Reaching Out and Touching our Solar System

Jet Propulsion Laboratory's Radar Program for Earth and Planetary Exploration

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The Radar Remote Sensing Concept

- Much like sound waves, radar waves carry information that echoes from distant objects
- The time delay of the echo measures the distance to the object
- The changes of the message in the echo determine the object characteristics
Why Radar Remote Sensing?

- The area to be investigated is too large, inaccessible or hazardous (e.g., the Amazon basin, other bodies in the solar system, around an active volcano) for in situ observation.
- Remote sensing systems may be sensitive to aspects of the environment that elude our senses.
- Remote sensing provides a mechanism to efficiently, objectively* and quantitatively* monitor the processes that govern changes to the environment either from natural or anthropogenic causes.

* (albeit often with models and assumptions)
What do we want to measure with radar?

- Topography
- Geography
- Chemistry
  - Composition
  - Phase
- Dynamics
  - Thermo-
  - Hydro-
  - Geo-
  - Bio-
Radar and Light Waves

- Radars operate at microwave frequencies, an invisible part of the electromagnetic spectrum
- Microwaves have wavelengths in the millimeter to meter range
- Like lasers, radars are coherent and nearly a pure tone

The Electromagnetic Spectrum

Common Radar Frequency Bands

<table>
<thead>
<tr>
<th>Band</th>
<th>Ka</th>
<th>Ku</th>
<th>X</th>
<th>C</th>
<th>S</th>
<th>L</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (cm)</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>6</td>
<td>12</td>
<td>24</td>
<td>75</td>
</tr>
<tr>
<td>Frequency (G-cycles/s)</td>
<td>30</td>
<td>15</td>
<td>10</td>
<td>5</td>
<td>2.5</td>
<td>1.2</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Classic Radar Remote Sensing

- Invert the signal measurement to infer reflectivity using the “radar equation”

\[
\text{SNR} = P_T \cdot G_T(\lambda) \cdot \frac{1}{4\pi R^2} \cdot \sigma(\lambda) \cdot \frac{1}{4\pi R^2} \cdot A_R \cdot \epsilon(\lambda) \cdot \frac{1}{kTB}
\]

- Use reflectivity to infer geophysical parameter using models or ground measurements
Surface and Volume Scattering Models for Radar

We can model simple scattering from particles or surfaces...

Cross section of a large sphere is its projected area.

Cross section of a large flat facet goes as area squared.
Surface and Volume Scattering Models for Radar

And we can develop intuition from combinations of these elements...

Rayleigh Roughness

\[ \delta h < \frac{\lambda}{8 \cos \theta_i} \]

\[
\begin{align*}
\theta_i & \quad \theta_i \\
\delta h & \quad \theta_i \\
\delta h & \quad \delta h \cos(\theta_i)
\end{align*}
\]
Types of Radar Sensors

**Altimeters** determine the height of a surface by measuring the round trip time it takes for a radar signal to reflect from the surface to determine surface elevation.

**Sounders/Profilers** measure the reflected power over range.

**Scatterometers** measure the magnitude of the backscattered reflected energy from the surface in the radar beam. The backscatter is related to both the surface composition, through the dielectric constant, and to the surface roughness at the wavelength scale.

**Synthetic Aperture Radar (SAR) Imagers** generate fine resolution backscatter imagery, using the motion of the platform to synthesize a long antenna.

**Polarimeters** generate backscatter measurements from multiple polarizations. Polarimetric information helps distinguish surface roughness from surface composition effects on the backscatter.

**Interferometers:** interferometric systems generally require fine resolution, hence are SAR systems. Data collected from different vantages determine topographic information. In interferometric systems the parallax is typically much less than a pixel so the topographic information is obtained from a phase measurement that makes highly accurate parallax measurements possible. These phase measurements are then converted into elevation measurements.
How it began in Space … The Legacy of SeaSat

**ALTIMETER**
- **TOPEX / Poseidon** (1992)
- **Jason -1** (2001)
- **Sea Winds** (2002)
- **Ocean Surface Topography Mission:** (2008)

