# GEOS 657 – MICROWAVE REMOTE SENSING

## GRADUATE-LEVEL COURSE AT THE UNIVERSITY OF ALASKA FAIRBANKS

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**Lecture 5: Detecting Microwaves; Antenna Design, Performance & Calibration**

UAF Course GEOS 657

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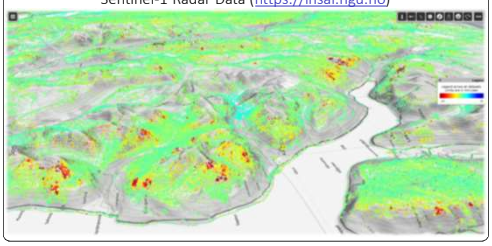
**"Radar in the News"**

NORUT releases Countrywide Surface Deformation Map Derived from Sentinel-1 Radar Data (https://insar.ngu.no)





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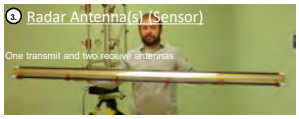
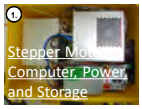
## GENERAL APPROACH TO DETECTING MICROWAVE SIGNALS

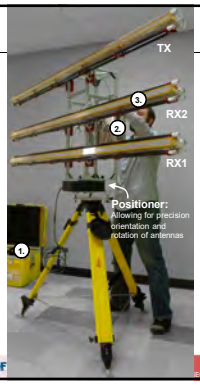
## Objective of Microwave Remote Sensing Systems

- **Detect and quantify EM radiation arriving at detector**
- **Measure the following parameters**: average intensity (highest priority), plus (in most cases) signal polarization and phase
- **To enable these measurements, we must address two problems**:
  - How to collect microwave radiation
  - How to quantify measure radiation parameters with sufficient accuracy

## Components of an Active Radar System



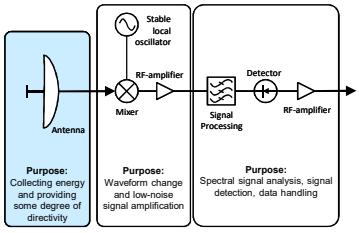








## Components of a Microwave Detection System

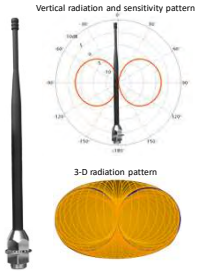
- **Goal:** Produce output voltage proportional to radiation collected at antenna
- **Components:**



## Types of Microwave Antennas
### 1. The Dipole Antenna

- **The Dipole Antenna:**
  - Most basic transmitting and receiving concept
  - Basically no directivity
  - Can only transmit and receive polarized in direction of axis (therefore, can be used to sense polarization)
- **Usage:**
  - Radios, cell phones (all devices for which directivity of sensitivity is not desired)
- **In Remote Sensing:**
  - Single dipole not useful due to lack of directivity
  - Array of dipoles that receive and transmit coherently gain directivity and were used in early radar systems (e.g., Chain Home)

Vertical radiation and sensitivity pattern



3-D radiation pattern

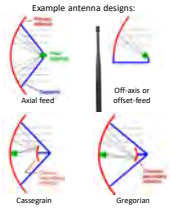




## Types of Microwave Antennas
### 2. Parabolic Antennas

- **Parabolic Antennas:**
  - Reflecting devices that focus energy from localized direction onto a detector
- **Usage:**
  - TV reception; satellite radio; Airport radars (because the SNR of parabolic antennas is higher than a dipole antenna if pointed in the right direction)
- **In Remote Sensing:**
  - While less popular than array antennas, parabolic antennas have some usage in higher-frequency radar
  - Are used, e.g., in the X-band systems SARLupe (Germany), TechSAR (Israel), COSMO-SkyMed (Italy)
  - The Magellan mission to Venus carried a parabolic S-band SAR antenna

Example antenna designs:

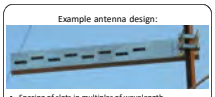



Example radiation and sensitivity pattern

## Types of Microwave Antennas
### 3. Slotted Waveguide Antennas

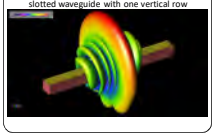
- **Slotted Waveguide Antennas**:
  - Waveguides are (like fiber optics) used to channel and guide microwave signals
  - Antenna panel composed of a series of slits (outlets) from an array of waveguides through which radiation is released and collected
  - Signal is coherent (as it comes from one source) and is therefore directed
- **Usage**:
  - Navigation radar; aircraft radar; cell phone towers
- **In Remote Sensing**:
  - Used in ground-based radars, where pointing can be performed by physical rotation

Example antenna design:



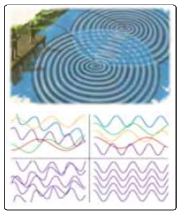
- Spacing of slots in multiples of wavelength
- Arrangement of slots determines radiation pattern

Example radiation and sensitivity pattern for a slotted waveguide with one vertical row



## Think – Pair – Share

**How do Slotted Waveguide Antennas Actually Work??**

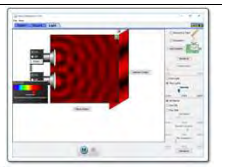


- **Two important concepts** of electromagnetic waves are the key to making slotted waveguide antennas work. We have discussed these concepts before (and will again). Can you think of them?
  - Hint: The figures on the right might help
- **Follow-up question**: Now that you know the two principles, can you use them to explain how slotted waveguide antennas use a series of slits to construct a narrowly focused radar beam?



## A Couple of JAVA Applets on this topic

- **Two Source Interference**:



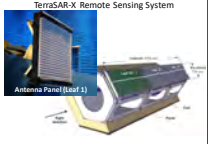
- **Multi-source interference**:

## Types of Microwave Antennas

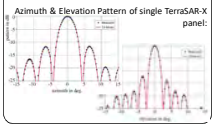
**4. Phased-Array Antenna**

- **Phased Array Antennas**:
  - Array of electronic elements transmitting microwaves at specific frequency and phases
  - Full control over amplitude and phase for each transmitter → full control over shape and direction of transmitted beam
  - Shape of radiation pattern defined by spatial arrangement of transmit-receive units
- **Usage**:
  - Broadcasting; satellite communication; surveillance; remote sensing
- **In Remote Sensing**:
  - Main antenna design for spaceborne (and most airborne) radars

Antenna panel and antenna mounting for TerraSAR-X Remote Sensing System

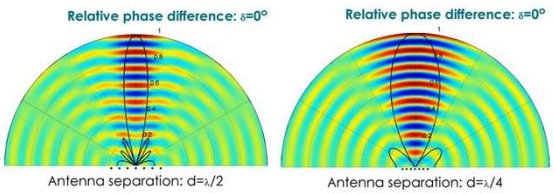



Azimuth & Elevation Pattern of single TerraSAR-X panel:



## How To Redirect a Beam Using Phase

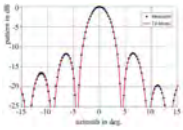
- **Adding relative phase shifts between radiation sources shifts the locations where positive interference happens** → redirection of beam






## Antenna Properties – Antenna Gain

- **Antenna (Gain) Pattern**:
  - Describes total amount of power that is received per direction
  - Ideally: Well defined narrow peak (main lobe)
  - Side-lobes exist for every real antenna (we'll discuss why a bit later)
  - The next slides explains what defines the shape of the antenna pattern (e.g., width of the main lobe)



- **Antenna Gain $G$**:
  - Combines antenna directivity $D$ (which depends on the antenna area $A$) with the antenna efficiency $\rho$

$$G = \rho D = \rho \frac{4\pi A}{\lambda^2}$$

- Size of antenna $A$ is constrained by practical limitations (size, weight)
- For imaging radars, additional constrains come from minimum required transmit power as well as required size of beam on ground



## Antenna Geometry and Shape of Beam

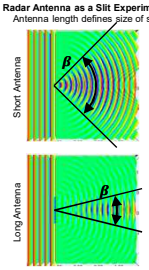
- Beam shape of radar antenna is defined by its geometry
- **Physical reason**: Diffraction
- Beam width $\beta$ of antenna of length $L$ defined by diffraction limit:

$$\beta = \frac{\lambda}{L}$$

with sensor wavelength $\lambda$

- **What does this mean:**
  - Short antenna → energy transmitted into large footprint
  - Long antenna → energy transmitted into small footprint

**Radar Antenna as a Slit Experiment:**
Antenna length defines size of slit

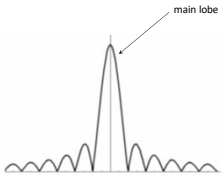


## Antenna Properties – Beam Width and Side-Lobe Structure

- **Beam Width**:
  - Usually described as *half-power beam width (HPBW)*
  - In dB, half-power value corresponds to a 3dB drop off of power relative to peak power → *3dB beam width*
  - For uniformly illuminated antenna:

$$HPBW \approx 1.02\,{}^{\lambda}/_{D}$$

- **Side-lobe structure**:
  - **PSLR**:
    peak-to-side lobe ratio (ratio of peak power to power of first (highest) side lobe)
  - **ISLR** (1-D or 2-D):
    integrated side-lobe ratio, ratio of energy in side lobes to energy in main-lobe

