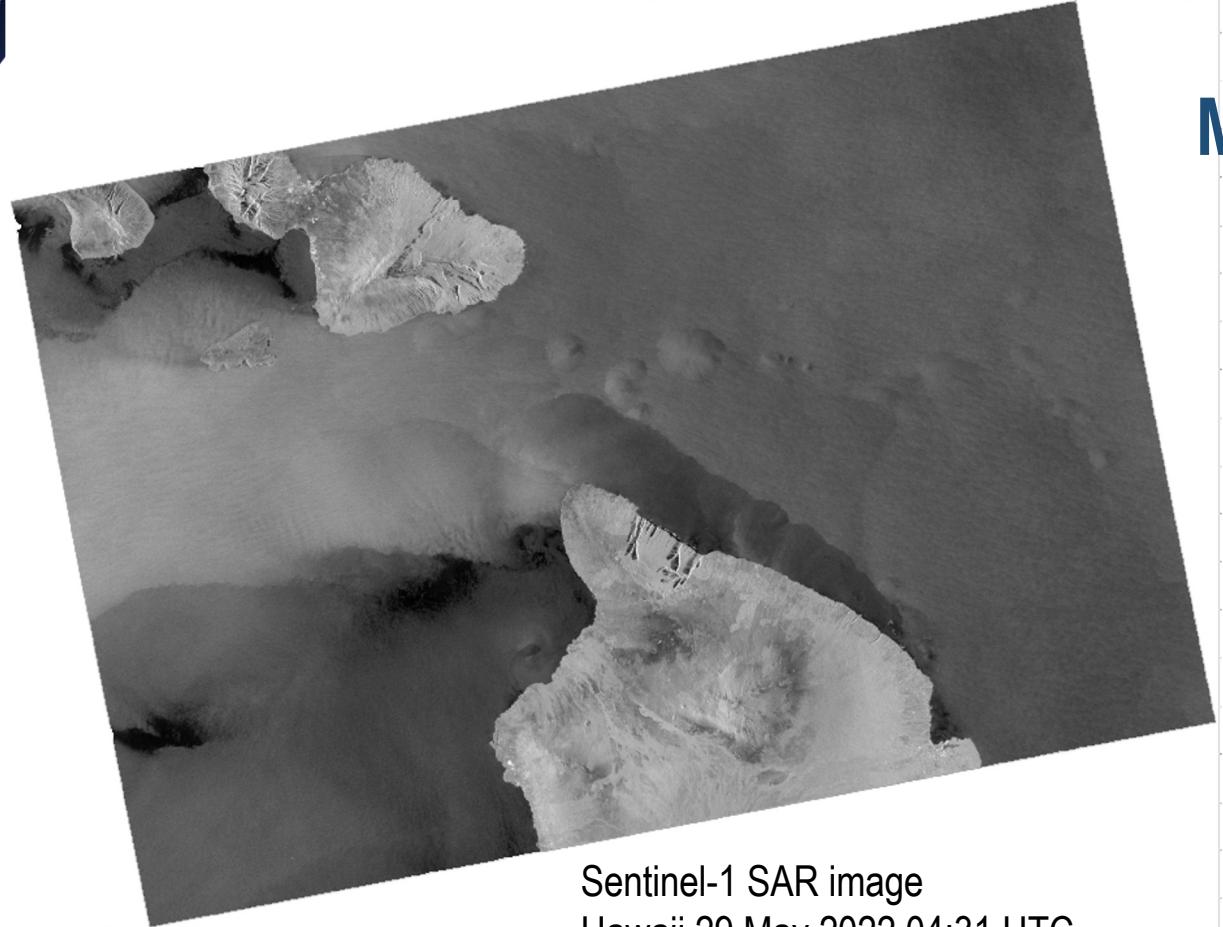


# An Overview of Synthetic Aperture Radar



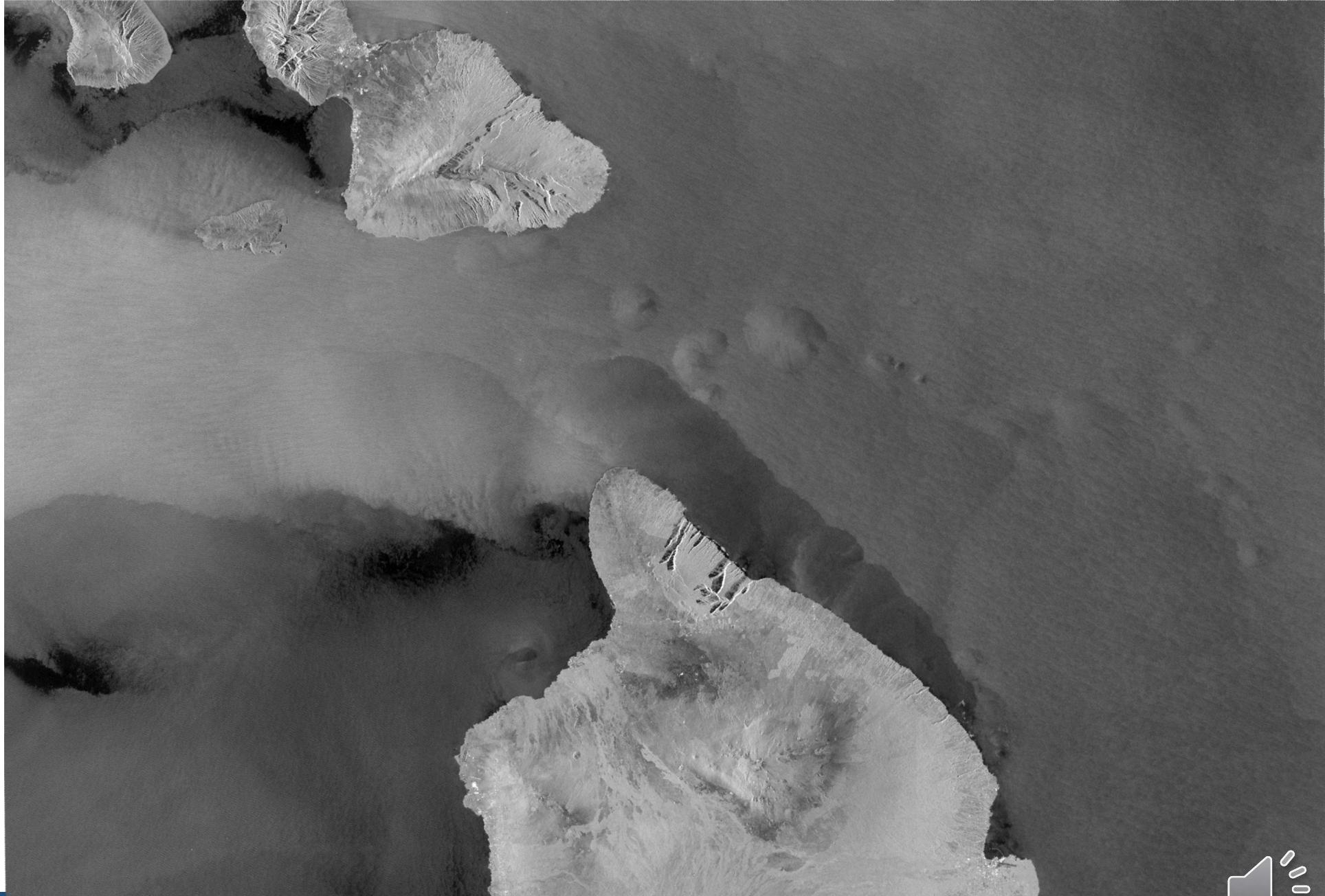
Last Updated: 1/4/2023

**Module 1: Synthetic Aperture Radar Series**  
**NOAA Coastwatch Satellite Courses**

[coastwatch.info@noaa.gov](mailto:coastwatch.info@noaa.gov)



**Sentinel-1  
C-Band VV  
image over  
Hawaii  
29 May 2022  
04:31 UTC**



# The CoastWatch Synthetic Aperture Radar instructional series

The CoastWatch Synthetic Aperture Radar (SAR) instructional series consists of three (3) training modules:

**Module 1:** An overview of SAR (this module)

**Module 2:** Descriptions of available SAR products and where to find them

**Module 3:** Examples of how various phenomena appear in SAR imagery



# Module 1: An overview of Synthetic Aperture Radar (SAR)

## Outline

Why should I care about SAR

- What can SAR measure?
- The pros and cons of using SAR

Background

- Radar and how it works
- How is SAR different from standard radar?

