Introduction to Soil Moisture Remote Sensing

importance, definitions, measuring soil moisture, *sensors, microwave retrievals methods, limitations, data products, SMAP*

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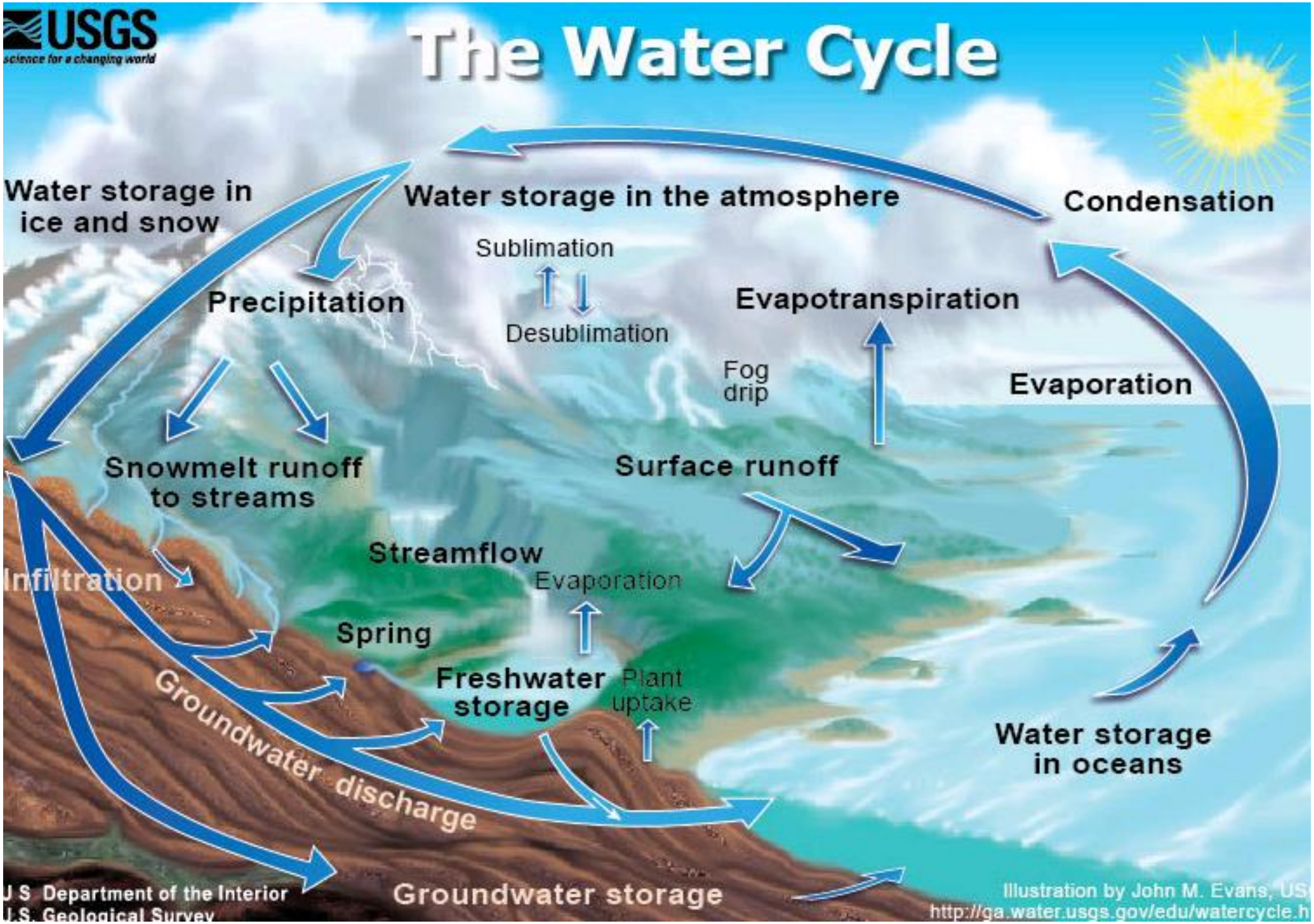
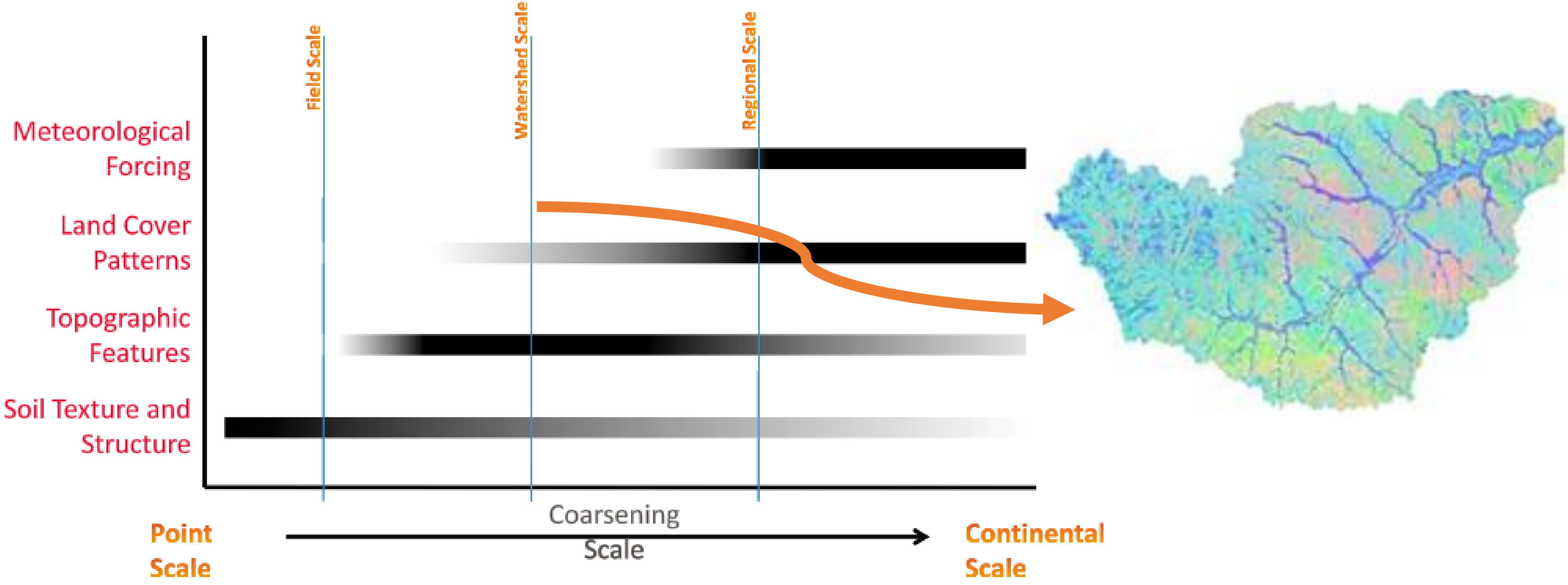
Terrestrial Hydrological Variables



Soil Moisture

- 75% of land precipitation globally enters the soil
- Soil moisture provides
  - all the water for natural and cultivated agriculture
  - and almost all the water that enters groundwater reservoirs (recharge)
- Soil moisture is highly variable spatially - controlled by different drivers depending on the scale → important especially for agriculture

Dominant physical controls on soil moisture spatial variability as a function of scale



(Crow et al., 2012)

Importance of Soil Moisture

"In the structure and functioning of landscapes, soils are the matrix through which energy, water, biomass, and nutrients flow…the interface in the cycling of water between the atmosphere and land…the location of large transformations of energy." Bonan, 2002

Uses for Soil Moisture Data

Time Scale	Applications	Users
Days	Daily weather forecasting & hydrology: • Convection initiation • Model initialization in NWP and hydrology • Low clouds and fog development • Runoff and flooding potential	• Meteorologists • Hydrologists • Numerical weather and hydrologic prediction
Weeks	Forecasting, monitoring, managing: • Watershed management for power generation, irrigation, municipal water supplies • Moisture availability for plant and crop growth • Potential hazards including floods, drought, and fires • Large-scale runoff • Surface energy budget for radiation models • Global and regional climate, seasonal precipitation patterns (especially mid-latitudes)	• Hydrologists • Water resource managers • Forest managers • Agriculture • Numerical weather, climate, and hydrologic prediction • General circulation modeling
Years	Monitoring soil moisture conditions for: • Global and regional climate simulations • Long-term drought prediction • Agricultural suitability • Land use planning	• Hydrologists • Climate modeling, prediction, and research • General circulation modeling • Water resource managers

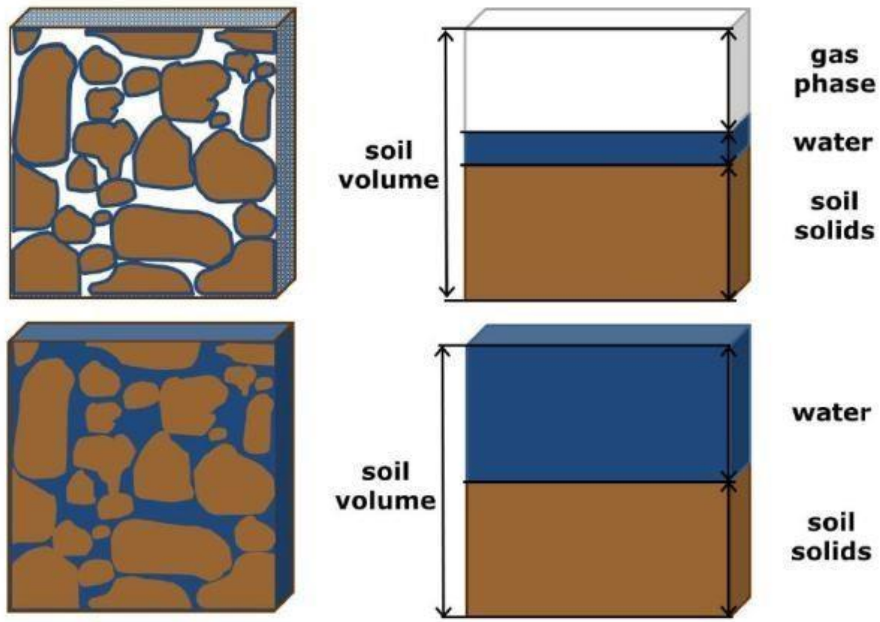
Definitions: Soil Moisture

Volumetric water content (theta) also called water content or soil moisture content

