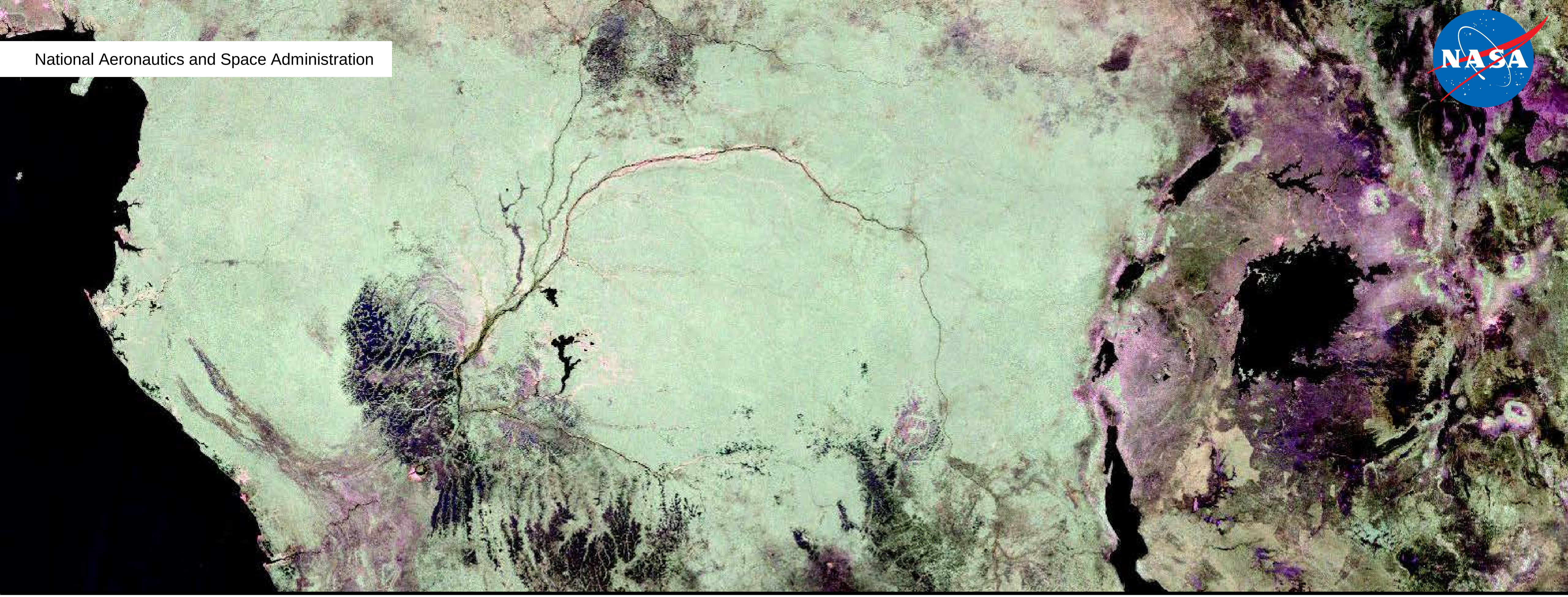


SAR for Mapping Soils and Crops

Heather McNairn and Xianfeng Jiao

14 August 2018

Learning Objectives

By the end of this presentation, you will be able to understand:

- how SAR configurations affect response from soils and crops
- the information content in SAR images relevant to soil and crop conditions
- the optimal sensor parameters for agriculture applications
- how to ingest, pre-process, and process SAR data for use in crop classification and soil moisture estimation

How do Radars Differ?

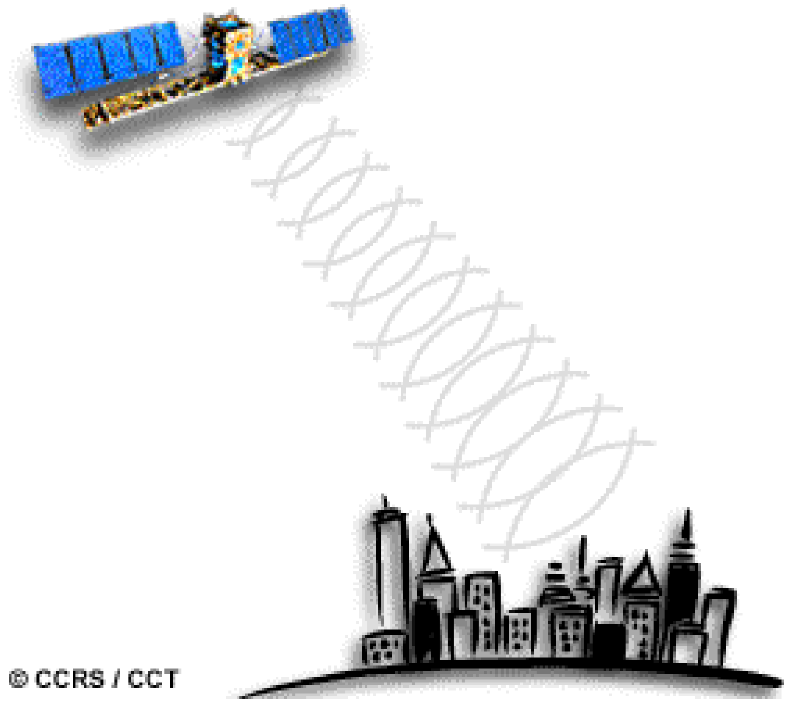
Longer Wavelengths

- "All weather" sensors (unaffected by cloud cover, haze, dust and all but the heaviest rainfall). Huge advantage for cloud-prone regions and time critical operations
- Deeper penetration into target relative to visible & IR wavelengths. This can be an advantage or disadvantage.

Active Systems

- Radars provide their own source of energy and are not dependent upon ambient energy; they can operate day or night. This can be important in areas with low illumination such as polar regions

RAdio **D**etection **A**nd **R**anging



Radar Geometry

Slant Range

- distance between antenna and target

Ground Range

- distance between the satellite ground track and the target

Azimuth

- along-track direction or distance

Incidence Angle

- angle between line of sight of radar and vertical to the terrain
- backscatter decreases with increasing incident angle
- rate and function of decrease is target specific

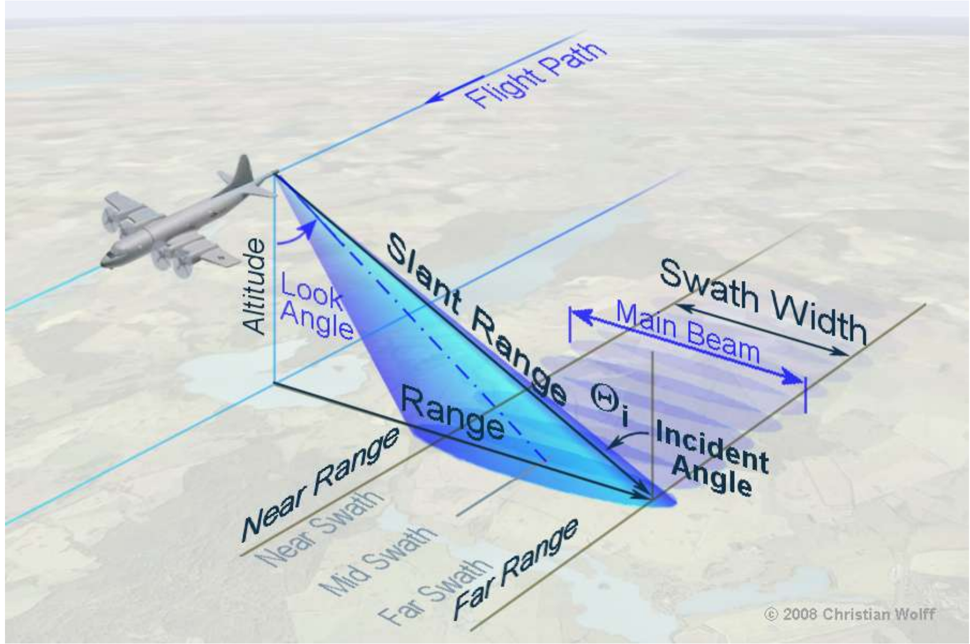
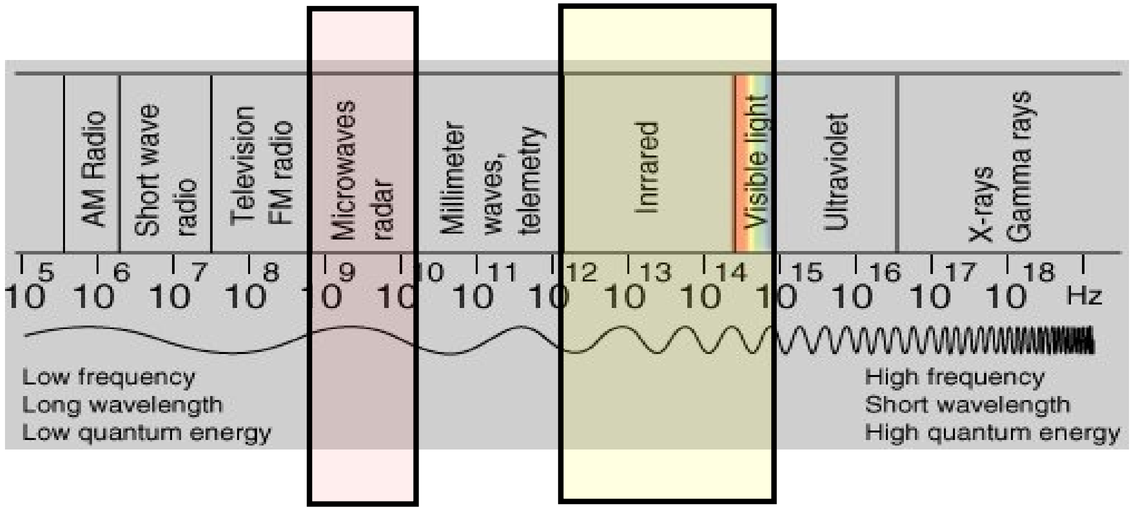


Image Credit: radartutorial.eu

Wavelength or Frequency



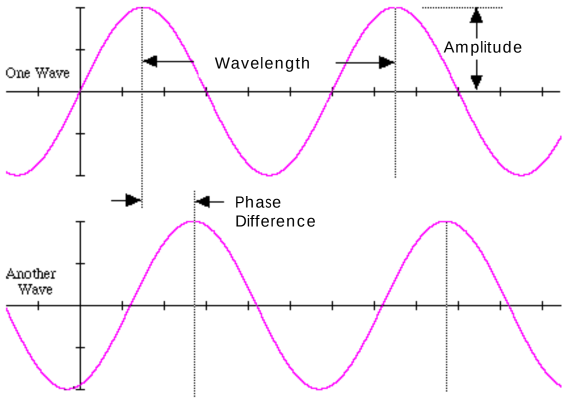
Wavelength and frequency are inversely related

c = $\lambda\nu$

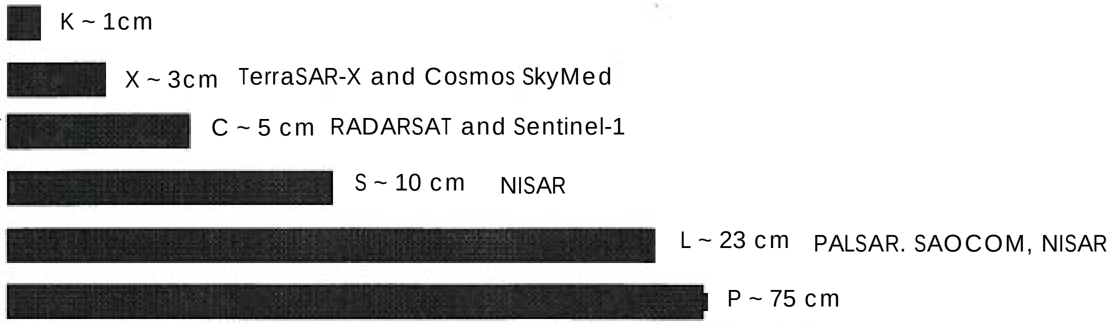
c = speed of light (3x10 m/s)

λ = wavelength (m)

ν = frequency (cycles per second, Hz)



Radars operate at longer frequencies between ~ 0.5 cm to ~100 cm in contrast to optical (visible and infrared)



Phase: the position of a point in time on a waveform cycle

Radar Geometry

Range Resolution

- pulse length: the duration of the transmitted pulse
- range resolution depends on the length of the pulse: shorter pulses results in higher resolutions
- if pulses are shortened, transmitted amplitude must be increased to maintain same total power in the pulse
- use range pulse compression by frequency modulation

Azimuth Resolution (real aperture radar)

- determined by the antenna beam width (A) and distance to the target
- Beam width directly dependent upon wavelength and inversely dependent upon on size of antenna (or aperture)
- difficult to achieve fine resolution as requires large antennas, which are difficult to deploy and operate in space

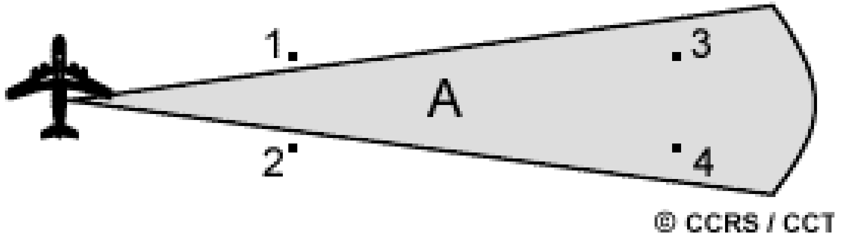


Image Credit: Natural Resources Canada

Radar Polarization

- Polarization: the orientation of the electric field of the electromagnetic wave
- To create a wave we simultaneously feed the radar antenna with components in two orthogonal polarizations
- the electric field will equal the vector sum of the horizontally (H) and vertically (V) polarized
- the phase difference between these two components determines whether the wave will be linearly, elliptically or circularly polarized

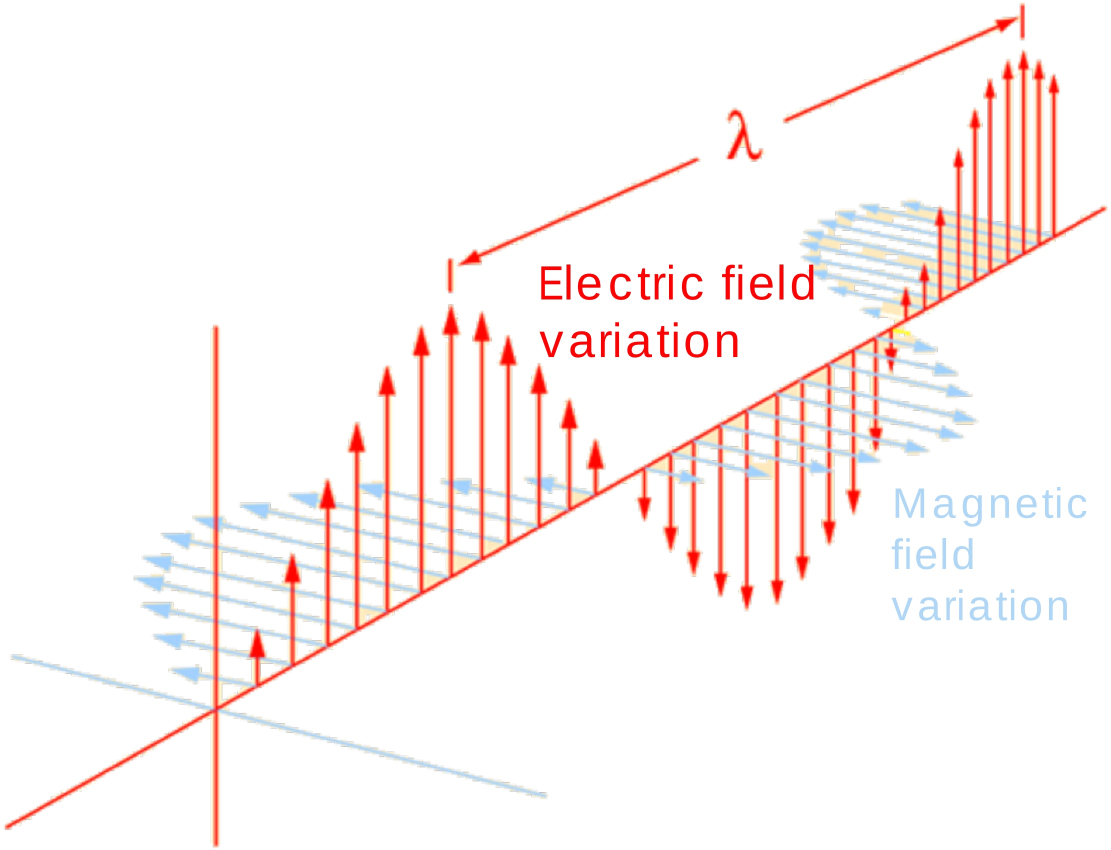
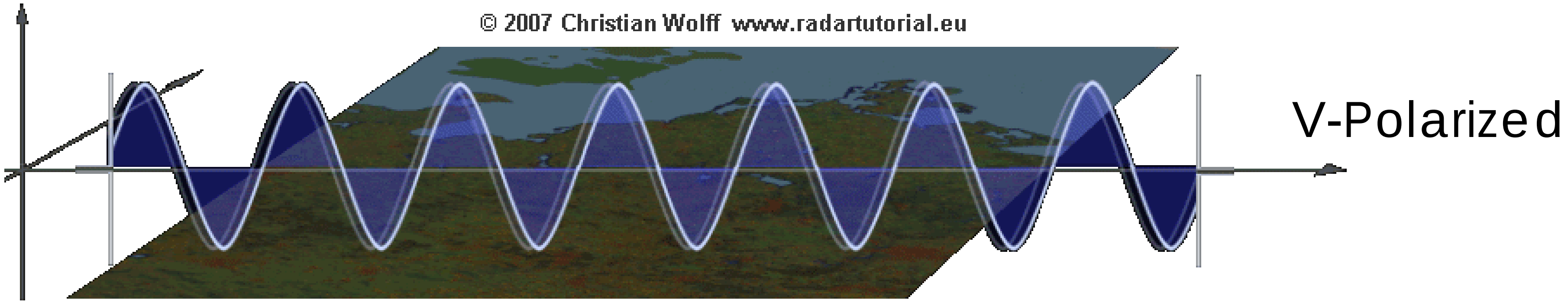
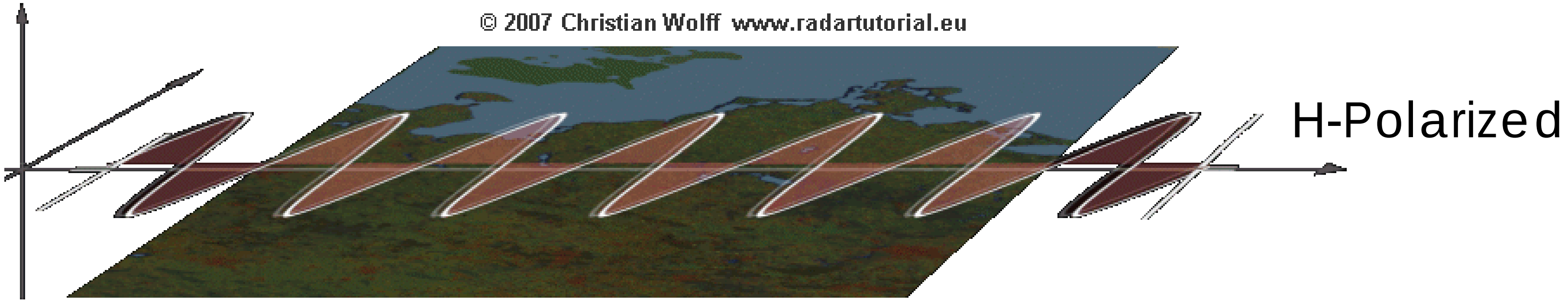