**SCATTEROMETER**
- **NSCAT** (1996)
- **QuikSCAT** (1998)
- **SeaWinds** (2002)

**RADIOMETER**
- **Sea Surface Salinity:** Aquarius (2009)
- **Soil Moisture & Freeze/Thaw:** SMAP (~2015)

**SYNTHETIC APERTURE RADAR**
- **SIR -A** (1981)
- **SIR -B** (1984)
- **SIR -C** (1994)
- **Magellan** (1989)
- **Cassini** (1997)
- **SRTM** (2000)
- **L-Band InSAR** (Proposed)
Altimeters

\[ h_t = h_p - \rho \]

- Radar altimeters are downward or nadir pointing sensors that measure terrain elevation.
- Although the basic concept of altimeter operation is very simple, in practice understanding the measurement is complex due to the fact that the terrain elevation is not constant within the footprint of the antenna beam on the ground and the manner in which microwaves backscatter from the terrain.
TOPEX-Jason 1-OSTM Altimetry

Less than a month after launch, the NASA-French space agency Ocean Surface Topography Mission (OSTM)/Jason 2 oceanography satellite produced its first complete maps of global ocean surface topography, surface wave height and wind speed.
“The projections do not include uncertainties in climate-carbon cycle feedbacks nor the full effects of changes in ice sheet flow, therefore the upper values of the ranges are not to be considered upper bounds for sea level rise.”
CloudSat – 94 GHz Profiling Cloud Radar

Typical Orbital Profile

Typhoon Profile
Mars Advanced Radar for Subsurface and Ionospheric Sounding on ESA Mars Express

Mission/Goals
- Primary Goal: To characterize the surface and subsurface electromagnetic behavior/variation in order to elucidate the geology (Search for water, material property, stratigraphy, structure, etc) at global scales with penetration depth of up to 5 km.
- Secondary Goal: To characterize the ionosphere of Mars
- NASA OSS, “follow the water”.

Technology Areas
- Large antenna size due to low HF operation frequency)
- Complicated Matching networks due to wide relative bandwidth (0.1-5.5 MHz)
- Low frequency (HF) operation close to ionospheric plasma frequency
- Instrument calibration
- Requires specialized on-board and ground post-processing algorithms for science data calibration
Scatterometry for Ocean Winds

Physics of ocean scattering

- Bragg resonance scattering
  - The geometry of the ocean’s surface affects its reflectivity
  - Wind roughens the surface of the ocean

- Sigma-0 is affected by the wind speed and direction
  - Higher wind speeds roughen the surface more, increasing sigma-0
  - Wind direction aligned with the viewing vector have a larger sigma-0 than wind directions that are perpendicular

- The sigma-0 of wind-driven ocean is a function of
  - Polarization, incidence angle, wind speed, and relative wind direction
  - Other things (salinity, sea surface temperature, swells, ...)

- Sigma-0 tends to increase as incidence angles decrease
Geophysical Model Function

For a given polarization, incidence angle, and wind speed:

\[ \sigma_0 = A_0 + A_1 \cos(\chi) + A_2 \cos(2\chi) \]

- Where \( \chi \) is the wind direction relative to the incident radiation, and \( A_0, A_1, \) and \( A_2 \) are constants
- Higher order terms are used when developing the model function, but are less significant

• The model function is determined empirically by comparing sigma-0 measurements to model wind fields and/or buoy measurements

- Vertical and horizontal polarization differ
  - V pol tends to have stronger backscatter than H pol
  - H pol has larger upwind/downwind asymmetry
  - V pol has larger upwind/crosswind asymmetry
Scatterometers for Ocean Wind

- Motivation
  - Obtain global wind vectors on a daily basis
    - Research, climatology, weather operations
  - Other applications
    - Ice edge detection, land change detection, snow cover, freeze/thaw detection
- Scatterometers are radar instruments that measure the reflective properties of the Earth’s surface
- A measure of radar reflectivity is the normalized radar cross section called sigma-0
SeaWinds

Beam geometry and polarization
Inner/Outer: H/V pol, 40°/46° look angle, 46°/54° incidence angle
RF: 13.402 GHz, Ku band, 185 Hz PRF
Swath width
1400/1800 km for inner/outer beam

90% daily coverage
Soil Moisture Active/Passive (SMAP)

