Agriculture and Agri-Food Canada   Agriculture et Agroalimentaire Canada

Case Study: Estimating Soil Moisture from SAR

Carleton University
Canada's Capital University

Natural Resources Canada   Ressources naturelles Canada

CSA ASC

Agriculture and Agri-Food Canada   Agriculture et Agroalimentaire Canada

Why Measure and Monitor Soil Moisture?

Flooding, excessive wetness, drought, pests, and disease

2017 and 2019: Record floods on Ottawa River

2001-02: Drought cost the Canadian economy $5.8 billion

2017: April/May set new rainfall records in eastern Canada

2014: Excess moisture insurance payments to Manitoba farmers who were unable to seed **~$65 million** (2,400 claims)

2011-12: more than **$420 million** was spent by Agri-Recovery on climate related disasters mostly related to excess moisture.

2011**:** total costs from the 2011 Manitoba Flood topped **$1 billion** with over **$320 million** going to the agriculture sector in Crop Insurance and Agri-Recovery Programs**.**

The common link: Not enough or too much soil moisture

Image source: AAFC

Why SAR?

- microwave response is very sensitive to the soil dielectric, which is a function of the amount of water in the soil

Careful: Penetration depth is dependent upon frequency and how wet soil is, but regardless, SARs are only sensing the top few centimetres

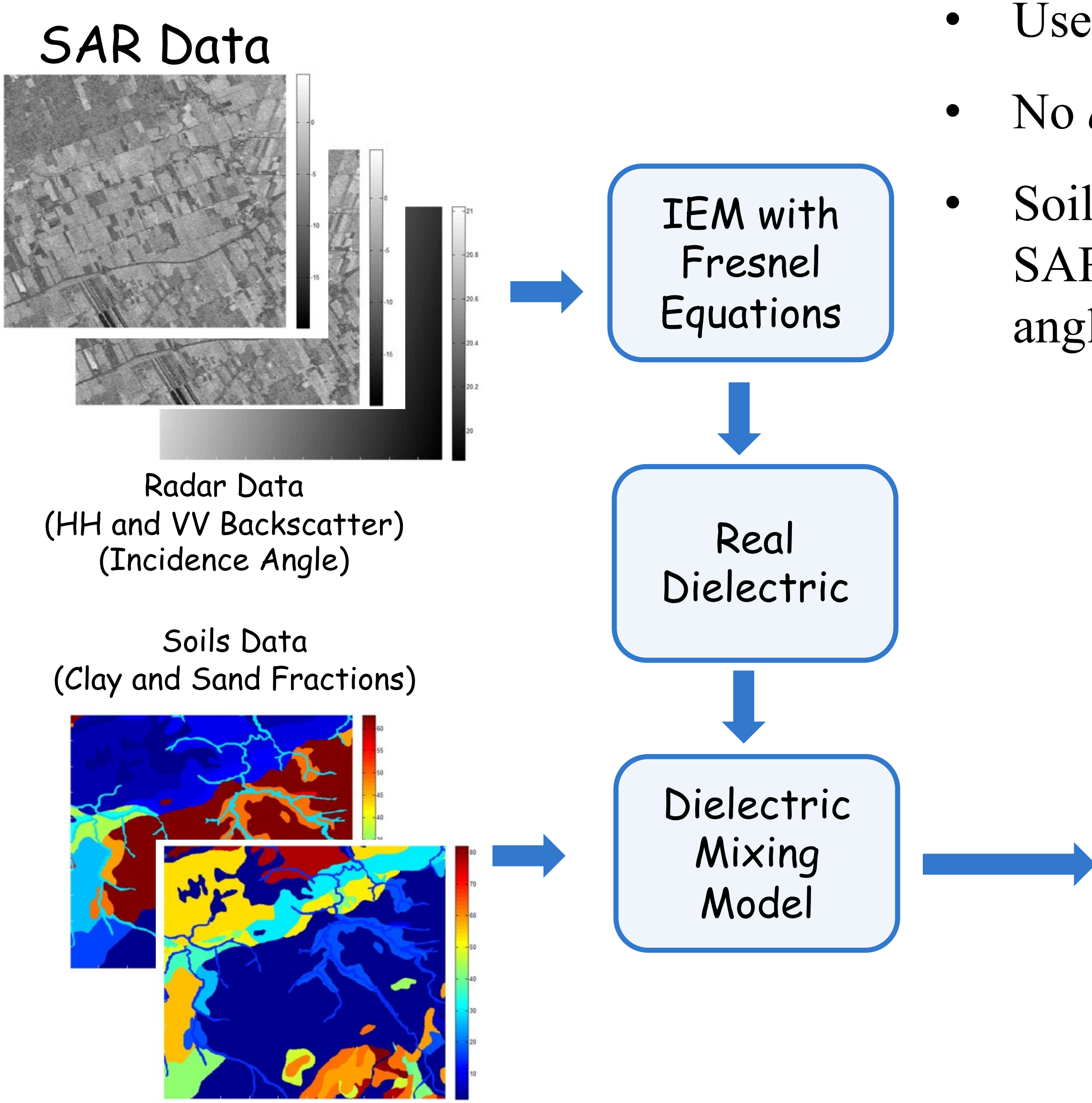
- AAFC tested several retrieval models and selected the IEM given its physical basis and larger range of validity (in terms of soil moisture and roughness)