Image Credit: Hyperphysics

Linear Polarization



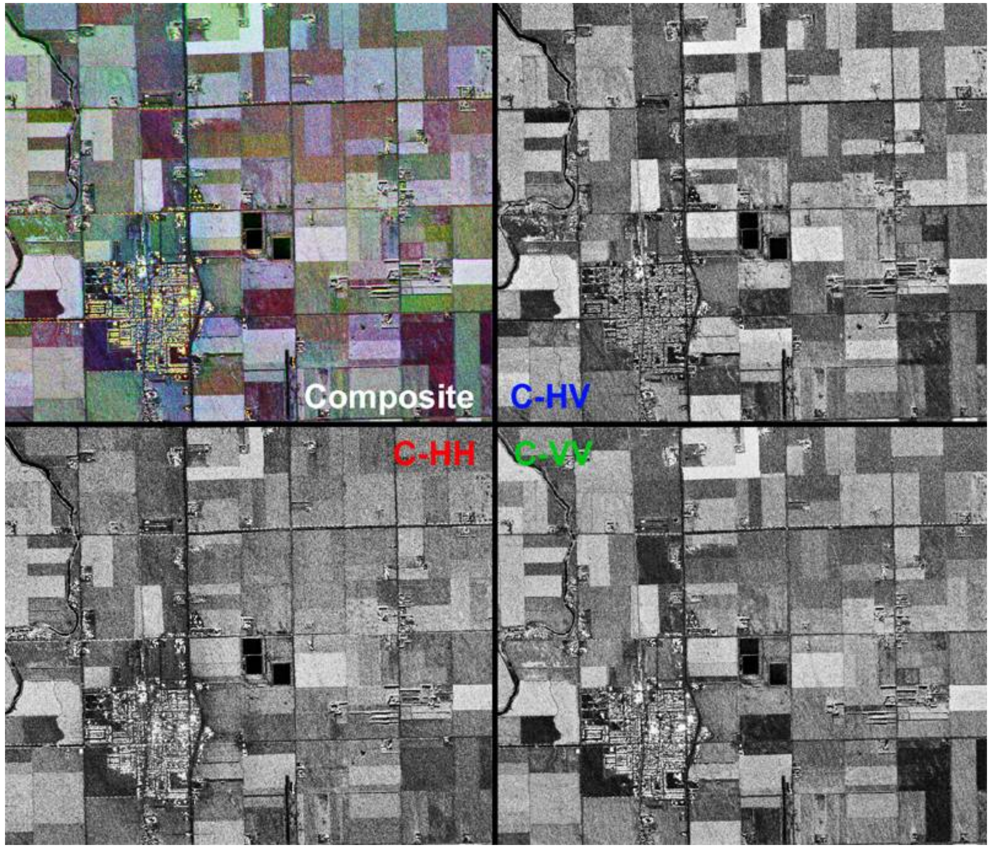


Linearly polarized wave has:

- no phase offset between transmitted H and V components
- propagation in a plane (H for horizontally polarized and V for vertically polarized)

Polarization – Transmit and Receive

- SARs transmit in one or more polarizations and then receive and record the scattered wave in one or more polarizations
- Like-Polarizations
  - HH (horizontal transmit-receive)
  - VV (vertical transmit-receive)
- Cross-Polarizations
  - HV (horizontal transmit-vertical receive)
  - VH (vertical transmit-horizontal receive)
  - HV and VH are theoretically identical and reciprocity is assumed
- Compact-Polarization
  - transmit right circular (R) and receive H and V **coherently** (RH and RV)
- Polarization affects interaction with the target

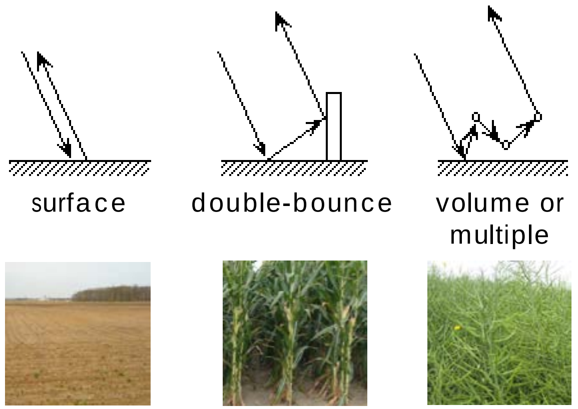


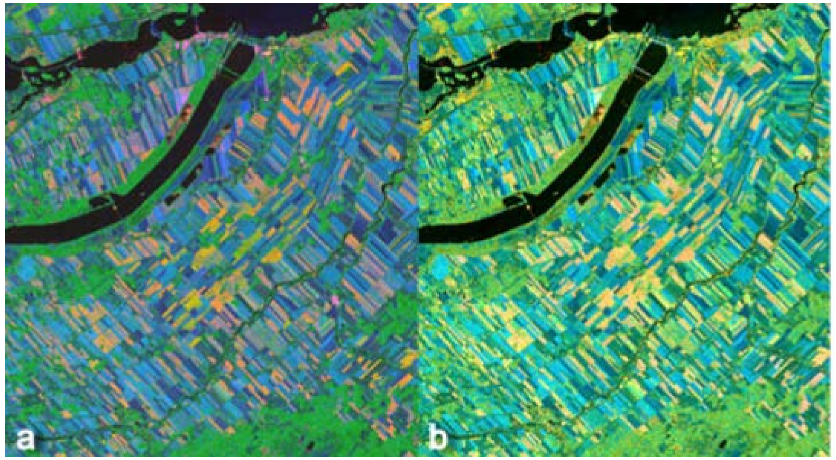
Fully Polarimetric SAR – What is This?

- transmits and receives two orthogonal polarizations (usually H and V) and retains the phase between these two polarizations
- permits the complete characterization of the scattering field

Why is this important?

- With these coherent systems one can:
  - synthesize any polarization (linear, circular or elliptical)
  - determine degree of polarization
  - decompose the signal to determine the dominant and secondary or tertiary types of scattering





(a) Freeman-Durden decomposition applied to RADARSAT-2 fully polarimetric data and (b) m-δ decomposition applied to simulated compact polarimetric data. Red (double bounce) Green (multiple/volume) Blue (single bounce)

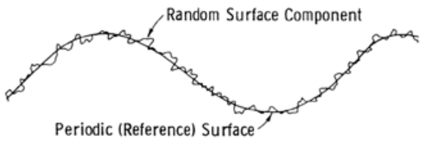
Image Source: Source: Dr. Francois Charbonneau

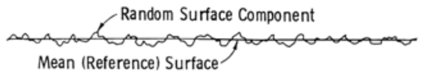
The Target

SARs respond to (basically) two fundamental characteristics of an agriculture target: structure and moisture

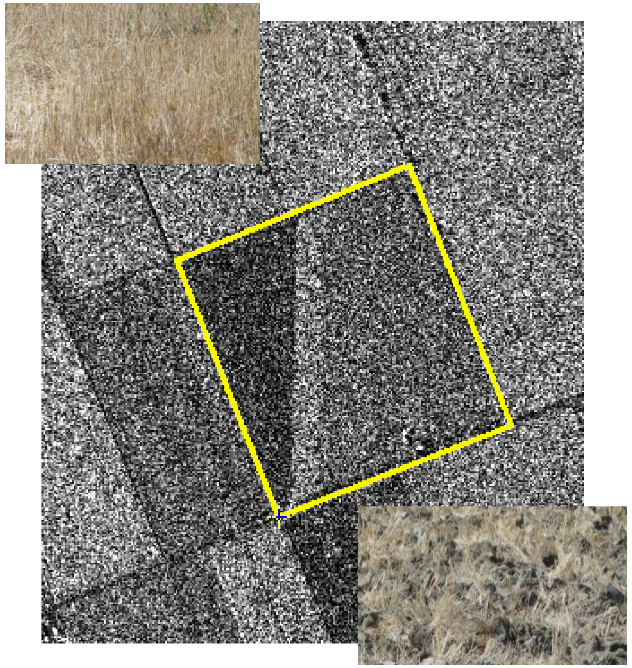
Roughness: the statistical variation of the random component of the surface height relative to a reference surface (in cm) (root mean square rms height)

For soils this means
- random roughness caused by tillage (and other farm operations) modified by soil erosion and weathering effects
- periodic row structures caused by tillage and planting





A field with low random roughness but significant periodic structure



TerraSAR-X (VV) captured tillage occurring on August 26, 2008

Image Credit: (right) DLR

How Does Roughness Affect Backscatter?

- Backscatter will increase as soil roughness increases
- Bottom line: rougher soils appear brighter in SAR images

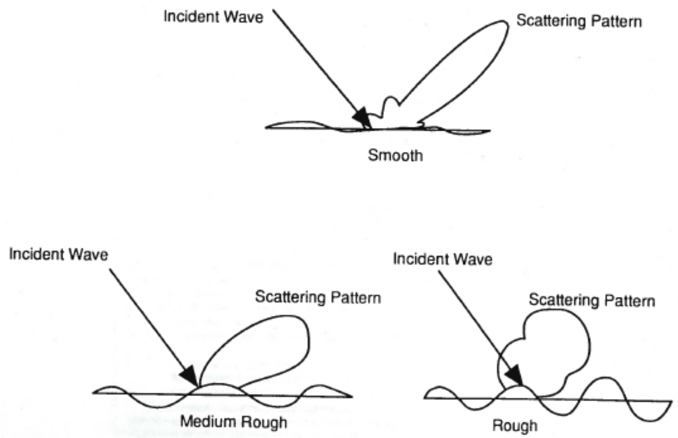
The impact of roughness on backscatter depends on the frequency and incident angle of the SAR. Roughness is a relative concept.

- According to the Rayleigh Criterion, a soil is smooth if

$$h < \frac{\lambda}{8\cos\theta}$$

where h is surface height variation in cm, λ is the wavelength in cm and θ is the incident angle in degrees

expected relative SAR response



It’s All Relative

Roughness less than “h” would be viewed as smooth by the SAR

Incident Angle of 30º	
TerraSAR-X (3.1 cm)	h < 0.45 cm
RADARSAT-2 (5.6 cm)	h < 0.81 cm
PALSAR (23.6 cm)	h < 3.42 cm
Incident Angle of 50º	
TerraSAR-X (3.1 cm)	h < 0.60 cm
RADARSAT-2 (5.6 cm)	h < 1.09 cm
PALSAR (23.6 cm)	h < 4.59 cm

Jackson, T.J., McNairn, H., Weltz, M.A., Brisco, B. and Brown, R.J. (1997). First order surface roughness correction of active microwave observations for estimating soil moisture. IEEE Transactions on Geoscience and Remote Sensing 35:1065-1069.

TABLE I
AVERAGE RANDOM ROUGHNESS (s) VALUES BASED ON SINGLE TILLAGE OPERATIONS [12].

Tillage Operation	s (cm)
Large offset disk	5.0
Moldboard plow	3.2
Lister	2.5
Chisel plow	2.3
Disk	1.8
Field cultivator	1.5
Row cultivator	1.5
Rotary tillage	1.5
Harrow	1.5
Anhydrous applicator	1.3
Rod weeder	1.0
Planter	1.0
No till	0.7
Smooth	0.6

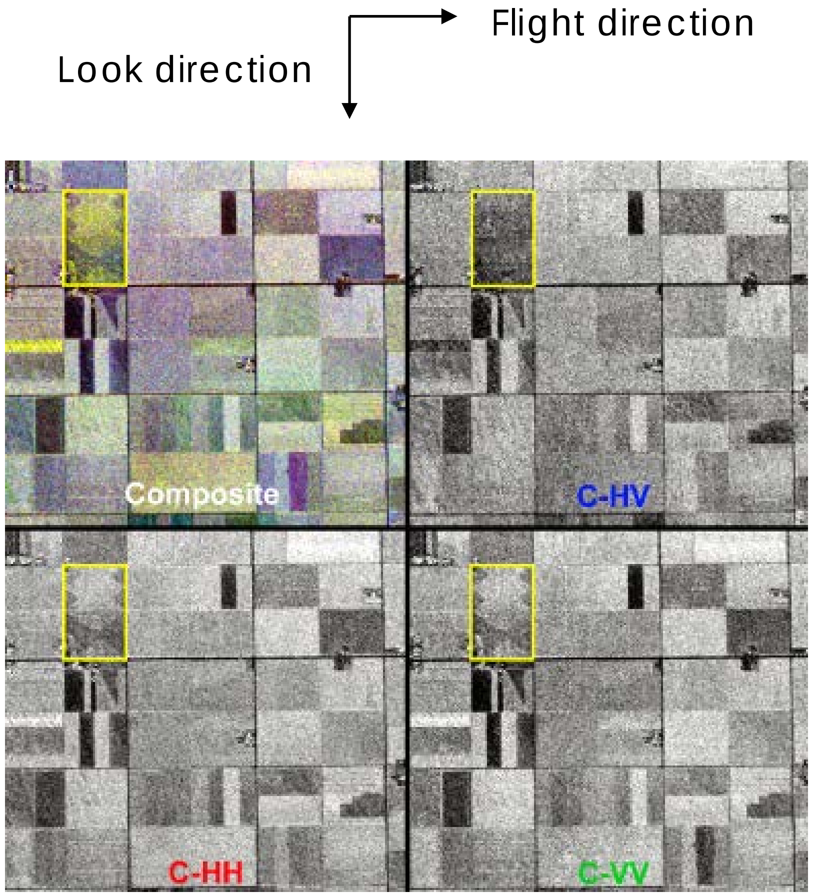
TerraSAR-X
RADARSAT-2
PALSAR

Viewed by SAR as rough at 50°

Viewed by SAR as smooth at 50°

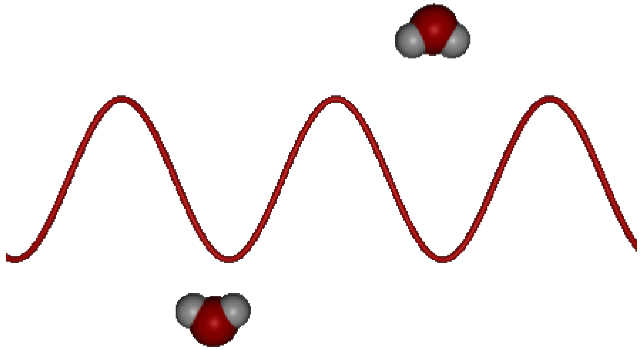
One Complication

- “Look direction” of SAR relative to the row direction impacts the strength of radar return. Creates a so-called “bow-tie” effect
- The strongest backscatter results are when the SAR look direction is perpendicular to the direction of the rows
- Row direction effects can result due to the direction of **planting, tillage, and harvesting**
- This phenomenon is not present when fields are imaged in cross-polarizations (HV and VH) as these polarizations are responding to volume scattering rather than surface scattering
  – among other reasons, this makes HV and VH attractive for vegetation monitoring



What About Water in the Target?

SAR is known to be sensitive to moisture, but **why**?



- a microwave will continue to propagate until it encounters a dielectric discontinuity, as happens when water is present in soil
- the dielectric constant is a measure of the ease with which dipolar molecules (such as water) rotate in response to an applied field
- dielectric constant (ε) is a complex value characterizing both the permittivity (ε') (real) and conductivity (ε'') (imaginary) of a material [$\varepsilon = \varepsilon' - j\,\varepsilon''$]
- when an electric field is applied, free water molecules easily rotate to align with the field
- frictional resistance is low and little energy stored in the rotation is lost when the wave passes and the molecule relaxes. Most of the stored energy is released.
- real dielectric ranges from ~3 (very dry soils) to 80 (water)

Image Credit: Anton Paar

What Does This Mean for SAR?

- a strong positive relationship between real dielectric constant and SAR backscatter
- a strong positive relationship between real dielectric constant and soil moisture
- In a nutshell: more water in the target = higher backscatter = brighter returns
- Applies to ANY target (soil, vegetation etc.)
- penetration depth (δ_p) into soil and/or crops is defined by the dielectric (ε), wavelength (λ), and incident angle
- penetration increases with wavelength and is greater when the target (soil or crops) is drier

Multi-Date RADARSAT-1 Composite
Outlook, Saskatchewan (Canada)

$$\delta_p = \frac{\lambda \sqrt{\varepsilon'}}{2 \pi \varepsilon''}$$

Image Credit: Canadian Space Agency

Vegetation Effects

The scale is very different from optical

- Scattering of longer-wavelength microwaves is driven by
  a) larger scale structures (size, shape and orientation of leaves, stems and fruit)
  b) the volume of water in the vegetation canopy (at the molecule level)

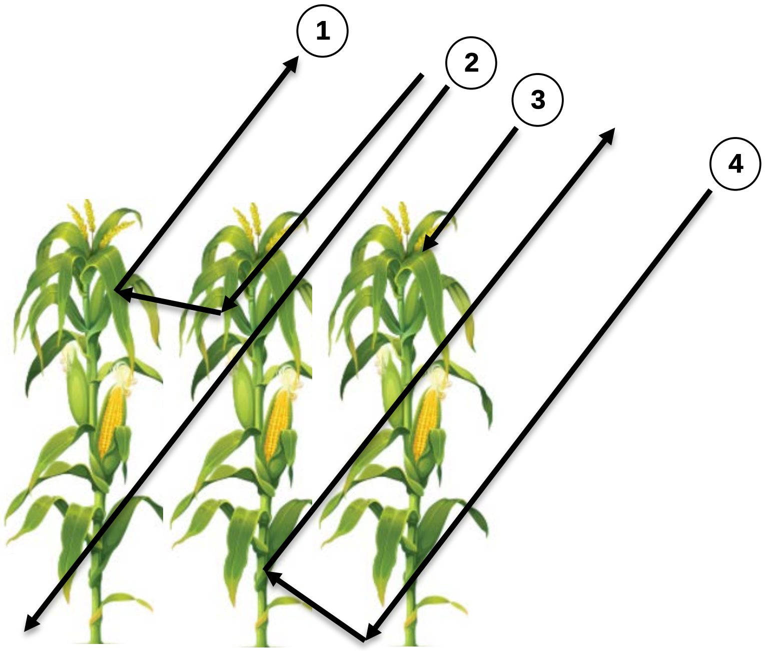
So why is SAR sensitive to crop type and crop development?