Freeze/Thaw from 1 km res SAR
Every other day

Root-zone moisture using
Radiometer, SAR, and model
Every 3 hours
Imaging Radar

CROSS-TRACK RESOLUTION
ACHIEVED BY SHORT
PULSE LENGTHS (HIGH
BANDWIDTH)

ALONG-TRACK RESOLUTION ACHIEVED
BY COHERENTLY COMBINING ECHOS
FROM MULTIPLE PULSES ALONG-TRACK
(SYNTHESIZE A LONG ANTENNA)
- RESOLUTION $\propto$ ANTENNA LENGTH
- INDEPENDENT OF RANGE/FREQUENCY
Magellan Mission to Venus
Radar Imaging Properties

- Radar images are distorted relative to a planimetric view.
- Slopes facing toward or away from the radar appear foreshortened.
- Steep slopes are collapsed into a single range cell called layover and areas occulted by other areas are said to be shadowed.

- Radar is primarily sensitive to the structure of objects being imaged whereas optical images are primarily sensitive to chemistry.
- The scale of objects relative to the radar wavelength determines how smooth an object appears to the radar and how bright or dark it is in the imagery.
Wavelength - A Measure of Surface Scale

Light interacts most strongly with objects on the size of the wavelength

**Forest:** Leaves reflect X-band wavelengths but not L-band

**Dry soils:** Surface looks rough to X-band but not L-band

**Ice:** Surface and layering look rough to X-band but not L-band
Visible (Upper) and Radar (Lower)

Nile in Sudan Showing Ancient Nile Course
Polarization - A Measure of Surface Orientations and Properties

Wave Polarization

Vertically polarized
Horizontally polarized

Polarization Filters

Vertical polarization passes through horizontally arranged absorbers.
Horizontal polarization does not pass through horizontally arranged absorbers.

Mostly horizontal polarization is reflected from a flat surface.
San Joaquin Valley, California

Applications: soil moisture estimation, vegetation classification

LHH-Red  LHV – Green  LVV – Blue
Multi-frequency, multi-polarization radar can measure the extent, thickness and morphology of the polar ice pack.

Red: CHH  Green: LHV  Blue: LHH

*Weddell Sea, Antarctica*
Phase and Radar Interferometry

- Interferometric phase is simply another means of measuring distance. Traditional stereoscopic measurement of the “parallax,” or relative displacement an object has from two stereo images, is proportional to the height of the object and the separation between the two imaging points.
- For SAR systems, the parallax is the range difference from a point to the two observation antennas.

\[ \phi = \frac{2\pi}{\lambda} \left( \frac{\Delta \rho}{\lambda} \right) \]

- Phase measurements in interferometric systems can be made with degree-level accuracy, and with typical radar wavelengths in 3-80 cm range this corresponds to parallax measurements having millimeter accuracy.
Phase - A Measure of the Range and Surface Complexity

The phase of the radar signal is the number of cycles of oscillation that the wave executes between the radar and the surface and back again.

Number of cycles

The total phase is two-way range measured in wave cycles + random component from the surface

Collection of random path lengths jumbles the phase of the echo
Radar Interferometry

- Radar has a coherent source much like a laser
- The two radar (SAR) antennas act as coherent point sources
- When imaging a surface, the phase fronts from the two sources interfere
- The surface topography slices the interference pattern

- The measured phase differences record the topographic information
Interferometric Phase Characteristics

Pixels in two radar images observed from nearby vantage points have nearly the same complex phasor representation of the coherent backscatter from a resolution element on the ground but a different propagation phase delay.

Angular separation $\ll 1$ degree
Coherent sum nearly unchanged

$$s_1 = A_b e^{j\phi_b} e^{-j\frac{4\pi}{\lambda} \rho_1} \quad s_2 = A_b e^{j\phi_b} e^{-j\frac{4\pi}{\lambda} \rho_2}$$

$$s_{int} = s_1 s_2^* = A_b e^{i\phi_b} e^{-i\frac{4\pi}{\lambda} \rho_1} A_b e^{-i\phi_b} e^{i\frac{4\pi}{\lambda} \rho_2} = A_b^2 e^{i\frac{4\pi}{\lambda} (\rho_2 - \rho_1)}$$

