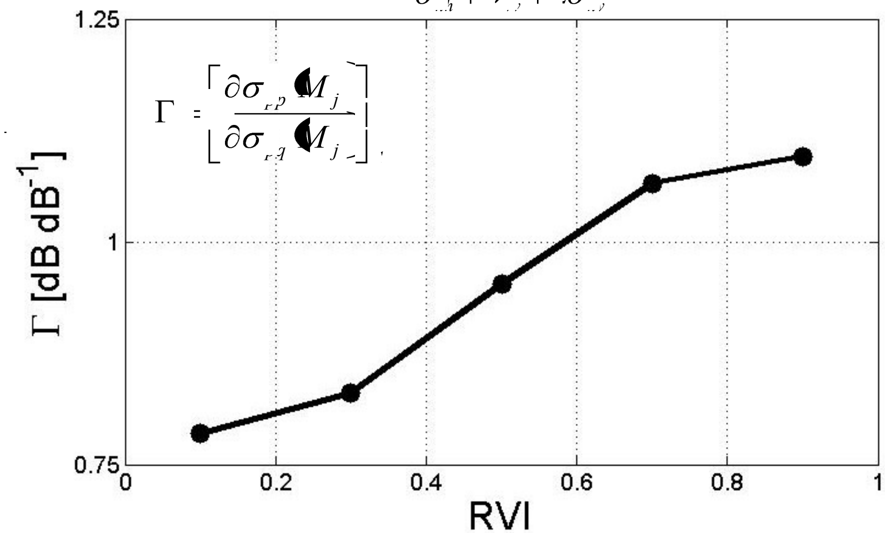
$$T_{B_p}(M_j) = T_{B_p}(C) + \beta(C)\cdot\left\{\left[\sigma_{pp}(M_j) - \sigma_{pp}(C)\right] - \Gamma\left[\sigma_{pq}(M_j) - \sigma_{pq}(C)\right]\right\}$$

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

Airborne observations from <u>four</u> field experiments with PALS combine to form test database