- Crop structure changes significantly from one crop to the next, and as crops move through their growth stages

Crop structure varies significantly among soybeans, wheat, and corn

Scattering from Crops – It's Complicated

- many different types and combinations of scattering can occur in a crop canopy
- a microwave entering a canopy may scatter directly off a leaf, or may scatter from the stem of one crop to the leaf of another, or may make its way to the soil where it scatters from the soil. The wave may also make its way out of the canopy without further scattering, or may hit parts of the canopy on its way out.
- these scattering events determine how much of the energy will return back to the SAR sensor, and how the phase between, for example, H and V components will change (offsets in phase and how random the phase becomes)
- these scattering characteristics tell us what type of crop is present and what the condition is of that crop

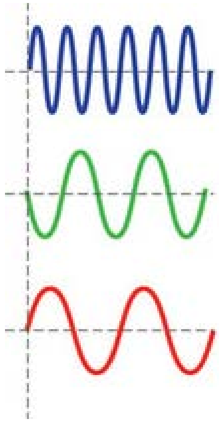


1. Multiple volume scattering from within canopy
2. Direct scattering from soil
3. Direct scattering from canopy
4. Multiple scattering between soil and canopy

SAR Configurations Relative to Crop Characteristics

Frequency:

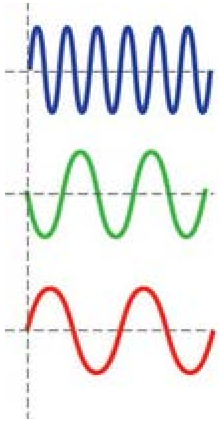
- canopies can attenuate or scatter microwaves
- the dominance of one or the other depends on the wavelength relative to the size of the canopy components
- scattering occurs when canopy component (such as a leaf) is close to or larger than wavelength
- some components (such as heads of wheat) will attenuate microwaves, especially at shorter wavelengths
- frequency also affects penetration depth; longer wavelengths penetrate deeper into the canopy and involve more interaction with the soil



SAR Configurations Relative to Crop Characteristics

What is the best frequency? It depends

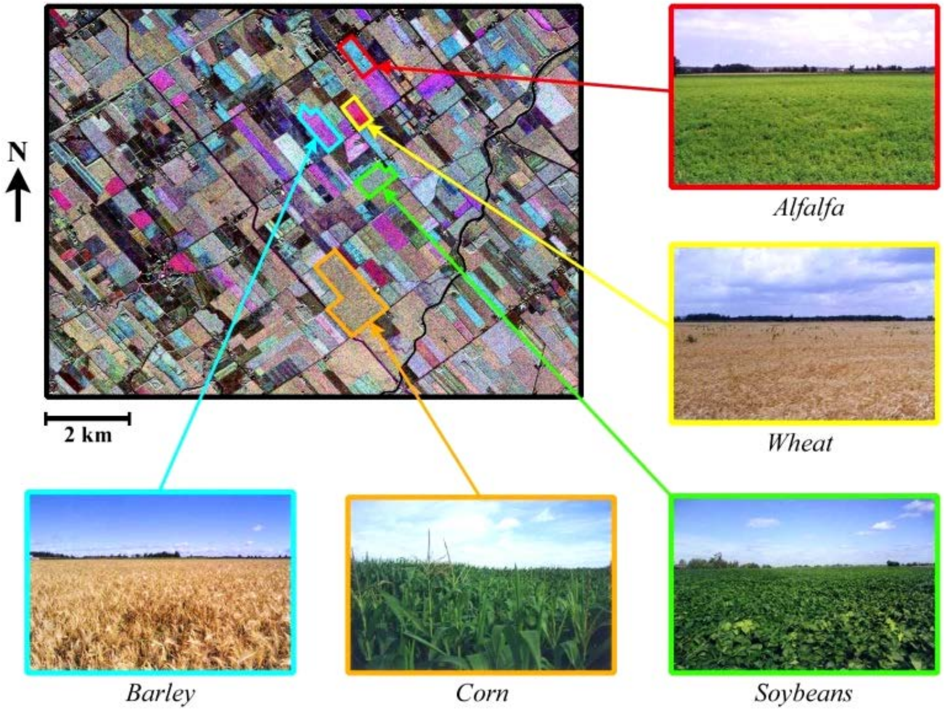
- <u>soil moisture</u>: longer wavelengths (like L-band) are better as they penetrate deeper into the canopy and interact with soil
- <u>crop classification and biophysical modeling</u>: depends on canopy
- need enough penetration into canopy (L- or C-band for corn, for example) but not too deep so that we have soil interference (C- or X-band for lower biomass crops like soybeans)



SAR Configurations Relative to Crop Characteristics

Polarization

- affects how microwaves interact with crop
- V-polarized waves couple with vertical structured vegetation and more of the energy is attenuated
- H-polarized waves have greater penetration through the canopy to the underlying soil
- cross-polarizations (HV/VH) are sensitive to the target volume and are not affected by row effects
- **HV or VH** is the single best polarization for either crop identification or crop biophysical estimation
- next best polarization is usually VV

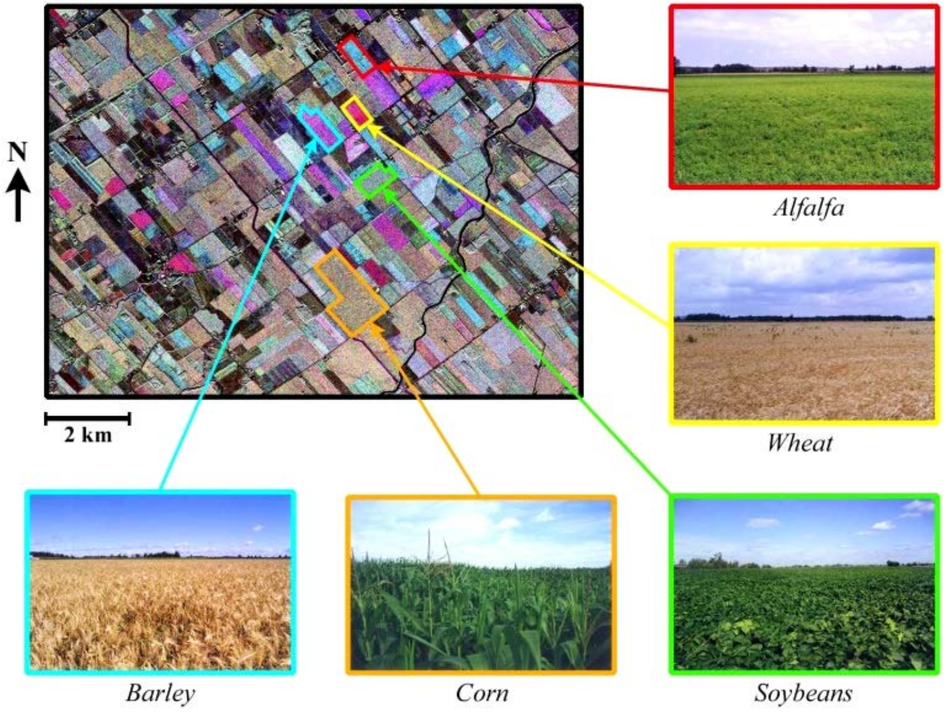


Airborne CV-580 C-Band SAR, South of Ottawa, 1998 July 9
R = HH G = HV B = VV

SAR Configurations Relative to Crop Characteristics

Incident Angle

- not as critical for crop identification
- for temporal change detection, do not mix angles
- for biophysical estimation, it's ok to mix angles as long as the model accounts for the incident angle



Airborne CV-580 C-Band SAR, South of Ottawa, 1998 July 9

R = HH G = HV B = VV

A Complication: The Environment

Always, always, always check the environmental conditions at the time of image acquisition before using SAR data

Rule 1: Never use SAR if it was raining at the time of the acquisition

- **Why**? Although SAR is considered "all weather" this does not include imaging during rain events as water in the atmosphere will cause SAR scattering. In some regions of world, risks are diurnally dependent.

Rule 2: Never use SAR if the ground is frozen

- **Why**? The dielectric constant drops close to zero when water changes to a frozen state. Thus even if there is water in the soil, the SAR will view the soil as dry. SAR can detect freeze/thaw events. Freezing often occurs overnight.

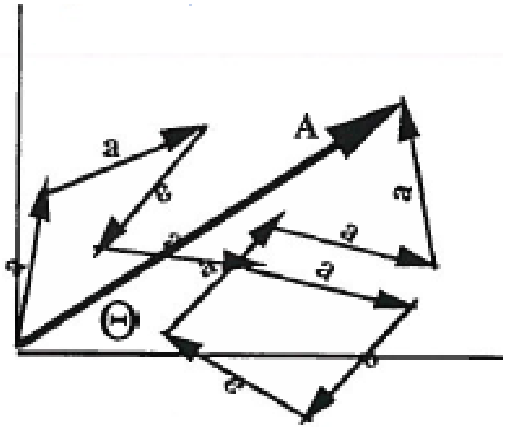
A Complication: The Environment

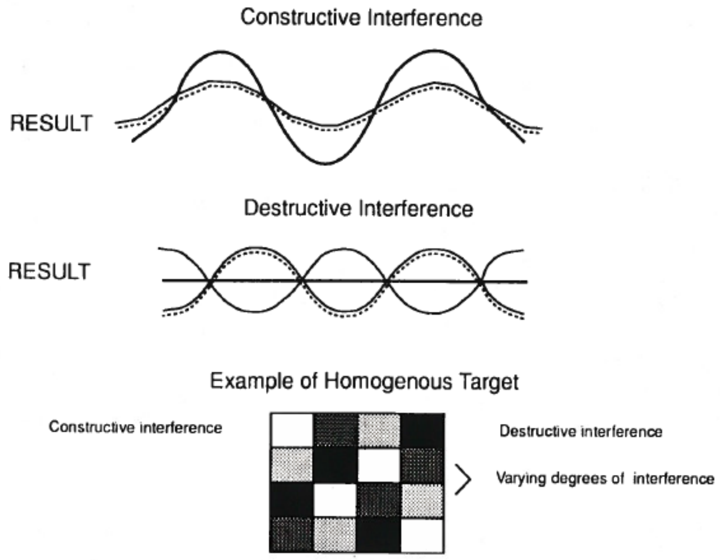
Rule 3: Consider if dew might be present during early morning acquisitions

- **Why**? Presence of water on leaves will increase backscatter (big problem for biophysical modelling). If water on canopy is significant (just after rain), contrast between targets can be reduced. Dew is most prominent in temperate regions in early morning hours.
- Select orbits (ascending – evening; descending – morning) carefully
- Always check in with meteorological stations

Another Complication: Noise in SAR

- when we think of SAR, each resolution cell is composed of many scattering elements, which contribute to the scatter
- these scattered waves have a phase determined by the scattering events
- the response from each resolution cell is the sum of the amplitude and phase from these scattering elements
- all of these scattered waves can lead to complex interference, sometimes this is constructive (bright pixels) and sometimes destructive (dark pixels)
- the result: speckle "salt and pepper" noise





Speckle Suppression

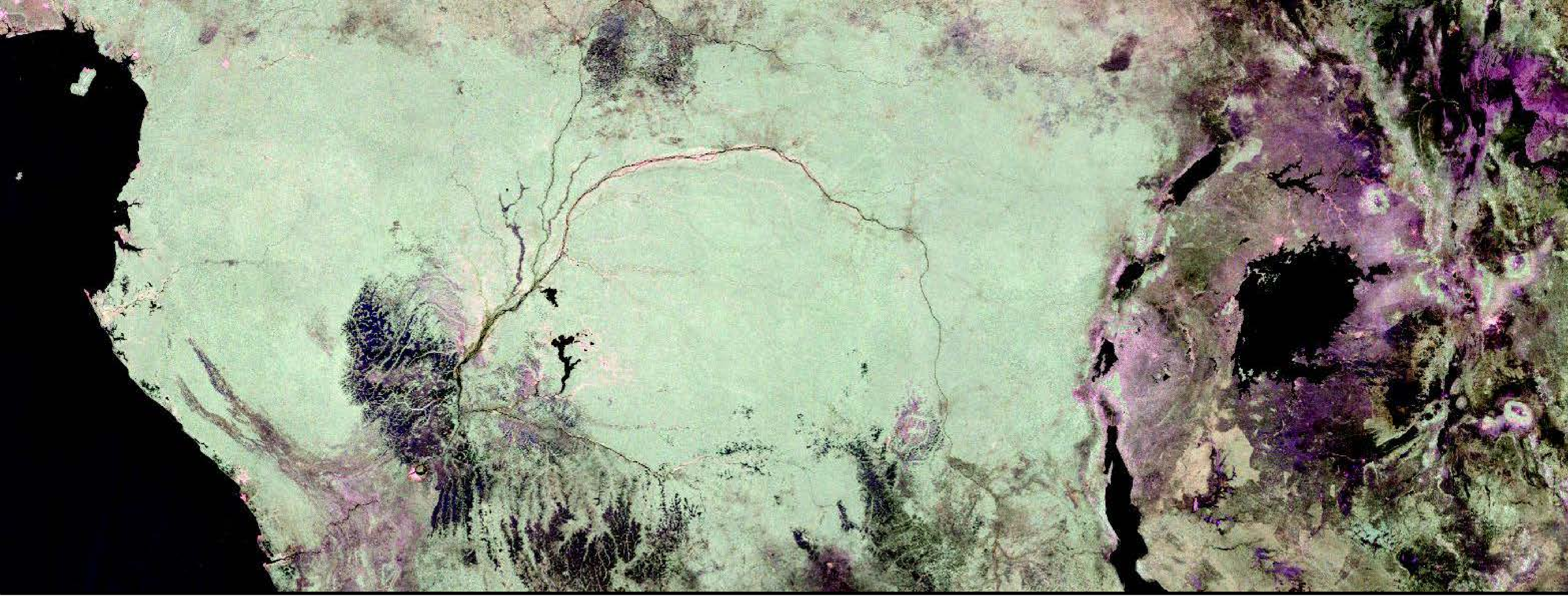
Speckle can be reduced two ways

- multi-look processing - divides the radar beam into several narrower sub-beams. Each sub-beam provides an independent "look." These looks are summed to form a final output image with reduced speckle
- spatial or temporal averaging – speckle reduction filters applied to the detected image
- multi-looking and spatial filtering reduce speckle at the expense of resolution

Adaptive radar speckle filters

- adaptive radar filters will reduce speckle while preserving the edges
- these filters will modify the image based on statistics extracted from the local environment of each pixel

Image Credit: Par B!eu Technologies



Hands-on Demonstration

Pre-Processing RADARSAT-2 QP SLC data with SNAP (6.0)

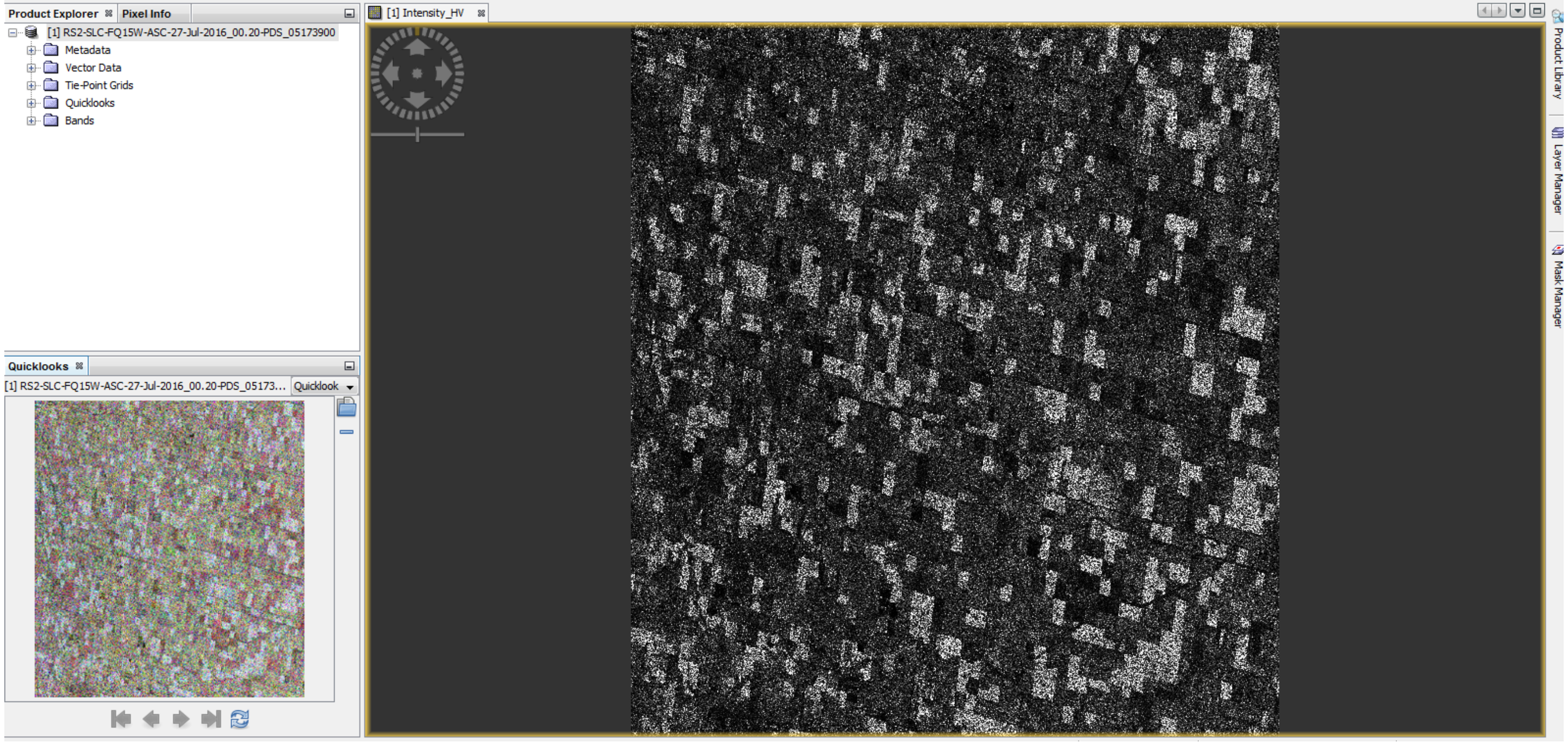
Extract Backscatter for Four Linear Polarizations

Read → Calibration → Polarimetric-Speckle-Filter → Terrain Correction → Write

Pre-Processing RADARSAT-2 QP SLC data with SNAP (6.0)