$\Theta = V_w/V_s$

Where V_w is the volume of water
V_s of the volume of the soil column

Θ ranges from > 0 to porosity



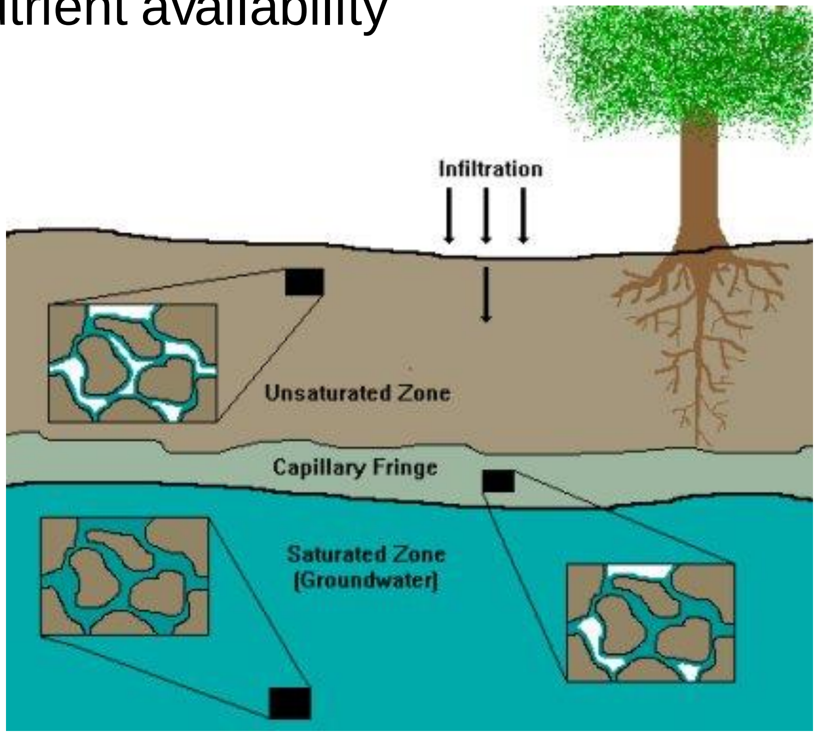
The total amount of water stored in any layer of soil (soil water storage) is usually expressed as depth (mm) of water which is

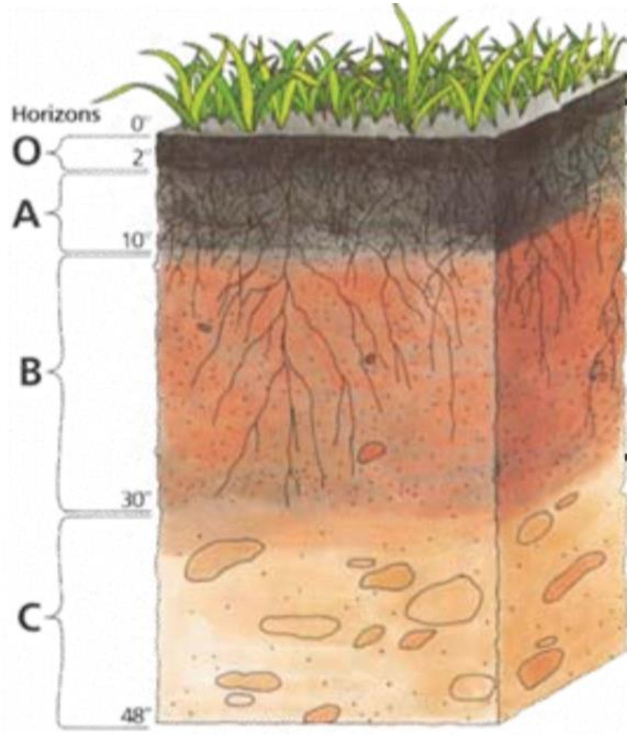
SM (mm) = Θ x depth of soil layer

Saturation or wetness is the proportion of the soil pores that contains water (0-1)

Definitions: Soil Structure

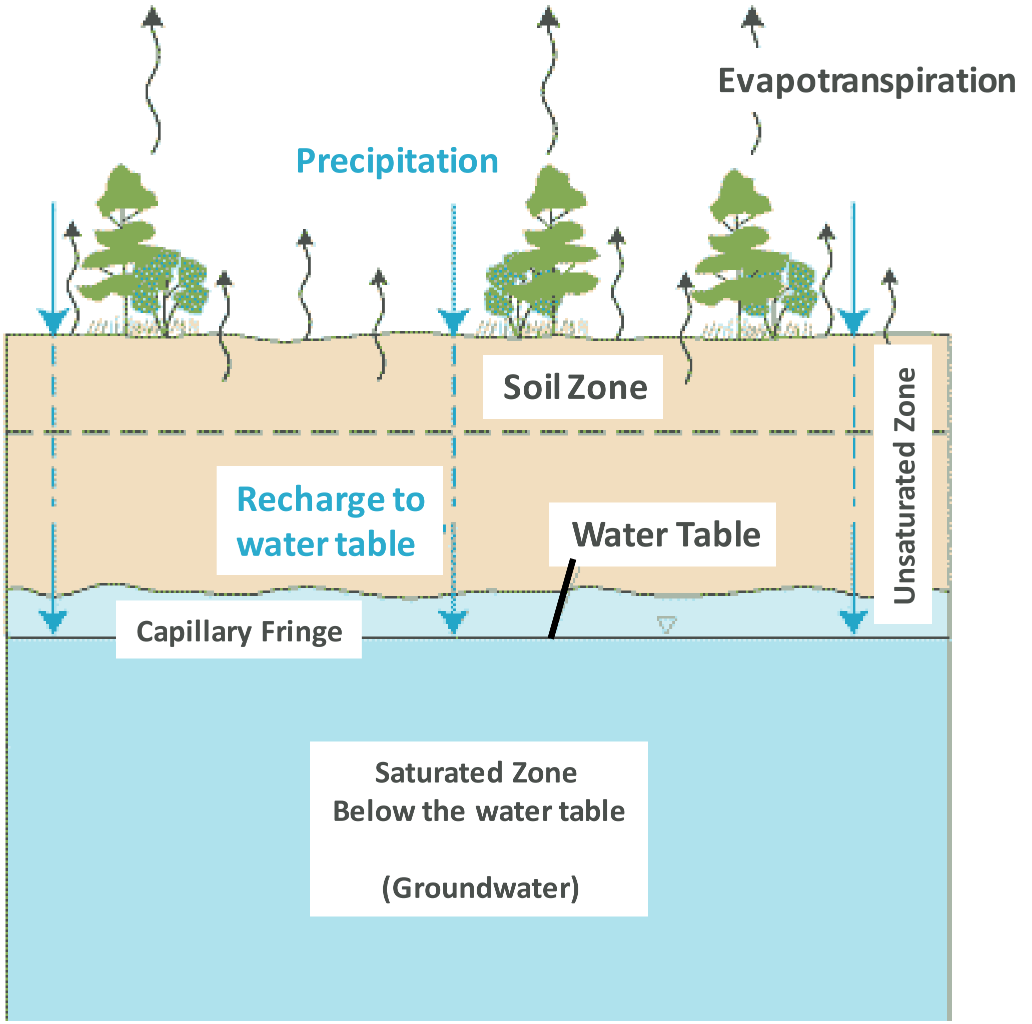
- Soils Composed of:
  - Organic Matter (>80% organic soil, <10% mineral soil)
  - Minerals (From parent geology, ~55% in mineral soil)
  - Air
  - Water
- Type, abundance, arrangement of particles govern heat flow, water flow, nutrient availability





Water Movement in the Unsaturated Zone

- Unsaturated (Vadose) Zone
  - Zone between the land surface and water table
  - Soil pores contain water and air (pressure < atmos)
- Infiltration
  - Occurs if soil pores near the surface are not completely filled
- Drainage
  - Water can move through the UZ to the saturated zone (GW) as recharge, via gravity and pressure gradients
- Water table
  - Divide between UZ and SZ
  - Pressure is at atmospheric
  - Capillary fringe just above the water table due to capillary forces
  - SZ is under positive pressure



Measuring Soil Moisture

MEASUREMENT OF SOIL MOISTURE

DIRECT METHODS
(Gravimetric or Thermo-gravimetric)
- Oven drying
- Alcohol burning
- Hot air drying
- Gypsum sorption plugs
- Infrared balance

INDIRECT METHODS

Tensiometric
- Tensiometer
- Pressure plate technique

Electrical or electromagnetic
- Gypsum blocks
- Granular matrix sensors
- Dielectric methods

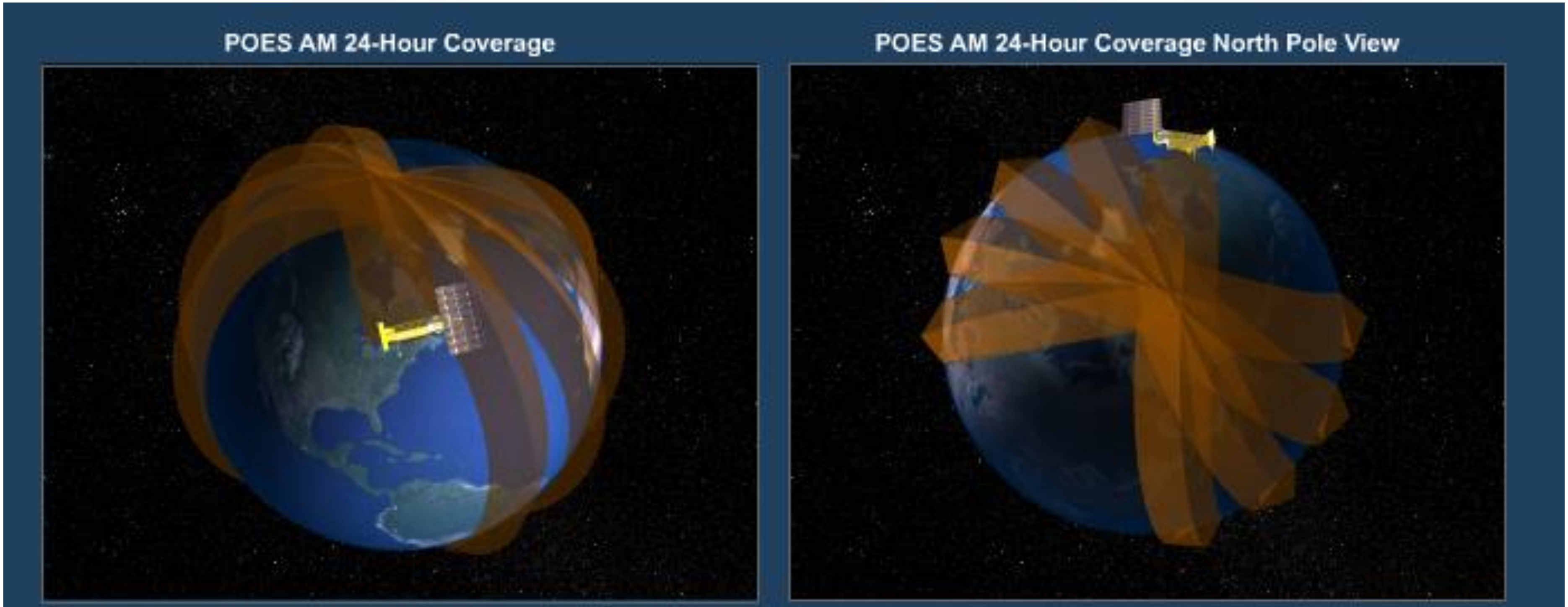
Radiation
- Neutron scattering
- Gamma-ray attenuation

