A Short Introduction to Microwave Remote Sensing of the Land Surface

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Remote Sensing Process

- Space Segment
  - Sensors & Platforms
- Applications
- Ground Segment
  - Algorithms & IT

Geometric Models
- Physical Models
- Data Processing

Flood Forecasting

\[ \Phi = \int_{0}^{\infty} x \exp\left(-x\xi\right) dx \]
Remote Sensing Data Pyramid

- Sensor Raw Data (Level 0)
- Calibrated Measurements (Level 1)
- Geophysical Products (Level 2)
- Value-Added Products (Level 3 and Level 4)
- Decision: Yes/No (1 Bit)

- Peta to Exa Byte
- Tera to Peta
- Giga to Tera
- Giga

TU WIE N

Peta to Exa Byte

Tera to Peta

Giga to Tera

Giga

Decision: Yes/No (1 Bit)
Electromagnetic Spectrum

- All EM waves are caused by accelerating charges
  - Radio waves/Microwaves
    - generated by electronic devices: $10^4 - 0.1$ m
    - Microwaves: 1 m – 1 mm
  - Infrared Waves
    - room-temperature objects
    - $10^{-3} - 10^{-7}$ m
  - Visible/UV
    - high-temperature objects (sun)
    - $4 - 7 \cdot 10^{-7}$ and $4 \cdot 10^{-7} - 10^{-10}$ m
  - X-rays
    - deceleration of high-energy electrons by a metal target
    - $10^{-8} - 10^{-12}$ m
  - Gamma rays
    - emission by radioactive nuclei
    - $10^{-10} - 10^{-14}$ m
Natural Radiation

- All matter radiates (non-coherent) electromagnetic waves
- Blackbody Radiation Law
  - Max Planck in 1900
  - Approximation in microwave domain:

\[
L_f = \varepsilon \frac{2kT}{\lambda^2}
\]

- \(L_f\) … brightness [W/sr/m²]
- \(\varepsilon\) … emissivity
- \(k\) … Boltzmann constant
- \(\lambda\) … wavelength [m]
Electromagnetic Waves

- James Clerk Maxwell (1831-1879)
  - His four equations suggested the existence of electromagnetic waves
- Heinrich Hertz (1857-1894)
  - Demonstrated the existence of electromagnetic waves by building an apparatus to produce and detect radio waves

\[ \oint A \cdot dA = \epsilon_0 \oint V \rho dV \]

\[ \oint A \cdot dA = 0 \]

\[ \oint_{CT} E \cdot dl = -\frac{d}{dt} \oint A \cdot dA \]

\[ \oint_{CT} B \cdot dl = \mu_0 \oint j \cdot dA \]

Electromagnetic Wave

- Wavelength, \( \lambda \)
- Speed of light, \( c \)
Why Microwaves for Remote Sensing

- Microwaves: 1 mm – 1m
- Band designations

- Advantages compared to optical/IR range
  - microwaves penetrate the atmosphere – to some extent – clouds and rain
  - independent of the sun as source of illumination
  - penetration depth into vegetation and soil
Transmission through Atmosphere, Clouds & Rain

**Atmosphere**

- Water Vapor Absorption Bands
- Oxygen Absorption Bands
- 35 GHz Window
- 90 GHz Window
- 135 GHz Window

**Clouds**

- Ice Clouds
- Water Clouds

**Rain**

- Percent Transmission One-Way, %
- Frequency (GHz)
- Wavelength (cm)
Penetration Depth

- The penetration of microwaves into vegetation, soil and snow generally increases with wavelength.

Response of a pine forest in X-, C- and L-band.
Measurement Principles

- Emission by objects
  - gamma radiation due to radioactive substances
  - thermal radiation in visible or microwave range
- Diffuse scattering of daylight (*incoherent* radiation)
- Transmission, scattering and recording of *artificial coherent* EM waves
Coherent Radiation

- While passive sensors measure natural incoherent radiation, active sensors transmit and receive coherent radiation.
- Coherence is a measure of predictability.
- Coherent waves may interfere.

**Constructive Interference**

\[ \phi = 0 \]

\[ \phi = \pi/2 \]

**Destructive Interference**

\[ \phi = 0 \]

\[ \phi = \pi \]
Phase Measurements

- Active sensors may record both the amplitude and phase.

