Vienna University of Technology
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Microwave Remote Sensing of Soil Moisture

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Soil Moisture

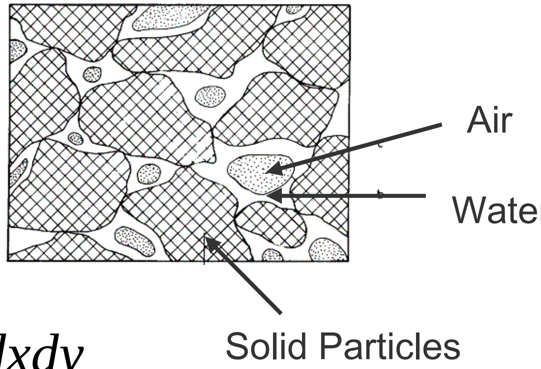
- Definition, e.g.

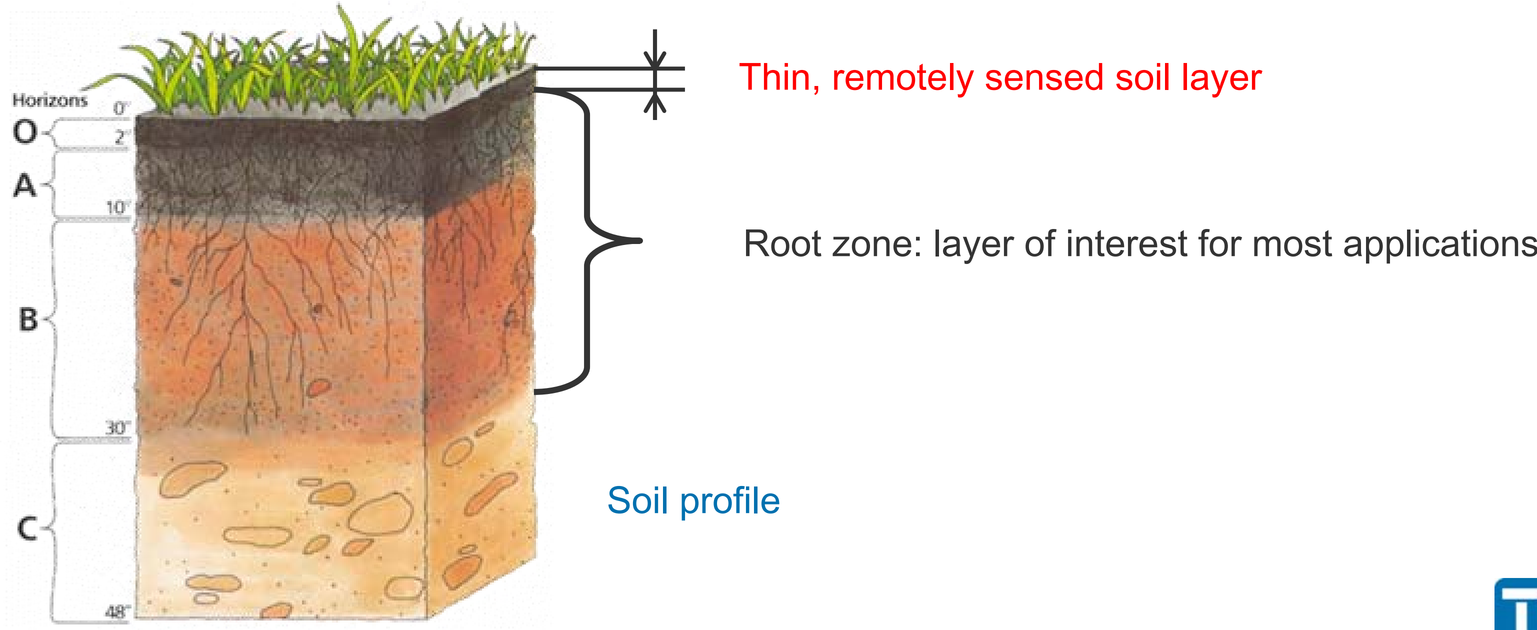
$$\theta = \frac{\text{Water Volume}\,(\text{m}^3)}{\text{Total Volume}\,(\text{m}^3)}$$

- Average

$$\langle\theta\rangle = \frac{1}{Area \cdot Depth} \int_{Area} \int_{Depth} \theta(x,y,z)\,dz\,dx\,dy$$

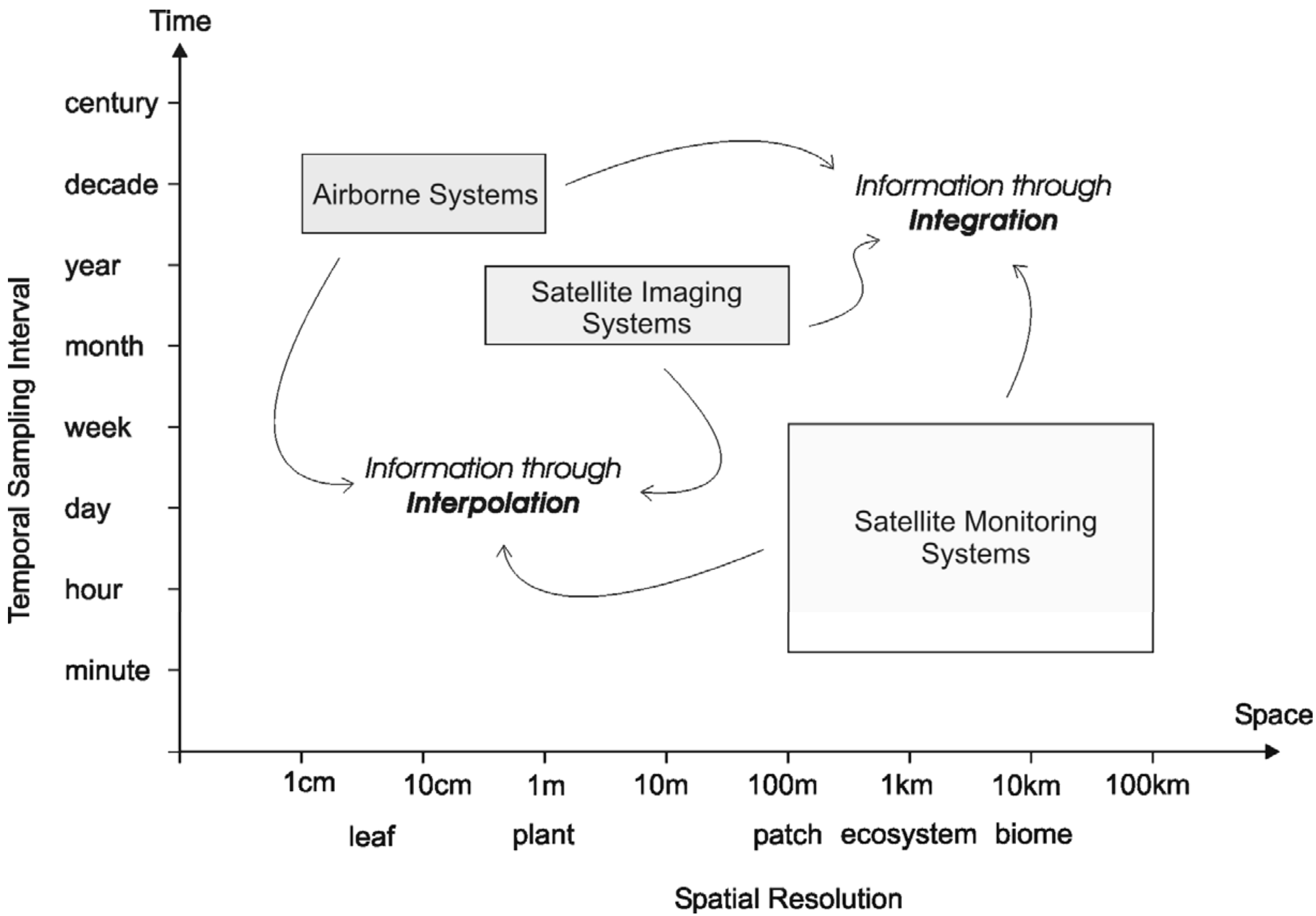
Cross-section of a soil





Soil profile

Measurement Scales



Scaling Issues

- The term “scale” refers to a
  - characteristic length
  - characteristic time
- The concept of scale can be applied to
  - Process scale = typical time and length scales at which a process takes place
  - Measurement scale = spatial and temporal sampling characteristics of the sensor system
  - Model scale = Mathematical/physical description of a process

Ideally: Process = measurement = model scale

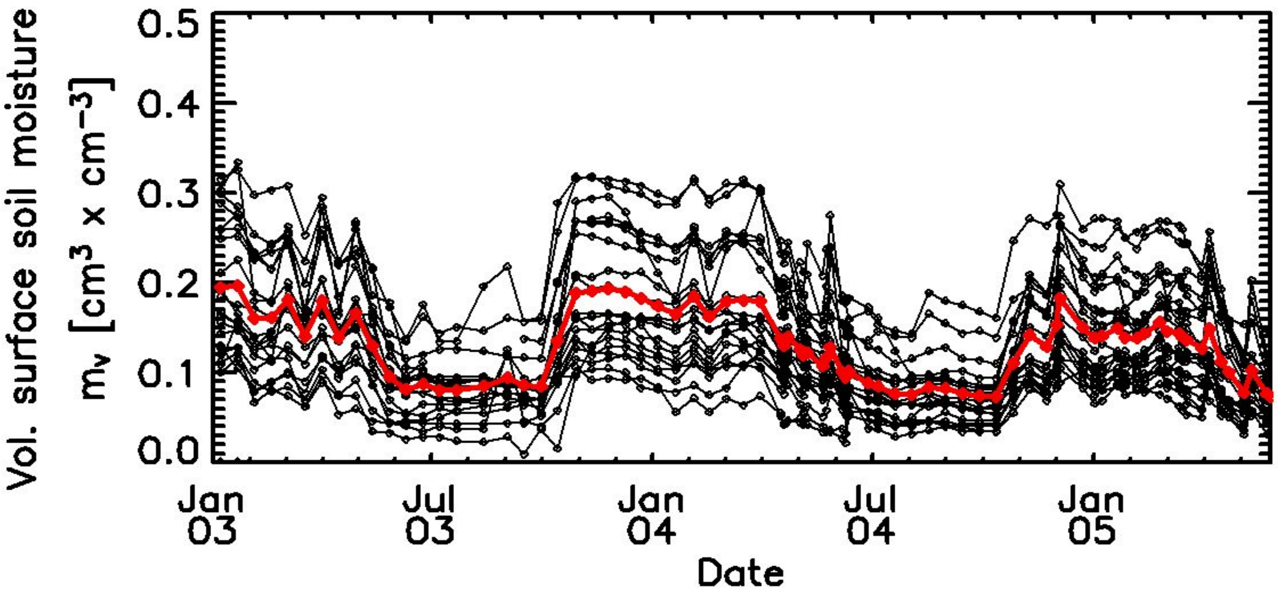
- Microwave remote sensing offers a large suit of sensors
  - Scaling issues must be understood in order to select the most suitable sensors for the application

Soil Moisture Scaling Properties

- High variability in time
  - Remotely sensed layer exposed to atmosphere
- Distinct but temporally stable spatial patterns

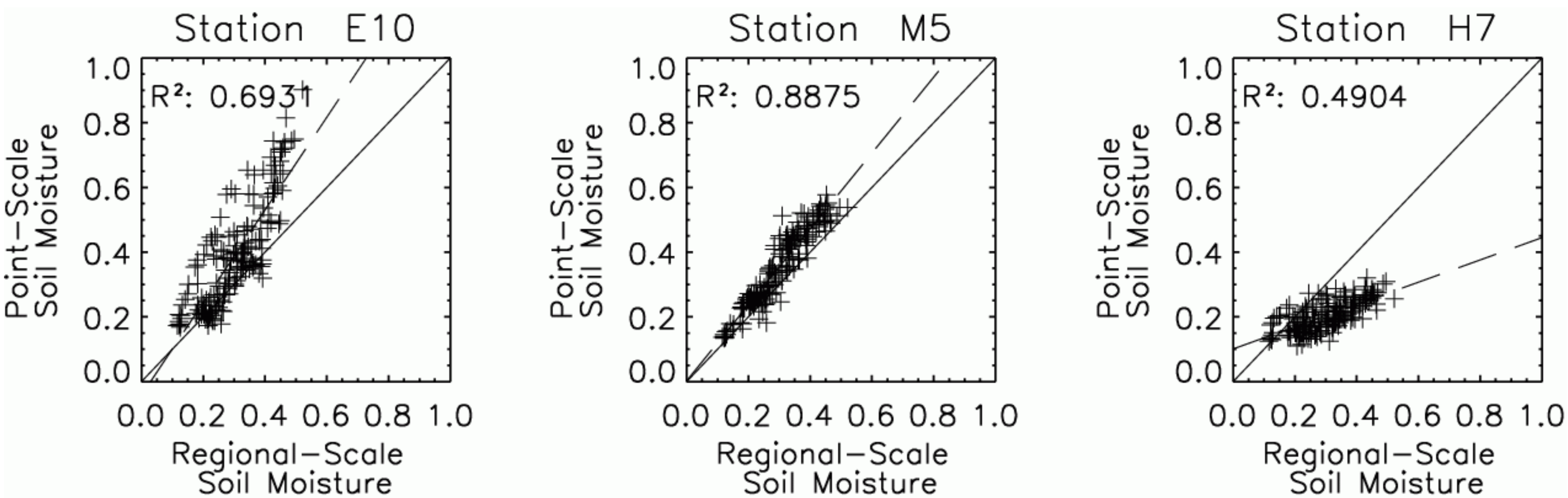
- Temporal stability means that spatial patterns persist in time
  - Vachaud et al. (1985)
    - Practical means of reducing an in-situ soil moisture network to few representative sites
  - Vinnikov and Robock (1996)
    - Large-scale atmosphere-driven soil moisture field
    - Small-scale land-surface soil moisture field

In-Situ Soil Moisture Time Series



Mean (red) and station (black) in-situ soil moisture time series. REMEDHUS network in Spain. © University of Salamanca

Time-Invariant Linear Relationship



Regional scale soil moisture

$$\theta_r(t) = \frac{1}{A_r} \iint_P \theta_p(x', y', t)\,dx'dy' = c_{rp}(x, y) + d_{rp}(x, y)\theta_p(x, y, t)$$

Local scale soil moisture

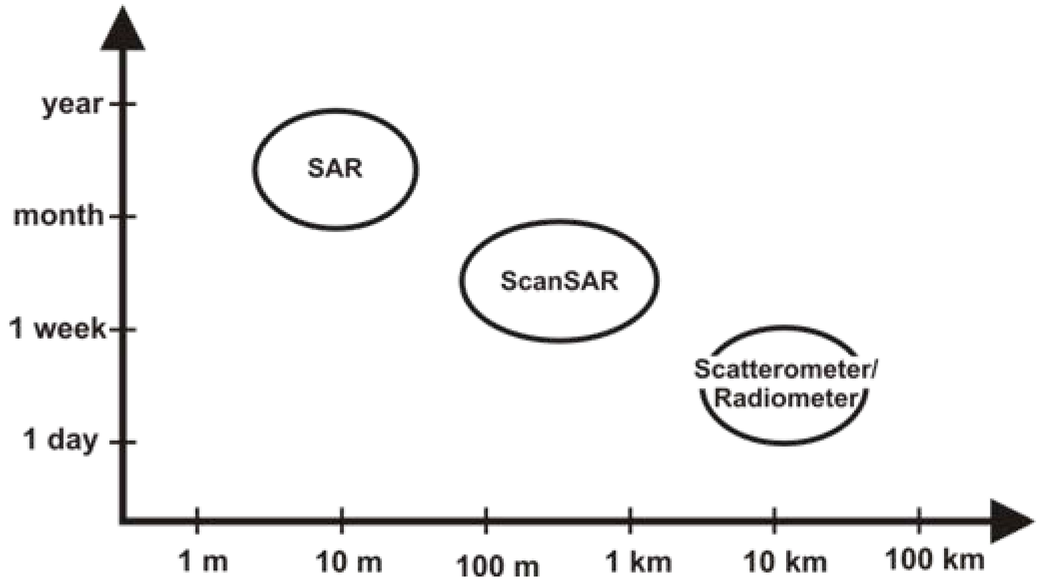
Linear scaling coefficients

Model Error ≅ 5 %

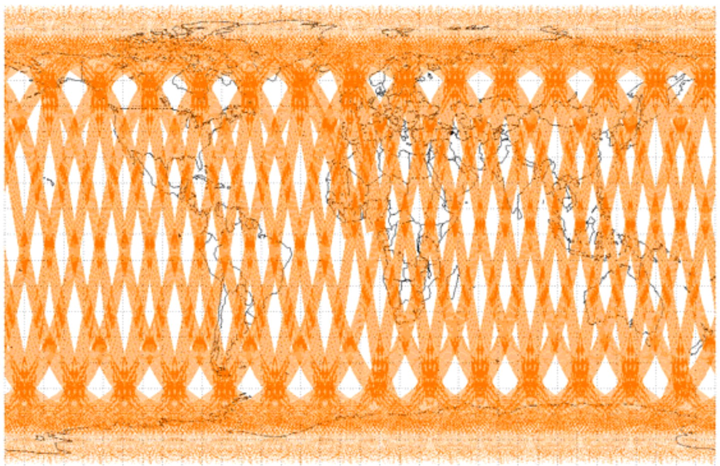
Satellite Sampling Requirements

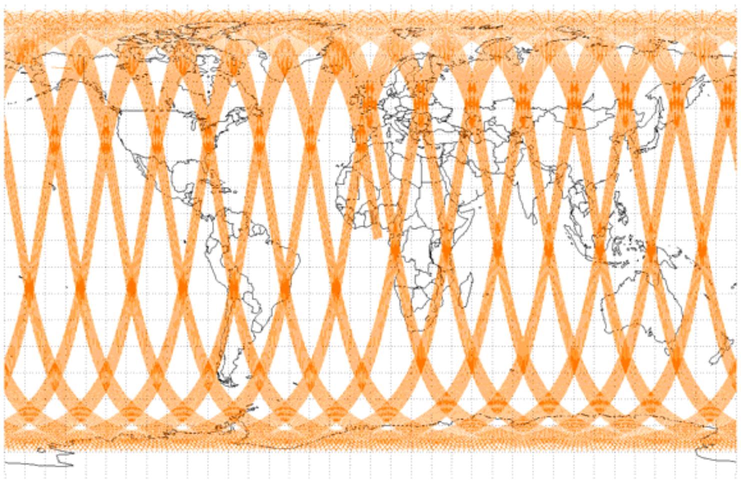
- Sampling requirements driven by
  - High temporal variability of soil moisture
  - Spatial resolution is of secondary concern