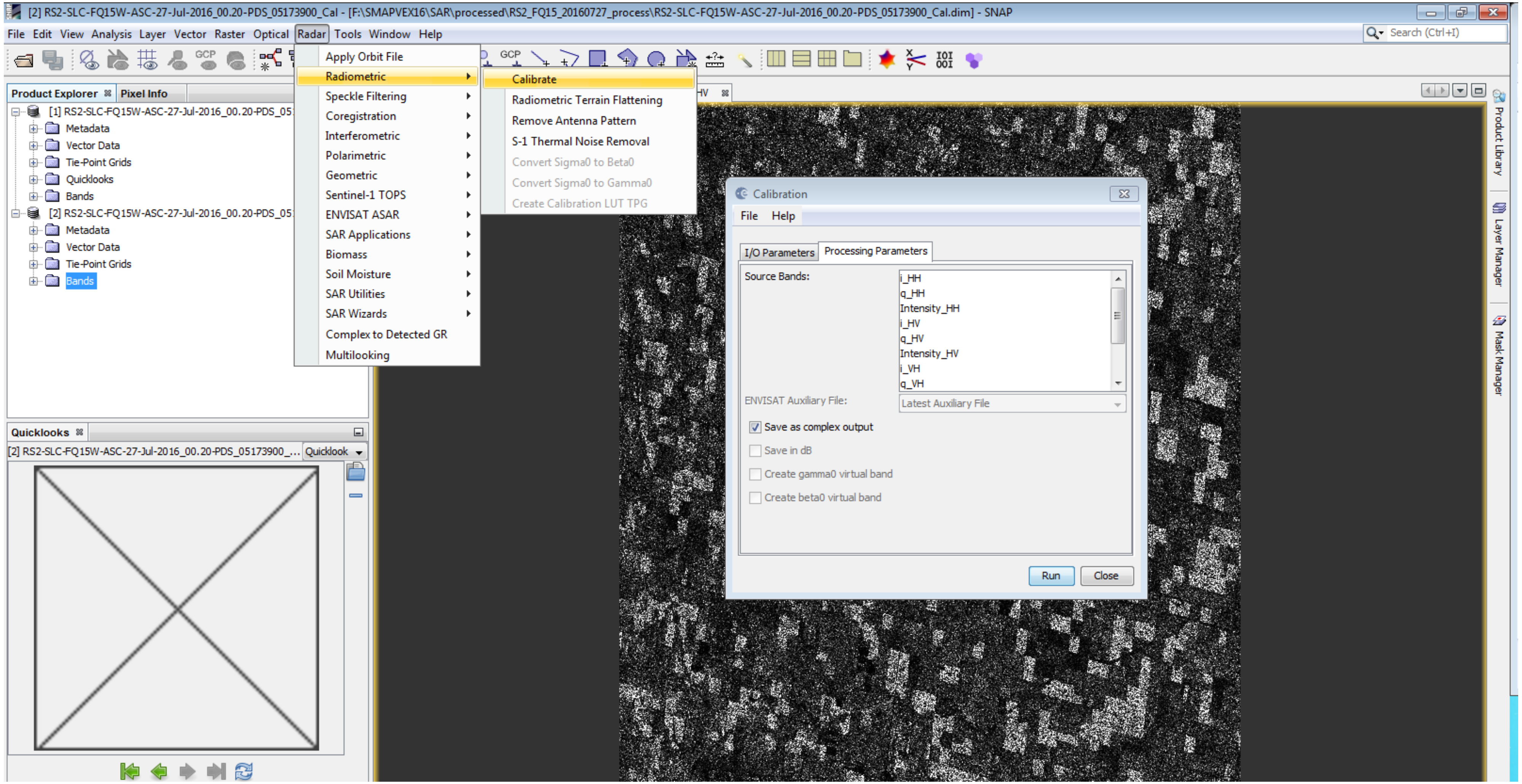
Read RS2 SLC .zip Image

Using RADARSAT-2 quad pol FQ15W mode SLC data acquired on July 27, 2016, over Carman, MB, Canada



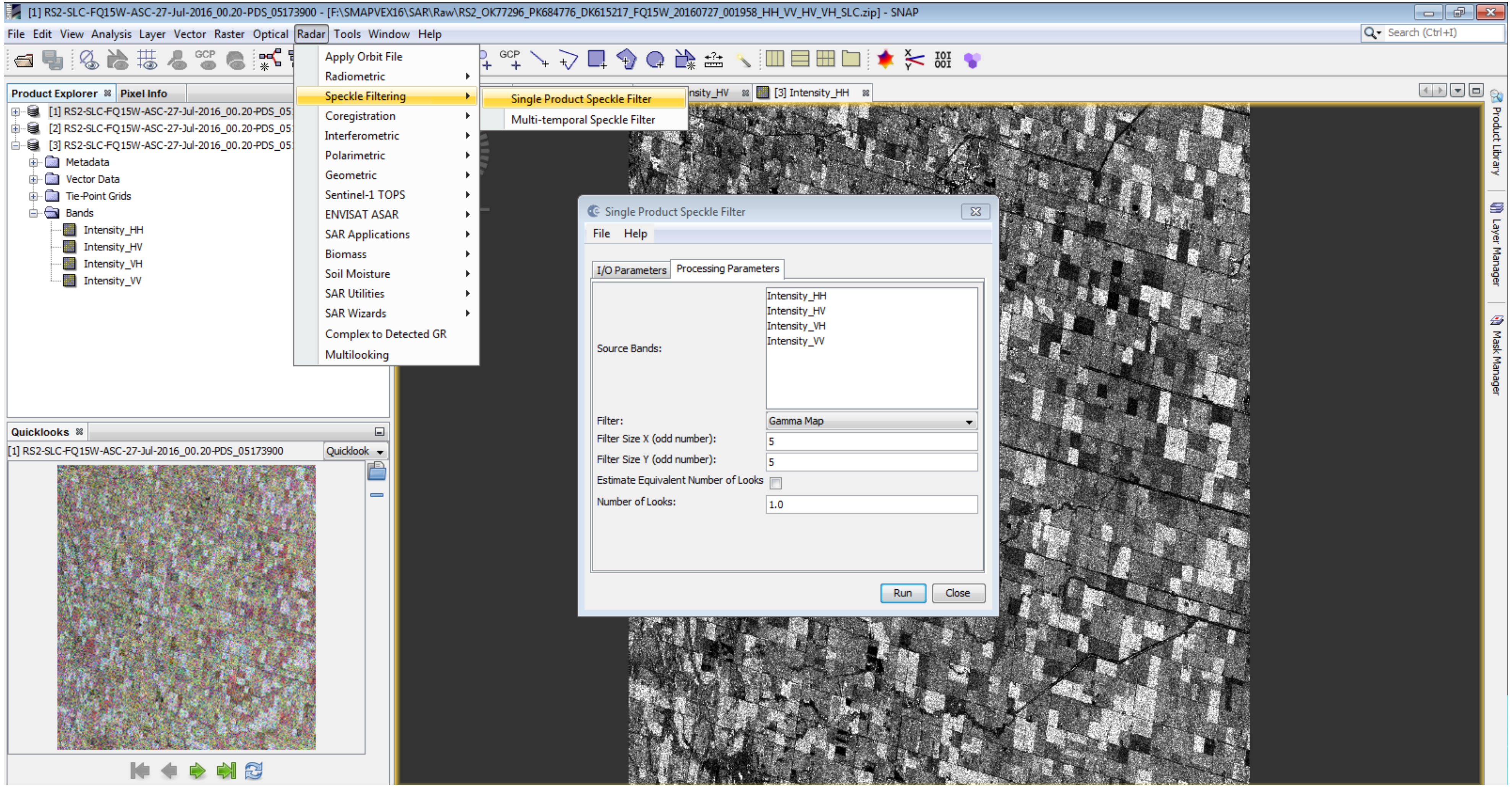
Pre-Processing RADARSAT-2 QP SLC data with SNAP (6.0)

Calibration: Convert Pixel Values to Radar Backscatter



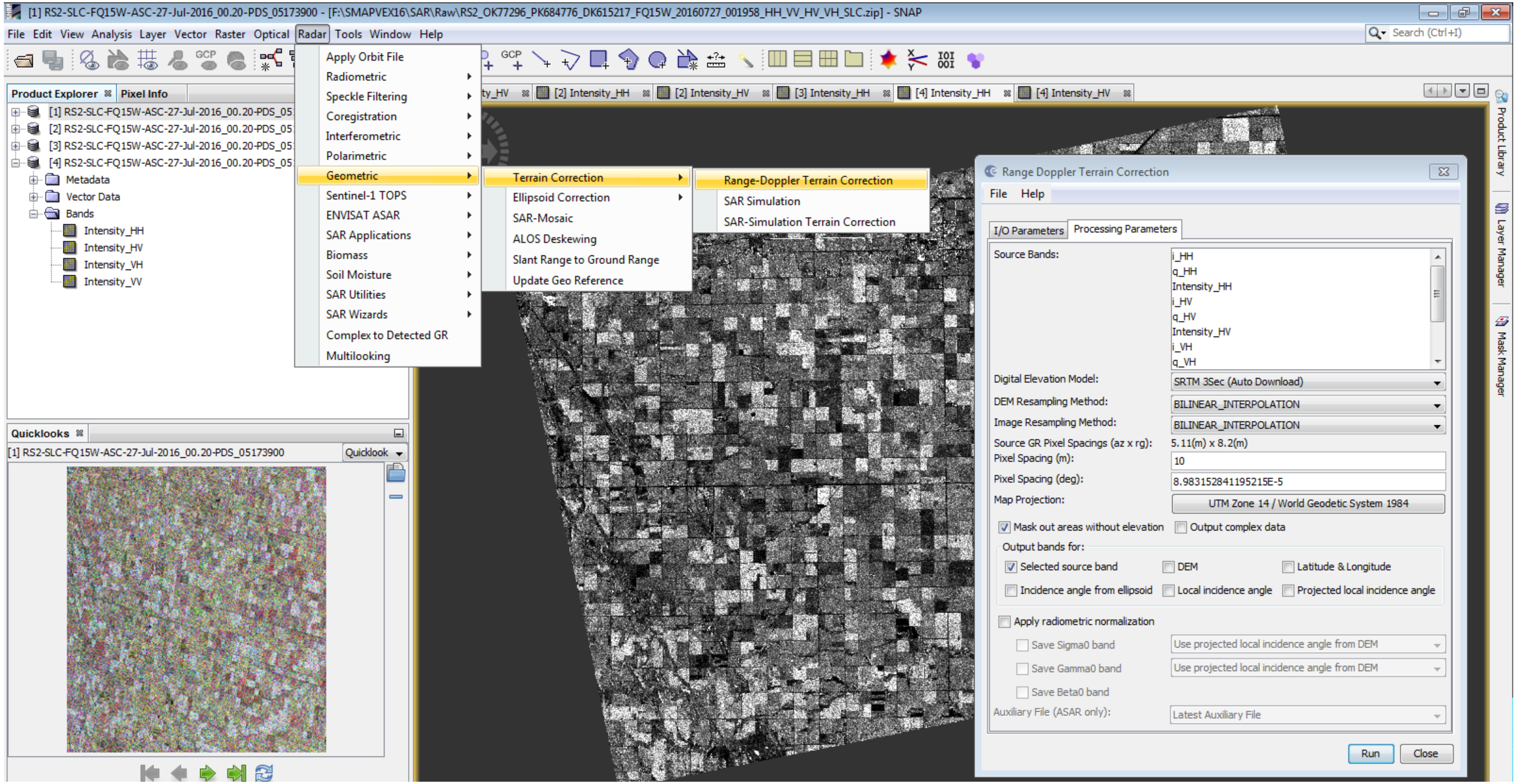
Pre-Processing RADARSAT-2 QP SLC data with SNAP (6.0)

Speckle Filter -- 5 by 5 Gamma Map

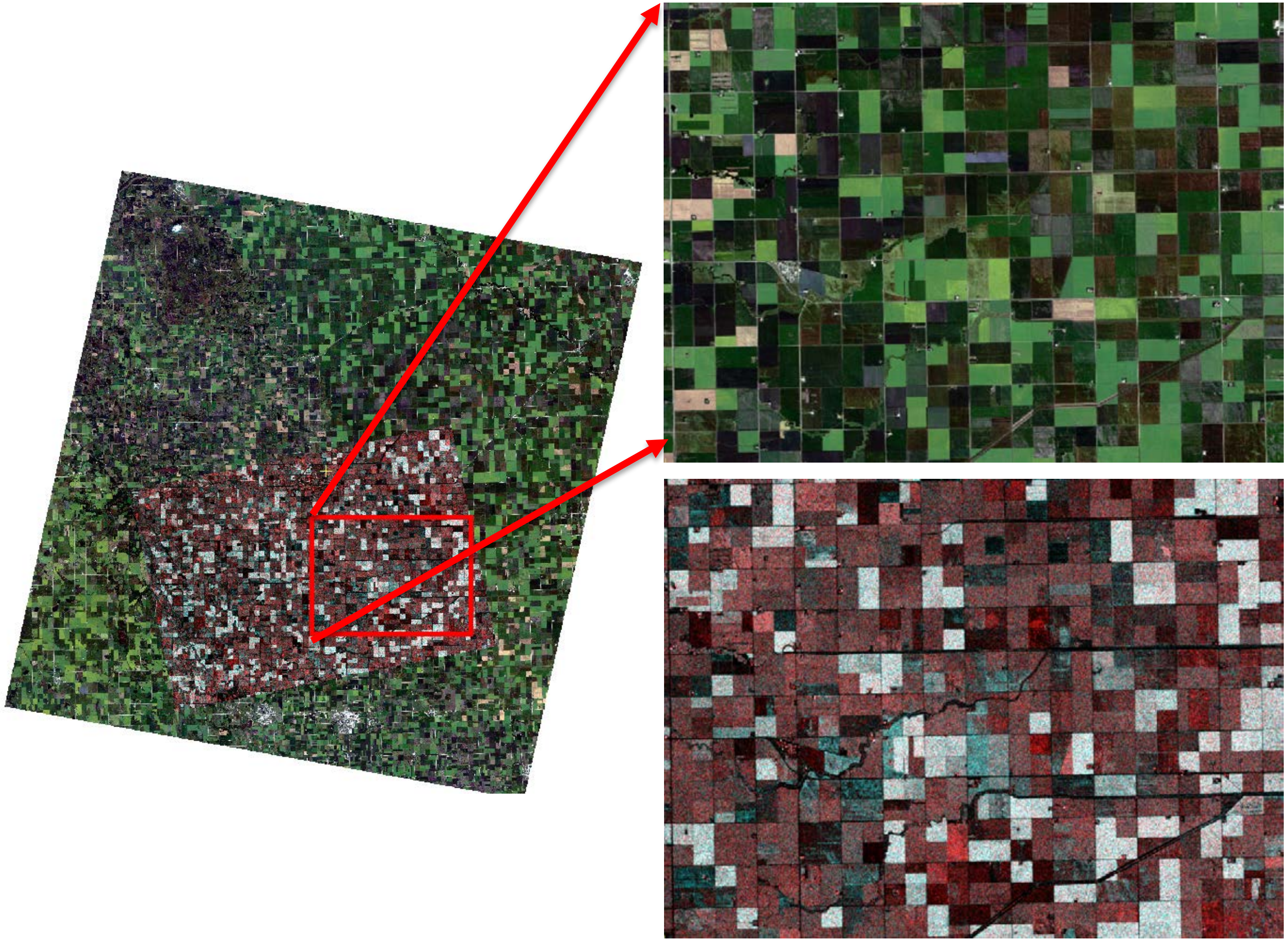


Pre-Processing RADARSAT-2 QP SLC data with SNAP (6.0)

Terrain-Correction



Pre-Processing RADARSAT-2 QP SLC data with SNAP (6.0)



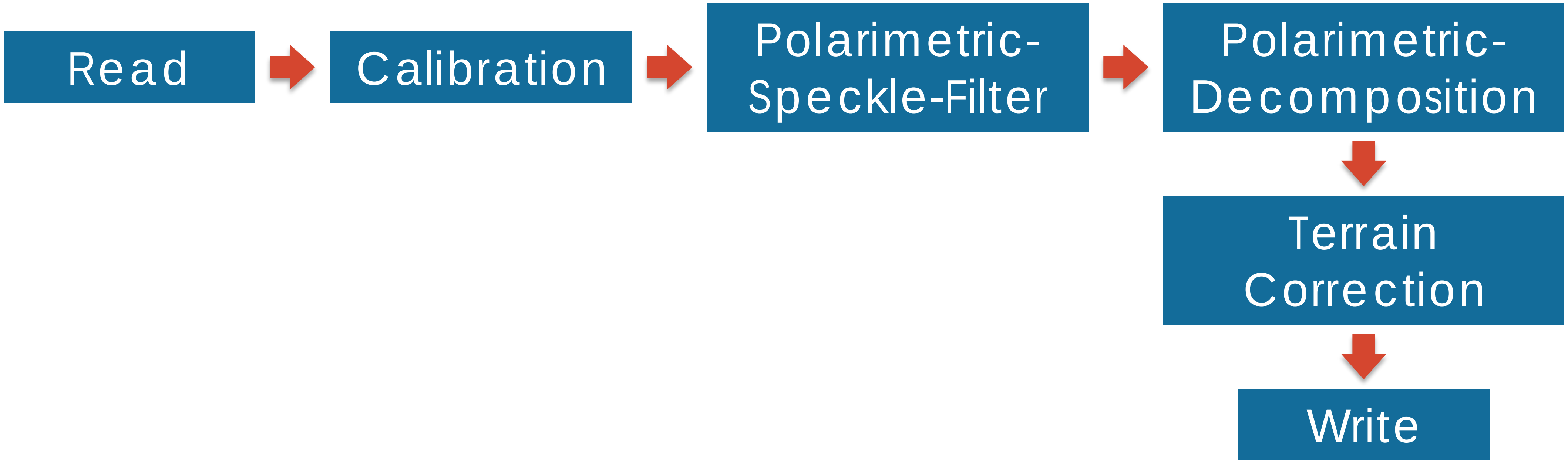
RapidEye natural color image acquired on July 22, 2016

RGB false color composite of RADARSAT-2 images acquired on July 27th , 2016.