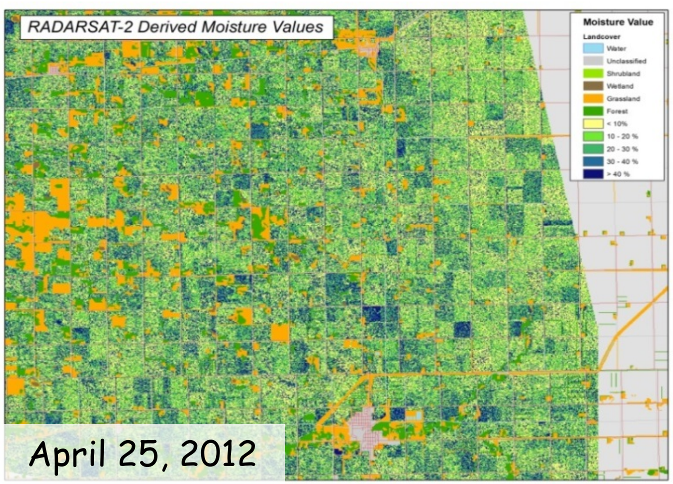
- **original Integrative Equation Model (IEM)**
  - 3 unknowns (dieletric constant, roughness RMS, roughness correlation length)
  - requires at least 3 measures of backscatter to resolve these 3 unknowns
  - backscatter measured at different polarizations or incidence angles can be used

- **Calibrated IEM (CIEM)**
  - reduces number of unknowns to 2 (dielectric constant and roughness RMS)
  - requires only two backscatter measures to resolve

Overview of Soil Moisture Retrieval

- Uses Integral Equation Model (IEM)
- No *a priori* information is needed
- Soil moisture is retrieved using only SAR data (backscatter and incidence angle)





Information and images from: Merzouki and McNairn, 2015.

Backscatter Model Inversion Schemes

Ascending mode (evening) image ($HH_{\theta 1}$, $VV_{\theta 1}$)

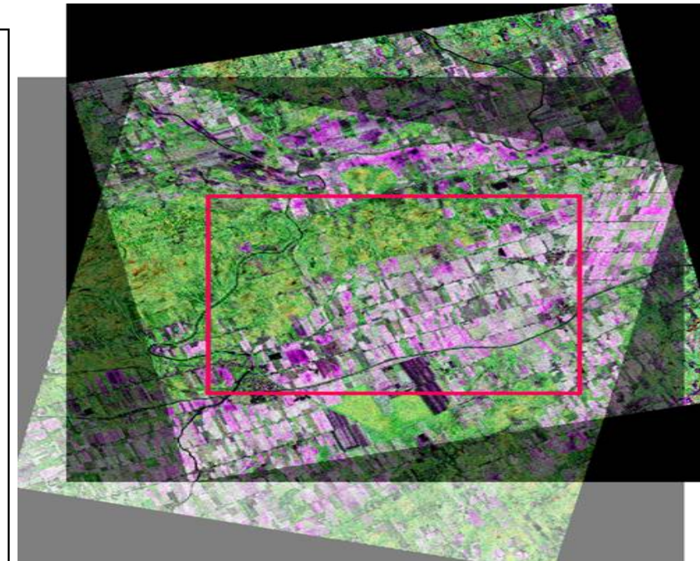
→ IEM/CIEM ↔ Inversion Schemes

Descending mode (morning) image ($HH_{\theta 2}$, $VV_{\theta 2}$)

where
θ1 = image acquired at incidence angle 1
θ2 = image acquired at incidence angle 2

<u>Inversion Schemes:</u>

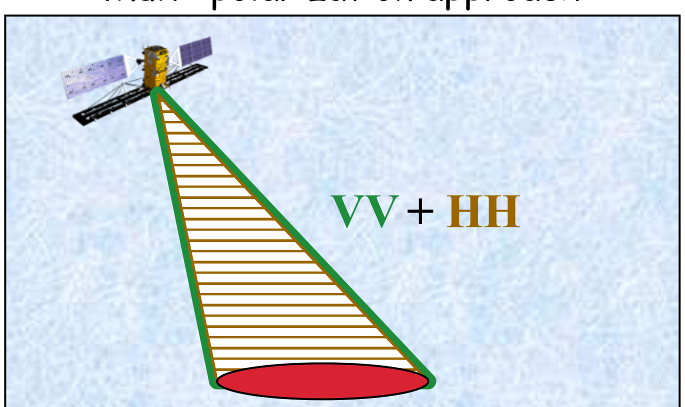
- Multi-polarisation:
  - $HH_{\theta 1}$ - $VV_{\theta 1}$
  - $HH_{\theta 2}$ - $VV_{\theta 2}$
- Multi-angles:
  - $HH_{\theta 1}$ - $HH_{\theta 2}$
  - $HH_{\theta 1}$ - $VV_{\theta 2}$
  - $VV_{\theta 1}$ - $VV_{\theta 2}$
  - $VV_{\theta 1}$ - $HH_{\theta 2}$
- Hybrid:
  - $HH_{\theta 1}$ - $VV_{\theta 1}$ - $HH_{\theta 2}$
  - $HH_{\theta 1}$ - $VV_{\theta 1}$ - $VV_{\theta 2}$
  - $HH_{\theta 2}$ - $VV_{\theta 2}$ - $HH_{\theta 1}$
  - $HH_{\theta 2}$ - $VV_{\theta 2}$ - $VV_{\theta 1}$
  - $HH_{\theta 1}$ - $VV_{\theta 1}$ - $HH_{\theta 2}$ - $VV_{\theta 2}$



Multi-angles configuration using 2011-04-17 acquisition pair (FQ2-FQ5)

Model inversion scenarios using original IEM and calibrated IEM

Multi-polarization approach



Multi-angle approach

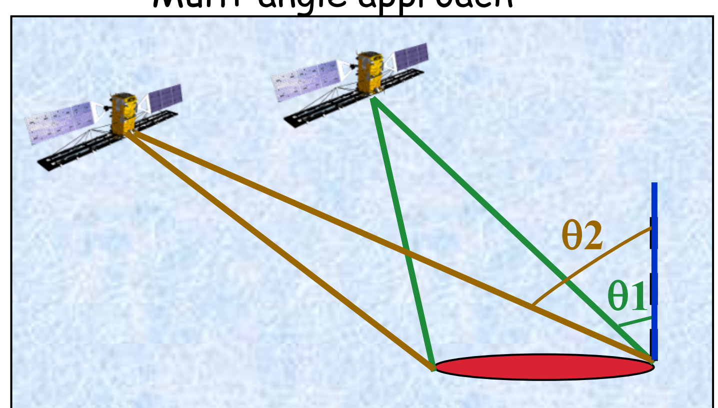


Image source: AAFC

IEM Inversion Method (1)

- Inversion of the IEM is difficult to achieve analytically. Therefore, a Lookup Table (LUT) approach was developed to estimate soil moisture.
- This method involves the creation of a table of backscatter values associated with surface real dielectric constant, roughness parameters and incidence angle values generated by performing multiple runs of the IEM within its validity range.