- Preference is for long-term, temporally dense data
  - Wide swath width
  - 100 % duty cycle
  - No conflicting modes



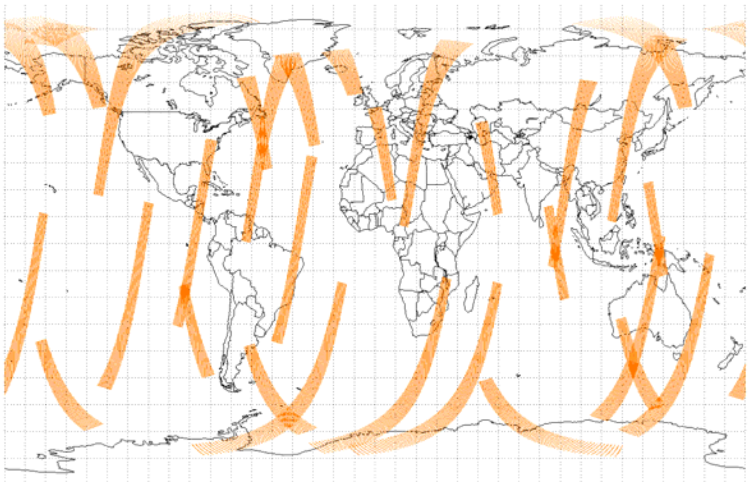
Daily Global Coverage of ASCAT and ASAR Global Monitoring Mode

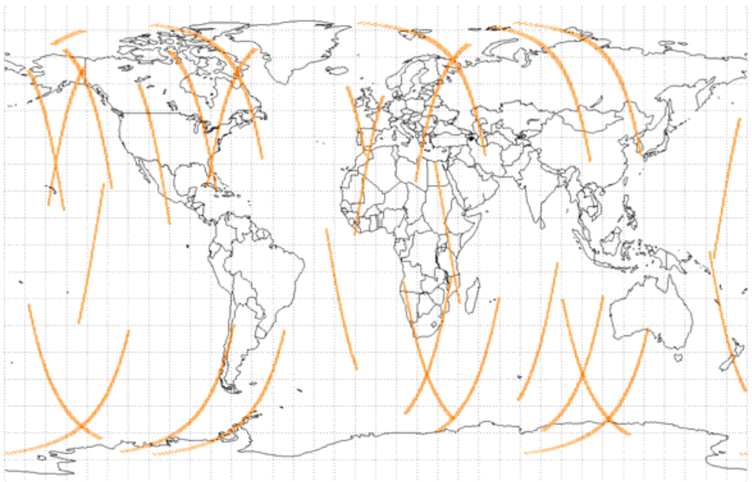




- METOP ASCAT
  - 2 swath with each 500 km
  - 25 km resolution
  - 100 % duty cycle
  - 82 % daily global coverage
- ASAR Global Monitoring Mode
  - 405 km swath
  - 1 km resolution
  - Potentially 100 % duty cycle
  - Background mission

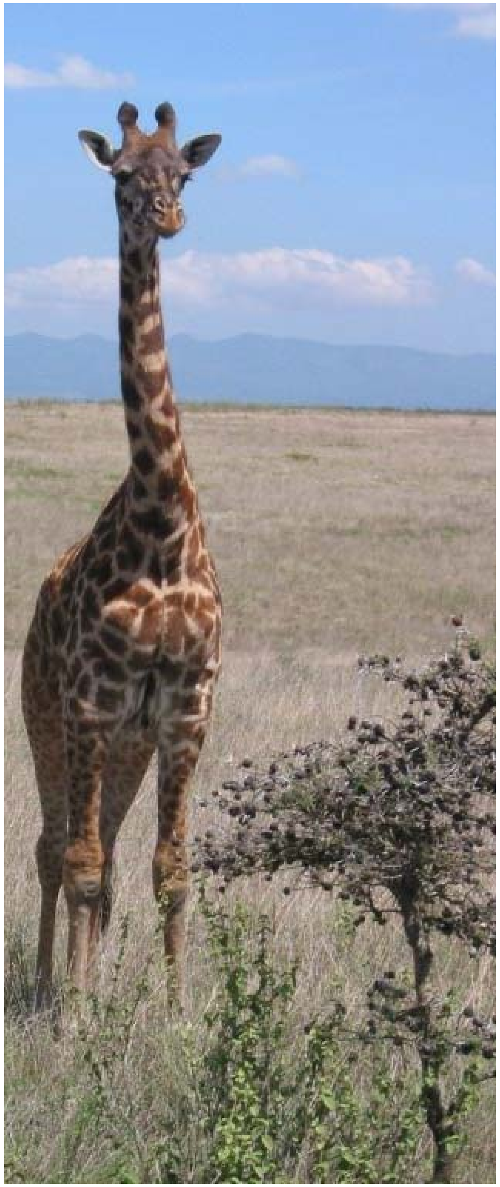
Daily Global Coverage of ASAR Wide Swath and Image Modes

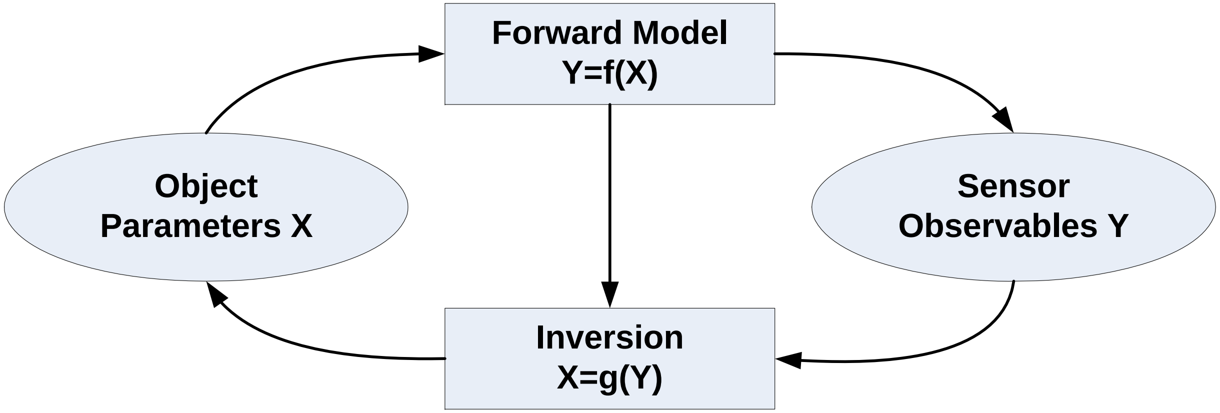




- ASAR Wide Swath Mode
  - 450 km swath
  - 150 m
  - Max. 30 % duty cycle
    - 20 min for descending orbit
    - 10 min for ascending orbit
- ASAR Imaging Mode
  - 100 km swath
  - 30 m resolution
  - Max. 30 % duty cycle

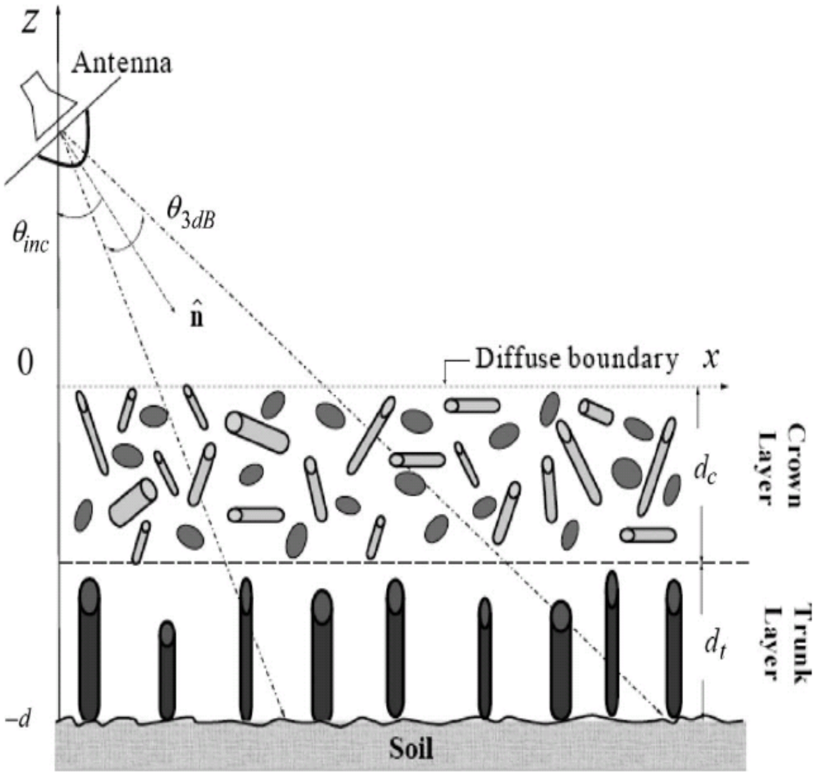
Geophysical Parameter Retrieval





- Abstraction of complex objects and measurement processes
  - Empirical models
  - Semi-empirical models
  - Theoretical models
- Inversion
  - Direct inversion
  - Least-square matching
  - Lookup tables and neural networks

Underdetermination and Ambiguity



Schematic representation of a vegetation scattering model. Kurum et al. (2009) TGRS

- Problem is underdetermined when N(**X**) >> N(**Y**)
- For complex models, two sets of input parameters $\mathbf{X}_1$ and $\mathbf{X}_2$ may result in very similar modelled **Y** values

$$Y_j = f\left(\mathbf{X}_1\right) \approx f\left(\mathbf{X}_2\right)$$

Equifinality

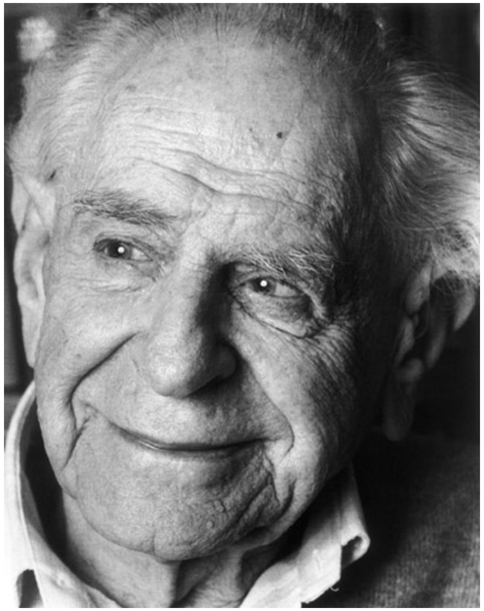
Two models are equifinal if they lead to an equally acceptable or behavioral representation of the observations

- The term is due to Karl Ludwig von Bertalanffy (1901-1972)
  - Biologist and philosopher borne in Vienna
  - Founder of General Systems Theory

Falsifiability

A theory should be considered scientific if and only if it is falsifiable

- Karl Popper (1902-1994)
  - Austrian/British philosopher borne in Vienna
  - "Logik der Forschung" in 1934

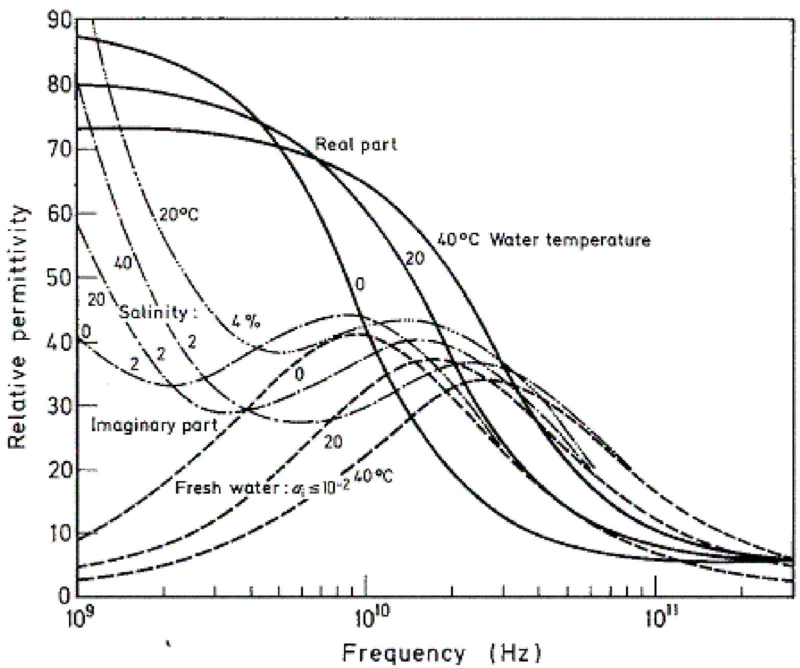


Approaches to Remote Sensing of Soil Moisture

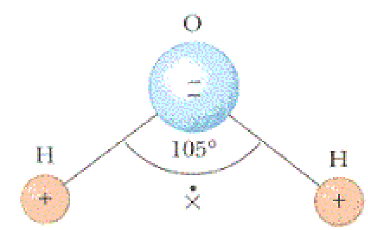
- Measurement principles
  - No direct measurement of θ possible, only indirect techniques
- Optical to Mid-Infrared (0.4 – 3 μm)
  - Change of "colour"
  - Water absorption bands at 1.4, 1.9 and 2.7 μm
- Thermal Infrared (7-15 μm)
  - Indirect assessment of soil moisture through its effect on the surface energy balance (temperature, thermal inertia, etc.)
- Microwaves (1 mm – 1 m)
  - Change of dielectric properties

Microwaves

- Microwaves (1 mm – 1 m wavelength)
  - All-weather, day-round measurement capability
  - Very sensitive to soil water content below relaxation frequency of water (< 10 GHz)
  - Penetrate vegetation and soil to some extent
    - Penetration depth increases with wavelength



Dielectric constant of water

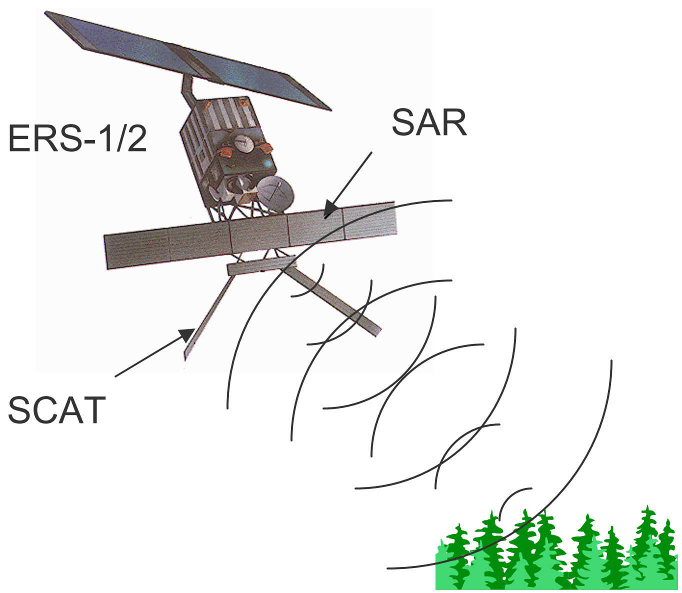


The dipole moment of water molecules causes "orientational polarisation", i.e. a high dielectric constant