Thermal
- Heat dissipation sensors
- Heat capacity sensors
- Soil psychrometer

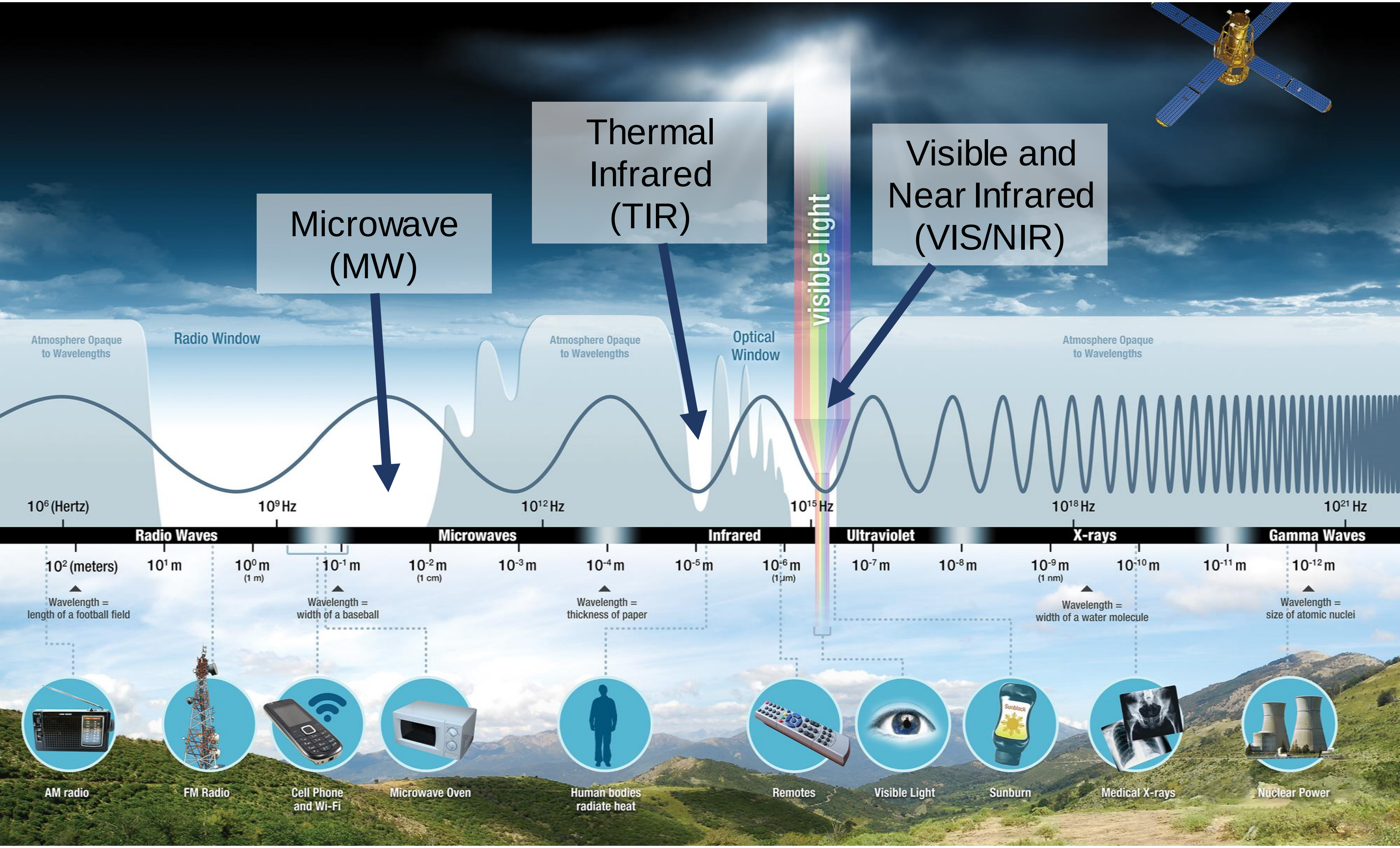
Remote sensing
- Infrared or electromagnetic properties of soil

Why Remote Sensing of Soil Moisture?

- Ground-based measurements of soil moisture have the advantage of frequent updates, but are generally sparse and unavailable in many parts of the world, and often short-term.
- RS provides **global** coverage at reasonably **high resolution**
- Many polar-orbiting satellites employ an **all-weather** microwave remote sensing capability that provides global coverage.
- Microwave radiation, particularly at lower frequencies, is very sensitive to changes in surface moisture and penetrates all but the densest and precipitating cloud cover.



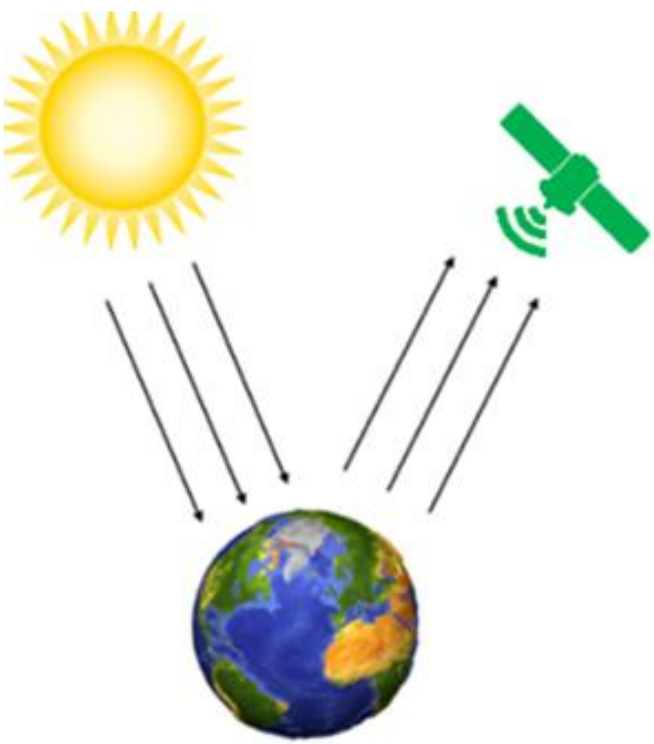
Electromagnetic Spectrum and Atmospheric Windows



Remote Sensing and Types of Sensors

Definition: acquisition of information about an object or phenomenon without making physical contact with the object and thus in contrast to in-situ observation

Passive sensors gather radiation that is emitted (terrestrial radiation) or reflected (e.g. sunlight) by the object.



Active sensors emit energy in order to scan objects whereupon a sensor then detects and measures the radiation that is reflected or backscattered from the target.

Types of Sensor Relevant for Water Resources

Active Sensors
(mostly MW penetrates clouds)

- Altimeter (MW radar or laser ranging)
  - measures pulse return time
  - changes in water levels (e.g. reservoirs, lakes, rivers)
- Ranger (MW)
  - measures distance between satellites due to gravity change
  - changes in total water storage
- Radar/Scatterometer (MW)
  - measures returned/backscattered signal
  - precipitation, soil moisture

Passive Sensors
(MW, TIR, VIS/NIR)

- Sounder (MW or VIS/NIR)
  - measures the atmospheric vertical profile
  - Humidity, temperature, precipitation
- Multispectral Radiometer (MW, TIR, VIS/NIR)
  - measures various atmospheric/surface properties in discrete spectral bands
  - Soil moisture, snow, surface temperature (ET), land imaging
- Hyperspectral Radiometer (TIR, VIS/NIR)
  - Measure various atmospheric/surface properties in 100s contiguous bands
  - Land surface properties, vegetation, agriculture

https://earthdata.nasa.gov/user-resources/remote-sensors

Approaches to Remote Sensing of Soil Moisture

- Measurement principles
  - No direct measurement of possible, only indirect techniques
- Optical to Mid-Infrared (0.4 – 3 m)
  - Change of “colour”
  - Water absorption bands at 1.4, 1.9 and 2.7 m
- Thermal Infrared (7 - 15 m)
  - 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

Dielectric permittivity (ε) is the ability of a substance to hold an electrical charge.

The **dielectric constant (Ka)** is the ratio of the permittivity of a substance to free space. The value of Ka in air is 1 and in water Ka is approximately 80.

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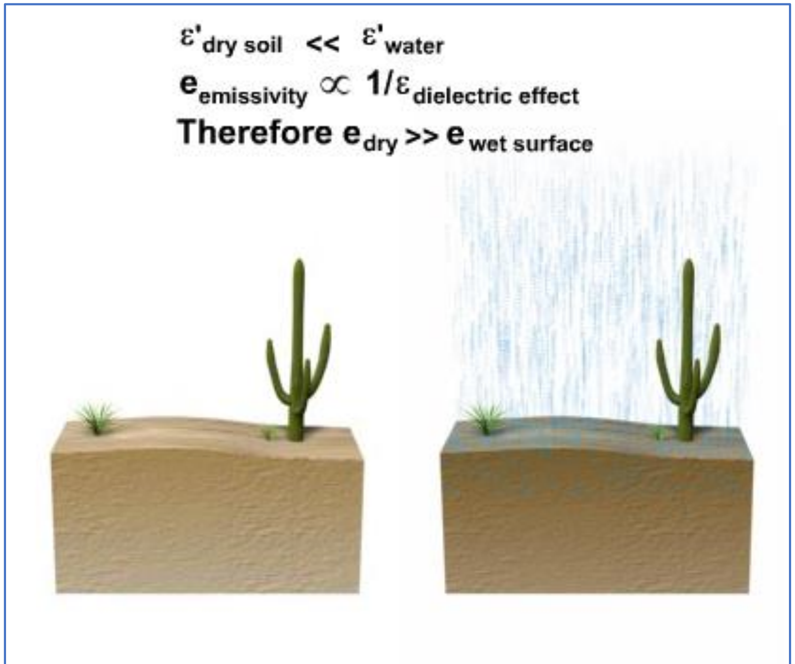
Observed Quantities

- **Microwave Radars (active)**
  - Measures the backscattering coefficient which is how reflective the Earth surface is
  - e.g. Advanced SCATterometer (ASCAT) aboard the EUMETSAT MetOp satellite

- **Microwave Radiometers (passive)**
  - Measures the brightness temperature $T_B = e \times T_s$ where e is the emissivity and T_s is the surface temperature
  - e.g. ESA's Soil Moisture Ocean Salinity (SMOS) microwave radiometer

- Passive and active methods essentially measure the same variables and are interrelated through Kirchhoff's law: $e = 1 - r$ where r is the reflectivity.

- Dielectric constant of water is much higher than dry soils
- There is a strong correlation between the dielectric effect and reflection (and therefore emissivity)
- So, if soil moisture increases:
  - Dielectric ↑
  - Reflection,Backscatter ↑ Emissivity ↓