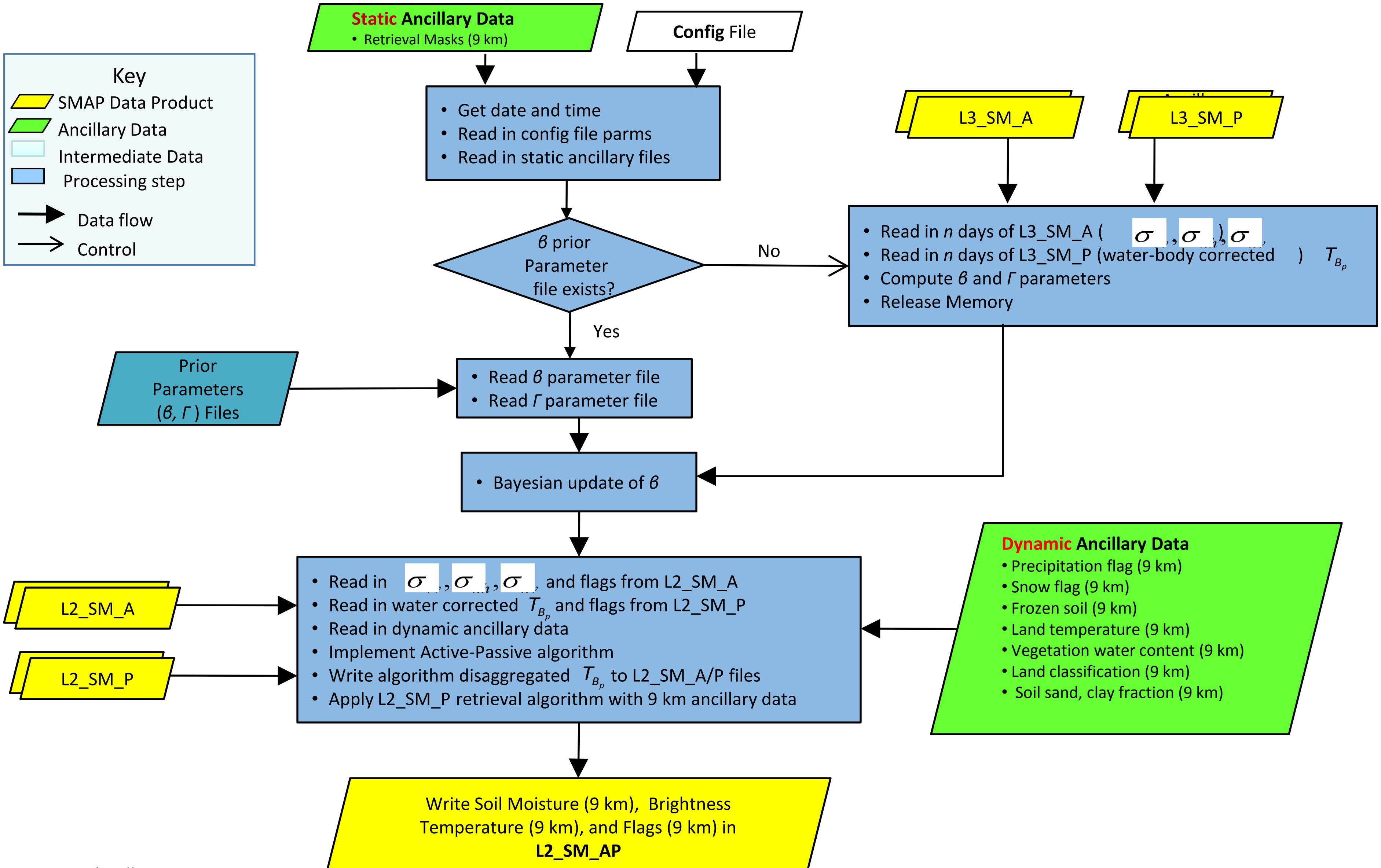


$$\mathrm{RVI} = \frac{8\sigma_{hv}}{\sigma_{hh} + \sigma_{vv} + 2\sigma_{hv}}$$



$$\Gamma = \left[\frac{\partial\sigma_{pp}(M_j)}{\partial\sigma_{pq}(M_j)}\right]_C$$

L2_SM_AP Algorithm Flow



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

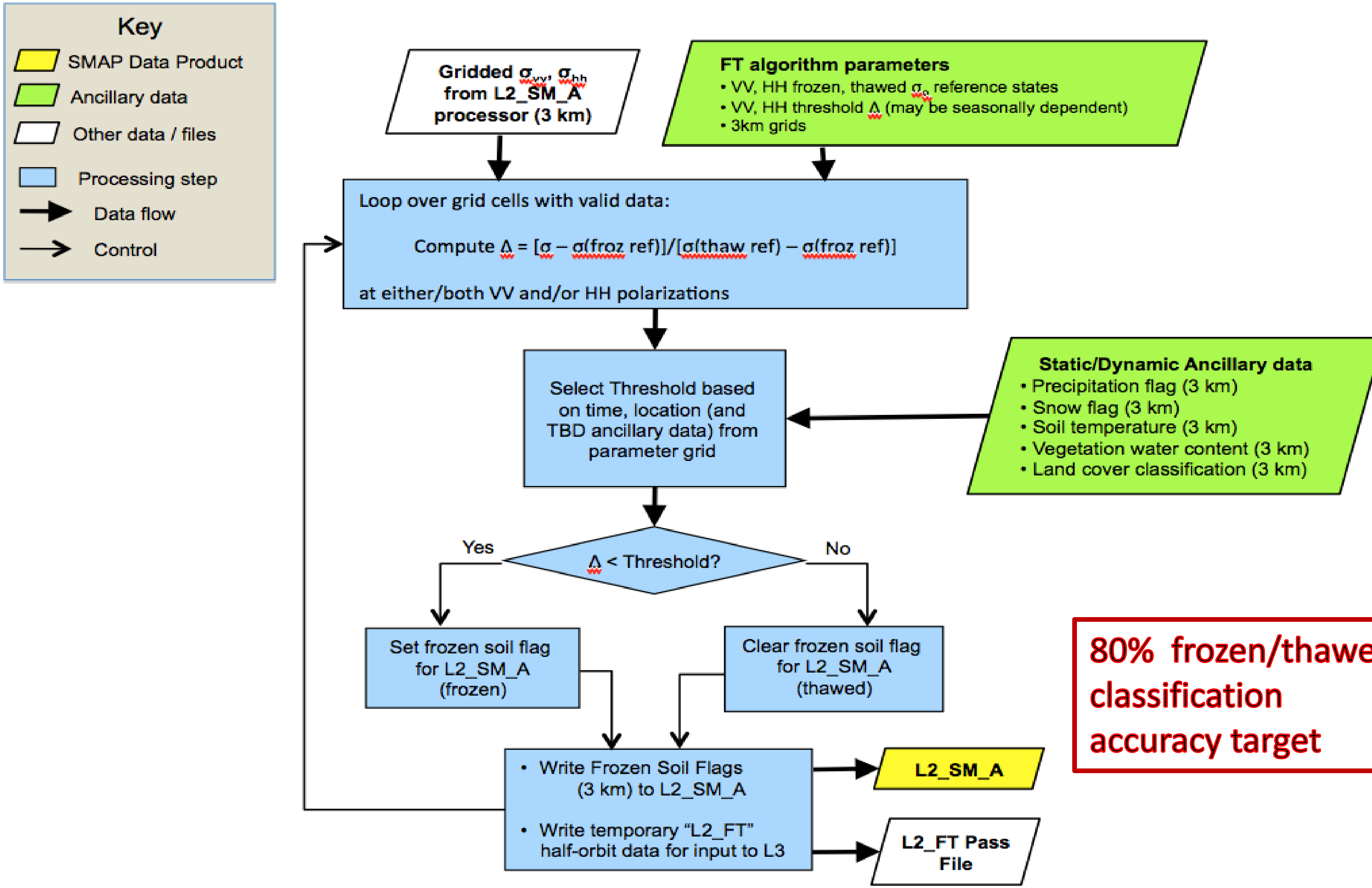
Baseline Algorithm: **Seasonal Threshold Approach**