Roughness rms | Roughness correlation length | Dielectric constant | HH backscatter | VV backscatter

Variables - IEM_cb_nt_RDC

IEM_cb_nt_RDC <583088x5 double>

	1	2	3	4	5	6	7
1	0.3000	1	3.1258	-14.8125	-11.6705		
2	0.3000	1	3.4299	-14.1961	-11.0004		
3	0.3000	1	3.7481	-13.6548	-10.4100		
4	0.3000	1	4.0804	-13.1746	-9.8848		
5	0.3000	1	4.4268	-12.7451	-9.4138		
6	0.3000	1	4.7873	-12.3582	-8.9885		
7	0.3000	1	5.1620	-12.0074	-8.6021		
8	0.3000	1	5.5507	-11.6876	-8.2493		
9	0.3000	1	5.9536	-11.3948	-7.9255		
10	0.3000	1	6.3706	-11.1254	-7.6273		
11	0.3000	1	6.8017	-10.8766	-7.3515		
12	0.3000	1	7.2469	-10.6460	-7.0955		
13	0.3000	1	7.7062	-10.4317	-6.8573		
14	0.3000	1	8.1796	-10.2319	-6.6350		
15	0.3000	1	8.6671	-10.0451	-6.4269		

Original IEM Look Up Table

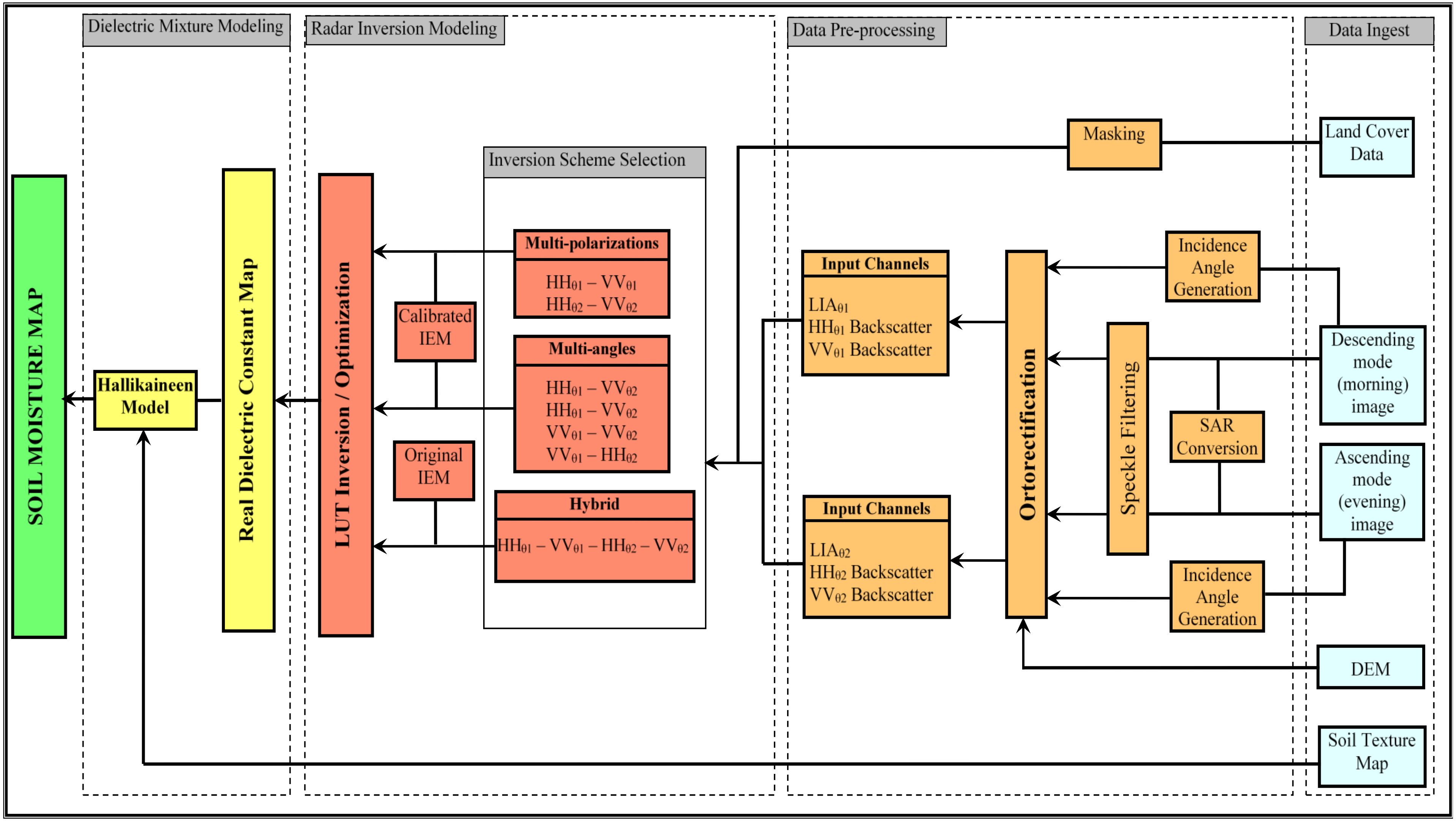
IEM Inversion Method (2)