Measurement Principles

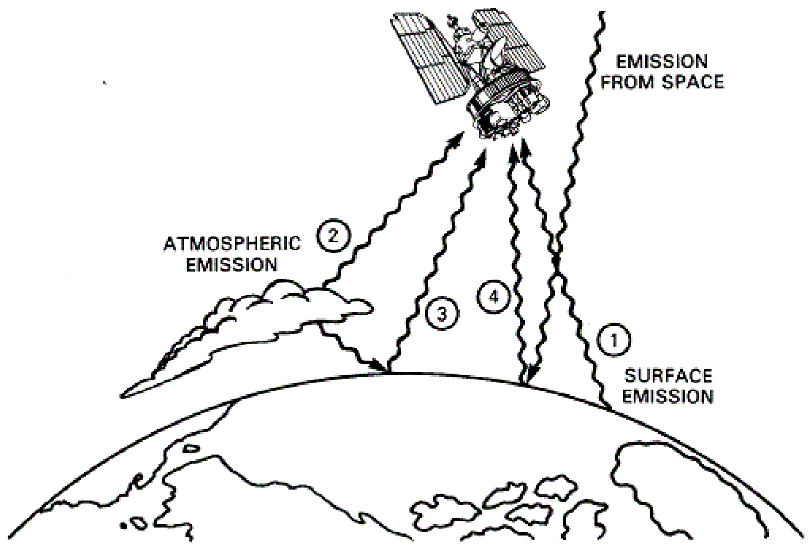
- Radars measure the energy scattered back from the surface
- Radiometers measure the self-emission of the Earth's surface

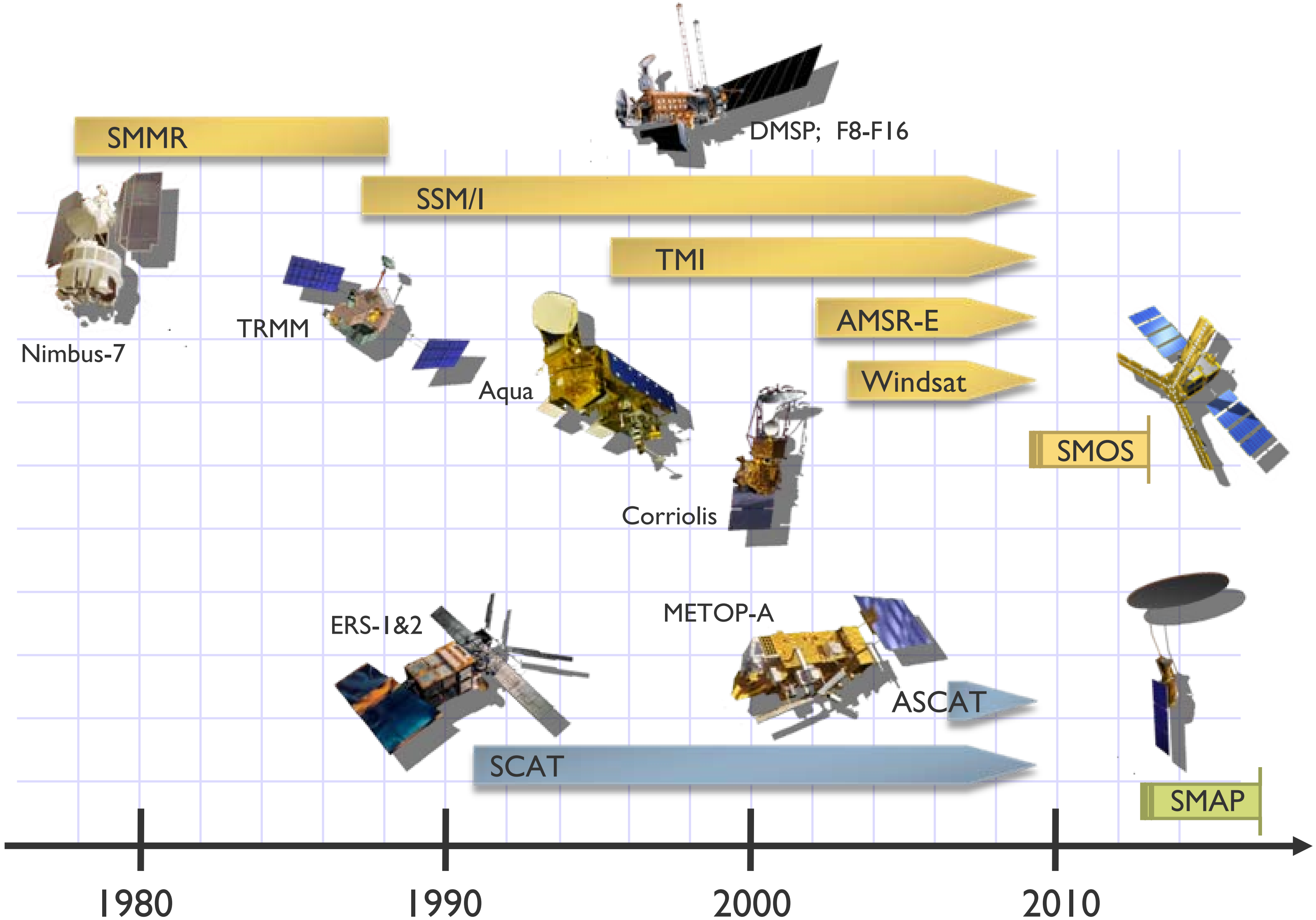
Active Sensors



SAR und scatterometer on European Remote Sensing Satellites ERS-1 and ERS-2

Passive Sensor





Active and passive microwave sensors for long-term soil moisture monitoring

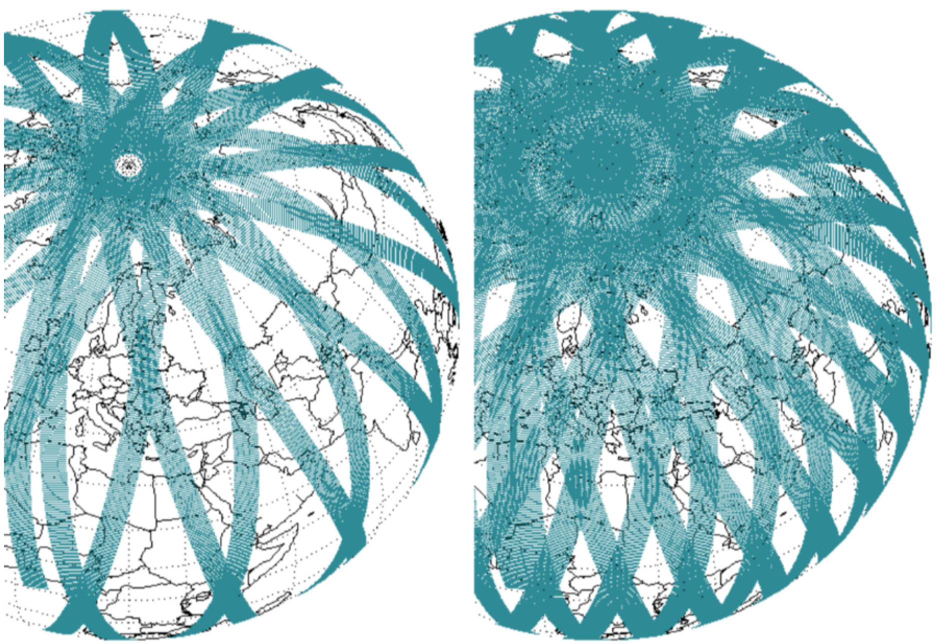
Observed Quantities

- Radars
  - Backscattering coefficient σ^0; a measure of the reflectivity of the Earth Surface
- Radiometers
  - Brightness temperature $T_B = e \times T_s$ where e = emissivity and T_s = temperature
- Active measurements are somewhat more sensitive to roughness and vegetation structure than passive measurements, but
  - are not affected by surface temperature (above 0°C)
  - have a much better spatial resolution
- Despite these differences both active and passive sensors measure essentially the same variables:
  - Passive and active methods are interrelated through Kirchhoff's law:
    - $e = 1 - r$ where r is the reflectivity
  - Increase in soil moisture content
    - backscatter ↑
    - emissivity ↓

European C-Band Scatterometers

- ERS Scatterometer
  - λ = 5.7 cm
  - VV Polarization
  - Resolution: 50 / 25 km
- Data availability
  - ERS-1: 1991-2000
  - ERS-2: since 1995
    - gaps due to loss of gyros (2001) and on-board tape recorder (2003)
  - Operations conflict with ERS SAR

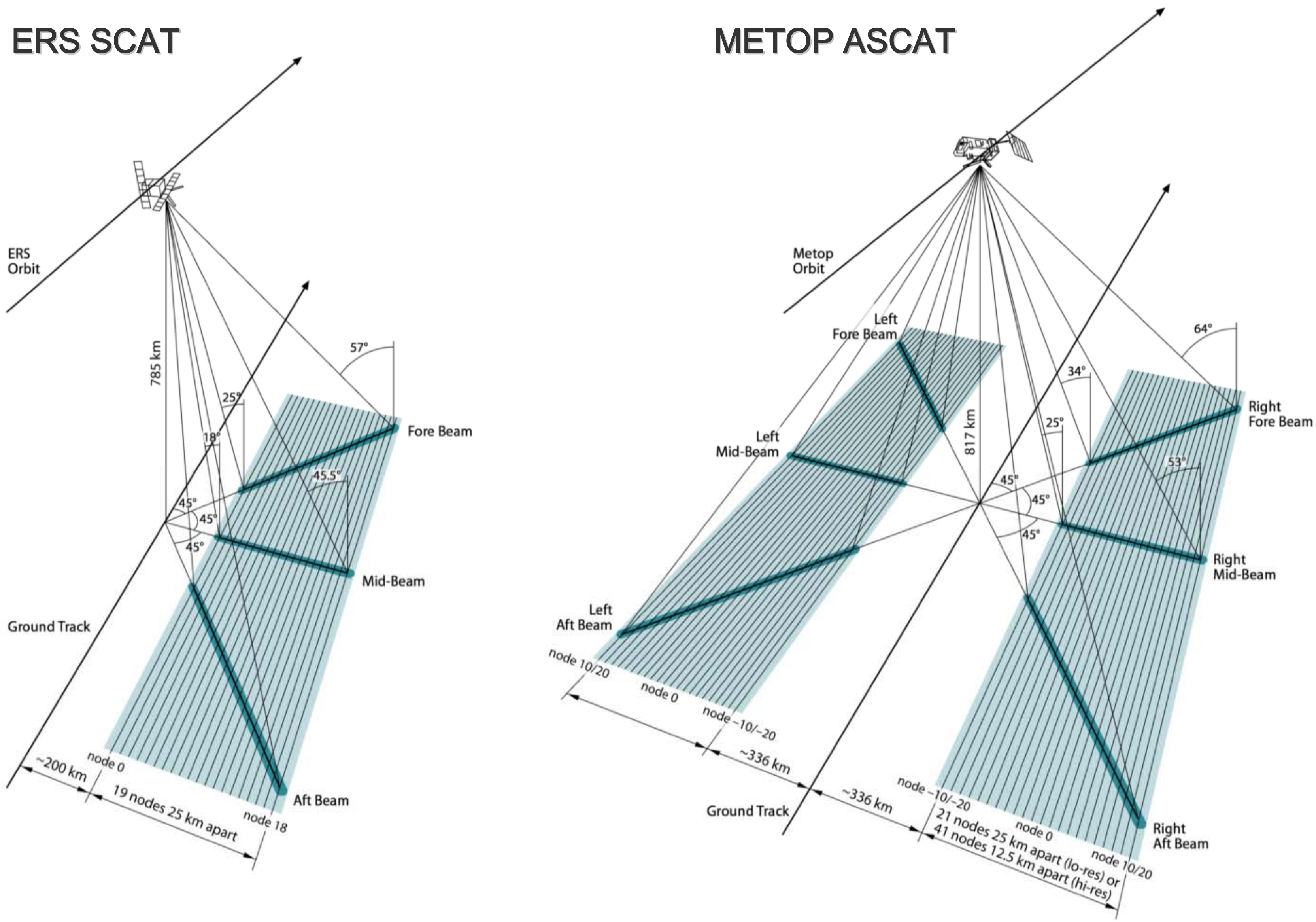
- METOP Advanced Scatterometer
  - λ = 5.7 cm
  - VV Polarization
  - Resolution: 50 / 25 km
- Data availability
  - At least 15 years
  - METOP-A: since 2006



Daily global scatterometer coverage:
ERS (left) and METOP (right)