The separation of two detectors $B_1$ and $B_2$ can be estimated from the phase difference $\Delta \varphi = (d/\lambda)2\pi$. For example, when $d = \lambda$, $\Delta \varphi = (1/2)2\pi = \pi$. For $d = 3\lambda/4$, $\Delta \varphi = (3/4)2\pi = (3/2)\pi$, or $270^\circ$.

Interference pattern of two nearby coherent sources.
Speckle

- Because of waves scattered backwards from different objects may interfere, SAR measurements may fluctuate in a quasi-unpredictable manner (= Speckle)
Representations of SAR Data & Speckle Statistics

- Real & Imaginary Components
- Phase & Amplitude
- Intensity & Log Intensity
Antennas

- For transmitting and receiving of electromagnetic waves
- Commonly used antenna types
  - Parabolic antennas
    - Solid metal
    - Wire mesh
  - Array antennas
    - Phased arrays allow electronic beam steering

Antenna types

ENVISAT ASAR Antenna
Antenna Radiation Pattern

- Beamwidth $\beta$ [sr] of major lobe
  \[ \beta = \frac{\lambda}{d} \]
  - $\lambda$ ... wavelength [m]
  - $d$ ... antenna size [m]

- Due to long wavelengths the antenna footprint on the ground may be very large
  - 1-50 km!
Sub-Footprint Resolution

- Radars can achieve a sub-footprint resolution by
  - Range discrimination
    - Pulsed radar
    - Frequency-modulated radar
    - Chirp radar
  - Aperture synthesis
    - Doppler shift
  - Interferometric techniques
    - Phase difference of two measurements

This figure shows a face-on disk of a planet such as Venus, showing a particular range and Doppler segment. The dark circle represents the area of the surface that lies equidistant from the antenna. The vertical strip shows the line of equal-Doppler shift caused by the rotation of the planet. From Woodhouse (2006)
Passive and Active Microwave Sensors

- **Passive**
  - Passive remote sensing systems record electromagnetic energy that is reflected or emitted from the surface of the Earth
  - Sensors
    - Microwave radiometers

- **Active**
  - Active remote sensors create their own electromagnetic energy
  - Sensors
    - Altimeters
    - Side-looking real aperture radar
    - Scatterometer (SCAT)
    - Synthetic Aperture Radar (SAR)
Microwave Radiometers

- Typically measure the brightness temperature at vertical and horizontal polarisation at different frequencies

- Signal is very low, so long integration times are chosen to improve signal to noise ratio (SNR)

- Resolution ~ 10-50 km
Soil Moisture and Ocean Salinity (SMOS)

- Launch on 2/11/2009
- Passive interferometer operated in L-band ($\lambda = 21$ cm)
Altimeters

- Nadir-looking active microwave sensors
- Measurement of height above ground
CryoSat

- Launch in spring 2010
- CryoSat will measure the thickness of the polar ice sheets and floating sea ice with a radar altimeter called SIRAL (Synthetic Aperture Radar Interferometric Radar Altimeter)
Side-Looking Airborne Radar

a. Intermap LearJet 36 Star 3i.

b. Typical active microwave system components.
Side-Looking Real Aperture Radar

- Range resolution is determined by the length of the transmitted pulses
- Azimuth resolution is determined by the size of the antenna
  
  \[\text{GRR} = \text{ground range resolution}\]
  \[\text{AR} = \text{azimuth resolution}\]
  \[\text{B} = \text{beam width}\]
Scatterometers

- Scatterometers are side-looking real aperture radars designed
  - to achieve a high radiometric accuracy
  - retrieve wind fields over the oceans ⇒ several look directions during one overpass

<table>
<thead>
<tr>
<th></th>
<th>SASS</th>
<th>ERS-1/2</th>
<th>NSCAT</th>
<th>SeaWinds</th>
</tr>
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<tbody>
<tr>
<td>FREQUENCY</td>
<td>14.6 GHz</td>
<td>5.3 GHz</td>
<td>13.995 GHz</td>
<td>13.6 GHz</td>
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<tr>
<td>POLAR.</td>
<td></td>
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<td>BEAM RESOLUTION</td>
<td>FIXED DOPPLER</td>
<td>RANGE GATE</td>
<td>VARIABLE DOPPLER</td>
<td>PENCIL-BEAM</td>
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<td>SCI. MODES</td>
<td>MANY</td>
<td>SAR, WIND</td>
<td>WIND ONLY</td>
<td>WIND/HI-RES</td>
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<tr>
<td>RESOLUTION</td>
<td>50/100 km</td>
<td>25/50 km</td>
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<td>25 km/6x25km</td>
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<tr>
<td>SWATH</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>INCIDENCE ANGS</td>
<td>0° - 70°</td>
<td>18° - 59°</td>
<td>17° - 60°</td>
<td>45° &amp; 54°</td>
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<tr>
<td>DAILY COVERAGE</td>
<td>VARIABLE</td>
<td>&lt; 41 %</td>
<td>78 %</td>
<td>92 %</td>
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</tbody>
</table>
Quikscat SeaWinds