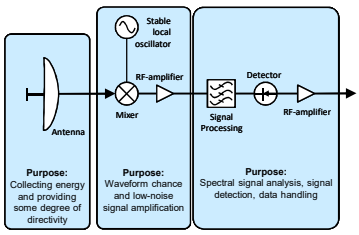



1-D cut through 2-D antenna pattern



## Components of a Microwave Detection System

- **Goal:** Produce output voltage proportional to radiation collected at antenna
- **Components:**






## Signal Amplification and Detection

- **Challenges**:
  - Amplify signals; measure very narrow-band signals; reject noise as much as possible
- **Requirement for Signal Waveform change:**
  - Microwave amplifiers and filters are difficult to build → downsampling to lower frequencies → more effective means for filtering and amplification at lower frequencies.
- Signal waveform change through mixing of received signal with constant frequency signal generated in a *local oscillator*
- Detector converts microwave energy into an electrical signal
- In a coherent system, the detector records both the amplitude *and* phase of the incoming signal

## Signal Amplification and Detection

- **Signal-to-noise ratio (SNR):**
  - There are many sources of noise in microwave systems (thermal noise, quantization noise, electrical leakage, …)

$$SNR = \frac{received\ signal}{system\ noise}$$

- The higher the SNR the better the system

- **Noise-Equivalent $\sigma^0$:**
  - Noise contributions are usually quoted as noise-equivalent sigma naught
  - Equivalent to determining the target radar cross-section that gives backscatter response with $SNR = 1$

System performance is quantified in a process called **System Calibration**.

SYSTEM CALIBRATION PROCEDURES



## Goals of System Calibration

- Establishment of relationships between radar backscatter of an object and its geographical parameters.
- Determination of sensor dependent parameters for conversion from detected signals to backscatter properties.
- Radar system is calibrated when the coefficients required for accurate radiometry have been determined.
- Radar image is calibrated only when those coefficients have been applied.
- Calibrating a radar system is the process of converting a linear amplitude image into a radiometrically calibrated power data.

## Goals of System Calibration

- Calibration is a fundamental prerequisite if geophysical parameters should be extracted from microwave acquisitions
- Calibration is absolutely necessary if multi-temporal studies are performed.
- Also important if radar images of a given area must be compared with other images of the same area acquired by different sensors



## The Radar Equation

transmit power: $P_t \quad [W]$

antenna gain: $g = \frac{4\pi A}{\lambda^2}$

power density at scatterer: $\frac{P_t g}{4\pi R^2} \quad \left[\frac{W}{m^2}\right]$

radar cross section: $\sigma \quad [m^2]$

power density at receiver: $\frac{P_t g}{(4\pi)^2 R^4}\sigma \quad \left[\frac{W}{m^2}\right]$

antenna area: $A \quad [m^2]$

reflected power: $\frac{P_t g}{4\pi R^2}\sigma \quad [W]$

received power: $P_r = A\frac{P_t g}{(4\pi)^2 R^4}\sigma = \frac{g\lambda^2}{4\pi}\frac{P_t g}{(4\pi)^2 R^4}\sigma = P_t\frac{g^2\lambda^2}{(4\pi)^3 R^4}\sigma \quad [W]$

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**BOARDWORK: THE RADAR EQUATION**

## Calibration Concepts

- **General approach:**
  - Feed signal with known properties into various stages of the signal path and compare system output to known signal
- **Instrument parameters to be calibrated:**
  - Transmit power
  - Receiver gain
  - Elevation antenna pattern (roll angle !)
  - Other sensor parameters (signal wavelength, internal delay, …)
- Calibration is a two-step procedure including internal calibration (pre-launch calibration & internal calibration loops in flight) and external calibration (calibration using calibration objects)
- We only care about external calibration in this lecture

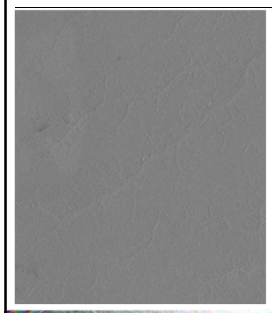


## External Calibration

- Use known signals from outside of the instrument to calibrate the full system including the antenna
- **Required:** External targets will well known scattering properties
- **Calibration objects for external calibration:**
  - Point targets (corner reflectors)
  - Active radar calibrators (ARC)
  - Distributed targets will known properties (mostly: rainforest)
- **Types of Calibration:**
  - **Radiometric Calibration**: Calibrating the received signal intensity or power
  - **Phase Calibration**: Calibrating the received signal phase in all signal channels
  - **Polarimetric Calibration**: Calibrate the polarimetric integrity of the signal recorded by a multi-polarimetric system
  - **Geometric Calibration**: Calibrating the geometric integrity including image shape and image geolocation



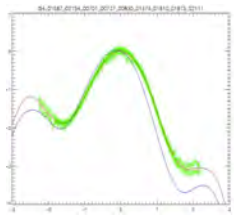
## Radiometric Calibration using Targets with known RCS