SAR specifications

- SAR Frequency Bands
- SAR Polarization

Overview of SAR satellite missions and products



# What can be detected by SAR?

## OCEANIC

### Surface Waves

- Significant Wave Height
- Wave Spectra

### Surfactants (Biogenic Slicks, Oil Seeps)

### Sea Ice

### Internal Waves

### Currents and Fronts

### Eddies

### Upwelling

### Underwater Topography

## ATMOSPHERIC

### Surface Wind

### Convection Cells / Rolls

### Storm Systems

### Vortex Streets

### Gravity Waves

### Rain Cells / Thunderstorms

## ANTHROPOGENIC

### Hard Targets (Ships/Oil Platforms)

### Ship Wakes

### Pollution (Oil Spills)

## COASTAL / LAND

### Flooding and Inundation

### Shorelines

### Land Use

### Land Deformation (interferometry)

### Burn Scar Identification

...there are many other applications



# The pros and cons of SAR measurements

## SAR Advantages

- Data collection is independent of lighting and cloud conditions
- Wide area coverage (100–450 km swath)
- High resolution coverage (30-100 m)
- Fine resolution is available (1m-3m)
- Many different products can be derived

## SAR Disadvantages

- Expertise is required to interpret the data
- Specialized software to read and calibrate
- Scheduled data acquisitions limit global coverage

## Traditional barriers

- Cost - free access is now available
- Difficulty in reading and interpreted data
- Irregular temporal revisit times



# What's RADAR?

The acronym RADAR stands for RAdio Detection And Ranging

- Any system that *actively* sends electromagnetic microwaves from a satellite or an aircraft (or police car) and detects the return signal

Ranging refers to measuring distance

- The distance from the sensor to the target

Radars are active instruments, sending signals to Earth's surface.

- They do not depend on solar illumination, so radar observations are possible both day and night

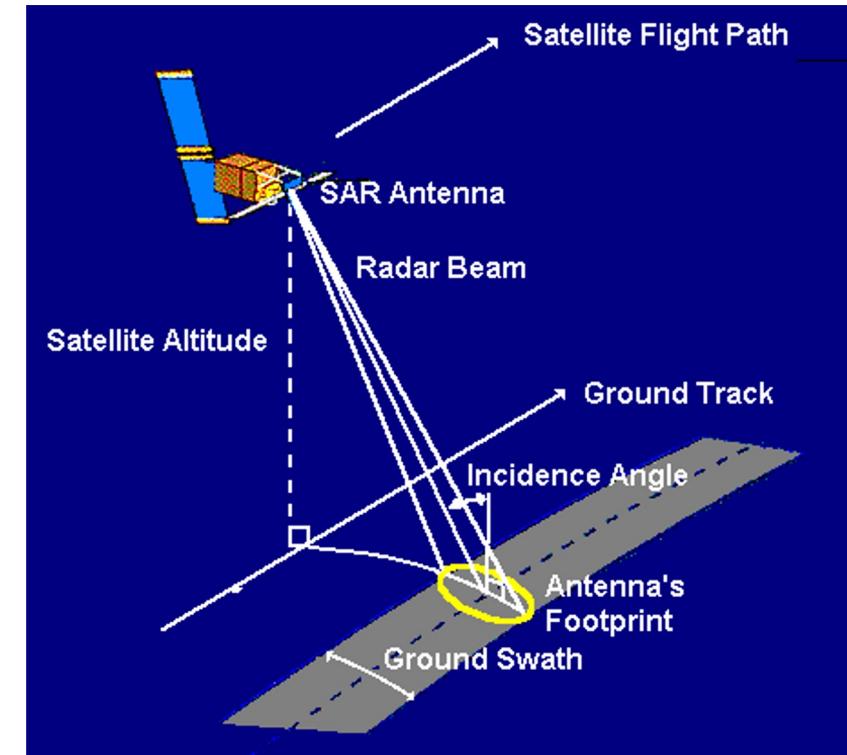
Radars use microwaves, which penetrate through clouds and rain

- Wavelengths are between a few millimeters up to 1 meter
- Radar observations are possible regardless of cloud cover



# RADAR is composed of a transmitter, a receiver, an antenna, and an electronic system

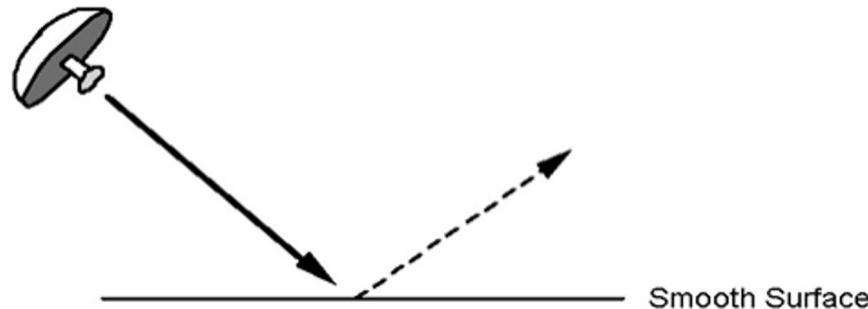
- The transmitter generates pulses of microwaves at regular intervals, which are focused by the antenna into a beam.
- The beam illuminates the surface of Earth.
- The antenna receives a portion of the transmitted signal that is reflected, or backscattered, from the Earth's surface.
- The antenna length is called the **aperture**.
- The electronic system processes and records the data.



<https://appliedsciences.nasa.gov/join-mission/training/english/arset-introduction-synthetic-aperture-radar>



# RADAR measures the portion of the transmitter radar energy that is backscattered to the antenna



Smooth surfaces scatter most of the radar energy away from the radar, so less signal is backscattered to the SAR antenna.  
These SAR images appear black.



Rough surfaces backscatter more the radar energy back to the SAR antenna.  
These SAR images appear brighter

**Normalized Radar Cross Section (NRCS)** is the measure of radar backscatter



# SAR image over the Gulf of Mexico

High backscatter (bright)

- Land, Oil Platforms

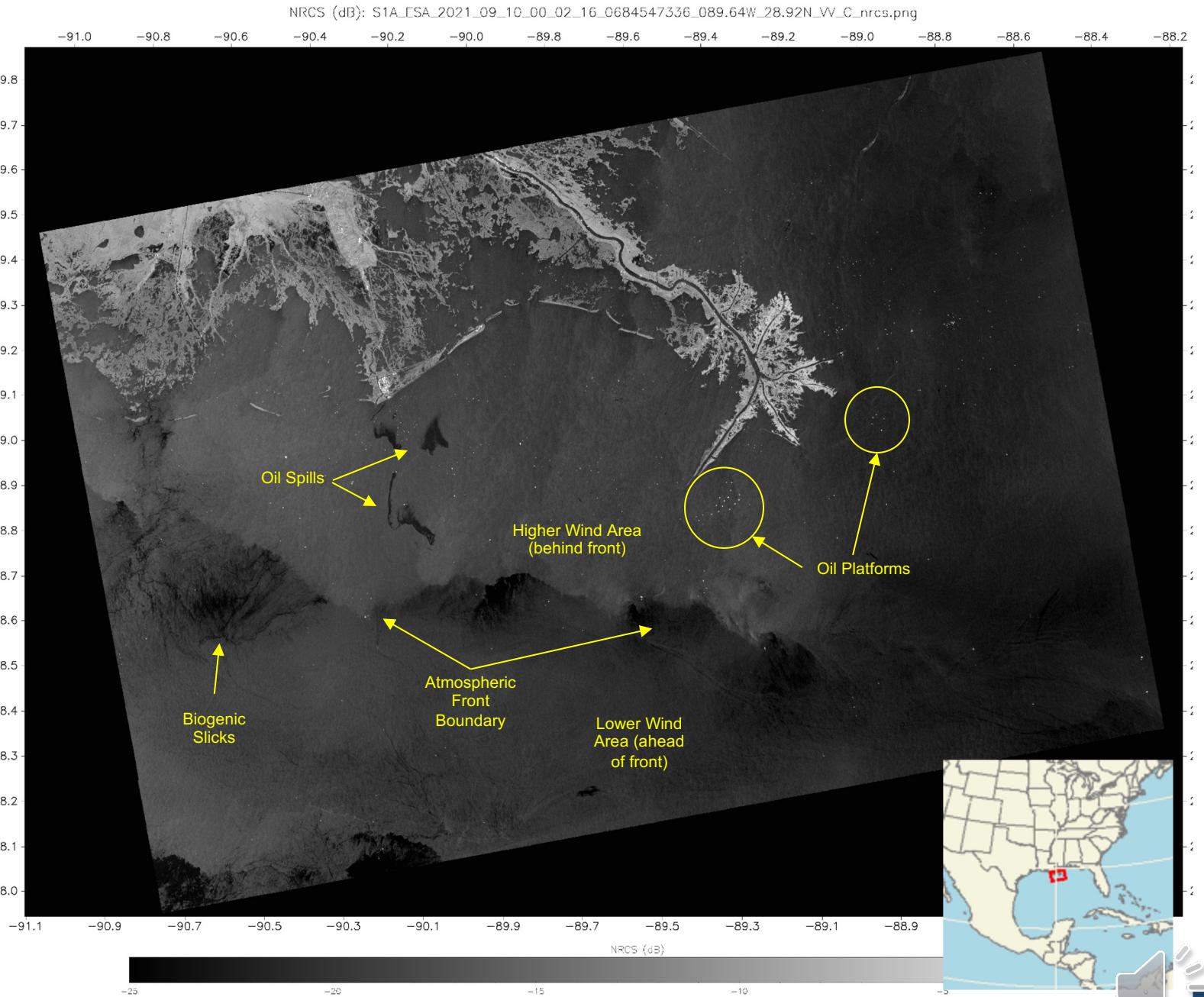
Low backscatter (dark)