(R=HH, G=HV,B=VV)

Pre-Processing RADARSAT-2 QP SLC data with SNAP

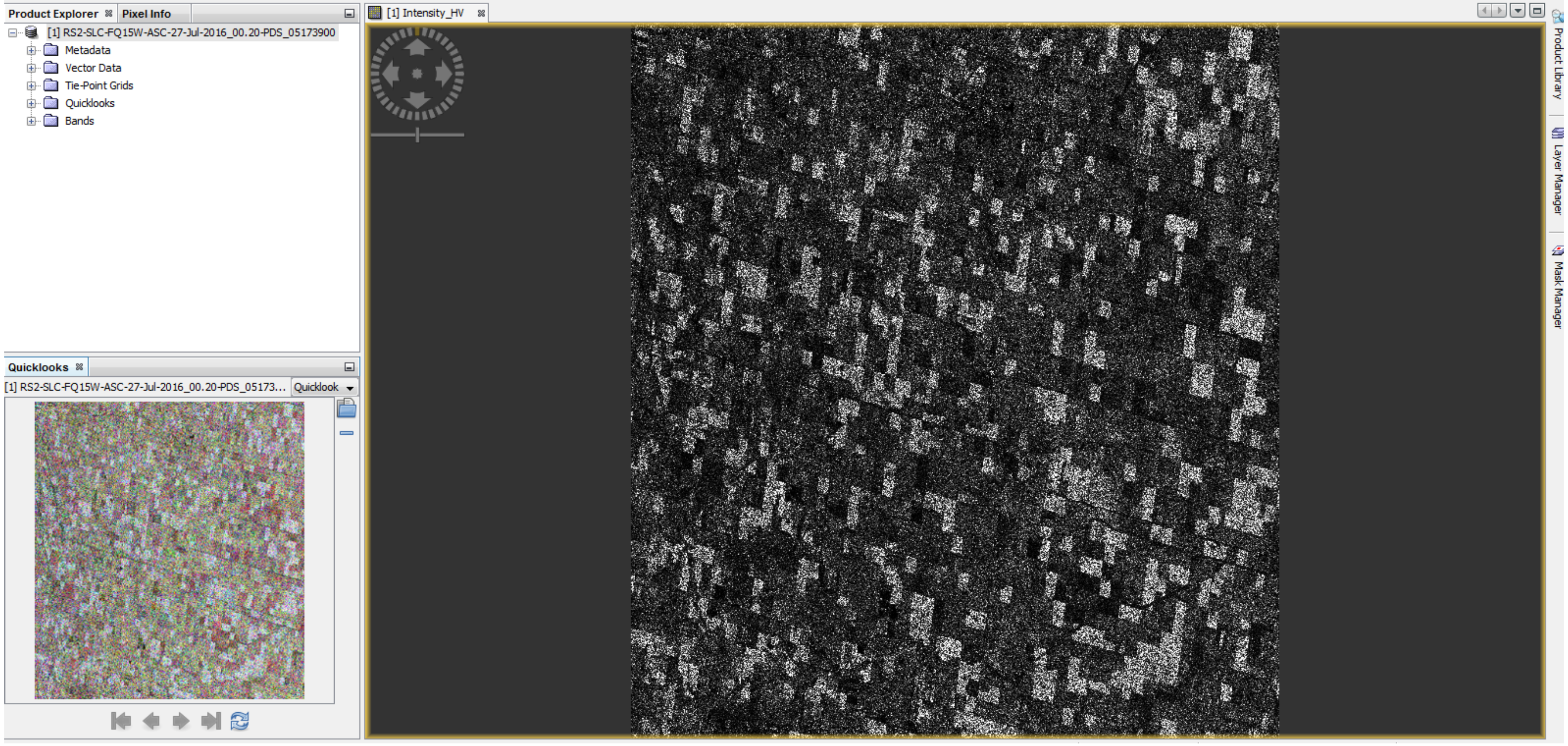
Implement Polarimetric Decomposition



Pre-Processing RADARSAT-2 QP SLC data with SNAP (6.0)

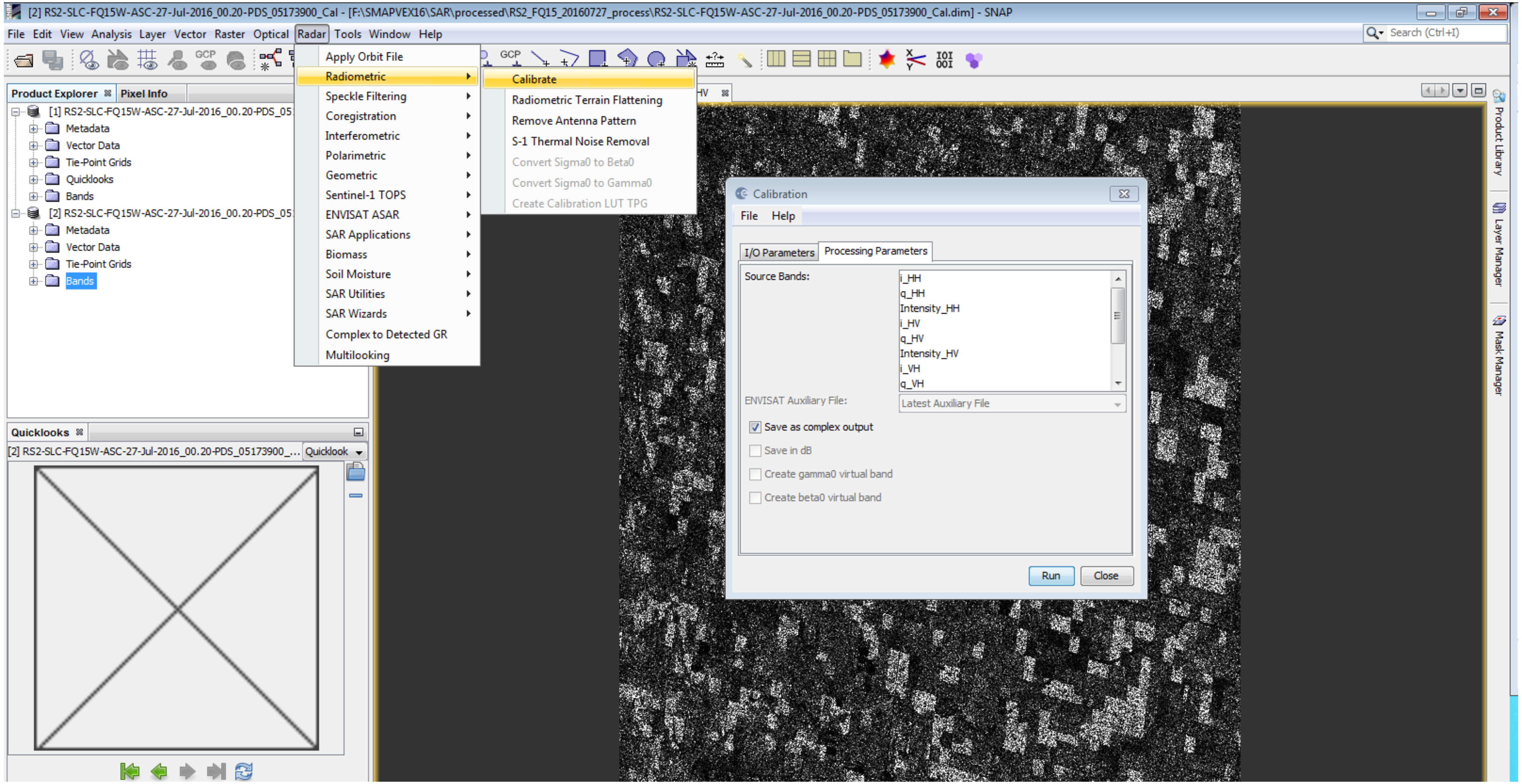
Read RS2 SLC .zip Image

Using RADARSAT-2 quad pol FQ15W mode SLC data acquired on July 27, 2016, over Carman, MB, Canada



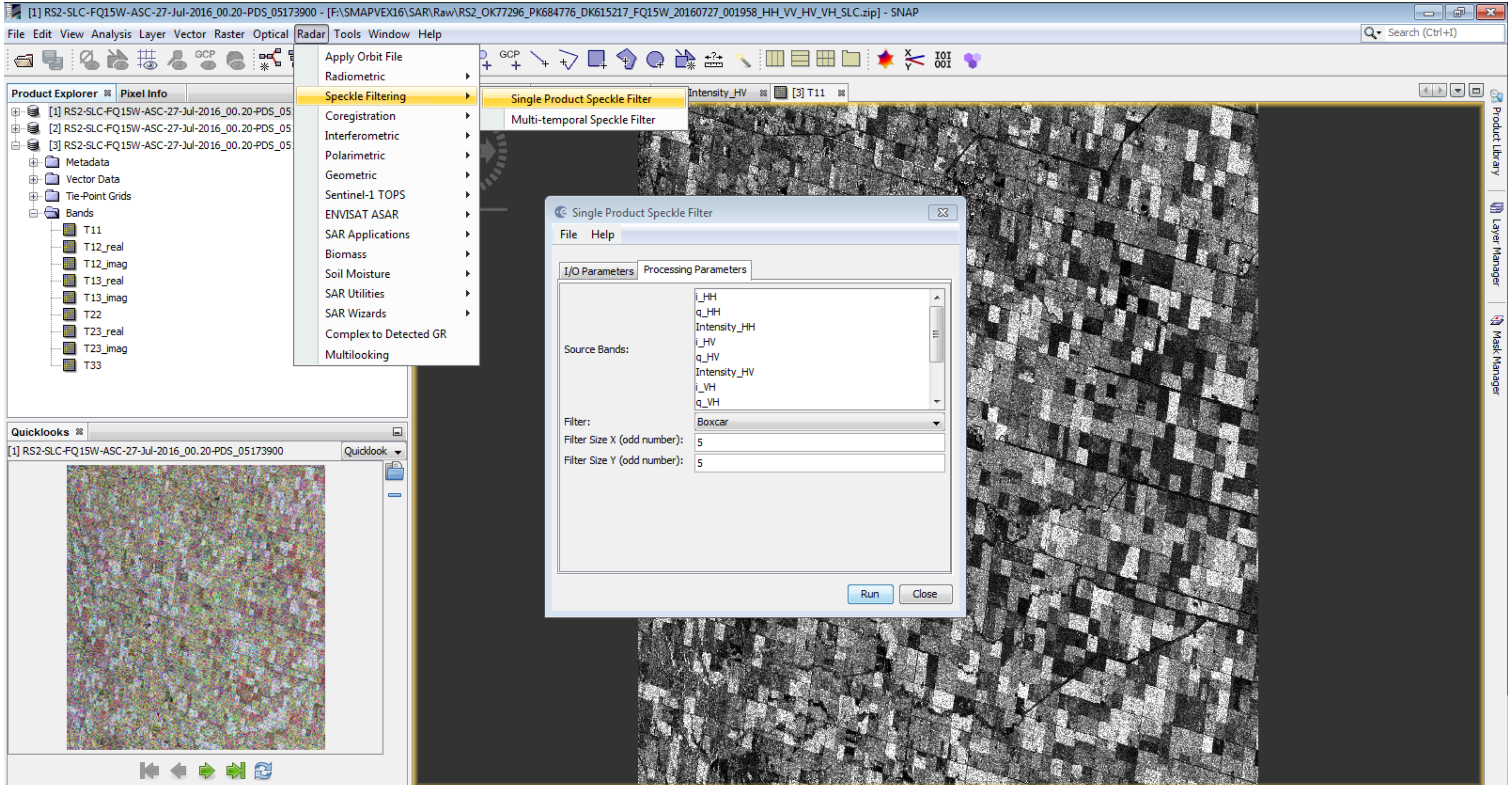
Pre-Processing RADARSAT-2 QP SLC data with SNAP (6.0)

Calibration: Convert Pixel Values to Radar Backscatter



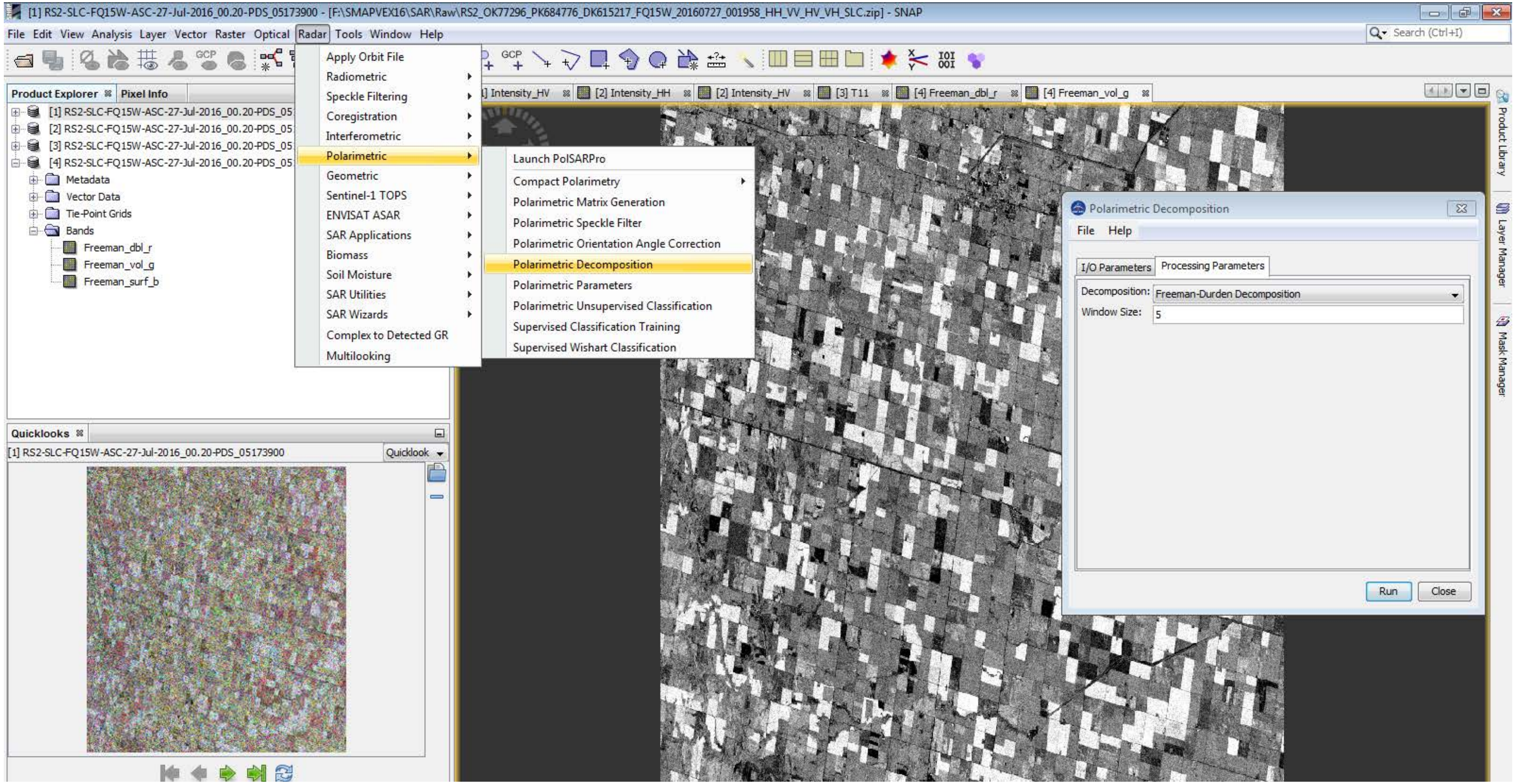
Pre-Processing RADARSAT-2 QP SLC data with SNAP (6.0)

Speckle Filter -- 5 by 5 Boxcar



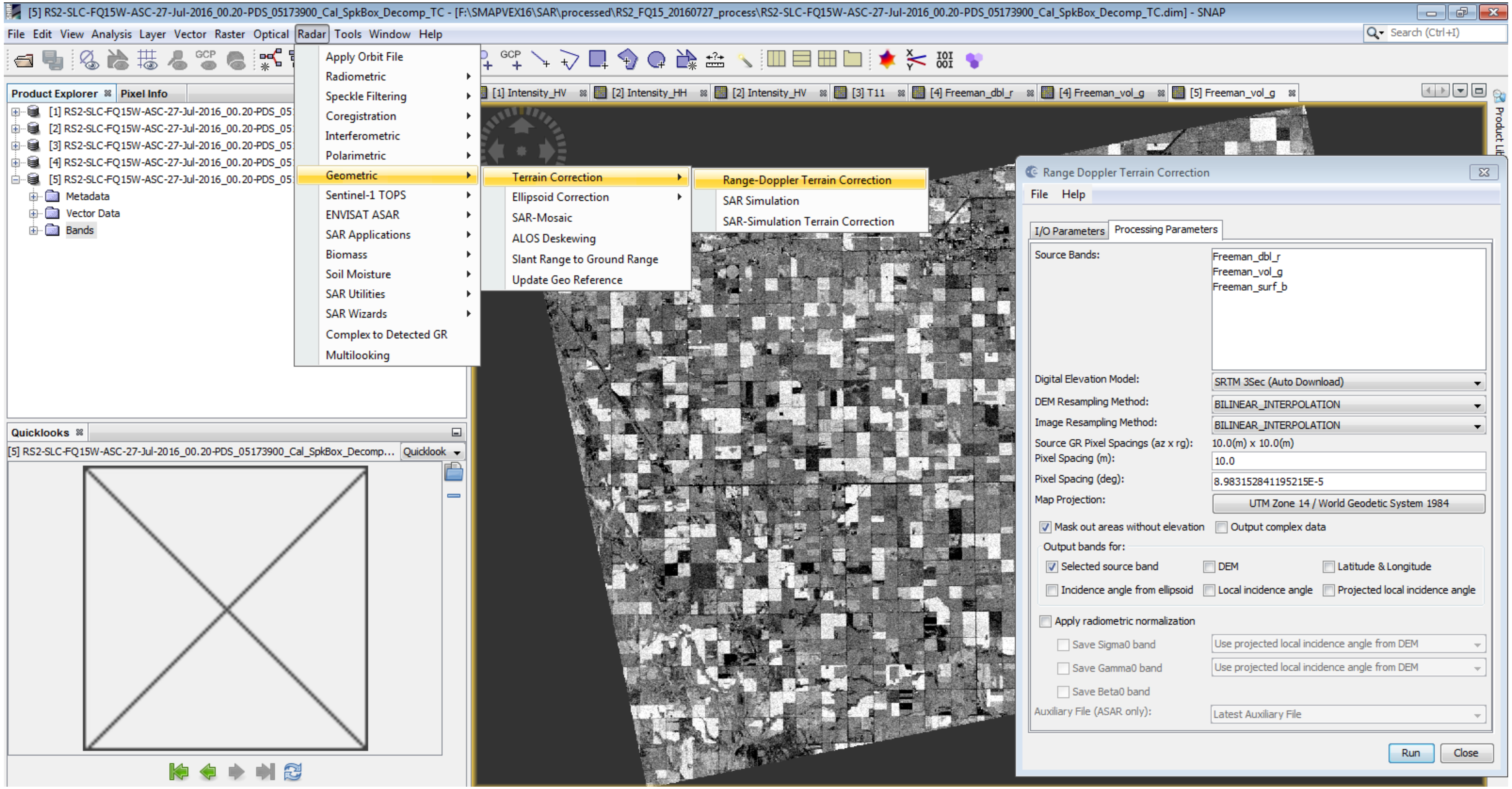
Pre-Processing RADARSAT-2 QP SLC data with SNAP (6.0)

Freeman Durden Decomposition



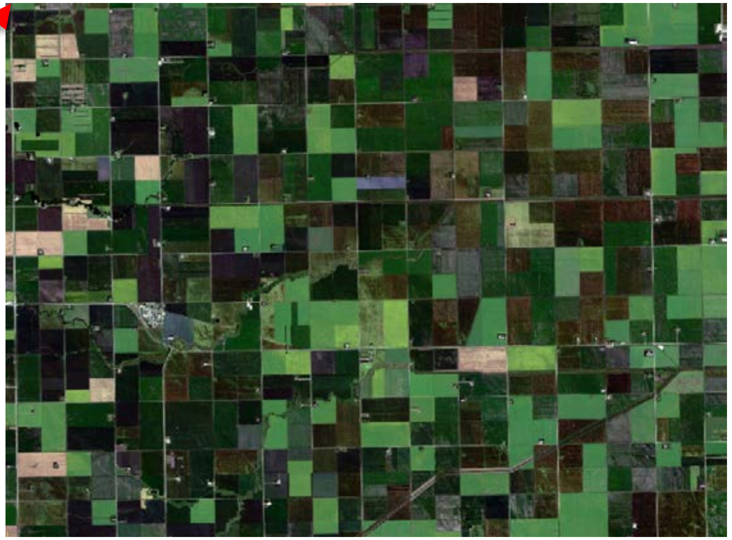
Pre-Processing RADARSAT-2 QP SLC data with SNAP (6.0)

