Remote Sensing Physics and Measurements

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Keck Institute for Space Studies Study Program

Unlocking a New Era in Biodiversity Science:
Linking Integrated Space Based and In-Situ Observations

October 1-5, 2018
Pasadena, California

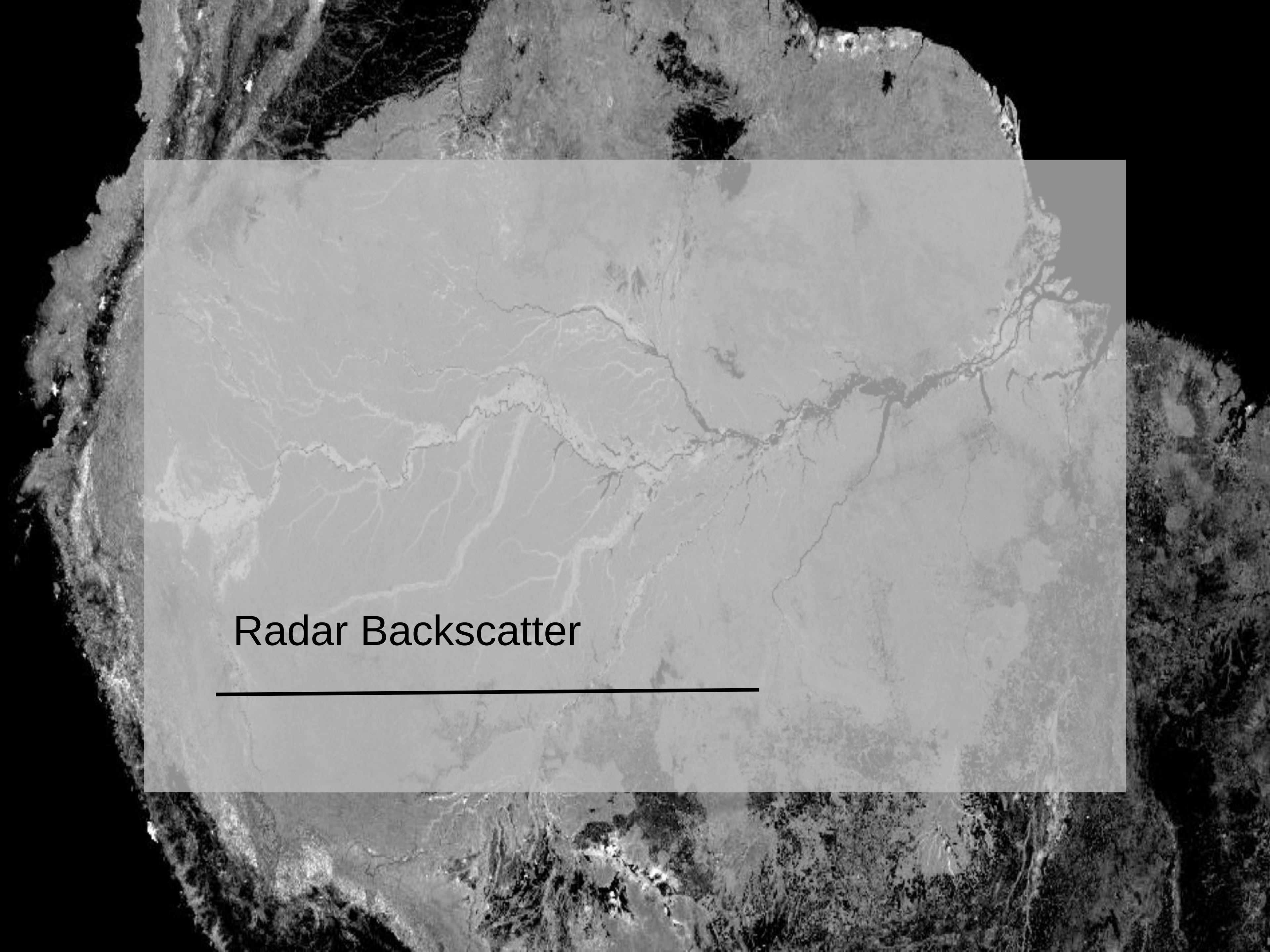
Remote Sensing Physics and Measurements

- **Radar**
- **Lidar**
- **SIF**

“When you can measure what you are speaking about, and express it in numbers, you know something about it. But when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind.”

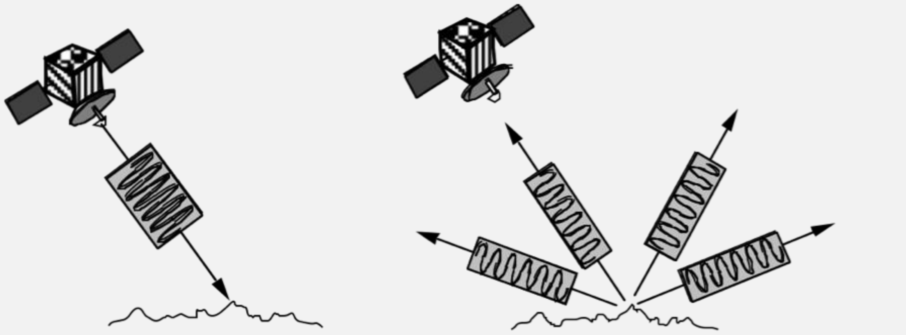
- Lord Kelvin

Radar Backscatter

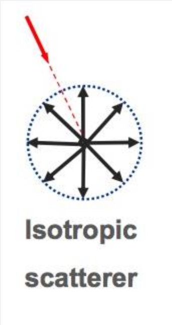


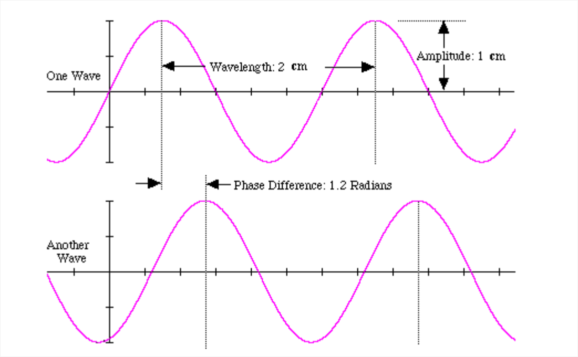
Radar Image Formation

1. Radar can measure amplitude (the strength of the reflected echo) and phase (the position of a point in time on a waveform cycle)
2. Radar can only measure the part of the echo reflected back towards the antenna (backscatter)
3. Radar pulses travel at the speed of light
4. The strength of the reflected echo is the backscattering coefficient (sigma naught) and is expressed in decibels (dB)



RADAR TRANSMITS A PULSE MEASURES REFLECTED ECHO (BACKSCATTER)

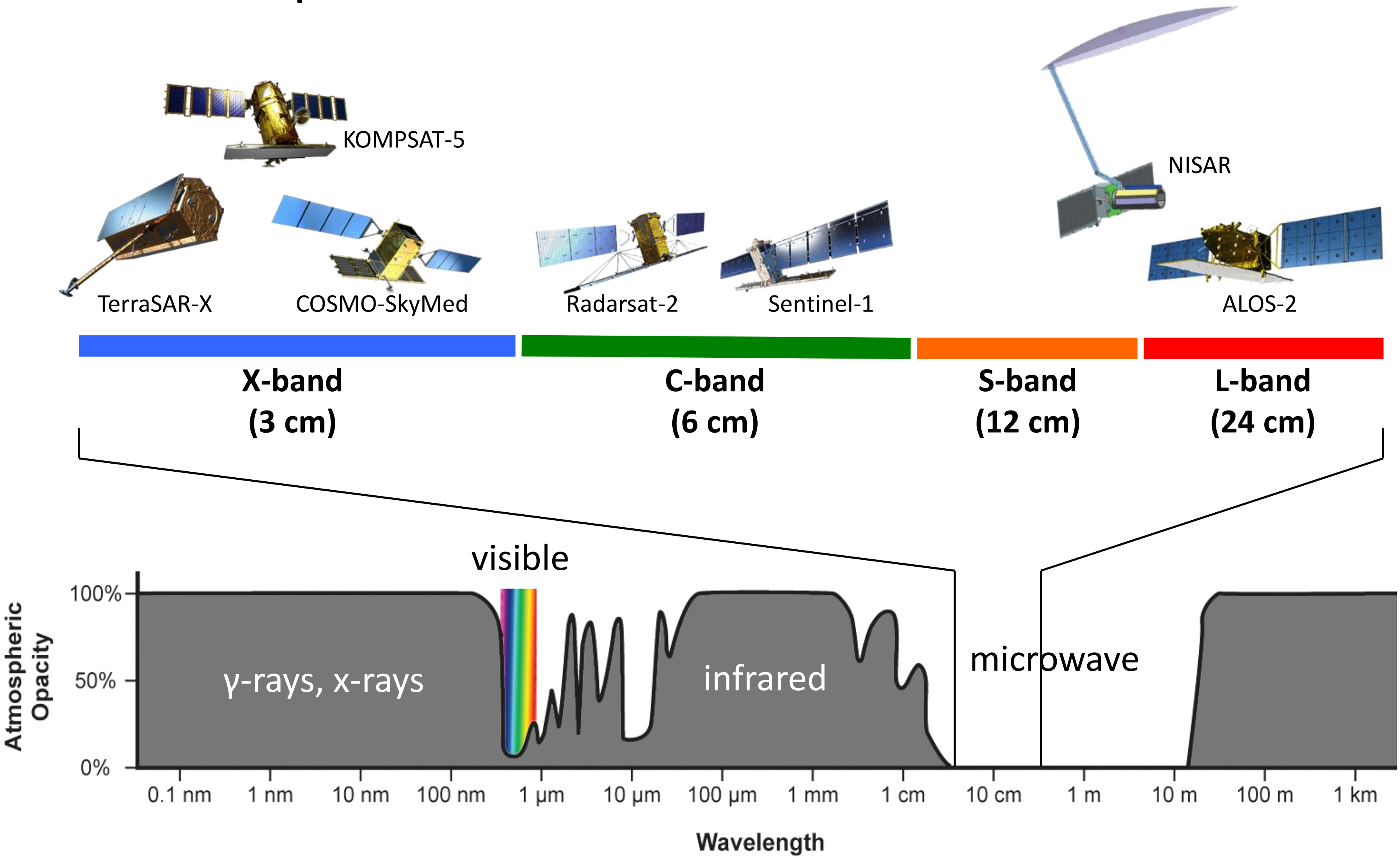




Coherent energy

Source: ESA- ASAR Handbook

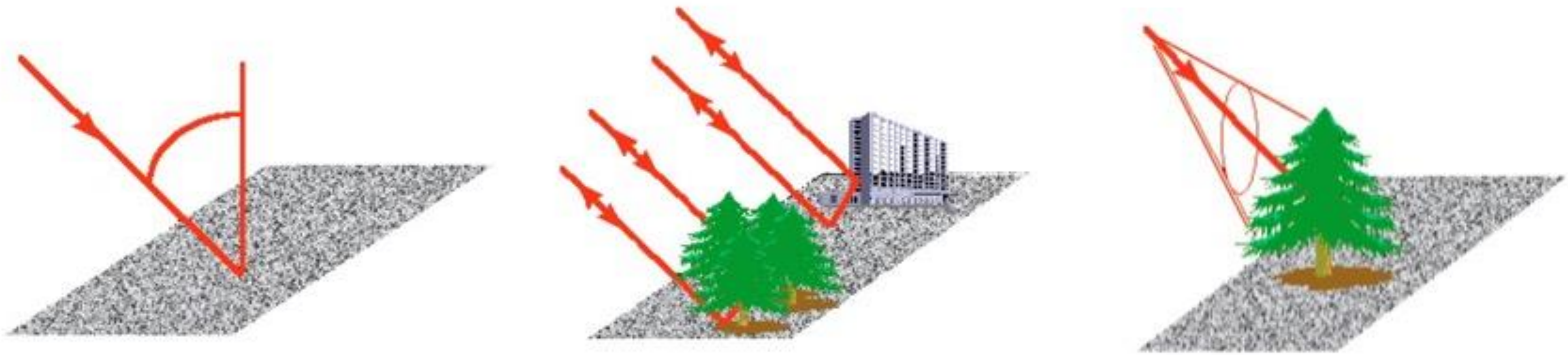
Atmospheric Windows & Current SAR Missions



Physical Interpretation of Radar Backscatter:

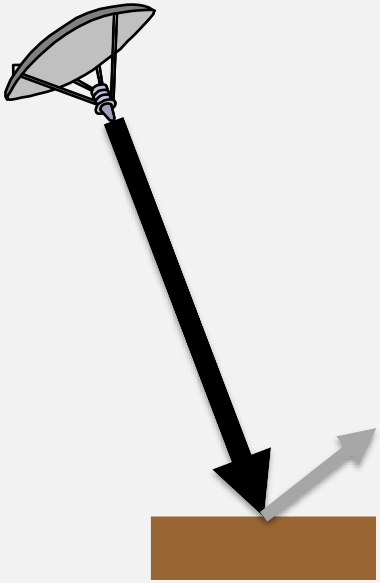
Scattering Mechanisms

Single Bounce Scattering (Rough Surface) | Double Bounce Scattering | Volume Scattering



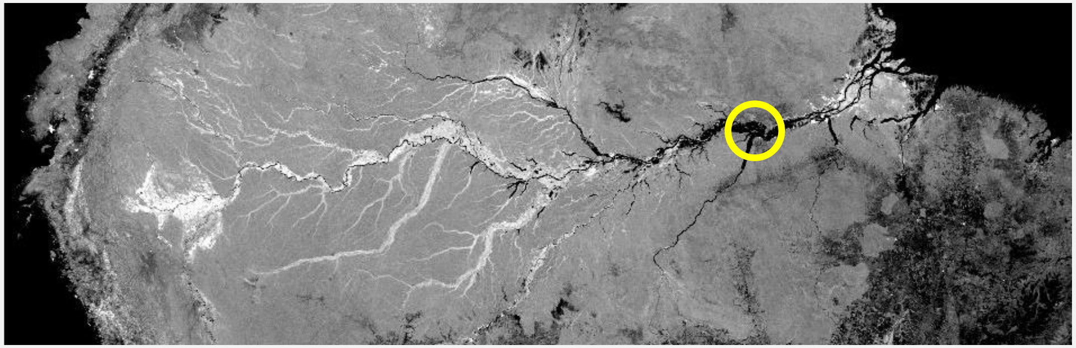
Examples of Radar Interaction

Smooth Surface Reflection (Specular Reflection)



Smooth, level surface
(open water, road)

SMAP Radar Mosaic of the Amazon Basin
April 2015 (L-band, HH, 3 km)



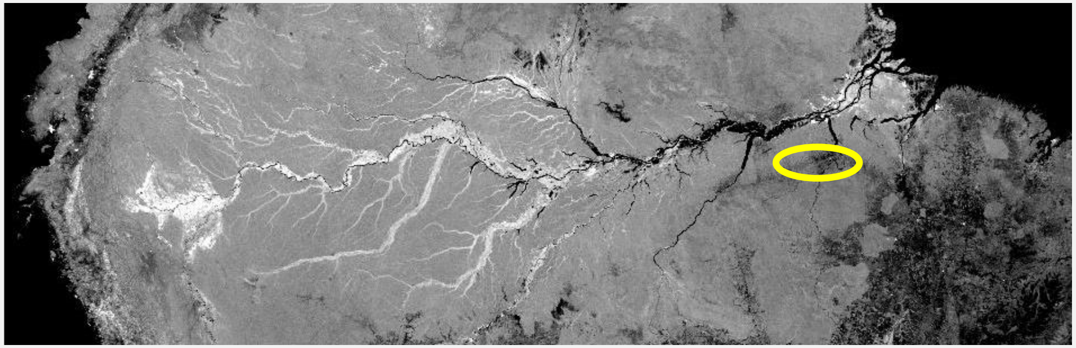
Pixel Color

Examples of Radar Interaction

Rough Surface Reflection

rough bare surface
(deforested areas, tilled agricultural fields)