Coherent backscatter term that is random from cell-to-cell cancels leaving phase that depends on differential path length!
Shuttle Radar Topography Mission (SRTM)

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

Landsat showing Merida

3-dimensional SRTM view of Los Angeles (with Landsat data) showing San Andreas fault
Shuttle Radar Topography Mission
Hardware and Electronics

Mast Length: 60 m
Mast + Cannister Mass: 1000 kg
Total Payload Mass: 13,600 kg
Total Data Volume over 10 days: 12.3 TB
Number of tapes for recording: 300
Shuttle Radar Topography Mission
Mast Characteristics

SRTM Boom Motion
Three Thruster Firings on Datatake 072.100

SRTM Roll Angle
Three Thruster Firings on Datatake 072.100
Both the absolute and relative SRTM height accuracy requirements are met.

- Both the absolute and relative SRTM horizontal accuracy requirements are met.
Data Collection Approaches

Single Pass

- Interferometric radar data can be collected in a single pass interferometry (SPI) mode where both antennas are located on the same platform. One antenna transmits and both antennas receive the returned echoes.

\[ \phi = \frac{2\pi}{\lambda} (\rho_2 - \rho_1) \]

Repeat Pass

- In the repeat pass mode (RPI) two spatially close radar observations of the same scene are made separated in time. The time interval may range from seconds to years.

\[ \phi = \frac{4\pi}{\lambda} (\rho_2 - \rho_1) \]

- Temporal decorrelation — scene changes between observations
- Propagation delay variations — changes in troposphere or ionosphere between observations
UAVSAR: NASA’s New Airborne Radar Science and Technology Testbed

Salient Features

- Robust repeat pass interferometry for deformation measurements
- Fully polarimetric at L-Band (1.2 GHz, 80 MHz BW)
- Initial tests on NASA’s Gulfstream III
- Plan for transition to UAV platform
- Steerable electronically scanned array antenna
- Flight path controlled to be within a 10 m tube using real-time GPS and modified autopilot
- Autonomous radar operation in flight
- Flexible, lightweight, reconfigurable design

Science

- Global and regional volcanic inflation, flooding, land and coastal erosion, fault strain, fire hazard, tectonic strain, precision topography
- Local continuous observation of deformation for prediction of eruption, landslide and flooding
- Provide crustal structure, high temporal resolution, regional deformation processes for increased predictability of earthquake and volcanic activity.
April 4, 2010 M 7.2 Baja California Earthquake

Airborne repeat-pass InSAR for geodetic imaging
Radar designs for proposed mission being studied in pre-Phase A

- L-band 5-80 MHz BW Quad-pol Radar
- 9-15 m mesh reflector
- 12-24 element transmit and receive array
- 12-24 dual-pol receive channels
- 180-360 km swath, full res, full-pol
- Better than -25 dB NES0 at 20 MHz BW
Radar Design to Meet Critical Requirements

Repeat Period requirement for Deformation science drives the Radar Swath
8M-day Repeat Period => 360/M-km Swath Width
Sensitivity requirement for Biomass (cross-pol) measurement drives Antenna
Size and Radar Power
Accuracy requirements for Deformation and Biomass drive Electronics &
Mechanical Stability and Calibration

A new SweepSAR technique was adopted as a means to achieve much wider
swath than conventional SAR strip-mapping, without the performance
sacrifices associated with the traditional ScanSAR technique

Conventional StripMap: <=~70km Swath
Resulting ~40 day repeat
does NOT meet proposed Deformation
and Ice Science
Requirements

Conventional ScanSAR: non-uniform along-track
sampling
Resulting degradation in
effective azimuth looks
does NOT meet proposed
Ecosystem Science
Requirements
New SweepSAR Technique to Meet Science Needs

- On Transmit, all Feed Array elements are illuminated (*maximum Transmit Power*), creating the wide elevation beam
- On Receive, the Feed Array element echo signals are processed individually, taking advantage of the full Reflector area (*maximum Antenna Gain*)

Uses *digital beamforming* to provide wide measurement swath
  - DBF allows multiple simultaneous echoes in the swath to be resolved by angle of arrival