- Ocean surface with oil or low winds

Moderate backscatter (gray)

- Ocean surface with moderate wind speeds (5-8 m/s)

Sentinel-1 VV SAR Image,  
10 September 2021 00:02 UTC,  
Bird's Foot Delta - Gulf of Mexico



# Components of ocean surface roughness contributing to backscatter

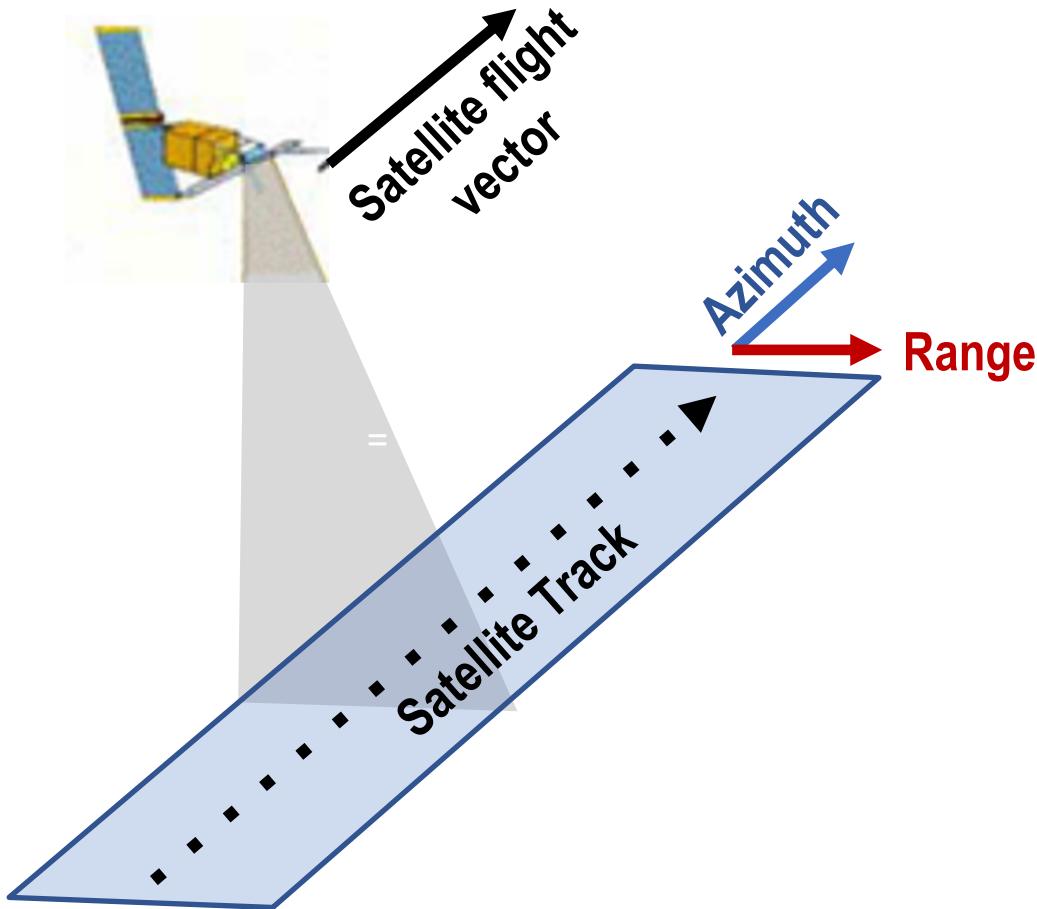
Wind-generated short waves (Capillary to short gravity waves) have wavelengths from a few centimeters to tens of centimeters and periods < 1 second

Therefore, radar wavelengths of a few centimeters are needed to observe ocean surface roughness and thereby obtain a measure of wind speed.

Longer gravity waves, currents, oil slicks, and other phenomena can be identified by the ways they affect the pattern of the wind-generated short waves.



# Antenna size and pulse bandwidth determine spatial resolution



**SAR systems are side-looking**

## Azimuth direction (along-track)

- Spatial resolution depends on the beam width
- Beam width is inversely proportional to the antenna length.
- **A longer antenna (aperture) produces a narrower beam and a finer resolution**

## Range direction (perpendicular to along-track)

- Spatial resolution depends on the bandwidth of the signal pulse
- Signal pulse length can be controlled for specific applications

Image modified from

<https://earth.esa.int/eogateway/missions/ers/radar-courses/radar-course-1>



# High-resolution radar imagery requires a very large antenna

## For a “real” aperture radar

**Range resolution is on the order of meters**

- a 100 MHz bandwidth pulse produces a resolution of ~ 1.5 meters

**Azimuth resolution is on the order of kilometers**

- a 12 meter antenna operating at 5 GHz gives a beam width of ~  $\frac{1}{4}$  degree
- At 700 km altitude this is ~3.5km on the ground

**The produce an azimuth resolution of 30 meters would require an antenna a few kilometers long**

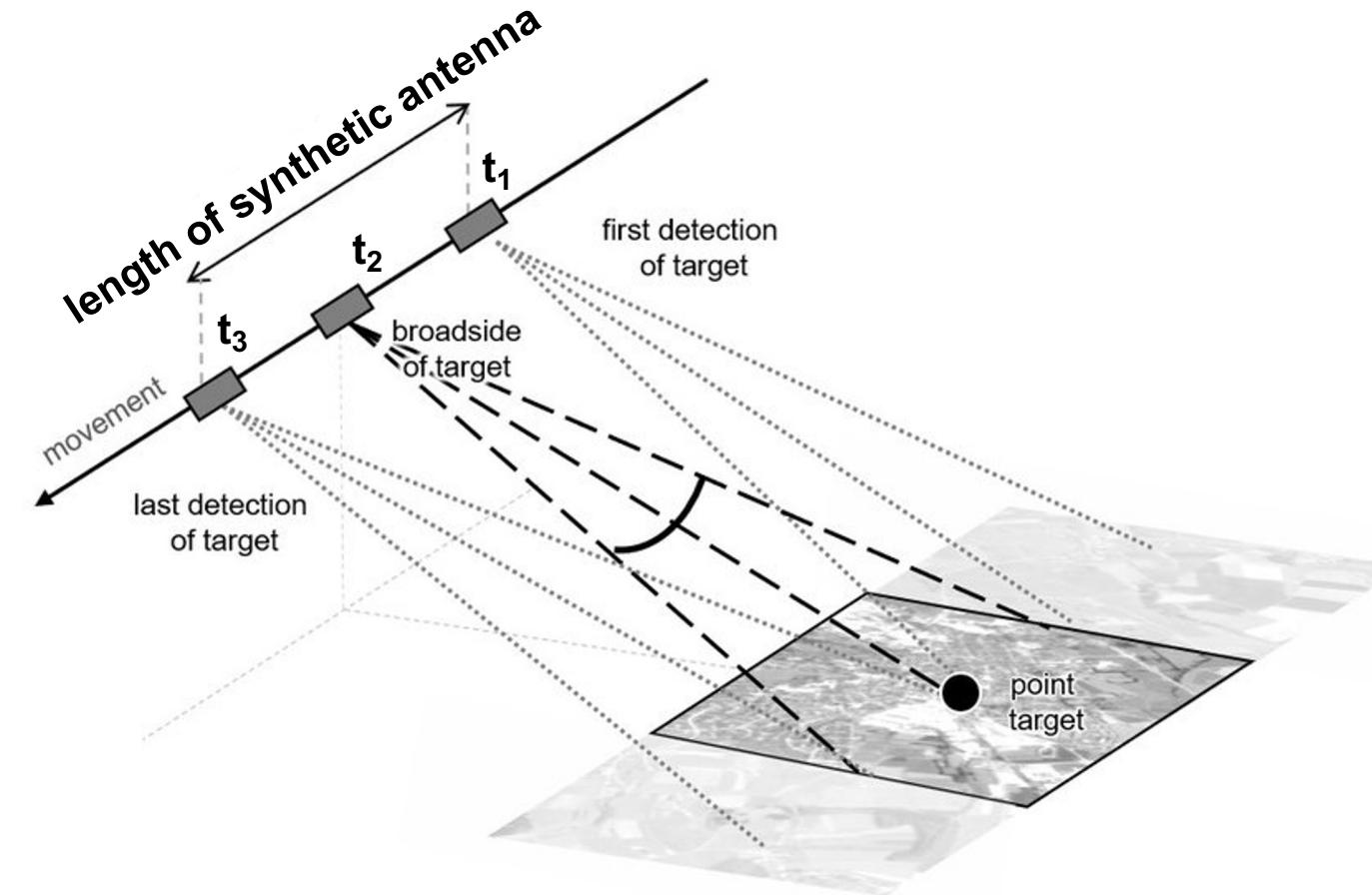
- It is not feasible to have a long (physical) antenna in space.