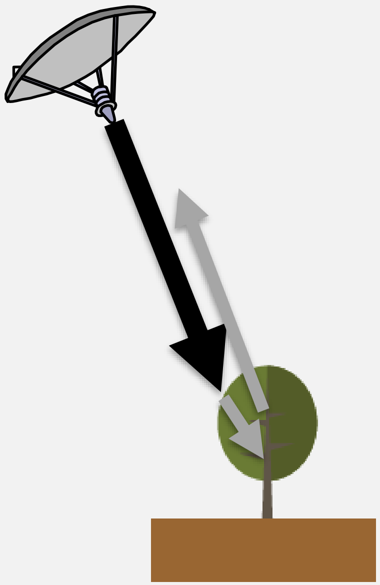
SMAP Radar Mosaic of the Amazon Basin April 2015 (L-band, HH, 3 km)



Pixel Color

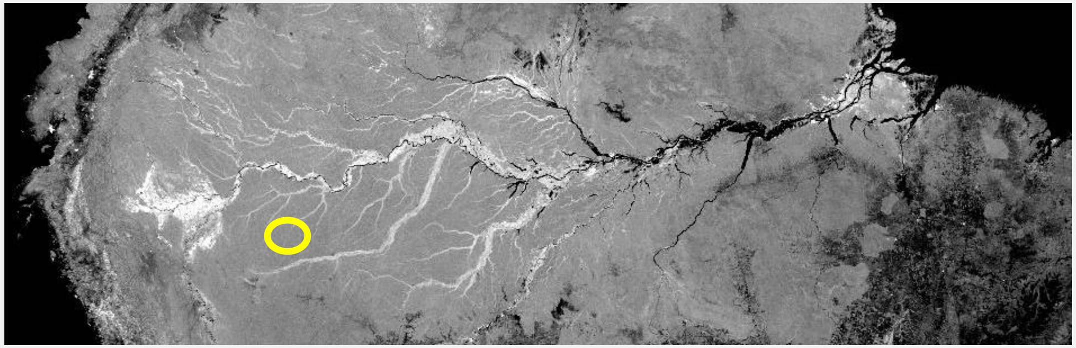
Examples of Radar Interaction

Volume Scattering by Vegetation



Vegetation

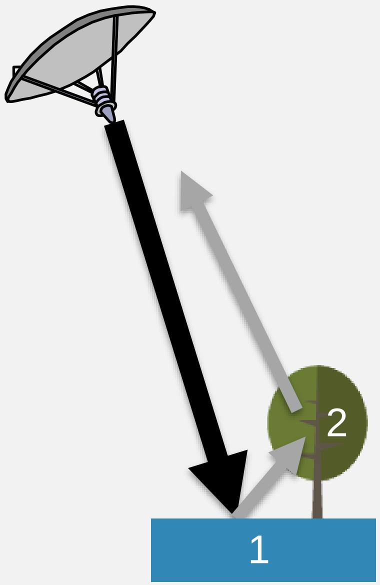
SMAP Radar Mosaic of the Amazon Basin
April 2015 (L-band, HH, 3 km)



Pixel Color

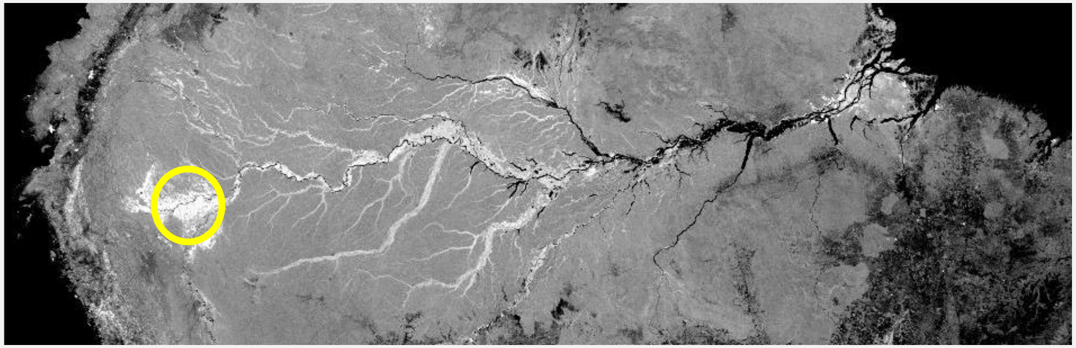
Examples of Radar Interaction

Double Bounce



Inundated Vegetation

SMAP Radar Mosaic of the Amazon Basin April 2015 (L-band, HH, 3 km)



Pixel Color

Radar Parameters: Polarization

- The radar signal is polarized
- The polarizations are usually controlled between H and V:
  - HH: Horizontal Transmit, Horizontal Receive
  - HV: Horizontal Transmit, Vertical Receive
  - VH: Vertical Transmit, Horizontal Receive
  - VV: Vertical Transmit, Vertical Receive
- Different polarizations can determine physical properties of the object observed

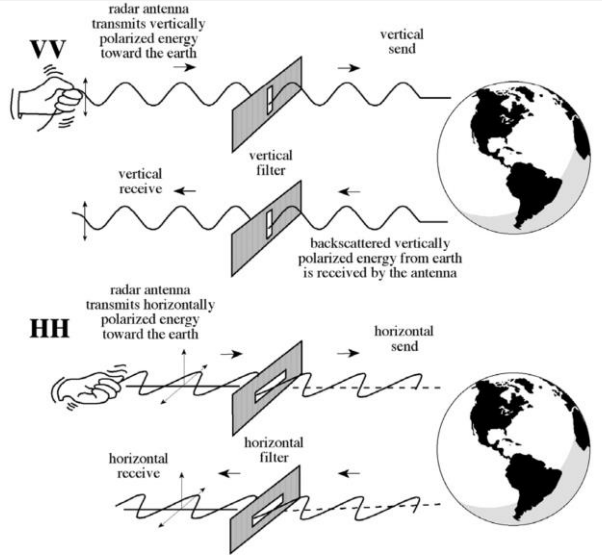


Image Credit: J.R. Jensen, 2000. Remote Sensing of the Environment

Example of Multiple Polarizations for Vegetation Studies

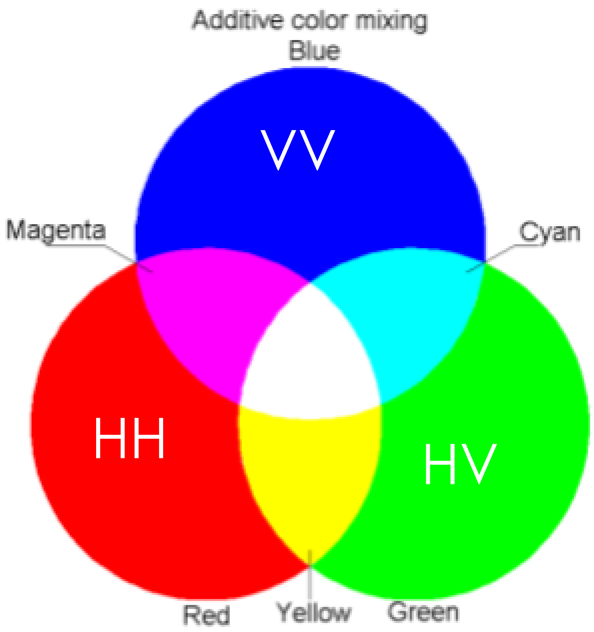
Pacaya-Samiria Forest Reserve in Peru

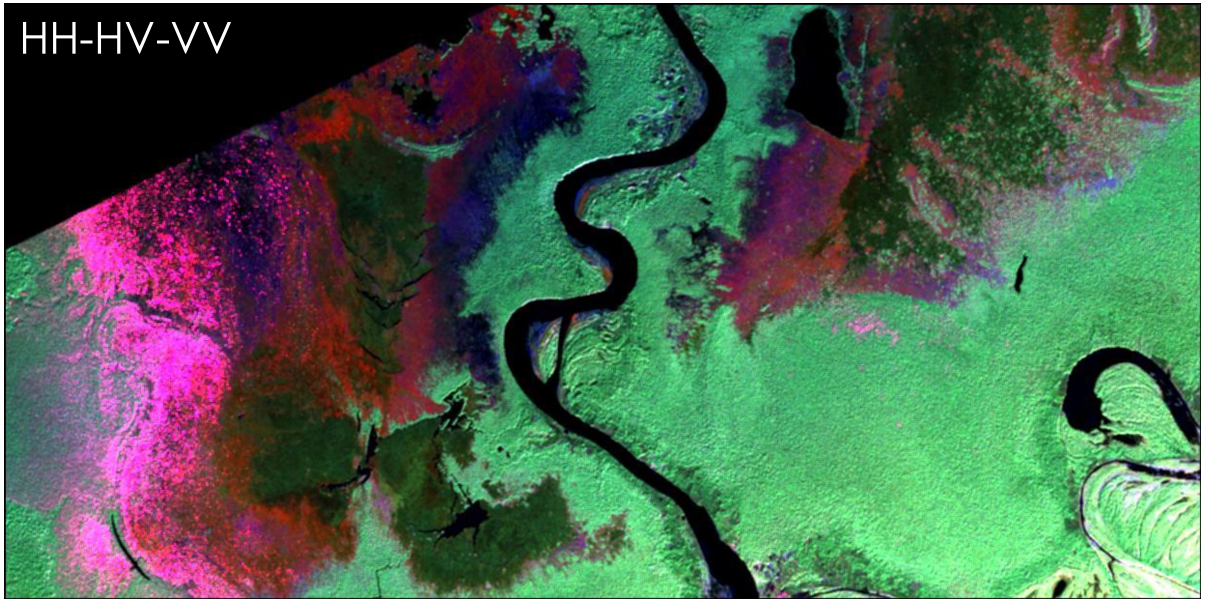
Images from UAVSAR (HH, HV, VV)

Example of Multiple Polarization for Vegetation Studies

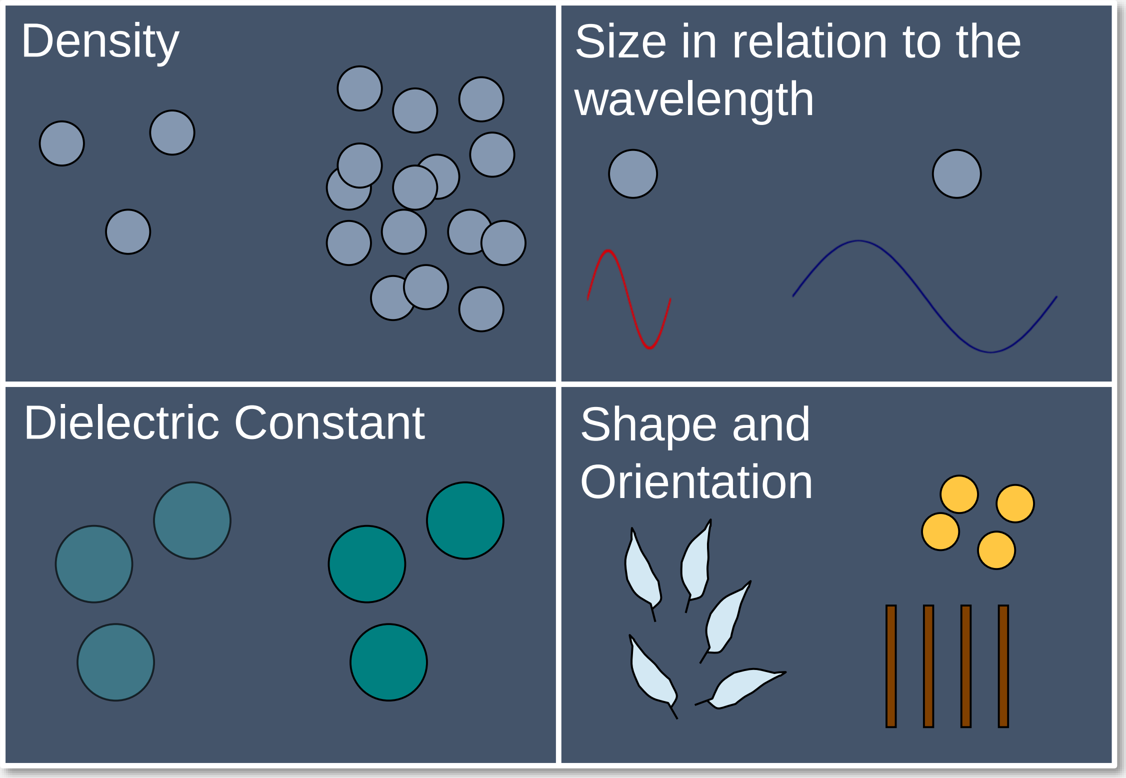
Pacaya-Samiria Forest Reserve in Peru

Images from UAVSAR (HH, HV, VV)





Backscatter Interactions with Surface Media



Size in Relation to Wavelength

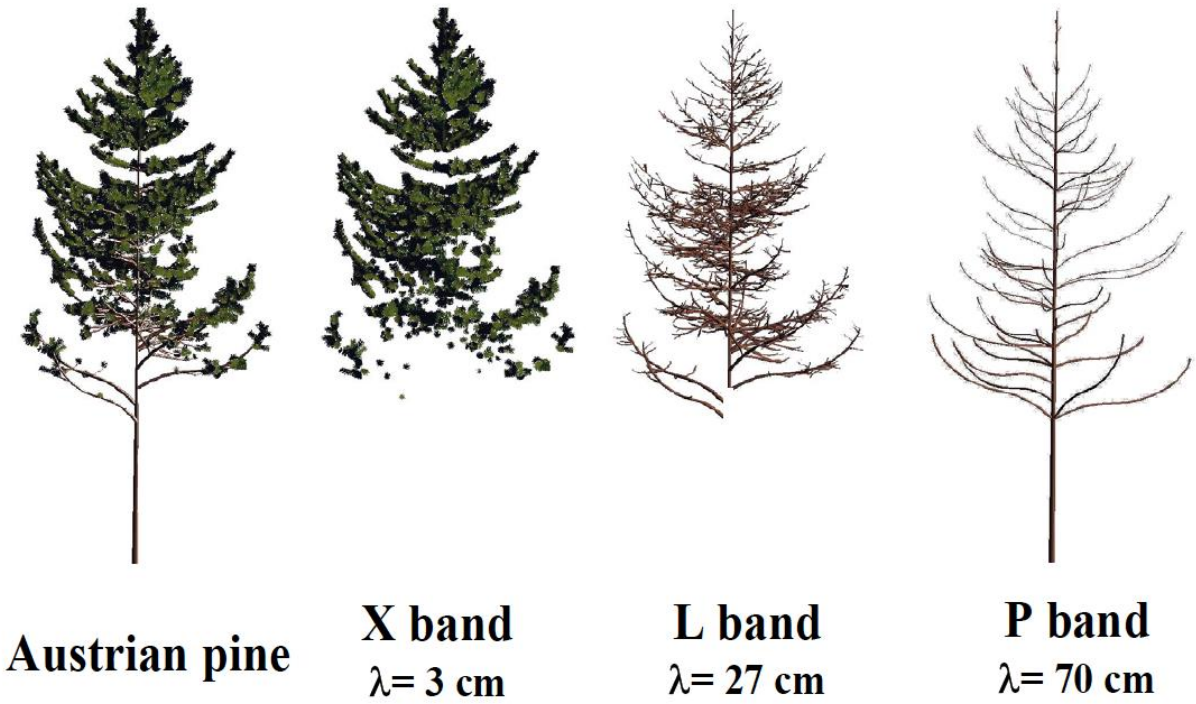


Image Credit: Thuy le Toan

Density

- Saturation Problem
- Data/Instrument
  - NASA/JPL polarimetric AIRSAR operating at C-, L-, and P-band
  - Incidence angle 40°-50 °

- C-band ≈ 20 tons/ha (2 kg/m2)
- L-band ≈ 40 tons/ha (4 kg/m2)
- P-band ≈ 100 tons/ha (10 kg/m2)

