Professional Development Short Course On:

Fundamentals of Synthetic Aperture Radar

Instructor:
Samuel Walt McCandless
Barton D. Huxtable, Ph.D.

ATI Course Schedule:  http://www.ATIcourses.com/schedule.htm
**Includes single user RadarCalc license for Windows PC, for the design of airborne & space-based SAR. Retail price $1000.

**What You Will Learn**

- Basic concepts and principles of SAR.
- What are the key system parameters.
- Performance calculations using RadarCalc.
- Design and implementation tradeoffs.
- Current system performance. Emerging systems.

**Course Outline**

1. **Applications Overview.** A survey of important applications and how they influence the SAR system from sensor through processor. A wide number of SAR designs and modes will be presented from the pioneering classic, single channel, strip mapping systems to more advanced all-polarization, spotlight, and interferometric designs.

2. **Applications and System Design Tradeoffs and Constraints.** System design formulation will begin with a class interactive design workshop using the RadarCalc model designed for the purpose of demonstrating the constraints imposed by range/Doppler ambiguities, minimum antenna area, limitations and related radar physics and engineering constraints. Contemporary pacing technologies in the area of antenna design, on-board data collection and processing and ground system processing and analysis will also be presented along with a projection of SAR technology advancements, in progress, and how they will influence future applications.

3. **Civil Applications.** A review of the current NASA and foreign scientific applications of SAR.

4. **Commercial Applications.** The emerging interest in commercial applications is international and is fueled by programs such as Canada's RadarSat, the European ERS series, the Russian ALMAZ systems and the current NASA/industry LightSAR initiative. The applications (soil moisture, surface mapping, change detection, resource exploration and development, etc.) driving this interest will be presented and analyzed in terms of the sensor and platform space/airborne and associated ground systems design and projected cost.

**Course Outline**


2. **Processing Basics.** Traditional strip map processing steps, theoretical justification, processing systems designs, typical processing systems.

3. **Advanced SAR Processing.** Processing complexities arising from uncompensated motion and low frequency (e.g., foliage penetrating) SAR processing.

4. **Interferometric SAR.** Description of the state-of-the-art IFSAR processing techniques: complex SAR image registration, interferogram and correlogram generation, phase unwrapping, and digital terrain elevation data (DTED) extraction.

5. **Spotlight Mode SAR.** Theory and implementation of high resolution imaging. Differences from strip map SAR imaging.

6. **Polarimetric SAR.** Description of the image information provided by polarimetry and how this can be exploited for terrain classification, soil moisture, ATR, etc.

7. **High Performance Computing Hardware.** Parallel implementations, supercomputers, compact DSP systems, hybrid opto-electronic system.

8. **Image Phenomenology & Interpretation.** Imagery of moving targets (e.g., train off the track), lay over, shadowing, slant-plane versus ground plane imagery, ocean imagery.

9. **Example Systems and Applications.** SIR-C, ERS-1, AirSAR, Almaz, image artifacts and causes. ATR, coherent change detection, polarimetry, along-track interferometry.
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## SAR History

<table>
<thead>
<tr>
<th>DATE</th>
<th>DEVELOPMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1951</td>
<td>Carl Wiley of Goodyear postulates the doppler beam-sharpening concept.</td>
</tr>
<tr>
<td>1952</td>
<td>University of Illinois demonstrates the beam-sharpening concept.</td>
</tr>
<tr>
<td>1957</td>
<td>University of Michigan produces the first SAR imagery using an optical correlator.</td>
</tr>
<tr>
<td>1964</td>
<td>Analog electronic SAR correlation demonstrated in non-real time (University of Michigan).</td>
</tr>
<tr>
<td>1969</td>
<td>Digital electronic SAR correlation demonstrated in non-real time (Hughes, Goodyear, Westinghouse).</td>
</tr>
<tr>
<td>1972</td>
<td>Real-time digital SAR demonstrated with motion compensation (for aircraft systems).</td>
</tr>
<tr>
<td>1978</td>
<td>First spaceborne SAR NASA/JPL SEASAT satellite. Analog downlink; optical and non-real-time digital processing.</td>
</tr>
<tr>
<td>1981</td>
<td>Shuttle Imaging Radar series starts - SIR-A. Non-real-time optical processing on ground.</td>
</tr>
<tr>
<td>1984</td>
<td>SIR-B. Digital downlink; non-real-time digital processing on ground.</td>
</tr>
<tr>
<td>1986</td>
<td>Spaceborne SAR Real-time processing demonstration using JPL Advanced Digital SAR processor (ADSP).</td>
</tr>
<tr>
<td>1987</td>
<td>Soviet 1870 SAR is placed in earth orbit.</td>
</tr>
<tr>
<td>1990</td>
<td>Magellan SAR images Venus.</td>
</tr>
</tbody>
</table>