- For both inversion methods (multi-pol and hybrid), the algorithm attempts to retrieve a global minimum through minimizing a cost function *Δ* representing the least square difference between measured ($\sigma^o_{pp,Meas}$) and simulated ($\sigma^o_{pp,IEM}$ or $\sigma^o_{pp,CIEM}$) backscatter coefficients of the form (*pp* is the transmitted/received polarization that can be HH or VV):

$$\Delta(Multi-pol) = \sqrt{\left(\sigma^o_{HH,Meas} - \sigma^o_{HH,CIEM}\right)^2 + \left(\sigma^o_{VV,Meas} - \sigma^o_{VV,CIEM}\right)^2}$$

$$\Delta(Hybrid) = \sqrt{\begin{array}{c}\left(\sigma^o_{HH\theta1,Meas} - \sigma^o_{HH\theta1,IEM}\right)^2 + \left(\sigma^o_{VV\theta1,Meas} - \sigma^o_{VV\theta1,IEM}\right)^2 \\ + \left(\sigma^o_{HH\theta2,Meas} - \sigma^o_{HH\theta2,IEM}\right)^2 + \left(\sigma^o_{VV\theta2,Meas} - \sigma^o_{VV\theta2,IEM}\right)^2\end{array}}$$

Soil Moisture Retrieval Processing Chain



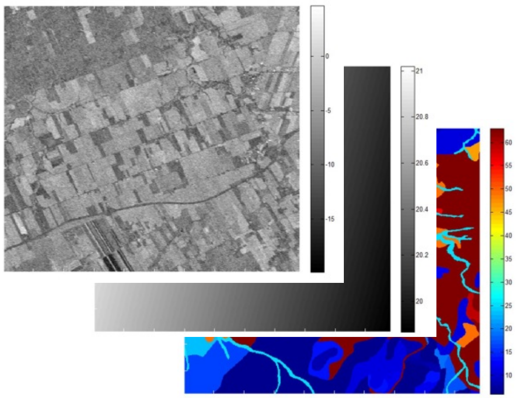
where

$LIA_{\theta 2}$ = local incidence angle band of the morning image

$LIA_{\theta 2}$ = local incidence angle band of the evening image

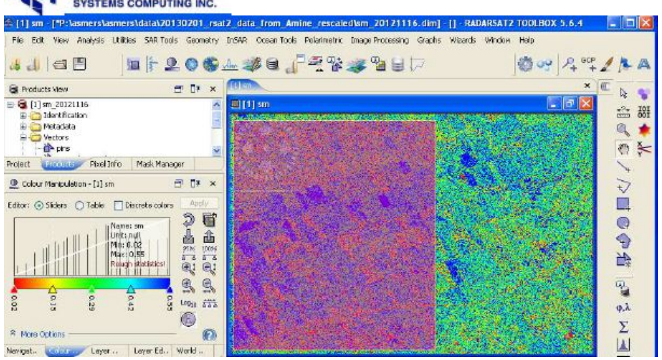
Soil Moisture Processing Using RADARSAT-2

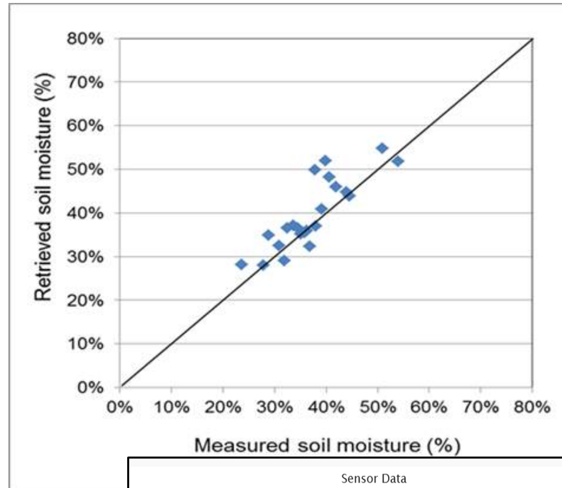
Inputs
- HH and VV backscatter
- incidence angle
- clay and soil fraction maps



Processing

ARRAY
SYSTEMS COMPUTING INC.