**In a “synthetic” aperture radar (SAR) signal processing combines many individual radar pulses to “synthesize” a larger antenna.**



# How a synthetic aperture is created

- Signals are transmitted to and received from the same object from successive sensor positions along the orbital path ( $t_1, t_2, t_3$  on the figure).
- Signals from successive sensor positions are coherently (preserved amplitude and phase) combined.
- The length of the orbit path where the object is observed is the synthetic aperture (length of the synthetic antenna).



<https://up42.com/blog/tech/sar-data-complementary-optical>

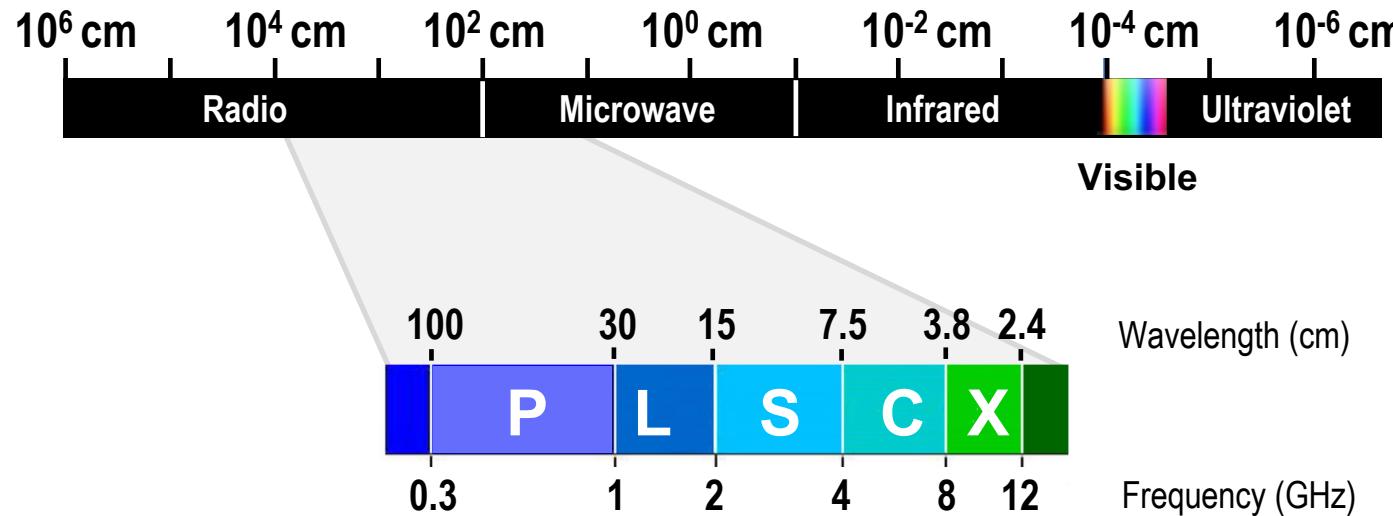


# Recap of Synthetic Aperture Radar

- SAR is an active sensor that transmits a radar pulse to the earth's surface and records the energy reflected back to the sensor (backscatter).
- The returned signals are coherently combined over a time interval to produce a 2D image of the normalized radar cross section
- The distance the radar sensor travels in this time interval is the synthetic aperture length.
- The synthetic aperture is much larger than the “real” antenna aperture allowing fine resolution in the azimuth (flight track) direction
  - Azimuth resolution is proportional to the wavelength ( $\lambda$ ) over radar aperture ( $L$ ), i.e.  $\lambda/L$
  - Range resolution is determined by the bandwidth of the radar pulse
- Radars use microwaves ( $\lambda = \text{few millimeters} - 1 \text{ meter}$ ), which penetrate through clouds and rain



# SAR wavelengths are grouped into labelled bands



Band	Frequency (GHz)	Wavelength (cm)
P	0.3-1	30-100
L	1-2	15-30
S	2-4	7.5-15
C	4-8	3.8-7.5
X	8-12	2.4-3.8

The labels were made intentionally confusing to deter spies during World War II.

from <https://www.earthdata.nasa.gov/learn/backgrounders/what-is-sar>



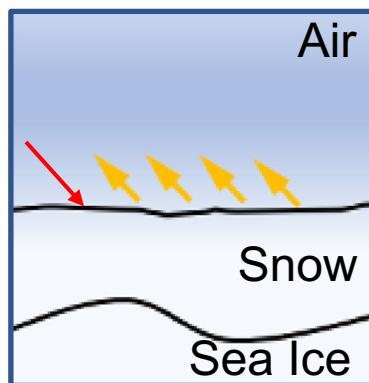
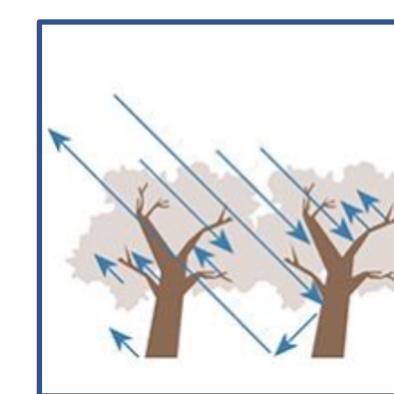
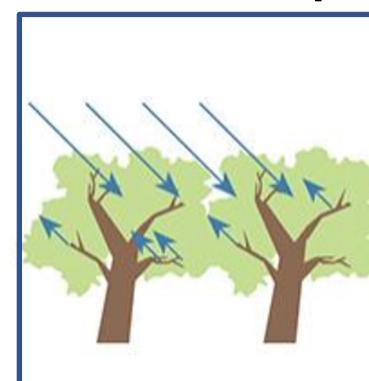
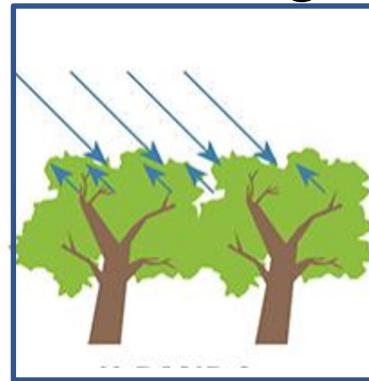
# Applications of SAR Bands

<b>Band</b>	<b>Frequency</b>	<b>Application</b>	<b>Satellite Based System</b>
X	8-12 GHz	High resolution SAR (urban monitoring, ice and snow, strong scattering from vegetation cover)	TerraSAR-X, TanDEM-X, COSMO-SkyMed, COSMO-SkyMed (2nd Gen), Iceye, Capella
C	4-8 GHz	Principle frequency for European and Canadian Systems. (ice, ocean maritime navigation)	Radarsat-2, Radarsat Constellation Mission, Sentinel-1A, ERS-1, ERS-2, Envisat ASAR, Radarsat-1, Sentinel-1B
S	2-4 GHz	Limited prior usage for earth observation.	NISAR, ALMAZ,
L	1-2 GHz	Medium resolution SAR (geophysical monitoring; biomass and vegetation mapping; high penetration)	ALOS-2, SAOCOM, NISAR, Seasat, JERS, ALOS,
P	0.3 - 1 GHz	Biomass. Vegetation mapping and assessment soil moisture	Systems in gray are no longer operational

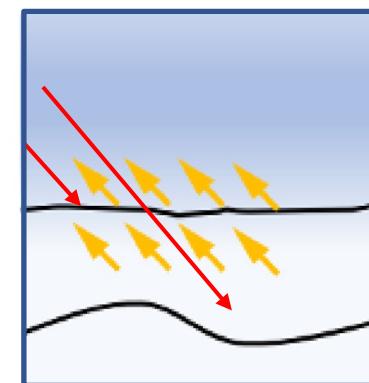


# Wavelength changes the penetration depth of the signal

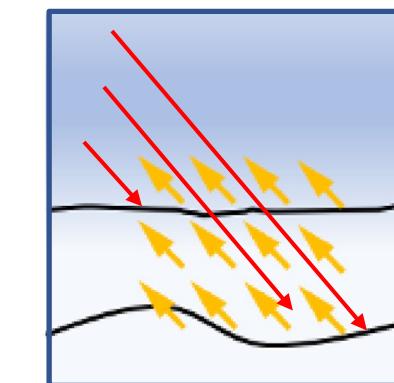
Longer wavelengths allow deeper penetration of the signal



X-Band  
( $\lambda$  ca. 3 cm)



C-Band  
( $\lambda$  ca. 6 cm)

