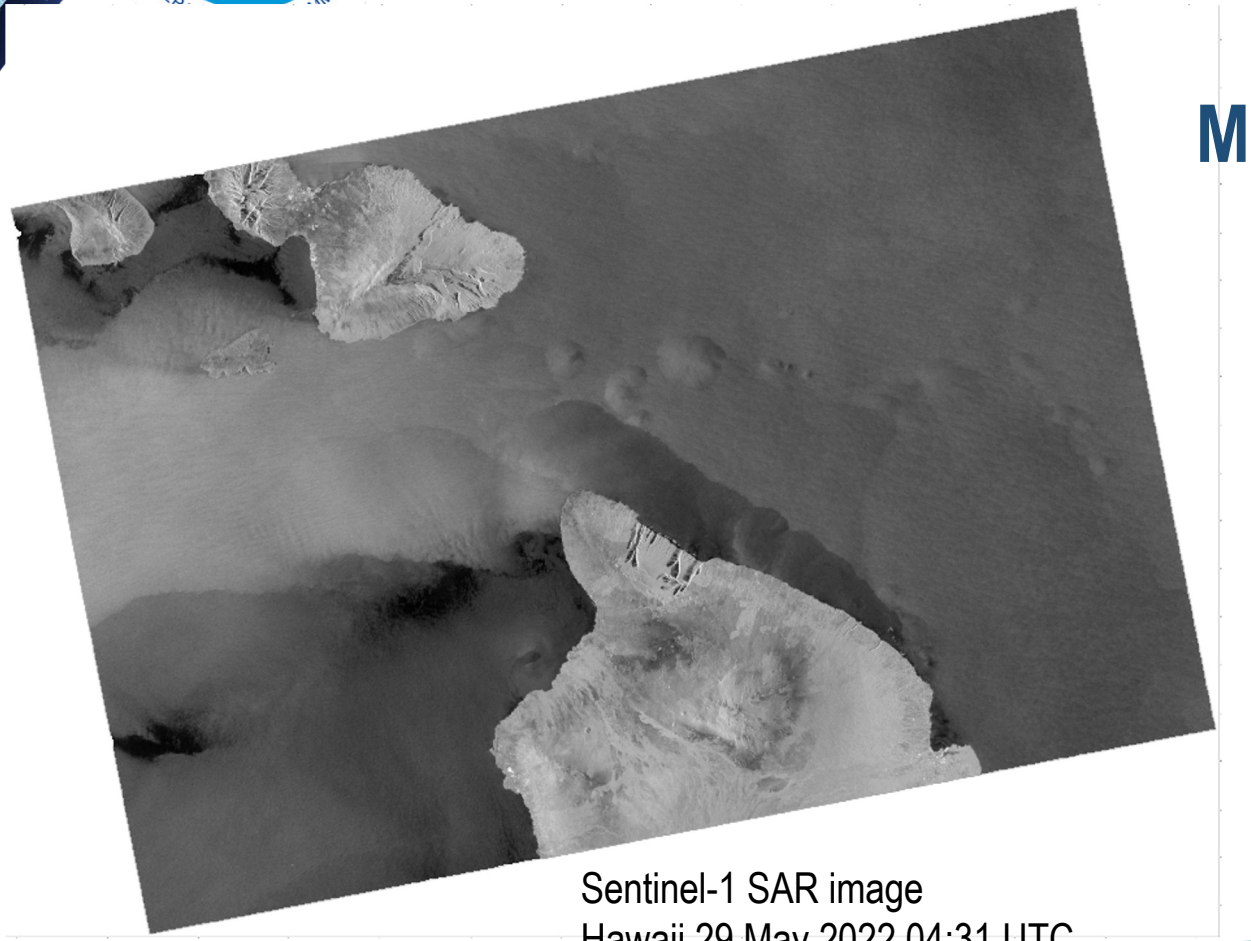
An Overview of Synthetic Aperture Radar



Sentinel-1 SAR image
Hawaii 29 May 2022 04:31 UTC

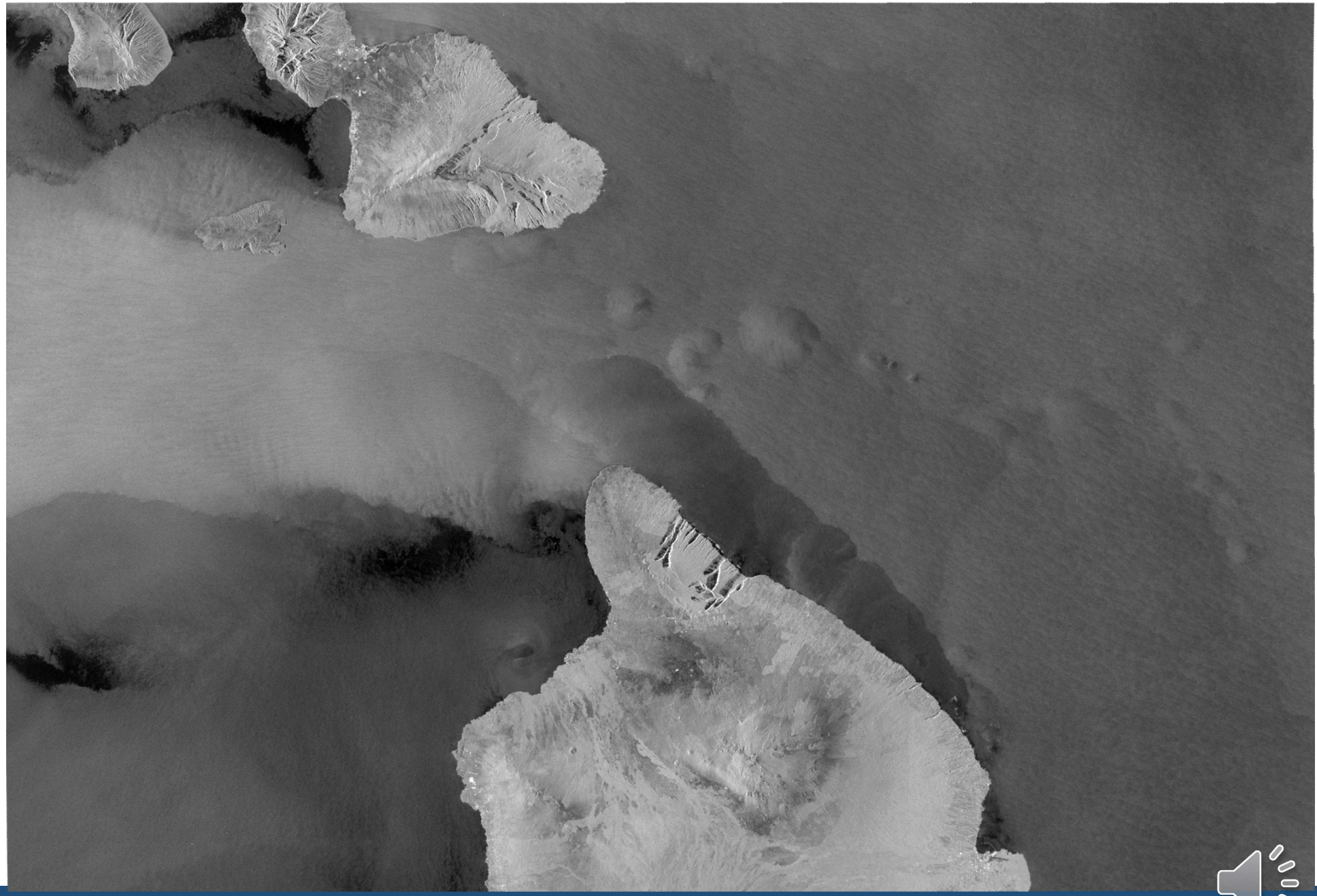
Module 1: Synthetic Aperture Radar Series

NOAA Coastwatch Satellite Courses

Last Updated: 1/4/2023

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.