- **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



80% frozen/thawed classification accuracy target

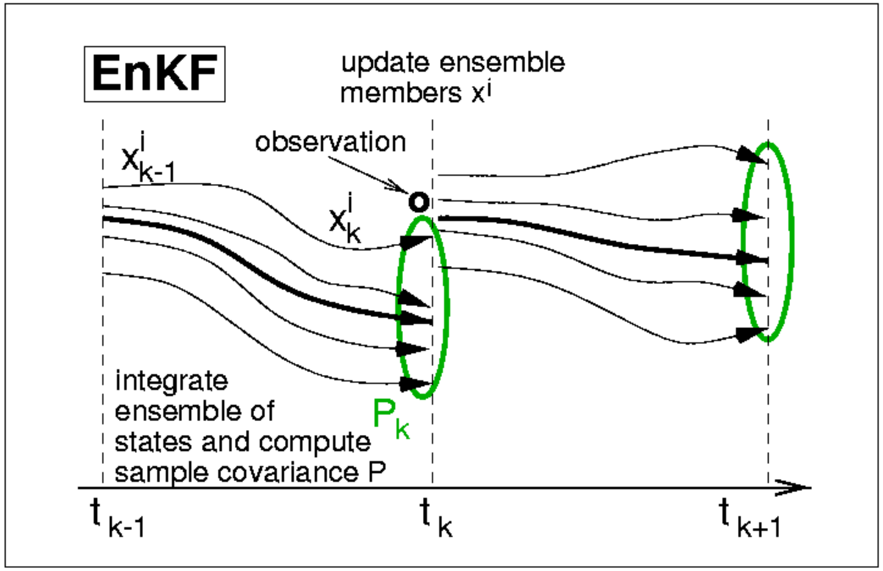
L4_SM Algorithm Concept

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:

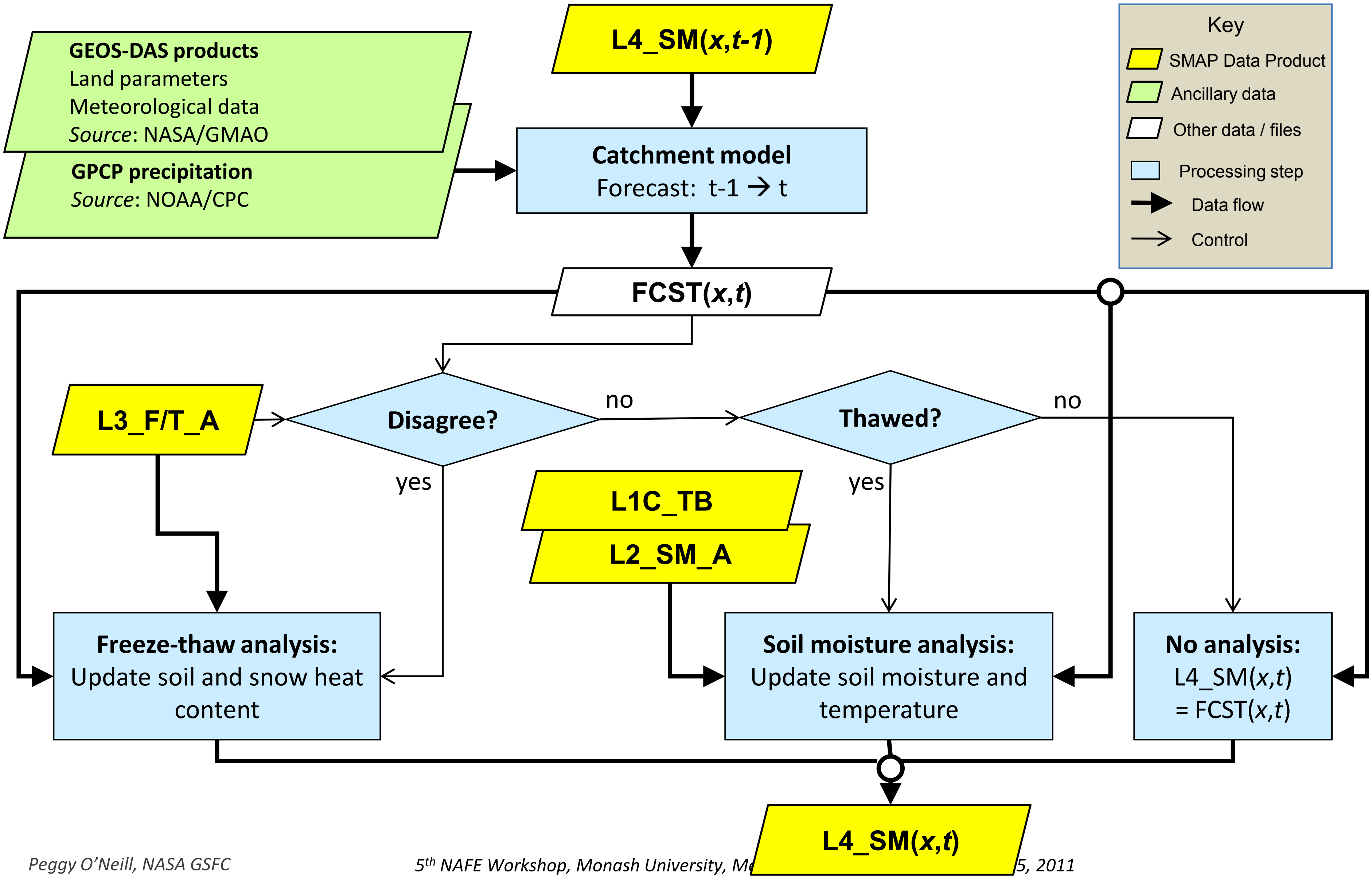
- Customized version of existing NASA/GEOS-5 Land Data Assimilation System
  - 3d Ensemble Kalman filter
  - Catchment land surface model



Optional algorithm extensions:

- Dynamic bias estimation and correction
- Adaptive filtering for dynamic estimation of input error parameters
- Ensemble smoothing

L4_SM Algorithm Flow



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)

L4_SM algorithm

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)**

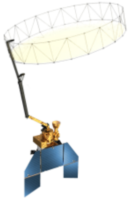
In units of $cm^3\ cm^{-3}$ and percentiles

- **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)