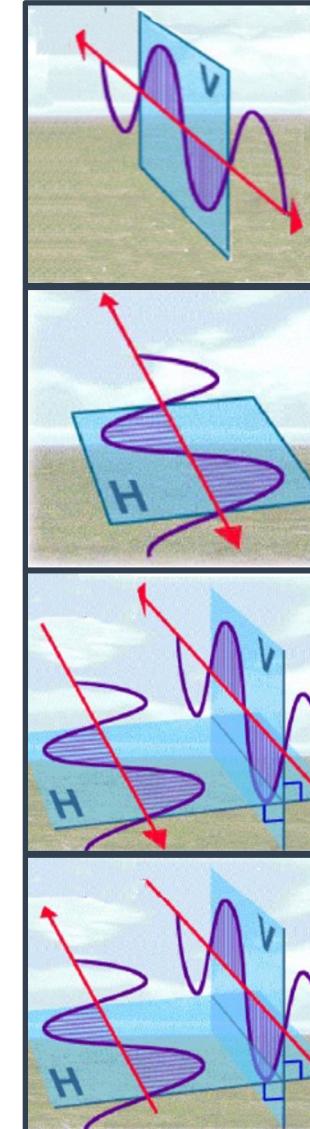


L-Band  
( $\lambda$  ca. 23 cm)



# Polarization

- Polarization refers to the orientation of the plane in which the transmitted electromagnetic wave oscillates.
- The polarization of the transmitted radar sensor beam can be precisely controlled.
- Measurement of the received signal strength in a selected plane of polarization can also be precisely controlled.
- How target surfaces interact with or change the polarization of the transmitted beam can help determine physical properties of the target surfaces.



VV: Vertical Transmit, Vertical Receive

HH: Horizontal Transmit, Horizontal Receive

HV: Horizontal Transmit, Vertical Receive

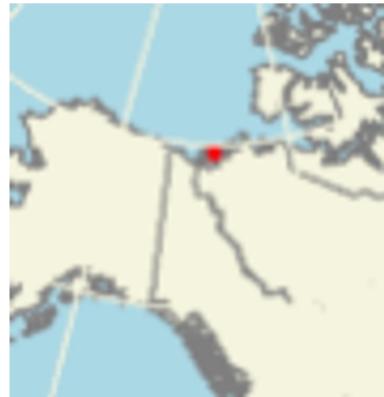
VH: Vertical Transmit, Horizontal Receive



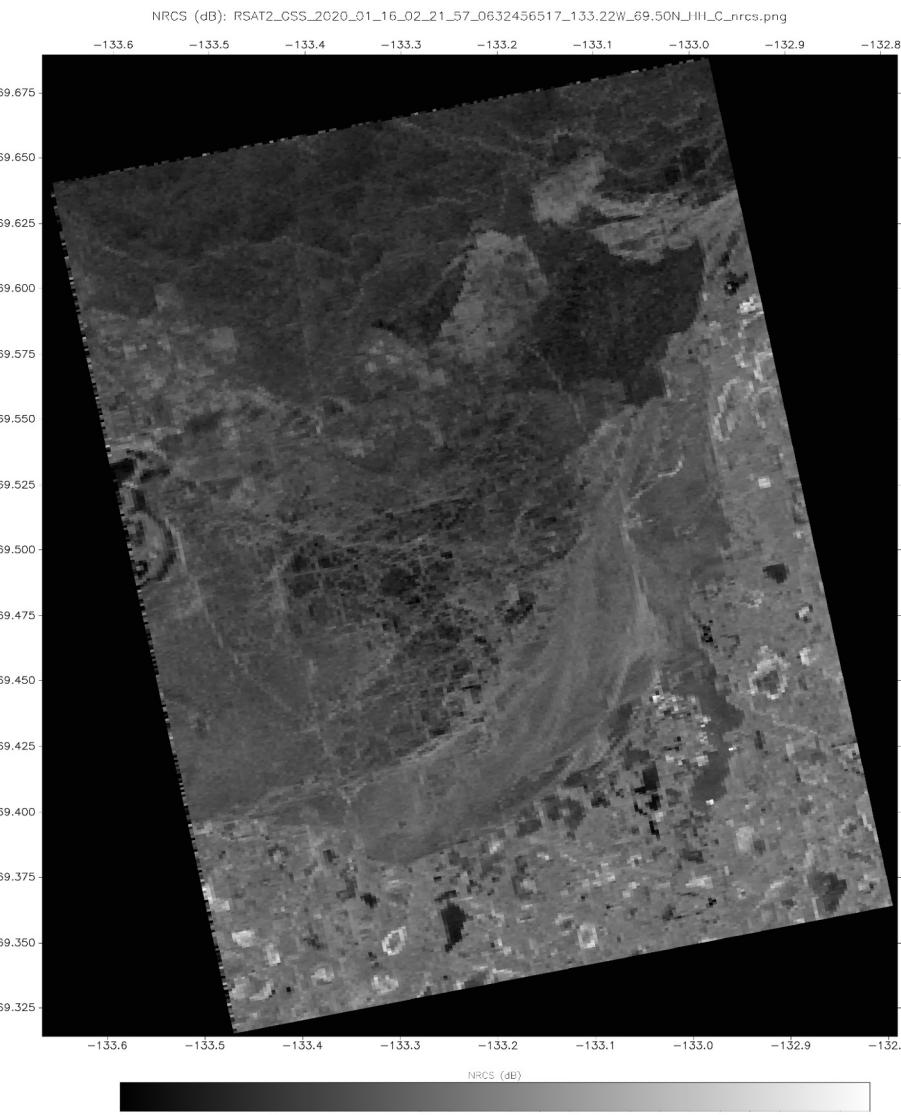
# Polarization

Radarsat-2  
16 January 2020  
02:22 UTC

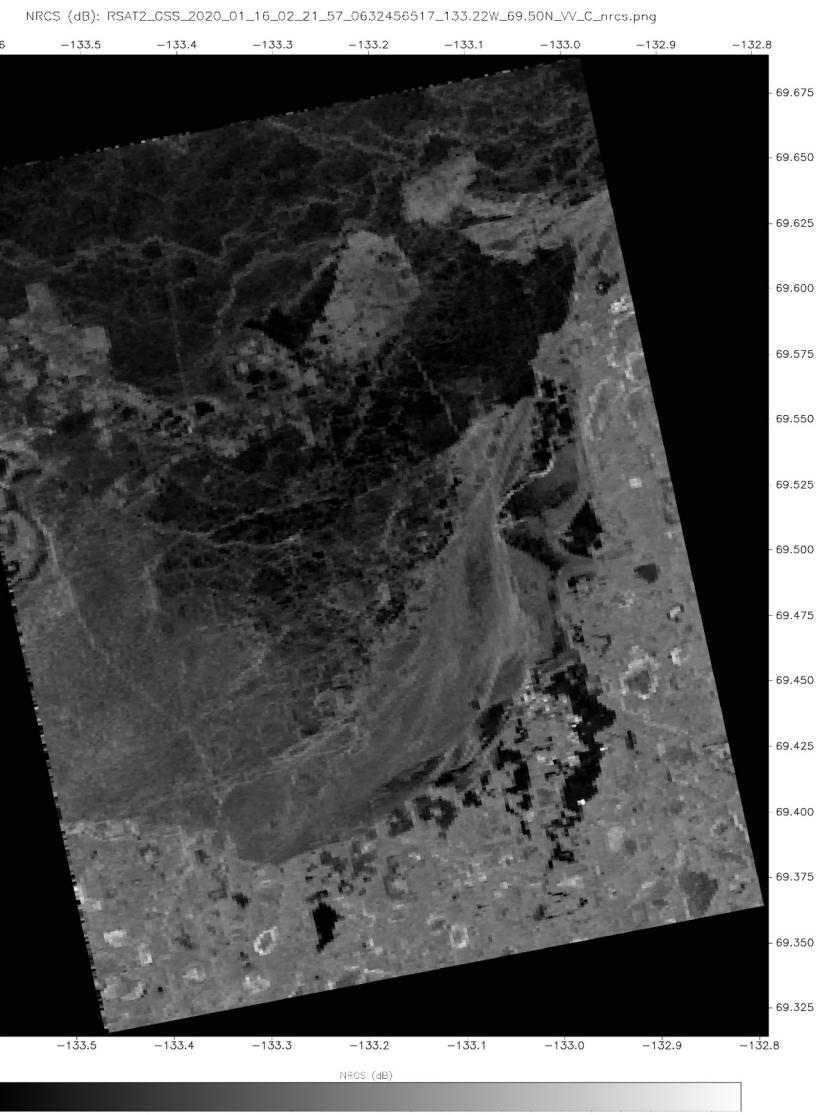
Sea Ice and  
Coastal Canada



HH Polarization



VV Polarization



RADARSAT 2 Data and Products Copyright MDA Geospatial Services Inc. 2022 All Rights Reserved  
RADARSAT is an official mark of the Canadian Space Agency  
Processed at NOAA/NFSDIS/ST/R/SOCD for National Ice Center 2022 Sep 15 03:04:42 UTC



