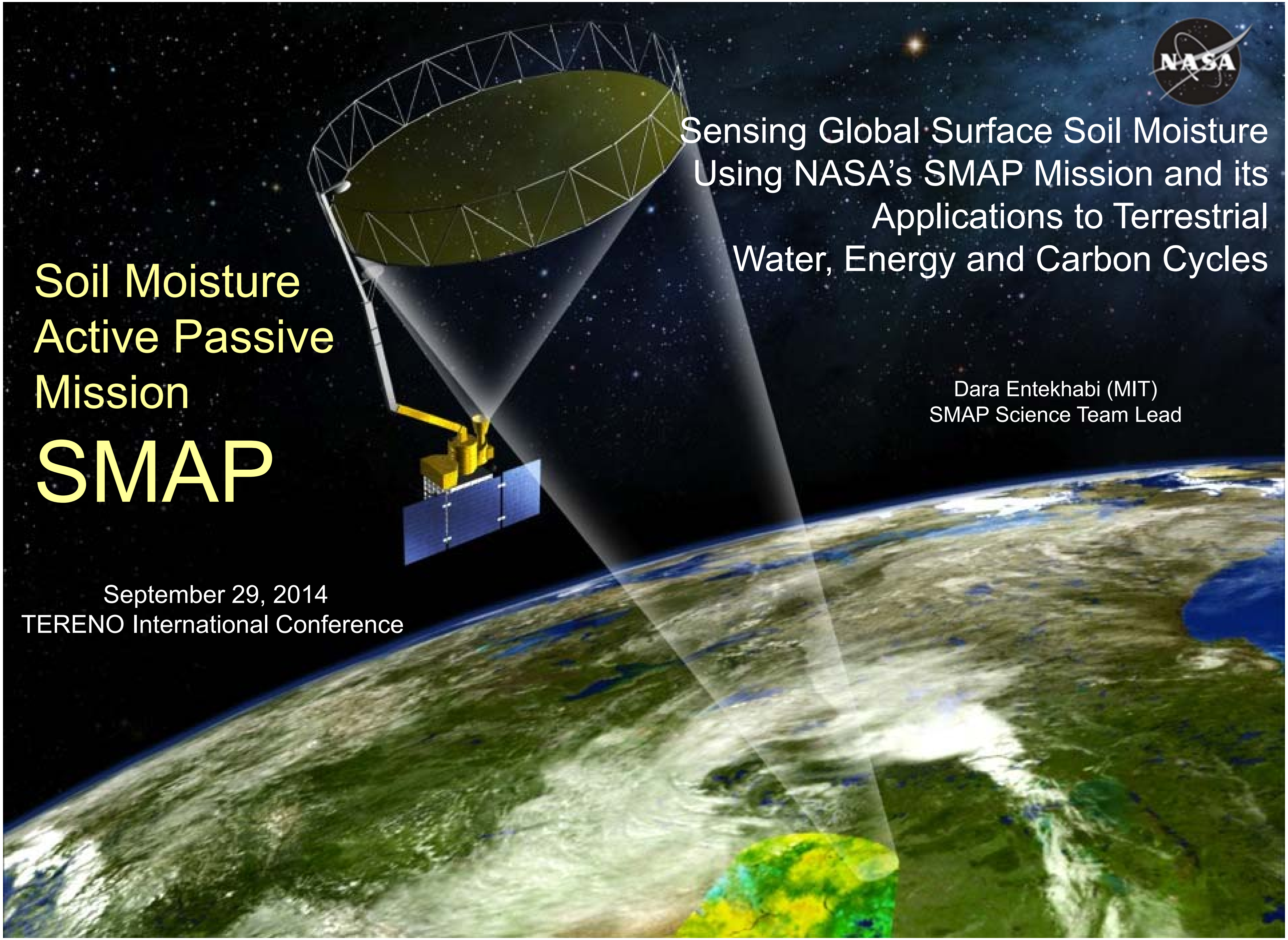


Sensing Global Surface Soil Moisture Using NASA's SMAP Mission and its Applications to Terrestrial Water, Energy and Carbon Cycles

Soil Moisture Active Passive Mission

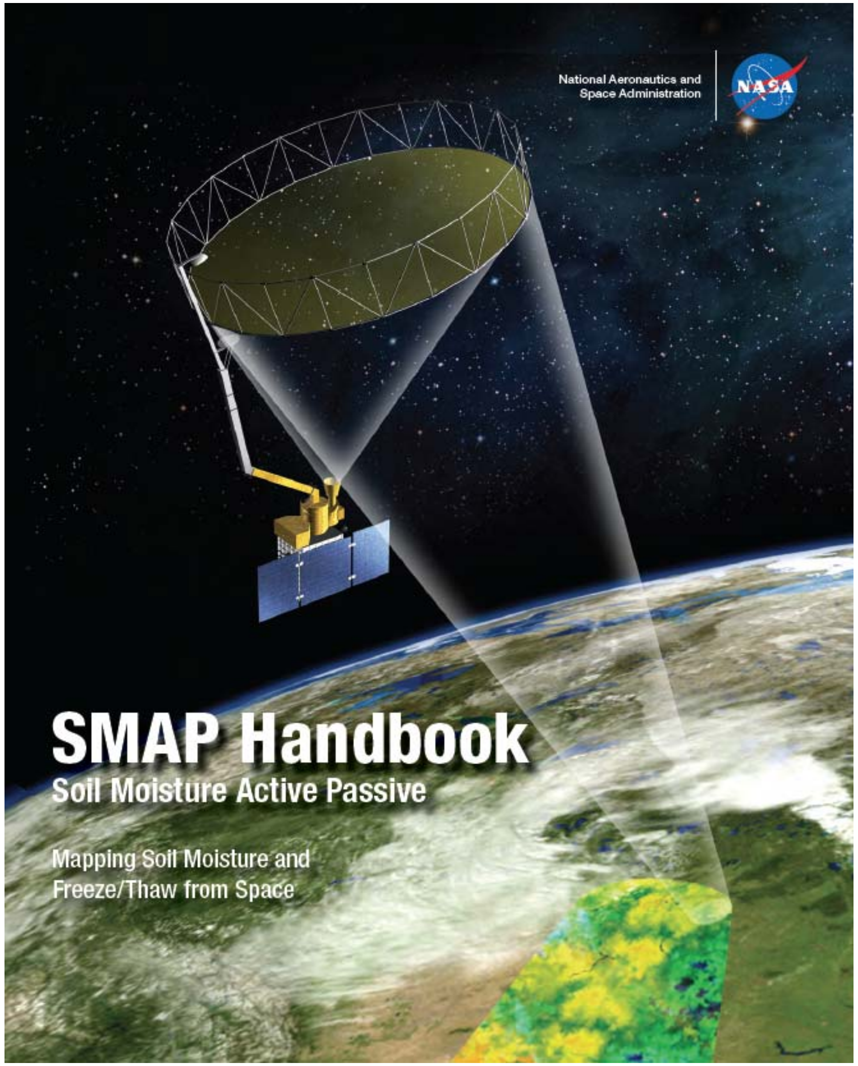
SMAP

Dara Entekhabi (MIT)
SMAP Science Team Lead

September 29, 2014
TERENO International Conference

Soil Moisture Active Passive (SMAP) Mission

Jet Propulsion Laboratory
California Institute of Technology



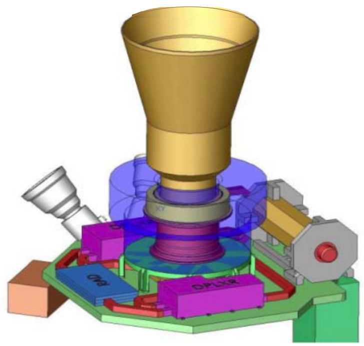
L-band unfocused SAR and radiometer system, offset-fed 6 m light-weight deployable mesh reflector.

- 1.26 GHz dual-pol Radar 1-3 km (30% nadir gap)
- 1.4 GHz polarimetric Radiometer at 40 km (-3 dB)

Conical scan, fixed incidence angle

Contiguous 1000 km swath 2-3 days revisit

Sun-synchronous 6am/6pm orbit (680 km)



Electronic Version at http://smap.jpl.nasa.gov/Imperative/

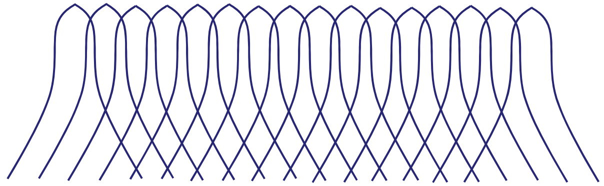
Print Version Available (182 Pages): smap_science@jpl.nasa.gov

SMAP's RFI Detection-Mitigation

Aggressive Approach to Radio-Frequency Interference (RFI) Detection and Mitigation

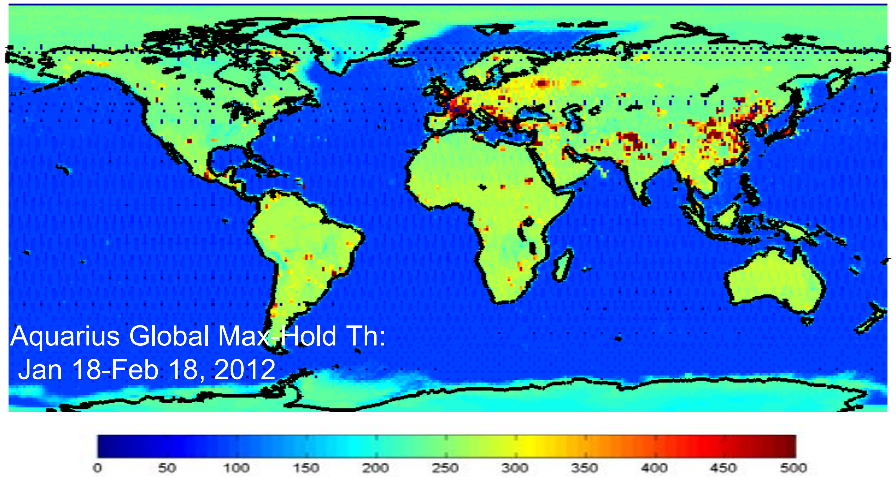
SMAP Radiometer's Multi-Layer Defense:

1. Time-domain Kurtosis
2. Acquire 3rd and 4th Stokes Parameters
3. Spectral and Temporal Resolution (16x10 Spectograph)



SMAP Radar RFI:

- Land Emitters
- Radio Navigation Signals (GPS, GLONASS, COMPASS, GALILEO)



