Forest Mapping and Monitoring with SAR Data: InSAR Processing and Forest Stand Height

Erika Podest &
Paul Siqueira, Yang Lei, Tracy Whelen, Simon Kraatz (University of Massachusetts)
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Course Outline

Part 1: Time Series Analysis of Forest Change

Part 2: Land Cover Classification with Radar and Optical Data

Part 3: Mangrove Mapping

Part 4: Forest Stand Height
A little something about FSH (Forest Stand Height)

Algorithms exist with varying complexity
  - Simple classification (one image)
  - Time-series & Machine learning
  - Polarimetry
  - Multi-frequency & Data fusion

So far, with Forest Mapping and Monitoring, you have used:
  - Time-Series Analysis of Basic Change
  - Land Cover classification with radar and optical data
  - Mangrove mapping using the double-bounce signature

FSH is another level of complexity that requires good knowledge of:
  - SAR processing
  - InSAR
  - NASA DAAC Data inquiries

Today is meant to be an introduction to that process
Microwave Remote Sensing Laboratory
Dept. of Electrical and Computer Engineering

• 40-year history of microwave sensor development
• Core skills in microwaves and remote sensing system development
• Research expertise in radar, SAR, InSAR, lidar and Hyperspectral imaging
• Application areas in forest, crops, atmospheric & ocean monitoring

✧ Close interaction with national space agencies, research institutes, and commercial industry
✧ Faculty have international reputation in microwave engineering, hyperspectral science, electromagnetics
Where Is Amherst?
Mission

• Design, build, and use microwave systems for studying the environment.
• Instrument capability from DC to 215 GHz (most systems between 100 MHz and 100 GHz).
The Ladder to Space

- Identify Need
- Concept and Application
- Design
- Laboratory Measurement
- Rooftop/Airborne Measurement
- Analysis & Redesign
- Spaceborne Mission
Outline of Today’s Interaction

• A little something about InSAR versus SAR
• The use of SAR data for mapping Forest Stand Height (FSH)
• Exercise: Estimating Forest Stand Height
• Q&A Session
Mode-Specific Science Targets in Observation Plan

- Each colored region represents a single radar mode chosen to satisfy multiple science objectives over that area.
- Avoids mode contention that would interrupt time series

- Planned Acquisitions
  - Background Land
  - Land Ice
  - Sea Ice
  - Urban (small targets)
  - US Agriculture
  - Himalayas
  - India Agriculture
  - India Coastal Ocean
  - Sea Ice Type

US-Quad-pol collection is likely to occur for the states of Illinois, Michigan, Ohio, and parts of Alaska.

Background Land satisfies most Solid Earth and Ecosystems objectives
• Active sensor and weather tolerance improves dependability
• For JERS-1, Every 44 days, a partial view of the Earth’s surface could be made

NISAR will collect similar data, regularly, every 12 days at a 10m SLC resolution.

HH and HV polarizations
240 km swath

The radiometric quality is not great for this image, but it shows very well the different orbits of JERS-1 and the methodical way that it was able to collect data with a 70 km swath. NISAR will offer a similar capability, with global-land coverage, two times every 12 days.
**NISAR Concept Science Observation Overview**

<table>
<thead>
<tr>
<th>NISAR Characteristic:</th>
<th>Would Enable:</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-band (24 cm wavelength)</td>
<td>Low Temporal Decorrelation and Foliage Penetration</td>
</tr>
<tr>
<td>S-band (9.4 cm wavelength)</td>
<td>Sensitivity to Light Vegetation</td>
</tr>
<tr>
<td>SweepSAR technique with Imaging Swath &gt; 240 km</td>
<td>Global Data Collection</td>
</tr>
<tr>
<td>Polarimetry (Single/Dual/Quad)</td>
<td>Surface Characterization and Biomass Estimation</td>
</tr>
<tr>
<td>12-day exact repeat</td>
<td>Rapid Sampling</td>
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<tr>
<td>3 – 10 meters mode-dependent SAR resolution</td>
<td>Small-Scale Observations</td>
</tr>
<tr>
<td>3 years science operations (5 years consumables)</td>
<td>Time-Series Analysis</td>
</tr>
<tr>
<td>Pointing control &lt; 273 arcseconds</td>
<td>Deformation Interferometry</td>
</tr>
<tr>
<td>Orbit control &lt; 500 meters</td>
<td>Deformation Interferometry</td>
</tr>
<tr>
<td>&gt; 30% observation duty cycle</td>
<td>Complete Land/Ice Coverage</td>
</tr>
<tr>
<td>Left/Right pointing capability</td>
<td>Polar Coverage, North and South</td>
</tr>
</tbody>
</table>