**TABLE 1. HIGHLIGHTS OF SAR HISTORY WITH SPACE EMPHASIS**
Basic Principles of Aperture Synthesis

**Distances**

\[ t_2 - t_1 \text{ DISTANCE SATELLITE MOVES TO ILLUMINATE TARGET (L_{SA} = SYTHETIC APERTURE LENGTH)} \]

**VeLOCITY**

\[ V \text{ VELOCITY (V)} \]

**Looking Time**

\[ \frac{L_{SA}}{V} = \frac{\lambda R}{VD_{AT}} \]

**Target Range**

\[ R \text{ TARGET RANGE (R)} \]

**Achievable Along-Track Resolution**

\[ \delta_{AT} = \frac{\lambda R}{2L_{SA}} = \frac{\lambda R}{2\lambda R} = \frac{D_{AT}}{2} \]

Achievable along-track resolution is independent of range and radar frequency and improves with smaller real antenna aperture.
Pulse Compression

**Transmitted Waveform Of A Linear FM Pulse**
- Amplitude: 
  - Transmitted Pulse
- Frequency: 
  - Linear Frequency Modulation
- Signal Amplitude: 
  - Transmitted Waveform

**Received Waveform Of The FM Pulse and Subsequent Pulse Compression**
- Amplitude: 
  - Received Waveform
- Frequency: 
  - Received Frequency
- Time Delay: 
  - Delay In Network
- Compressed Pulse
SAR Point Target Return
Space-Based SAR System Components

**WAVEFORM GENERATOR**

**LINEAR AMPLIFIER**

**PHASER TOLERANCES**

**XMTR EXCITER**

**RECEIVER**

**BASEBAND OR I/Q**

**A/D SAMPLING AND QUANTIZATION**

**COLLECTION**

**RECORD, PLAYBACK, DIRECT TRANSMISSION**

**ANALYSIS**

**SIGNATURE DETECTION & ENHANCEMENT**

**IMAGINE PROCESSING**

**PHASE COHERENT SIGNAL PROCESSING**

Fundamentals of SAR: Principles and Applications
Scattering Cross-Sections for Simple Shapes

<table>
<thead>
<tr>
<th>Variation with Wavelength Class</th>
<th>Target/Aspect</th>
<th>Radar Cross-Section, $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda^{-2}$</td>
<td>Flat surface of arbitrary shape and area $A$</td>
<td>$\frac{4\pi A^2}{\lambda^2}$</td>
</tr>
<tr>
<td></td>
<td>NorMal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Triangular corner reflector with edge length $a$</td>
<td>$\frac{4\pi a^4}{3\lambda^2}$</td>
</tr>
<tr>
<td>$\lambda^{-1}$</td>
<td>Cylinder of Length $L$ and radius $a$</td>
<td>$\frac{2\pi a L^2}{\lambda}$</td>
</tr>
<tr>
<td></td>
<td>NorMal To Axis</td>
<td></td>
</tr>
<tr>
<td>$\lambda^0$</td>
<td>Prolate spheroid with semi-major axis $a$ and semi-minor axis $B$</td>
<td>$\frac{\pi B^4}{a^2}$</td>
</tr>
<tr>
<td></td>
<td>Paraboloid with apex radius of curvature $\rho_0$</td>
<td>$\frac{\pi \rho_0^2}{a^2}$</td>
</tr>
<tr>
<td>$\lambda^1$</td>
<td>Cylinder of length $L$ and radius $a$ (averaged over several lobes about and angle $\theta$ off normal)</td>
<td>$\frac{a \lambda}{2\pi \theta^2}$</td>
</tr>
<tr>
<td>$\lambda^2$</td>
<td>Infinite cone with half cone angle $\theta_0$</td>
<td>$\frac{\lambda \tan^4 \theta_0}{16\pi}$</td>
</tr>
</tbody>
</table>
The Radar Equations Interpreted for SAR (cont’d)