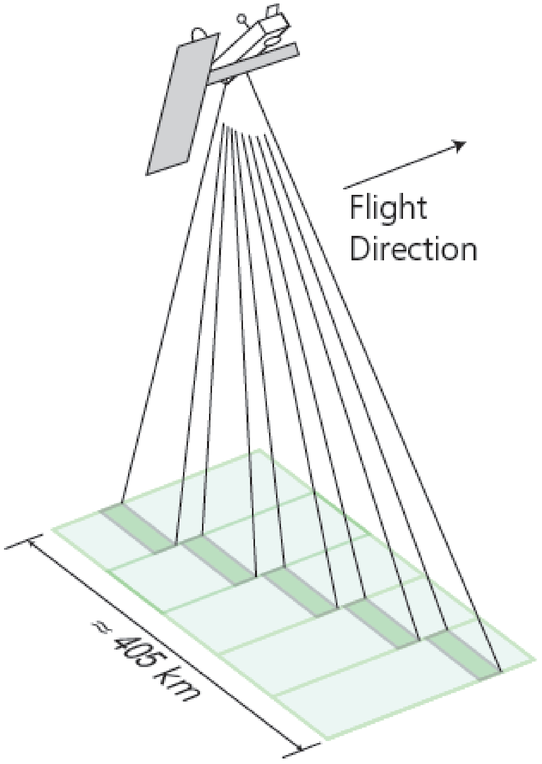
ERS SCAT

METOP ASCAT

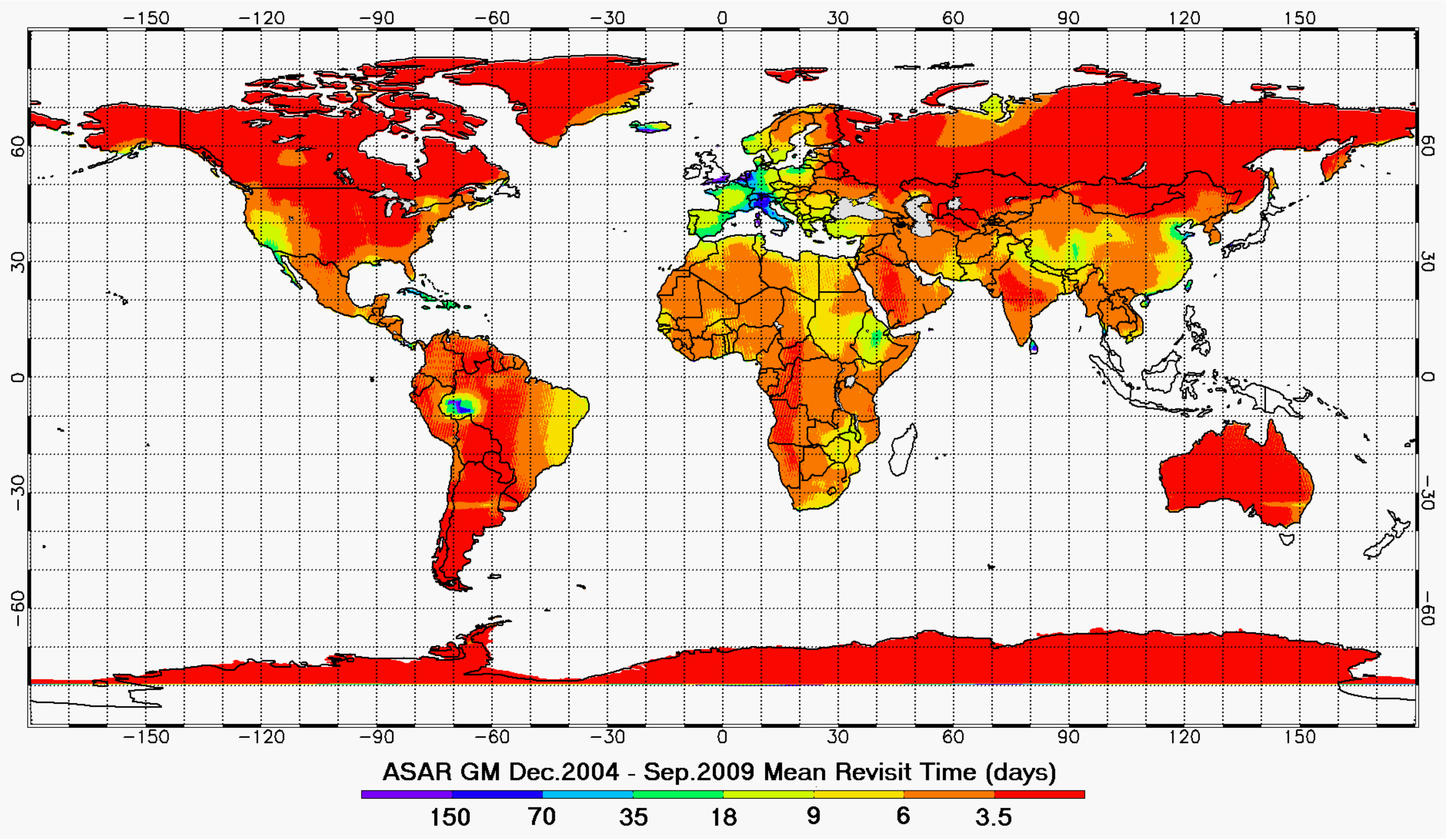


ENVISAT ASAR

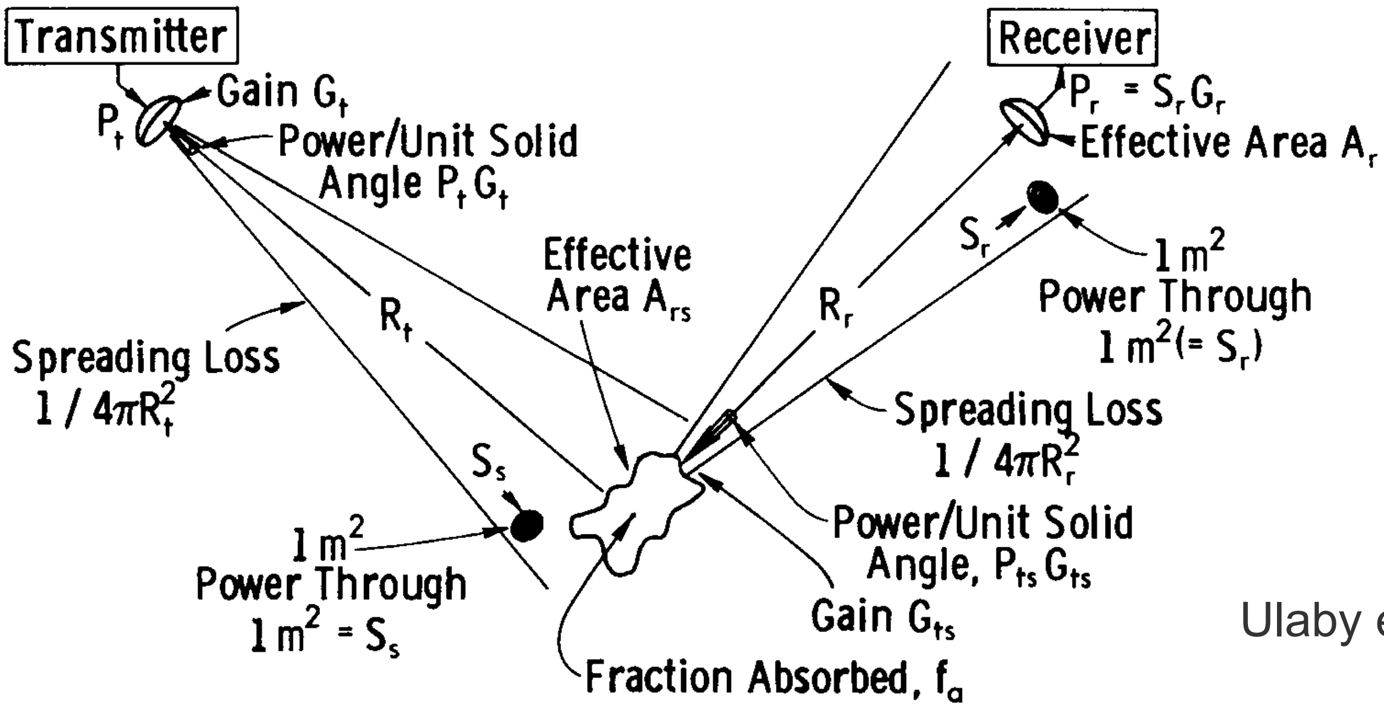
- ENVISAT
  - Launched March 1, 2002
  - Sun-synchronous, near-polar orbit
  - Altitude of 795 km
  - 14 orbits per day and nominal repeat rate 35 days
- ASAR
  - C-band SAR
    - λ = 5.67 cm / f = 5.331 GHz
  - ScanSAR modes
    - Wide Swath Mode
    - Global Mode (background mission)



ASAR Global Monitoring Mode Coverage



Radar Equation



Ulaby et al. (1982)

$$P_r = P_t \cdot G_t \cdot \frac{1}{4\pi R^2} \cdot \sigma \cdot \frac{1}{4\pi R^2} \cdot A_r$$

Target cross section

Cross Section and Backscattering Coefficient

- Radar scattering cross section σ
  - Describes the scattering properties of the targets
  - Depends on geometry and dielectric properties of targets
  - Given in m^2

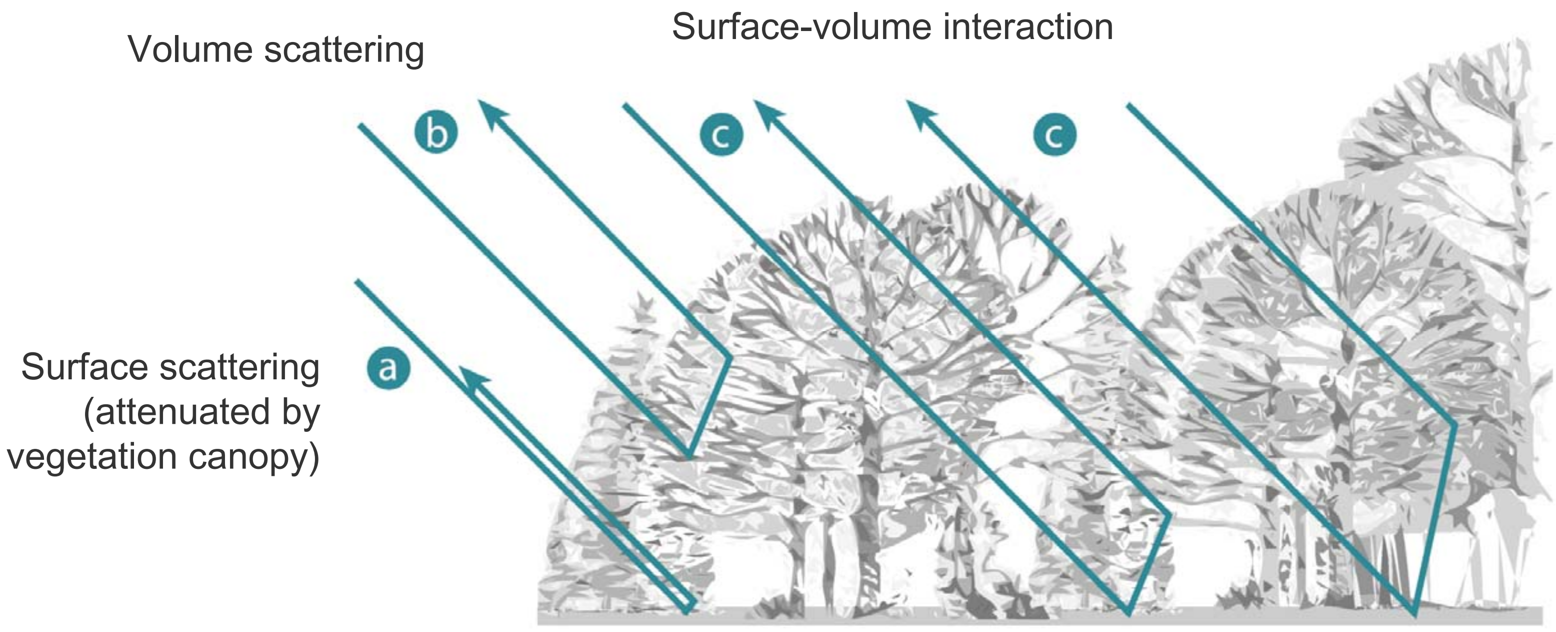
- Radar backscattering coefficient σ^0
  - Used for area-extensive targets
  - Given in m^2m^{-2} or Decibels (dB)

$$\sigma^0\left[m^2 m^{-2}\right] = \frac{\sigma}{A} \qquad \sigma^0[dB] = 10 \log \sigma^0\left[m^2 m^{-2}\right]$$

Backscatter from Vegetated Surfaces

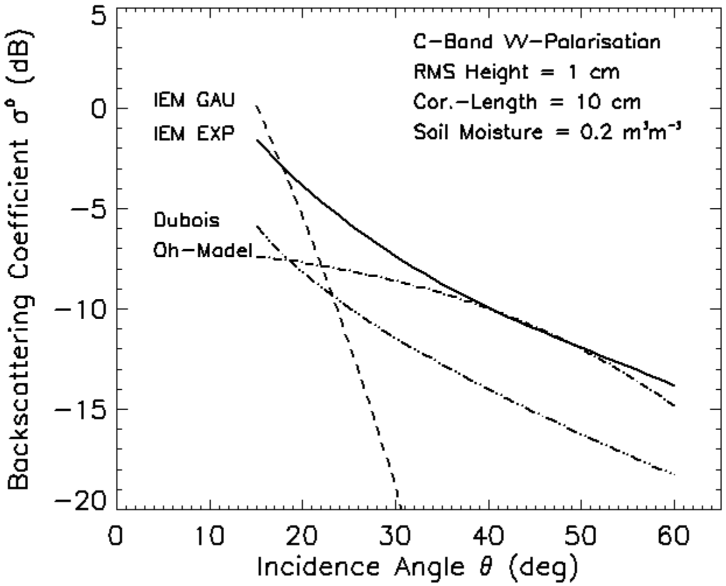
- Except for dense forest canopies, backscatter from vegetation is due to surface-, volume- and multiple scattering

$$\sigma^0_{total} = \sigma^0_{volume} + \sigma^0_{surface} + \sigma^0_{interaction}$$



Bare Soil Backscatter Models

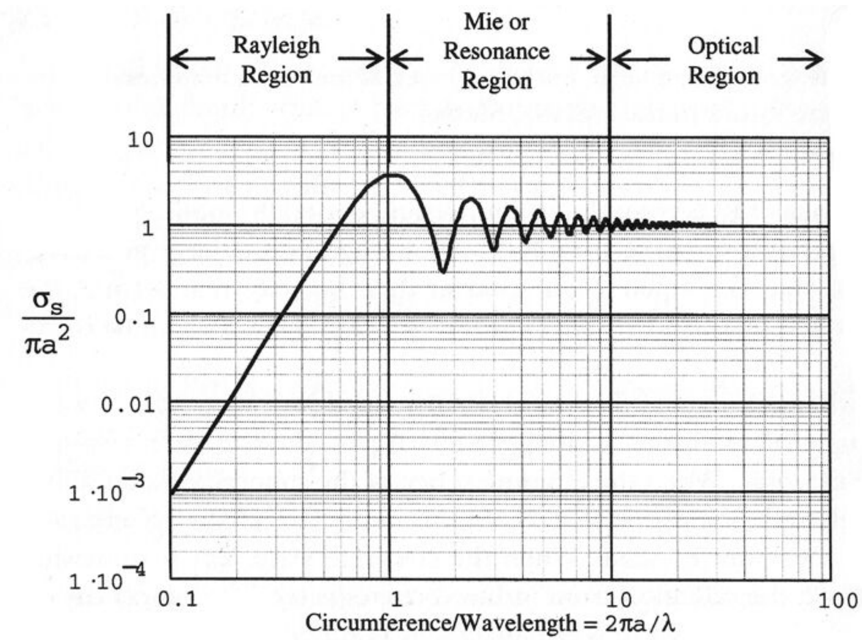
- Modelling of rough surface backscatter is still a problem
  - Models like Fung's IEM are believed to work "in theory"
  - Restricted validity ranges
  - Problem of correct statistical description of surface roughness still not solved
- The problem can be circumvented if a change detection approach is chosen
  - Scale must be taken into account



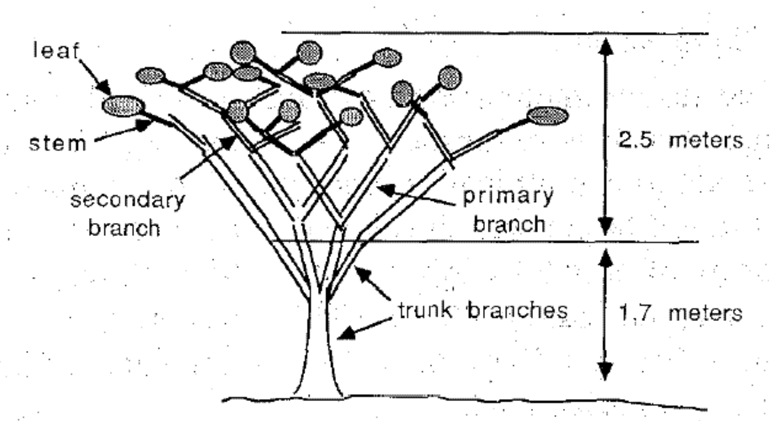
Comparison of different bare soil backscatter models using the same roughness parameters

Vegetation Backscatter Models

- Vegetation elements can be larger, comparable, and smaller then the wavelength
  - Simplifying, yet reasonable assumptions difficult to find
- Wide range of models
  - Cloud Model → MIMICS



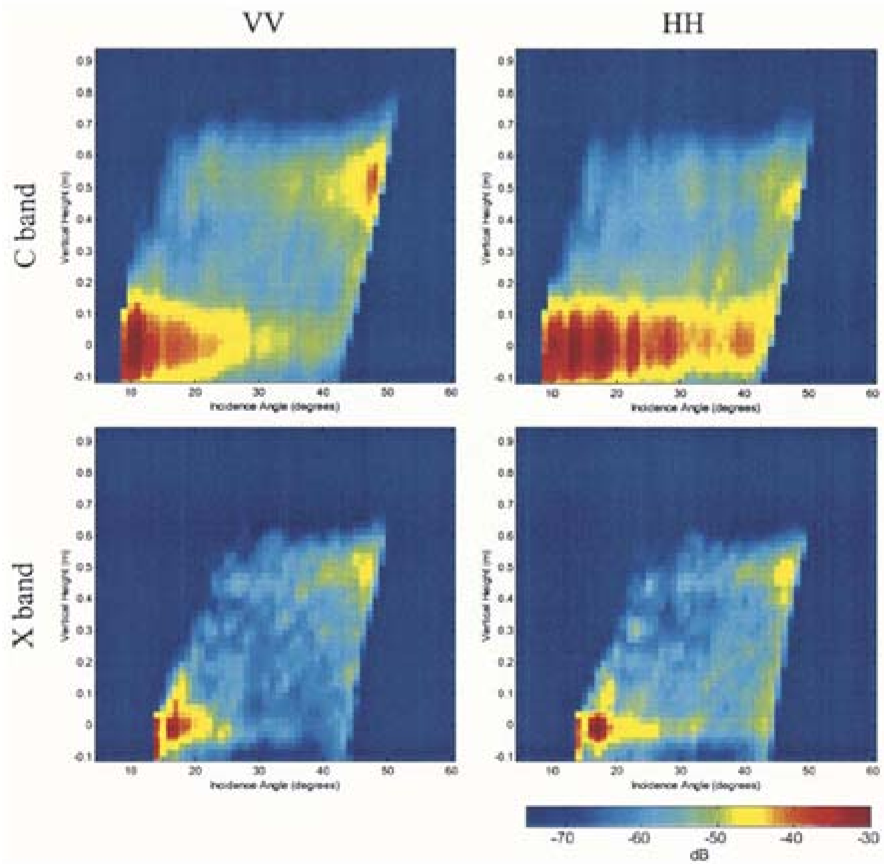
Cross section of a sphere



MIMICS backscatter model of a tree

3D Backscatter Measurements of Vegetation

„significant disagreements between measurements and models"
„attenuation [in raditative transfer models] is significantly overestimated"