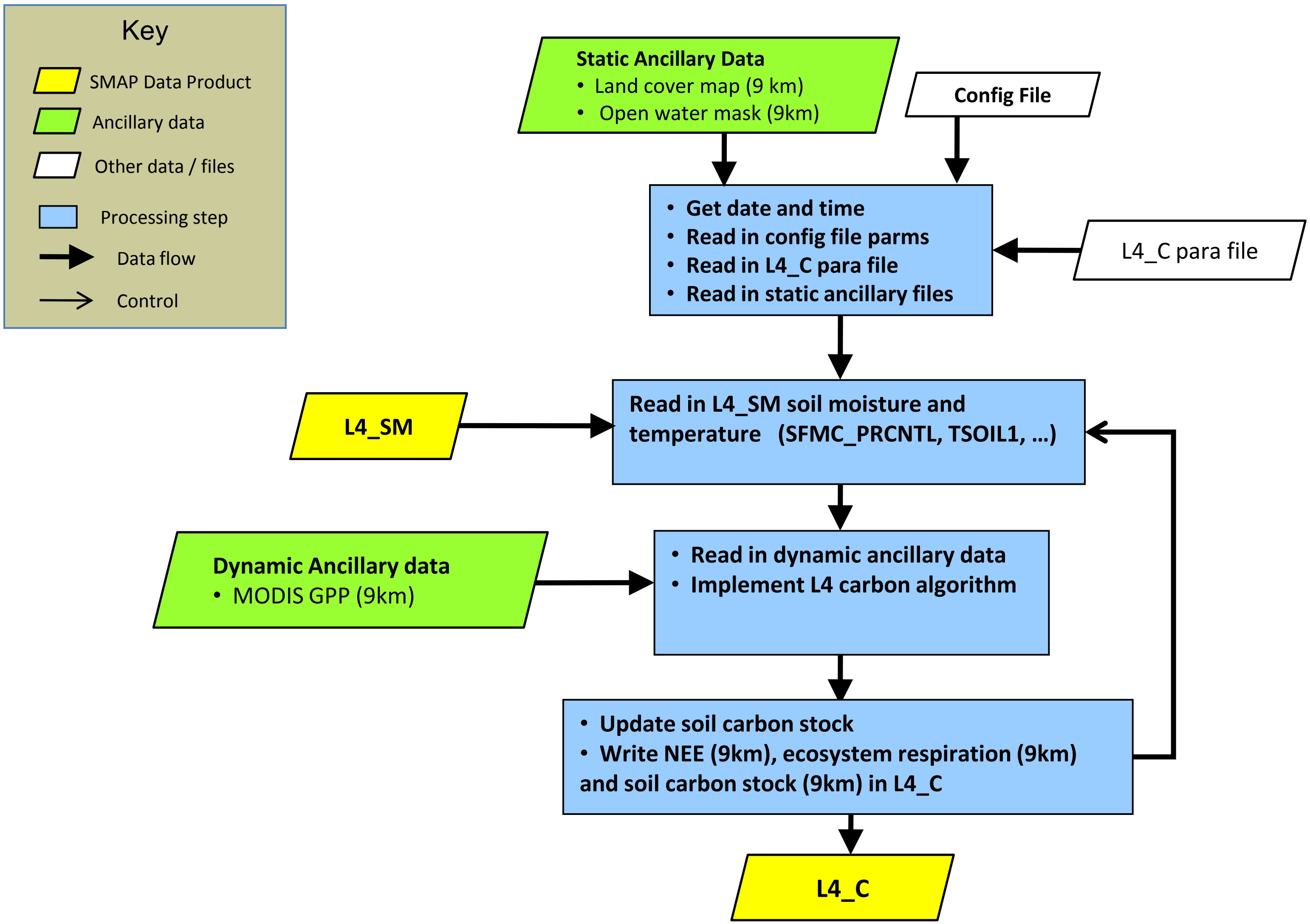
L4_C Algorithm Concept

Baseline: Land-atmosphere CO_2 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 CO_2 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 CO_2 obs.
  (RMSE ≤ 30 $g\ C\ m^{-2}\ yr^{-1}$ and 1.6 $g\ C\ m^{-2}\ d^{-1}$)



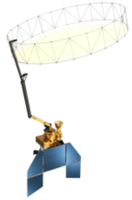
L4_C Algorithm Flow



Summary

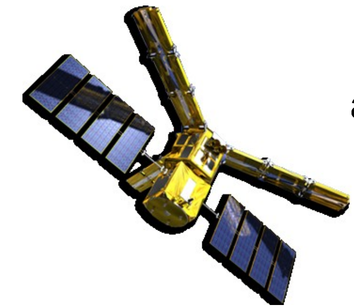
- **SMAP provides high-resolution and frequent-revisit global mapping of soil moisture and freeze/thaw state that has:**
  - Science value for Water, Carbon and Energy Cycles
  - Applications benefits in Operational Weather, Flood & Drought Monitoring, other areas
  - Addresses priority questions on 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



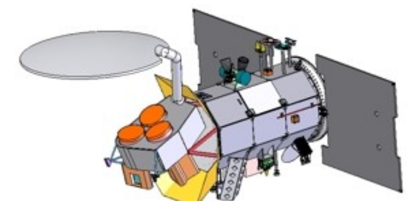
Synergistic Data and Experience from SMOS and Aquarius