**NISAR Uniquely Captures the Earth in Motion**

**Observation Geometry**

- Orbit: 6 AM / 6 PM
- Earth Surface
- Observation Geometry:
  - 747 km
  - 33°
  - 47°
  - > 240 km
NISAR Ecosystems Science Drivers*

- Biomass Estimation
- Disturbance Monitoring
- Inundation Extent
- Agricultural Area Mapping
- Coastal Wetlands

Paul Siqueira
Sassan Saatchi
Josef Kellndorfer
Bruce Chapman
Ralph Dubayah
Kyle McDonald
Nathan Torbick
NISAR Ecosystems
NASA & ISRO Teams

Paul Siqueira  Bruce Chapman  Josef Kellndorfer  Sassan Saatchi  Ralph Dubayah  Nathan Torbick  Kyle McDonald


Praveen Kumar Gupta  Shashi Kumar  Ratheesh Ramakrishnan  Darmendra Pandey  More??  John Armston  Erika Podest
Regions with AGB < 100 Mg/ha
50% of area

Regions with AGB > 100 Mg/ha
50% of area

Regions with AGB < 20 Mg/ha
50% of area

Regions with no woody vegetation

Open Water
NISAR Biomass Requirement

- Measure aboveground woody vegetation biomass annually at the hectare scale (1 ha) to an RMS accuracy of 20 Mg/ha for 80% of areas of biomass less than 100 Mg/ha.

- This requirement must be validated after launch.

- This is a NASA requirement on the L-band SAR.

NISAR background land observations of 60 HH/HV observations per year over all land surfaces is meant to be an enabling data set to allow many different algorithms and applications that are relevant to biomass and vegetation mapping.
The global distribution of regions dominated by woody biomass < 100 Mg/ha.

- Green: Regions with AGB < 100 Mg/ha (50% of area)
- Red: Regions with AGB > 100 Mg/ha (50% of area)
- Yellow: Regions with AGB < 20 Mg/ha (50% of area)
- White: Regions with no woody vegetation
- Blue: Open water
Track/Frame Data Collection

- Data are planned to be collected in track/frame coordinate system
- 173 unique tracks that comprehensively span the equator
- Within a single track/frame, data collection mode will be uniform, at the lowest bandwidth
- Higher bandwidth segments delivered separately
- Vegetation is green (HV – Volume scattering)
- Water is blue (HH/HV – smooth surfaces are very bright)
• Sensors such as Sentinel-1 and NISAR are creating unprecedented, dependable time series of SAR data.
• Compare HH and HV RCS for different landcovers
• Compare HH and HV RCS for different landcovers
Single-Look Complex (SLC) Imagery

- Single-Look Complex (SLC) images are radar data that have been processed to their full resolution.
- The units of each pixel in an SLC is the complex electric field.
- The magnitude of the field is proportional to the Radar Cross Section and the distance to the target, measured in phase (fractions of a wavelength; 360 deg = 24 cm for L-band).
Doppler Interpretation

- Another way to interpret the resolution of SAR is through the concept of the Doppler Shift.
- As a target is approaching the radar, its frequency is shifted up.
- As the target recedes from the radar, its frequency is shifted down.
- At broadside, the Doppler shift is zero, also called Zero Doppler.
• Each target in a given radar scene will have a unique range and Doppler history.
• All targets in the imaged region will have unique range-doppler histories.

• With matched filtering, these histories can be extracted to make a high-resolution image.