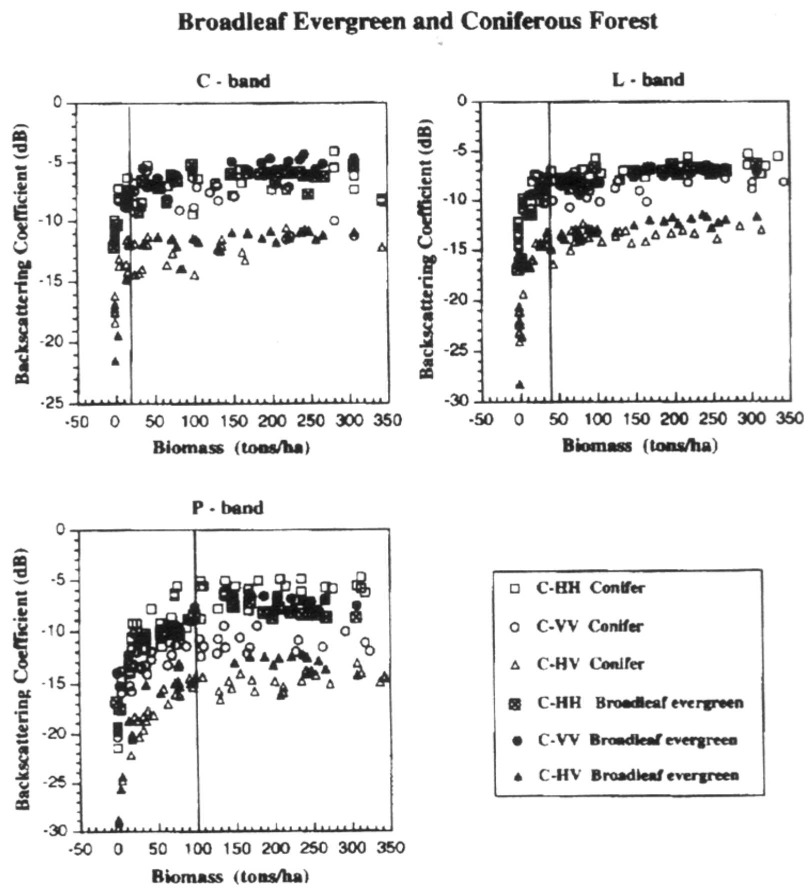
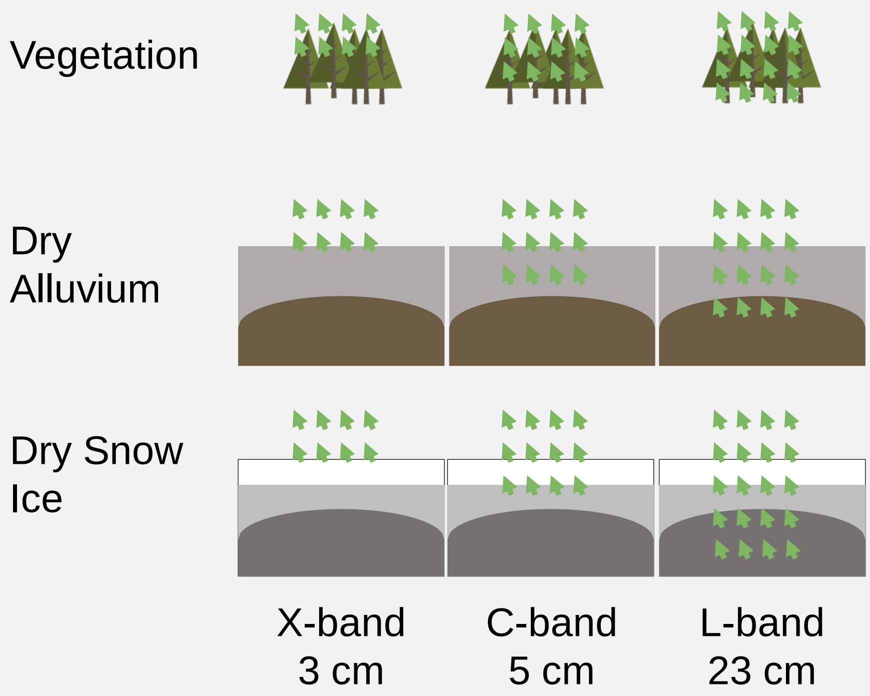


Image Source: Imhoff, 1995:514)

Penetration as a Function of Wavelength



- Waves can penetrate into vegetation and (in dry conditions) soil
- Generally, the longer the wavelength, the stronger the penetration into the target

Image based on ESA Radar Course 2

Radar Signal Penetration into Vegetation

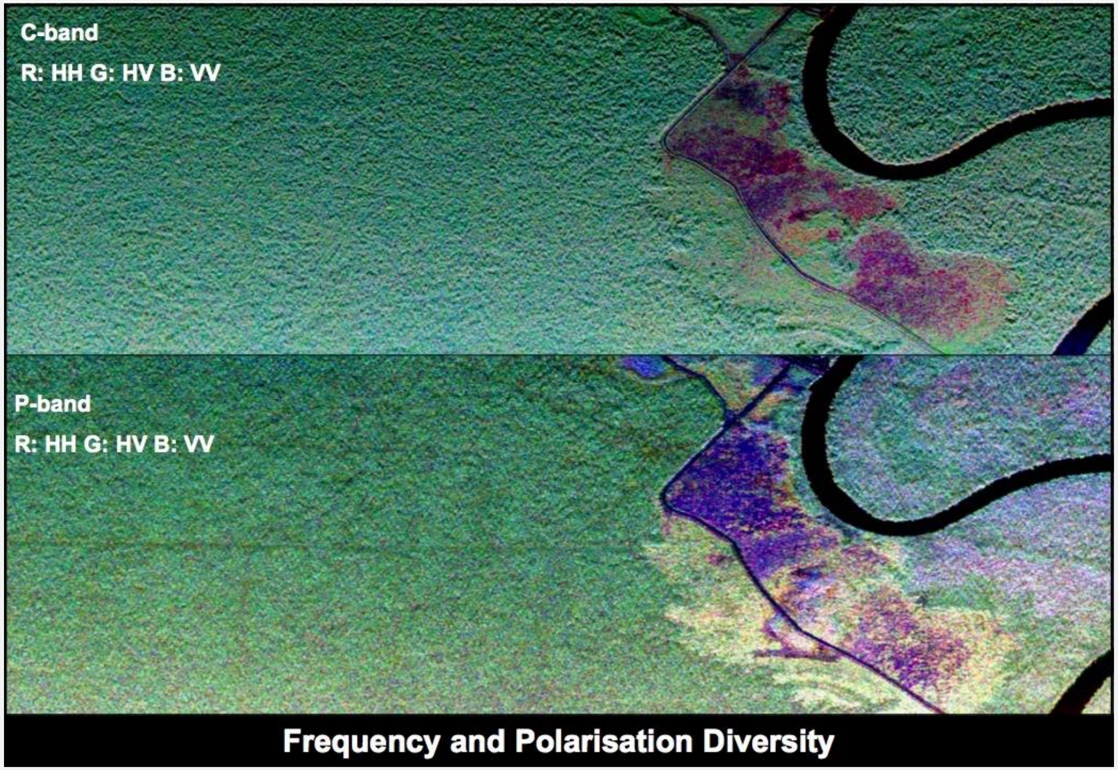
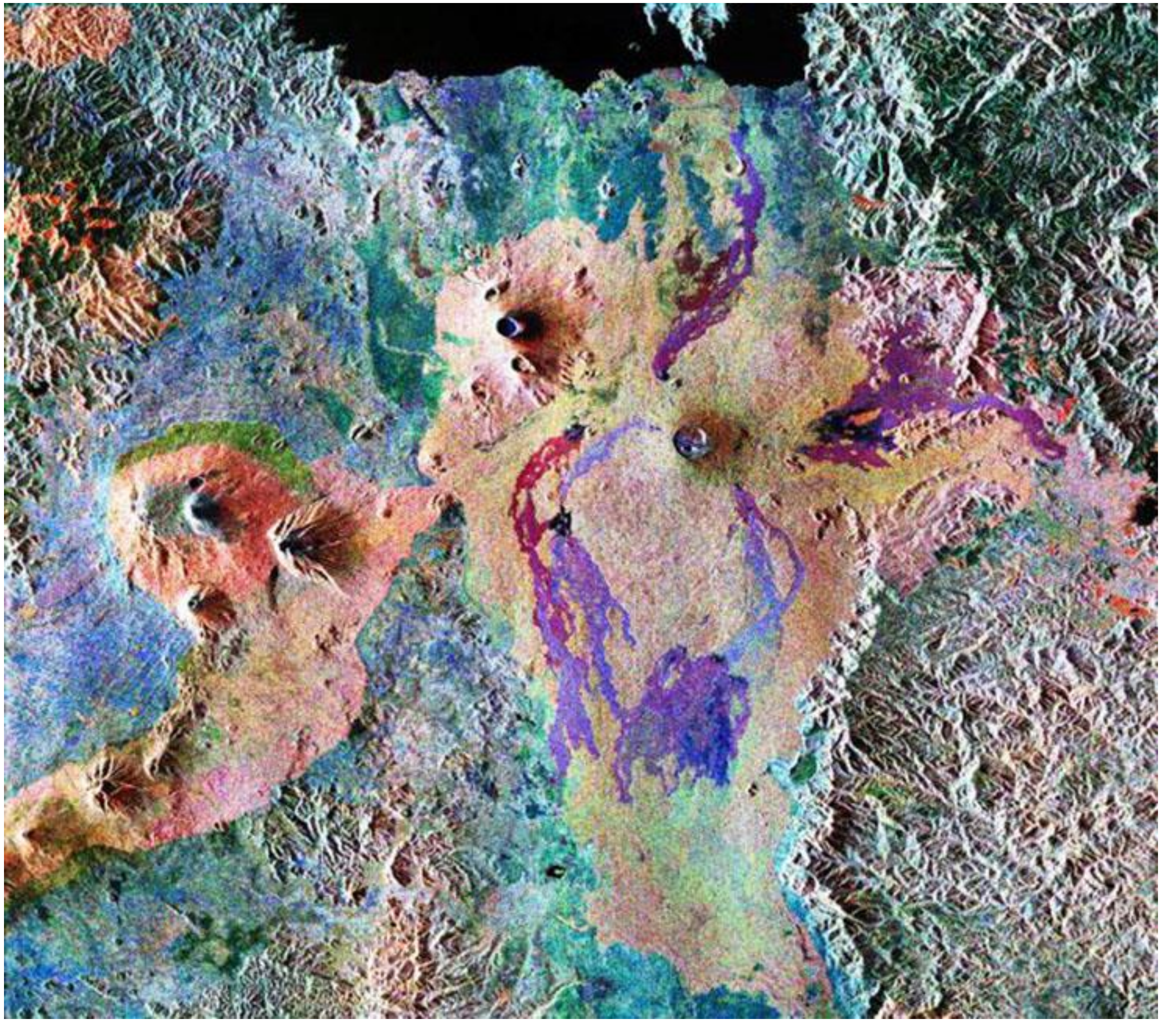


Image Credit: A Moreira - ESA

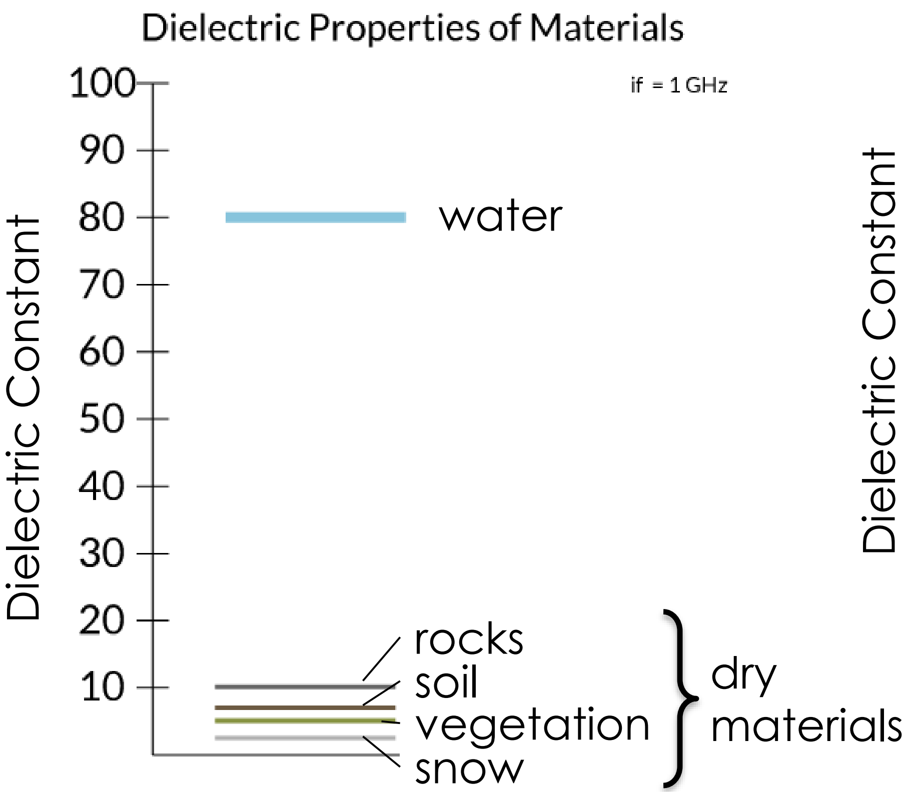
SIR-C False Color Composite Karasokie, Central Africa