Terrain-Correction

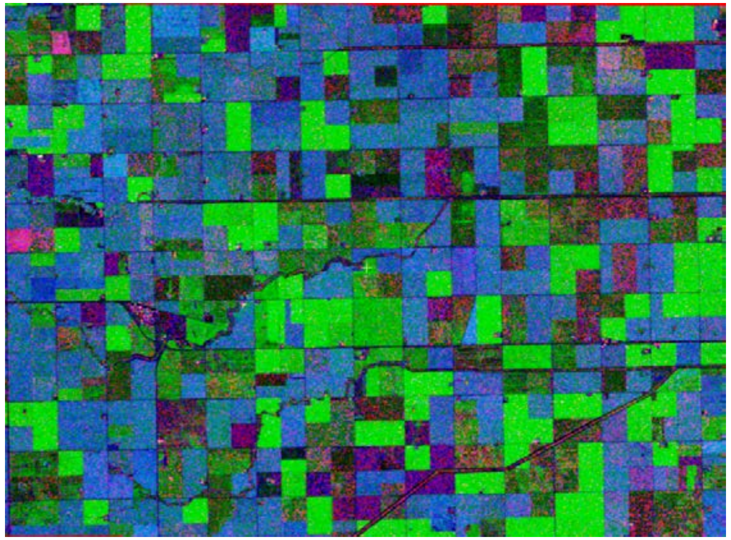


Pre-Processing RADARSAT-2 QP SLC data with SNAP (6.0)

Freeman-Durden decomposition image extracted from RADARSAT-2 QP data acquired on July 27, 2016



RapidEye natural color image acquired on July 22, 2016

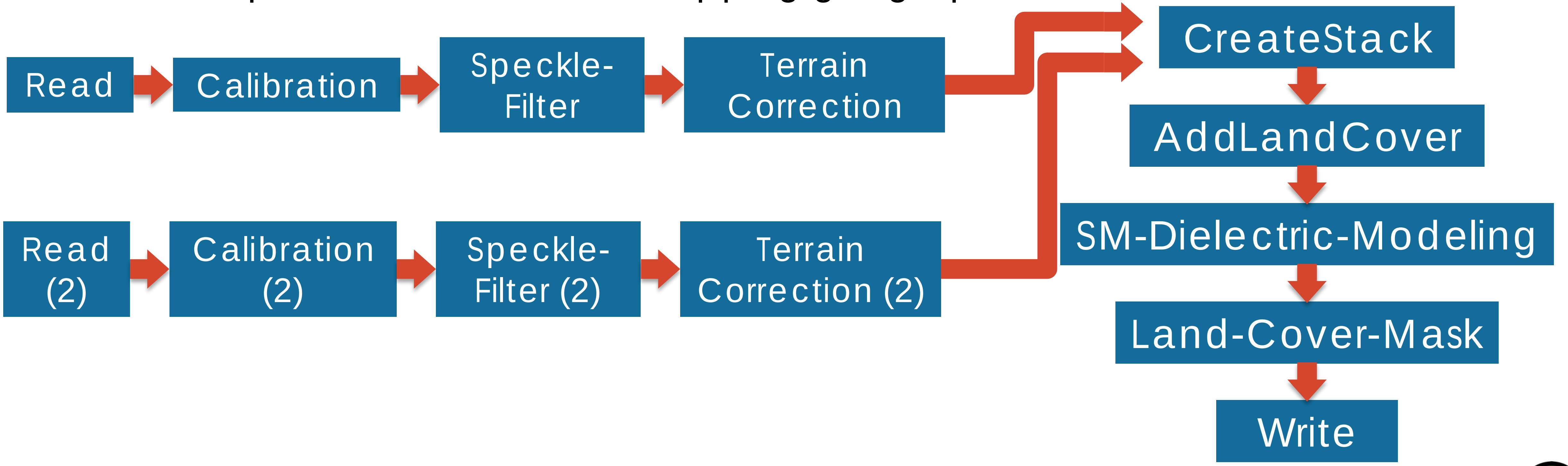


RGB false color composite of Freeman-Durden decomposition images (extracted from RADARSAT-2 acquired on July 27, 2016).

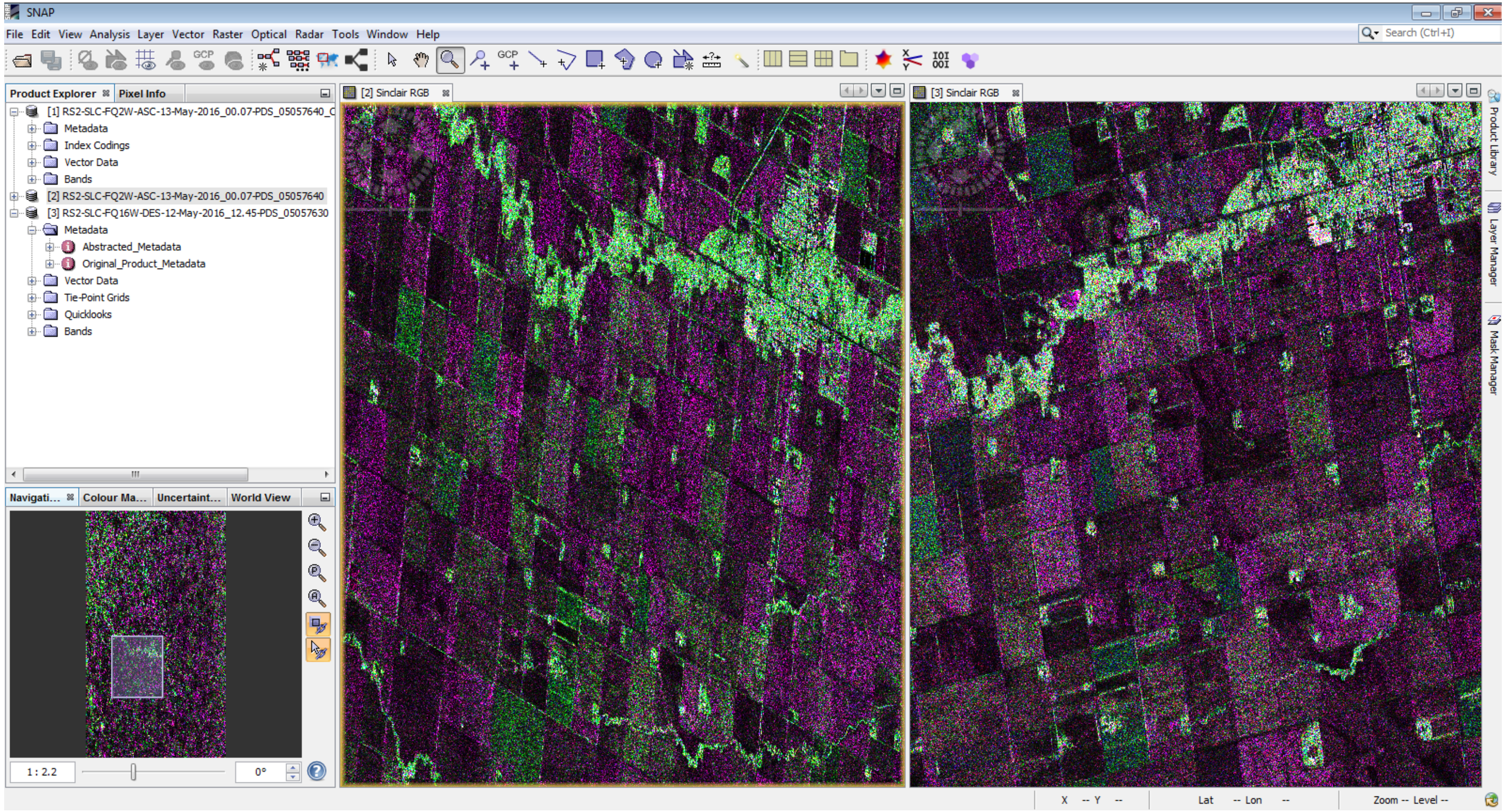
R=Surface, **G=Volume**, **B=Double**

Soil Moisture Processing with the Soil Moisture Toolbox in the SNAP Software Using RADARSAT-2 Data

- Soil moisture map derived from one a.m. RADARSAT-2 acquisition and one p.m. RADARSAT-2 acquisition using multi-angle approach
- RADARSAT-2 a.m. and p.m. data collected only one date apart. The inversion method is performed on the overlapping geographic area.



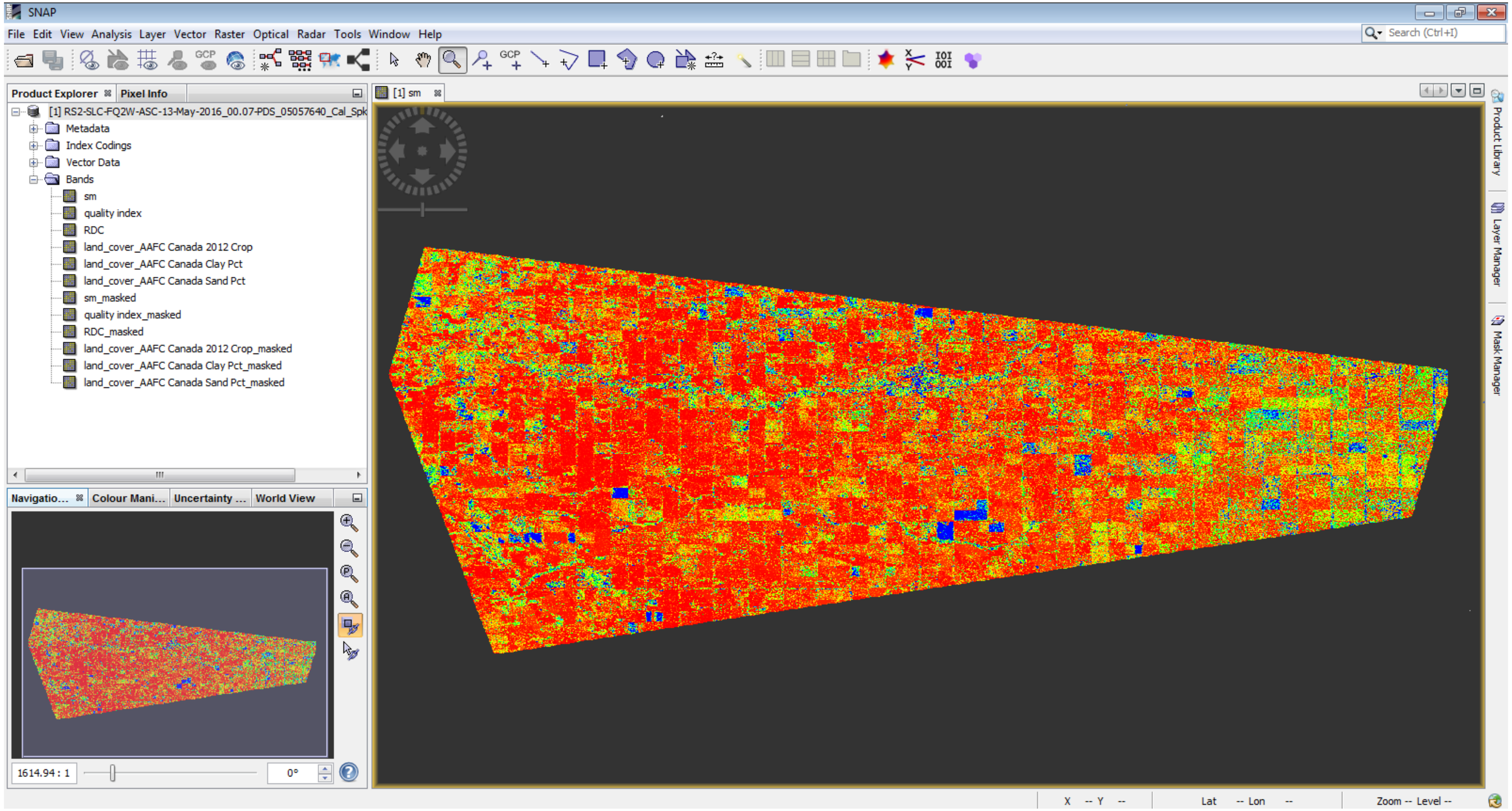
Soil Moisture Processing with the Soil Moisture Toolbox in the SNAP Software Using RADARSAT-2 Data



RADARSAT-2 SAR image acquired on May 13, 2016 Ascending pass

RADARSAT-2 SAR image acquired on May 12, 2016 Descending pass

Soil Moisture Processing with the Soil Moisture Toolbox in the SNAP Software Using RADARSAT-2 Data

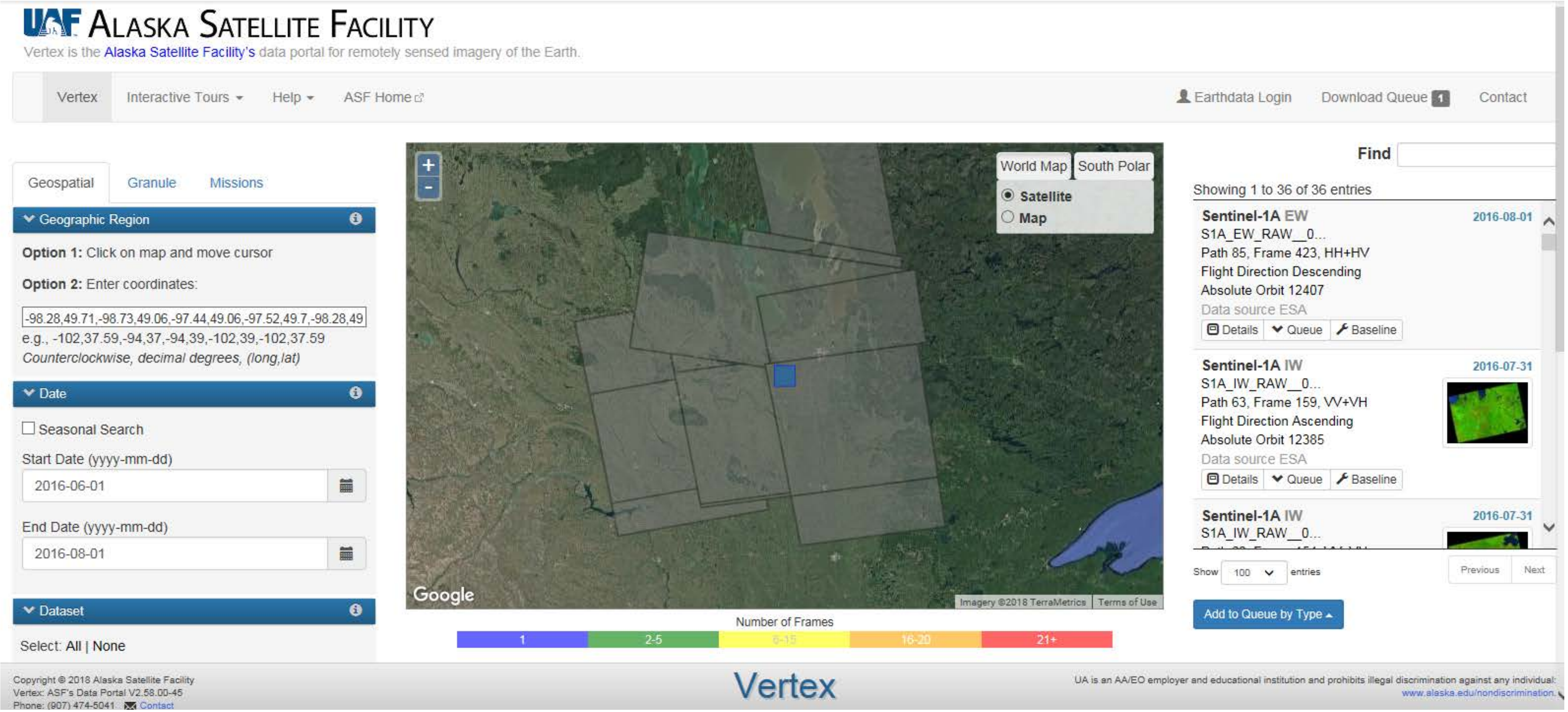


Pre-Processing Sentinel-1 SAR GRDH Data with SNAP (v 6.0)

Read → Apply-Orbit-File → Multilook → Calibration → Speckle-Filter → Terrain Correction → Write

Access Sentinel -1 SAR data from Vertex

https://vertex.daac.asf.alaska.edu/

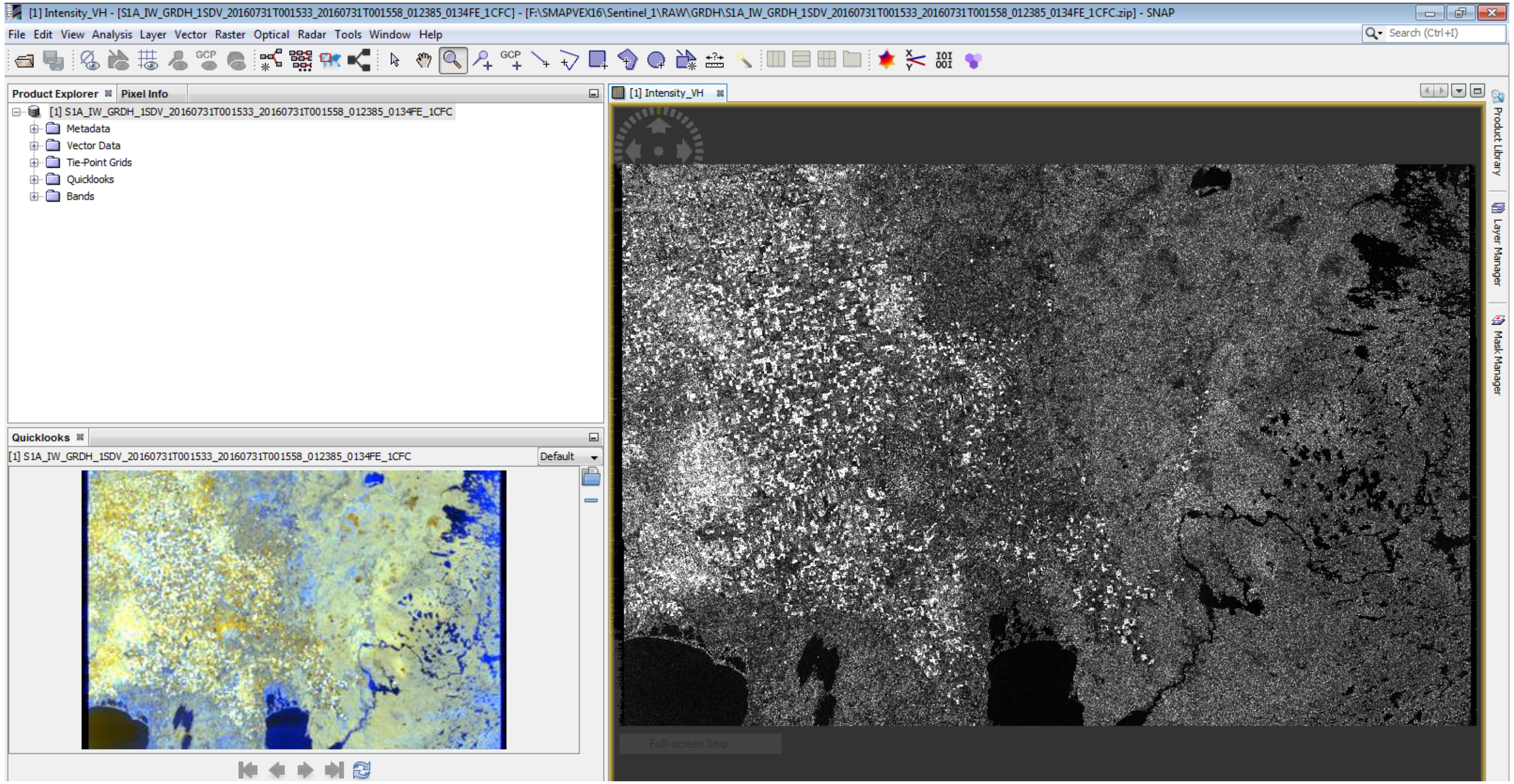


Sentinel -1 SAR GRDH Data Pre-Processing with SNAP (v 6.0)