• Results are based on well known metrics such as the Nyquist sampling theorem and the relationship between bandwidth and resolution ($\Delta f$ and $\Delta t$).
Aperture Synthesis

Timing information onboard a satellite can be used to mimic (or synthesize) a large antenna array, fixed in space.
The processing flow of raw radar data (collected as numbers flowing out of an analog-to-digital converter) to SLC and higher-level products is the processing flow of radar data.

Different processing packages are used to carry the data to the next level of processing.

These levels, and some common processing packages, are listed below.
<table>
<thead>
<tr>
<th>Header Information (720 bytes)</th>
<th>IQ A/D Samples (10800 bytes)</th>
</tr>
</thead>
</table>

**RAW SAR DATA**
After range compression and correction for range migration, the data is compressed in the azimuth direction, yielding a Slant-Range SLC image that has both magnitude and phase.
• Once projected into **ground range**, features in the imagery become much more apparent.

• Because of the projection, some information is lost in the process.
Output Products

Radar Cross Section  Topographic Phase  Correlation Magnitude  Differential Interferogram
Single-Look Complex (SLC) Imagery

- Single-Look Complex (SLC) images are radar data that have been processed to their full resolution.
- The units of each pixel in an SLC is the complex electric field.
- The magnitude of the field is proportional to the Radar Cross Section and the distance to the target, measured in phase (fractions of a wavelength; 360 deg = 24 cm for L-band).
When working with interferometry, the return from a target at a given range is compared for two antennas at the end of a baseline.

This provides the interferometric phase.

\[ \theta = \sin^{-1}\left(\frac{-\lambda \Delta \phi}{4 \pi B}\right) + \xi \]

\[ z(y) = H - R \cos\left(\xi - \sin^{-1}\left(\frac{\lambda \phi}{4 \pi B}\right)\right) \]
Different antenna positions, separated by a baseline, are used for uniquely determining the angle of arrival for the signal return.
Path length difference can be used to resolve positional ambiguity and determine the height of the terrain. Accuracy is on the order of meters, with a 25m resolution.

\[ h = H - \rho \cos \left( \sin^{-1} \left( \frac{\lambda \phi}{4 \pi B} \right) \right) \]

When the signal return comes from multiple heights, a unique signature is observed by the interferometer.
Interferometry combines two radar scenes to create one, consisting of complex numbers (magnitude and phase).

- Interferometric magnitude is called the “Coherence”.
- Interferometric phase is related to the topography.
**Interferometric Processing Chain**

- **Master**
  - Radar Data 1
    - Data Formatting
  - Single-look Complex (SLC)
  - Multi-look Intensity (MLI)
  - Orbit parameter refinement
  - Resample SLC (RSLC)
  - Resample MLI (RMLI)

- **Slave**
  - Radar Data 2
    - Data Formatting
  - Single-look Complex (SLC)
  - Multi-look Intensity (MLI)
  - Orbit parameter refinement
  - Resample SLC (RSLC)
  - Resample MLI (RMLI)

- **Satellite Orbit Data**
  - DEM
  - Simulated SAR Image
  - Generate Lookup Table for Geocoding
  - Interferogram Generation
  - Remove topographic phase
More Output Products

- Optical
- Polarizations (HH, HV, VV)
- DEM
- Interferogram
- Simulated Interferogram
Surface Area Correction
SLC1-pol
SLC2-pol
Simulated RCS
NRCS1-pol
Differential Interferogram
Calculating Forest Stand Height from SAR

Focus is on L-band because of its relatively low frequency and sensitivity to the more permanent woody-structures of the forest.

Possible approaches for measuring vertical structure of vegetation for the SAR/InSAR component of the proposed NISAR mission and the existing ALOS missions.

- Relate backscatter to biomass (scatterer counting)
- If we could measure height, like lidar, that is a possibility too.
- This requires two satellites, or a repeat-pass observation
- Temporal Decorrelation \text{→} “The $500M$ question”
ALOS-1 Basic Observing Strategy and newly open data policy provides a large database for exploring interferometric correlation.
\[ \gamma_{obs} = \gamma_{SNR} \cdot \gamma_{vol} \cdot \gamma_{temporal} \cdot \gamma_{geom} \Rightarrow \gamma_{v&t} \approx \frac{\gamma_{obs}}{\gamma_{SNR} \gamma_{geom}} \propto (h_v)^{-1} \]