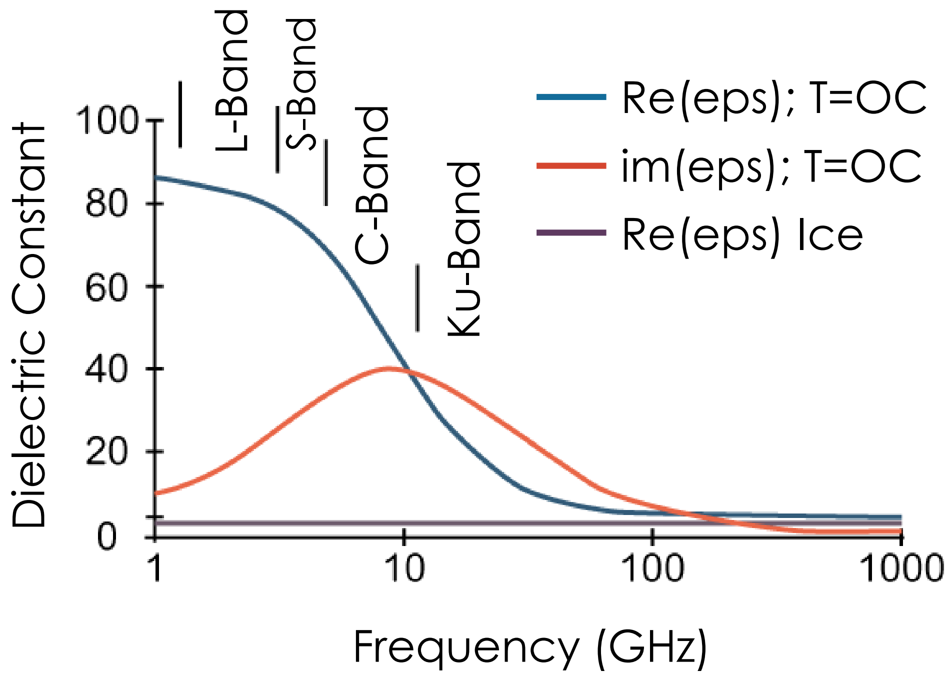


L-band HV
C-band HH
C-band HV

Source: JPL/Caltech

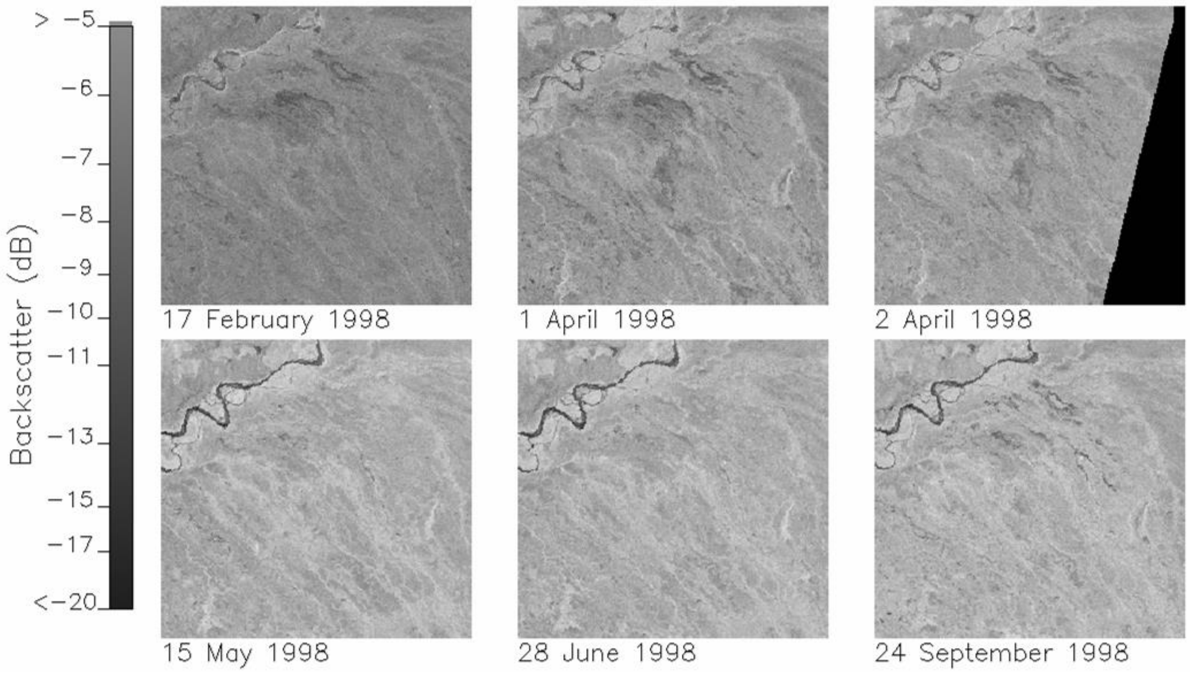
Surface Parameters: Dielectric Constant



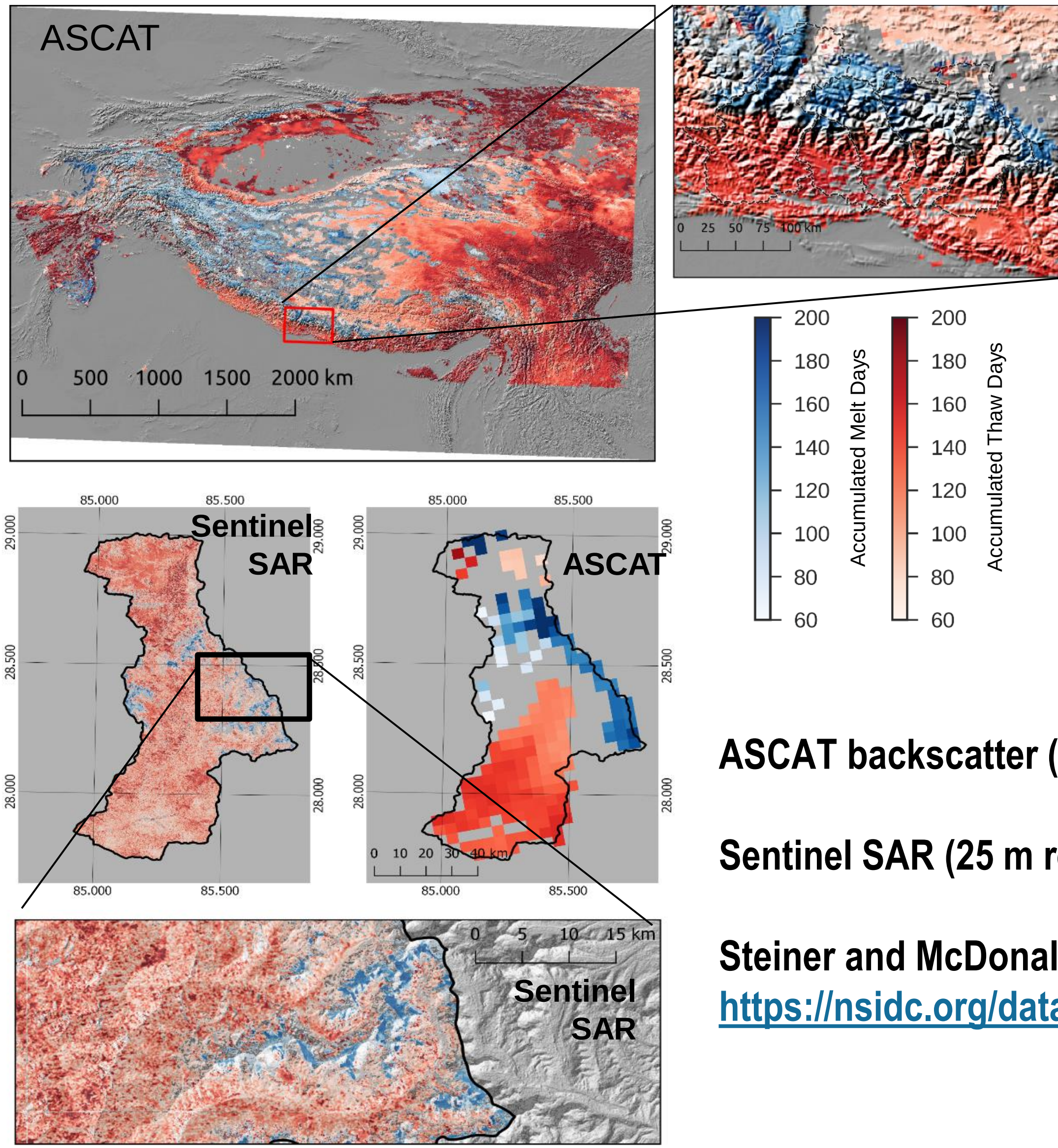


Dielectric Properties of the Surface

- During the land surface freeze/thaw transition there is a change in dielectric properties of the surface
- This causes a notable increase in backscatter



Freeze-Thaw-Melt Monitored with C-band Radar



High Mountain Asia

Land surface freeze/thaw status combined with snowmelt

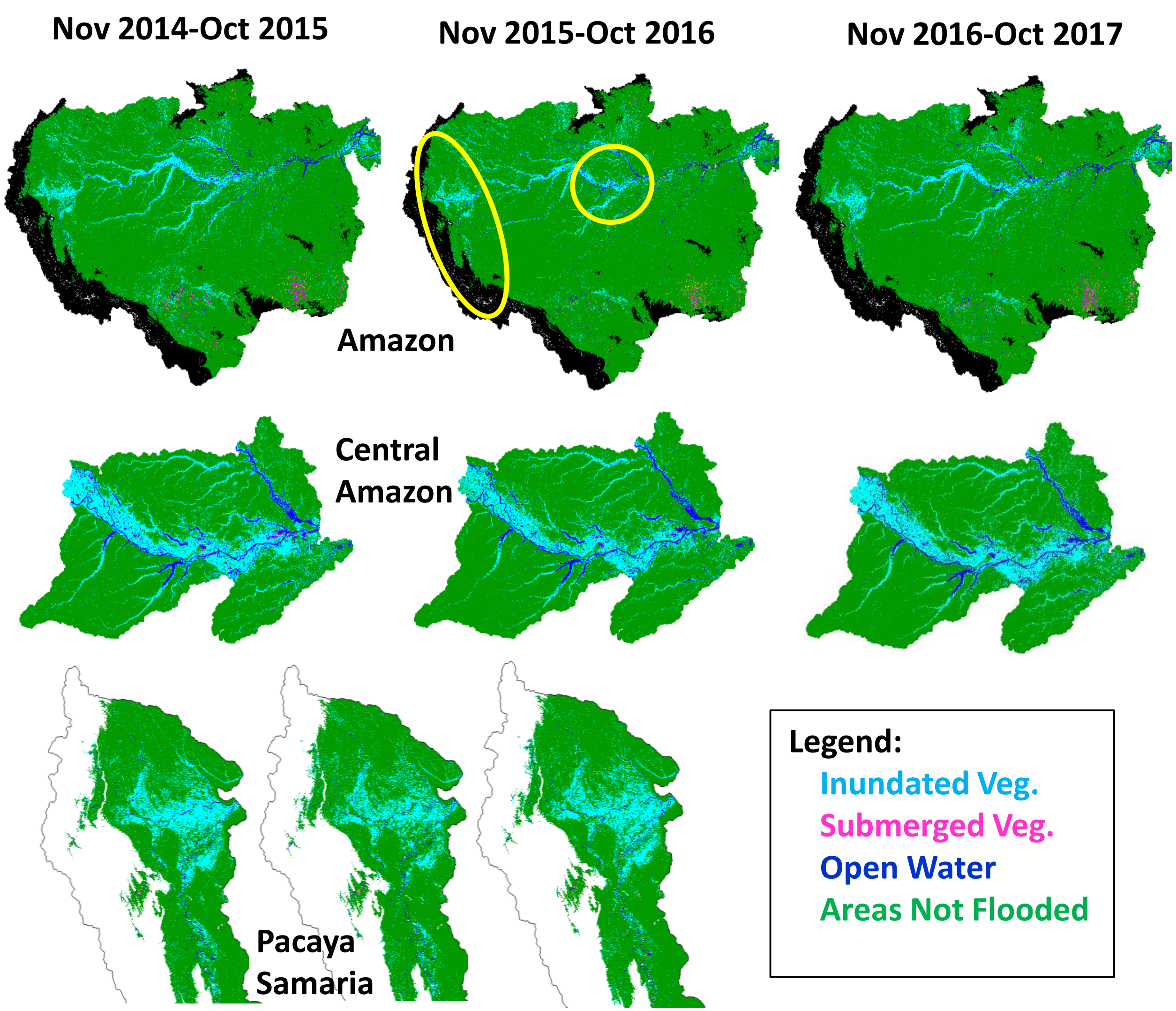
Seasonally snow covered land and permanent ice cover (glaciers) linked to river flow and hydropower generation.

ASCAT backscatter (4.45 km resolution)

Sentinel SAR (25 m resolution)

Steiner and McDonald 2018
https://nsidc.org/data/HMA_FreezeThawMelt_ASCAT

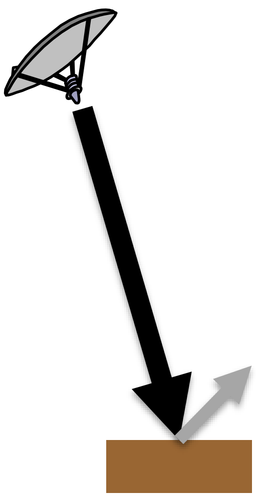
Annual Maximum Inundation in the Amazon derived from L-band HH and HV PALSAR2

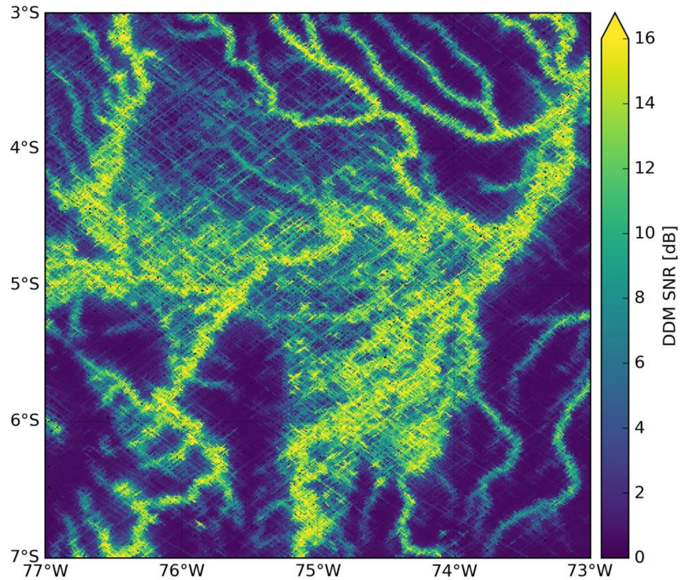


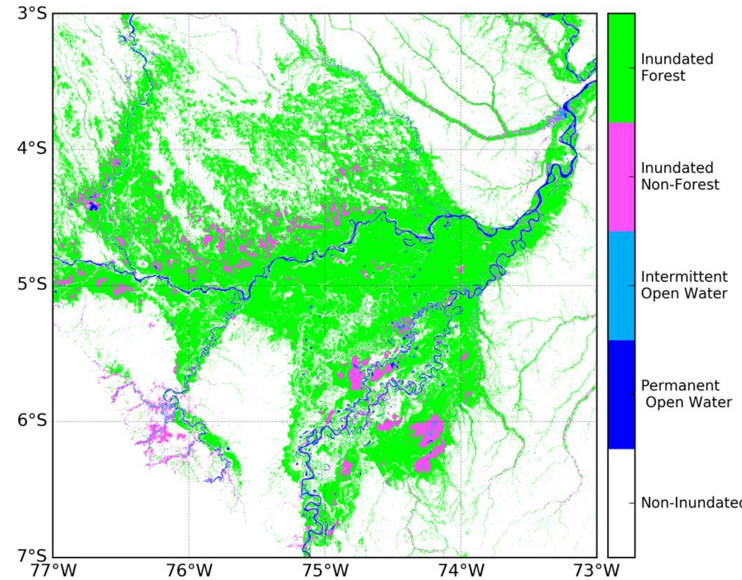
Rosenqvist et al , in prep

GNSS-R and SAR for Detecting Wetland Inundation Dynamics

Pacaya Samaria National Reserve, Peru







CYGNSS receives
GPS Reflections

Seasonal Classification from
L-band HH & HV-pol PALSAR2
time series

Jensen et al, Remote Sensing, 2018

Speckle

Speckle is a granular 'noise' that inherently exists in and degrades the quality of SAR images