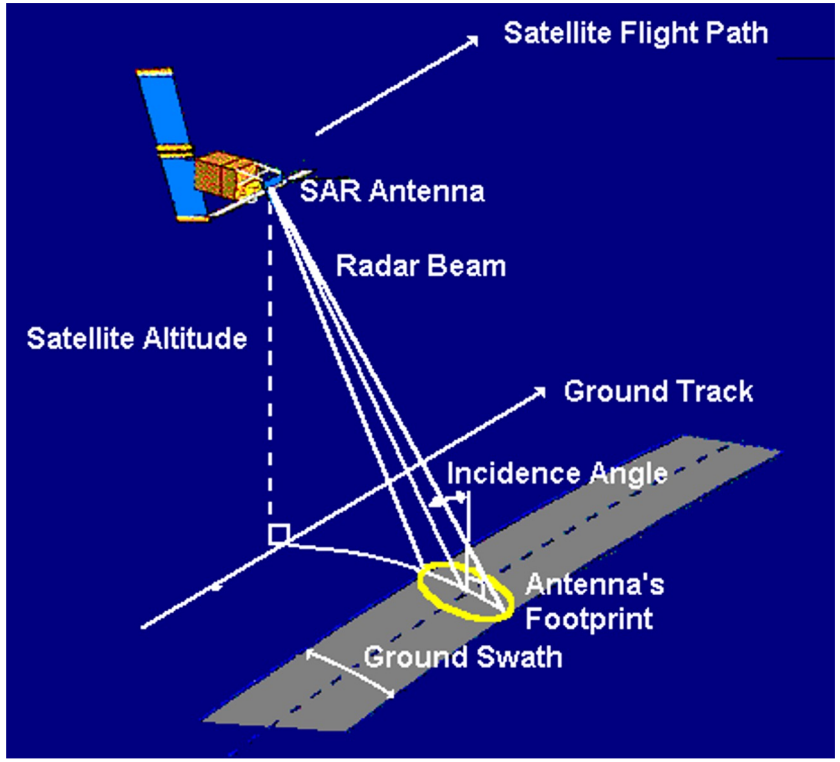
- They do not depend on solar illumination, so radar observations are possible both day and night

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

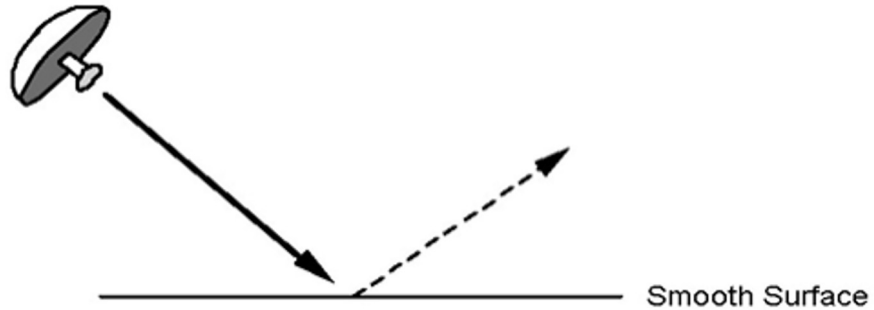
RADAR is composed of a transmitter, a receiver, an antenna, and an electronic system

- 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

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

SAR image over the Gulf of Mexico

High backscatter (bright)

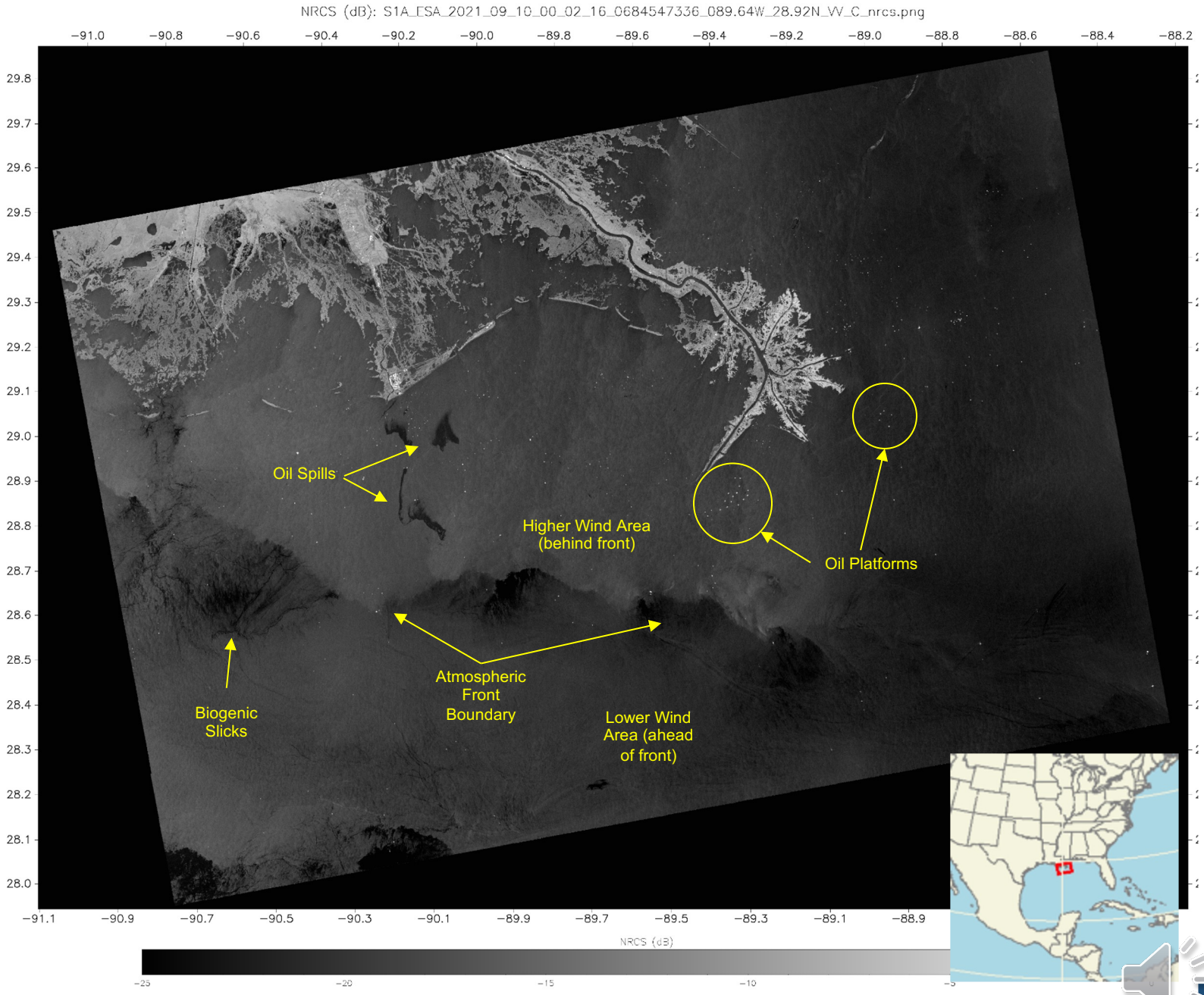
- Land, Oil Platforms

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

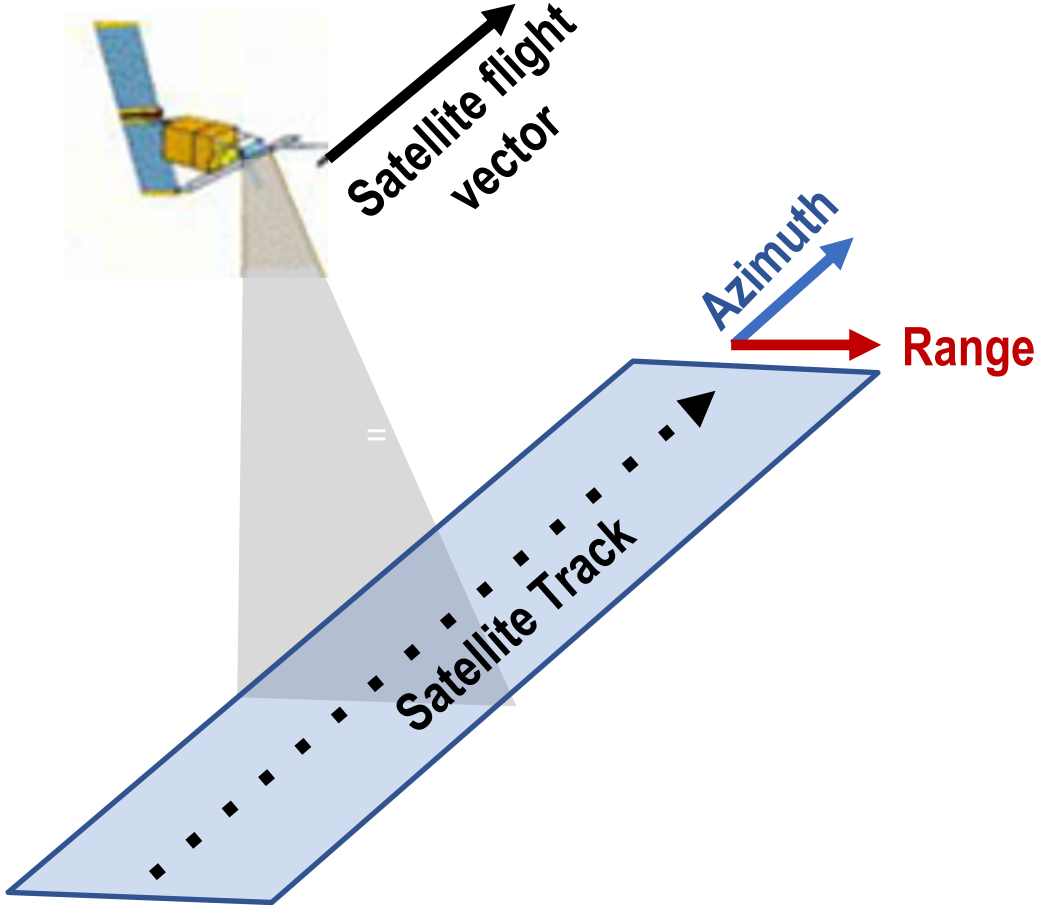
Components of ocean surface roughness contributing to backscatter