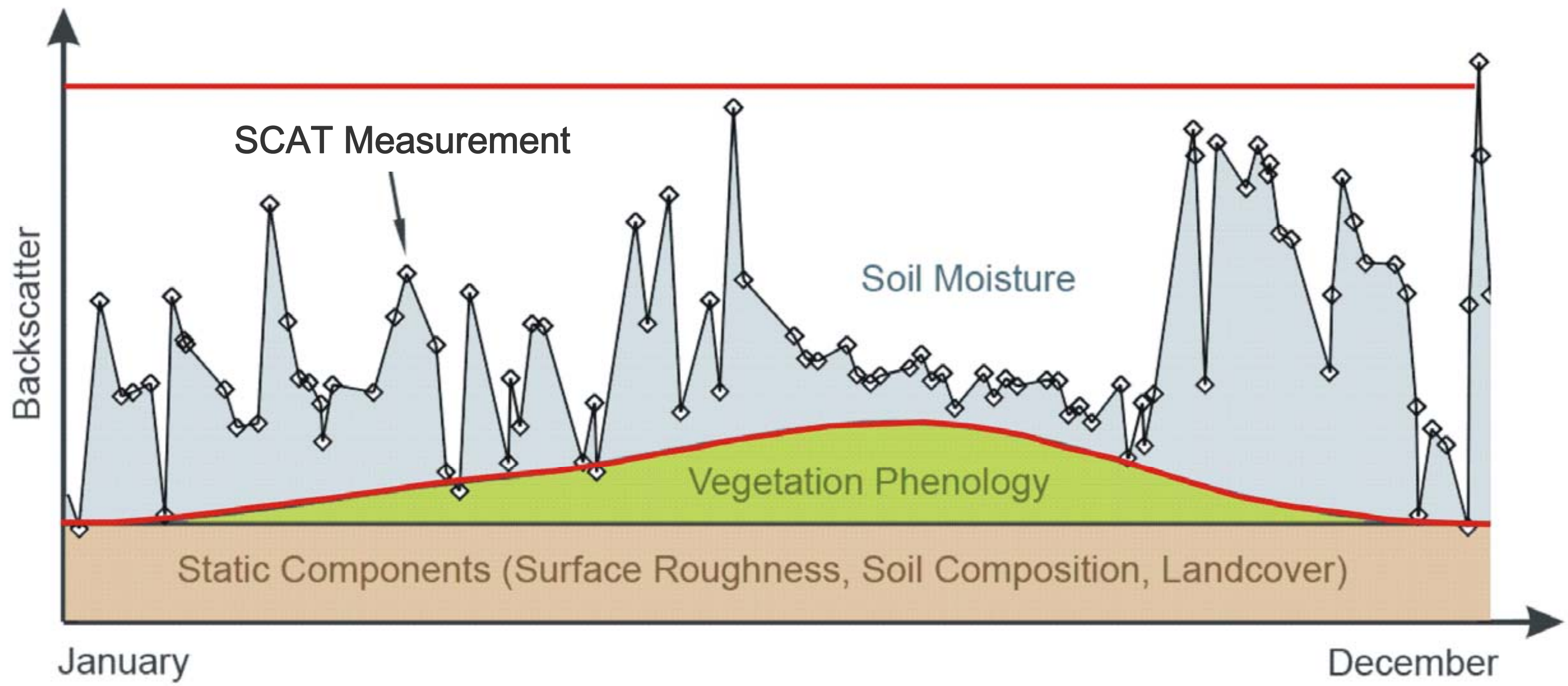
3D radar measurements of a 58 cm high wheat canopy

Brown SCM, Quegan S, Morrison K, et al. (2003) High-resolution measurements of scattering in wheat canopies - Implications for crop parameter retrieval IEEE Transactions on Geoscience and Remote Sensing, 41(7), 1602-1610.

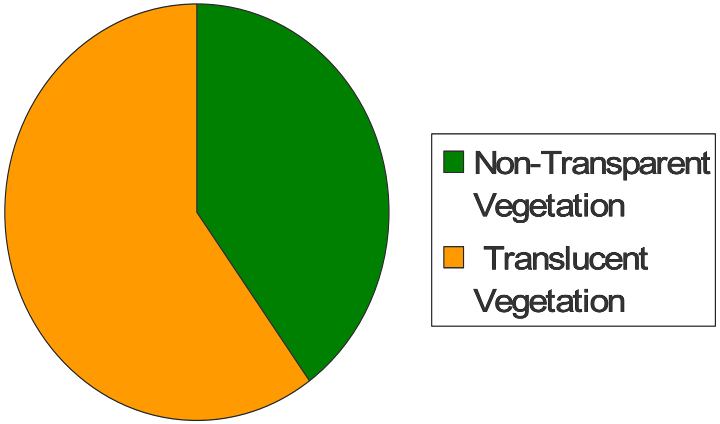
TU Wien Change Detection Approach

- Change detection
  - Accounts indirectly for surface roughness and land cover

$$m_s(t) = \frac{\sigma^0(t) - \sigma^0_{dry}(t)}{\sigma^0_{wet}(t) - \sigma^0_{dry}(t)}$$



Semi-Empirical Mixed Pixel Model



- First-order radiative transfer solution
  - "Cloud Model" + Vegetation-Surface Interaction term
  - "Linear" bare soil backscatter model

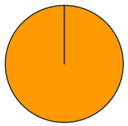
$$\sigma^0 = (1 - A_{nt}) \cdot \sigma^0_{tr} + A_{nt} \cdot \sigma^0_{nt}$$

$$\sigma^0_{nt} = \frac{\omega_{nt} \cos\theta}{2}$$

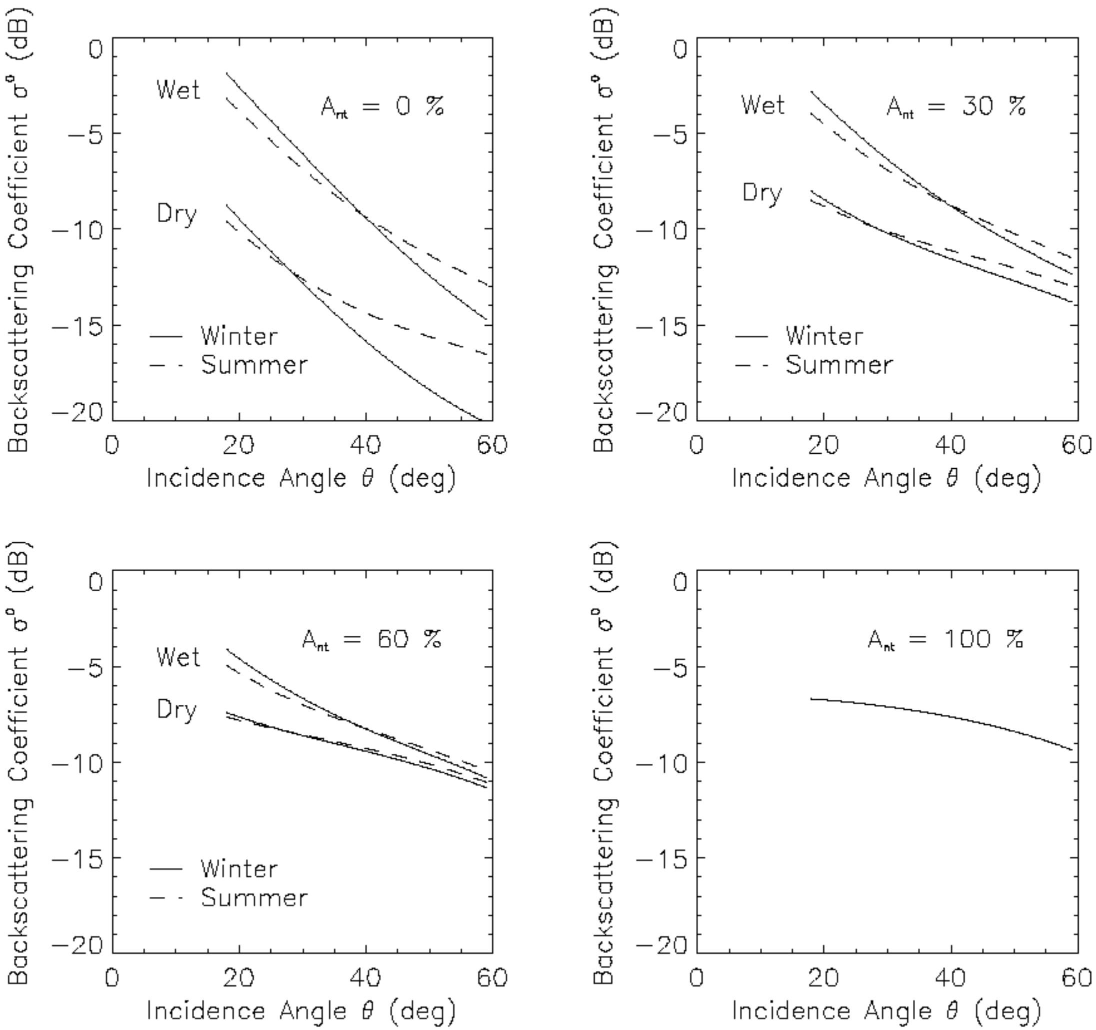
$$\sigma^0_{tr} = \frac{\omega_{tr} \cos\theta}{2}\left(1 - e^{-\frac{2\tau_{tr}}{\cos\theta}}\right) + \sigma^0_s(\theta) e^{-\frac{2\tau_{tr}}{\cos\theta}} + 2\chi\Gamma_0\omega_{tr}\tau_{tr} e^{-\frac{2\tau_{tr}}{\cos\theta}}$$

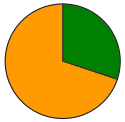
$$\sigma^0_s = \sigma^0_{s,dry}(40) + \sigma'_s \cdot (\theta - 40) + S_s m_s \qquad \text{in dB}$$

Model Simulations

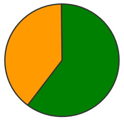


Grassland & agriculture

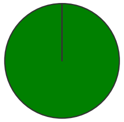




Grassland & agriculture with 30 % forest cover



Grassland & agriculture with 60 % forest cover

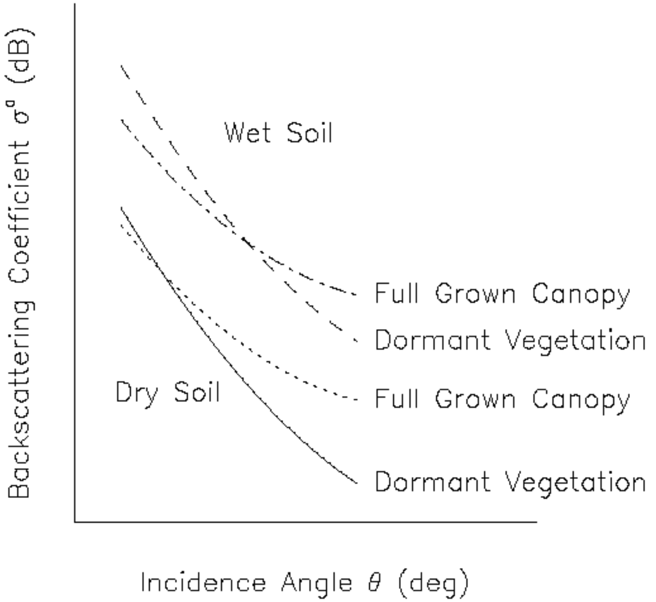


Dense Forest

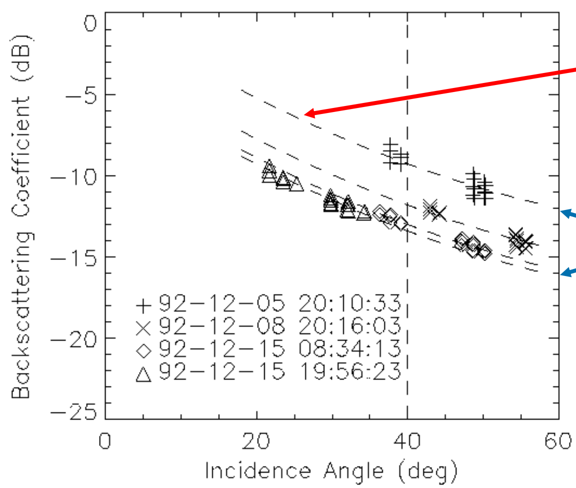
Simulations performed with a radiative transfer mixing model

TU Wien Model

- Formulated in decibels (dB) domain
- Linear relationship between backscatter (in dB) and soil moisture
- Empirical description of incidence angle behaviour
- Seasonal vegetation effects cancel each other out at the "cross-over angles"
  - dependent on soil moisture