Approach With Tunable Radar Instrument

Mission Status

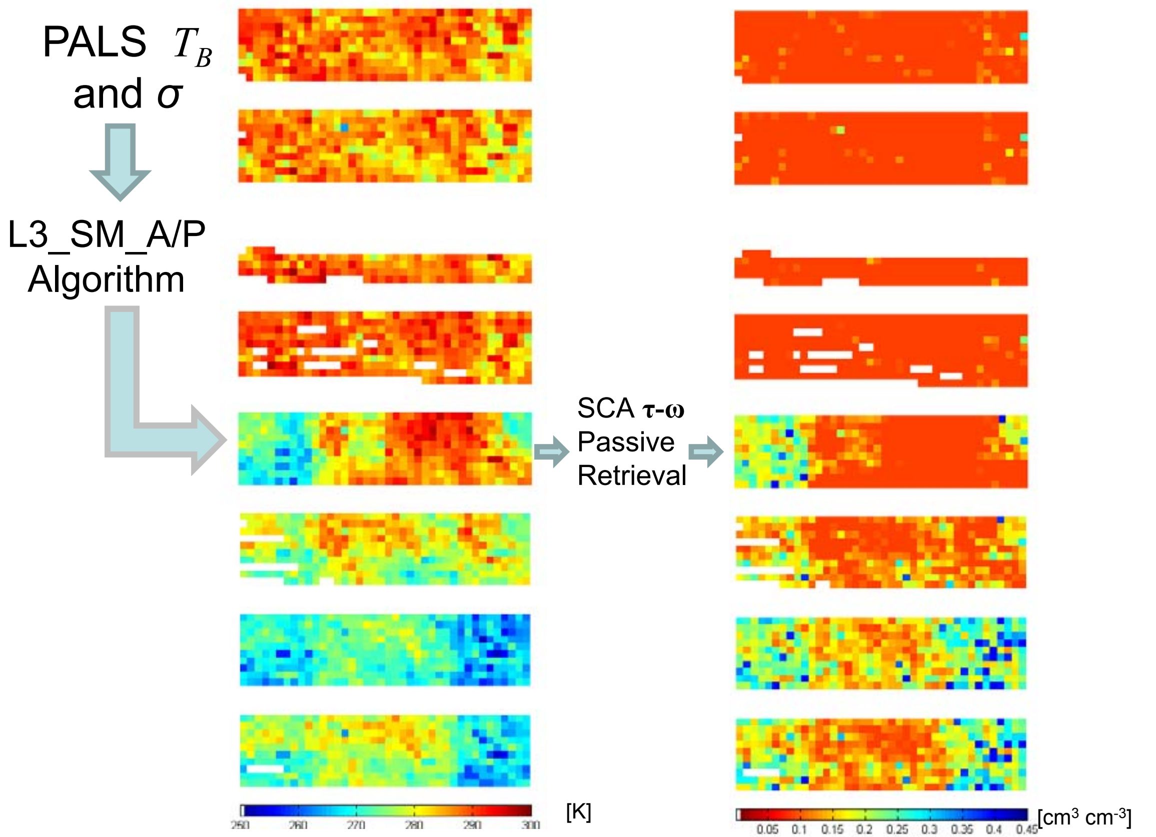
Jet Propulsion Laboratory
California Institute of Technology

January 29, 2015
Launch Schedule

Flagship Active-Passive Product

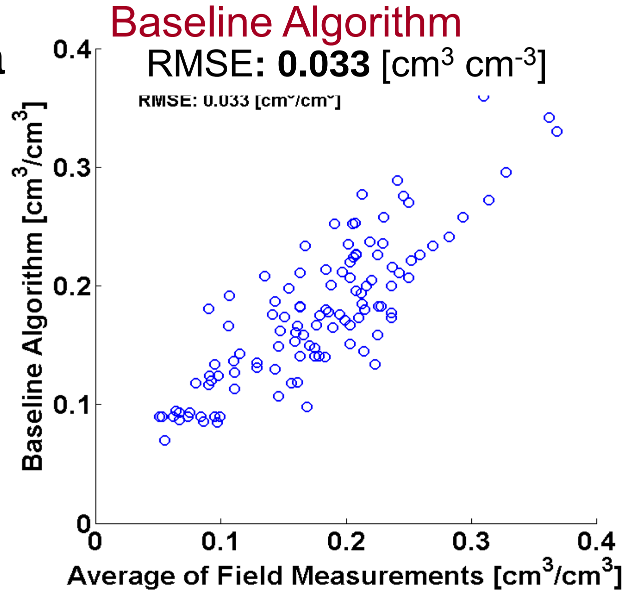
Jet Propulsion Laboratory
California Institute of Technology

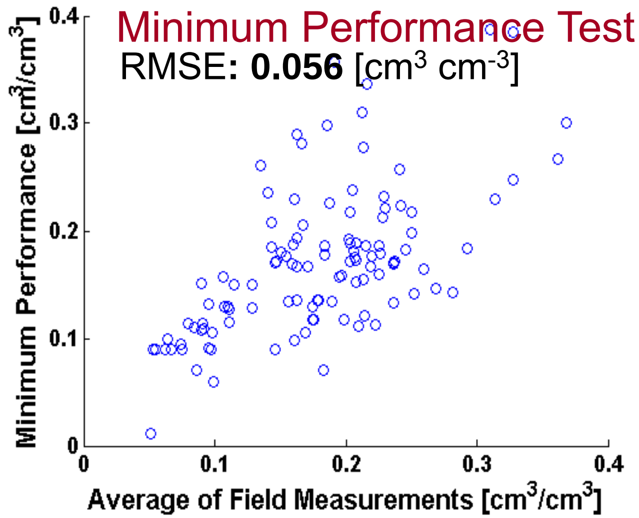
Test of Baseline Algorithm Using SMEX02 PALS Data



Disaggregated T_B (0.8 km)

Estimated Soil Moisture (0.8 km)



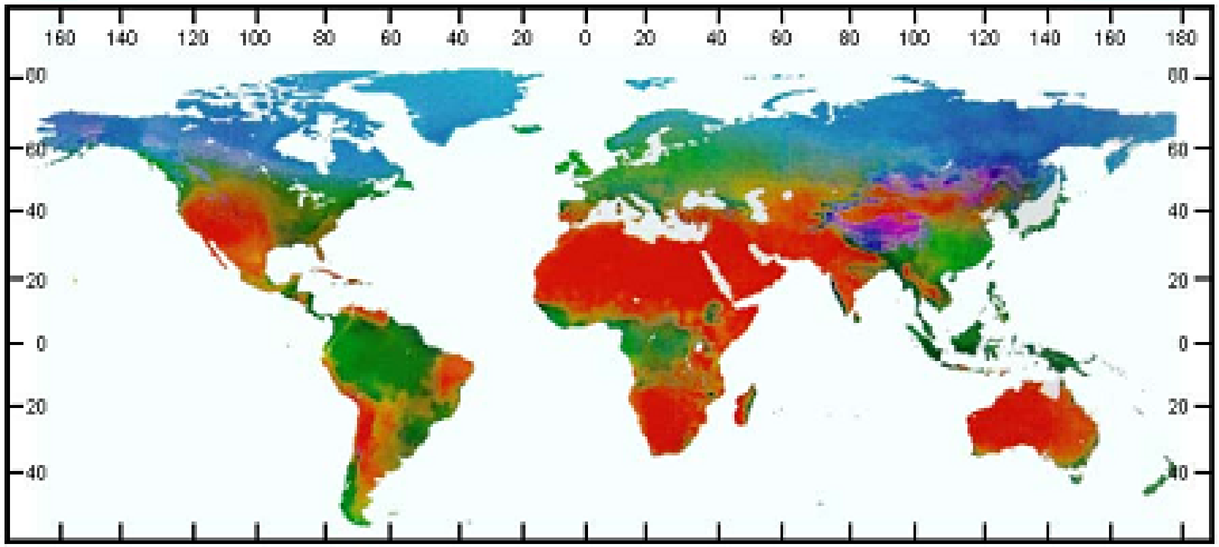


Mission Science Objectives

Jet Propulsion Laboratory
California Institute of Technology

Global mapping of soil moisture and freeze/thaw state to:

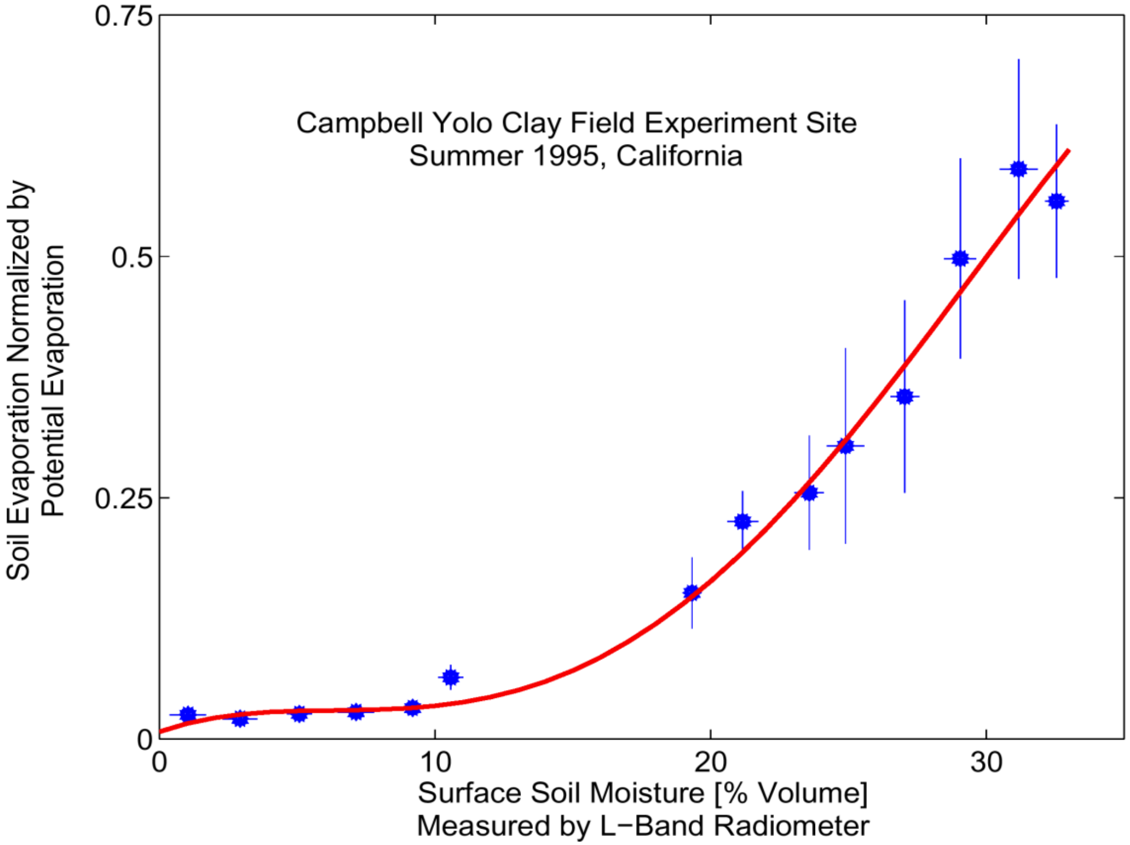
- Understand processes that *link* the terrestrial water, energy and carbon cycles
- Estimate global water and energy fluxes at the land surface
- Quantify net carbon flux in boreal landscapes
- Enhance weather and climate forecast skill
- Develop improved flood prediction and drought monitoring capability



Primary controls on land evaporation and biosphere primary productivity

Key Determinants of Land Evaporation

Jet Propulsion Laboratory
California Institute of Technology



Cahill et al., JAM(38), 1999.

Latent heat flux (evaporation) links the water, energy, and carbon cycles at the surface.

All models of water and energy balance (LSM or SVATs) include (explicitly or implicitly) a form for the closure:

e.g., $\beta(\theta)=E/E_p$ or $r_g(\theta)$ …

Parameterized Closure Functions But Without Strong Evidence

Jet Propulsion Laboratory
California Institute of Technology

NOAH

model grid cell and

$$\beta = \left(\frac{\Theta_1 - \Theta_w}{\Theta_{\mathrm{ref}} - \Theta_w} \right)^f \qquad (7)$$

represents a normalized soil moisture availability term where Θ_w is the wilting point and Θ_{ref} is the field capac-

CLM

functional type and the soil water potential of each soil layer

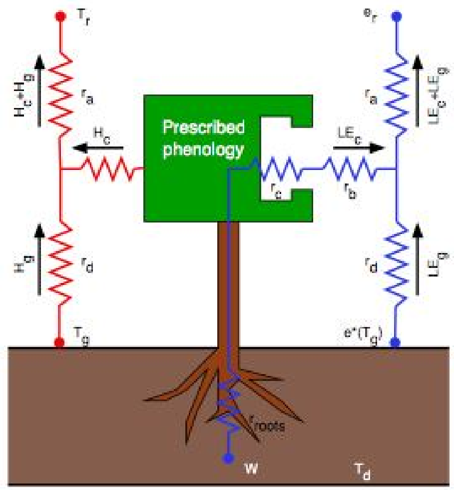
$$\beta_t = \sum_i w_i r_i \geq 1 \times 10^{-10} \qquad (8.10)$$

where w_i is a soil dryness or plant wilting factor for layer i, and r_i is the fraction of roots in layer i.