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

Image modified from
https://earth.esa.int/eogateway/missions/ers/radar-courses/radar-course-1

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

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 ~ ¼ degree
- At 700 km altitude this is ~3.5km on the ground

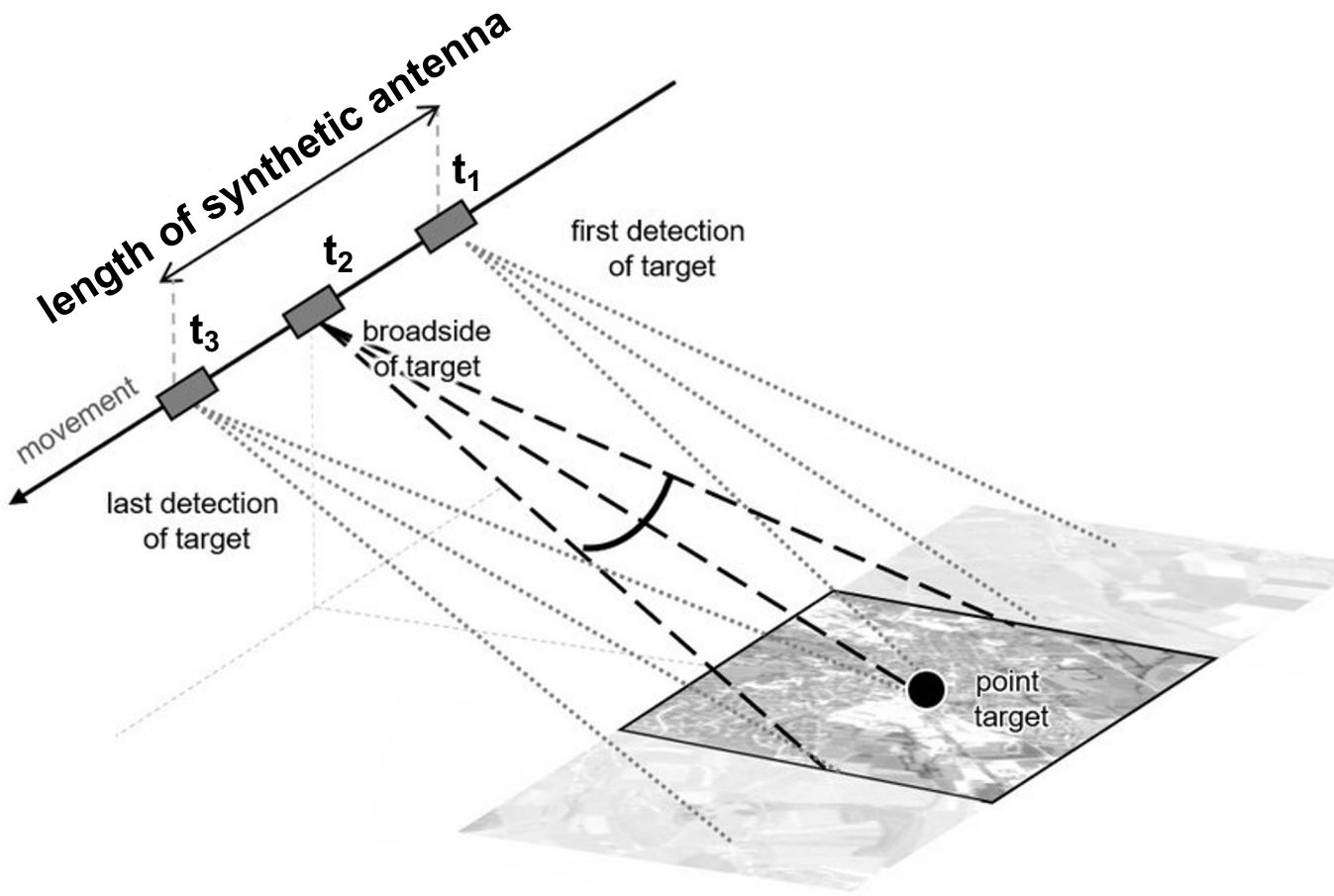
The produce an azimuth resolution of 30 meters would require an antenna a few kilometers long

- 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 (t1, t2, t3 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).

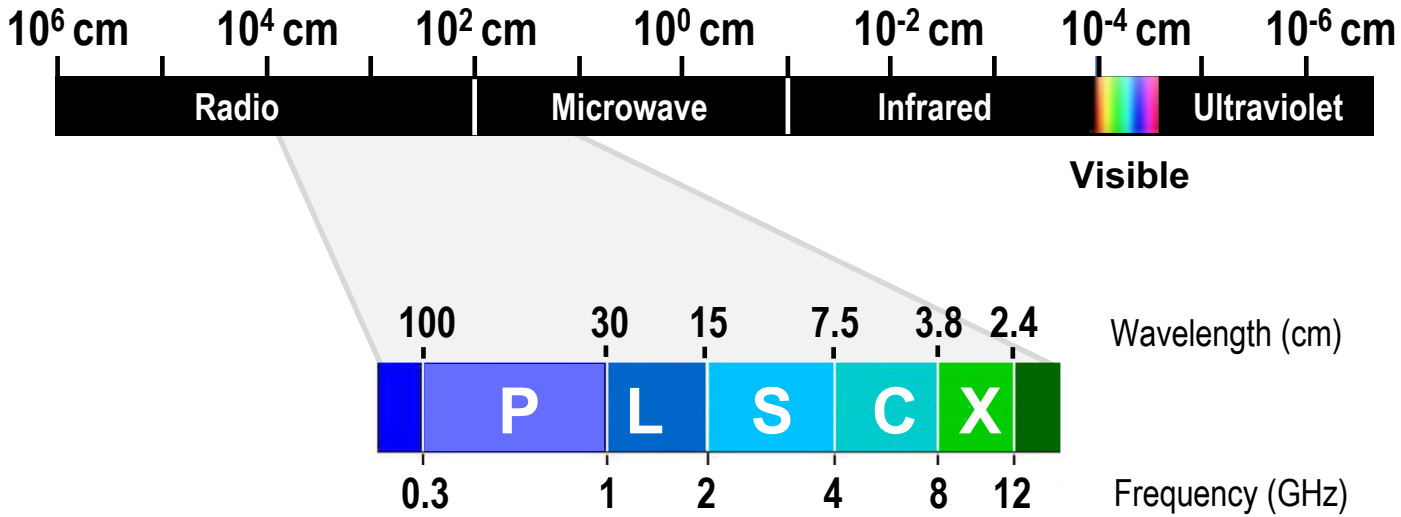


https://up42.com/blog/tech/sar-data-complementary-optical

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 (λ) over radar aperture (L), i.e. λ/L
  - Range resolution is determined by the bandwidth of the radar pulse
- Radars use microwaves (λ = few millimeters - 1 meter), which penetrate through clouds and rain