ERS Scatterometer measurements

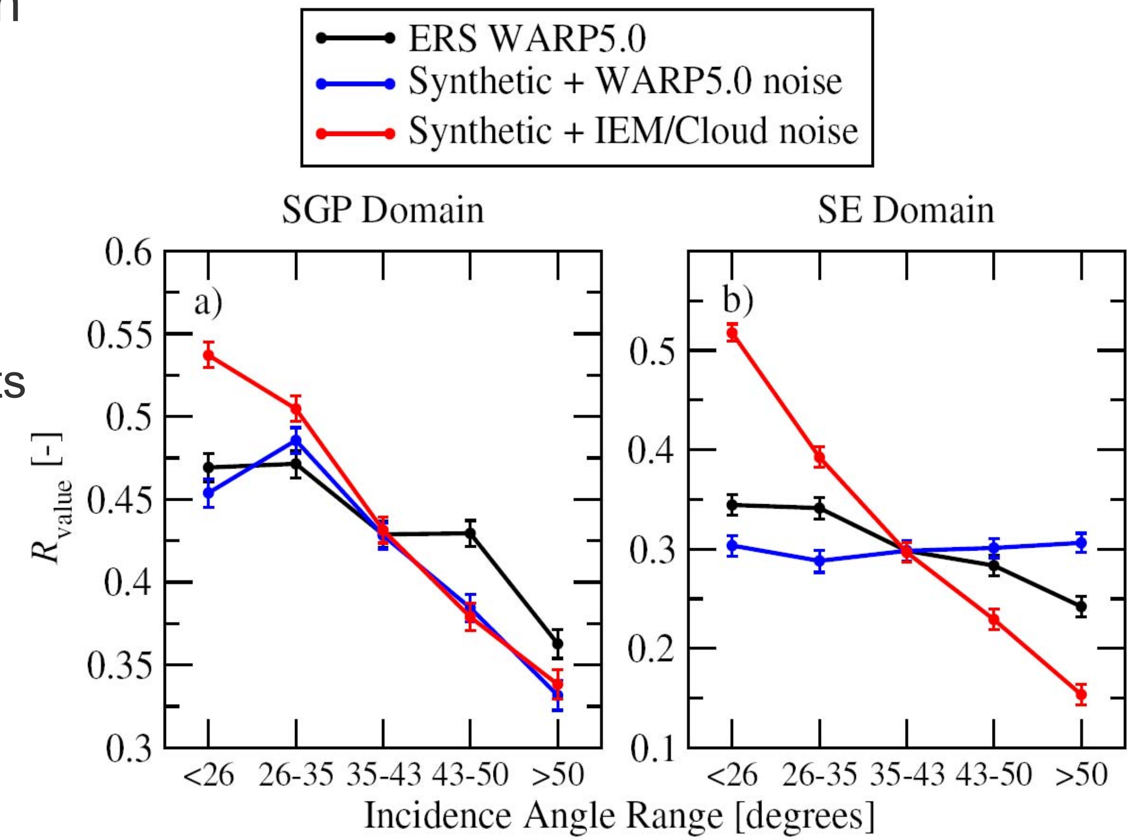


Incidence angle behaviour is determined by vegetation and roughness roughness

Changes due to soil moisture variations

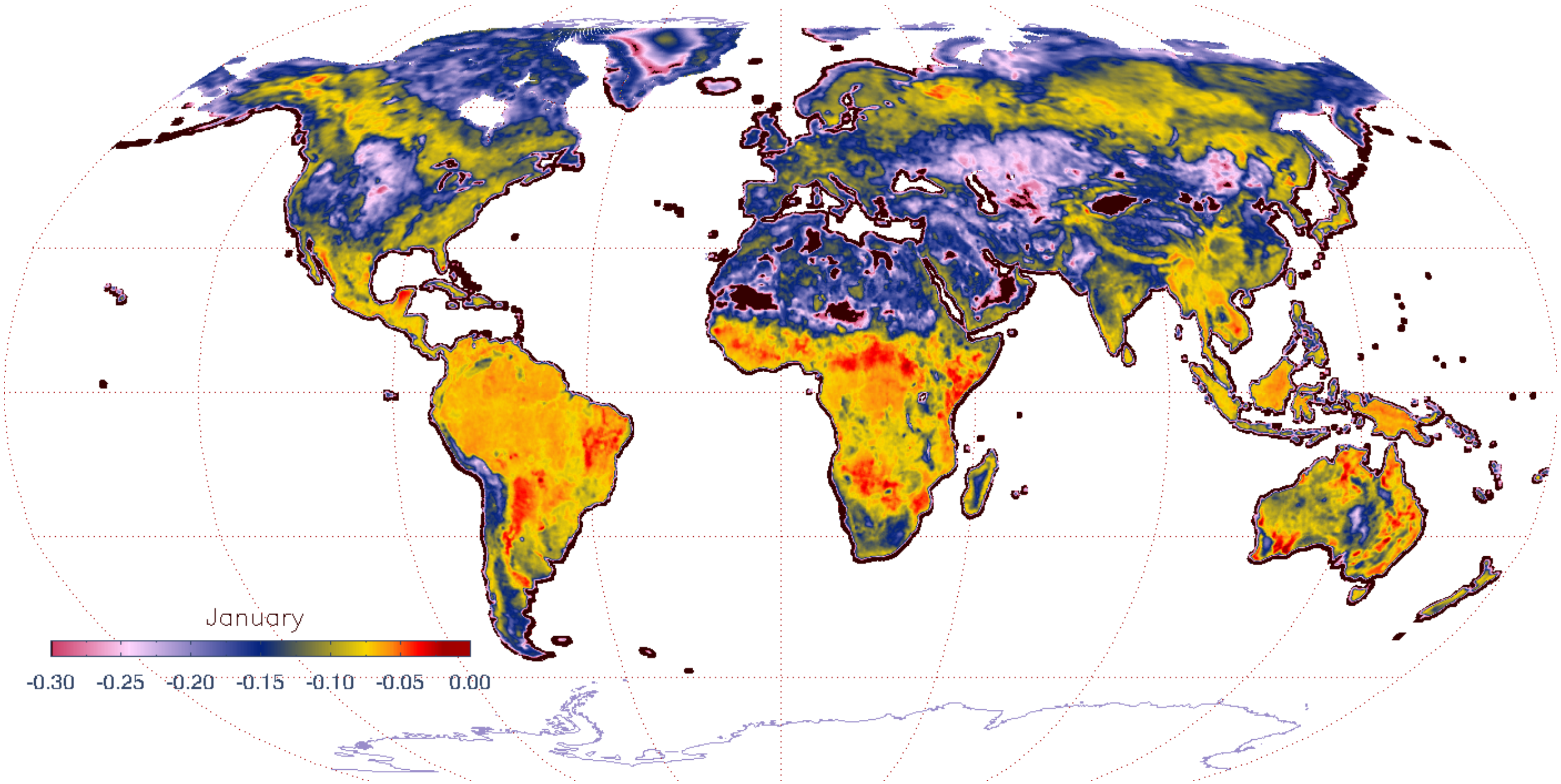
Impact of Incidence Angle on Retrieval Skill

- A new study by Wade Crow using his data assimilation approach reveals
  - 30 % reduction in soil moisture retrieval skill from near to far range
  - TU Wien (WARP 5) models vegetation effects with varying incidence angle quite well (better than with IEM + Cloud Model)



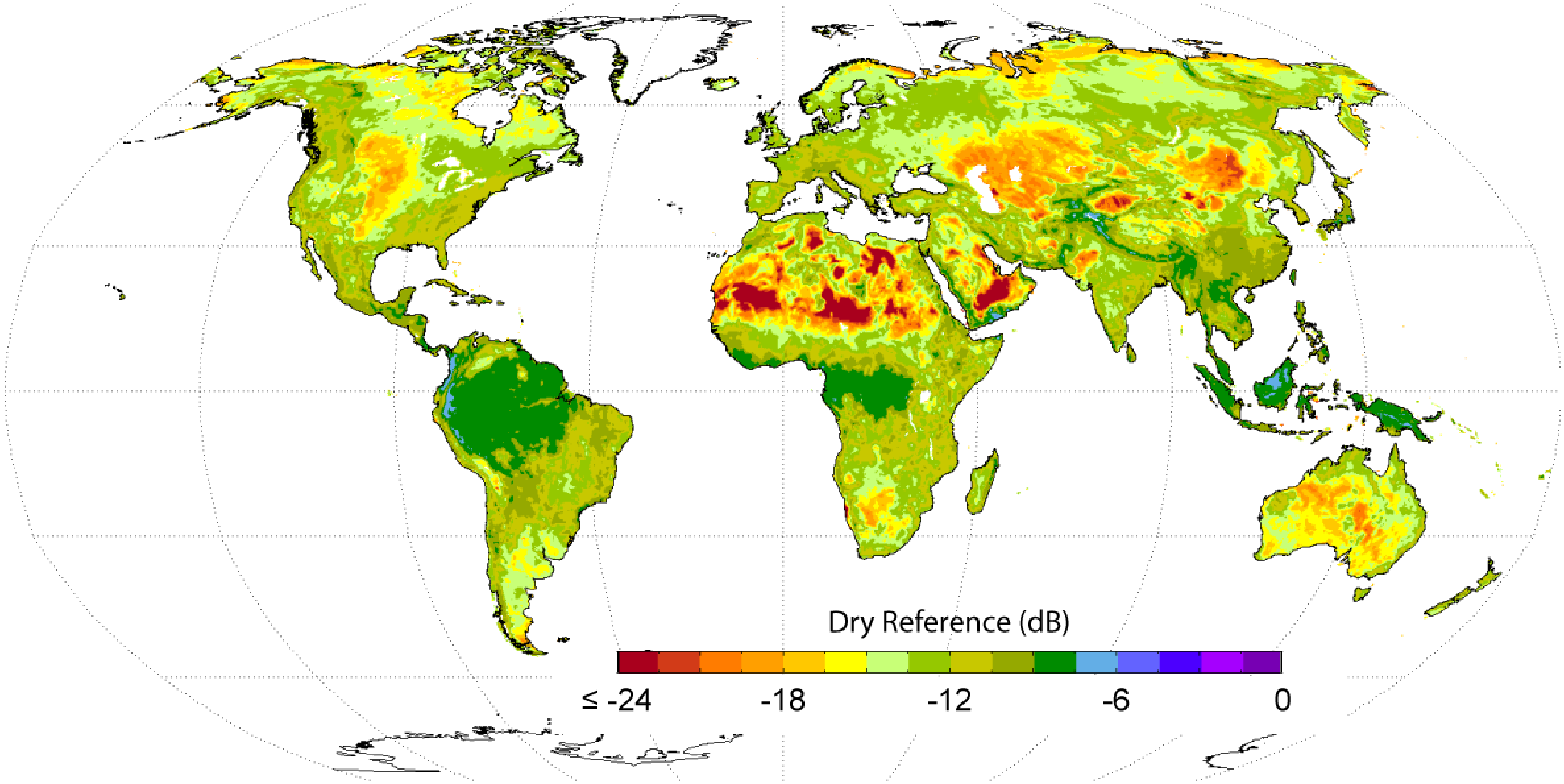
Crow, W.T., W. Wagner, V. Naeimi (2010) The impact of radar incidence angle on soil moisture retrieval skill, Geoscience and Remote Sensing Letters, in press.

Global Monthly Slope



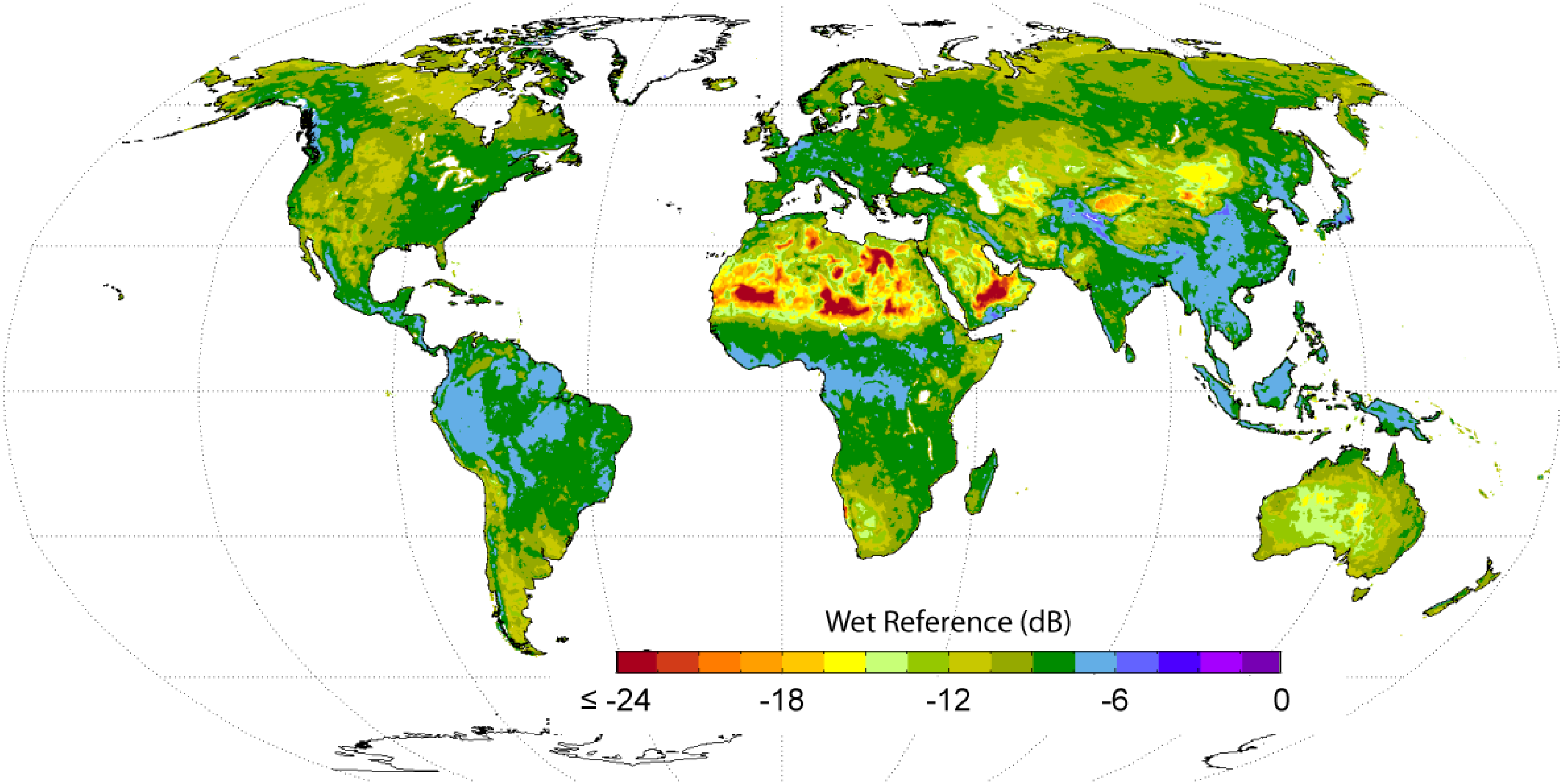
Historically Driest and Wettest Conditions

- Dry backscatter reference at 40° incidence angle



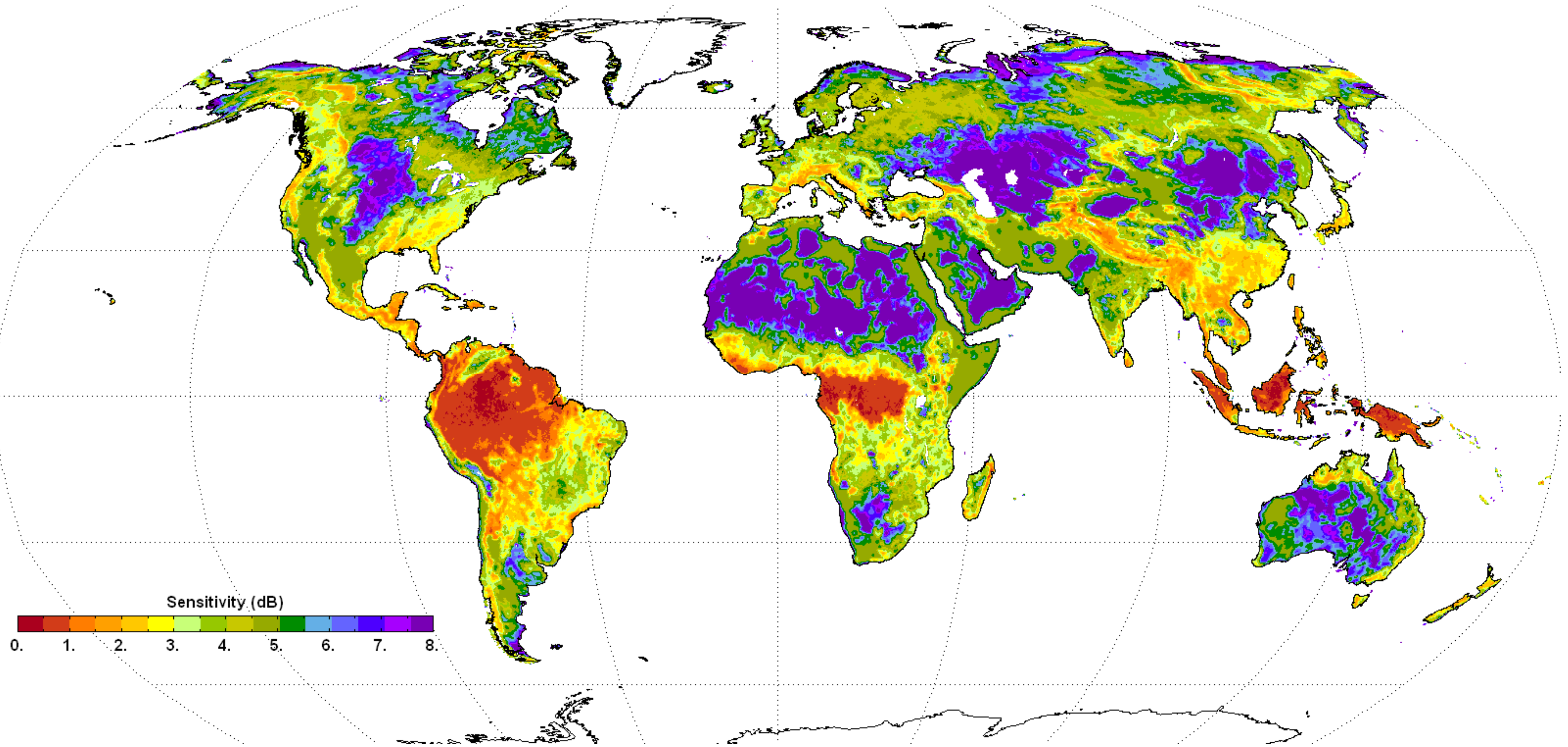
Wet Backscatter Reference

- In deserts saturated conditions are not reached (corrections necessary)