Uses large reflector to provide high aperture gain
  - Full-size azimuth aperture for both transmit and receive
  - Full-sized elevation aperture on receive

Only need data from feed array elements being illuminated by an echoes
  - These elements can be predicted *a priori*
Animation of SweepSAR Concept

National Aeronautics and Space Administration

5th Annual Military Radar Summit

Earth Orbiting Radar Simulated Operations Concept

Approved for unlimited release CL# 12-0576
Eric M. De Jong, Paul A. Rosen, Michael Stetson, Koji Kuramura, Jason Craig, Zareh Gorjian, Peter Xaypraseuth, Ryan J. Ollerenshaw, Shigeru Suzuki,
Solar System Visualization Project,
Jet Propulsion Laboratory, California Institute of Technology.
Artist rendering of spacecraft based on publicly available information
Titan Observation Geometry

SAR imaging takes place from around ±16 minutes from closest approach with altitude Titan ranging from 4000 km to 1000 km.

Closest Approach For Titan Passes 950-1500 km

Titan:
- Only moon with significant atmosphere ($N_2$)
- Surface Temperature: 85°C
- Radius: 2575 km
- Surface: Methane and other hydrocarbons ices and liquids
Cassini Radar Results

(Courtesy S. Hensley)

Wye et al. (Icarus, 2007)

Hayes et al., Icarus 2010
Lakes on Titan

- Although not suitable for swimming at 77°C, the Cassini radar detected the first liquid surfaces in the solar system not on Earth.
- These lakes are composed of liquid hydrocarbons like methane.
Timeline of Major Mission Events During Curiosity's August 5, 2012 Landing

- **Time Event Occurrence Received on Earth (PDT)**
- **[10:24:33.8 PM]** Atmospheric Entry
- **[10:28:53.0 PM]** Parachute Deploy
- **[10:29:12.7 PM]** Heat Shield Separation
- **[10:31:26.7 PM]** Rover Separation (from Descent Stage)
- **[10:31:45.4 PM]** Touchdown
Terminal Descent Sensor (Radar) Flight Model
Key TDS Technologies

Antennas: six individual slotted waveguide antennas built by EMS-Atlanta (now Honeywell) – 22 cm diameter, 1 cm thick

Transmit / Receive Modules: Ka-band microelectronic hybrid circuits. 2W peak power, 7-9 dB noise figure, fast switching speeds (sub-10m minimum range)

Single Board Digital Subsystem: SPARC onboard computing, Xilinx-based onboard 10000x data reduction and processing, telemetry acquisition, and all radar timing

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Reaching Out and Touching our Solar System
EM Radar of Radar on Descent Stage
Assembling the Powered Descent Vehicle
At Kennedy Space Center
Extensive Field Testing of TDS Throughout Flight Envelope
Some Animations

What It’s Like to Land on Mars
Some Animations


Dropping in on Mars in High-Res
JPL enjoys a long history of collaboration with, and observations of, Alaska!

- The Radarsat Geophysical Processor System was developed by JPL in the 1990s and installed for operations at the Alaska SAR Facility
- Conducted joint study of digital elevation mapping of Alaska using JPL TOPSAR data ERS-1/2 tandem observations
- JPL AIRSAR and UAVSAR data are presently distributed from the ASF Distributed Active Archive Center
- JPL presently working with ASF personnel to reprocess historical SeaSAT SAR data
- Collaborative work includes calibration activities of numerous SAR data sets using corner reflectors installed at Delta Junction, AK, ionospheric effects on long-wavelength SAR with UAF (F. Meyer)
Summary

- The NASA/JPL radar program is a broad-based, science-driven research and development effort.
- Science requirements lead to specific sensor and mission configurations offering first of a kind capabilities to the nation.
- Generation of the source of illumination by radar instruments allows a degree of control that is as close to reaching out and touching the object as possible in the context of remote sensing.
Magellan Map of the Surface of Venus

Composite image of one Cycle (about 2000 orbits) of Magellan imagery
Coupled Airborne and Spaceborne Radar Programs

Rocket Radar mounted on NASA CV-990. (L-band only.)

SeaSAT

AIRSAR re-built on DC-8

SIR-C

IFSARE/*3I

SRTM

GeoSAR

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