Read Sentinel-1 .zip Image

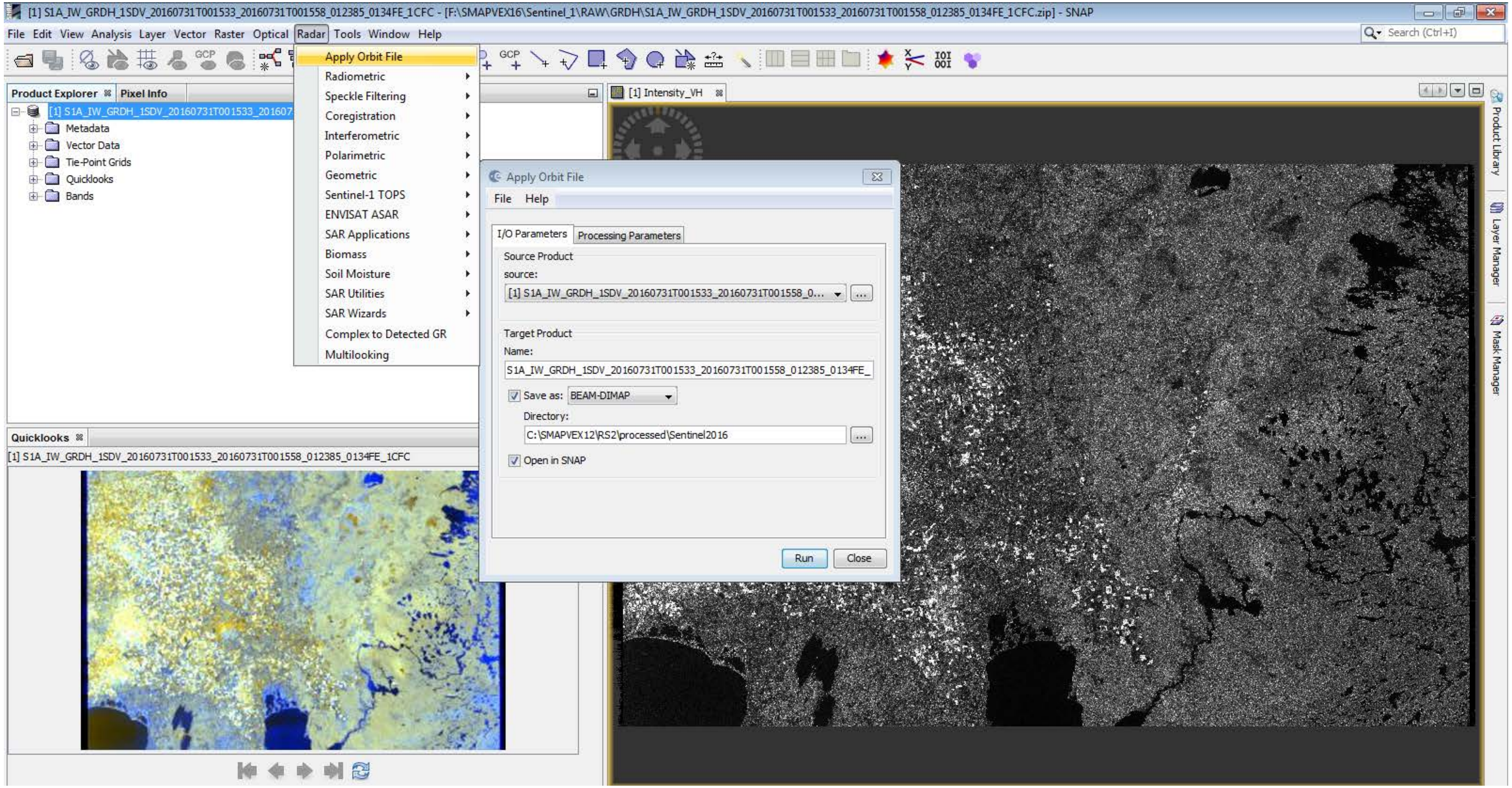
Using Sentinel-1A IW mode GRDH level -1 data acquired on July 31, 2016, over Carman, MB, Canada

HR	20 x 22	10 x 10	5 x 1	4.4



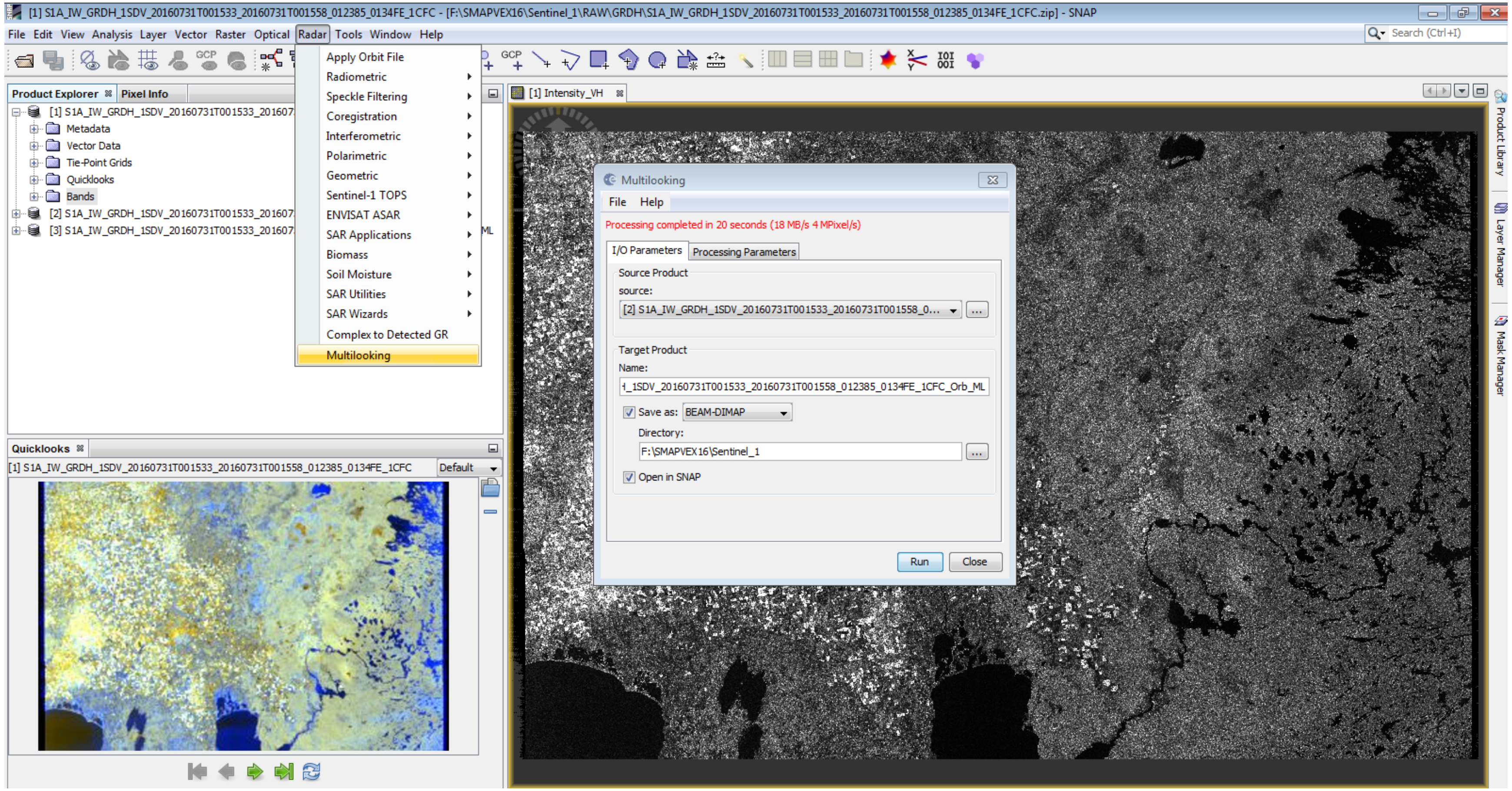
Sentinel -1 SAR GRDH Data Pre-Processing with SNAP (v 6.0)

Orbital Correction



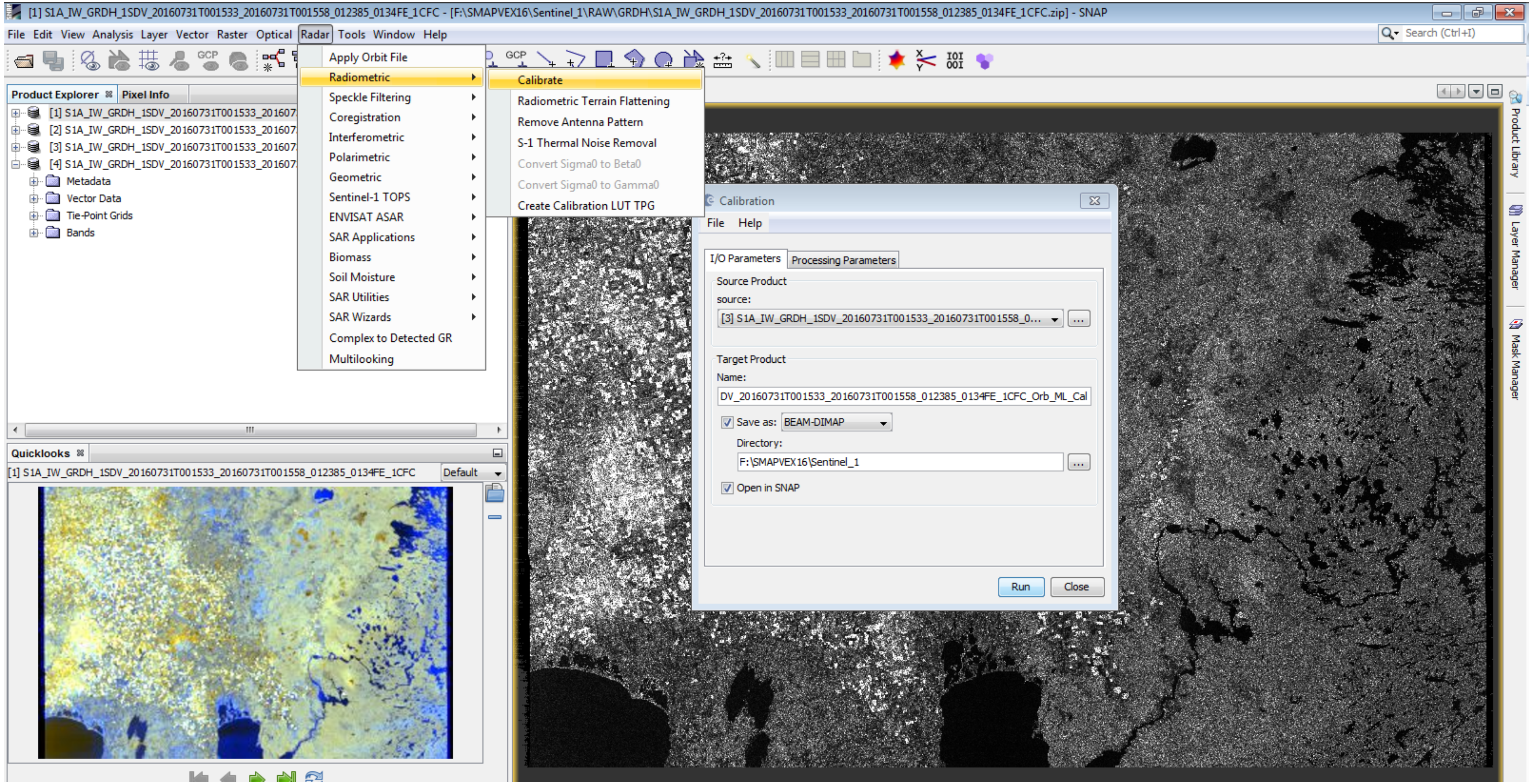
Sentinel -1 SAR GRDH Data Pre-Processing with SNAP (v 6.0)

Multilooking: average the power across a number of lines in both the azimuth and range directions, 3 by 3



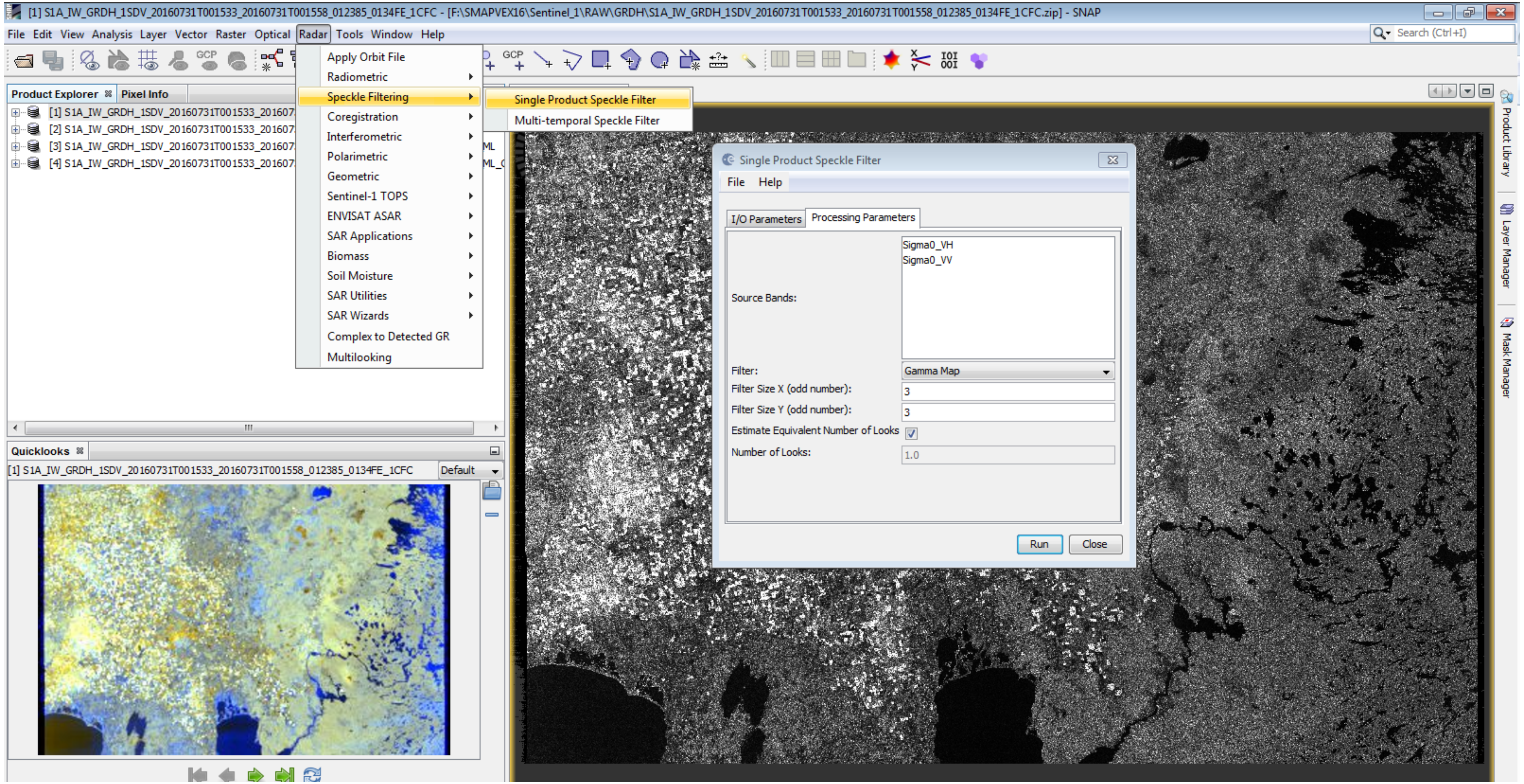
Sentinel -1 SAR GRDH Data Pre-Processing with SNAP (v 6.0)

Calibration: Convert Pixel Values to Radar Backscatter



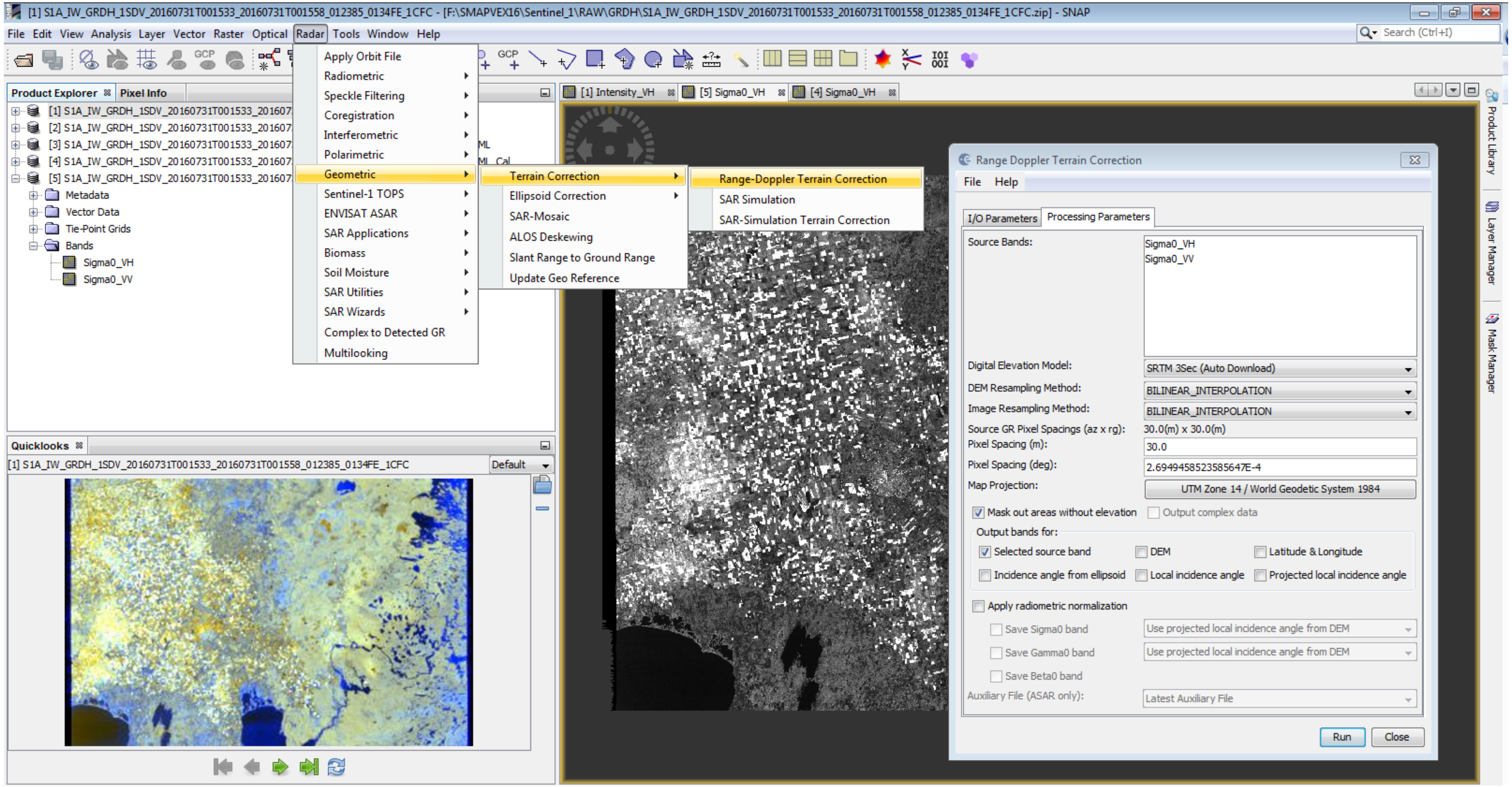
Sentinel -1 SAR GRDH Data Pre-Processing with SNAP (v 6.0)