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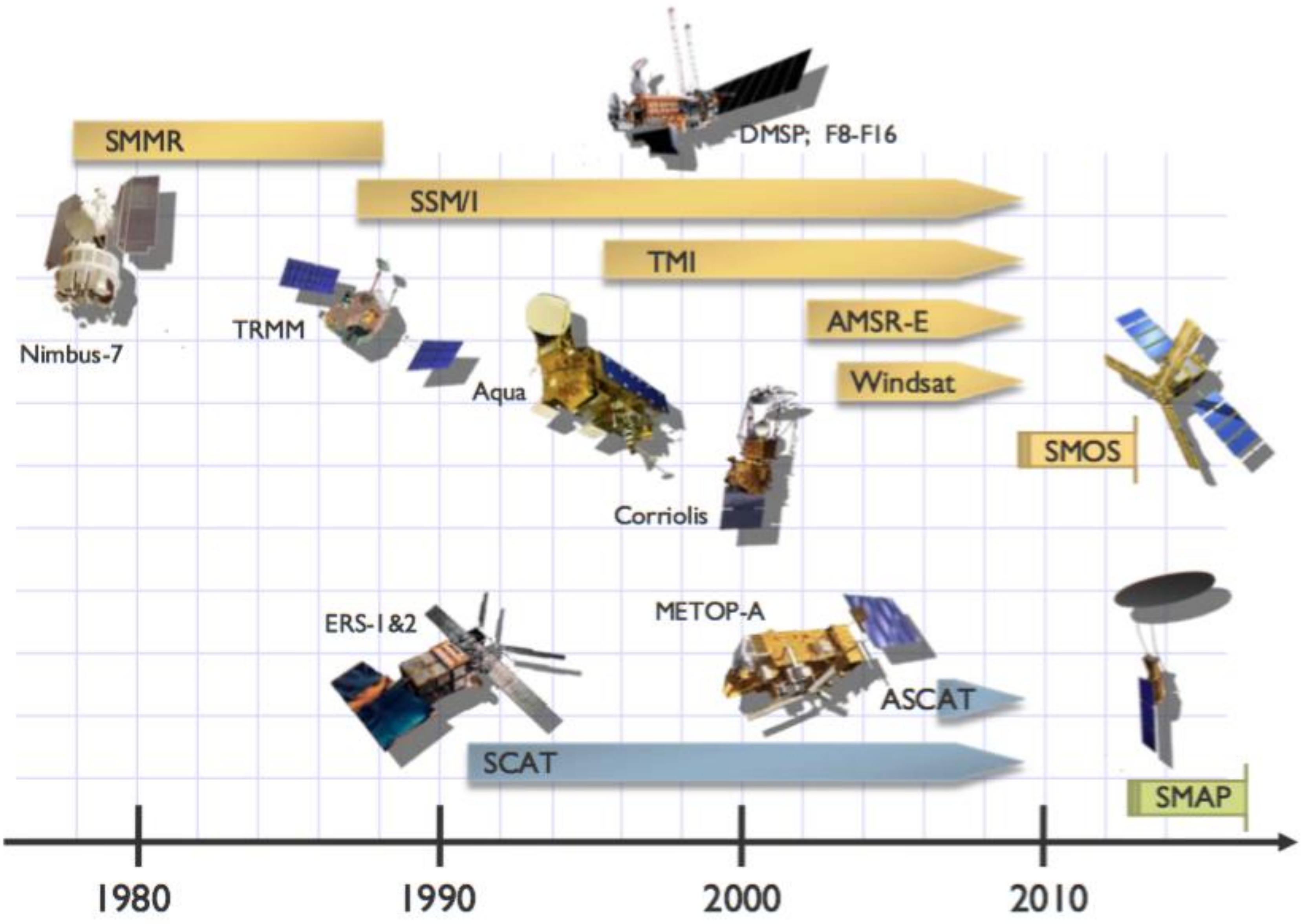
Past and Current Sensors for Soil Moisture



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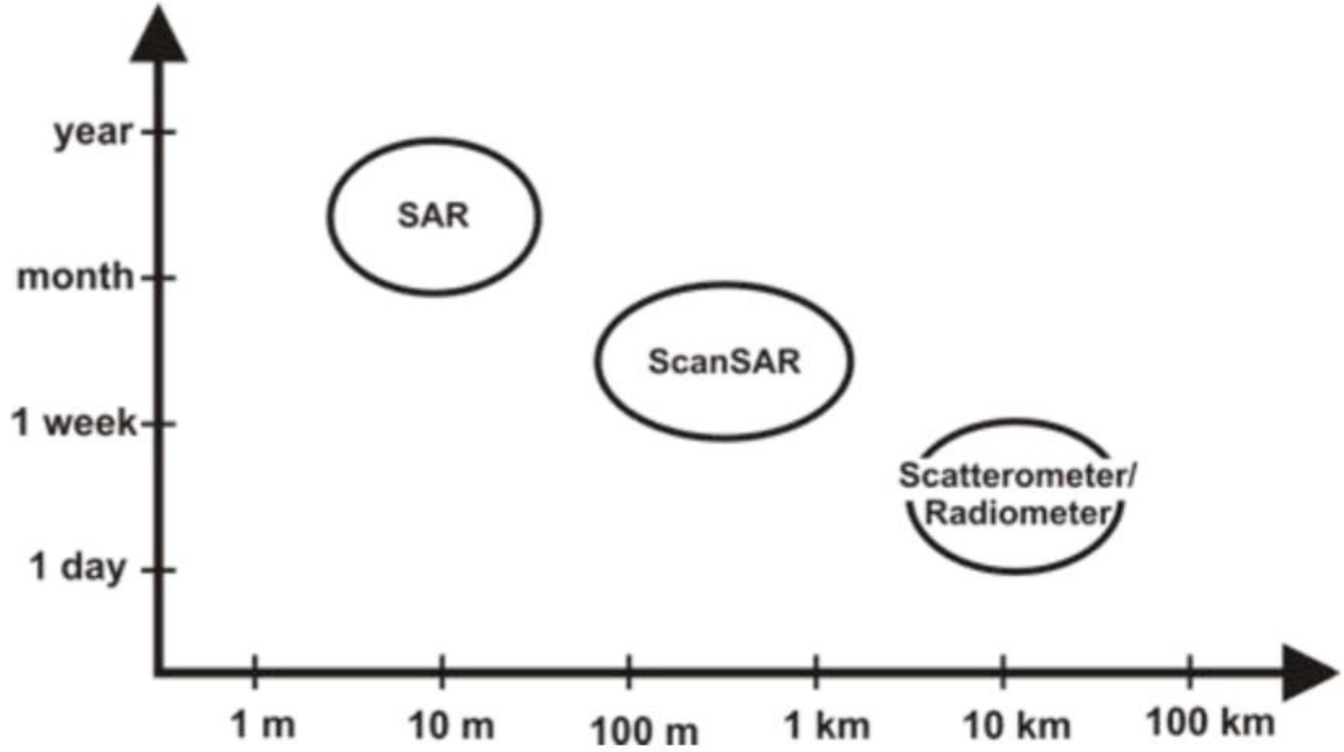
Satellite Sampling Requirements

Sampling requirements driven by

- High temporal variability of soil moisture
- Spatial resolution is also important depending on the application
- Preference is for long-term, temporally dense data



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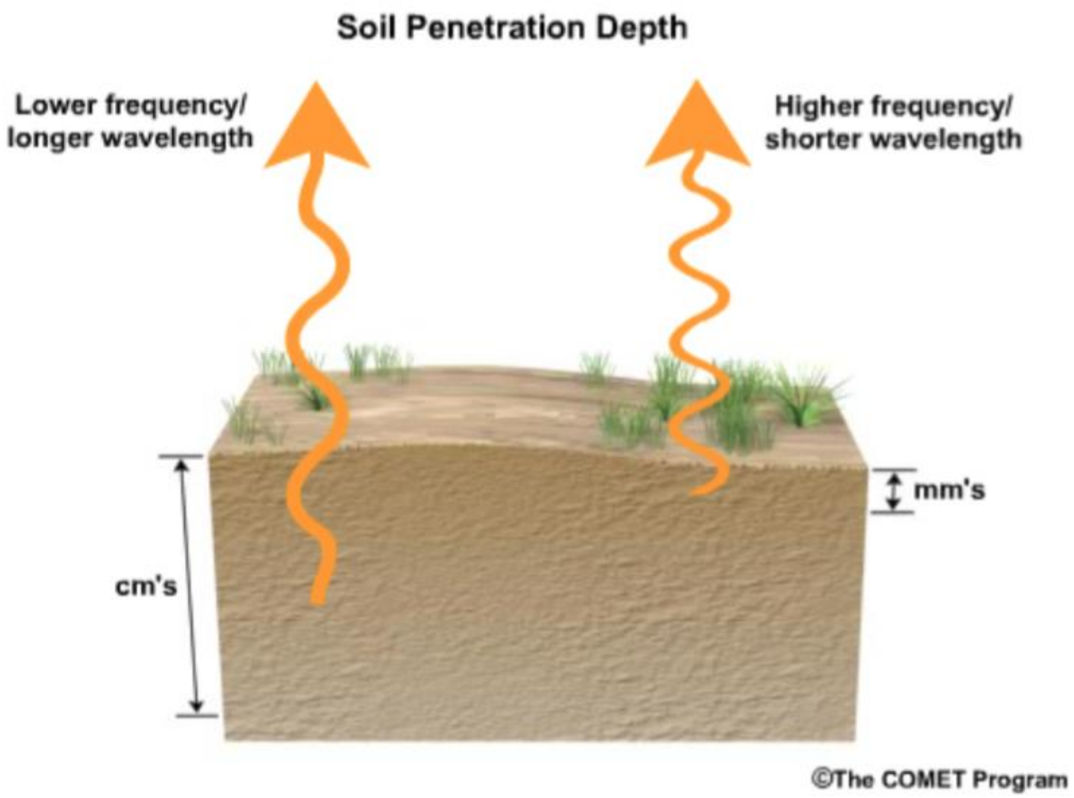
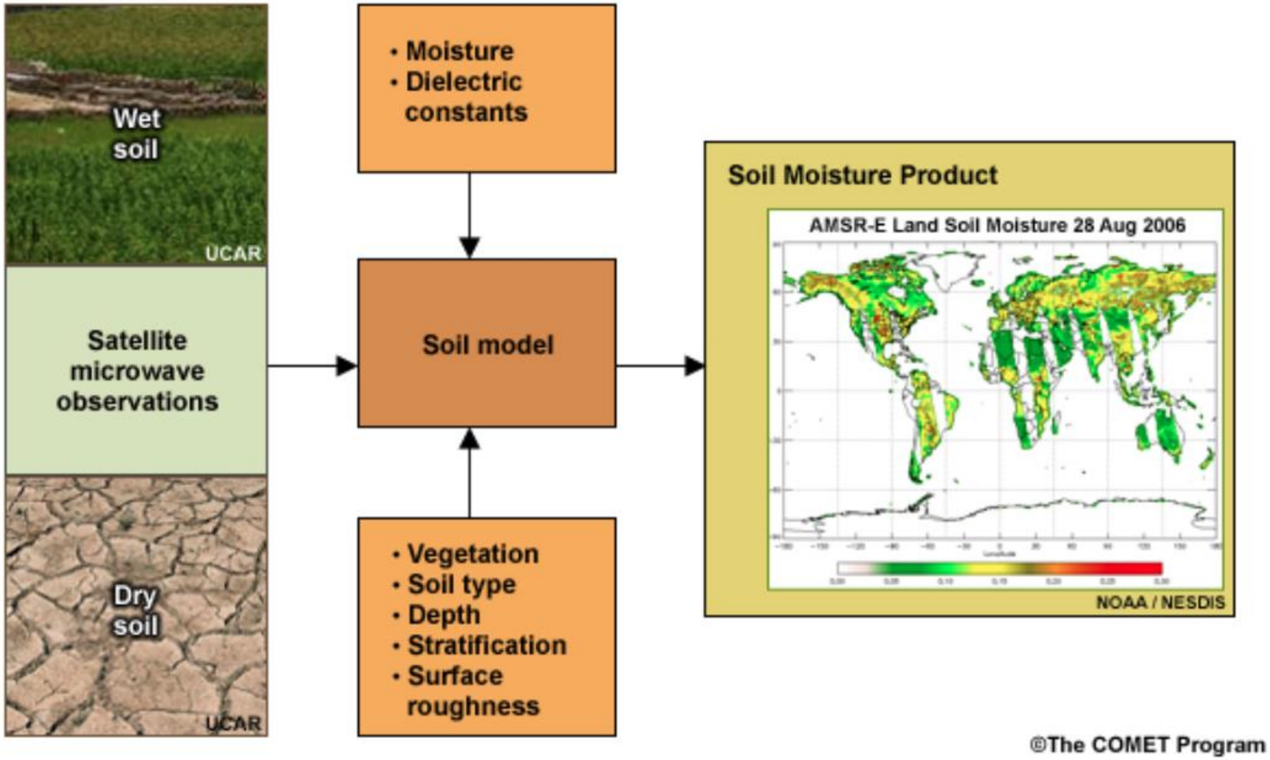
What the Satellite Sensor "Sees"

- Another important consideration when observing soil with microwave wavelengths is the penetration depth.
- The penetration depth is deeper for lower microwave frequencies (1-10 GHz for example) because the longer wavelengths are less absorbed and scattered by the soil.
- In contrast, the penetration is significantly less at higher frequencies (e.g. 85-89 GHz), only convey information about the top few millimeters of soil.