SAR wavelengths are grouped into labelled bands



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

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

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

≠–

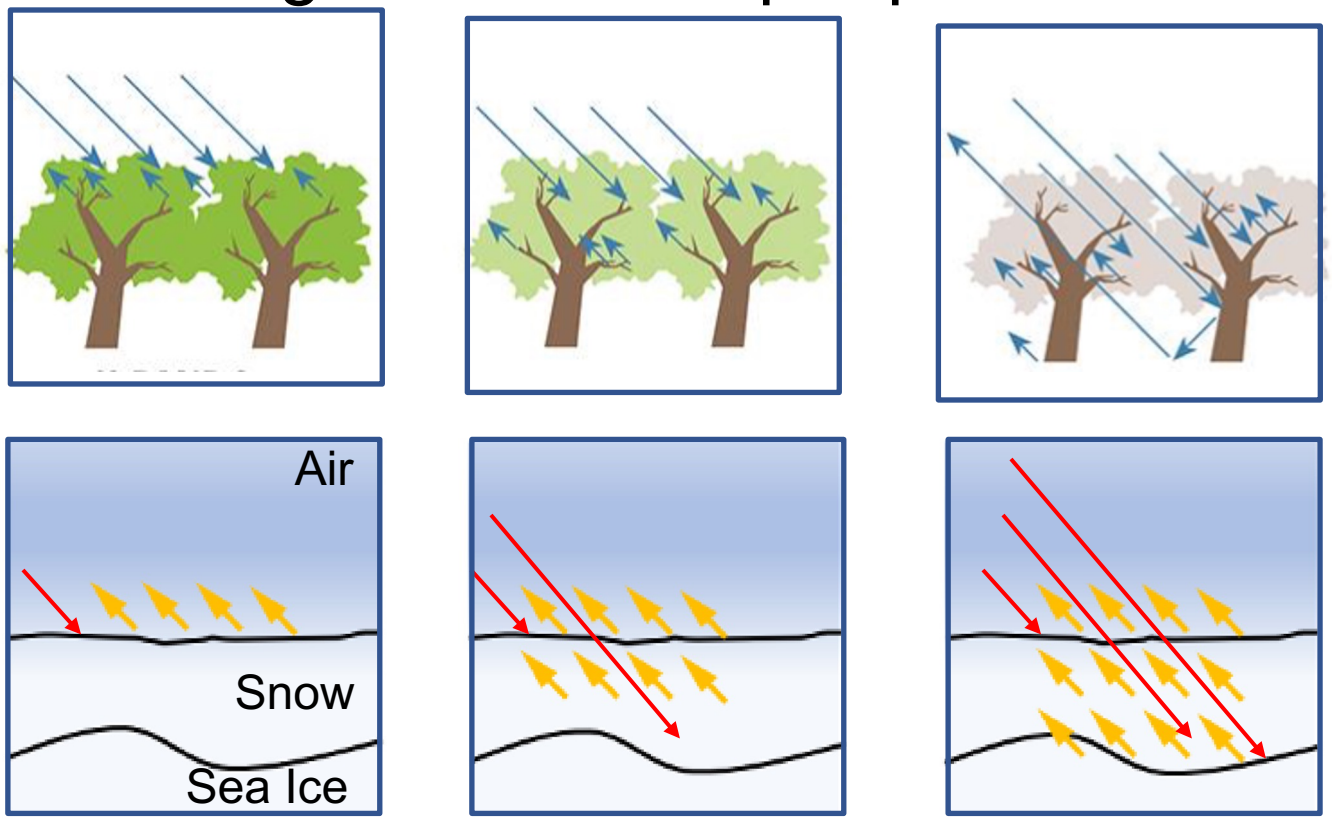
Applications of SAR Bands

Band	Frequency	Application	Satellite Based System
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

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

Wavelength changes the penetration depth of the signal

Longer wavelengths allow deeper penetration of the signal



X-Band
(λ ca. 3 cm)

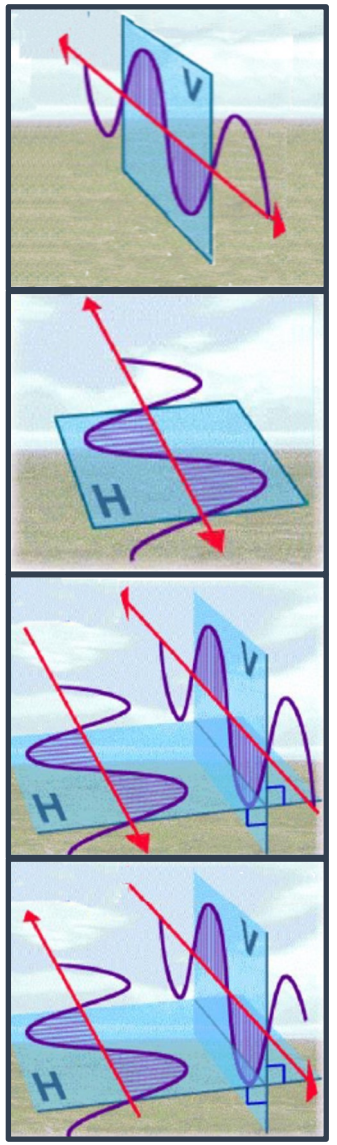
C-Band
(λ ca. 6 cm)

L-Band
(λ ca. 23 cm)

https://elib.dlr.de/145667/1/Master_Thesis_Galassi_20210629_Signed.pdf

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

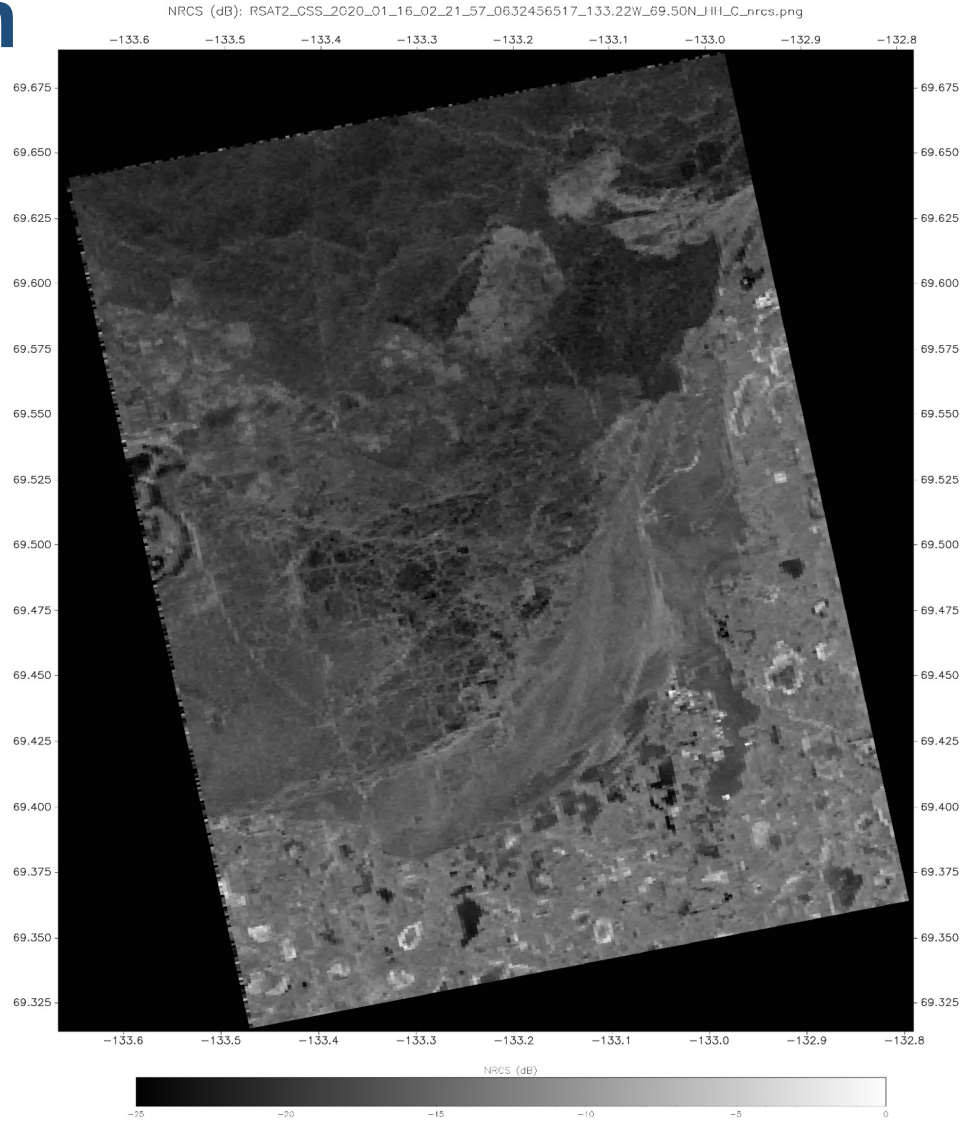
VH: Vertical Transmit, Horizontal Receive