Workflow of Forest Stand Height Inversion

1. SAR image #1
2. SAR image #2
3. Interferogram
   - Correct for geometric decorrelation, thermal noise decorrelation, and correlation sampling bias
4. Temporal change parameters \( S_{scene}, C_{scene} \)
5. Estimated forest height
6. Sinc inversion model with Gauss-Newton algorithm
7. Ground validation forest height
Simplified Model
(HV polarization; small $k_z$)

\[
|\gamma_{v,t}| = S_{\text{scene}} \text{sinc} \left( \frac{h_v}{C_{\text{scene}}} \right)
\]

$S_{\text{scene}}$
(dielectric change)

$C_{\text{scene}}$
(random motion)

46 days later
18 SAR Scenes in Central Maine (119_890)

18 separate dates collected using the same observing mode (FBD, path 119, frame 890) in Central Maine

This creates a total of 153 unique combinations
Results (Howland Forest)

Optical  LVIS  InSAR correlation magnitude  InSAR correlation magnitude w/o water

Water bodies removed by using NLCD 2006
Qualitative Comparison of Methods

Test Region

RCS (HV)

Intf. Phase

Intf. Correlation
Assuming that forest stand height (FSH) is a proxy for biomass, we can fit observations of RCS, InSAR differential height from the known DEM (phase) and the correlation magnitude height to the LVIS observed heights.

- Low heights work best with RCS.
- Large Heights have best performance with InSAR correlation magnitude.
ALOS-1 and ALOS-2 Results Compared to Lidar
94 ALOS/PALSAR imageries are selected to cover the entire state of Maine, from which 37 interferograms are formed and identified as having relatively high correlation magnitude.

Interferometric pairs utilized for the generation of the state mosaic of forest height

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<th>Orbit #</th>
<th>Frame #</th>
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</table>
An automatic mosaicking algorithm for the generation of a large-scale forest height map using spaceborne repeat-pass InSAR correlation magnitude

Yang Lei and Paul Siqueira

Article
Results (From Central Maine to the State Mosaic)
Assembling the Mosaic

The “wallpapering” problem
Results (From Central Maine to the State Mosaic)

Instrumental Parameters

Model-Fitting Parameters
Comparison to Other State-Wide Metrics
To improve accuracy:

- Multiple-scene mosaicking
- Shorter temporal baseline

RMSE < 4 m at 6 ha resolution
Application of Mosaicking
Work with AGS & Mark Ducey

- RH100 lidar data over the Howland Forest and ALOS-1 correlation w/mosaicking used to propagate FSH parameters to lidar validation site, some 300 km away.
- Compare results with single-scene FSH estimation from ALOS-1 and ALOS-2.
• County-level accuracy (RMSE) is 1.6 m, comparable to FIA accuracy
- Algorithm is automated using Python
- Available at github/leiyangleon/FSH


ALOS repeat-pass data can be found on the Alaska Satellite Facility’s Vertex Search Engine (vertex.daac.asf.alaska.edu).

Best scenes to use are ALOS-1 FBD (dual-polarization) that are close together in time (although ALOS-1 lasted from 2006 – 2011 it is freely available and a good proxy for ALOS-2 and NISAR data).
Level 1.0 or Level 1.1 data can be downloaded and further processed into interferograms using

- ISCE
- ROI_PAC
- Gamma
- SARScene
- Other

For this work, ISCE is preferred
Out of 12 chosen files, there are 66 possible combinations (12 pick 2) for making interferograms.

We chose those interferograms that have the largest value of correlation magnitude (coherence).

Shown here are a collection of such interferograms

2009: June 22 and August 7
2010: June 25 and August 10
2010: August 10 and October 25
2009: August 7 and September 22
2010: May 10 and June 25
2008: May 4 and June 19
2007: November 2 and December 18
Improved Resolution over ICESAT
What’s next? Fusion of NISAR and GEDI
Combining of ALOS/NISAR and GEDI data
Use the "Filters selection to find data that is Level 1.0 and FBD (dual-polarization).