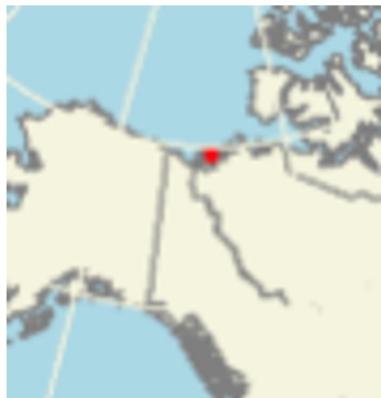
RADARSAT 2 Data and Products Copyright MDA Geospatial Services Inc. 2022 All Rights Reserved  
RADARSAT is an official mark of the Canadian Space Agency  
Processed at NOAA/NFSDIS/ST/R/SOCD for National Ice Center 2022 Sep 15 03:03:23 UTC



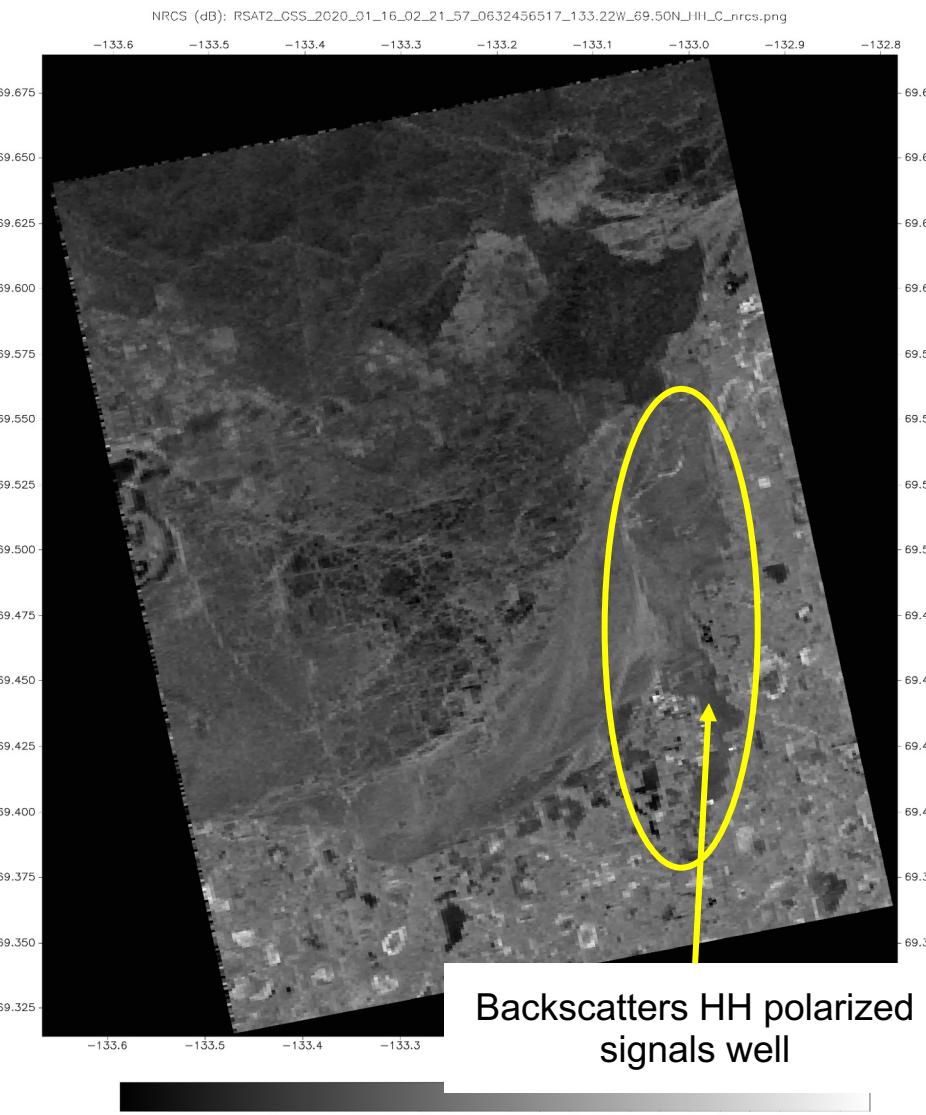
# Polarization

Radarsat-2  
16 January 2020  
02:22 UTC

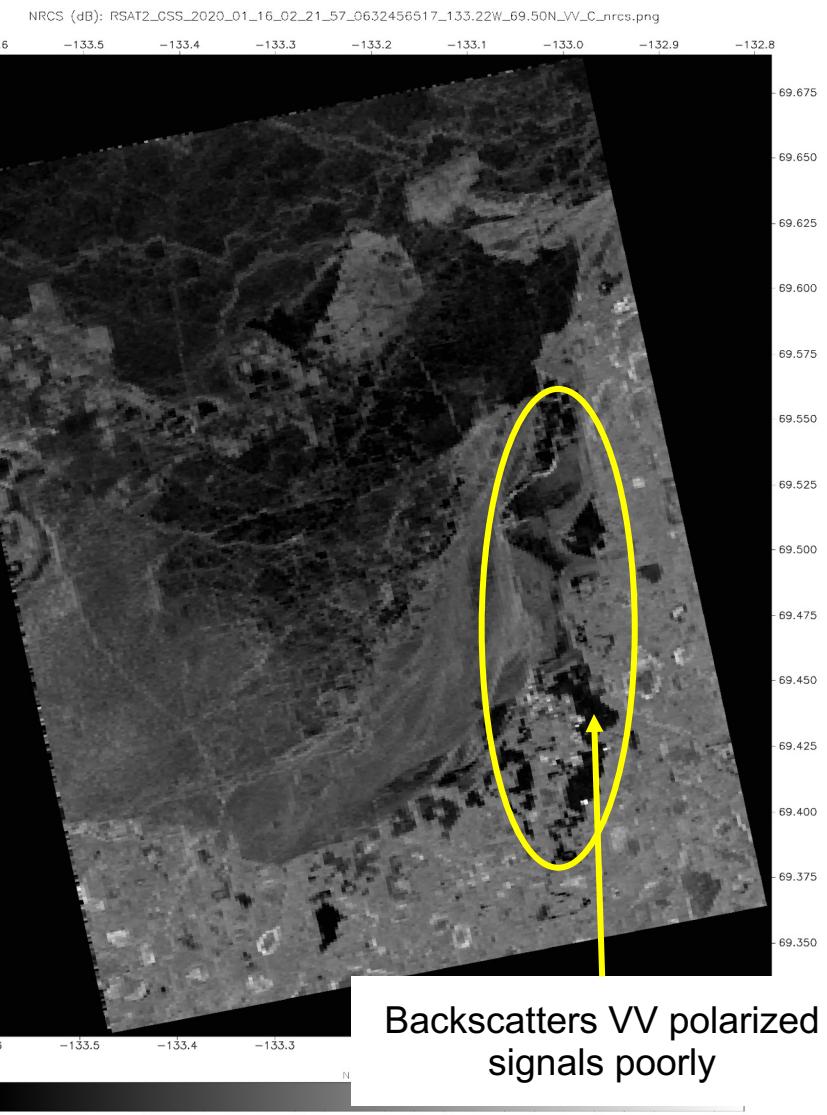
Sea Ice and  
Coastal Canada



HH Polarization



VV Polarization



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Processed at NOA/NFSDIS/ST/R/SOCD for National Ice Center 2022 Sep 15 03:04:42 UTC



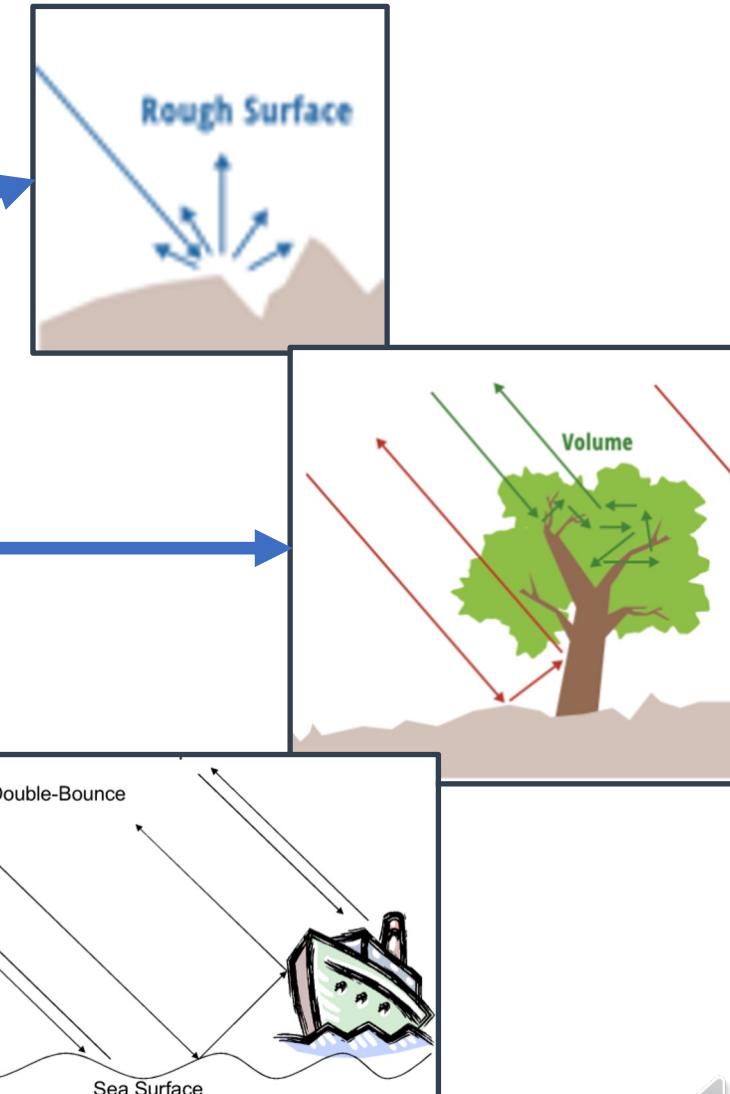
RADARSAT 2 Data and Products Copyright MDA Geospatial Services Inc. 2022 All Rights Reserved  
RADARSAT is an official mark of the Canadian Space Agency  
Processed at NOA/NFSDIS/ST/R/SOCD for National Ice Center 2022 Sep 15 03:03:23 UTC