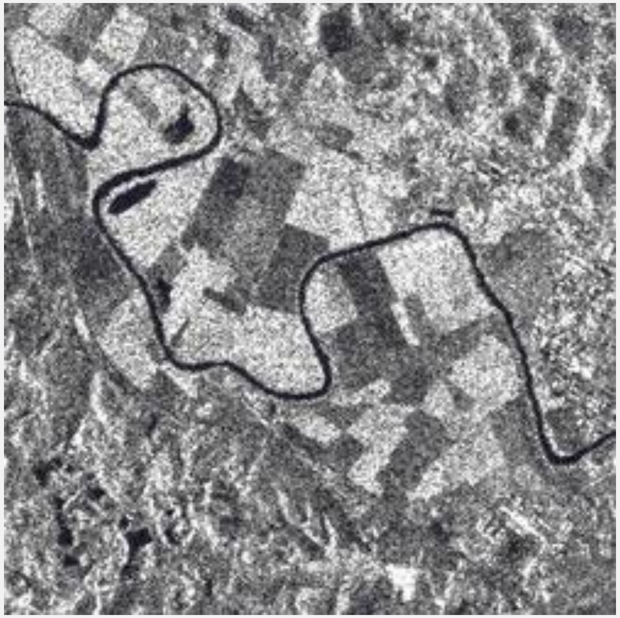


Image Credit: ESA

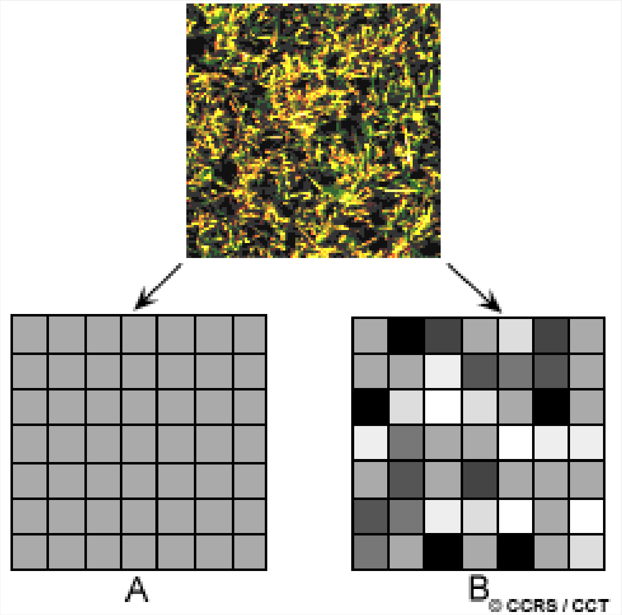
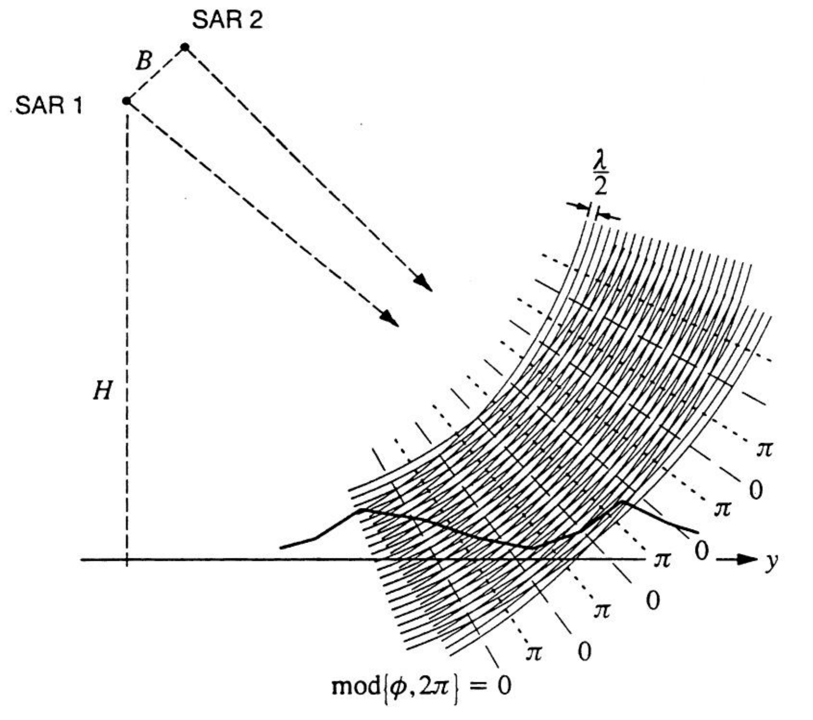


Image Credit: Natural Resources Canada

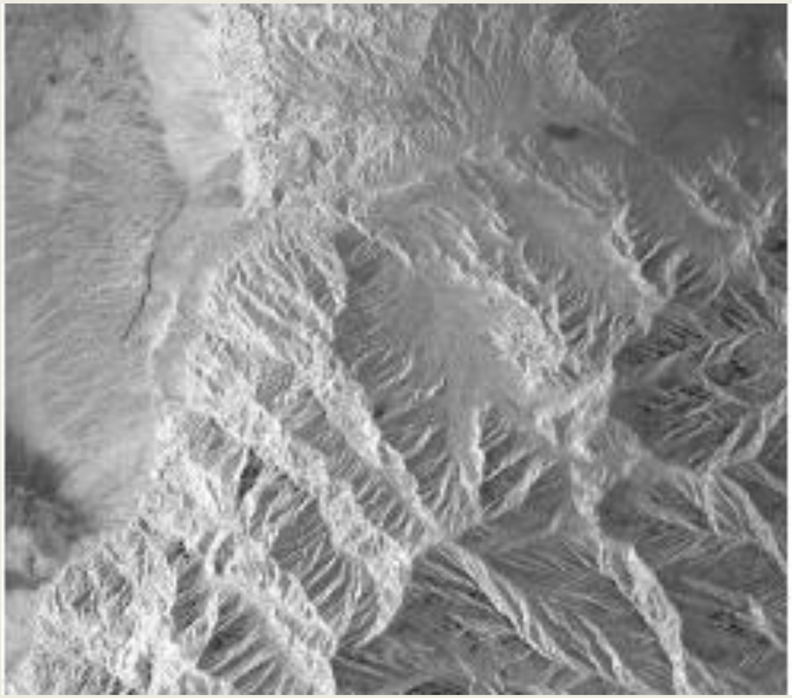
Radar Interferometry

- Radar has a coherent source much like a laser
- The two radar (SAR) antennas act as coherent point sources
- SAR images are acquired independently, and act as amplitude and phase detector of the surface
- Two SAR images can be combined to observe the interference pattern of the surface.

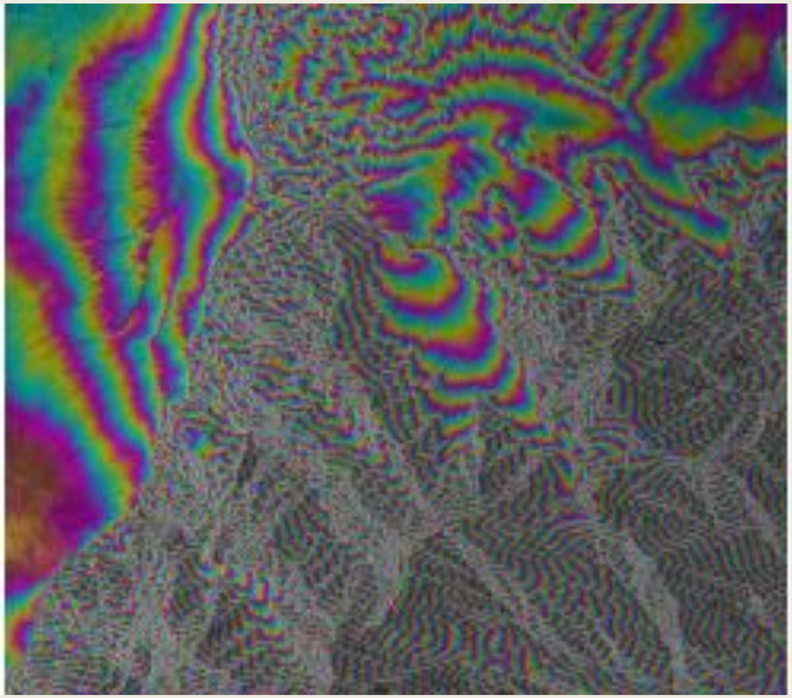


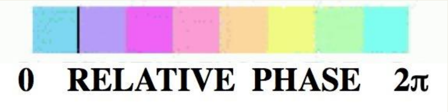
Radar Interferometry Example

Standard Radar Image



"Interferogram"



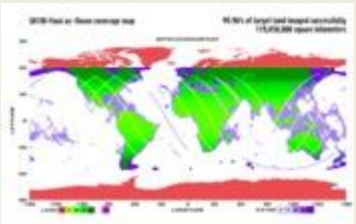


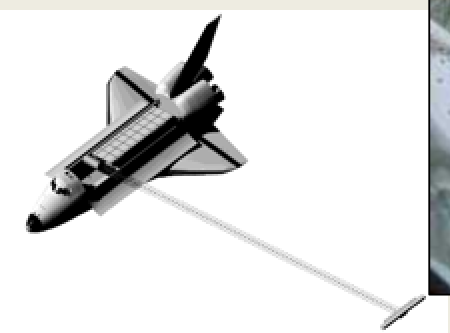
An "interferogram" is a complex image:

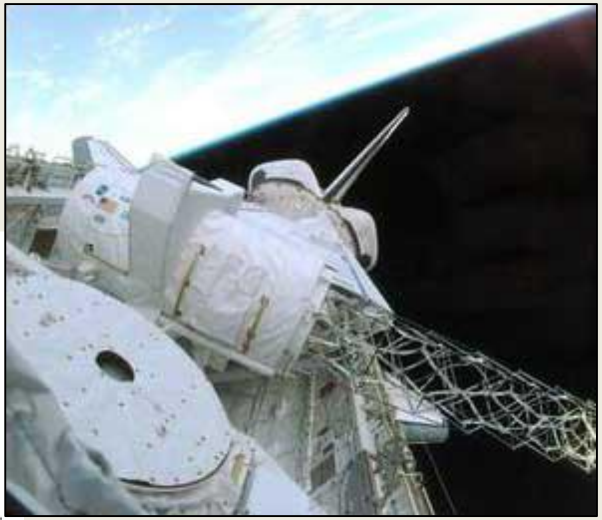
- Its magnitude is related to correlation
- Its phase is related to geometry differences

- One cycle of color represents one cycle of relative phase
- Once cycle of relative phase represents 1/*p* wavelengths of path difference, p=1 or 2

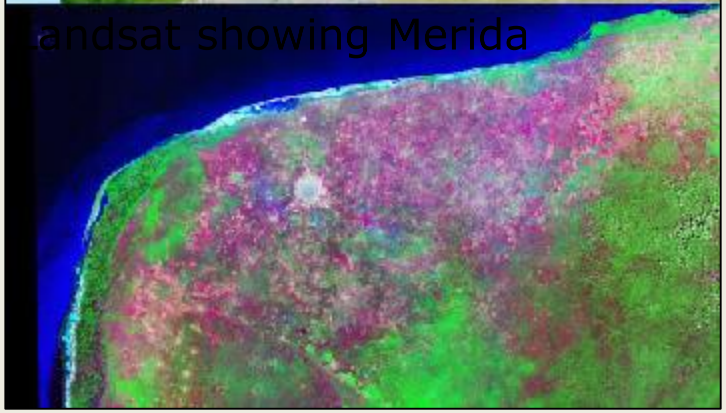
Shuttle Radar Topography Mission (SRTM)







SRTM image of Yucatan showing Chicxulub Crater, site of K-T extinction impact.

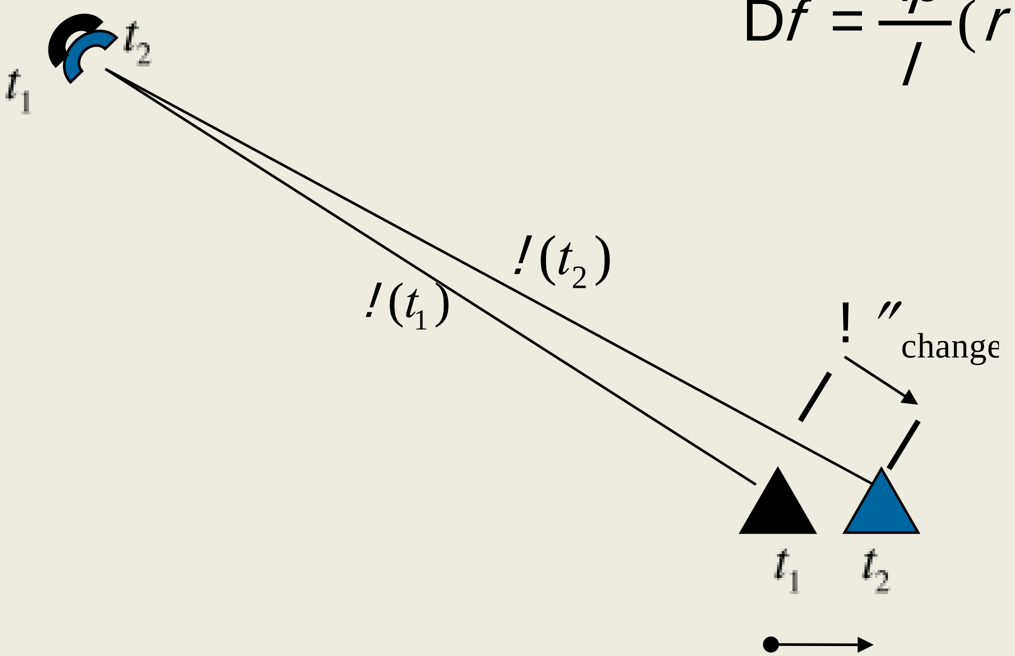


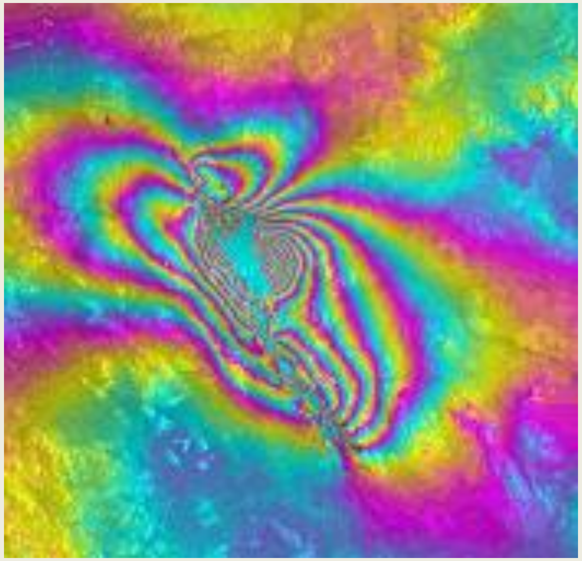
3-dimensional SRTM view of Los Angeles (with Landsat data) showing San Andreas fault

Differential Interferometry

- When two observations are made from the same location in space but at different times, the interferometric phase is proportional to any change in the range of a surface feature directly.

$$Df = \frac{4p}{l}(r(t_1) - r(t_2)) = \frac{4p}{l}Dr_{change}$$



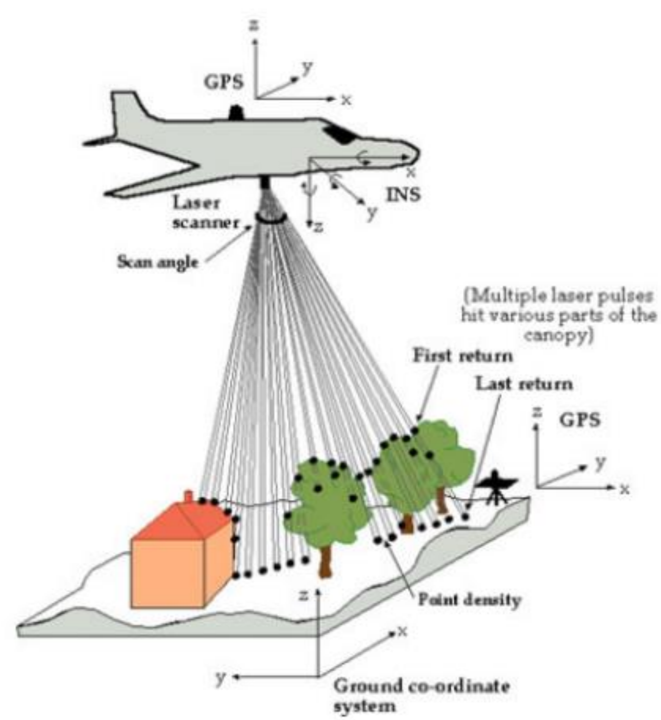


Lidar: Light Detection and Ranging
Basic Principle

- Laser ranging: measures the distance (ranging) between the sensor and the tar elapsed time between emission reflected return

- Lidars produce their own signal active sensors

- Lidars are optical sensors. Near- used for most terrestrial applica
  - Cannot penetrate clouds