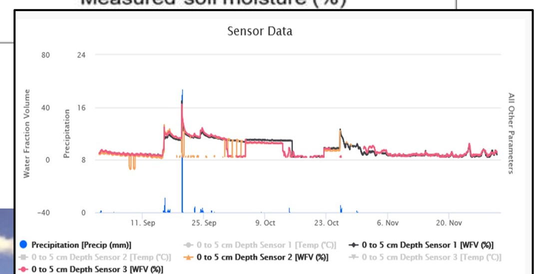


Image source: AAFC

Validation

Product Output

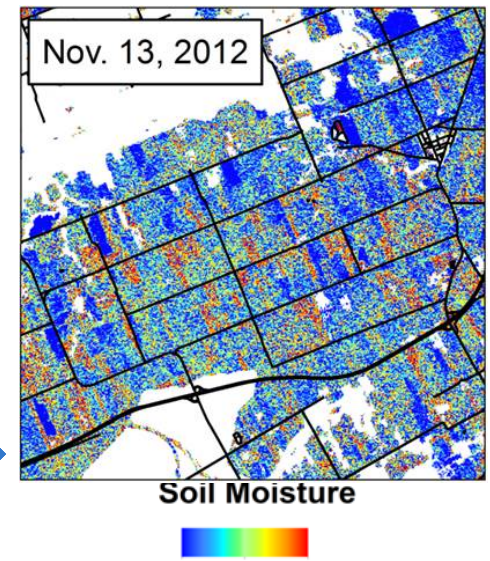
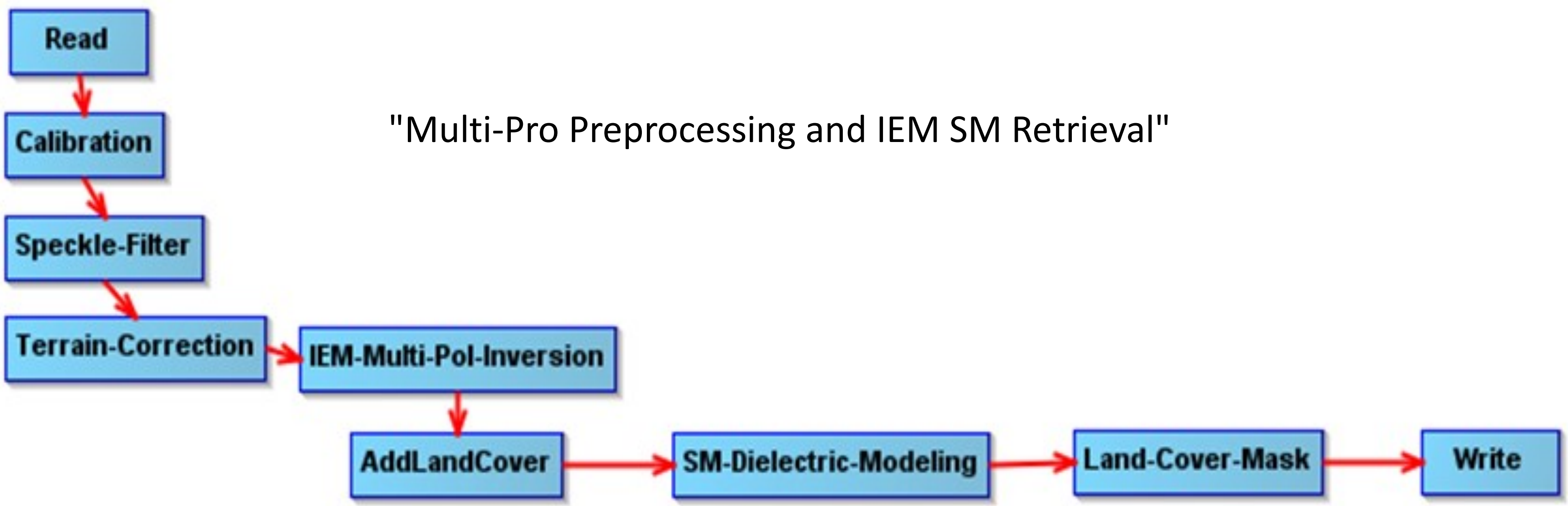


Image source: Merzouki and McNairn, 2015

Soil Moisture Processing in SNAP: Multi-pol Method (1)

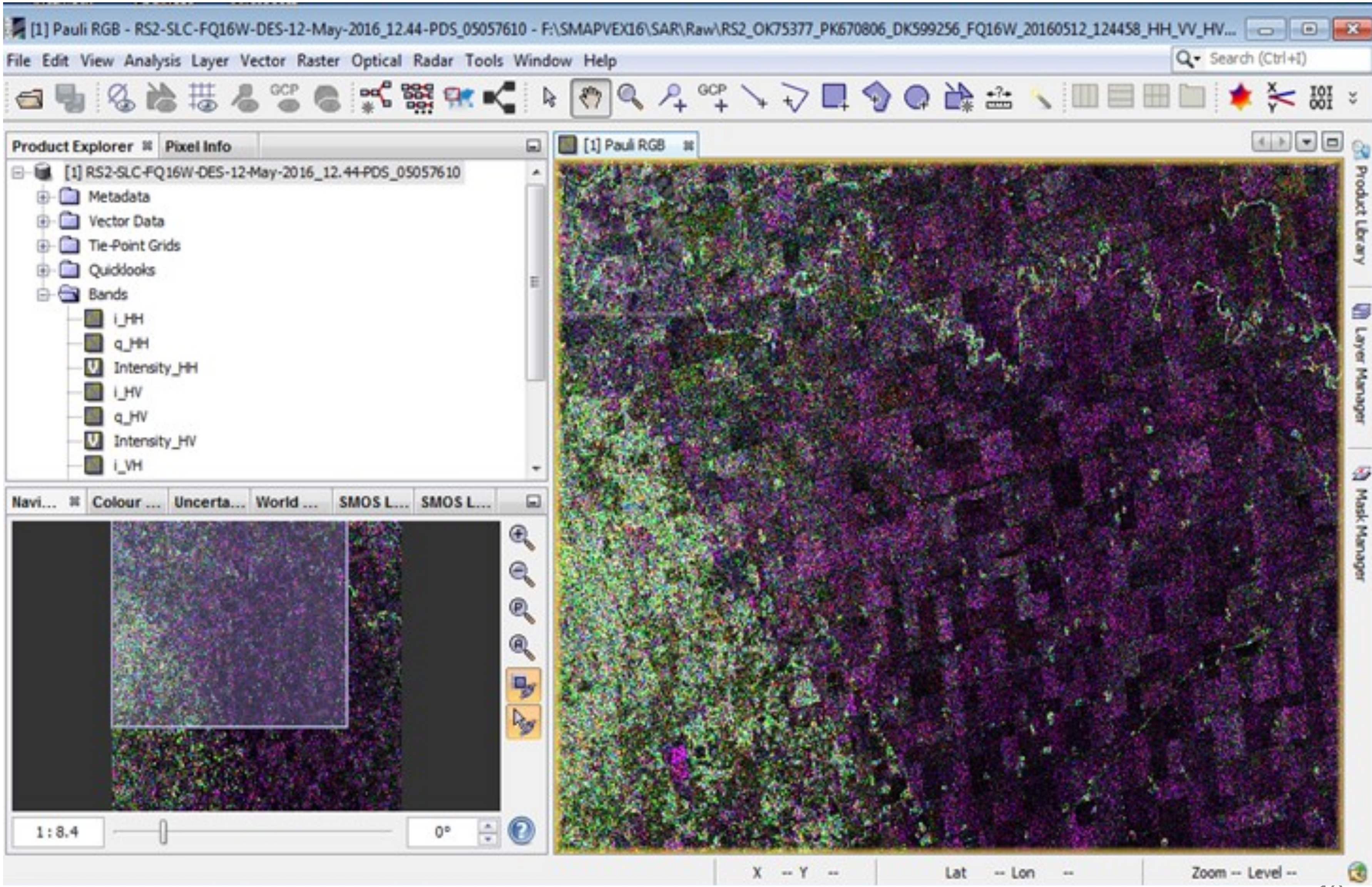
- Soil moisture map derived from one RADARSAT-2 acquisition using the multi-polarization approach