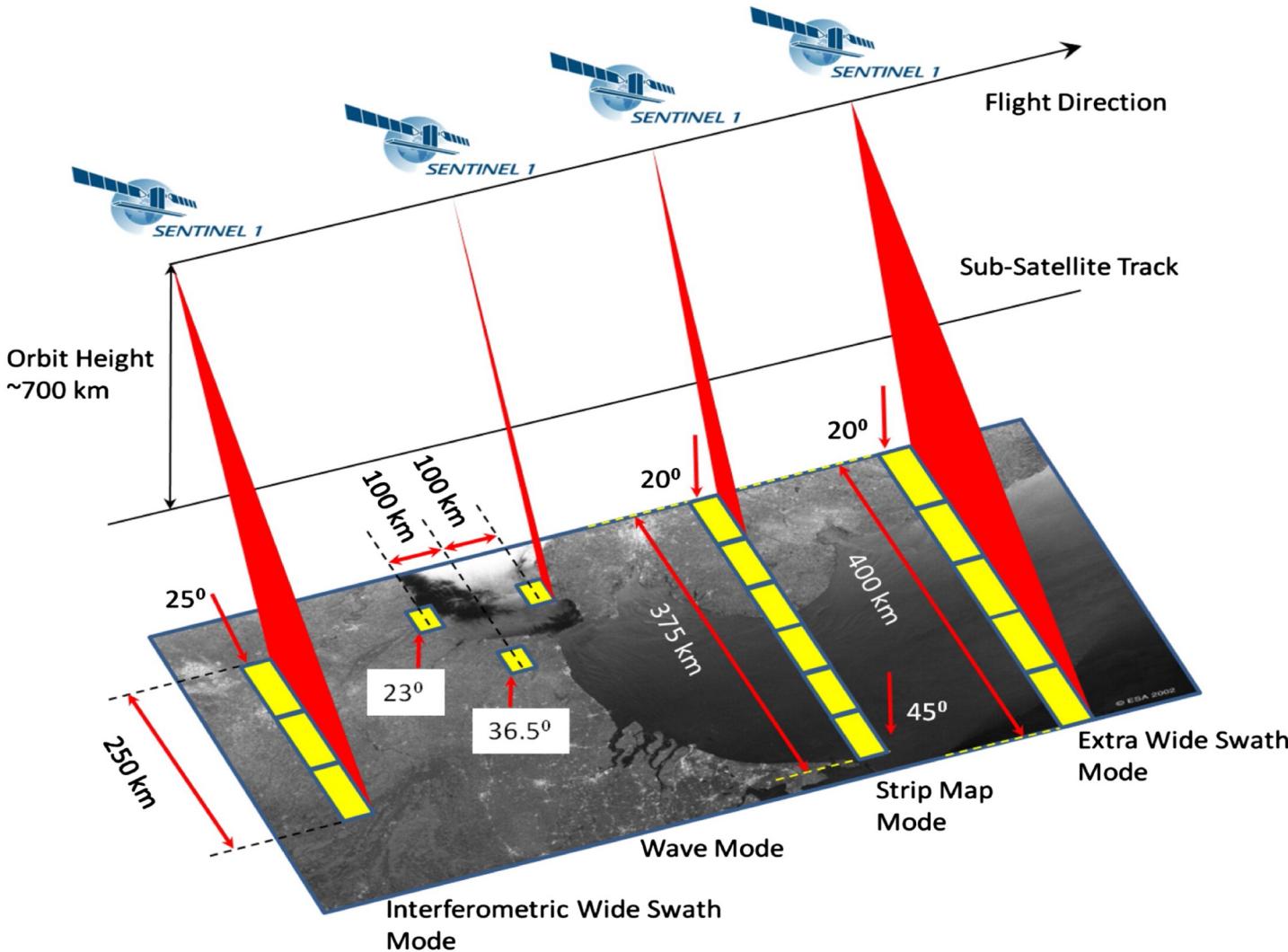
# SAR Scattering and Polarization

Examining these different polarizations carries information about the structure of the imaged surface, based on the following types of scattering and how surfaces interact with polarized beam:

- **Rough surface scattering (single bounce):**  
Sensitive to VV scattering. Used for surface wind speeds.
- **Volume (multiple bounce) scattering:**  
Volume scattering, (e.g.caused by the leaves and branches in a forest canopy) is most sensitive to cross-polarized data like VH or HV.
- **Double bounce scattering:**  
double bounce, is caused by buildings, tree trunks, or inundated vegetation and is most sensitive to an HH



# Sentinel-1 is the current generation of SAR



The latest generation of SAR have very sophisticated capabilities offering a wide variety of data collection modes

For a SAR on a polar-orbiting satellite, this imagery can have fine spatial resolution of <100 meters over a swath that can be as wide as 500 kilometers

- Tradeoffs between coverage area and resolution

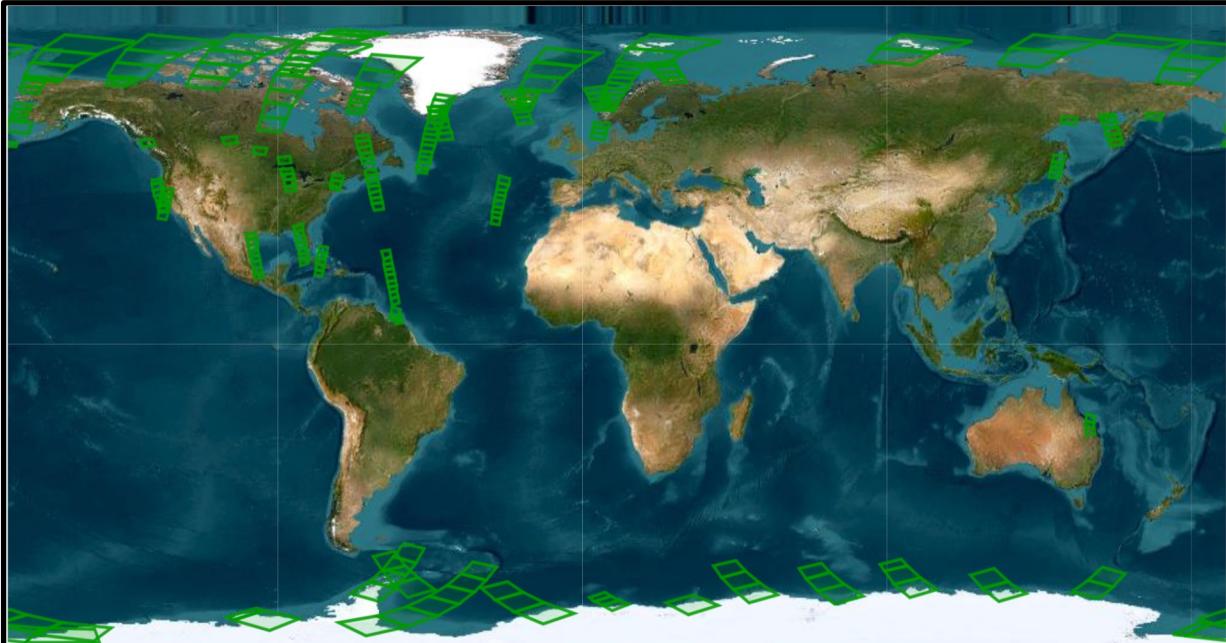
Imaging Modes for Sentinel-1

Beam Mode	Swath	Incidence Angle (deg)	Beam Information
Stripmap (SM)	80 km	18.3 - 46.8	Has 6 possible positions
Interferometric Wide (IW)	240 km	29.1 - 46	Composed of 3 sub-swath
Extra Wide Swath (EW)	410 km	18.9-47	Composed of 5 sub-swaths