- **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**

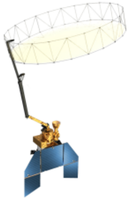


(ESA)
aunch

Aquarius
2011 LRD

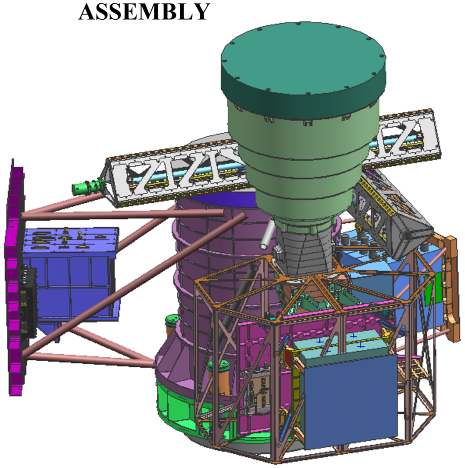


Mission	LRD	Measurement	Instrument Complement	Resolution / Revisit
SMOS	Nov '09	Soil Moisture Ocean Salinity	L-band Radiometer	50 km / 3 days
Aquarius	June '11	Ocean Salinity Soil Moisture (experimental)	L-band Radiometer, Scatterometer	100 km / 7 days
SMAP	Nov '14	Soil Moisture Freeze/Thaw State	L-band Radiometer, SAR (unfocused)	10 km / 2-3 days

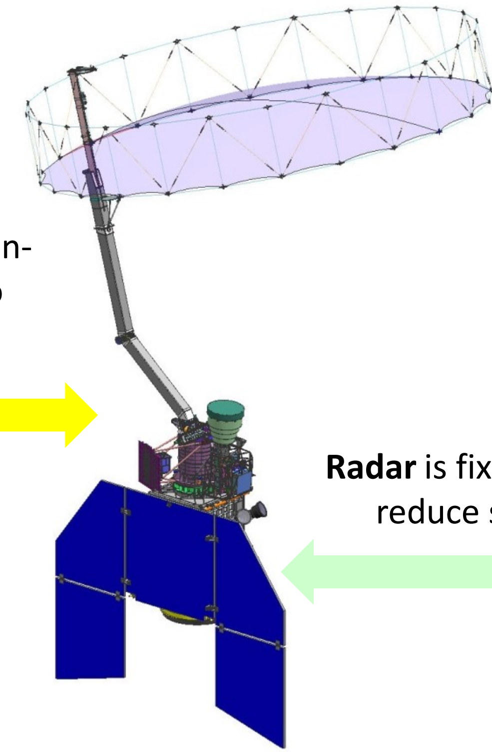


Instrument Overview

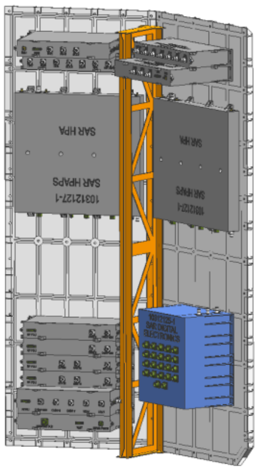
SPUN INSTRUMENT
ASSEMBLY



Radiometer is spun-side mounted to reduce losses



Radar is fixed-mounted to reduce spun inertia

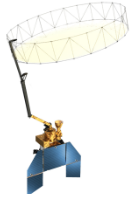


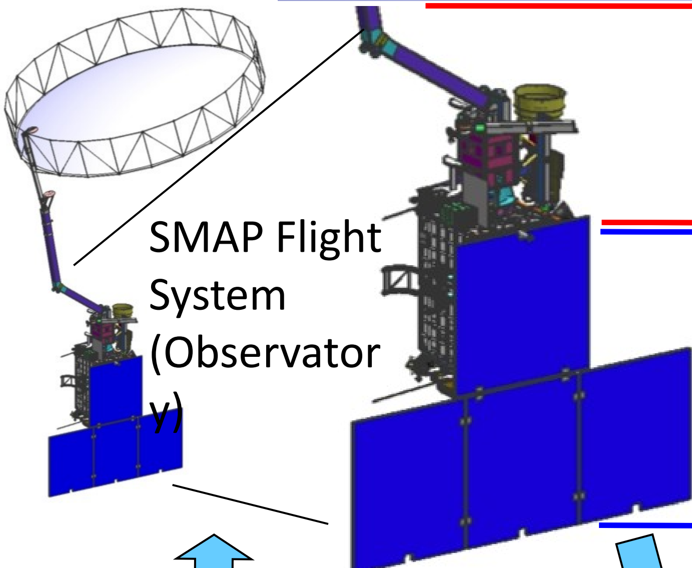
- **Radiometer**
  - Provided by GSFC
  - Leverages off Aquarius radiometer design
  - Includes RFI mitigation (spectral filtering)