Polarization

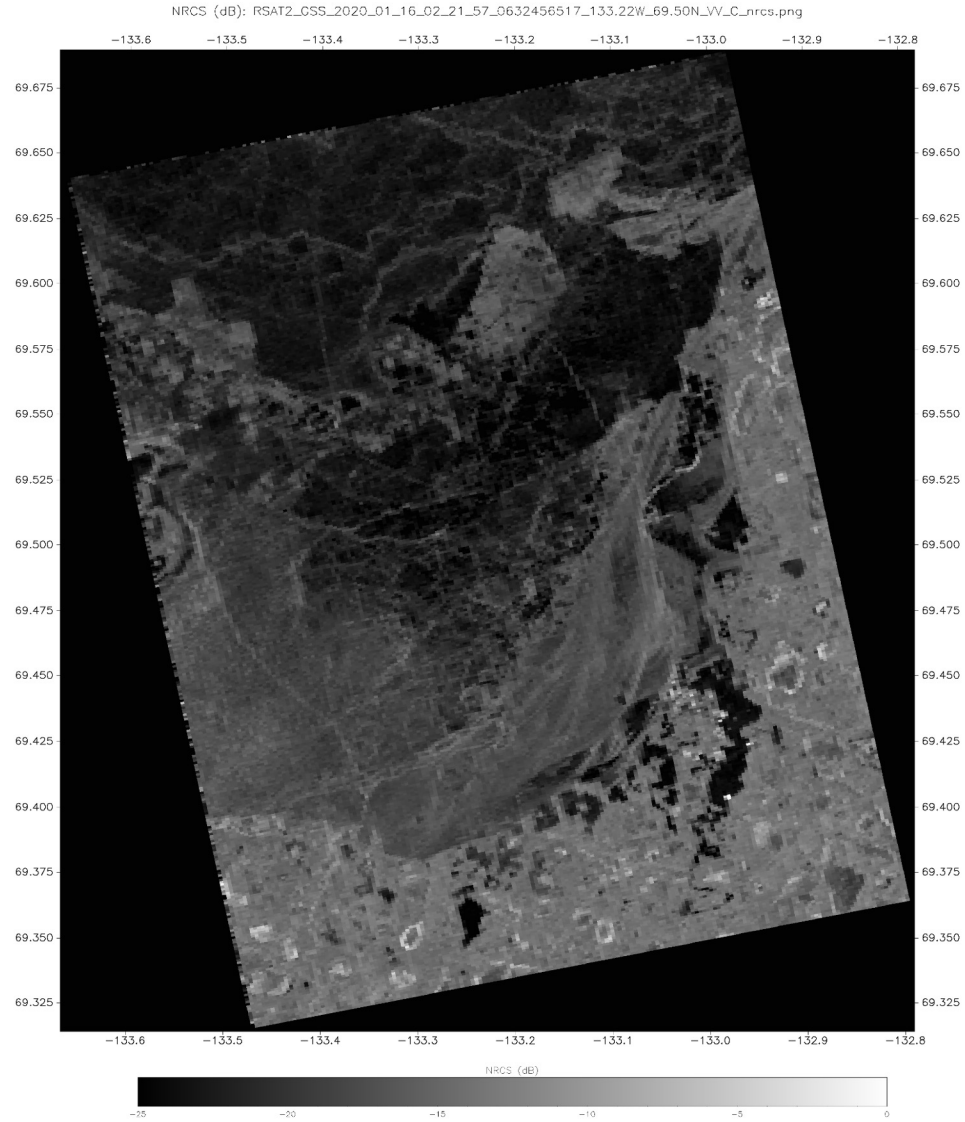
Radarsat-2
16 January 2020
02:22 UTC

Sea Ice and
Coastal Canada

HH Polarization



VV Polarization



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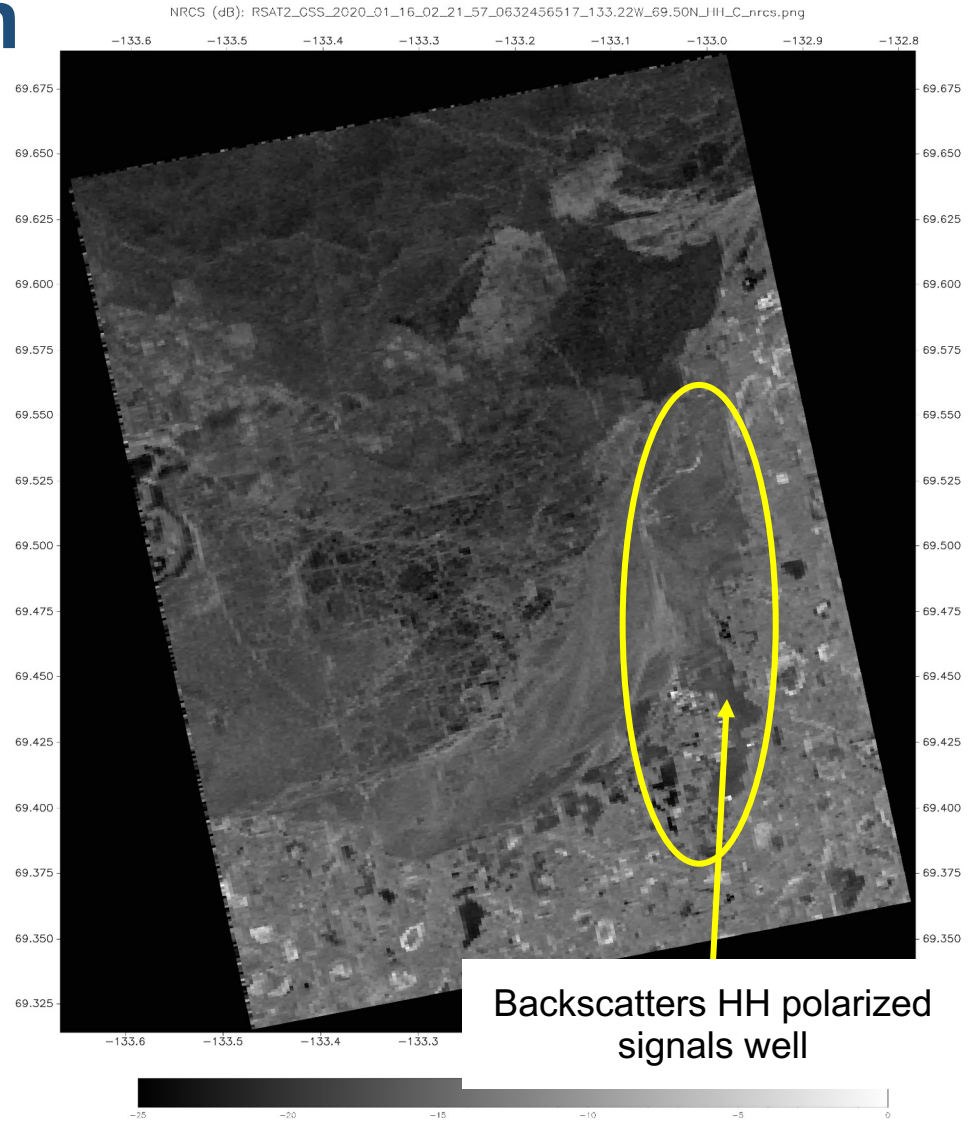
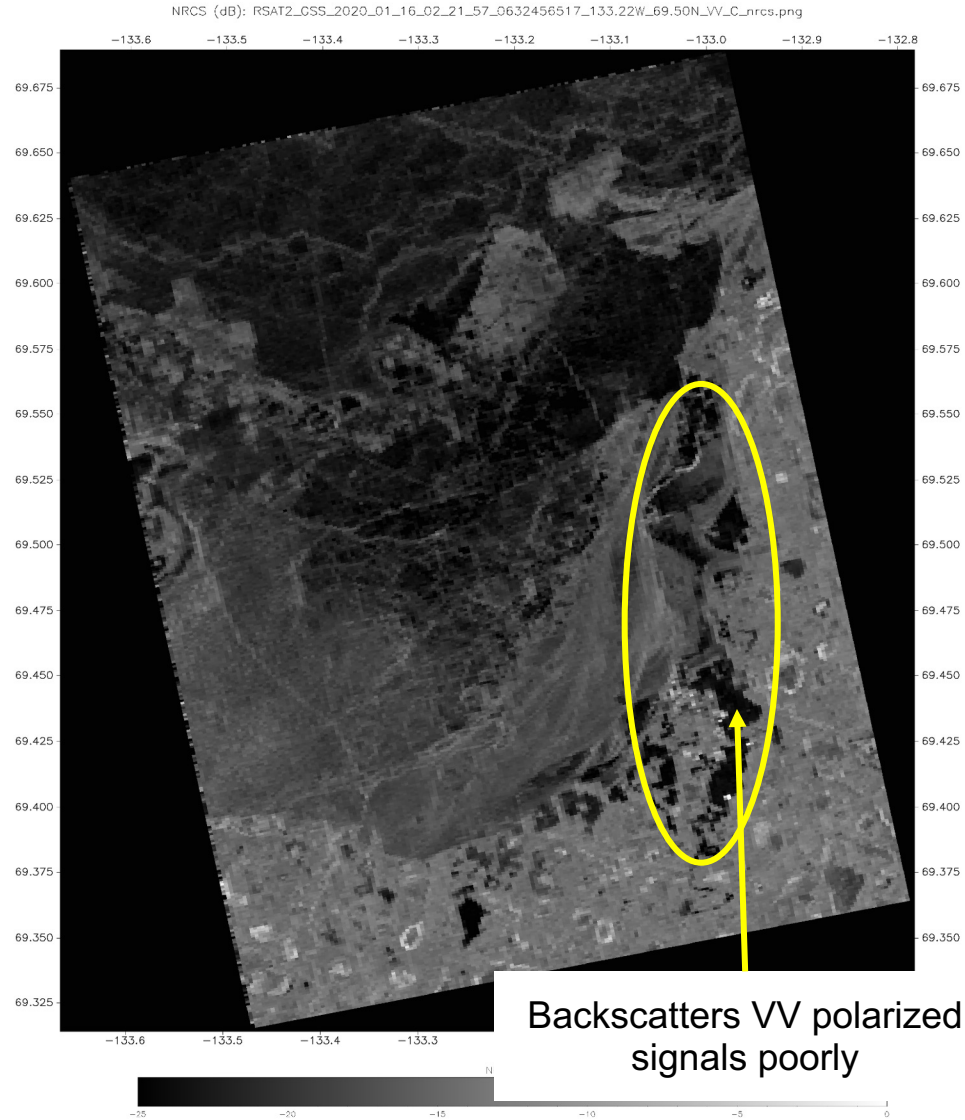