Sensitivity

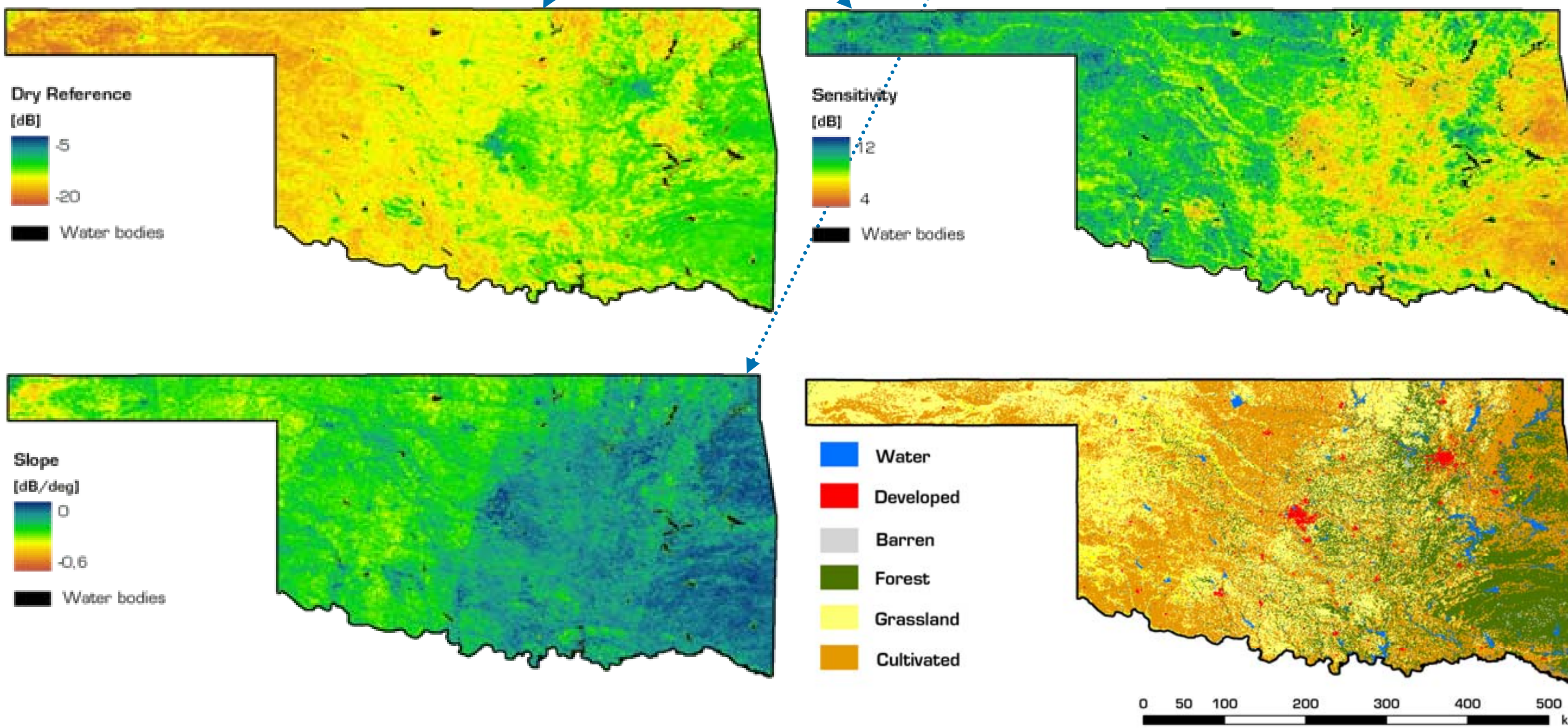
- The sensitivity describes the signal response to soil moisture changes and depends strongly on land cover



ASAR Backscatter Model

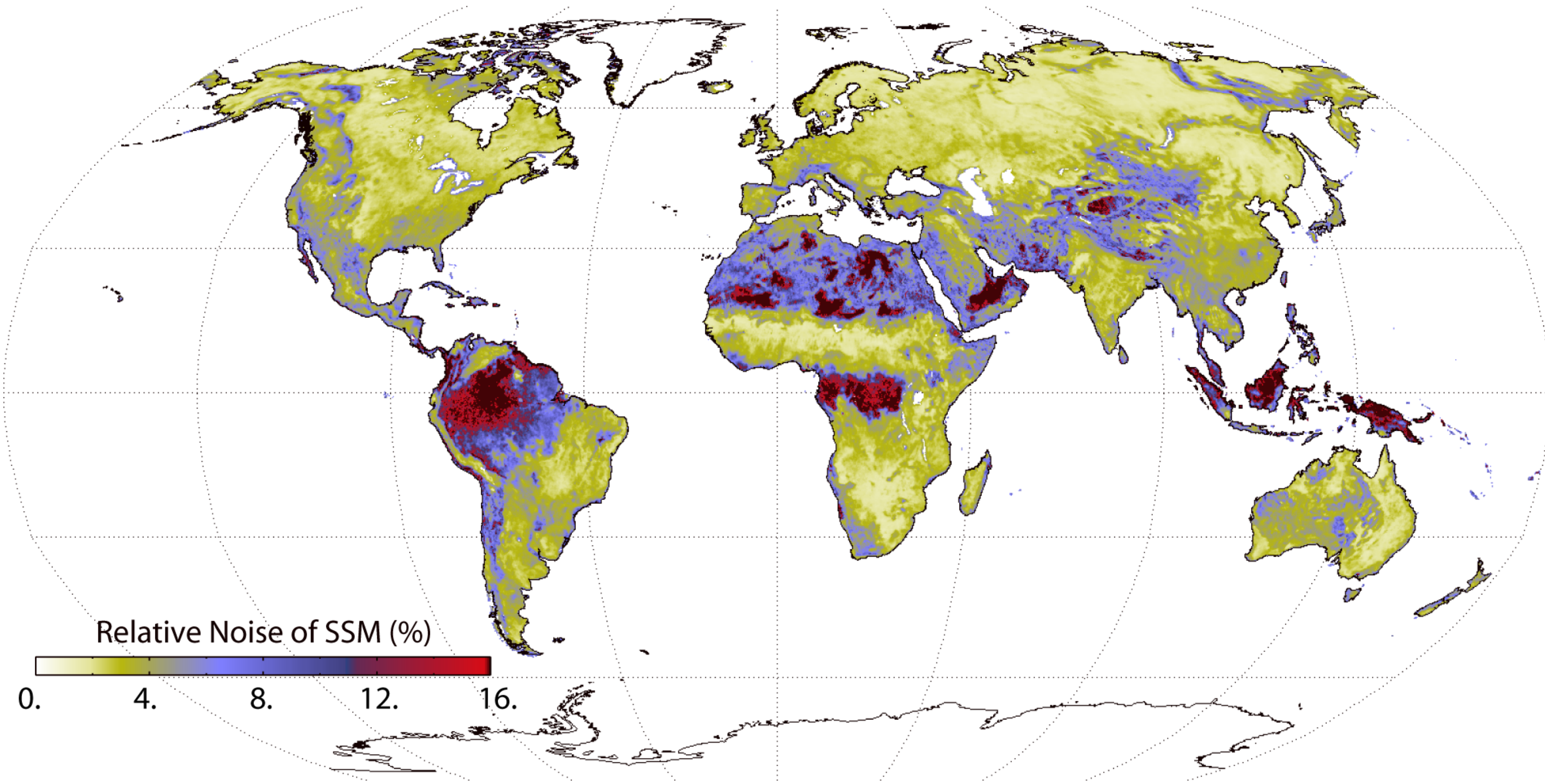
- Simplified version of the SCAT backscatter model

$$\sigma^0(t,\theta) = \sigma^0_{dry}(30) + S \cdot m_s(t) + \beta(\theta - 30)$$

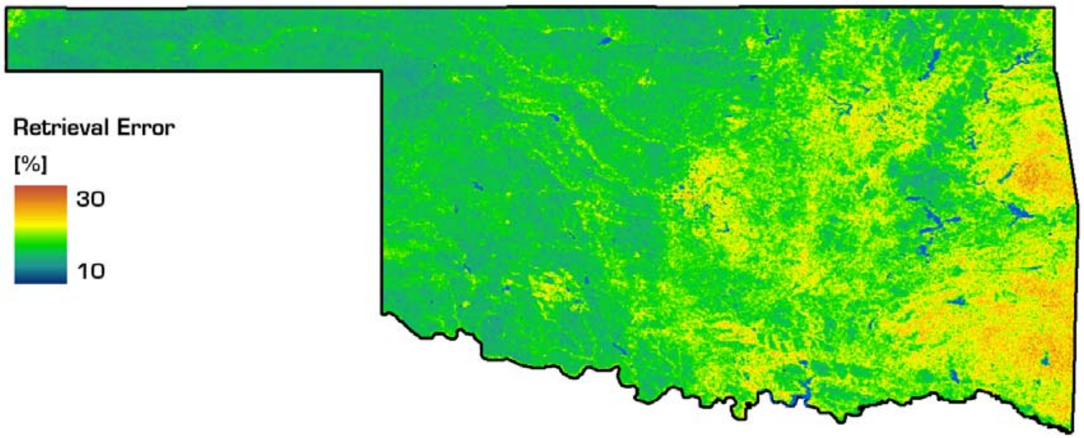


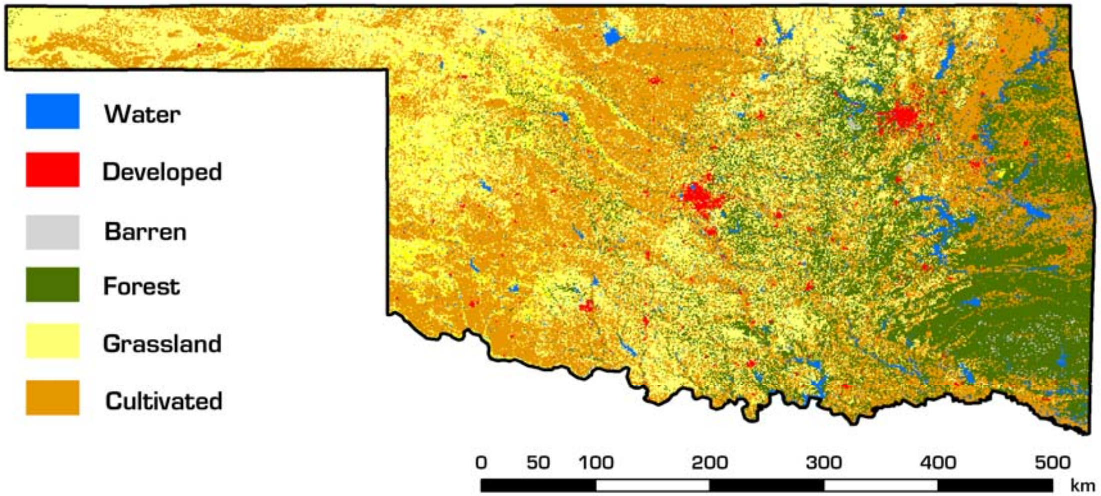
ASAR backscatter model parameters and land cover map of Oklahoma, USA.