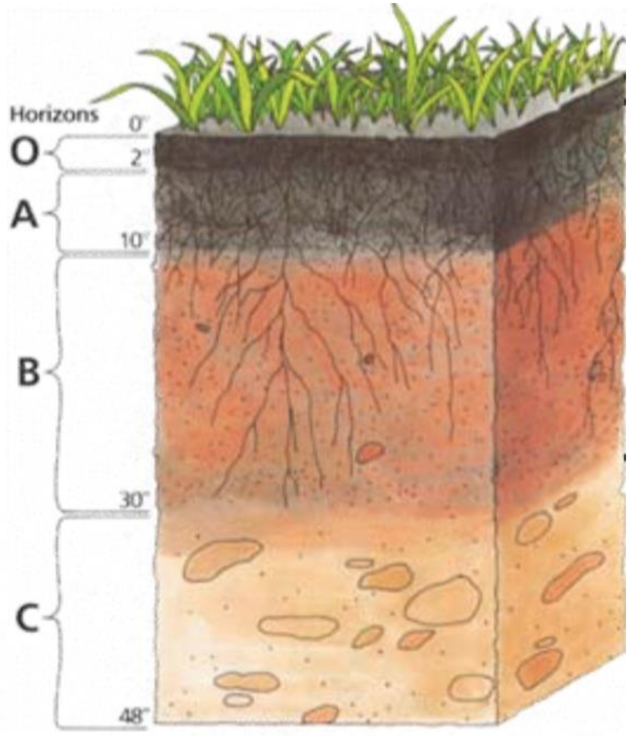
Retrieving Soil Moisture

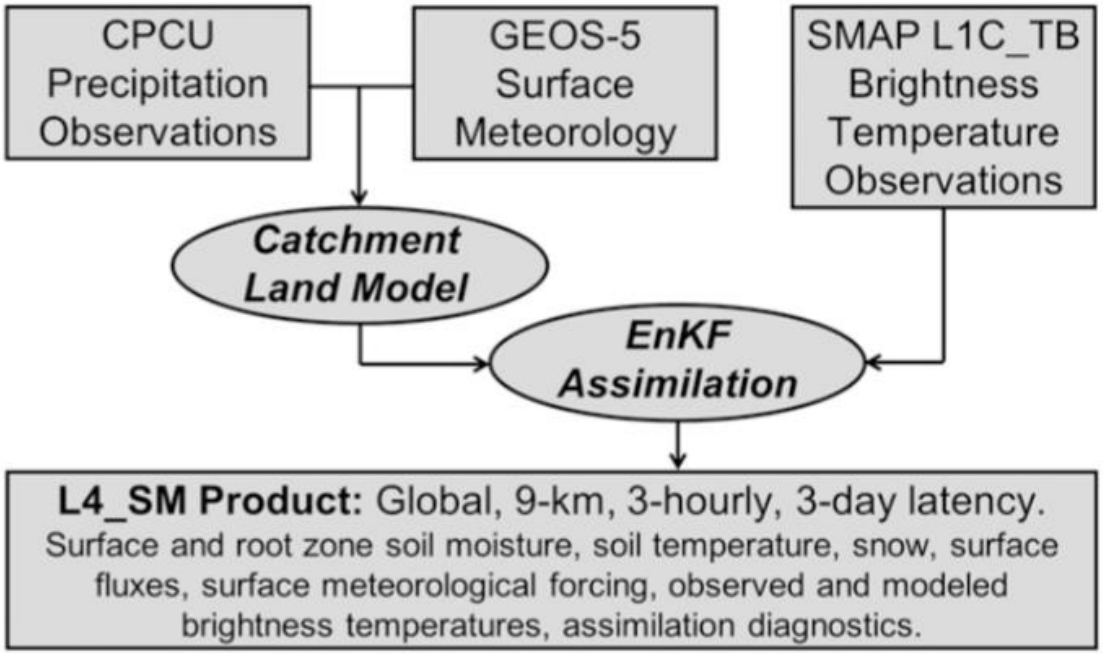
- Extracting quantitative information on soil moisture is a relatively complex process that takes into consideration a number of factors and limitations
- and then combines satellite and conventional observations as well as a priori information within the framework of a soil model.
- Examples of a priori information include surface type, soil composition, soil structure, and climatological profiles of temperature and moisture.



Retrieving Root Zone Soil Moisture

- Sensors only measure the top mm to few cms of the soil, but the root zone is the most important for applications
- RZSM can be retrieved by assimilating satellite soil moisture measurements (retrieved soil moisture or brightness temperature) into a land surface or hydrological model

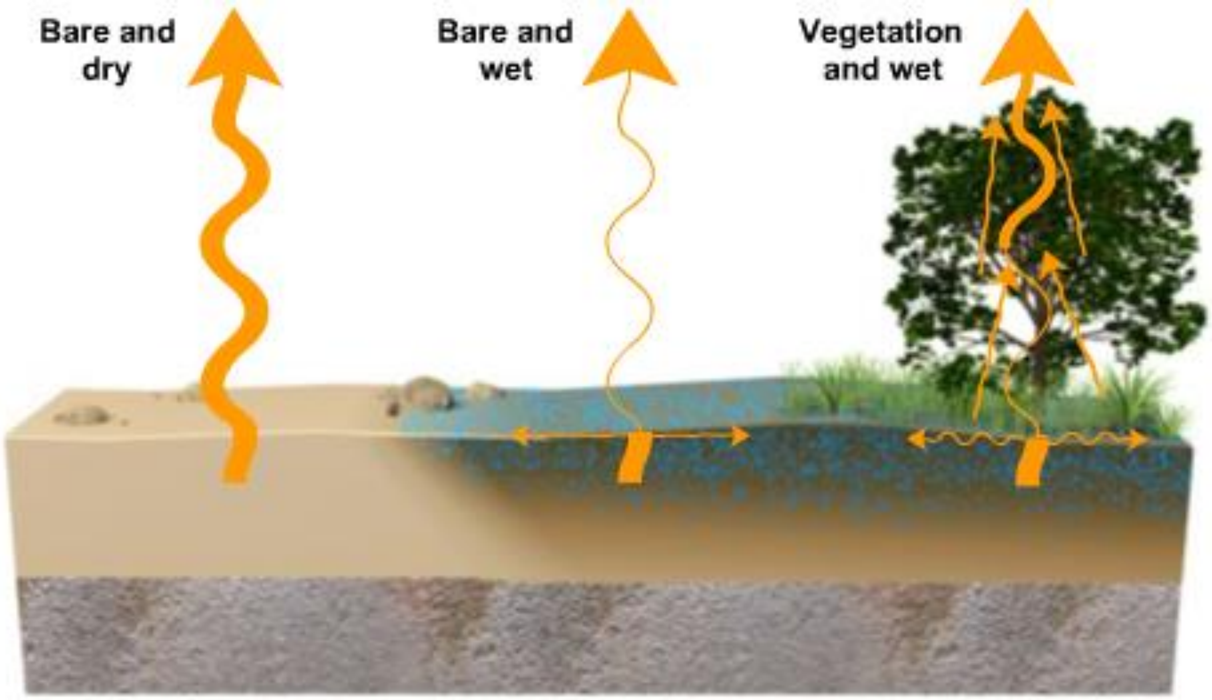




Reichle et al., 2017

Complicating Factors

- Vegetation and surface roughness interfere with the signal being emitted from the Earth's surface.
- Vegetation emits its own microwave radiation, which can be confused with the desired soil emission.
- As the figure shows, vegetation acts to increase the emissivity for an otherwise wet surface below.
- This increases the observed microwave brightness temperature and makes the surface appear dryer than it really is.



Trade-Offs in Microwave Sensing of SM

Active measurements are somewhat more sensitive to surface roughness and vegetation structure than **passive** measurements but:

- Are not affected by surface temperature (above 0°C)
- Have a much higher spatial resolution

Disadvantages of microwave soil moisture Sensors:

- only see the top cm of soil
  - → use models to get RZSM
- cannot penetrate dense vegetation
  - → restrict to less vegetated areas or estimate vegetation water content
- low resolution for passive (10s km) because of low energy in MW region
  - → Combine with active or downscale with models
- radio frequency interference
  - → remove or restrict to outside of RFI

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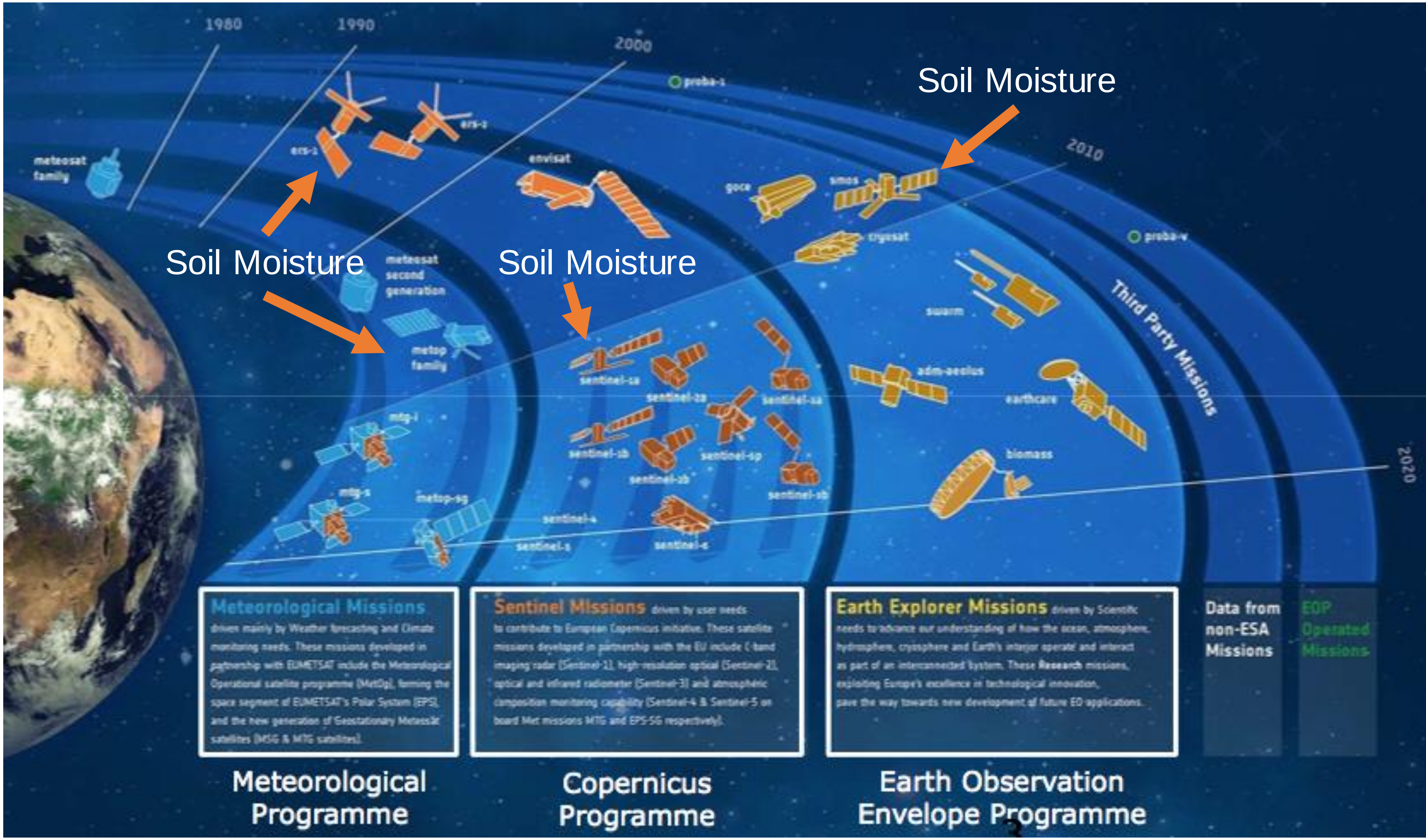
European Space Agency (ESA) Satellites