Backscatters HH polarized signals well

VV Polarization

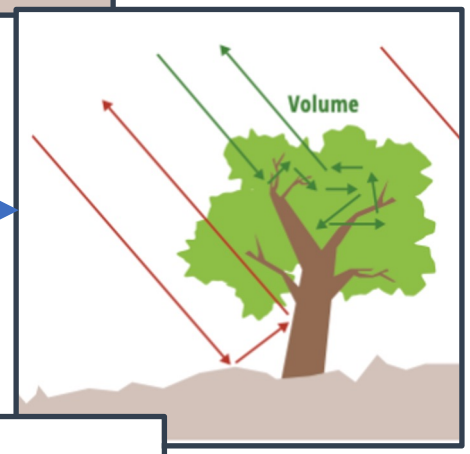


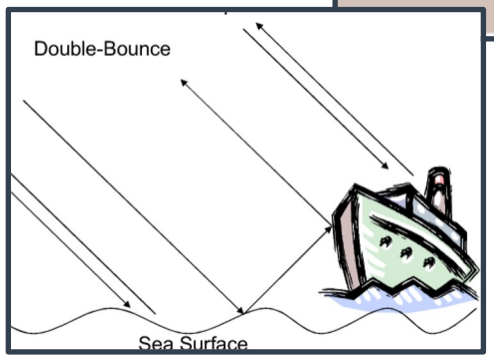
Backscatters VV polarized signals poorly

SAR Scattering and Polarization

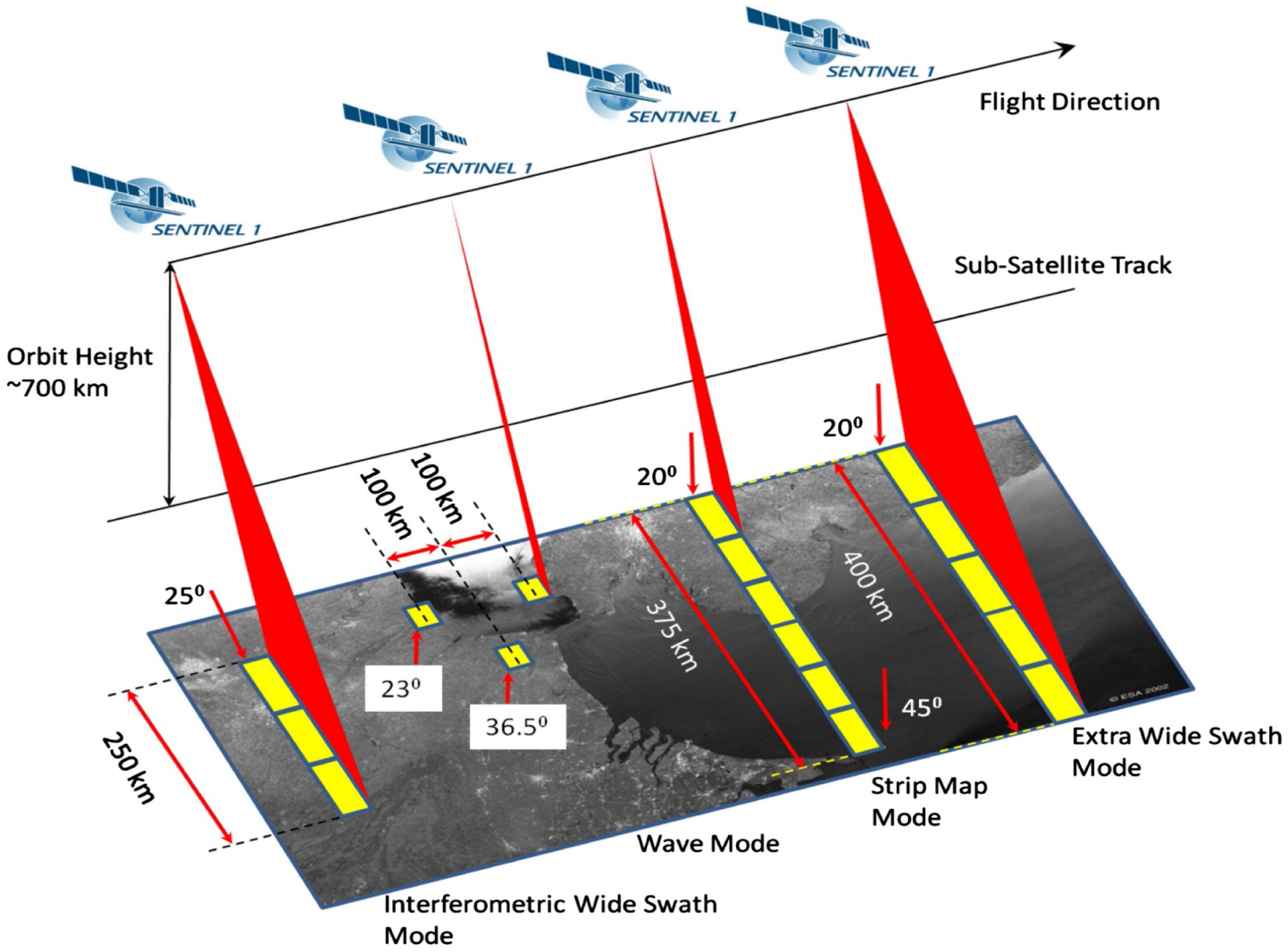
Examining these different polarizations carries information about the structure of the imaged surface, based on the following types of scattering and how surfaces interact with polarized beam:

- **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

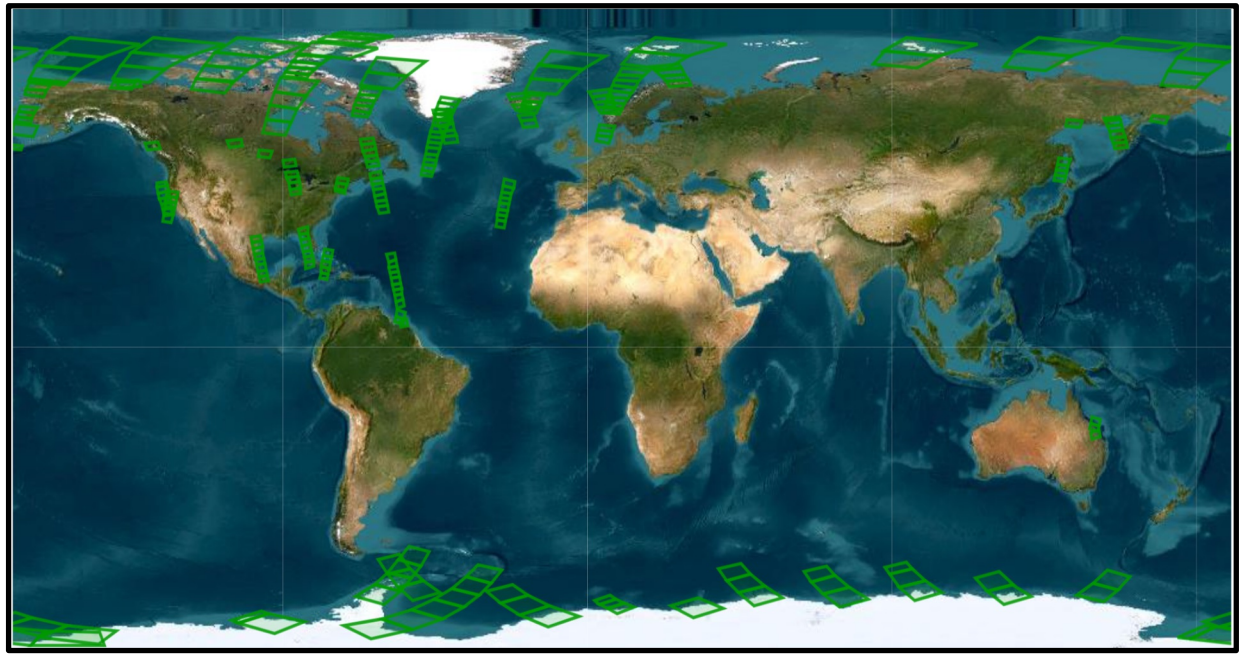
- Tradeoffs between coverage area and resolution