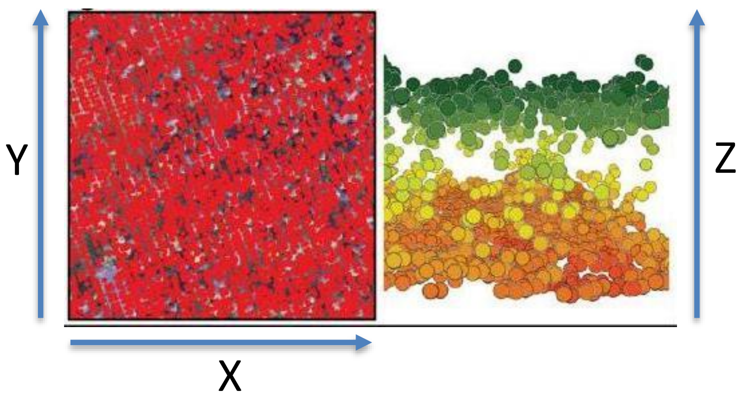


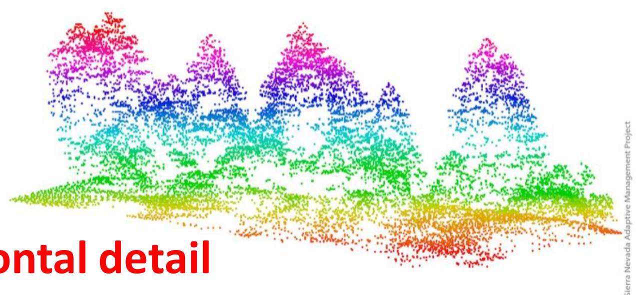
Dowman, 2004

Courtesy of Naiara Pinto, JPL

Lidar Instrument Types
How the reflected energy is digitized

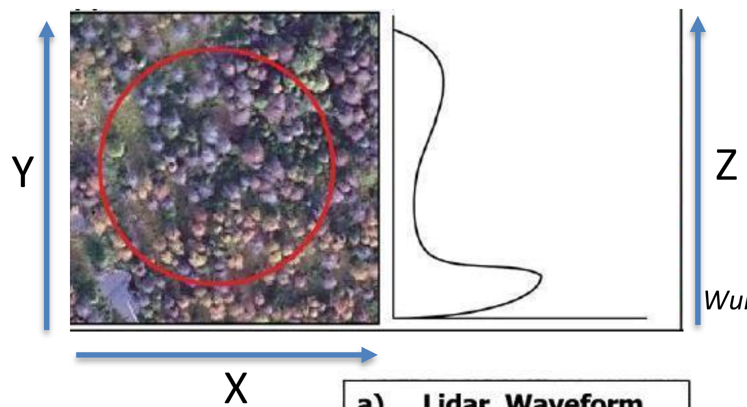
Discrete Return



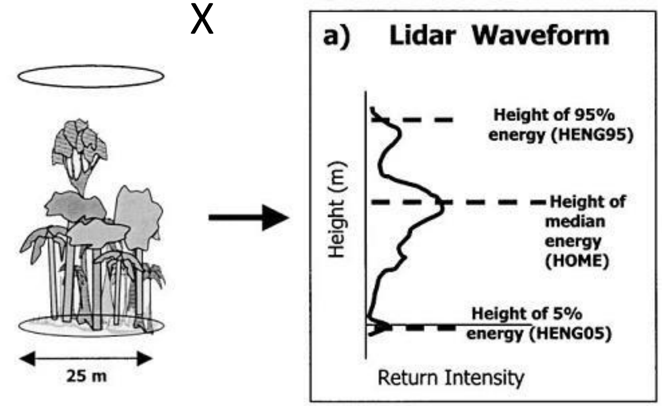


more horizontal detail

Full Waveform



Wulder et al., 2012



more vertical detail

Drake et al., 2002

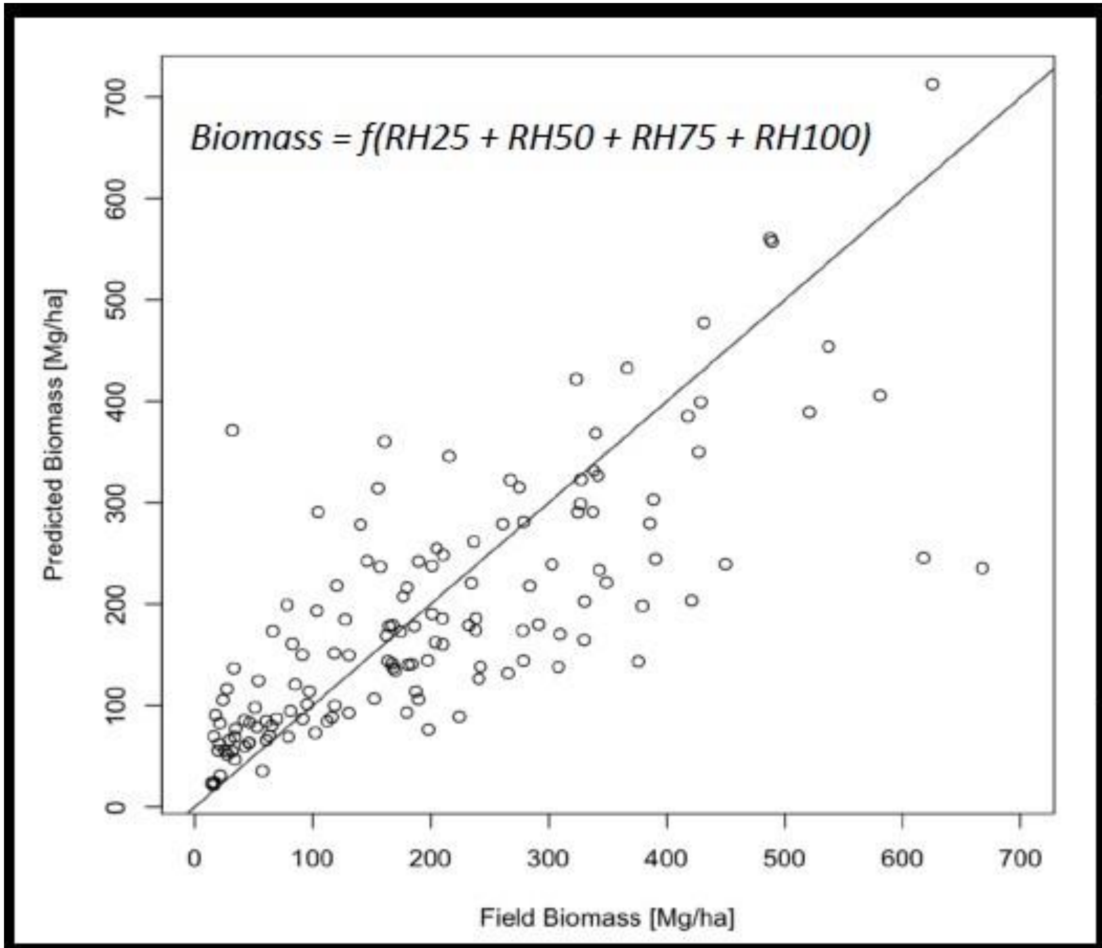
<u>Point cloud</u>

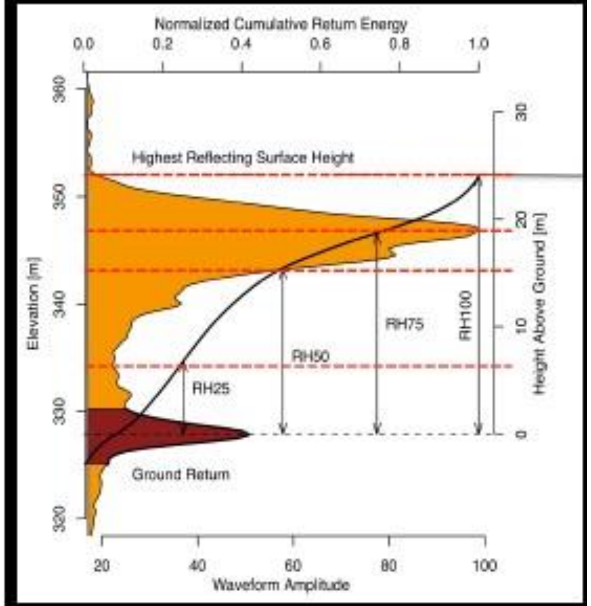
- XYZ coordinates
- Intensity (optional)

<u>Waveform</u>

normalized reflectivity (intensity) as a function of time (height)

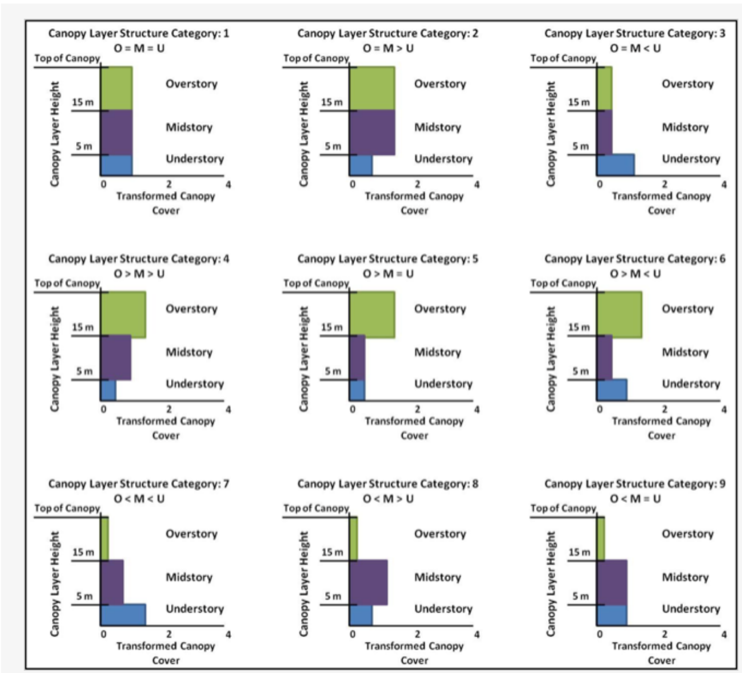
Waveform Lidar: Biophysical measurements