\[ N = (\text{PRF}) \text{ (Dwell Time)} = \frac{(\text{PRF}) (L_{SA})}{v} \]

\[ L_{SA} = \frac{\lambda R}{D_{AT}} \quad N = \frac{(\text{PRF}) \lambda R}{v D_{AT}} \]

\[ (S/N)_F = \frac{J G_T A_R \sigma \lambda R (\text{PRF})}{(4\pi)^2 R^4 L K T_S v 2 \delta_{AT}} \]

\[ (S/N)_F = \frac{P_{AVE} A_R^2 \sigma}{8\pi \lambda R^3 L K T_S v \delta_{AT}} \]
Range Ambiguity

- Range ambiguity refers to uncertainty in range from which received radar energy was scattered
- Causes incorrect range overlaps in radar imagery

![Diagram showing range ambiguity and energy scattering](image)
Example: RADARSAT Modes

- Unique ability to shape and steer its beam

- Enables a wide variety of area coverage and resolution combinations
SAR Mission Requirements

MISSION OBJECTIVES
- Detection
- Classification
- Location
- Motion
- Context

DATA PRESENTATIONS
- Mapping
- Change Detection
- Moving Target Detect
- Interferometry
- Polarimetry
- Soil Moisture
- Multi-Frequency
- Foliage Penetration
- Terrain Classification

IMAGING REQUIREMENTS
- Resolution
- Incidence Angles
- Swath Width
- Coverage Rate
- Noise Equiv. sigma-0
- Calibration Accuracy
- Geolocation Accuracy

RADAR SYSTEM PERFORMANCE
- Peak Power
- Pulse Length
- Antenna Area
- PRF
- ISLR, PSLR
- Noise Figure
- Stability
- Dynamic Range
- Data Rate

PLATFORM DESIGN
- Duration
- Launch Date/Time
- Altitude
- Orbit Node
- Attitude Steering, Control & Stability
- Ephemeris Accuracy
- Data Link

Requirements Flow Down
Scattering Matrices

A “Scattering Matrix” is constructed from the transmitted and scattered signal and is a way to quantify how the polarization state of the wave changed between transmit and receive

\[
\begin{pmatrix}
E_h' \\
E_v'
\end{pmatrix}_{\text{sc}} = e^{ikr / kr} \begin{pmatrix}
S_{h'h'} & S_{h'v'} \\
S_{v'h'} & S_{v'v'}
\end{pmatrix}
\begin{pmatrix}
E_h \\
E_v
\end{pmatrix}_{\text{ill}}
\]

Where:
- \( S_{h'h'} \) is the complex ration of the electric field of the horizontally polarized parts of the scattered wave and illuminated wave
- \( sc \) is the scattered signal, \( ill \) is the illuminating signal
- \( h \) is horizontal wave component
- \( v \) is vertical wave component
- \( r \) is distance to target,
- \( k \) wave number

A fully polarimetric SAR is necessary to measure all of the matrix components
- \( S_{v'h'} = S_{h'v'} \) after calibration for backscatter returns
Intermediate IFSAR Processing Results

SAR Images

Phase Difference

Unwrapped Phase or DEM
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