- **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

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

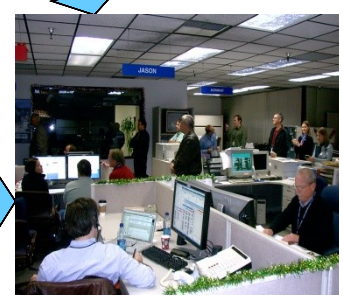
- JPL-Developed & Built
- JPL's Multi-mission System Architecture Platform Avionics
- Commercial Space Components

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

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

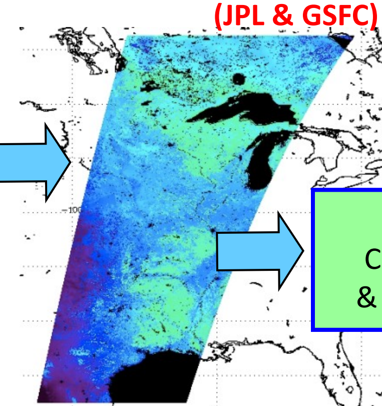
Near Earth Network

Surface Validation



SMAP Mission Operations & Data Processing (JPL, GSFC)

SM & FT Science Data Products (JPL & GSFC)



Data Center (Location: TBD)

Scientific Community & Data Users

Microwave Emission Model for L2_SM_P

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

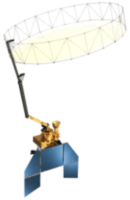
$$T_{Bp} = T_s\,(1 - r_p)\,\exp(-\tau_c) + T_c\,(1 - \omega)\,[1 - \exp(-\tau_c)]\,[1 + r_p\,\exp(-\tau_c)]$$

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 $e_p = (1 - r_p)$]
- τ_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]
- ω is the vegetation single scattering albedo
- soil roughness can be corrected as $r_{p\ smooth} = r_{p\ rough}\ /\ \exp(-h)$
- $r_{p\ smooth}$ is then related to the soil dielectric constant ε 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 $T_c \approx T_s = T_{eff}$, the effective temperature over the microwave sampling depth



L2_SM_P Error Analysis

Single-Channel Algorithm*:

Error Source	Estimated T_B Error (K)
Soil Temperature (2°C error)	1.7
Vegetation Water Content (10%)	1.6
Model Parameterization (h, ω, b, all at 5% error, classification, etc.)	1.4
Surface Heterogeneity	0.9
Total RSS of Geophysical Errors	2.87
Radiometer Precision & Calibration Stability	1.3
Total RSS Error	3.15

[* 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.

$$d(t) = \sum_{ch}^{HH,VV} {}'_{ch}(\sigma^0_{ch,measured} - \sigma^0_{ch,datacube}(m_{v,retrieve}, rough_{retrieve}, vegetation))^2 \;\&\; D = \sum_{t}^{N} \quad t)$$

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

$$m_v = A \times \sigma^0 + B$$

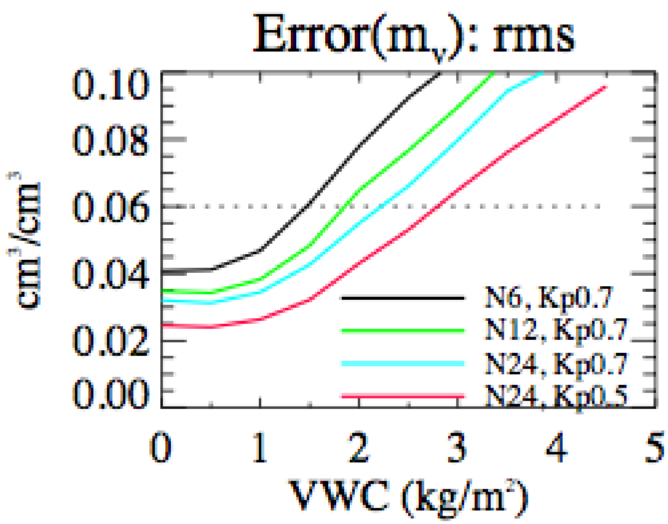
(3) Wagner change detection algorithm: assumes time-invariant roughness and vegetation. Provides indexes of soil moisture change. 6 levels of change were detected.

$$M_S = \left({}^0(t) - \sigma^0_{dry} \right) / \left({}^0_{wet} - \sigma^0_{dry} \right)$$