Daily global coverage of the SeaWinds scatterometer (outer beam) on board of the Quikscat satellite

SeaWinds: 2 Beams
Frequency: 13.6 GHz (Ku-Band)
Spatial Resolution: 25 km, 6×25 km
Daily Global Coverage: 92 %
Incidence Angles: 45° (Inner), 54° (Outer)
Polarization: VV (Outer), HH (Inner)
Synthetic Aperture Radar (SAR)

- To improve the azimuth resolution, a very long antenna is synthesised electronically
  - Many pulses are sent towards the object
  - Due to the motion of the platform the frequency of the echoes is Doppler shifted
SAR Satellites

- Since 1991 launches of civil spaceborne SARs by Europe, Russia, Japan, Canada, etc.

<table>
<thead>
<tr>
<th>SAR</th>
<th>Launch</th>
<th>Origin</th>
<th>Band</th>
<th>Wavelength (cm)</th>
<th>Polarisation</th>
<th>Resolution (m)</th>
<th>Swath Width (km)</th>
<th>Altitude (km)</th>
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<tr>
<td>SEASAT</td>
<td>1978</td>
<td>USA</td>
<td>L</td>
<td>23.5</td>
<td>HH</td>
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<td>ENVISAT</td>
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<td>5.3</td>
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<td>TerraSAR-X</td>
<td>2007</td>
<td>Germany</td>
<td>X</td>
<td>3.1</td>
<td>Multi</td>
<td>1-16</td>
<td>30-100</td>
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</table>
Radarsat Modes
TerraSAR-X und Tandem-X

- PPP between DLR and Astrium
- Launches
  - TerraSAR-X: 15 June 2007
  - Tandem-X: 21 June 2010
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<th>IR-Orthophoto 2001</th>
<th>RGB-Orthophoto 2006</th>
<th>TerraSAR-X StripMap</th>
<th>TerraSAR-X SpotLight</th>
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<td>resolution: 3m</td>
<td>resolution: 1.2m</td>
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**Additional Images:**

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Sentinel-1
SAR Interferometry

- Exploit the coherent nature of SAR sensors for measuring phase differences between two or more SAR images
  - Single-pass interferometry
  - Multi-pass interferometry
  - Differential interferometry
Comparison of GTOPO30 DEM and SRTM-derived DEM of Mount Kilamanjaro in Tanzania and Kenya

a. GTOPO30 1 x 1 km digital elevation model.
b. SRTM-derived 30 x 30 m digital elevation model.
c. GTOPO30 1 x 1 km digital elevation model observed from an oblique vantage point looking W-NW.
d. SRTM-derived 30 x 30 m digital elevation model.
Single Antenna Illumination
Two Antennas: Baseline = 0
Baseline $>> 0$
Geocoded Coherence Map

Site: siberia

Source: E1/2 tandem data
Acquis. Date: 25-09-1997
Orbit / Frame: 32400 2529
Baseline: 242.3 m / 38.2
Scene Center: 91.3, 53.3

Projection: ESA TM UT46
Easting Northing
Res 100.0 100.0 m
NW 329750.0 5973850.0 m
SE 450550.0 5851650.0 m

Courtesy of W.K.
Final Remarks

- Microwave remote sensing is a rapidly developing discipline, with an increasing number and diversity of specialised sensors.
- Its foundation is the electromagnetic theory.
  - Microwave data should not be treated as "images" but as "measurements".
- Visual metaphors dominate the remote sensing literature, but for microwaves an audio metaphor is more appropriate.

Schematic diagram comparing the human ear and a microwave receiver. From Woodhouse (2006)
Recommended Reading

- E. Schanda (1986) Physical fundamentals of remote sensing, Springer Verlag, Berlin Heidelberg