The plant wilting factor w_i is

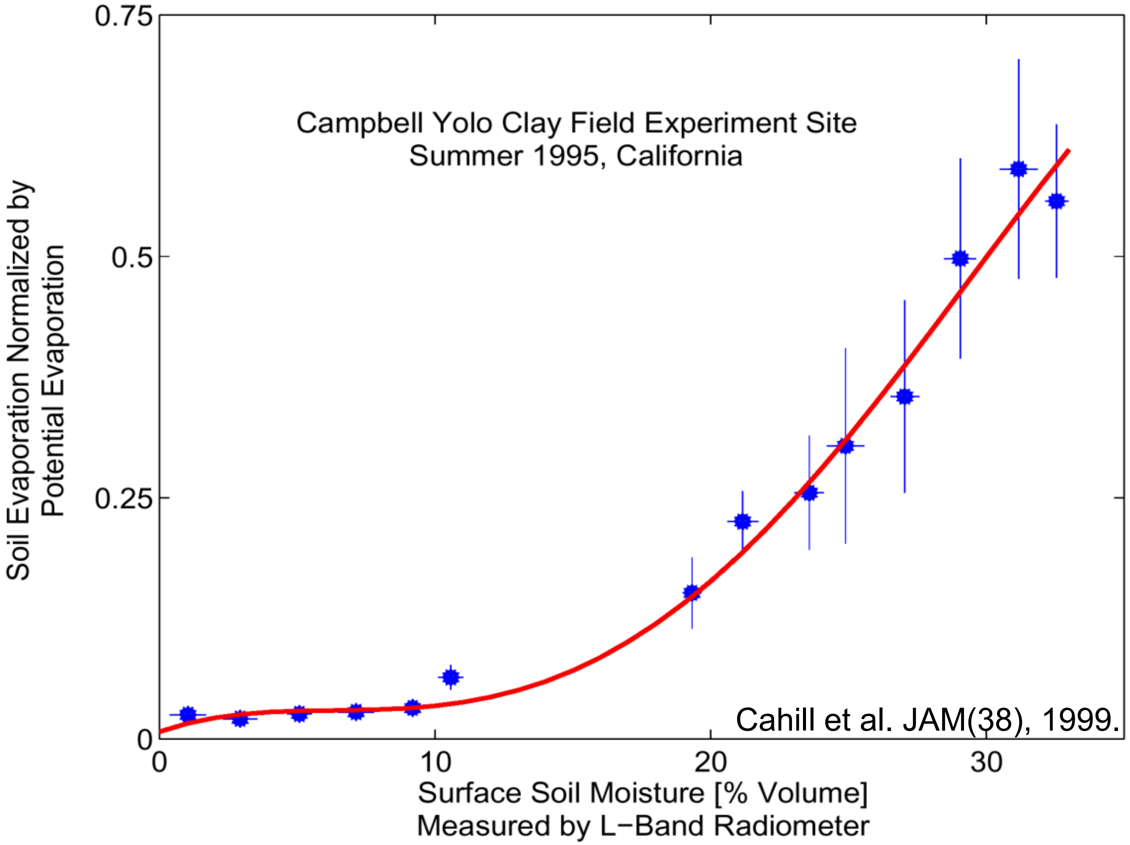
$$w_i = \left\{ \frac{\psi_{\max} - \psi_i}{\psi_{\max} + \psi_{sat,i}} \quad \text{for } T_i > T_f \right\} \qquad (8.11)$$

$$\beta = \begin{cases} \frac{1}{4}\left[1 - \cos\left(\frac{\theta_1}{\theta_{fc}}\pi\right)\right]^2 & \theta_1 < \theta_{fc} \\ 1 & \theta_1 \geq \theta_{fc} \quad \text{or} \quad q_{air} > \alpha q_{sat}(T_g) \end{cases}, \qquad (5)$$



R. Stöckli and P. L. Vidale (ETH)

Key Determinants of Land Evaporation



To estimate this closure function, **independent** observations of

<u>soil moisture state</u>

and

<u>evaporation flux</u>

are required.

…the science objective

Variational Adjoint-State Assimilation

Jet Propulsion Laboratory
California Institute of Technology

Observation equation:

$$\mathbf{T}_{obs} = \mathbf{M} \cdot \mathbf{T}_s + \boldsymbol{\varepsilon}$$

Multiple satellite platforms and resolutions

Minimize least-squares penalty function:

Remote sensing

$$\underset{EF,C_H}{Minimize} \quad J = \left[\mathbf{T}_{obs} - \mathbf{M} \cdot \mathbf{T}_s \right]^T \mathbf{G}_{\mathbf{T}_s}^{-1} \left[\mathbf{T}_{obs} - \mathbf{M} \cdot \mathbf{T}_s \right] +$$ Measurement misfit penalty

$$+ \left[EF - \overline{EF} \right]^T G_{EF}^{-1} \left[EF - \overline{EF} \right] + \left[C_H - \overline{C_H} \right]^T G_{CB}^{-1} \left[C_H - \overline{C_H} \right]$$ Priors penalty

$$+ \int_{\upsilon} \Lambda^T \left[\frac{d\mathbf{T}_s}{dt} - \mathbf{F}\left(\mathbf{T}_s, EF, C_H \right) \right] dt$$ Adjoined physical constraint

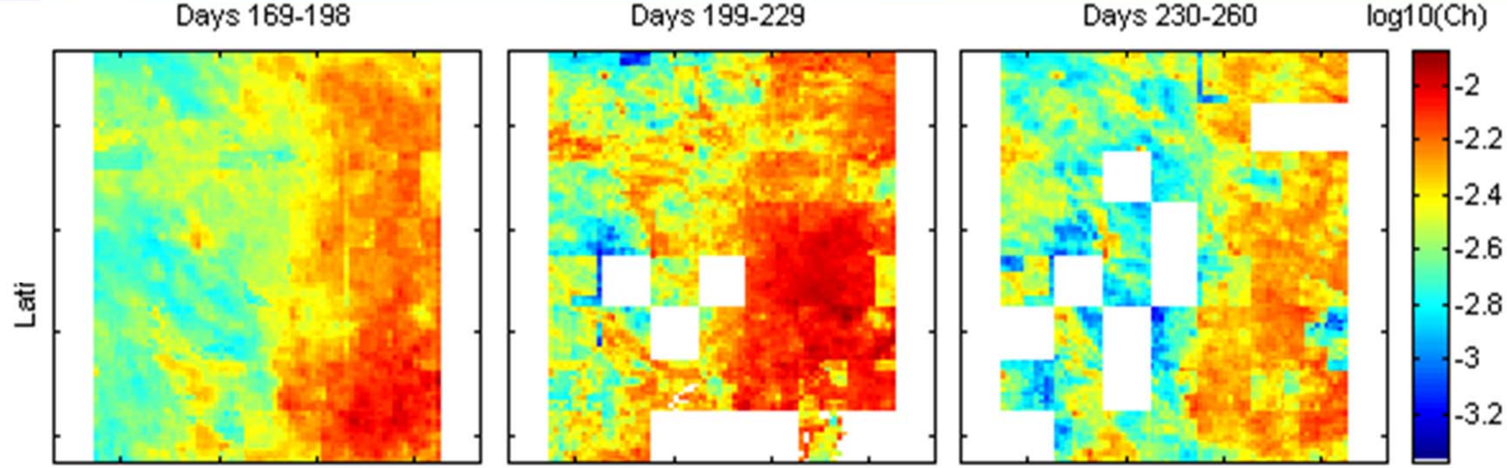
Forcing: $T_a \quad \|U\| \quad R^{\downarrow}$

EF varies **daily.**
$\boldsymbol{C_H}$ varies **monthly**.

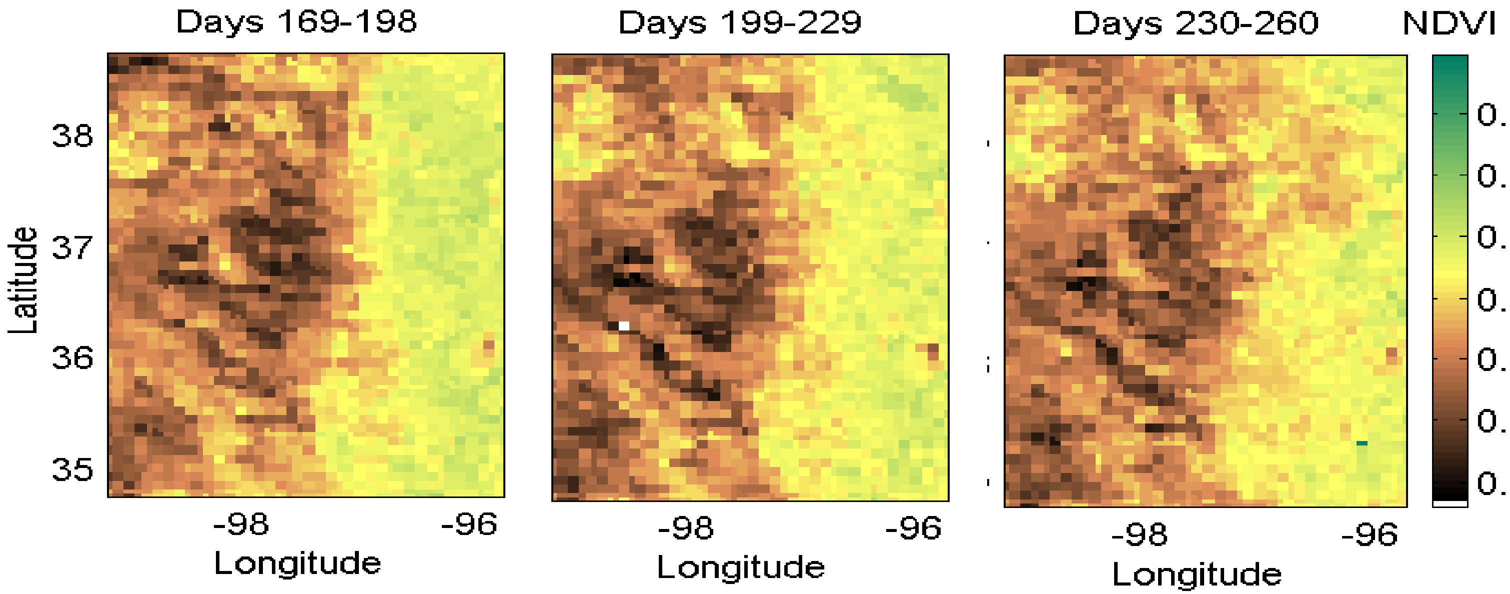
Bateni and Entekhabi (2012b)

Estimation of Turbulent Transfer Coefficient

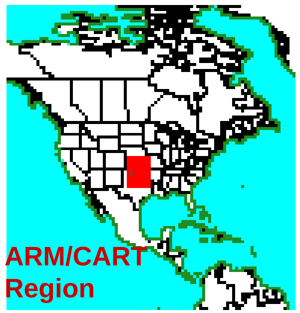
Jet Propulsion Laboratory
California Institute of Technology