Imaging Modes for Sentinel-1

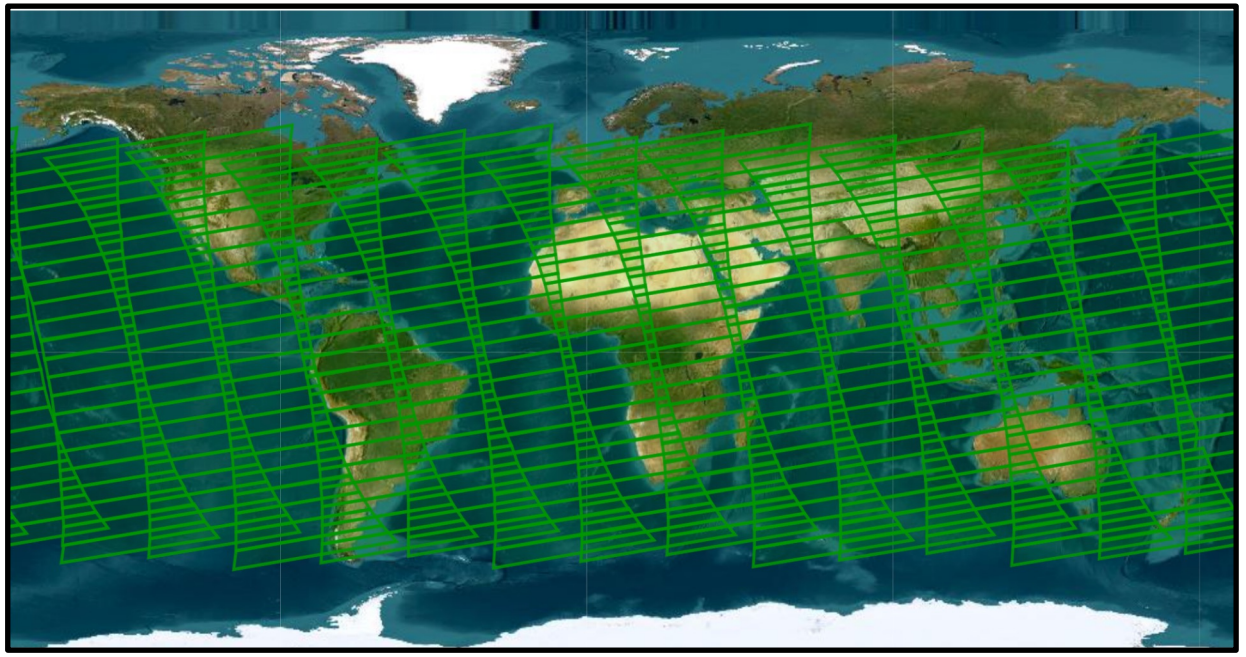
Beam Mode	Swath	Incidence Angle (deg)	Bean Information
Stripmap (SM)	80 km	18.3 - 46.8	Has 6 possible positions
Interfermoetric Wide (IW)	240 km	29.1 - 46	Composed of 3 sub - swath
Extra Wide Swath (EW)	410 km	18.9-47	Composed of 5 sub-swaths

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*

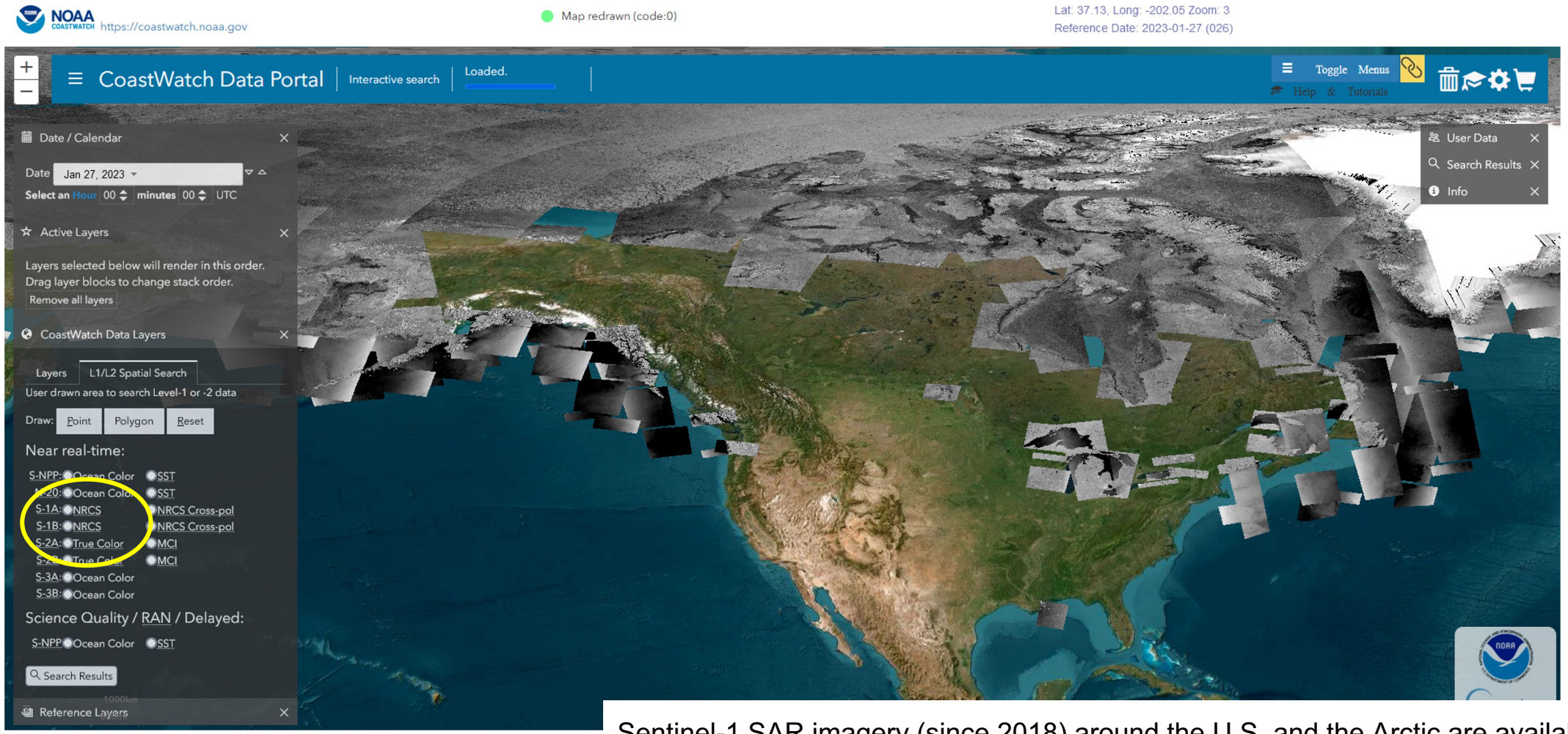


- SAR data is collected in small footprint over only a portion of an orbit.
- Limited by power, duty cycle and data volume

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

+Additional S1 scenes over Europe and Asia are not shown
*VIIRS collections over the North and South pole are not shown