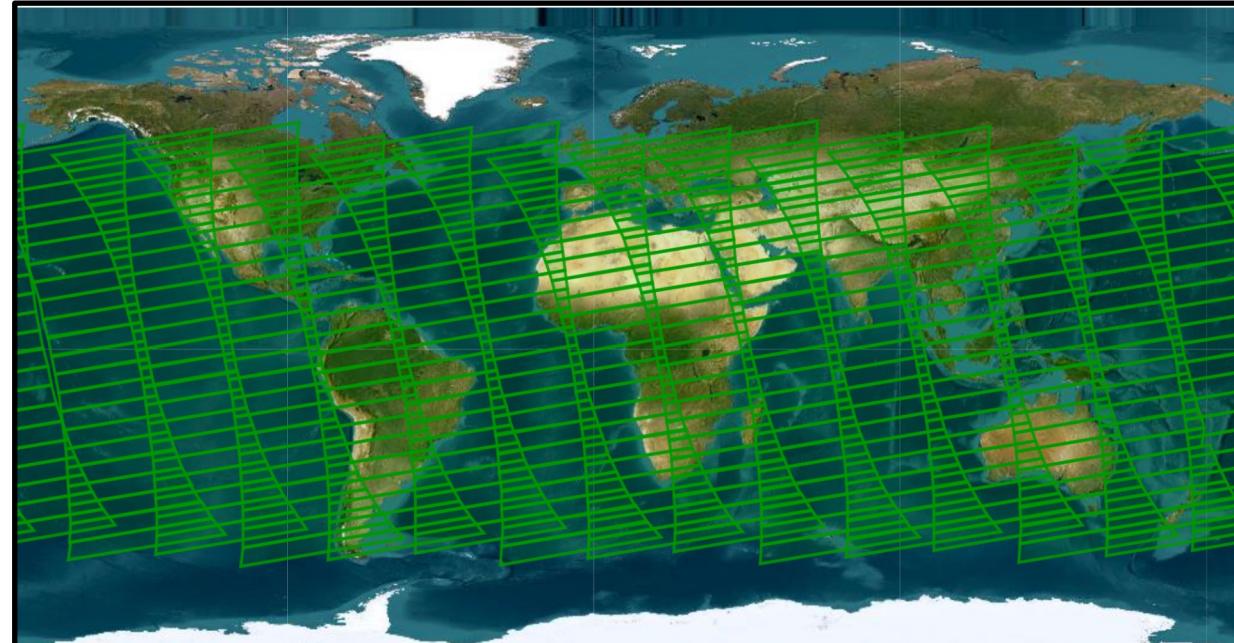


# Comparison of a Sentinel-1(SAR) and VIIRS-SNPP (Ocean Color)

Sentinel-1: Scenes collected, 29 March 2021+



VIIRS SNPP: Scenes collected, 29 March 2021\*



- SAR data is collected in small footprint over only a portion of an orbit.
- Limited by power, duty cycle and data volume

+Additional S1 scenes over Europe and Asia are not shown

\*VIIRS collections over the North and South pole are not shown

	Sentinel-1	VIIRS-SNPP
<b>Swath width</b>	40-400 km	3000 km
<b>Spatial resolution</b>	5-100 m	750 m
<b>Revisit time - Polar - Mid-latitudes</b>	<1-3 days 12 days	multiple/day 2 times/day
<b>Minutes of collection/orbit</b>	25 min	continuous
<b>Scenes/day</b>	600	240



# SAR Data at CoastWatch



Map redrawn (code:0)

Lat: 37.13, Long: -202.05 Zoom: 3  
Reference Date: 2023-01-27 (026)

CoastWatch Data Portal | Interactive search | Loaded.

Date / Calendar

Date: Jan 27, 2023  
Select an Hour: 00 minutes 00 UTC

Active Layers

Layers selected below will render in this order.  
Drag layer blocks to change stack order.  
Remove all layers

CoastWatch Data Layers

L1/L2 Spatial Search  
User drawn area to search Level-1 or -2 data

Draw: Point, Polygon, Reset

Near real-time:

- S-NPP: Ocean Color  SST
- S-20: Ocean Color  SST
- S-1A: NRCS  NRCS Cross-pol
- S-1B: NRCS  NRCS Cross-pol
- S-2A: True Color  MCI
- S-2C: True Color  MCI
- S-3A: Ocean Color  MCI
- S-3B: Ocean Color  MCI

Science Quality / RAN / Delayed:

- S-NPP: Ocean Color  SST

Search Results

Reference Layers

The map displays various satellite imagery layers, including Sentinel-1 SAR imagery, over the continental United States and the Arctic region. The SAR imagery is represented by dark, textured patches against a lighter background. The map interface includes a date and time selector, active layer management, and a spatial search function. A legend on the left identifies the different data sources and their properties. A yellow circle highlights the 'NRCS' option for the S-1A sensor in the 'Near real-time' dropdown menu.

Sentinel-1 SAR imagery (since 2018) around the U.S. and the Arctic are available at CW  
The data are in NetCDF format and can be previewed with PNG images

[https://coastwatch.noaa.gov/cw\\_html/cwViewer.html](https://coastwatch.noaa.gov/cw_html/cwViewer.html)



# SAR Data at Alaska Satellite Facility

The screenshot shows the ASF Data Search interface. At the top, there are navigation links for NASA EARTHDATA, Other DAACs, Feedback, and Sign in. The main search area includes fields for Search Type (Geographic Search), Dataset (Sentinel-1), Start Date (1/27/2023), End Date (1/27/2023), Filters, and a SEARCH button. It also displays 1,000 of 595 Files. Below the search bar is a map of the world with many blue rectangular overlays representing search results. The map includes labels for countries like Russia, Canada, United States, Mexico, and many others. A search bar at the top right says "Search all ASF". At the bottom, there are buttons for 595 Scenes (595 of 595 Files), Zoom, Queue, and On Demand. A file path S1A\_IW\_GRDH\_1SDV\_20230128T04441... 491F and a timestamp January 28 2023 04:44:10Z are shown at the bottom left.

- The Alaska Satellite Facility Data Archive host data from a variety of SAR sensors (Sentinel-1, ALOS-1, ERS).
  - The data are available in a variety of formats
  - Specialized software is needed to read the native data formats
  - Requires registration with NASA (free) to download the imagery.

<https://search.asf.alaska.edu/#/>



# Sentinel-1 Data at ESA's Copernicus Scientific Data Hub

The screenshot shows the Copernicus Open Access Hub interface. On the left, there is a search sidebar with advanced search filters for Sensing Date (Descending), Sensing period (2023/01/27 to 2023/01/27), Ingestion period (empty), and Mission selection (Sentinel-1, Sentinel-2, Sentinel-3). The main area features a world map with numerous red rectangular overlays representing Sentinel-1 imagery coverage. These overlays are concentrated over North America, Europe, and parts of Africa and Asia. The map also displays country names and city labels.

<https://scihub.copernicus.eu/dhus/#/home>

- Sentinel-1 imagery are available at the Copernicus Scientific Data Hub.
- The data are available in the S1 native format (xml/geotiff)
- Requires registration to download the imagery.



# SNAP Toolbox for SAR data

Here you can download the latest installers for SNAP and the Sentinel Toolboxes.

Data provision is available to all users via the [Sentinel Data Hub](#).

### Current Version

The current version is 9.0.0 (29.06.2022 15:00 UTC).

For detailed information about changes made for this release please have a look at the release notes of the different projects: [SNAP](#), [S1TBX](#), [S2TBX](#), [S3TBX](#), [SMOS Box](#), [PROBA-V Toolbox](#)

We offer three different installers for your convenience. Choose the one from the following table which suits your needs. During the installation process, each toolbox can be excluded from the installation. Toolboxes which are not initially installed via the installer can be later downloaded and installed using the plugin manager. Please note that SNAP and the individual Sentinel Toolboxes also support numerous sensors other than Sentinel.

If you previously used SNAP before, we recommend uninstalling the older SNAP version before installing the latest version.

<https://step.esa.int/main/download/snap-download/>

- SNAP will read the native format of most SAR system
- Users can calibrate and manipulate the data (sub-set or composite)



# References and other online trainings

- <https://www.star.nesdis.noaa.gov/socd/mecb/sar/publications.html>
- <https://ntrs.nasa.gov/api/citations/20190002563/downloads/20190002563.pdf>
- <https://www.earthdata.nasa.gov/learn/backgrounders/what-is-sar>
- <https://earth.esa.int/eogateway/missions/ers/radar-courses/radar-course-1>
- <https://appliedsciences.nasa.gov/join-mission/training/english/arset-introduction-synthetic-aperture-radar>
- <https://eo-college.org/courses/echoes-in-space/>



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**Module 1:** An overview of SAR (this module)

**Module 2:** Descriptions of available SAR products and where to find them  
(in development)

**Module 3:** Examples of how various phenomena appear in SAR imagery  
(in development)