C_{H_N}

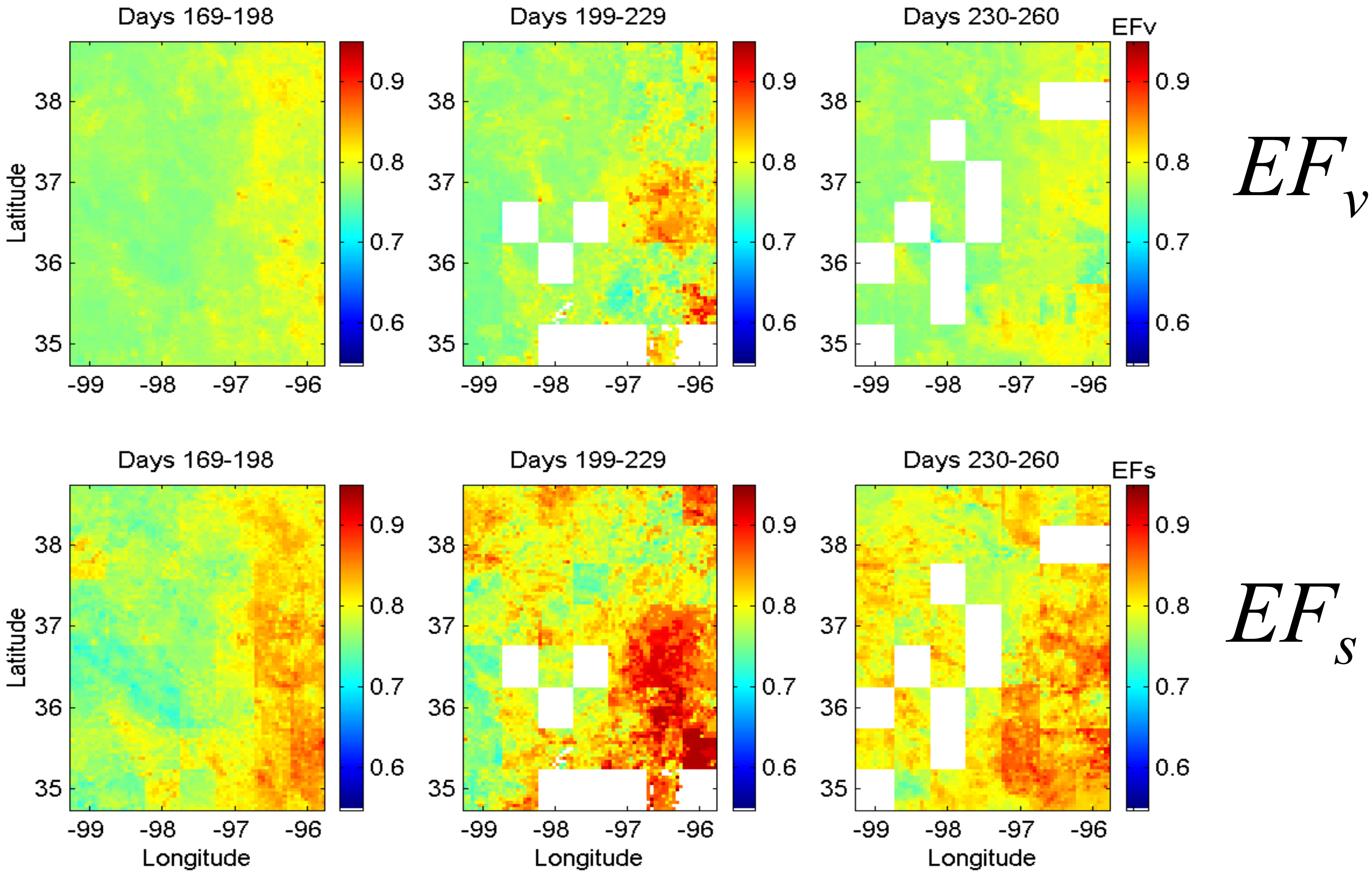


NDVI (withheld from estimation)



Bateni and Entekhabi (2012b)

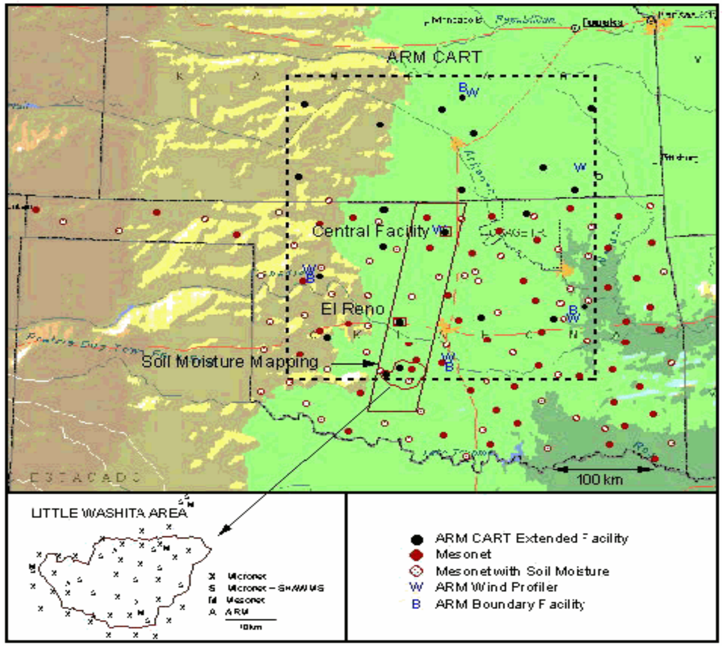
Components of Evaporative Fraction



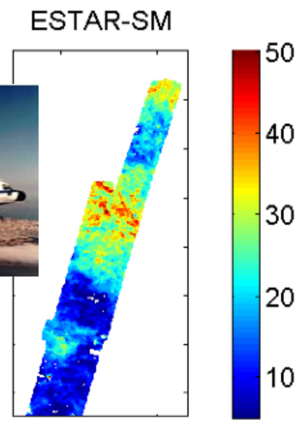
Bateni and Entekhabi (2012b)

ARM/CART Site Application

Well-instumented DoE's Atmospheric Radiation Measurement (ARM) Cloud and Radiation Testbed (CART)



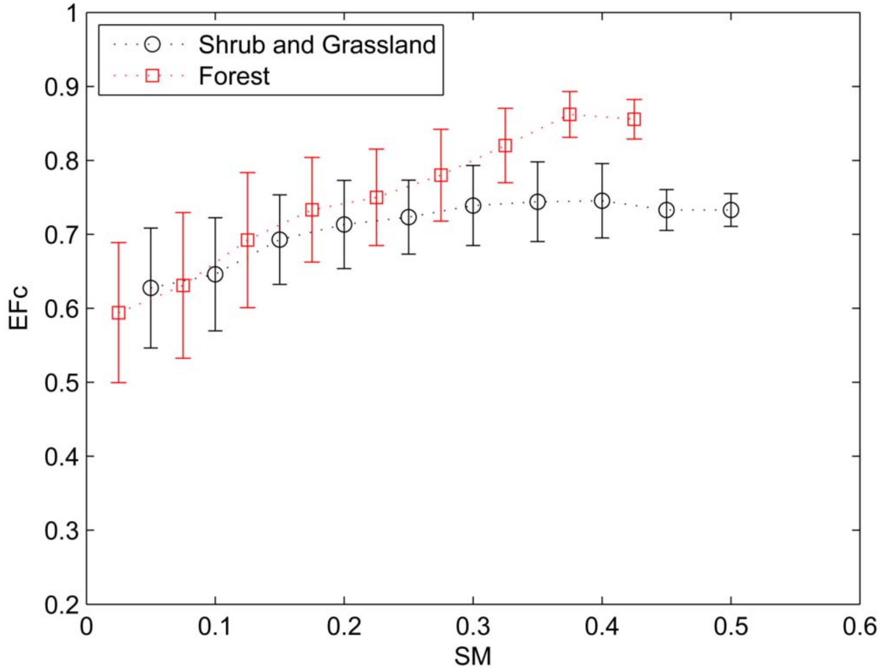
Southern Great Plain (SGP97)



Airborne L-Band Radtiometer ESTAR (Electronically Scanned Thinned Array Radiometer)

Example $EF(\theta)$ Closure Relationship Estimation

Jet Propulsion Laboratory
California Institute of Technology

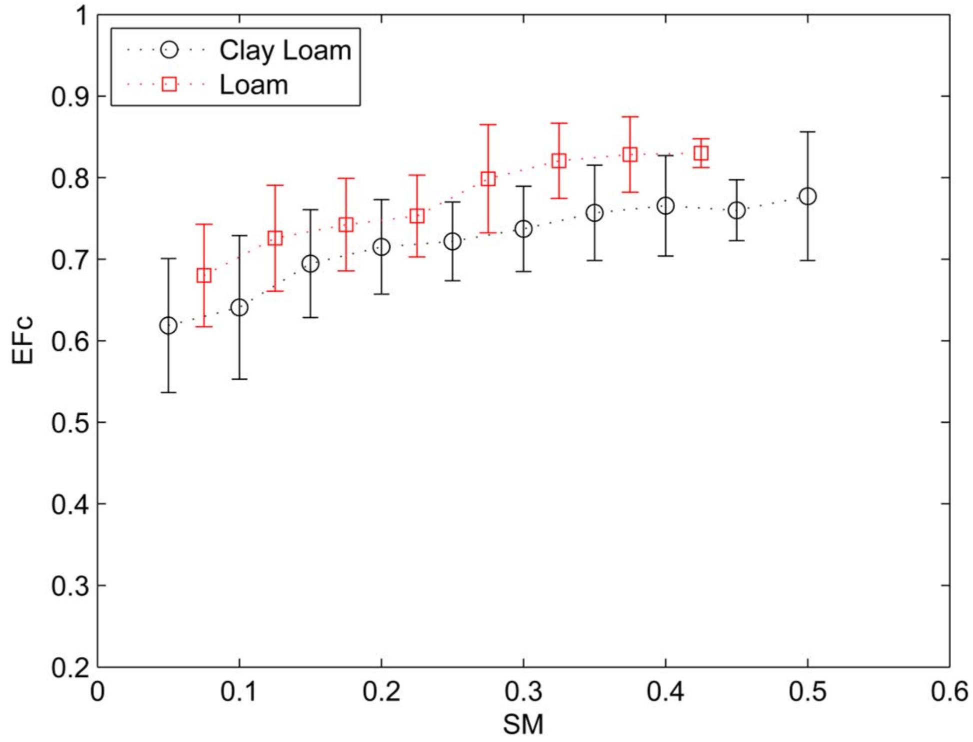


Vegetation type

Taller woody vegetation can extract moisture from deeper in the root zone and maintain higher EF values.