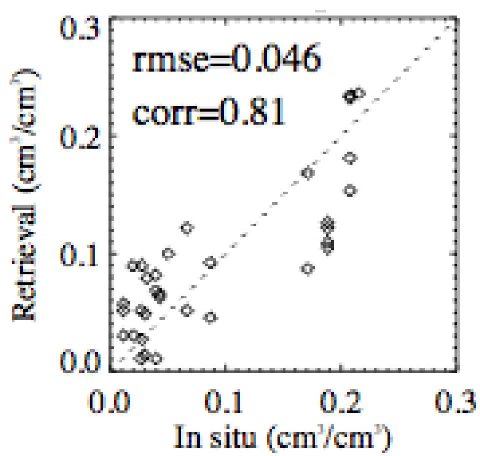
L2_SM_A Error Analysis

Monte Carlo

Number of the pair of HH and VV radar backscatter used as time-series input	24 (~2 months)	
Kp noise (dB, 1σ)	0.5	0.7
Vegetation water content error (1σ)	10%	
Data cube error (physics modeling & grid resolution)	TBD	
Conversion error from dielectric constant to soil moisture	TBD	
Effect of scaling and scene heterogeneity	TBD	
Soil moisture retrieval error (cm^3/cm^3) at VWC of 3 kg/m^2	0.065	0.080

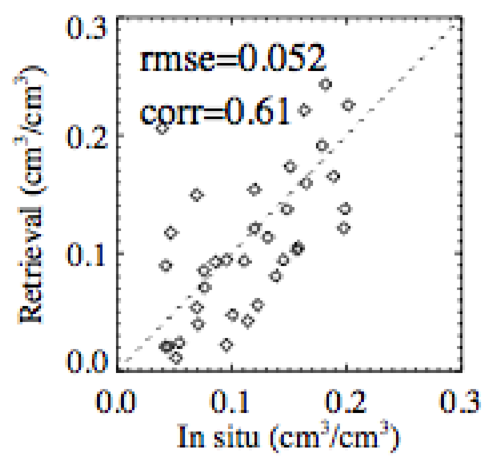


Baseline data-cube time-series retrieval performed on the Hydros OSSE domain using the Dubois/Oh/Ulaby data cube. *N* = Number of passes in time-series data.



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

PALS/truck σ_0 and in situ soil moisture



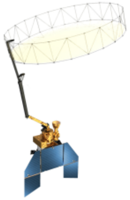
Baseline data-cube time-series for SGP99 grass (VWC of 0.5 to 1 kg/m^2). *N* = 6. (Data cubes from Dr. Leung Tsang.

Both analyses suggest ~0.06 cm^3/cm^3 error target is feasible (up to 1-3 kg/m^2 VWC at 0.5 dB Kp)

L2_SM_AP Error Analysis

	Error Sources	Estimated Error						Nominal Value
1	Radiometer precision and calibration	1.30 [K]						1.30 [K]
2	Faraday rotation	0.20 [K]						0.20 [K]
3	Atmospheric gases	0.10[K]						0.10 [K]
4	Non-Precipitating clouds	0.10 [K]						0.10 [K]
5	**Tb RSS error (L1_TB) RSS**	**1.32** [K]						**1.32** [K]
6	Gridding error	0.20 [K]						0.20 [K]
7	Waterbody fraction (3%, 5% 10%)	0.16		0.45	2.00 [K]			0.45 [K]
8	**Adjusted Corrected Tb RSS**	**1.35**		**1.41**	**2.41** [K]			**1.41** [K]
9	Radar S0(*pp*) and S0 (*pq*) errors*	**2.00** [K]						2.00 [K]
10	**Disaggregated Tb (9 km) RSS**	**2.41**		**2.45**	**3.13 [K]**			**2.45** [K]
11	VWC** (0-1, 1-2, 2-3, 3-4, 4-5 [kg/m2]) 10% error	0.003	0.010	0.015	0.020	0.025	[%vol]	0.025 [%vol]
12	Soil temperature (2 [K])	0.010	0.013	0.015	0.020	0.025	[%vol]	0.025 [%vol]
13	Soil dielectric model (5% error in sand & clay fraction)	0.002	0.003	0.003	0.004	0.004	[%vol]	0.004 [%vol]
14	Parameters (*h*, *ω*, and *b*) 5% error each	0.003	0.004	0.004	0.006	0.010	[%vol]	0.010 [%vol]
15	**Soil moisture retrieval at 9 km RSS**	**0.011**	**0.017**	**0.022**	**0.029**	**0.037**	**[%vol]**	**0.037** [%vol]

* 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

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

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