Additional filtering can be used to select just one scene.
Siqueira – NISAR Ecosystems Lead

An outline for all of the scenes fitting these criteria can be displayed on the map.
Or a set of quick-look images displayed, as well as a Shopping Cart that can be used to collect and download these files.

Note that the size of the files can be quite large (437.95 MB here).

If there are 10 of these files, then that is 4.4 GB.
• The basic input for the FSH algorithm is the correlation magnitude derived from a repeat-pass interferogram.

• Using ISCE & ROI_PAC, this is called “topophase.cor.geo”

• To download and install ISCE, go to the website: https://github.com/isce-framework/isce2

Additional materials about ISCE can be found here

• Once you download and install ISCE, you next have to create interferograms

• Start by editing the file `stripmapApp.xml`

```xml
<stripmapApp>
  <component name="stripmapApp">
    <property name="sensor name">ALOS</property>
    <component name="Master">
      <property name="IMAGEFILE">
        /home/jovyan/siqueira_notebooks/ALOS_Colombia_data/ALPSRP242010040-L1.0/IMG-HV-ALPSRP242010040-H1.0__A
      </property>
      <property name="LEADERFILE">
        /home/jovyan/siqueira_notebooks/ALOS_Colombia_data/ALPSRP242010040-L1.0/LED-ALPSRP242010040-H1.0__A
      </property>
      <property name="OUTPUT">20100925</property>
    </component>
    <component name="Slave">
      <property name="IMAGEFILE">
        /home/jovyan/siqueira_notebooks/ALOS_Colombia_data/ALPSRP248720040-L1.0/IMG-HV-ALPSRP248720040-H1.0__A
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      </property>
      <property name="OUTPUT">20100810</property>
    </component>
  </component>
</stripmapApp>
```

• Execute by typing the command line (or python): `stripmapApp.py stripmapApp.xml`

→ This can take a while to execute
Output data from ISCE2 processing

- Use the ISCE2 tool, `mdx`, to look at files:
  
  ```
  mdx -s 3026 topophase.cor.geo -rmg topophase.flat.geo -c8
  ```
• Or download a sub-set of these files, and the FSH scripts from GitHub: github.com/leiyangleon/FSH

Forest Stand Height (FSH) Python Scripts

- Windows (Anaconda Prompt)
- Linux
- OSX

This software performs the automated forest height inversion and mosaicking from spaceborne repeat-pass L-band HV-pol InSAR correlation magnitude data (e.g. JAXA's ALOS-1/2, and the future NASA-ISRO's NISAR) that have been pre-processed by JPL's ROI_PAC and/or ISCE programs.

Produced by the University of Massachusetts Microwave Remote Sensing Laboratory.

Yang Lei, (ylei@caltech.edu, leiyangfrancis@gmail.com), Paul Siqueira (siqueira@umass.edu).

Here you will find the folders: • scripts, • scripts_Py3 and • test_example_ISCEースripmapApp
• Within the data directory, test_example_ISCE_stripmapApp, type the following command (also given in the GitHub page)

```python3 /Users/siqueira/Downloads/FSH-Master/scripts_Py3/forest_stand_height.py \
3 2 2 5 "linkfile.txt" \ 
 "flagfile.txt" \ 
 "Howland_LVIS_NaN.tif" \ 
 "Maine_NLCD2011_nonwildland.tif" \ 
 "/Users/siqueira/Downloads/test_example_ISCE_stripmapApp/" \ 
 "gif json kml mat tif" --flag_proc=1
```

(or you can edit a file, test_script.sh, and execute it as needed)

There are several files here that you can look at

• **Linkfile.txt** (a simple file indicating which scenes are linked to one another)
• **Flagfile.txt** (a text file that provides index numbers, scene names and directory names)
• **Howland_LVIS_NAN.tif** (geotiff of measured forest heights from lidar, ground validation, GEDI, or other)
• **Main_NLCD2011_nonwildland.tif** (a simple classification mask to remove water bodies and cities)
Demo
FSH input files

<table>
<thead>
<tr>
<th>Linkfile.txt</th>
<th>Flagfile.txt</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 1</td>
<td>001 890_120_20070727_HV_20070911_HV 070727 070911 890 120 HV</td>
</tr>
<tr>
<td>2 3</td>
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</tr>
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<td></td>
<td>003 890_118_20070808_HV_20070923_HV 070808 070923 890 118 HV</td>
</tr>
</tbody>
</table>

[boreal 233 ] test_example_ISCE StripmapApp : test_script.sh

Namespace(N_pairwise=20, N_self=10, Nd_pairwise=20, Nd_self=10, bin_size=100, edges=2, ...)