Soil texture

Soils with more clay content have greater root water extraction resistance and lower EF_c



Bateni and Entekhabi (2012b)

Aquarius Space-Borne Analogue

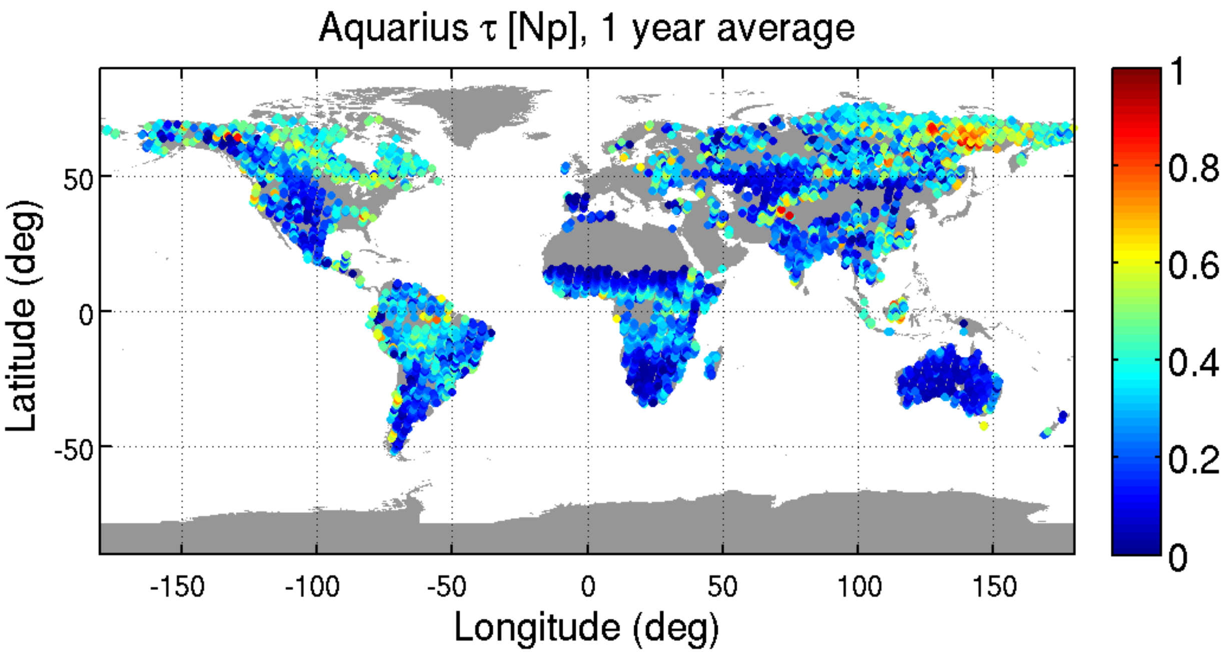
NASA Aquarius mission:

- Three L-band radiometers (θ= 29^o, 39^o, 46^o)
- L-band scatterometer
- ~ 90 km resolution (3 dB)
- ~ 7-day repeat
- ~ 3 Years of measurements

Example of future SMAP global ecology science applications

Low Frequency Microwave Active and Passive Vegetation Status Mapping

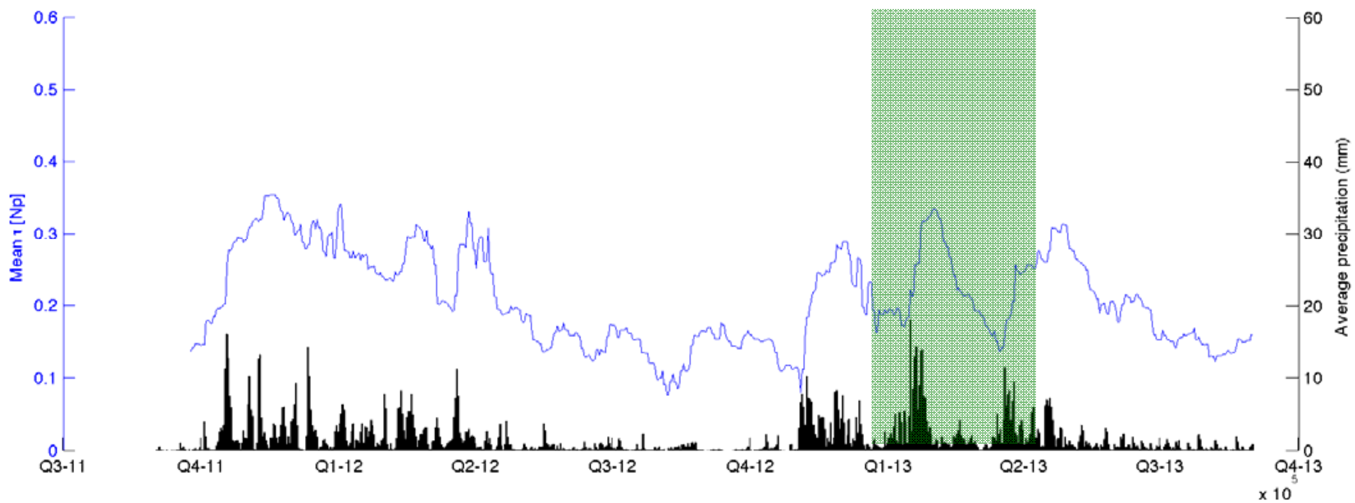
Jet Propulsion Laboratory
California Institute of Technology



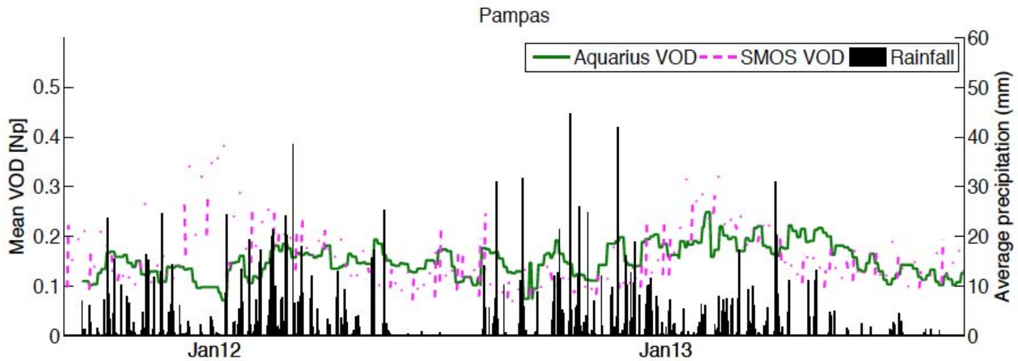
Aquarius-based feasibility study to map vegetation opacity due to water content.

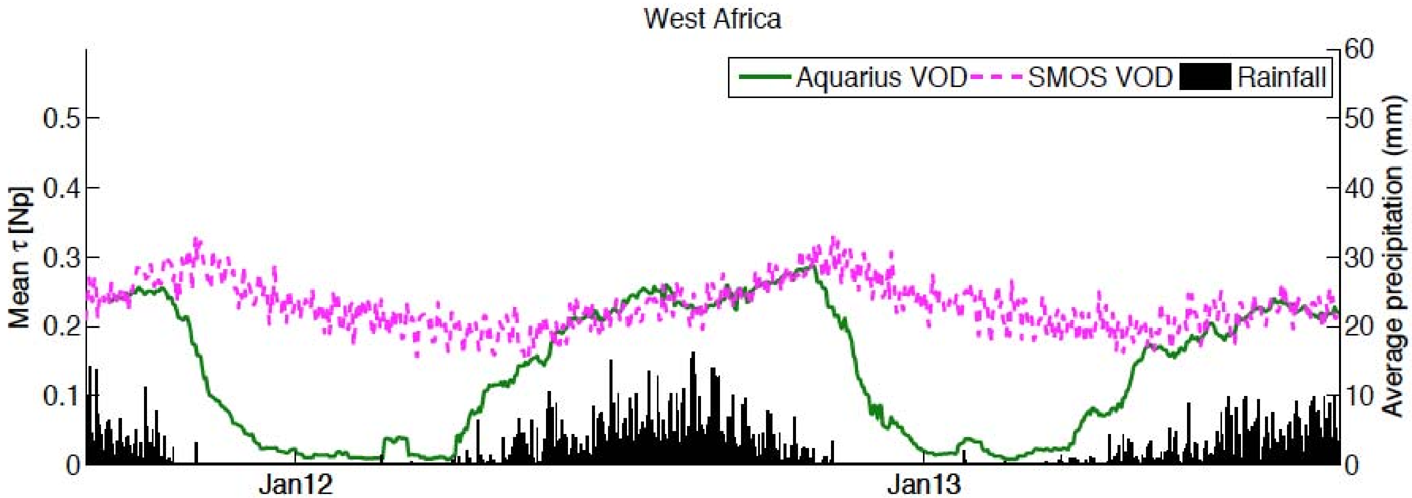
SMAP active passive measurements are at much higher resolution that is needed for vegetated landscapes.

Nordeste Region Example With a Sharp Drying Episode



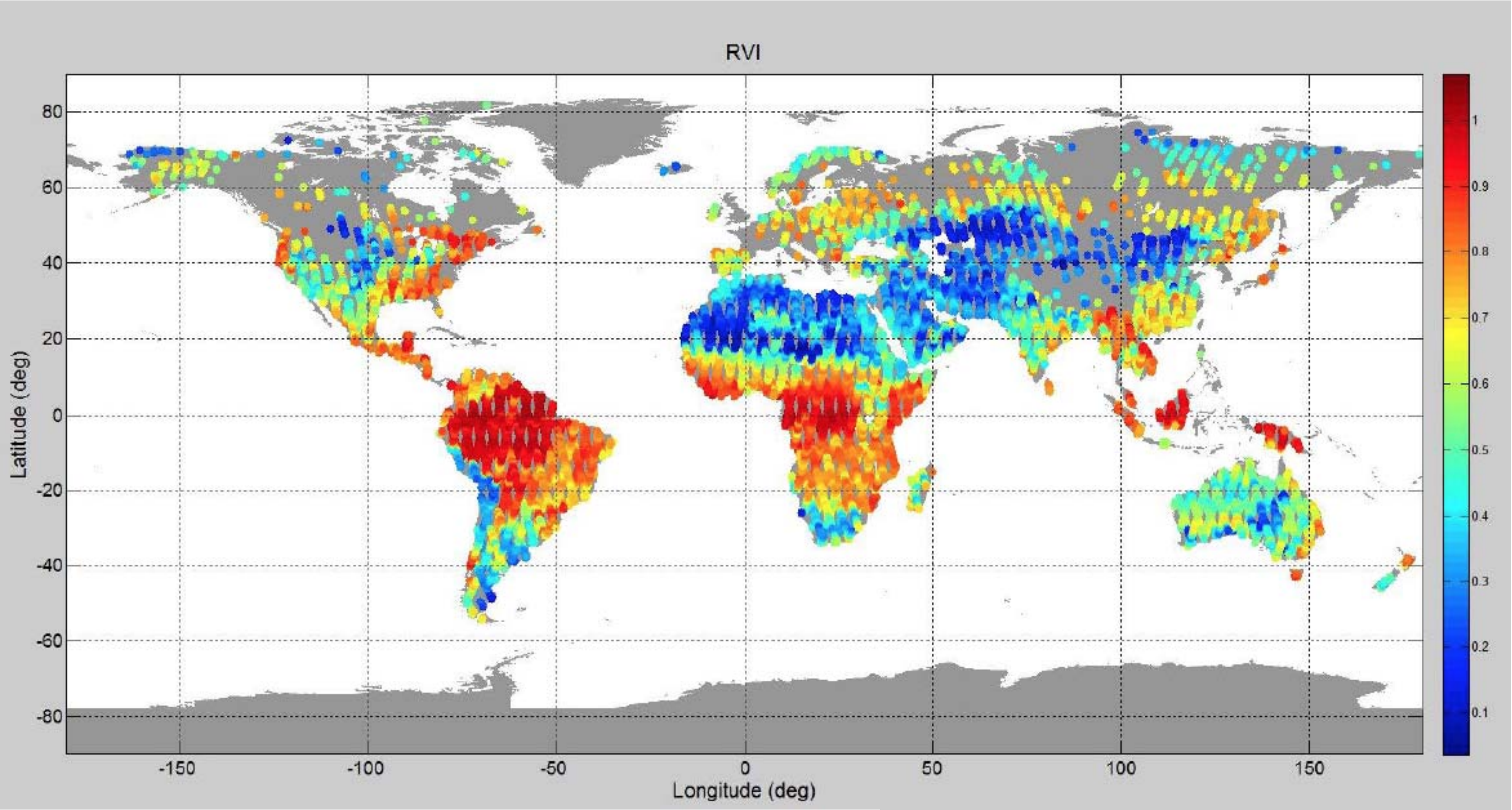
Vegetation Microwave Opacity and Biomass Water Content





Piles, Konings, Rötzer & Entekhabi (2014)