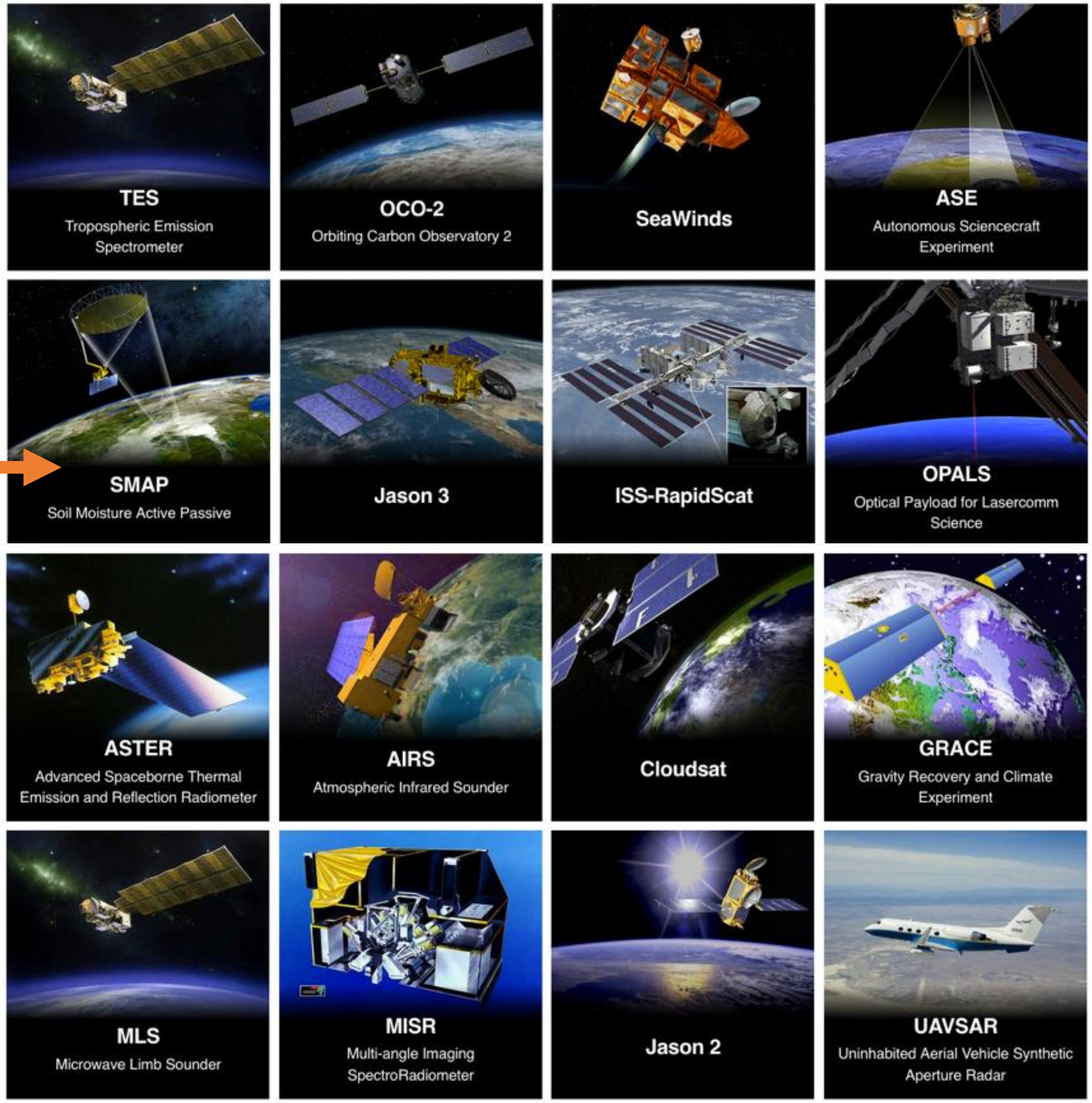
Weather monitoring and forecasting

Applications and earth monitoring

Earth Science

(Some) Current NASA Earth Observation Satellites

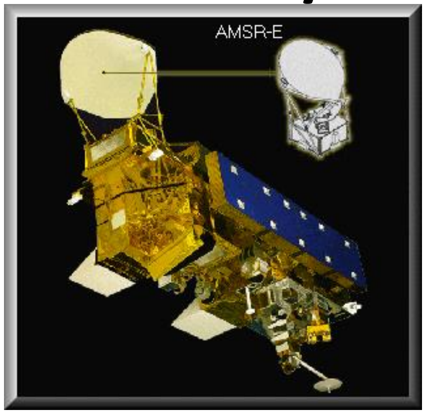
Soil Moisture

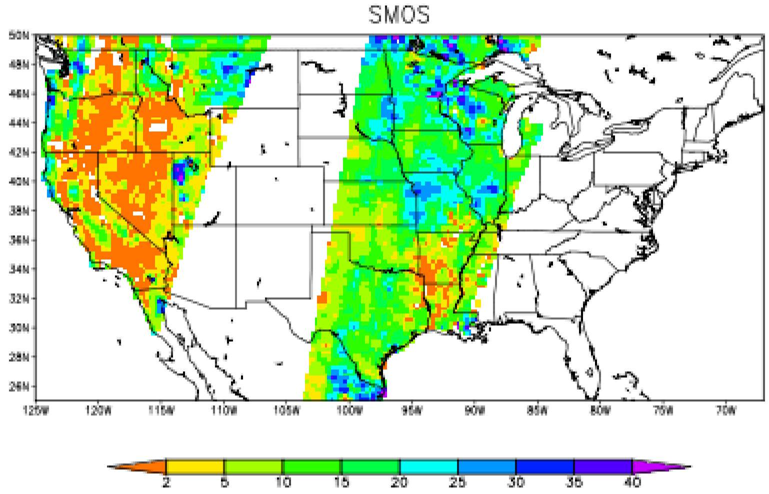


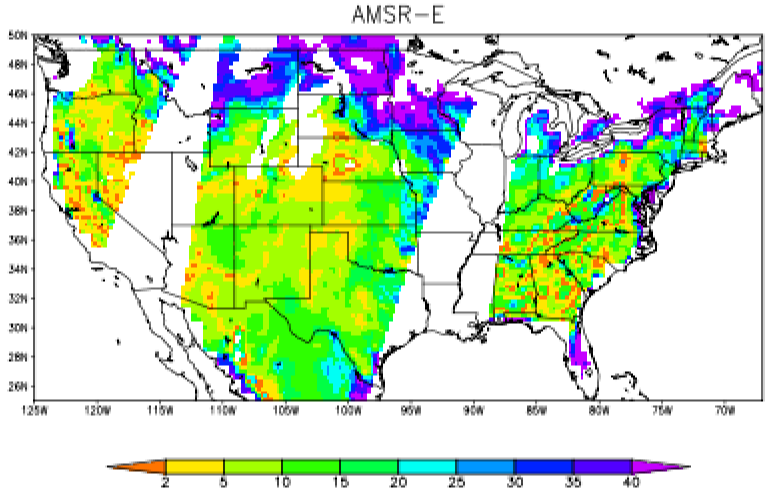
Soil Moisture from Microwave Measurements

SMOS

AMSR-E/2

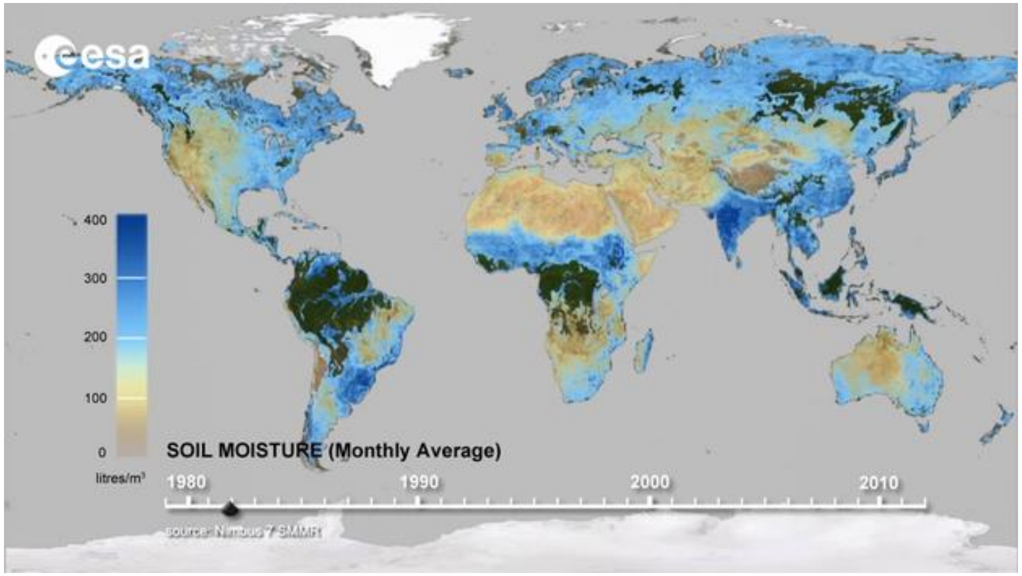


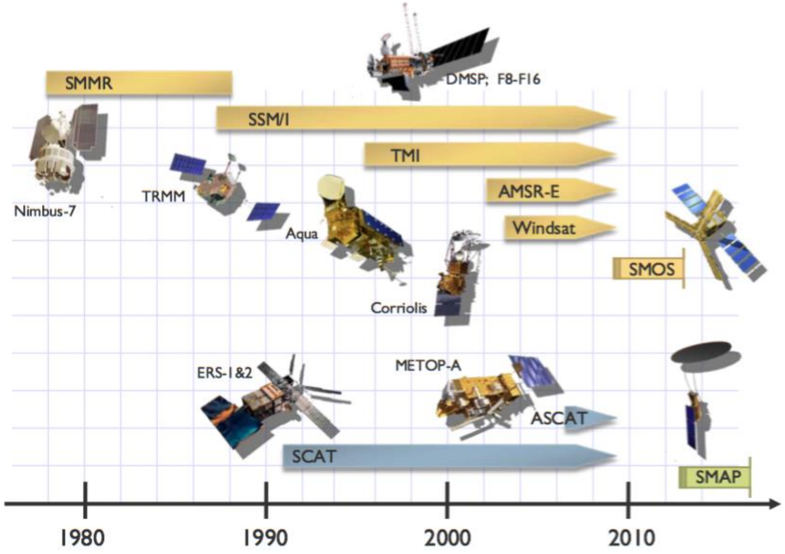




ESA-CCI 30-year Merged Global Product

- The data record was generated by merging two soil moisture datasets.
- The first is based on active microwave datasets processed by the Vienna University of Technology and is based on observations from the C-band scatterometers on Europe's ERS-1, ERS-2 and MetOp-A satellites.
- The other dataset was generated by the Vrije University of Amsterdam in collaboration with NASA, based on passive microwave observations from the Nimbus-7, DMSP, TRMM and Aqua missions.
- The harmonisation of these datasets aimed to take advantage of both types of microwave techniques - difficult owing to sensor degradation, drifts in calibration and algorithmic changes in the processing systems.