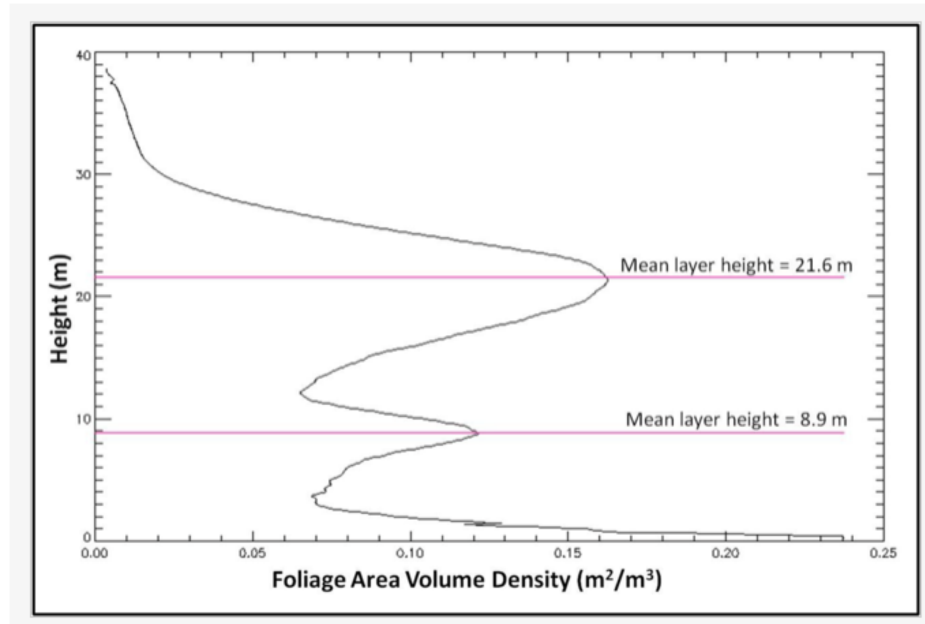


Source: Ralph Dubayah

Lidar Example: Forest vertical stratification



Relative contribution of vertical layers



Vertical location of layers

Whitehurst et al., 2013

Courtesy of Naiara Pinto, JPL

Lidar Example: Niche Modeling

Discrete Return Lidar

↓

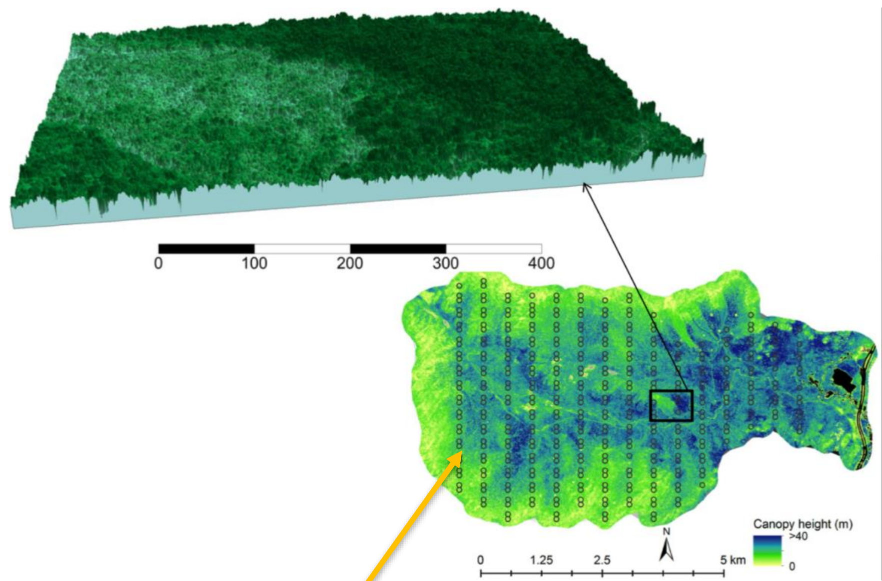
Crown delineation

↓

Crown-area weighted height

↓

+ ancillary remote sensing
-Optical
-Radar

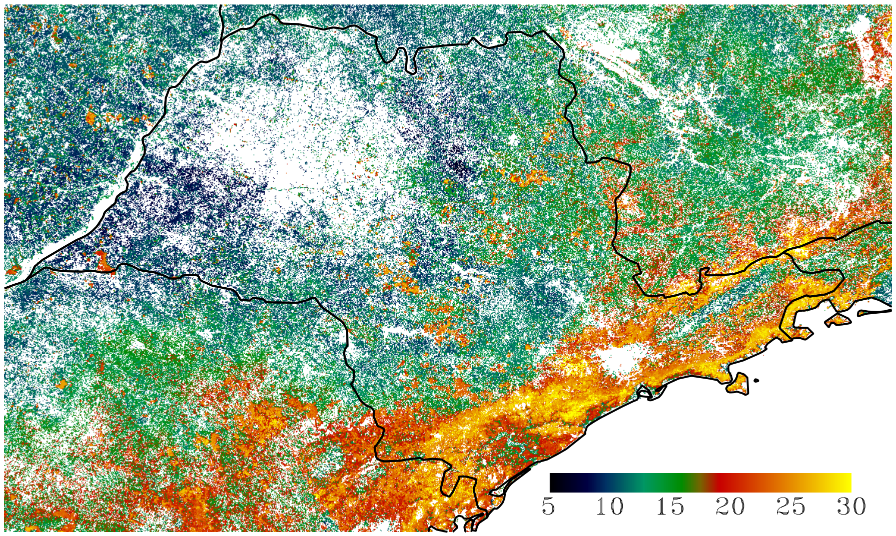


Bird surveys

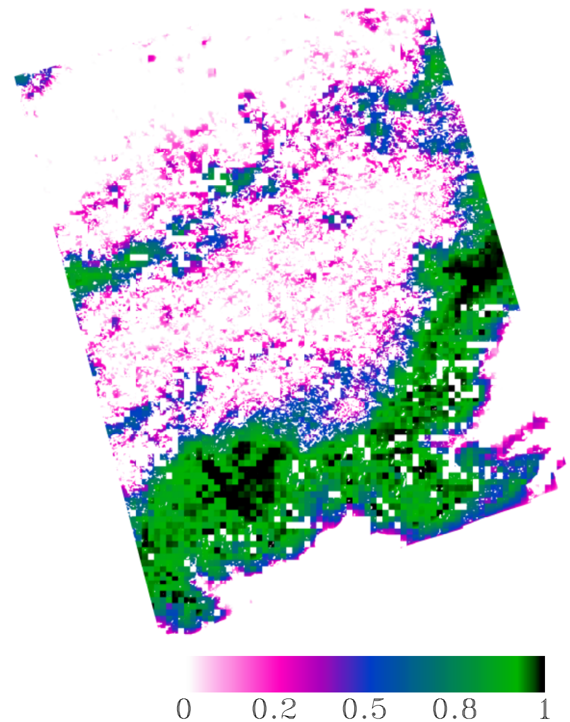
Courtesy of Naiara Pinto, JPL

Swatantran et al., 2012

Lidar Example: Habitat Fragmentation



3D Contiguity Index



ICESat

↓

Canopy Height

+

Radar

↓

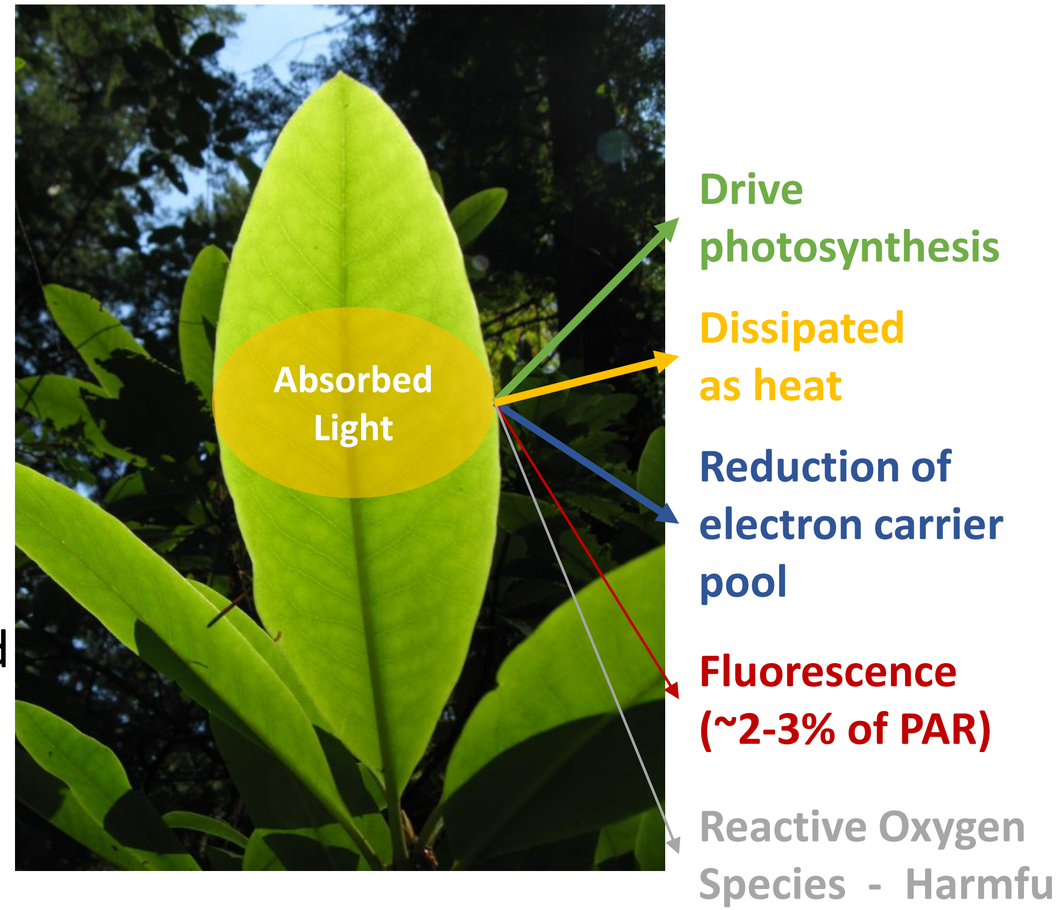
High-resolution forest patch delineation

Simard et al., 2011
Pinto et al., 2011

Courtesy of Naiara Pinto, JPL

Chlorophyll Fluorescence

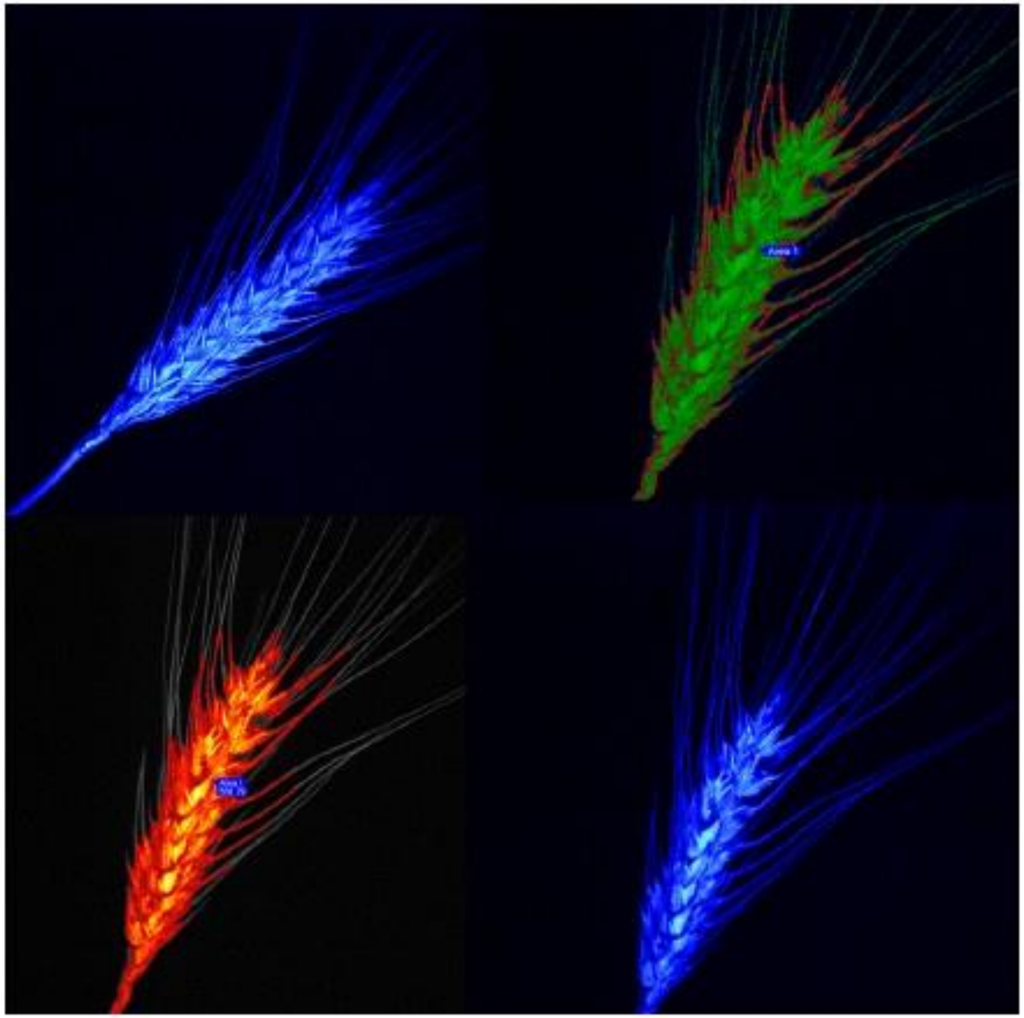
- Absorbed photons drive photochemistry, but those not used in reactions are dangerous to the plant cell
- Excess photons are dissipated as heat and fluorescent light
- Plant physiologists have long used Pulse Amplitude Modulated (PAM) Fluorescence to measure these dynamics at the leaf-level



Slide courtesy of Jaret Reblin (Bowdoin College) and Andrew Reinmann (CUNY)

Fluorescence detection

But in the laboratory, you can filter out incoming NIR light and photograph chlorophyll emission using NIR sensitive detectors…



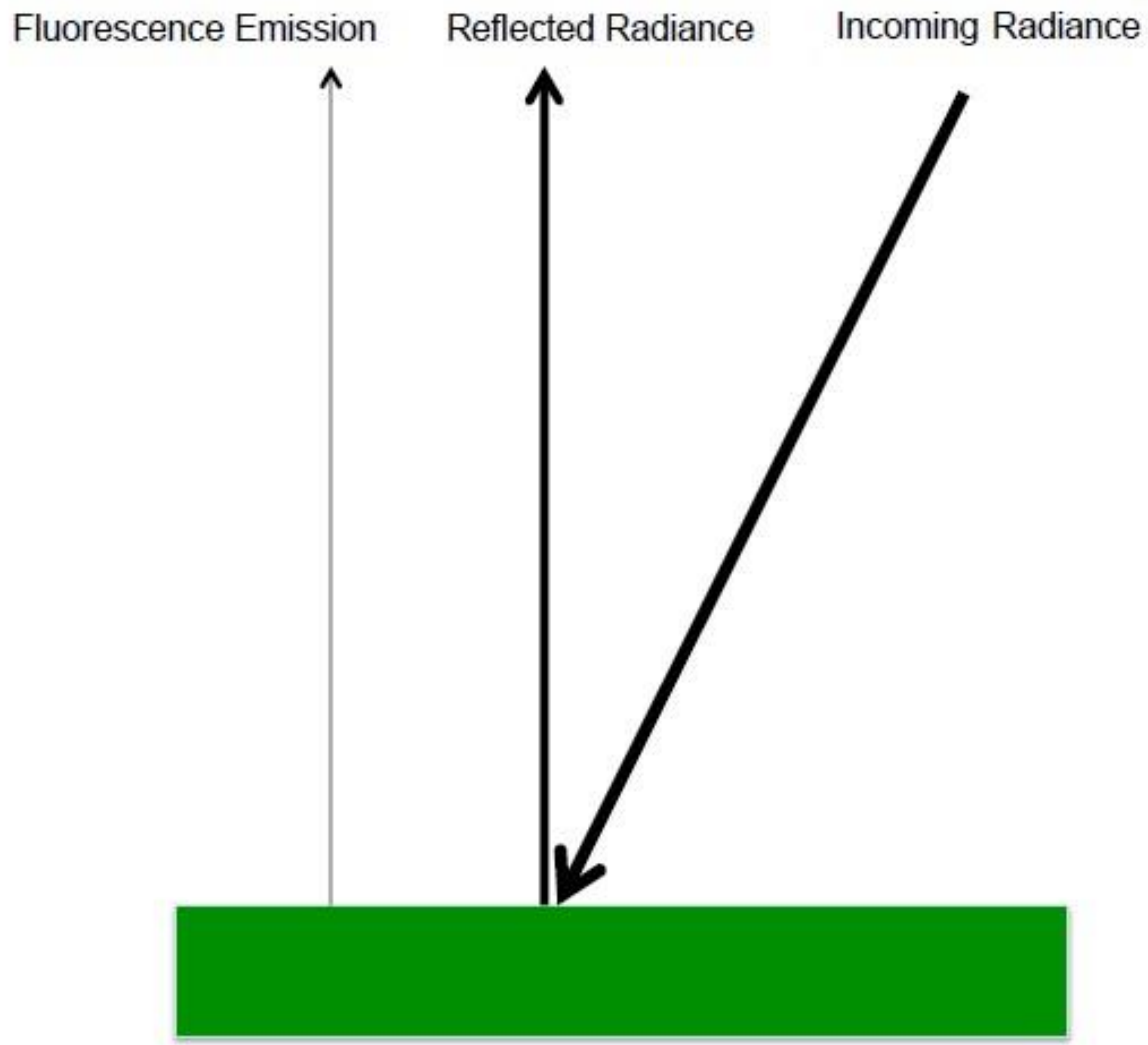
Chlorophyllx4, © Image by Eleanor Gates-Stuart, http://stellrscope.com/tag/chlorophyll-fluorescence-imaging/

Source: Frankenberg (KISS 2012)

Chlorophyll fluorescence

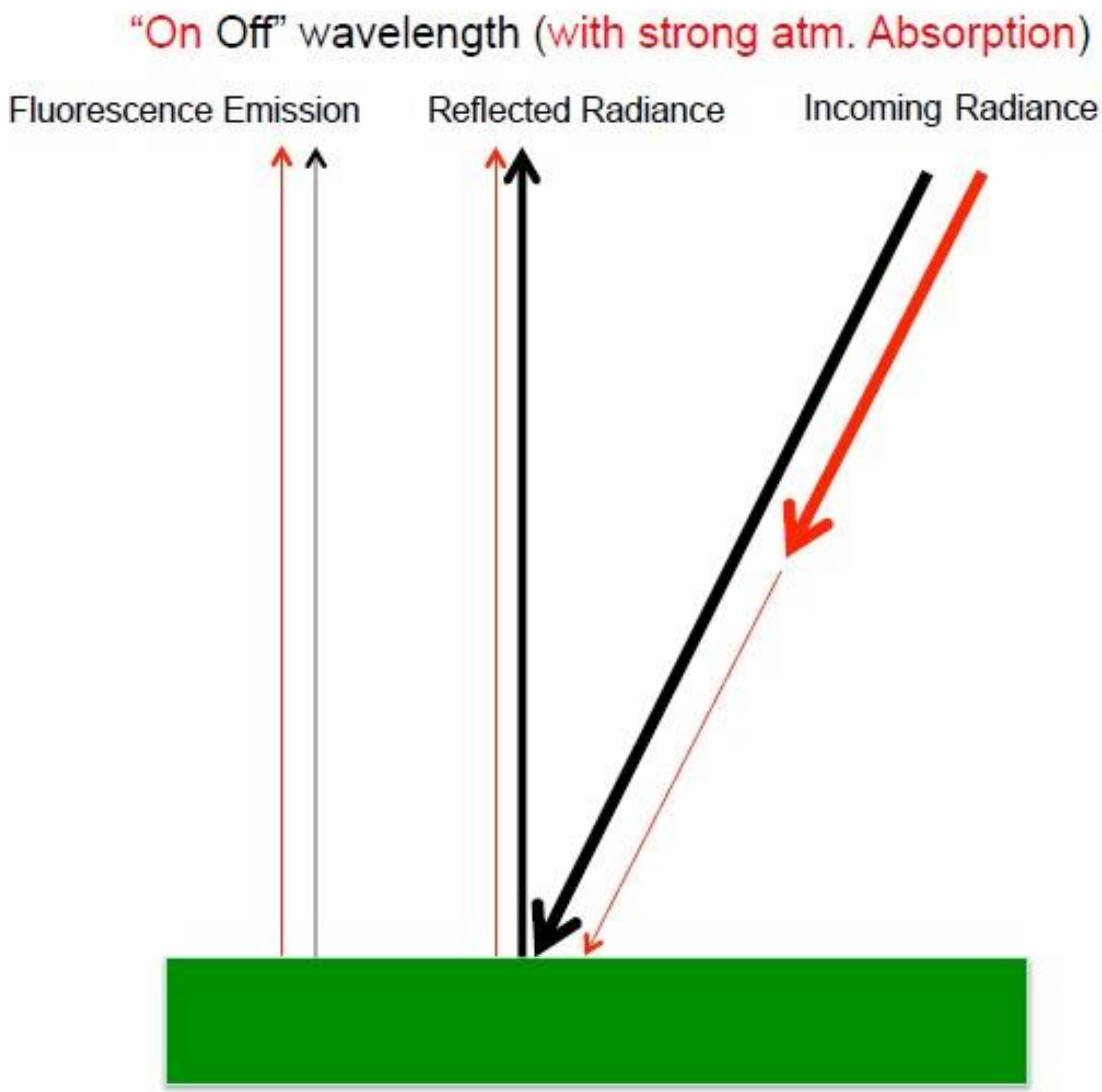
Basic problem for fluorescence retrievals:

- Fluorescence emission is "*contaminated*" with reflected solar light in the far red / near infrared.
- This reflected solar light dominates the signal (about 100 times stronger).
- Need "on/off" wavelengths where the atmosphere (or incoming light) is opaque.