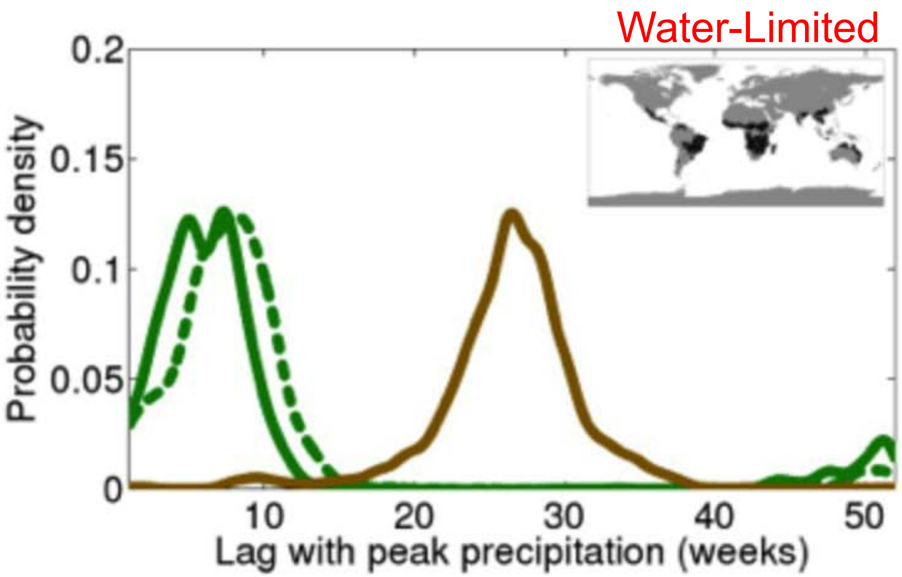
Microwave Radar Vegetation Index

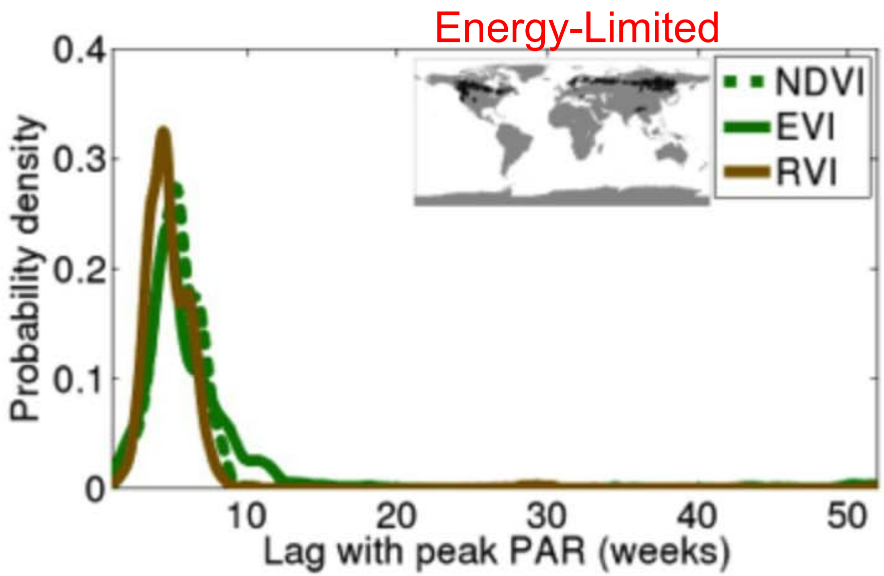


$$\mathrm{RVI} = \frac{8\sigma_{\mathrm{HV}}}{\sigma_{\mathrm{HH}} + \sigma_{\mathrm{VV}} + 2\sigma_{\mathrm{HV}}}$$

Kim and van Zyl, IGARSS 2000

Early Science Applications



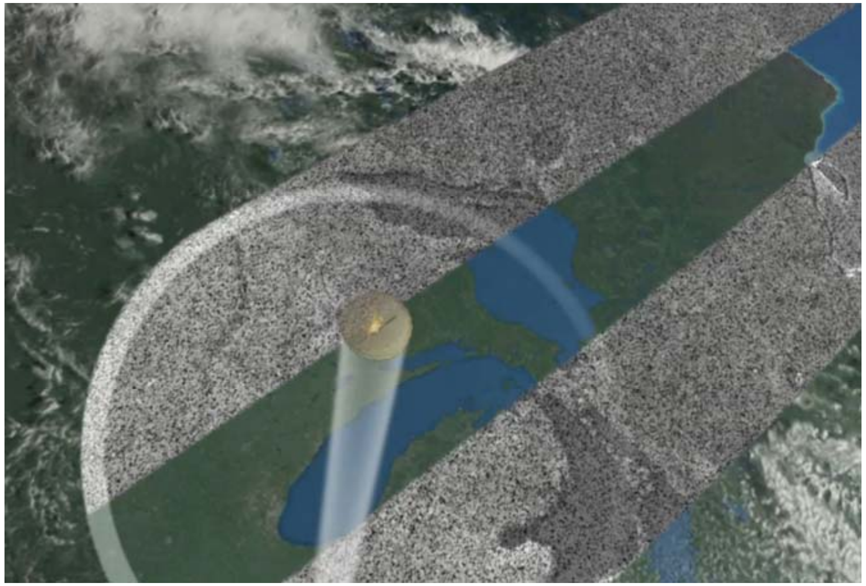


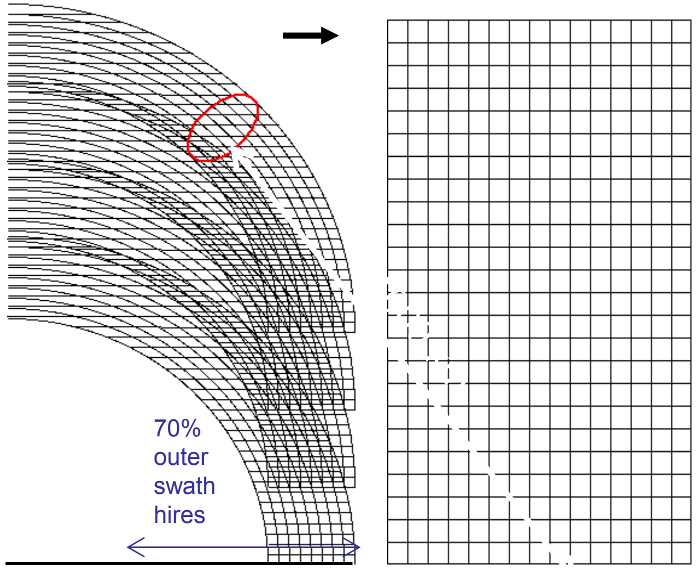
SMAP Radar Measurements

Jet Propulsion Laboratory
California Institute of Technology

HH, VV, HV
L-Band 1.26 GHz

Through Clouds and Regardless of Illumination





Single-Look

<u>1.0 dB Accuracy</u>

3 km with **2-3 days** revisit

or

1 km with **8 days** revisit

Summary

- NASA SMAP mission hardware and data systems ready for launch on January 29, 2015

- Radiometer-Radar combination for high resolution surface soil moisture estimation

- Aggressive RFI detection and mitigation hardware and software development

- With SMOS and Aquarius global L-band radiometry continuity (~decade-long data)

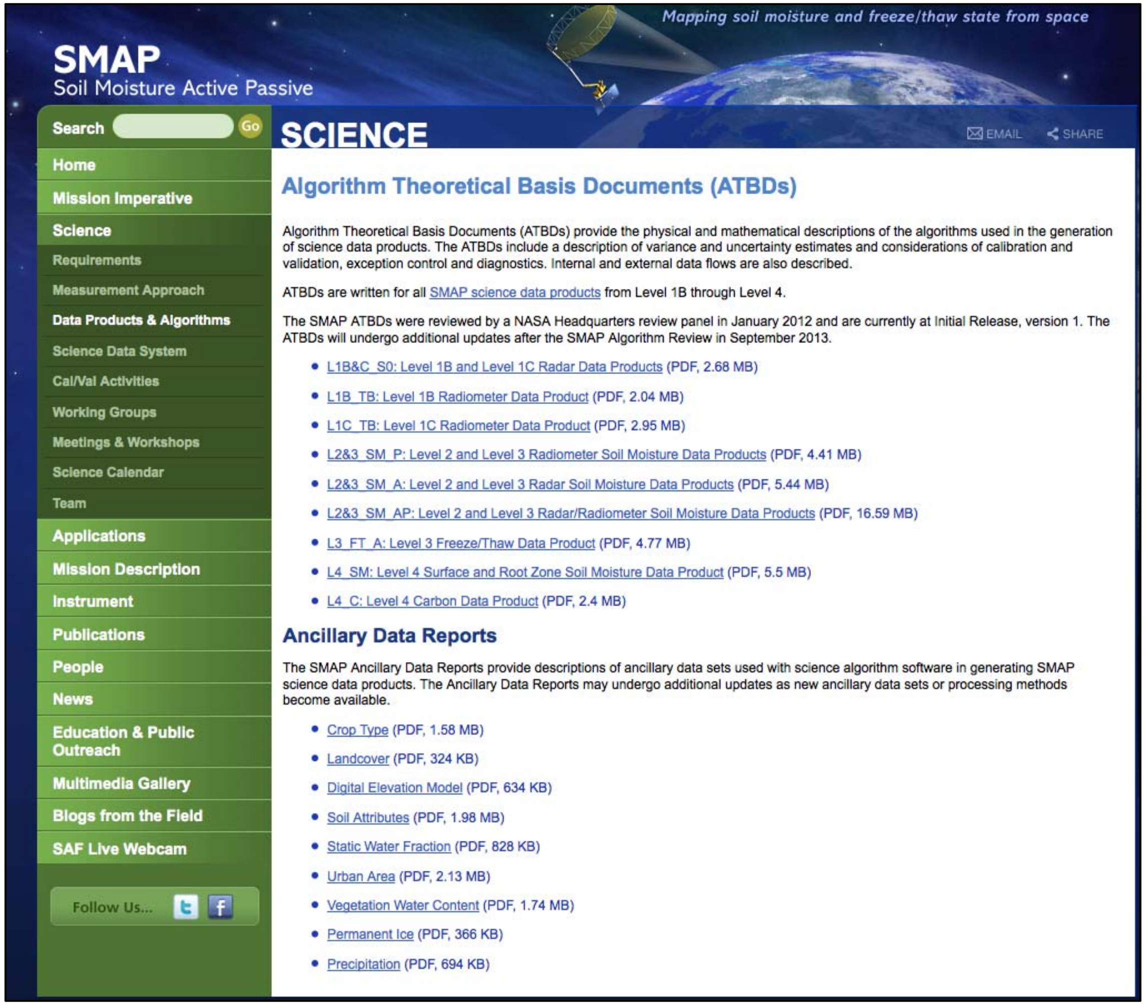
- Science impacts highlighted here:
    1. *Link* water-energy-carbon cycle over land
    2. Vegetation response to water and energy limitation

Back-Up Slides

Project Documents Availability

<u>Online:</u>

ATBDs x 9
Ancillary Data Reports x 9
Cal/Val Plan
Applications Plan



http://smap.jpl.nasa.gov/science/dataproducts/ATBD/

SMAP Requirements Traceability

Science Objectives	**Scientific Measurement Requirements**	**Instrument Functional Requirements**	**Mission Functional Requirements**
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.	Soil Moisture: ~4% volumetric accuracy in top 5 cm for vegetation water content < 5 kg m^{-2}; Hydrometeorology at 10 km; Hydroclimatology at 40 km	L-Band Radiometer: Polarization: V, H, U; Resolution: 40 km; Relative accuracy*: 1.5 K L-Band Radar: Polarization: VV, HH, HV; Resolution: 10 km; Relative accuracy*: 0.5 dB for VV and HH Constant incidence angle** between 35° and 50°	DAAC data archiving and distribution. Field validation program. Integration of data products into multisource land data assimilation.
	Freeze/Thaw State: Capture freeze/thaw state transitions in integrated vegetation-soil continuum with two-day precision, at the spatial scale of landscape variability (3 km).	L-Band Radar: Polarization: HH; Resolution: 3 km; Relative accuracy*: 0.7 dB (1 dB per channel if 2 channels are used); Constant incidence angle** between 35° and 50°	
	Sample diurnal cycle at consistent time of day Global, 3-4 day revisit; Boreal, 2 day revisit	Swath Width: 1000 km Minimize Faraday rotation (degradation factor at L-band)	Orbit: 670 km, circular, polar, sun-synchronous, ~6am/pm equator crossing
	Observation over a minimum of three annual cycles	Minimum three-year mission life	Three year baseline mission***