- Amazon rainforest
  - Uniform
  - Relatively stable
  - Isotropic scatter
  - Known $\sigma^0$ value (-6.5 dB)
- Amazon test site at
  - 5° S, 69° W
  - 5° S, 66° W
  - 7° S, 66° W
  - 7° S, 69° W

## Radiometric Calibration Example

- **Rainforest is also used to control the health and shape of the antenna pattern**
- **Example to the right:**
  - Control of ENVISAR ASAR elevation antenna pattern **IS4**, VV Polarization
  - **Green**: Rainforest estimates
  - **Blue**: Pre-launch pattern
  - **Red**: In-flight pattern as polynomial fit
  - **X-axis**: off-reference angle [deg]
  - **Y-axis**: two-way gain [dB]

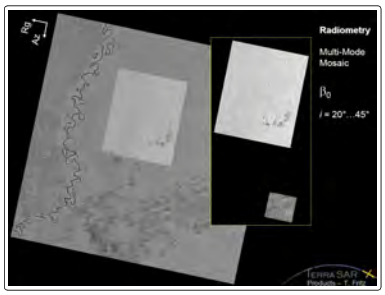


Zink & Rosich (2006): SP-520 Envisat Calibration Review



## Verification of Radiometric Calibration

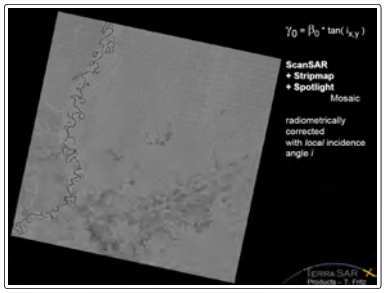
Example TerraSAR-X






## Verification of Radiometric Calibration

Example TerraSAR-X



## Geometric and Phase Calibration

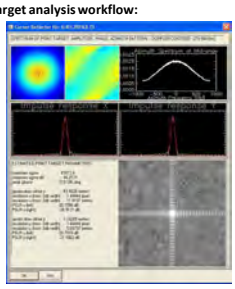
- Done using corner reflectors at known geographic locations
- At corner reflector measure:
  - Peak-to-side lobe ratio (PSLR)
  - Integrated side-lobe ratio (ISLR)
  - Resolution
  - Geolocation accuracy

## Point-Target Analysis

- **Point-target analysis workflow:**
  - Calibration of complex data
  - Projection of corner reflector coordinates into the image
  - Semi-automatic selection of signal peak
  - Geometric and radiometric analysis

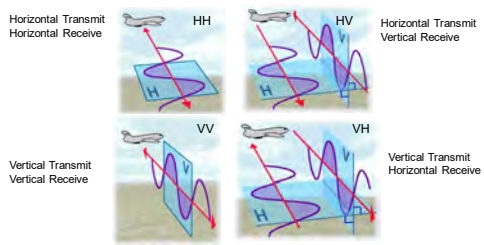
## Point-Target Analysis

- **Point-target analysis workflow:**



Determined output information

## Polarimetric Calibration






## Polarimetric Scattering Matrix

In a quad-pol SAR, every pixel is represented by a matrix of four complex numbers, representing ratios of received and transmitted electric-field amplitudes:

$$[S] = \begin{pmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{pmatrix} \quad \text{(scattering or Jones matrix)}$$

For (monostatic) SARs: $S_{VH} = S_{HV}$ (reciprocity)

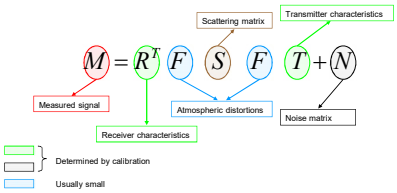
$$[S] = \begin{pmatrix} S_{HH} & S_{HV} \\ S_{HV} & S_{VV} \end{pmatrix} \quad \text{(Sinclair matrix)}$$

$\Rightarrow$ 3 amplitudes + 2 independent phases per pixel



## Measurements of a Polarimetric Radar

- **For a full-polarimetric system the measured signal *M* is given by:**



## Polarimetric System Calibration

- **Calibration determines**
  - System noise matrix
  - Difference between channel gain and phase (amplitude and phase imbalance)
  - Energy leakage from one channel to another (crosstalk) and corrects them to zero
- **Calibration achieved from**
  - Corner reflectors
  - Active transponders
  - Uniform areas of known scattering properties (rainforest)
- **After calibration**
  - matrices *R*, *T*, and *N* are known and can be removed
  - *M* is directly related to *S*



## Reading Assignment

- To prepare for next lecture, please read:

**Woodhouse (2006), "Introduction to Microwave Remote Sensing"**

**pp. 179 – 186 & 200 – 202**

**"Atmospheric Sounding"**