19:36:00
auto_tree_height_many finished at 19:36:09
1 edge file(s) created at 19:42:07
2 edge file(s) created at 19:48:44
intermediate() complete - overlap areas calculated at 19:51:23

.... some intermediate updates ....

auto_mosaicking_new finished at 19:53:13
write_deltaSC completed at 19:53:13
all tree height map files written at 20:02:19
• File outputs in many standard formats
  
kml  geotiff  json  matlab  gif

• Files can be found in data directories

[boreal 242 ] test_example_ISCE_stripmapApp : ls f890_o119
890_119_20070710_HV_20071010_HV_fsh.json  890_119_20070710_HV_20071010_HV_fsh_255.kml
890_119_20070710_HV_20071010_HV_fsh.mat  890_119_20070710_HV_20071010_HV_fsh_255.tif  int_070710_071010
890_119_20070710_HV_20071010_HV_fsh.tif  890_119_20070710_HV_20071010_HV_geo.txt
890_119_20070710_HV_20071010_HV_fsh_255.gif  890_119_20070710_HV_20071010_HV_orig.mat

[boreal 243 ] test_example_ISCE_stripmapApp : more f890_o119/890_119_20070710_HV_20071010_HV_geo.txt
width: 4124
nlines: 4106
corner_lat: 45.739722
corner_lon: -69.167500
post_lat: -0.000278
post_lon: 0.000278

• Display results and input files in QGIS
• An illustration of some of the intermediate files shown on QGIS

LVIS Lidar data overlain on GoogleEarth imagery

LVIS Lidar data overlain on NLCD-derived forest mask
Demo QGIS files
Generation of large-scale moderate-resolution forest height mosaic with spaceborne repeat-pass SAR interferometry and lidar
Yang Lei, Paul Siqueira Member, IEEE, Nathan Torbick, Mark Ducey, Diya Chowdhury, and William Salas

Detection of Forest Disturbance With Spaceborne Repeat-Pass SAR Interferometry
Yang Lei, Richard Lucas, Member, IEEE, Paul Siqueira, Member, IEEE, Michael Schmidt, and Robert Treuhaft

Estimation of Forest Height Using Spaceborne Repeat-Pass L-Band InSAR Correlation Magnitude over the US State of Maine
Yang Lei and Paul Siqueira

A physical scattering model of repeat-pass InSAR correlation for vegetation
Yang Lei, Paul Siqueira and Robert Treuhaft

An Automatic Mosaicking Algorithm for the Generation of a Large-Scale Forest Height Map Using Spaceborne Repeat-Pass InSAR Correlation Magnitude
Yang Lei and Paul Siqueira
https://servirglobal.net/Global/Articles/Article/2674/sar-handbook-comprehensive-methodologies-for-forest-monitoring-and-biomass-estimation
You know you have arrived when you have a youtube video
Summary

• We talked about different levels of SAR data usage
• FSH requires Interferometric SAR, which can be challenging
• FSH works best with L-band HV-data collected with small spatial baseline
• Data can be found on NASA’s Alaska Satellite Facility’s DAAC
• Results shown for the US State of Maine
  • Height estimation RMSE < 4 m over 3-6 ha stands (~250 m)
  • Large-scale mosaic (11.6 million ha) created using small piece of LiDAR training samples (44,000 ha)
• Estimation error further reduced by 1) mosaicking, 2) small repeat cycle, and 3) using a large amount of LiDAR samples.
• Need to be aware of weather effects on interferometric decorrelation signature
• ISCE2 & FSH software, along with FSH demo data can be downloaded from GitHub
• We went through a "demo" for how to process data into estimates of Forest Stand Height
Questions

• Please enter your questions into the chat box
• We will post the questions and answers to the training website following the conclusion of the course
Obrigado & Felicidades!