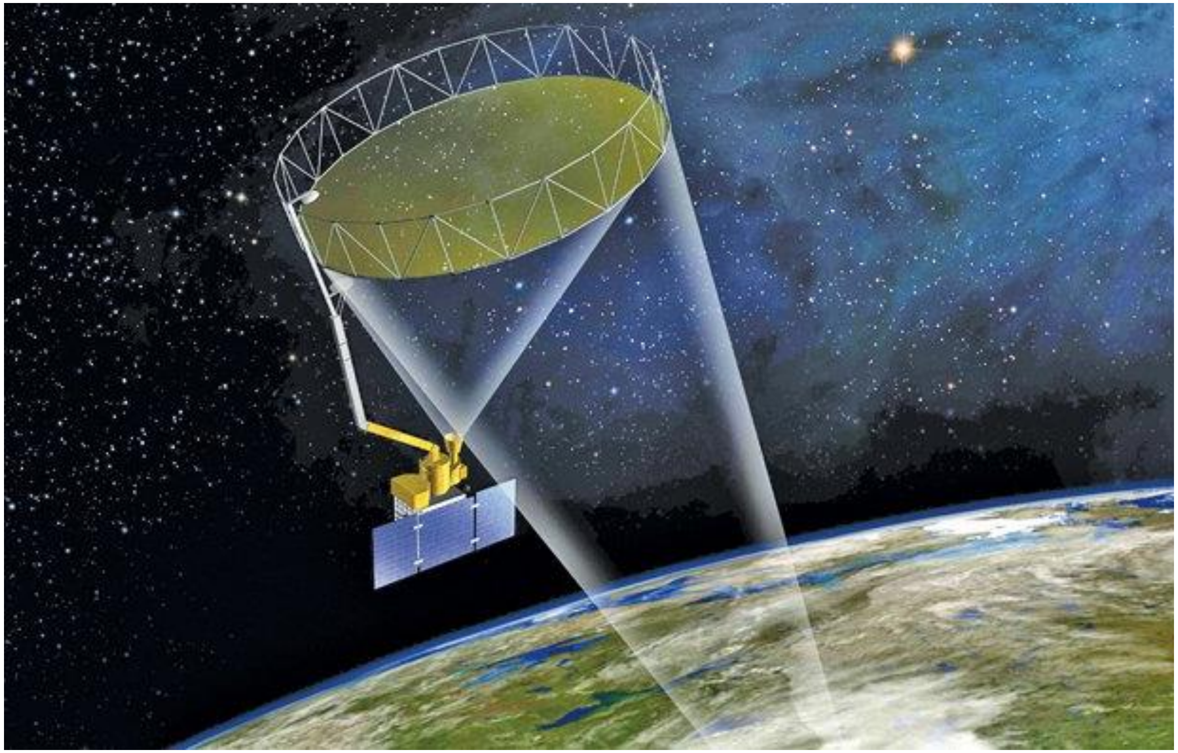




SMAP Mission for Soil Moisture

SMAP: Soil Moisture Active and Passive

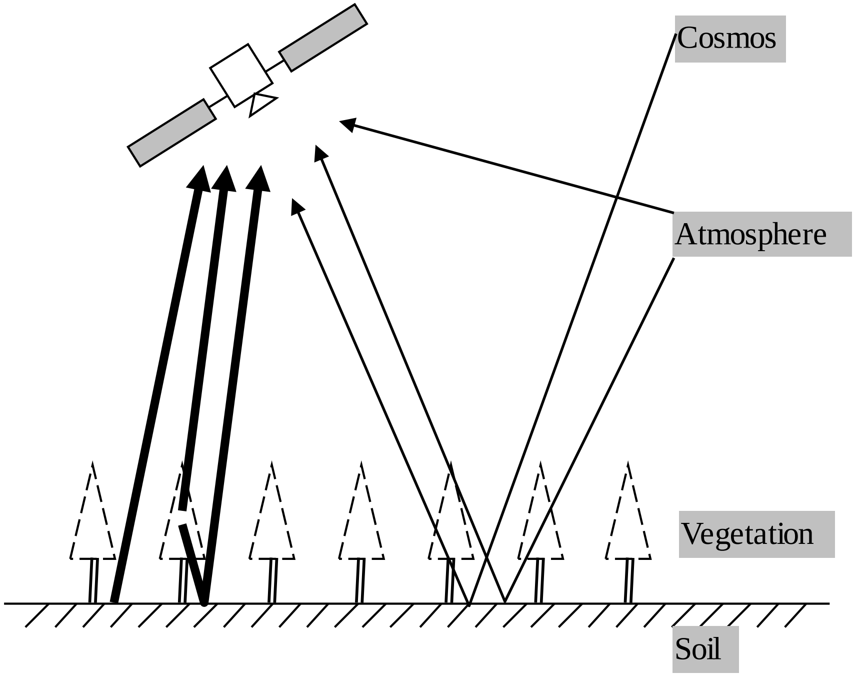
- 1.41 GHz radiometer（passive），1.26 GHz radar（active，failed）
- ~40 km resolution（radiometer），~3 km radiometer（radar）
- 4% soil moisture retrieval errors
- 2-3 day revisit time
- Sun-synchronous orbit
- 6 am/pm overpasses
- Launched January 2015

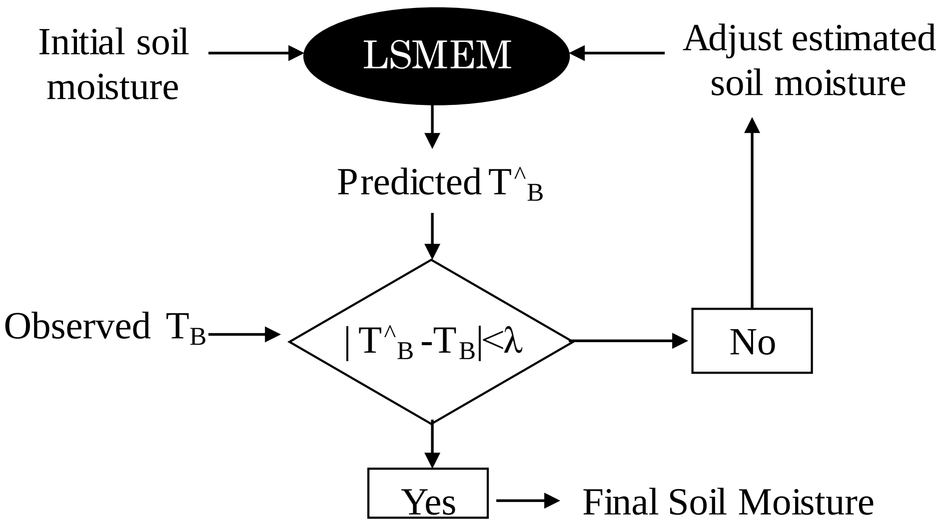


Retrieval of Near Surface Soil Moisture

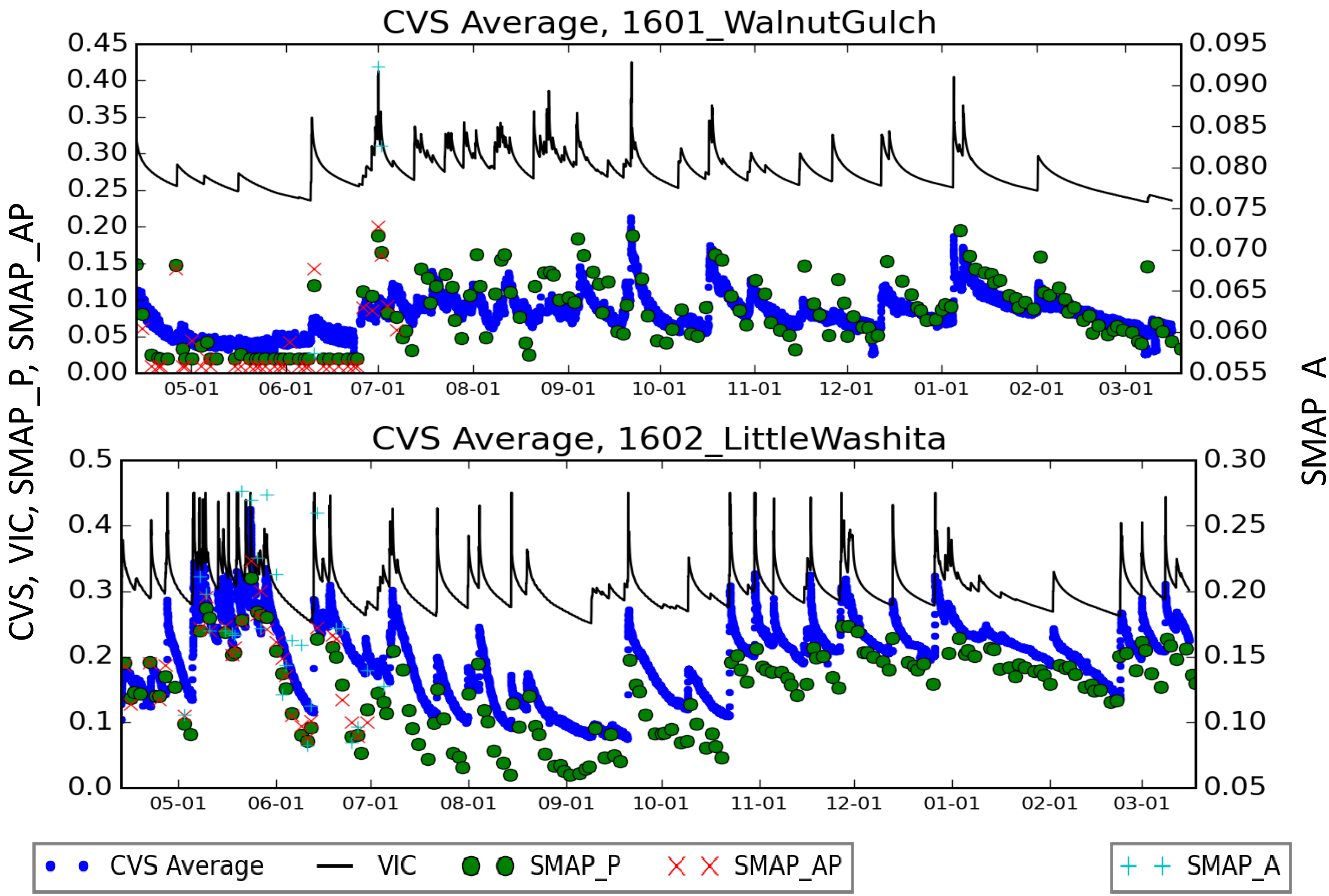
Radiative Transfer Model (RTM)

- Surface->TOA radiative transfer model
- Based on physical parameters
  - Soil
  - Vegetation
  - Surface properties
  - Surface water
- To retrieve soil moisture, a simple inversion (i.e. root finding) is employed to find the soil moisture values that gives the best match to the observed brightness temperature.