Speckle Filter -- 3 by 3 Gamma Map

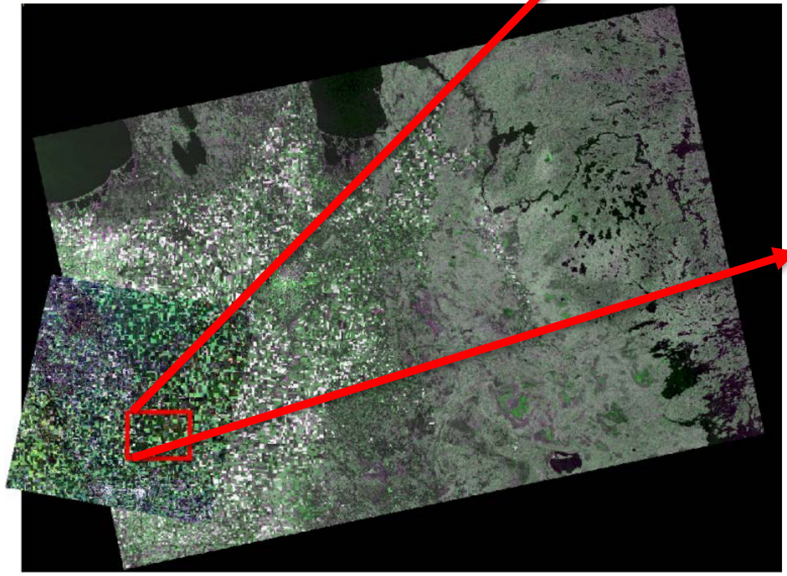


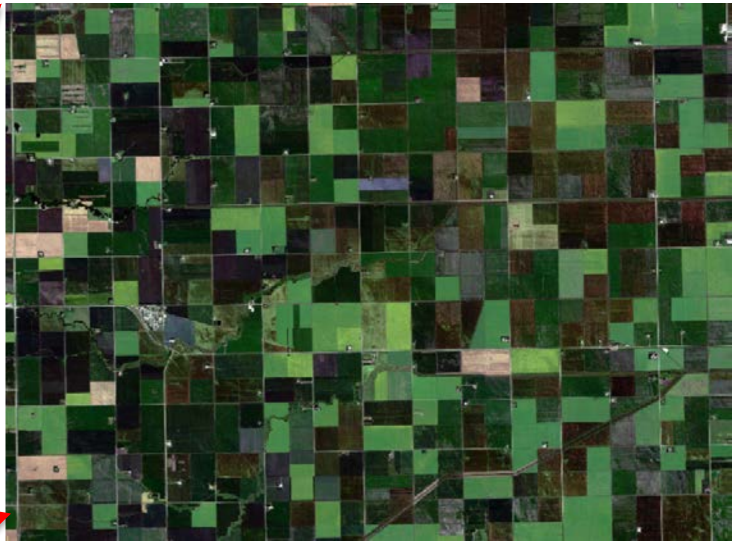
Sentinel -1 SAR GRDH Data Pre-Processing with SNAP (v 6.0)

Terrain-Correction

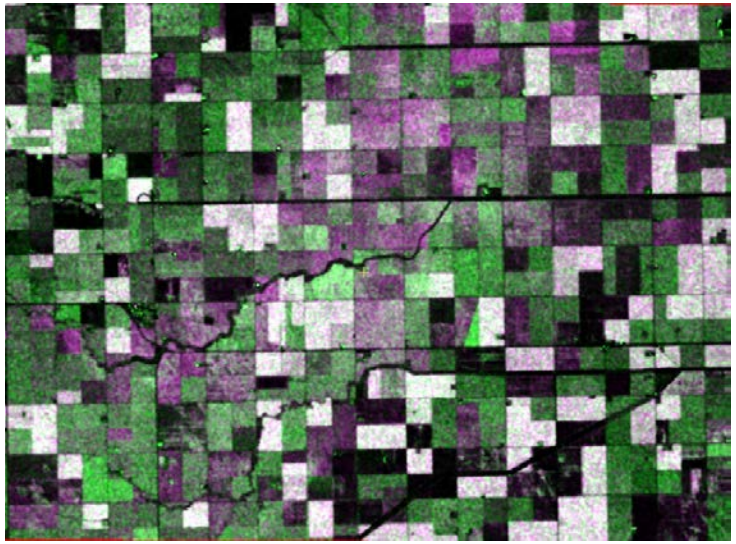


Sentinel -1 SAR GRDH Data Pre-Processing with SNAP (v 6.0)





RapidEye natural color image acquired on July 22, 2016

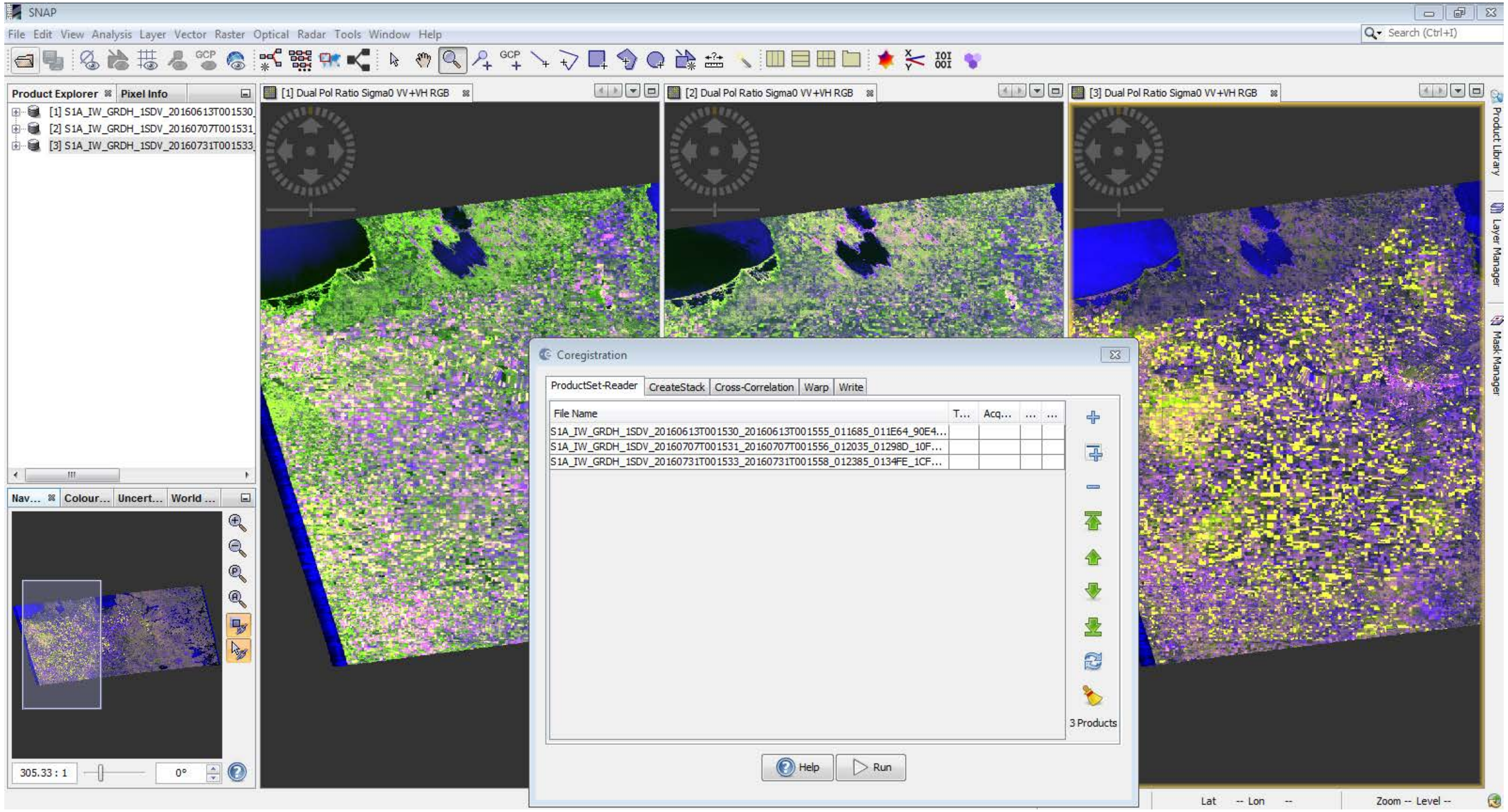


RGB false color composite of Sentinel 1 SAR VH,VV image acquired on July 31, 2016

(R=HH,G=HV,B=HH)

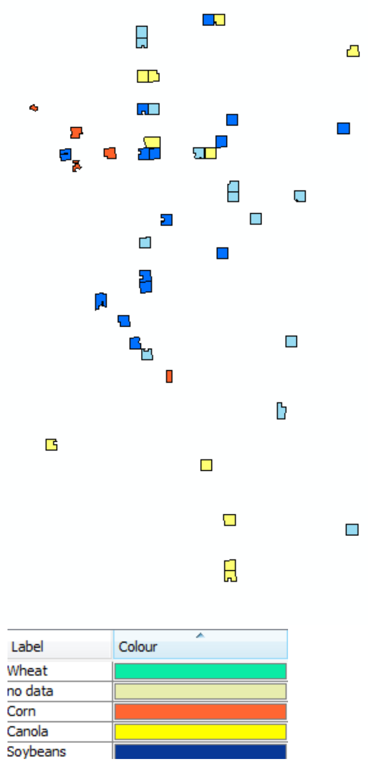
Sentinel -1 SAR GRDH Data Pre-Processing with SNAP (v 6.0)

Co-Registration: spatial alignment of images acquired on June 13, July 7, and July 31, 2016

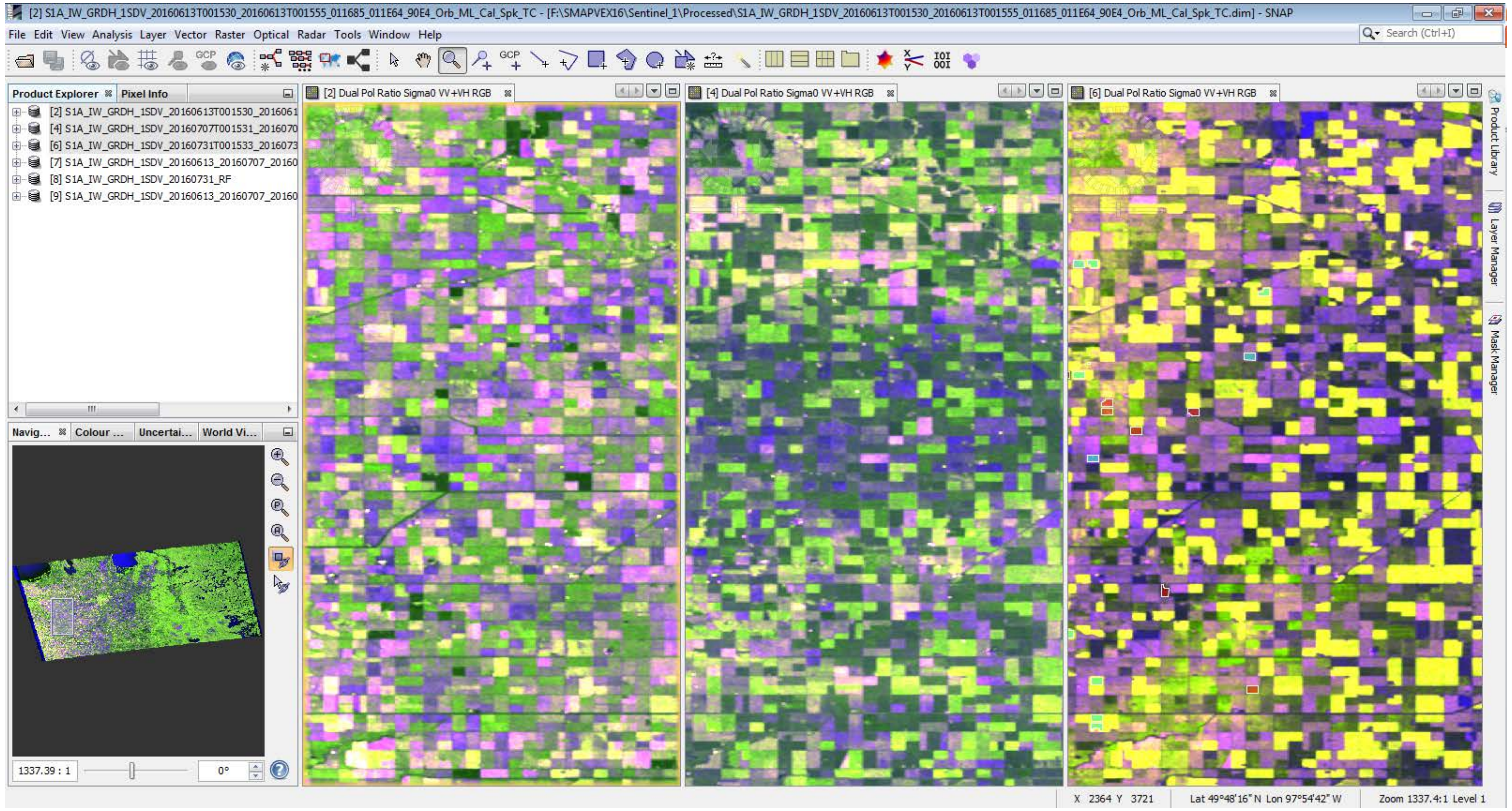


Crop Classification Using Multi-Temporal Sentinel-1 SAR Images with SNAP

Data preparation for supervised classification



Training data collected from 2016 SMAPVEX field campaign



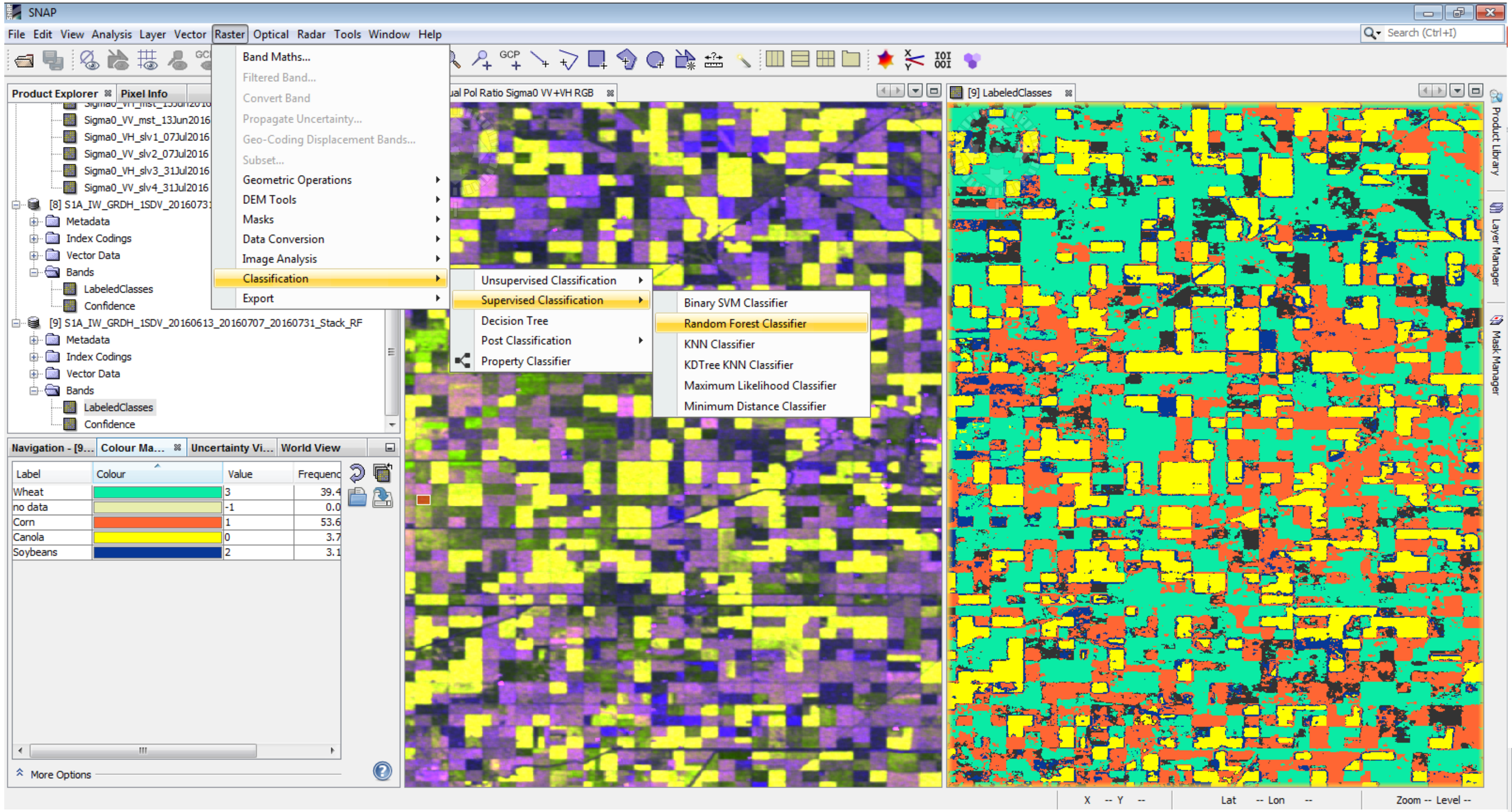
Sentinel-1 SAR image acquired on June 13, 2016

Sentinel-1 SAR image acquired on July 7, 2016

Sentinel-1 SAR image acquired on July 31, 2016

Crop Classification Using Multi-Temporal Sentinel-1 SAR Images with SNAP

Random Forest Classification of Crop Type Maps



crop type classification map