Remote Sensing Physics and Measurements

Kyle McDonald (with contributions from others)

Department of Earth and Atmospheric Sciences
City College of New York
and
Jet Propulsion Laboratory, California Institute of Technology

Keck Institute for Space Studies Study Program

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

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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
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)

Source: ESA- ASAR Handbook
Atmospheric Windows & Current SAR Missions

- TerraSAR-X
- COSMO-SkyMed
- Radarsat-2
- Sentinel-1
- ALOS-2
- KOMPSAT-5
- NISAR

X-band (3 cm)
C-band (6 cm)
S-band (12 cm)
L-band (24 cm)

Wavelength
0.1 nm 1 nm 10 nm 100 nm 1 μm 10 μm 100 μm 1 cm 10 cm 1 m 10 m 100 m 1 km

Atmospheric Opacity
0% 25% 50% 75% 100%

γ-rays, x-rays
visible
infrared
microwave
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)

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

Smooth, level surface (open water, road)
Examples of Radar Interaction

Rough Surface Reflection

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

Pixel Color

rough bare surface
(deforested areas, tilled agricultural fields)
Examples of Radar Interaction

Volume Scattering by Vegetation

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

Vegetation

Pixel Color
Examples of Radar Interaction

Double Bounce

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

Inundated Vegetation
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
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

- **Density**
- **Size in relation to the wavelength**
- **Dielectric Constant**
- **Shape and Orientation**
Size in Relation to Wavelength

Austrian pine
X band
\(\lambda = 3\) cm

L band
\(\lambda = 27\) cm

P band
\(\lambda = 70\) cm

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

Vegetation

Dry Alluvium

Dry Snow

Ice

X-band 3 cm

C-band 5 cm

L-band 23 cm

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

Source: JPL/Caltech
Surface Parameters: Dielectric Constant

Dielectric Properties of Materials

Dielectric Constant

- Water
- Rocks
- Soil
- Vegetation
- Snow
- Dry materials

Frequency (GHz)

Dielectric Constant

Re(eps); T=OC
im(eps); T=OC
Re(eps) Ice

L-Band
S-Band
C-Band
Ku-Band
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

Legend:
- Inundated Veg.
- Submerged Veg.
- Open Water
- Areas Not Flooded

Nov 2014-Oct 2015
Nov 2015-Oct 2016
Nov 2016-Oct 2017

Amazon
Central Amazon
Pacaya Samaria

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

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

Landsat showing Merida
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.

\[
D_f = 4\pi l (r(t_1) - r(t_2)) = \frac{4\pi l \Delta r}{\text{change}}
\]
Lidar: Light Detection and Ranging

Basic Principle

• Laser ranging: measures the distance (ranging) between the sensor and the target by recording the elapsed time between emission and reflected return

• Lidars produce their own signals: active sensors

• Lidars are optical sensors. Near-infrared wavelength is used for most terrestrial applications
  - Cannot penetrate clouds

Dowman, 2004

Courtesy of Naiara Pinto, JPL
Lidar Instrument Types
How the reflected energy is digitized

Discrete Return
- Point cloud
  - XYZ coordinates
  - Intensity (optional)

Full Waveform
- Waveform
  - Normalized reflectivity (intensity) as a function of time (height)

Drake et al., 2002
Wulder et al., 2012

more
horizontal detail

more
vertical detail
Waveform Lidar: Biophysical measurements

Biomass = f(RH25 + RH50 + RH75 + RH100)

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

Canopy Height

High-resolution forest patch delineation

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

3D Contiguity Index

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

Drive photosynthesis
Dissipated as heat
Reduction of electron carrier pool
Fluorescence (~2-3% of PAR)
Reactive Oxygen Species - Harmful
Fluorescence detection

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


Source: Frankenberg (KISS 2012)
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)
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 $\rightarrow$ 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)

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 $\rightarrow$ independent information

Source: Frankenberg (KISS 2012)
Chlorophyll fluorescence – complication from space
How to tackle the problem: 2) Use solar lines.

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