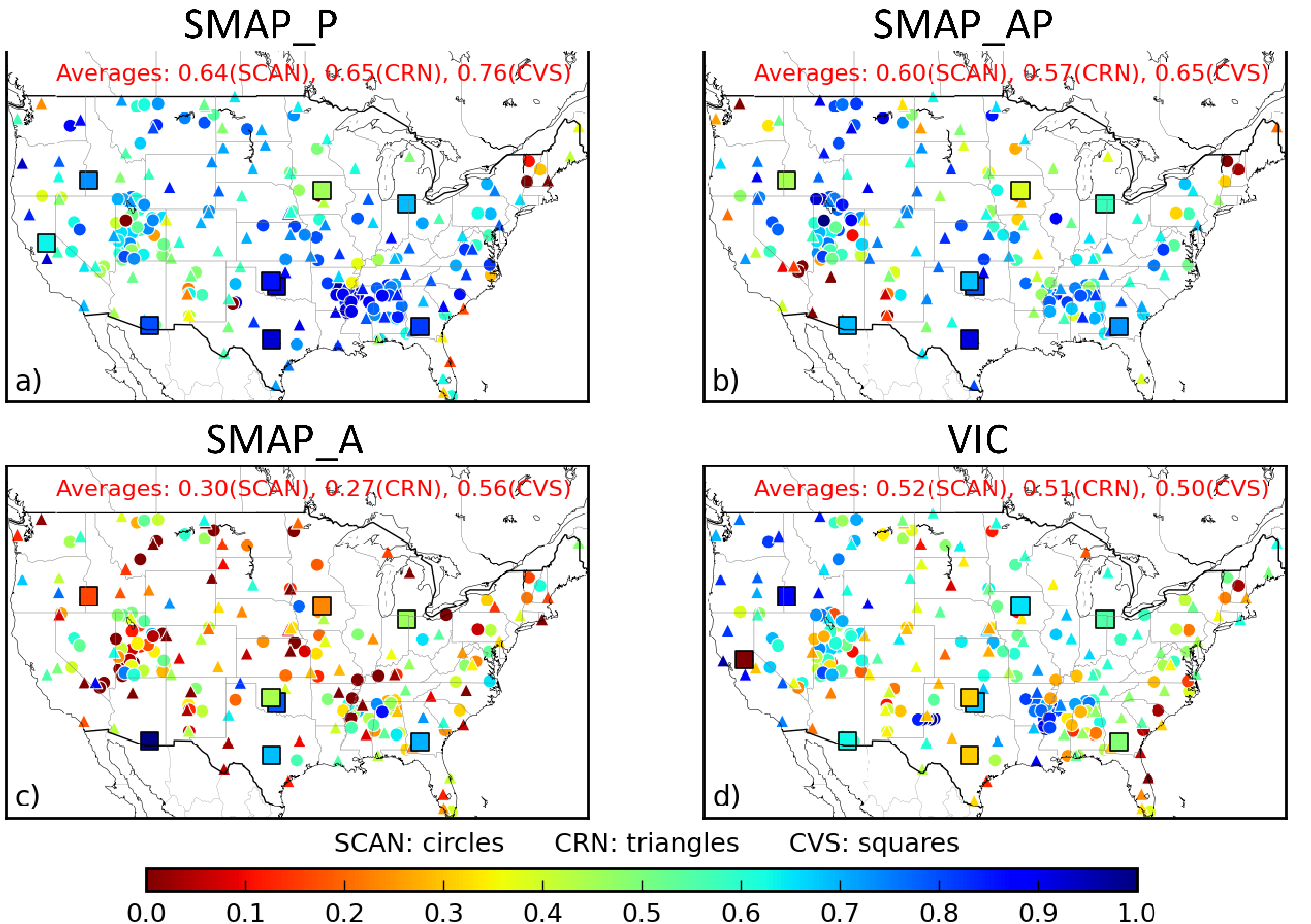




SMAP Ground Validation



SMAP Ground Validation - Correlation



Questions?

Practical

Downloading and visualizing SMAP Soil Moisture Data using NASA Worldview

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

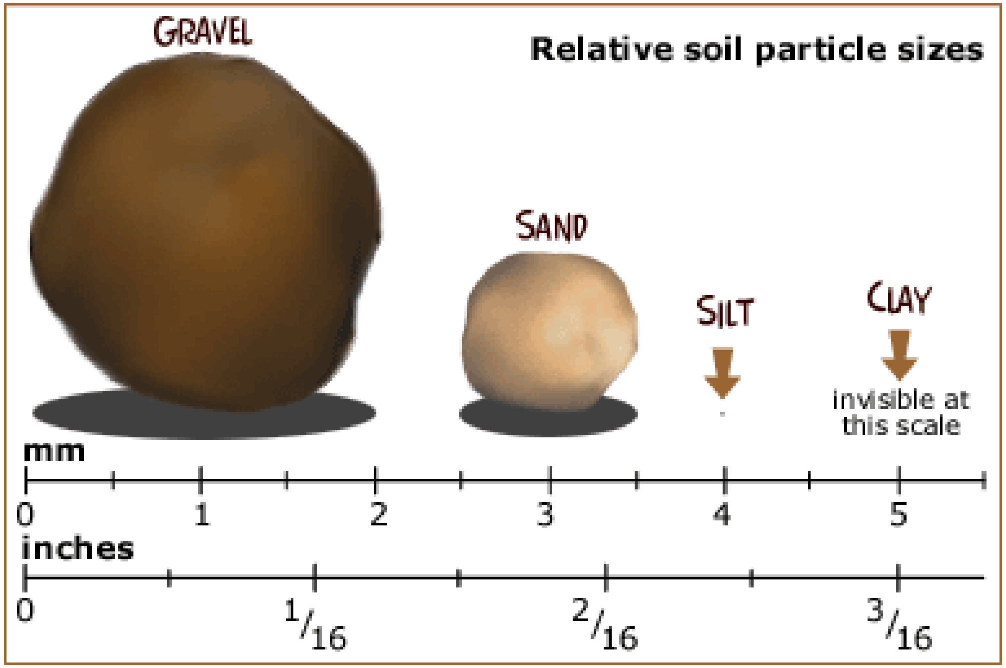
Distinct but temporally stable spatial patterns

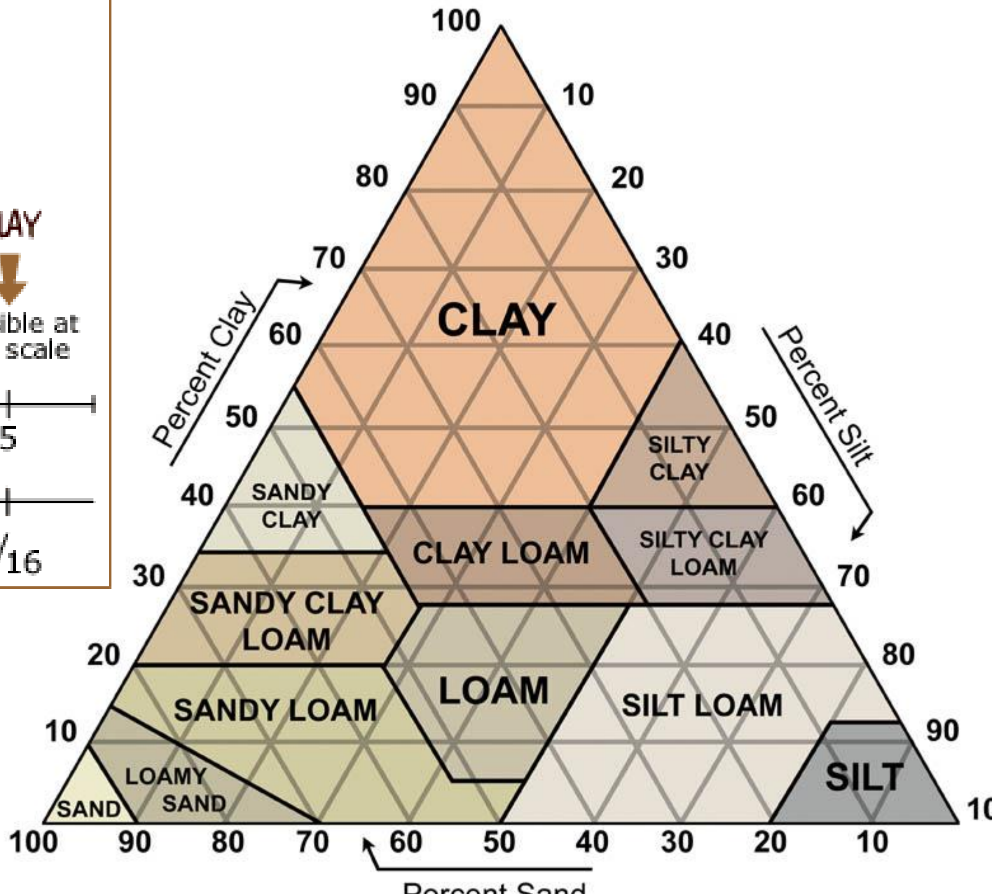
Temporal stability means that spatial patterns persist in time

- 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

Definitions: Soil Texture and Porosity

- Relative abundance of sand, silt, and clay determines soil texture
- Irregular shapes create voids, called pore spaces
- Porosity = Volume of soil occupied by air and water

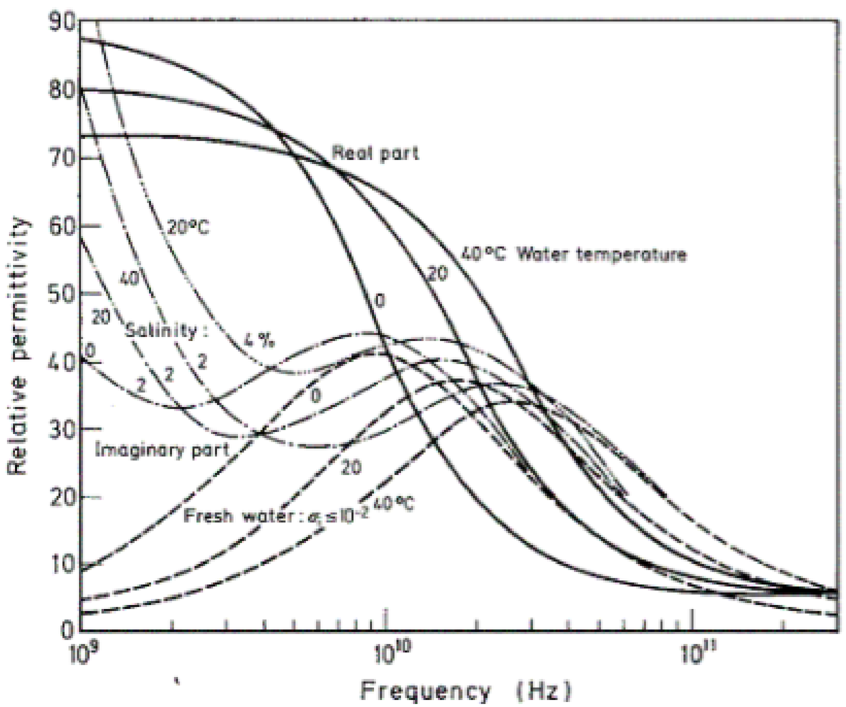


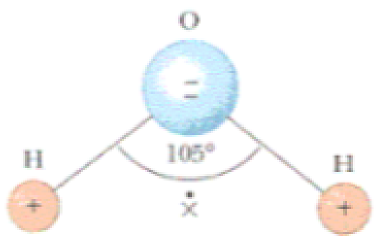


Microwave Approaches

Microwaves (1 mm – 1 m wavelength)

- All-weather, all-day 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





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

Dielectric constant of water

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