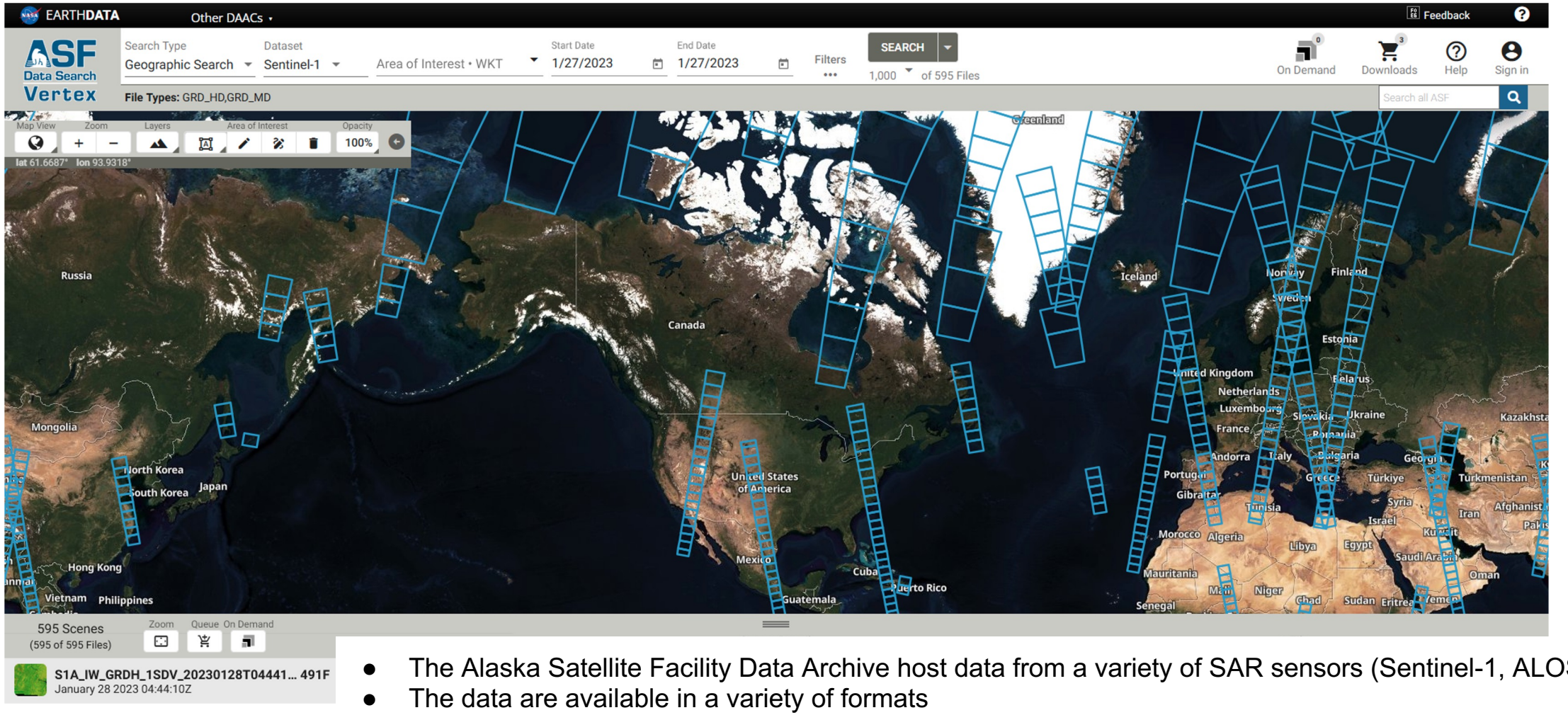
SAR Data at CoastWatch



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

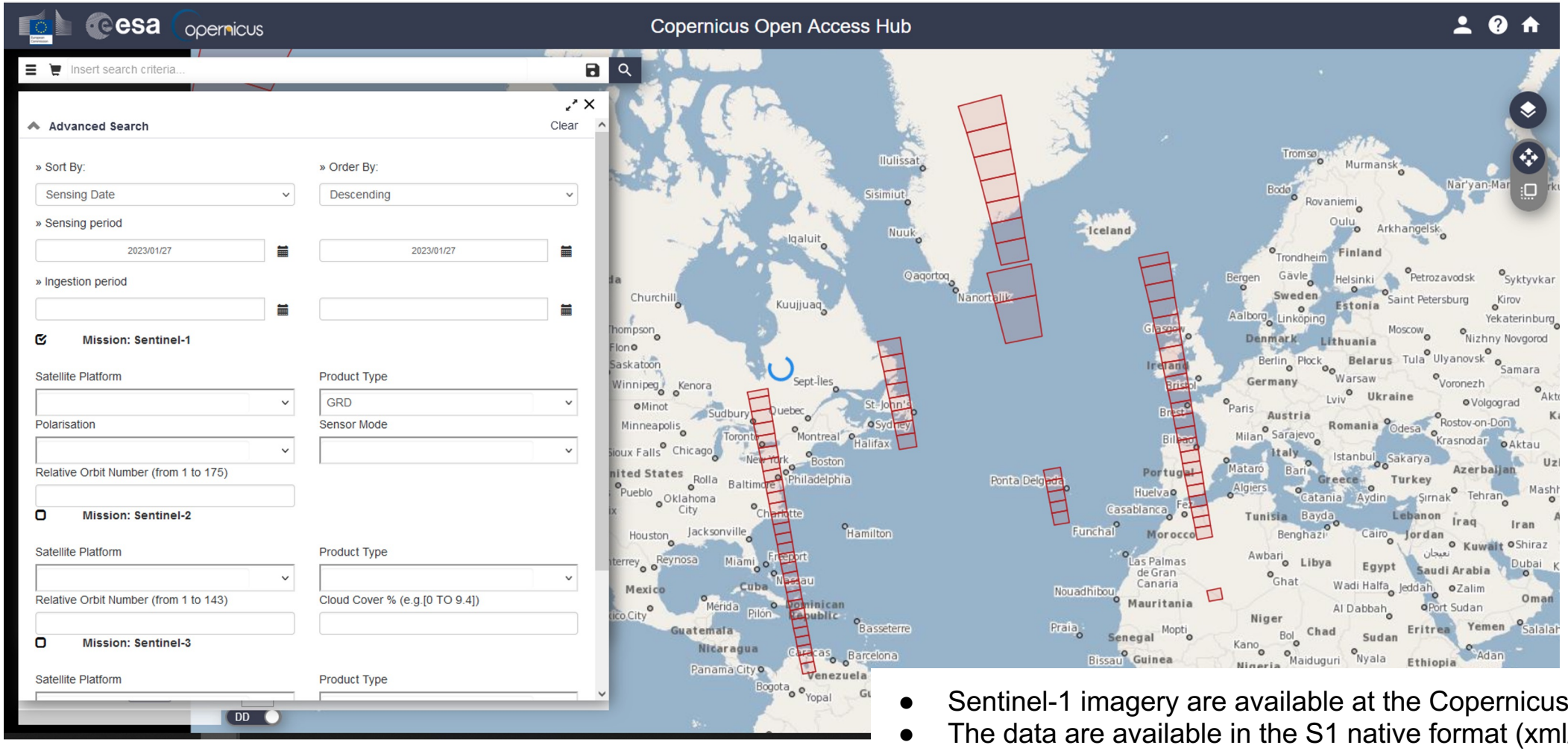
SAR Data at Alaska Satellite Facility



- 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/#/

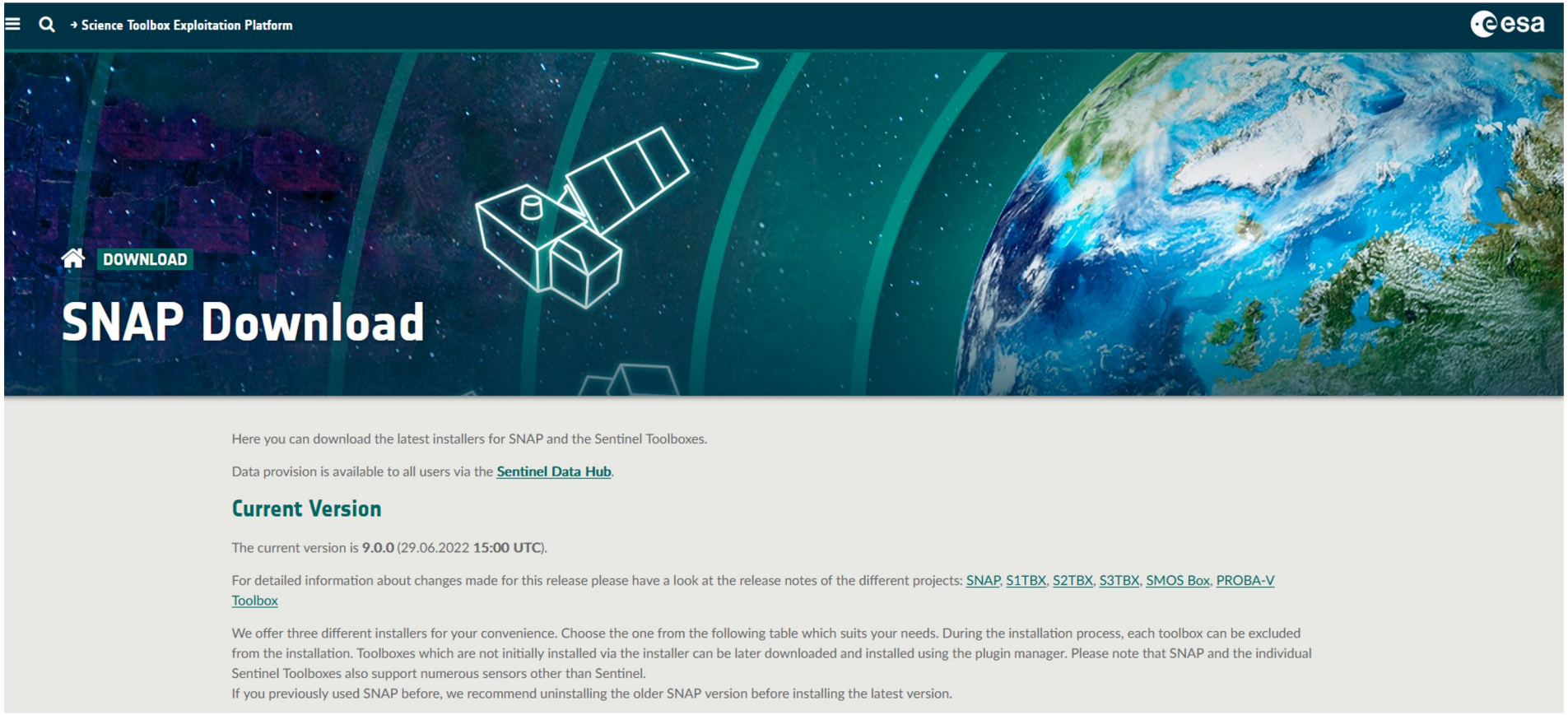
Sentinel-1 Data at ESA's Copernicus Scientific Data Hub



- 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.

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

SNAP Toolbox for SAR data



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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