SCAT Noise from Error Propagation

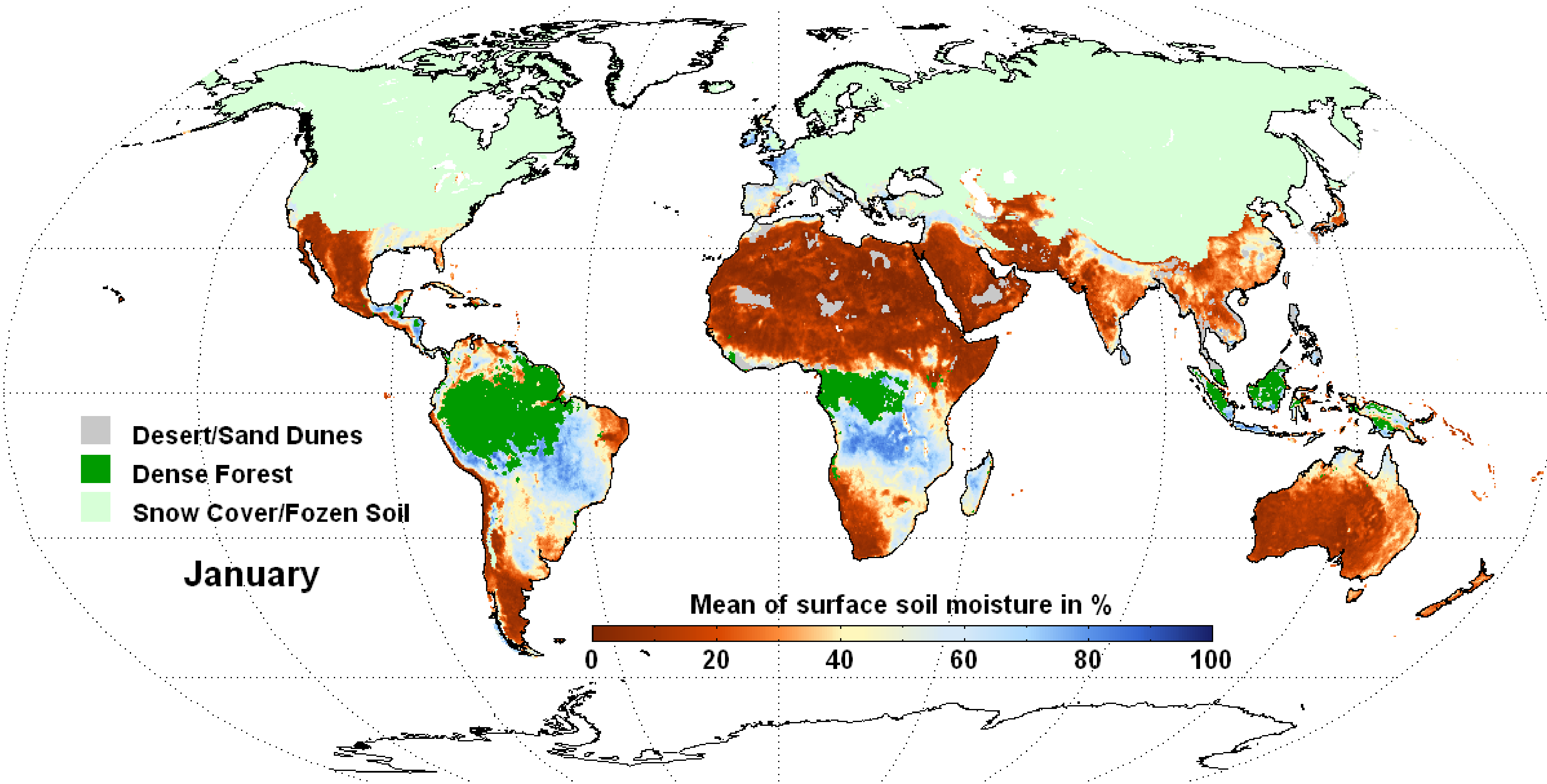


ASAR Noise from Error Propagation



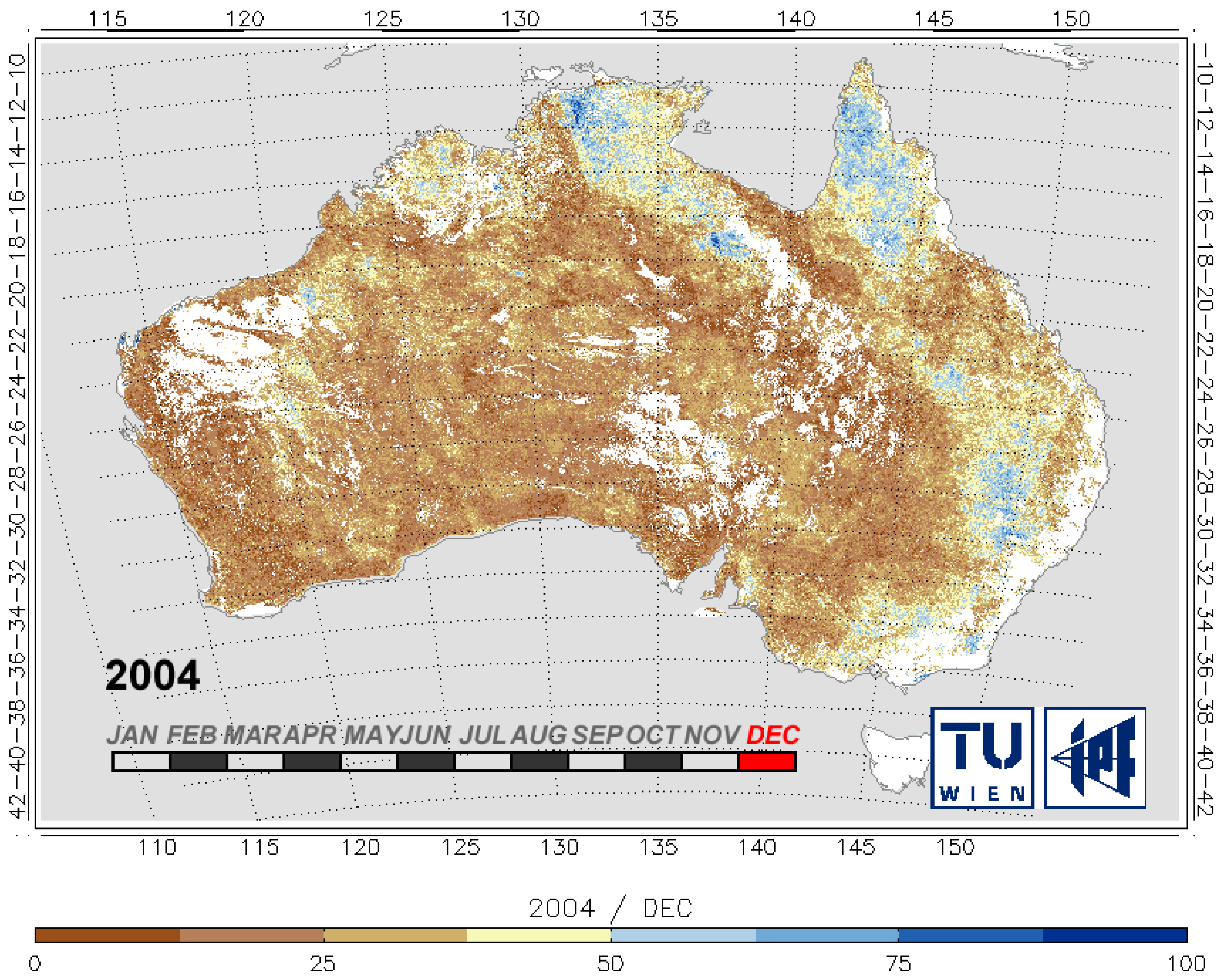


SCAT Seasonal Soil Moisture Dynamics



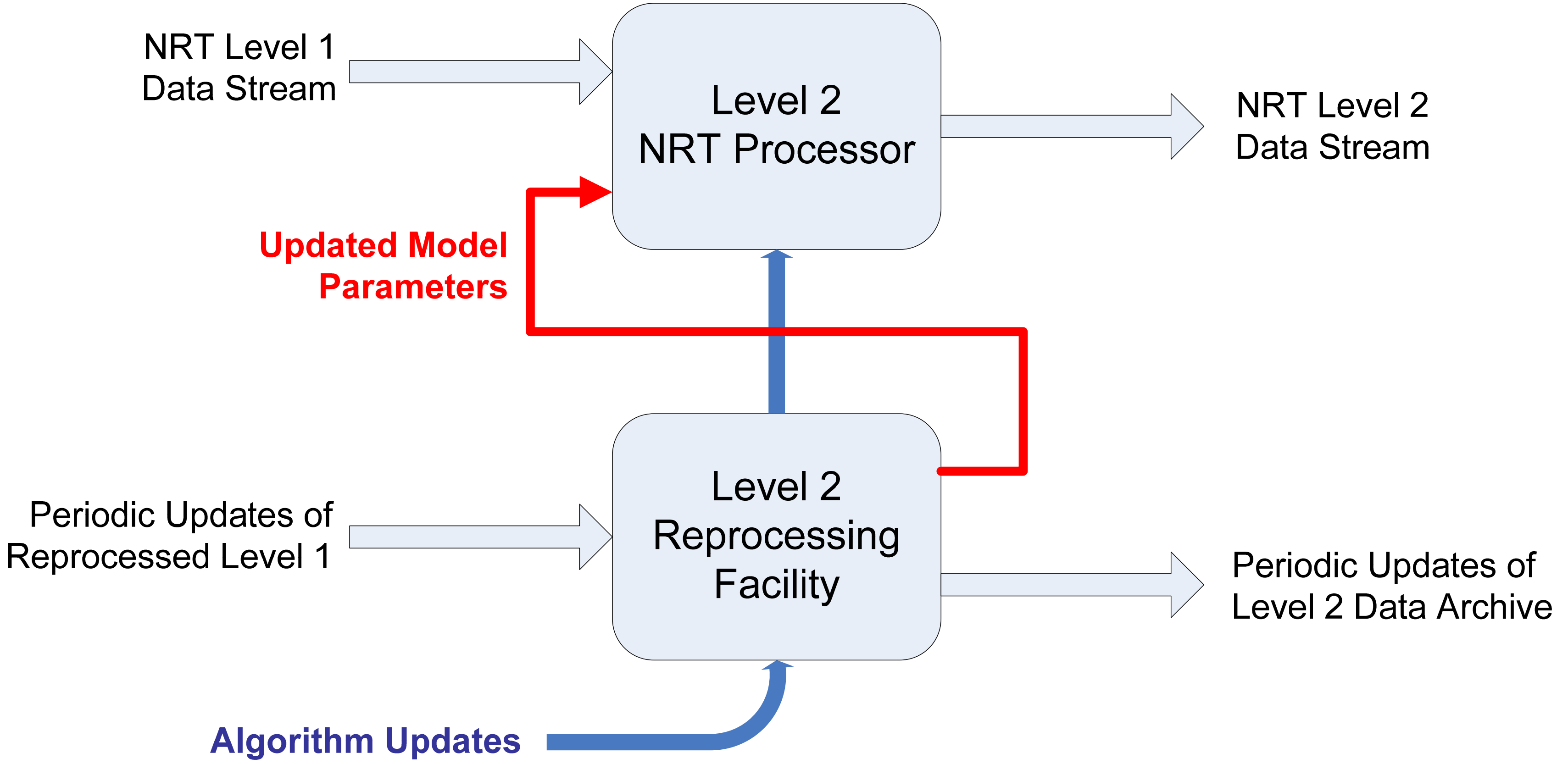
Mean ERS scatterometer surface soil moisture (1991-2007)

ASAR Soil Moisture



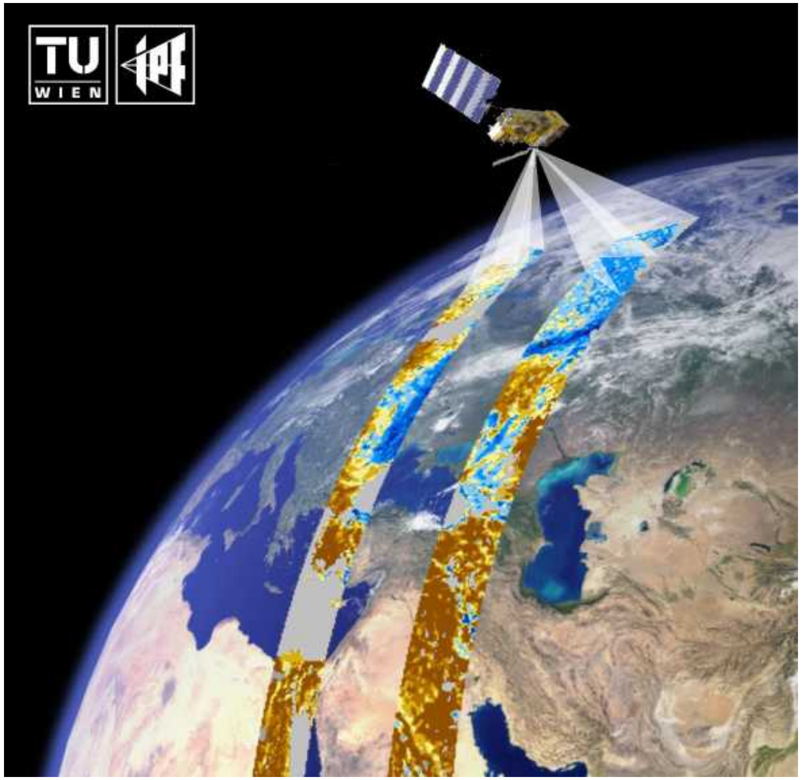
Processing Architecture

- Model parameters are estimated off-line in the Reprocessing Facility and fed into the near-real-time (NRT) processor



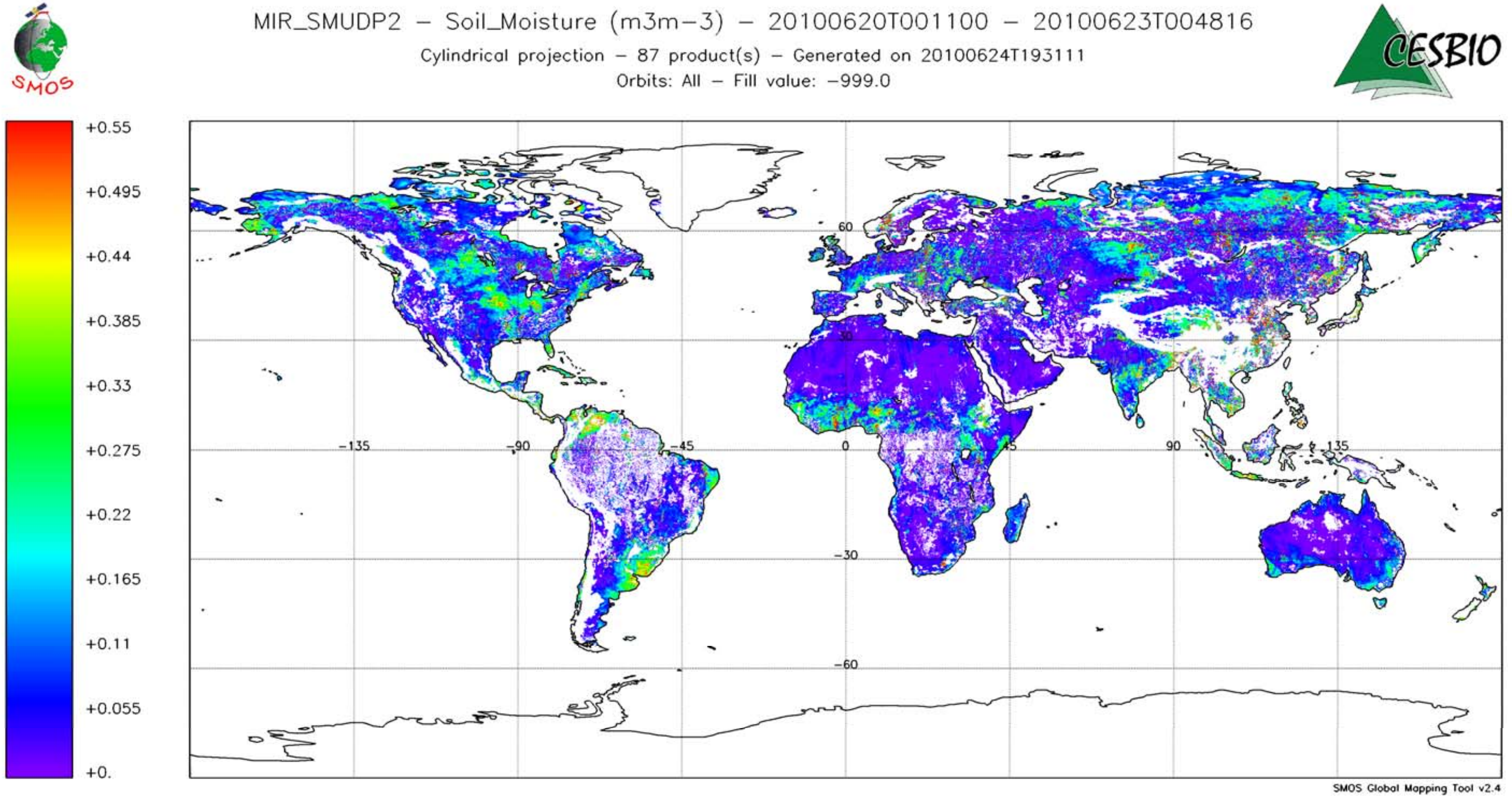
Operational NRT METOP ASCAT Product

- EUMETSAT processes and delivers global 25 km ASCAT surface soil moisture data to user within 130 minutes after sensing



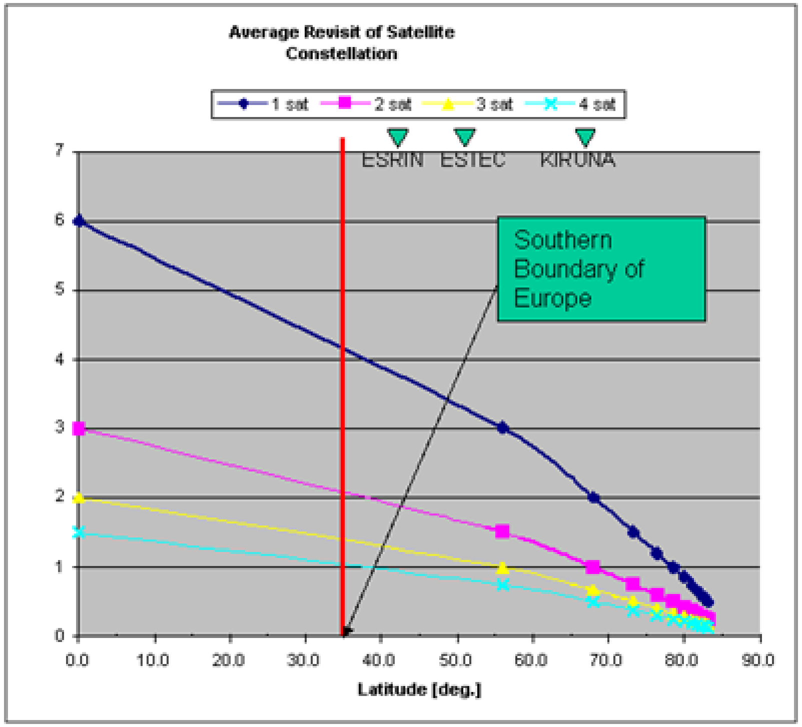
http://www.ipf.tuwien.ac.at/radar/dv/ascat/

First SMOS Soil Moisture Image



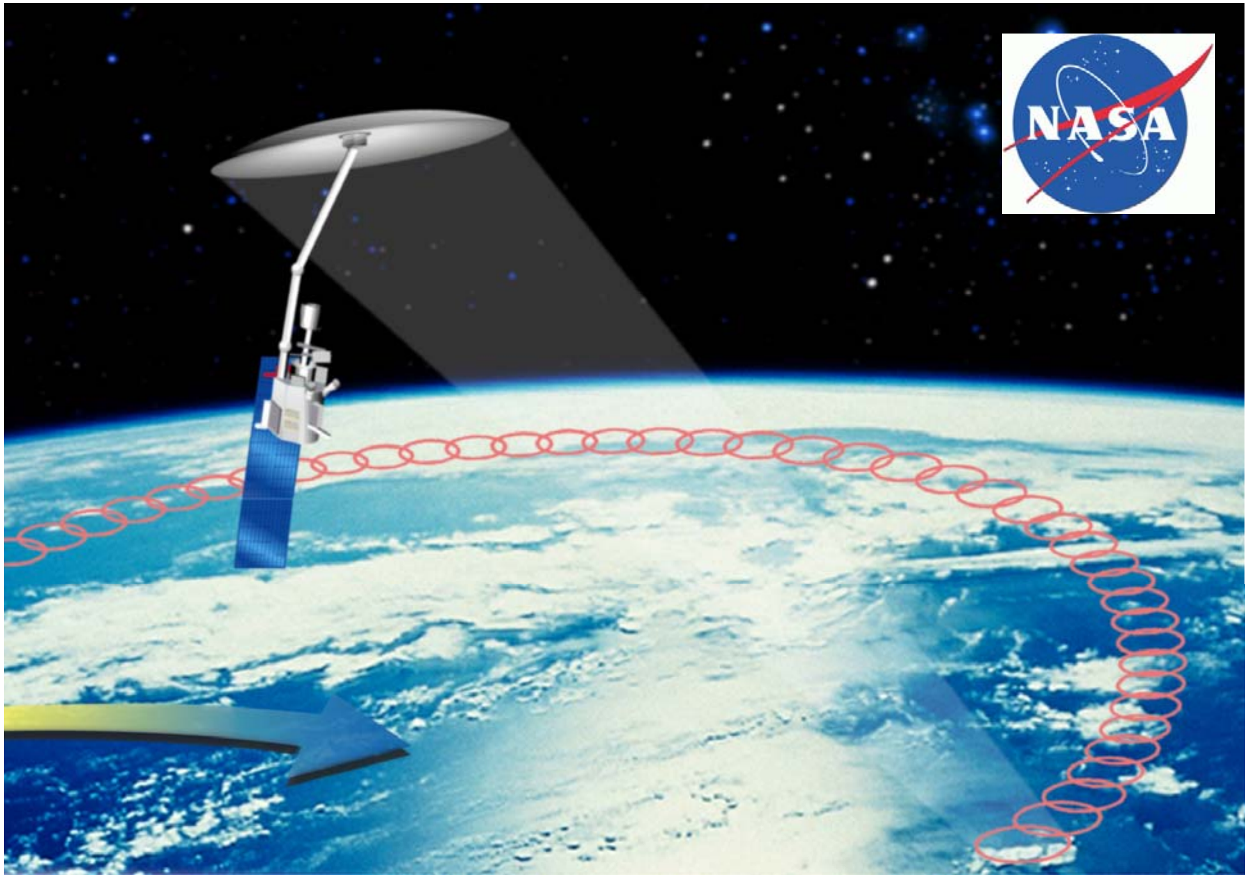
Sentinel-1

- With two satellites and a fixed acquisition scenario (IWS mode in HH polarisation over land) Sentinel-1 can overcome all shortcomings of ENVISAT ASAR GM mode!



Soil Moisture Active Passive (SMAP)

- Launch in 2014/15
- Active/passive microwave instrument in L-band
- Rotating antenna with ∅ = 6 m



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