Source: Frankenberg (KISS 2012)

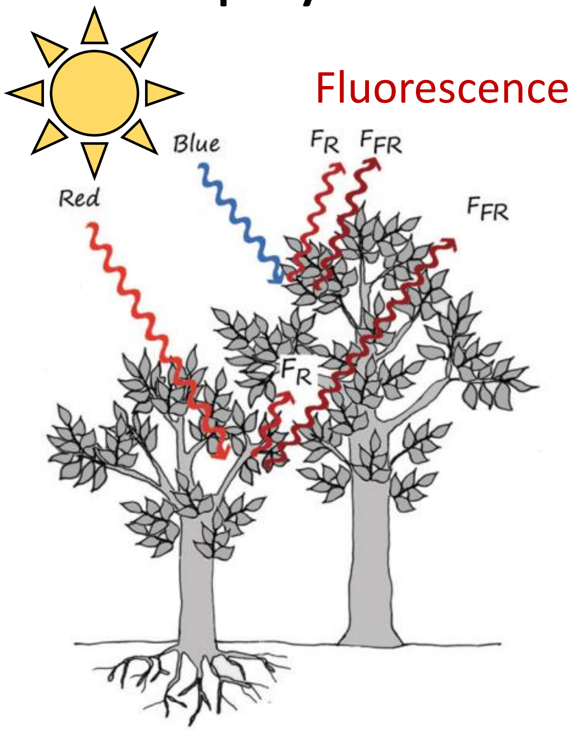
Chlorophyll fluorescence

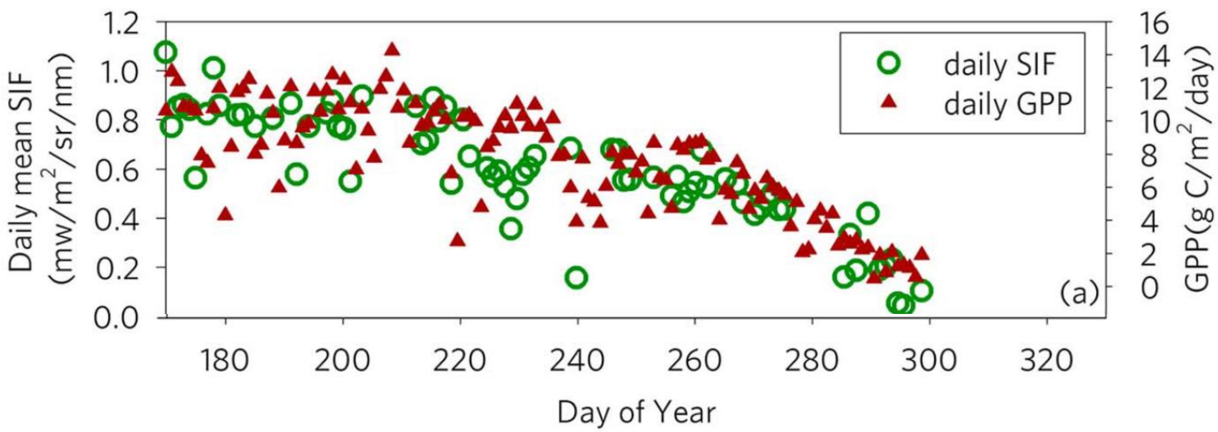


In spectral regions with high atmospheric absorption (e.g. strong oxygen absorption bands), the fluorescence emission at canopy level can dominate the measured radiance (as opposed to transparent regions, where it barely adds to the signal)

Source: Frankenberg (KISS 2012)

Chlorophyll Fluorescence → Solar Induced Fluorescence (SIF)





Empirical tower-based measurements of SIF from a temperate deciduous forest at Harvard Forest show strong positive correlations between SIF and flux tower estimates of GPP

Slide courtesy of Julia Marrs (Boston University) and Andrew Reinmann (CUNY)

Porcar-Castell et al. 2014; Yang et al. 2015

Airborne fluorescence studies (Maier et al 2003)

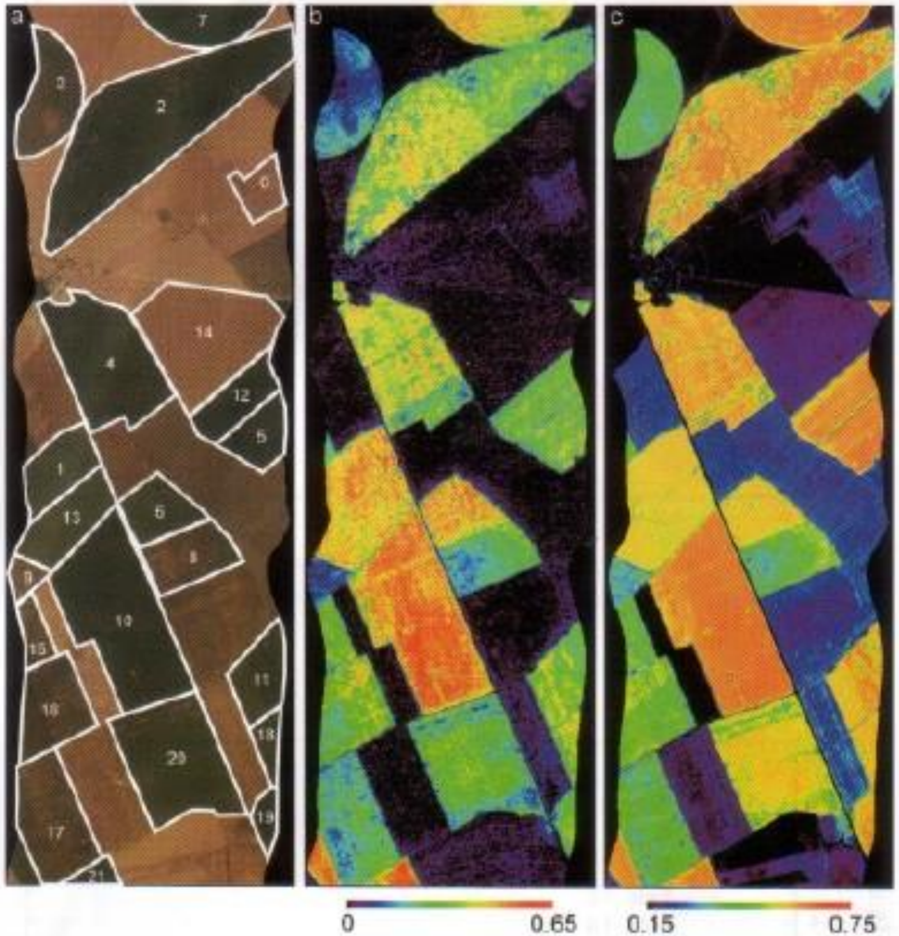
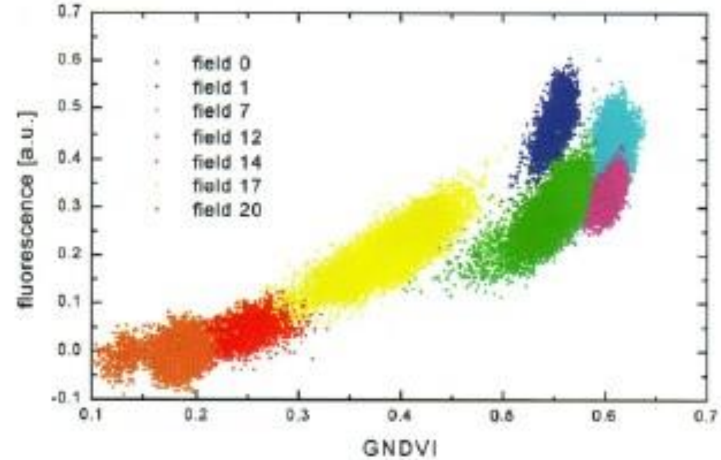


Plate 16–1. ROSIS images from the Barrax test site on 29 June 2000 at 12:23UTC (flight altitude was 3048 m above ground). (a) true color image with field marking. (b) sun-induced fluorescence in relative units. (c) GNDVI.



From airplane O_2 lines still usable (depending on altitude) and high spatial resolution allows use of reference targets (in heterogeneous terrain).

NDVI and fluorescence correlated but relationship differs per field → independent information

Source: Frankenberg (KISS 2012)

Chlorophyll fluorescence – complication from space

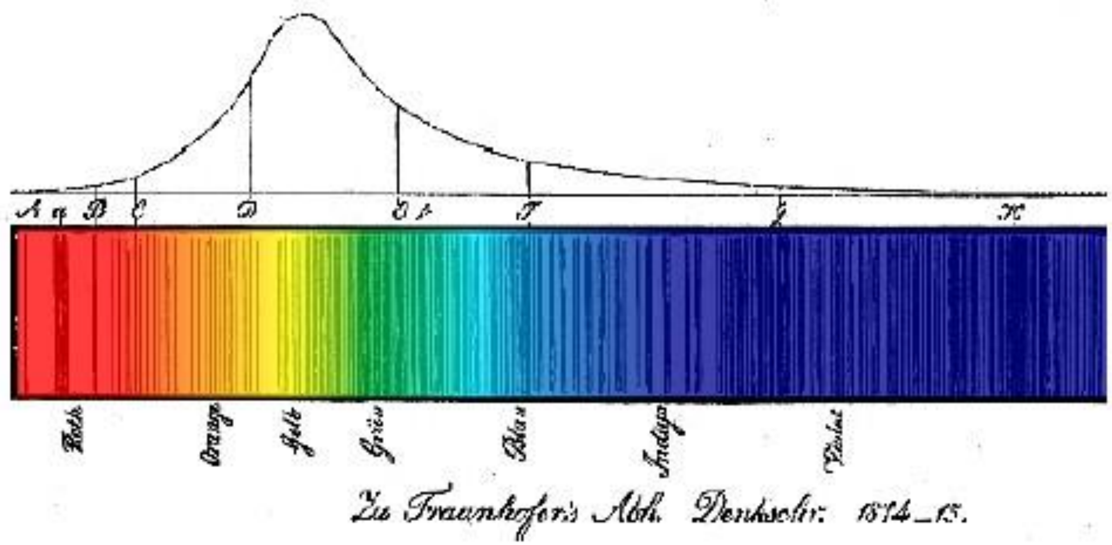
How to tackle the problem: 2) Use solar lines.

Joseph von Fraunhofer

Born	6 March 1787 Straubing, Bavaria
Died	7 June 1826 (aged 39)

The solar spectrum is not a pure black-body spectrum but exhibits absorption lines from elements (e.g. Fe, Mg, Na) present in colder outer layers.

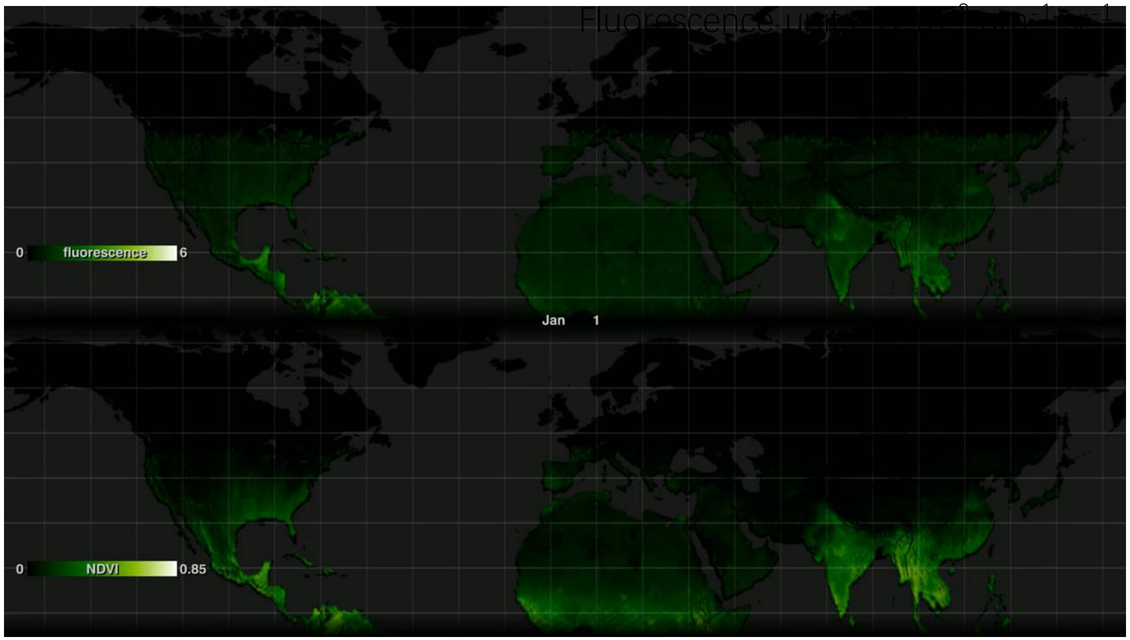
However, dark features are very narrow.



Source: Frankenberg (KISS 2012)

Measuring SIF at Satellite Scale

- Measuring chlorophyll fluorescence at satellite scale (e.g., GOME, OCO-2)
- Lots of promise for accurately tracking NPP
  (Frankenberg et al. 2014, Joiner et al. 2014)
- SIF captures seasonal patterns in GPP better than NDVI



NASA's Goddard Space Flight Center Scientific Visualization Studio

Slide courtesy of Julia Marrs (Boston University) and Andrew Reinmann (CUNY)

Opportunities for Synergism

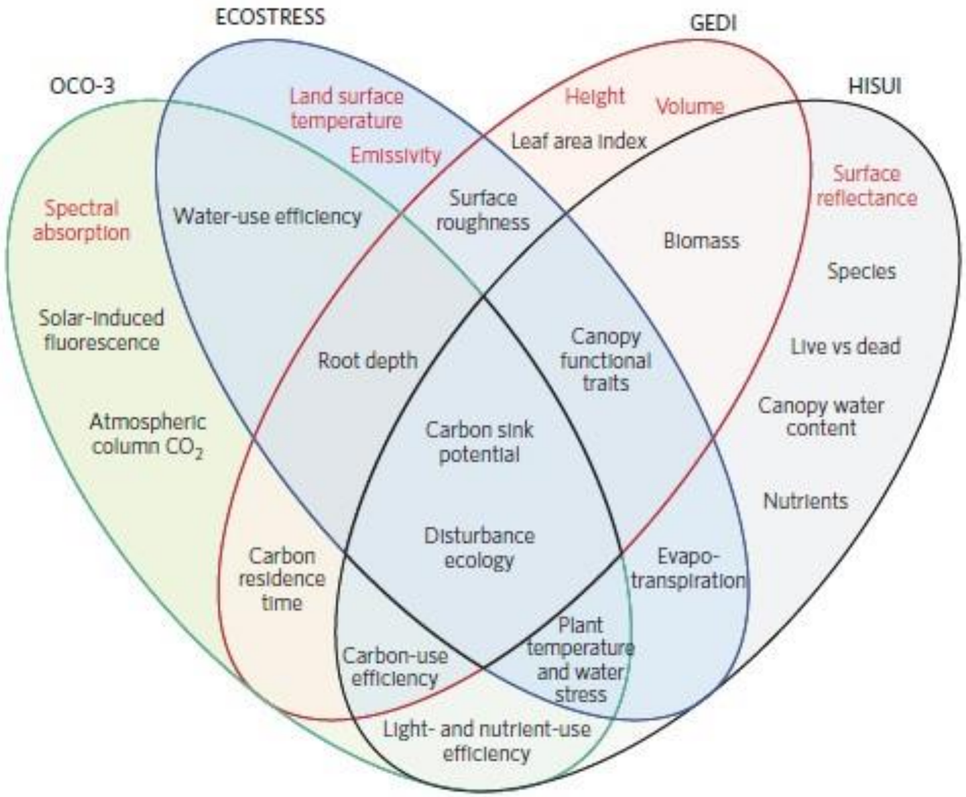


Figure 1 | Spatial and temporal synergy of observations and their applications. A pretzel diagram of observations (red text) from each instrument (coloured shapes) and the synergistic physical parameters that can be derived (black text) when observations are taken at synchronous and complementary spatial and temporal resolutions.

Stavros et al, 2017