"Multi-Pro Preprocessing and IEM SM Retrieval"



Multi-pol inversion graph using a single RADARSAT-2 image

Soil Moisture Processing in SNAP: Multi-pol Method (2)

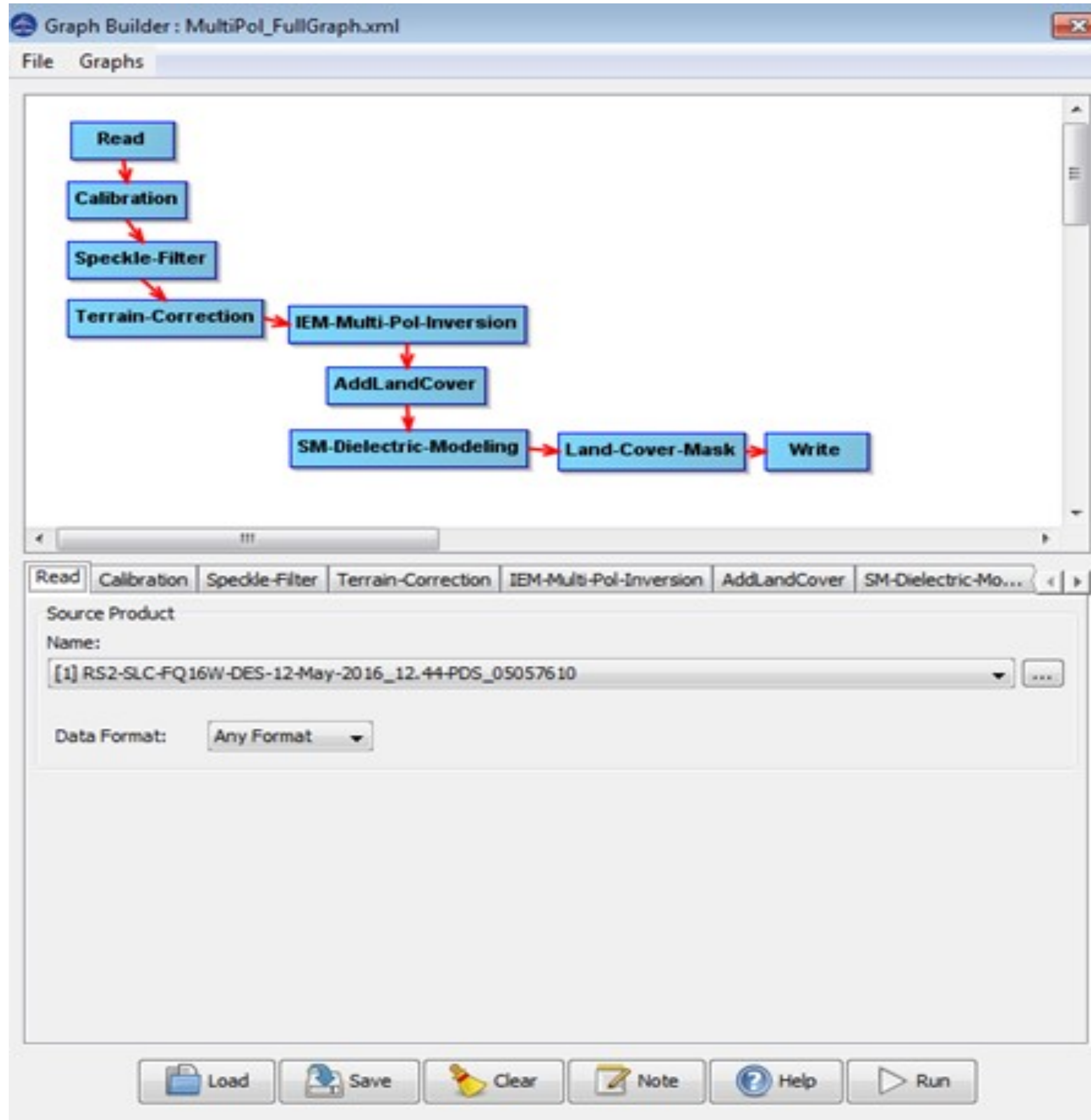


Raw RADARSAT-2 image acquired May 12th 2016 in southern Manitoba

Soil Moisture Processing in SNAP: Multi-pol Method (3)

Read Raw Data:

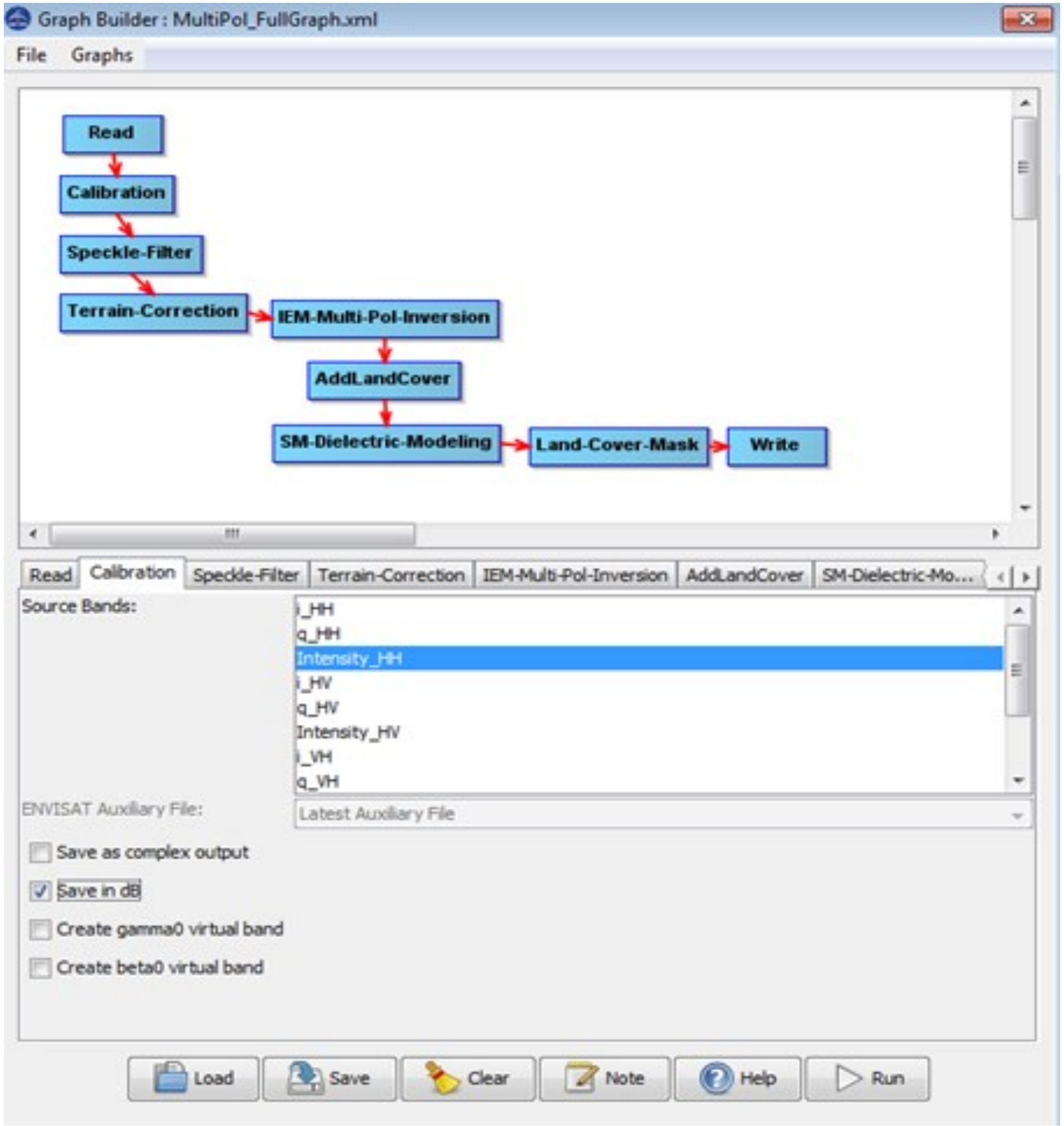
1. Browse to the RADARSAT-2 image to be processed
2. Select the zipped folder containing the raw image



Soil Moisture Processing in SNAP: Multi-pol Method (4)

Calibration:

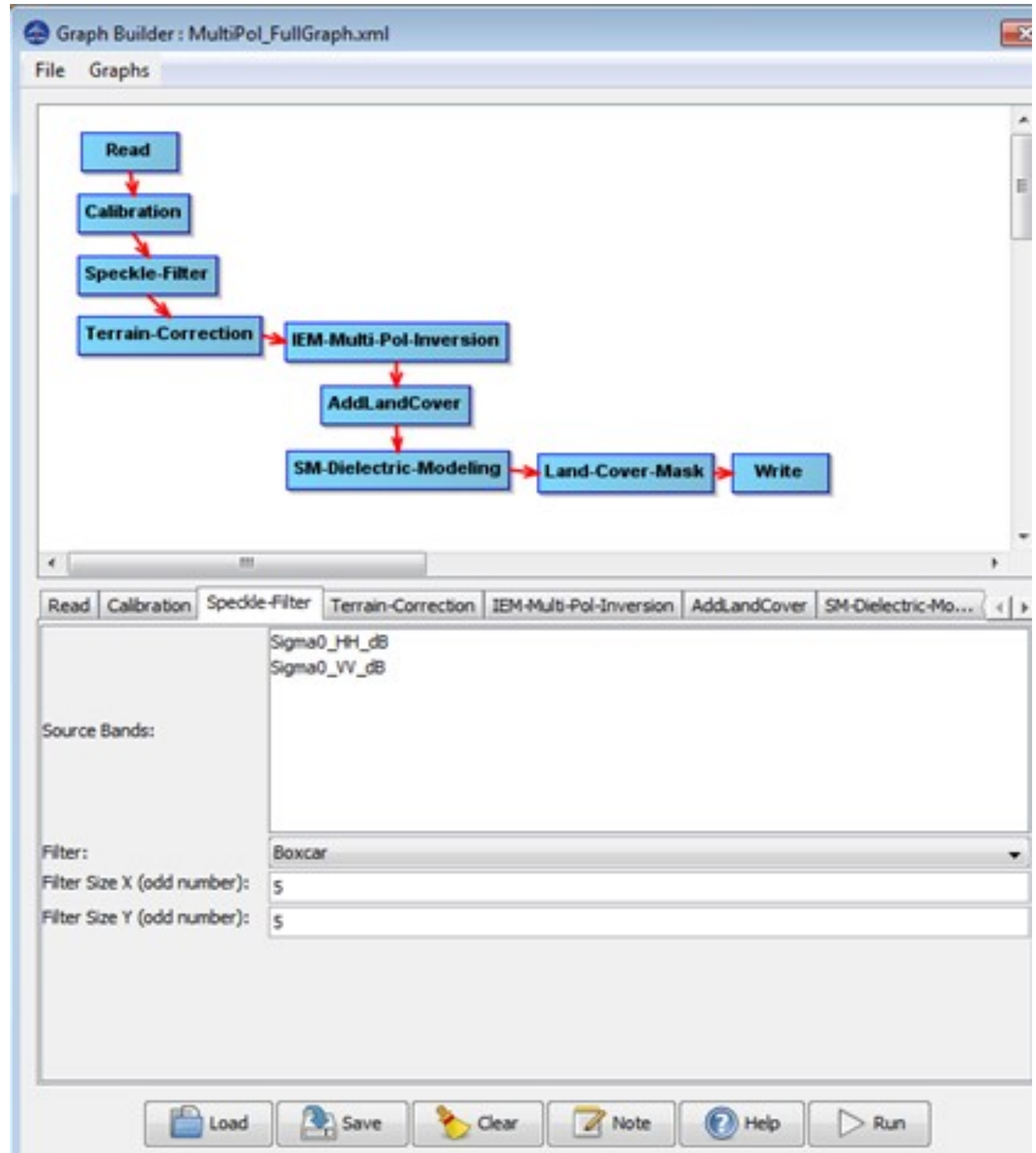
1. Select HH and VV intensity bands
2. Save in dB