* Includes precision and calibration stability, and antenna effects

** Defined without regard to local topographic variation

*** Includes allowance for up to 30 days post-launch observatory check-out

Regions Where SMAP is Expected to Meet Science Requirements

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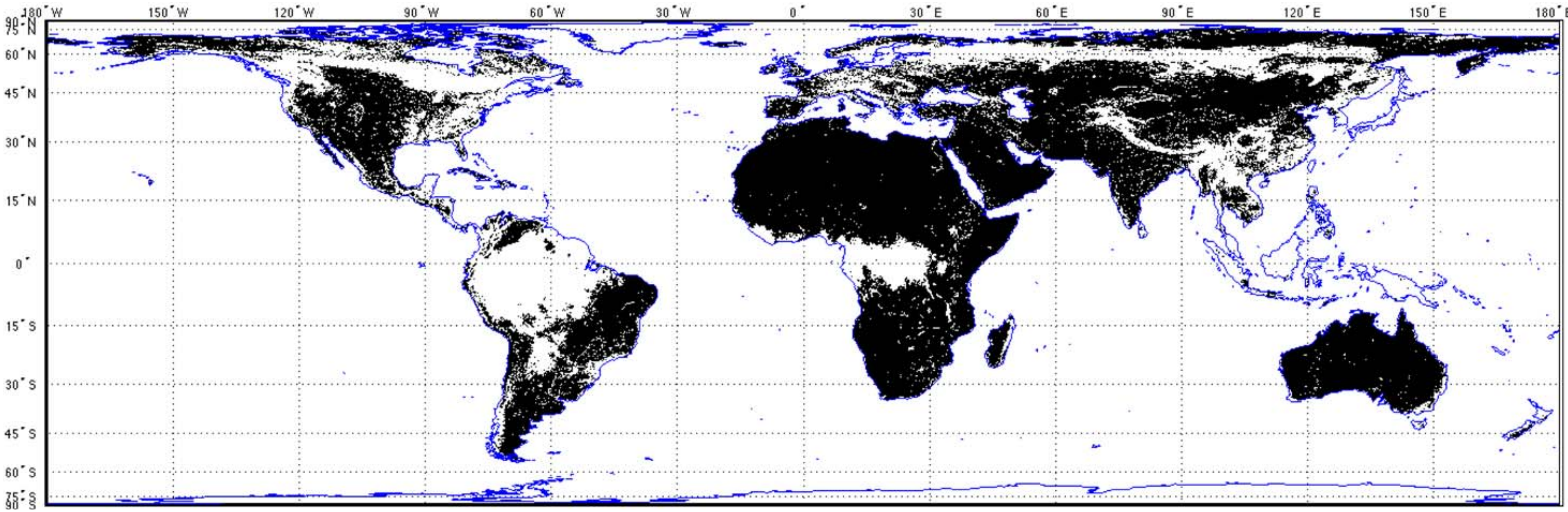
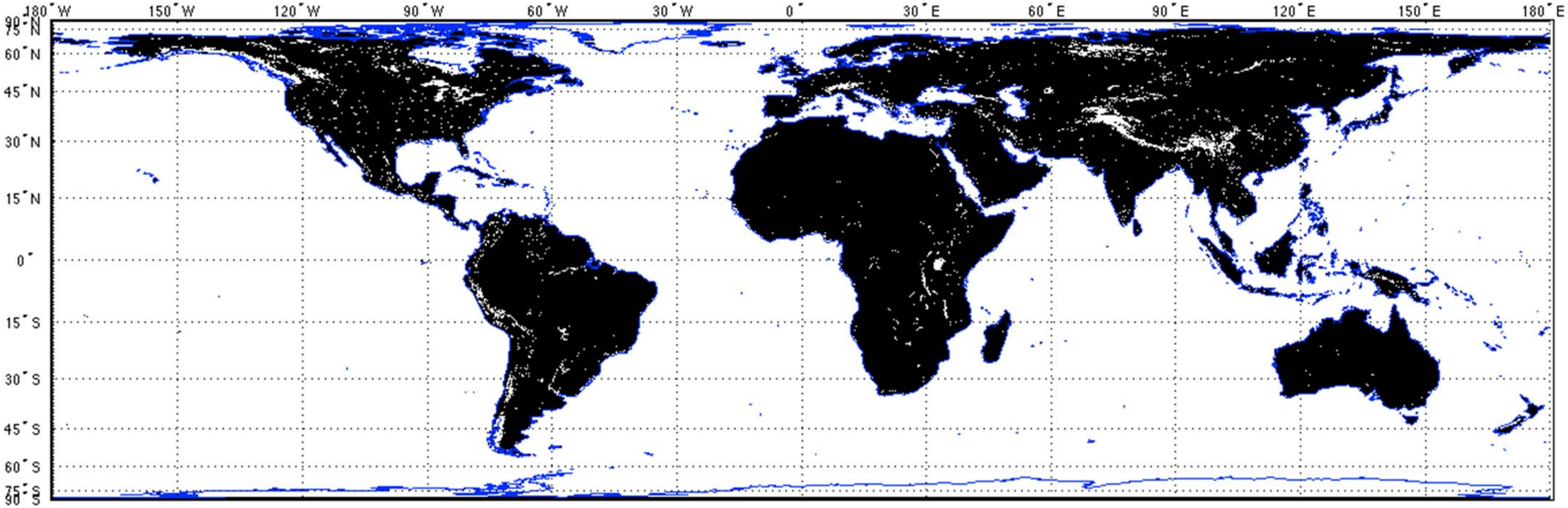


<u>At 9 km</u>:
VWC ≤ 5 kg m^{-2}
Urban Fraction ≤ 0.25
Water fraction ≤ 0.1
Elevation Slope Standard Deviation ≤ 3 deg

Regions Where SMAP Soil Moisture Algorithms Will be Executed



Retrievable Mask (Black Colored Pixels) Prepared with Following Specifications:

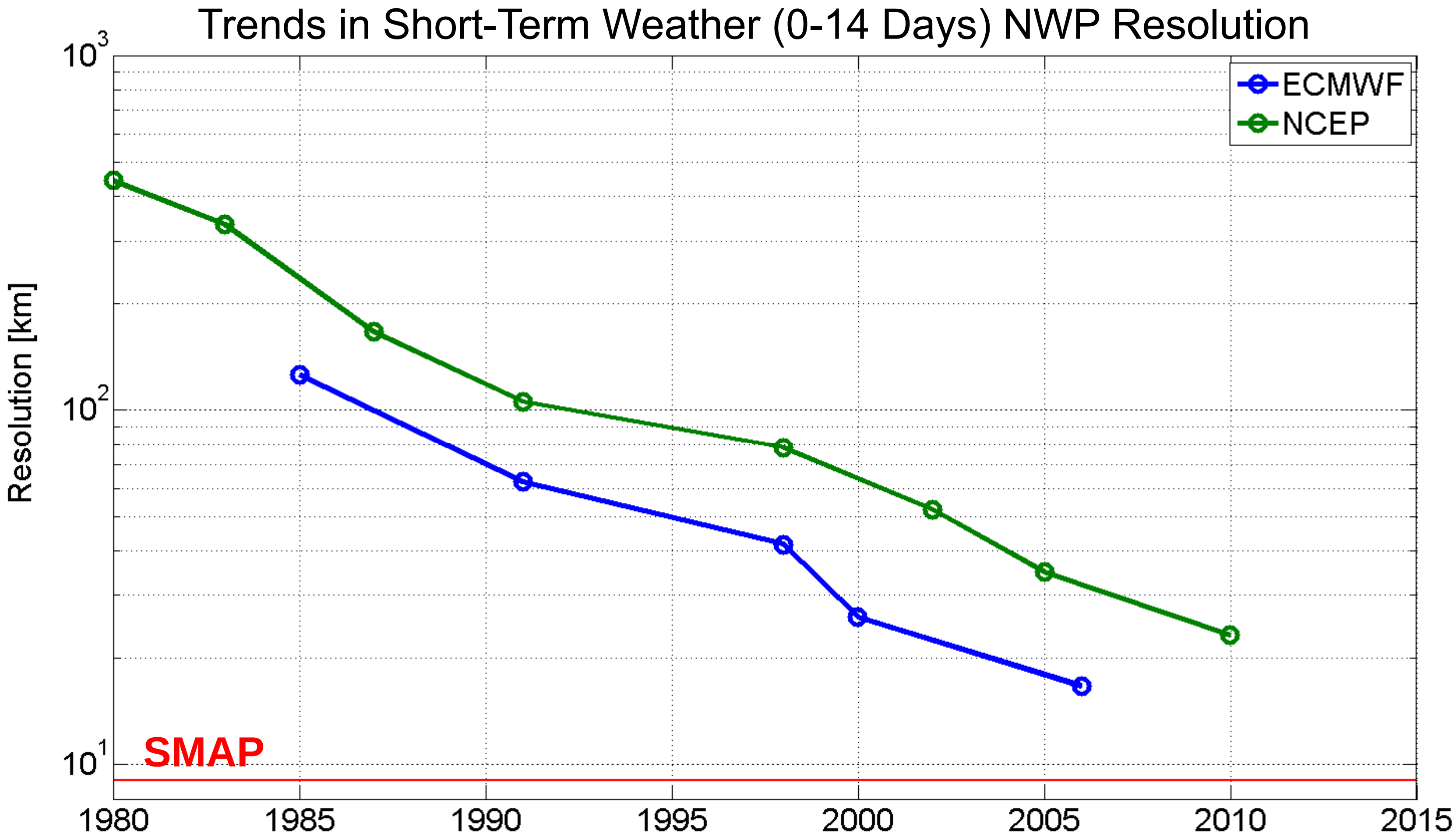
a) Urban Fraction < 1
b) Water Fraction < 0.5
c) DEM Slope Standard Deviation < 5 deg

SMAP Science Products

Jet Propulsion Laboratory
California Institute of Technology

Product	Description	Gridding (Resolution)	Latency**	
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	(36x47 km)	12 hrs	
L1B_S0_LoRes	Low Resolution Radar σ_o in Time-Order	(5x30 km)	12 hrs	
L1C_S0_HiRes	High Resolution Radar σ_o in Half-Orbits	1 km (1-3 km)	12 hrs	
L1C_TB	Radiometer T_B in Half-Orbits	36 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_AP	Soil Moisture (Radar + Radiometer)	9 km	24 hrs	
L3_FT_A	Freeze/Thaw State (Radar)	3 km	50 hrs	Science Data (Daily Composite)
L3_SM_A	Soil Moisture (Radar)	3 km	50 hrs	
L3_SM_P	Soil Moisture (Radiometer)	36 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	

Hydrometeorology Applications: NWP



Sources:
Global Forecast/Analysis System Bulletins
http://www.emc.ncep.noaa.gov/gmb/STATS/html/model_changes.html

The ECMWF Forecasting System Since 1979
http://ecmwf.int/products/forecasts/guide/The_general_circulation_model.html

Brightness Temperature Disaggregation Algorithm

Jet Propulsion Laboratory
California Institute of Technology

Evaluate

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

at scales C and M:

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

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

Subtract one from another:

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

Add and subtract $\beta(C) \cdot \sigma_{pp}(M)$ to rewrite as:

Disaggregated brightness temperature

Radiometer scale-C brightness temperature

Scale-C sensitivity parameter β times smaller scale-M variations in σ_{pp}

Contribution of scale-M variations of the parameters

L2_SM_AP Radar-Radiometer Algorithm

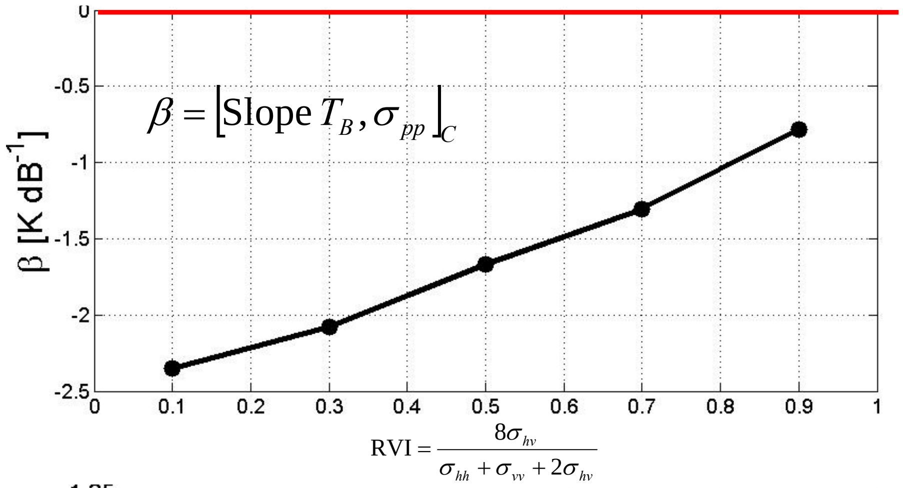
Jet Propulsion Laboratory
California Institute of Technology

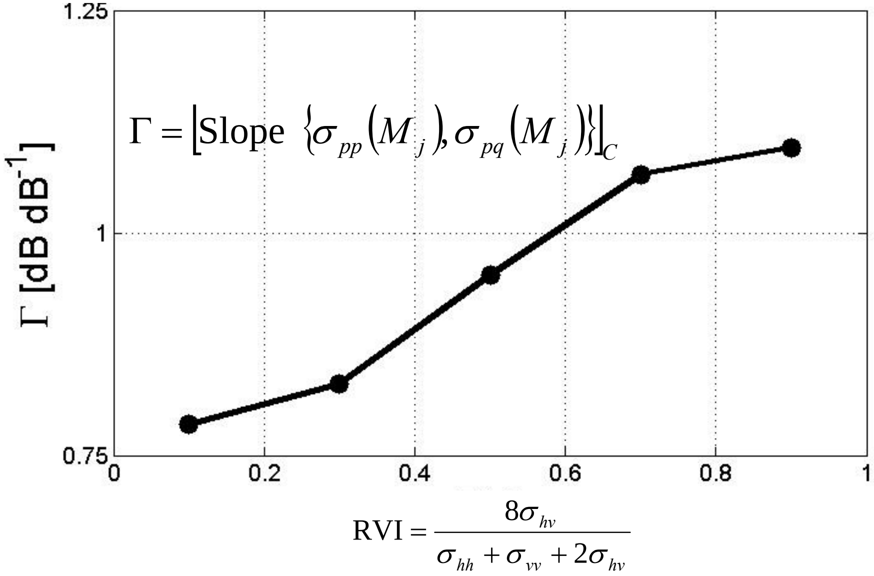
T_B-disaggregation algorithm becomes:

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

$T_B(M_j)$ is used to retrieve soil moisture at 9 km

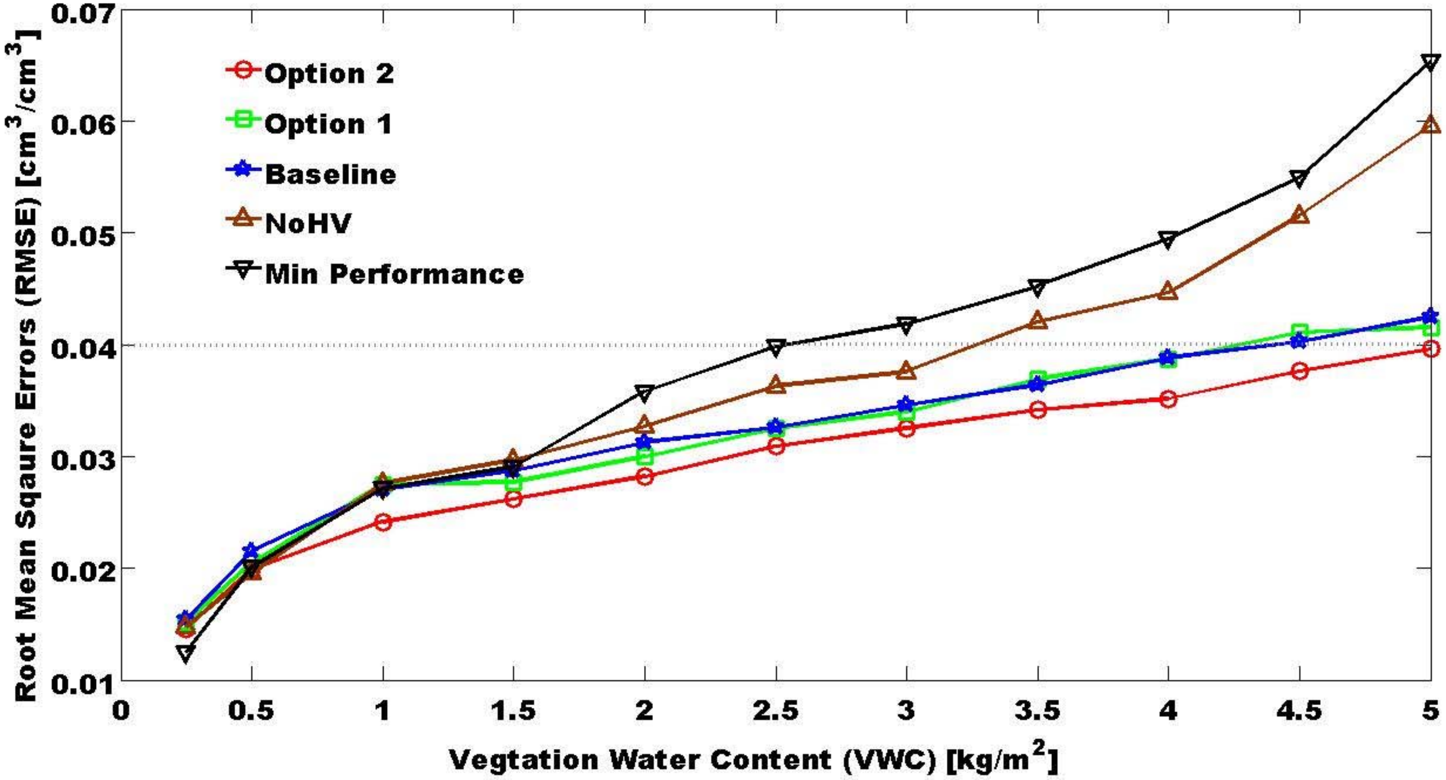
Based on PALS Observations From:
SGP99, SMEX02, CLASIC and SMAPVEX08





Summary Retrieval Error Statistics

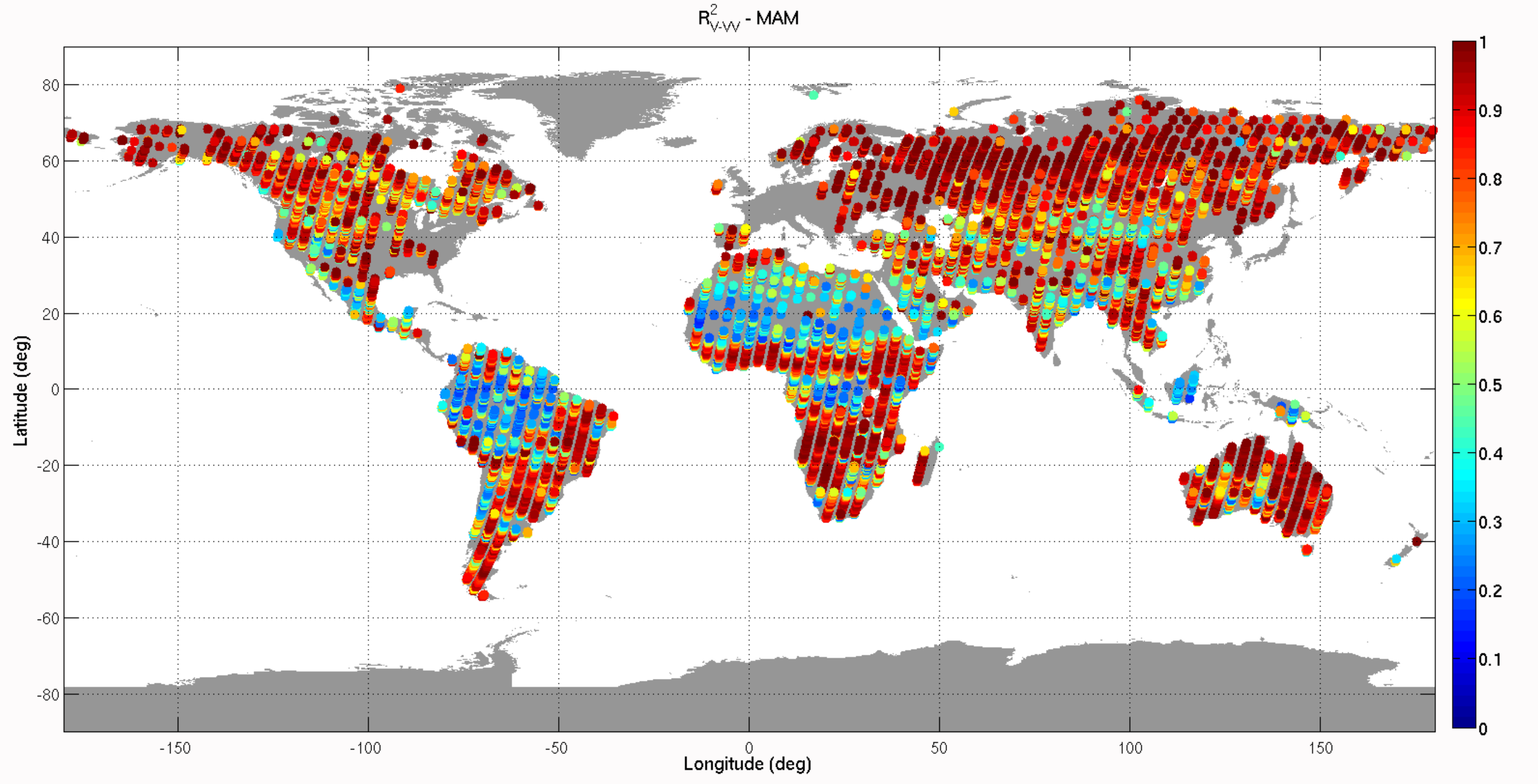
Jet Propulsion Laboratory
California Institute of Technology



- Baseline and Option Algorithms Have Comparable Performance
- Active-Passive Algorithm Meets *L1 Science Requirements and Mission Success Criteria* in GLOSIM-2 Tests
- Minimum-Performance and No-HV Algorithms Underperformance Indicate the Role of Active and Passive Measurement in Meeting Requirements

Strength of ε_V - σ_{VV} Relationship in Aquarius Measurements

Jet Propulsion Laboratory
California Institute of Technology



Percentage Explained-Variance (R^2)