Soil Moisture Processing in SNAP: Multi-pol Method (5)

Speckle Filter:

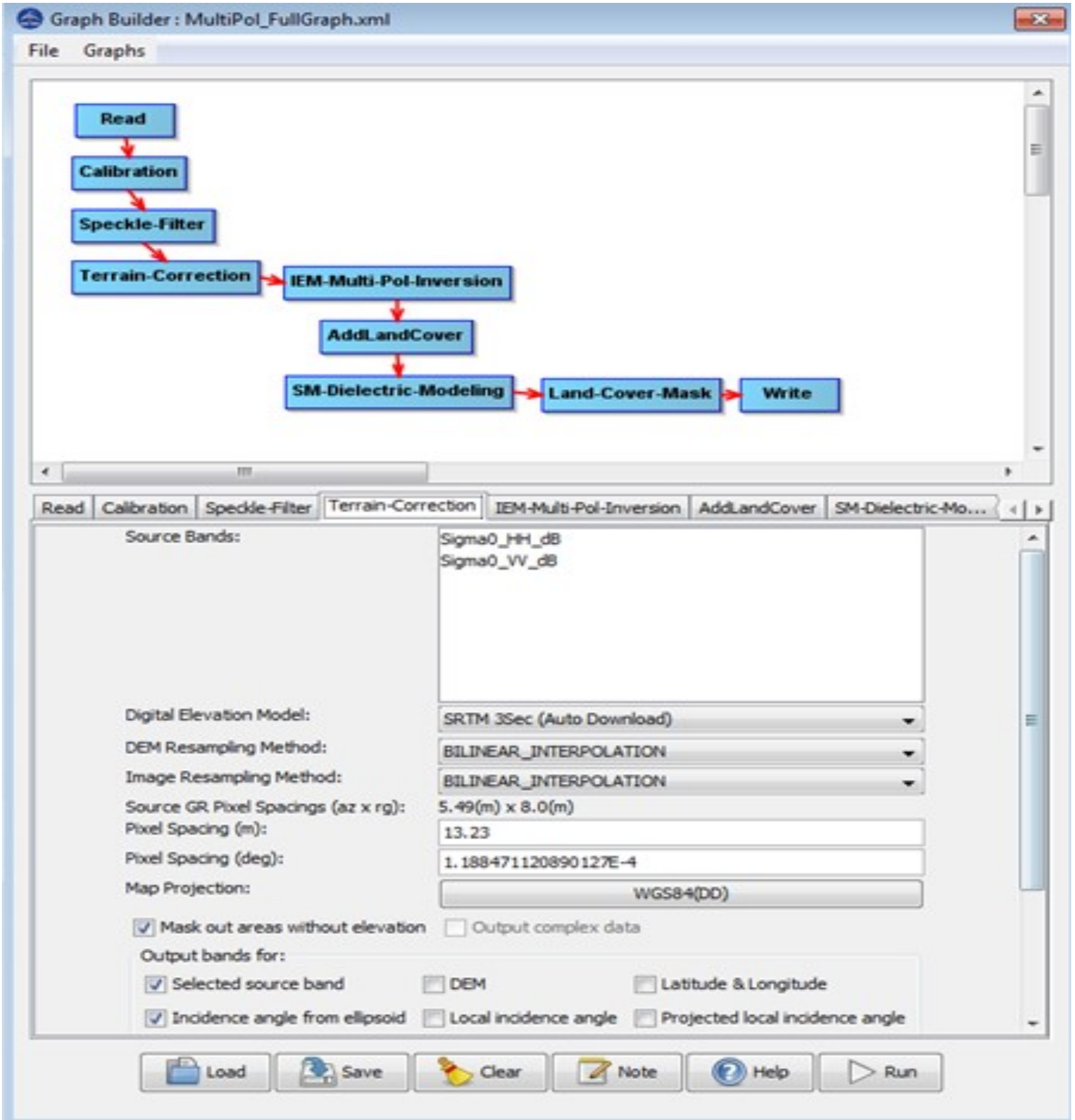
1. Select Boxcar filter
2. Use 5 x 5 filter size



Soil Moisture Processing in SNAP: Multi-pol Method (6)

Terrain Correction:

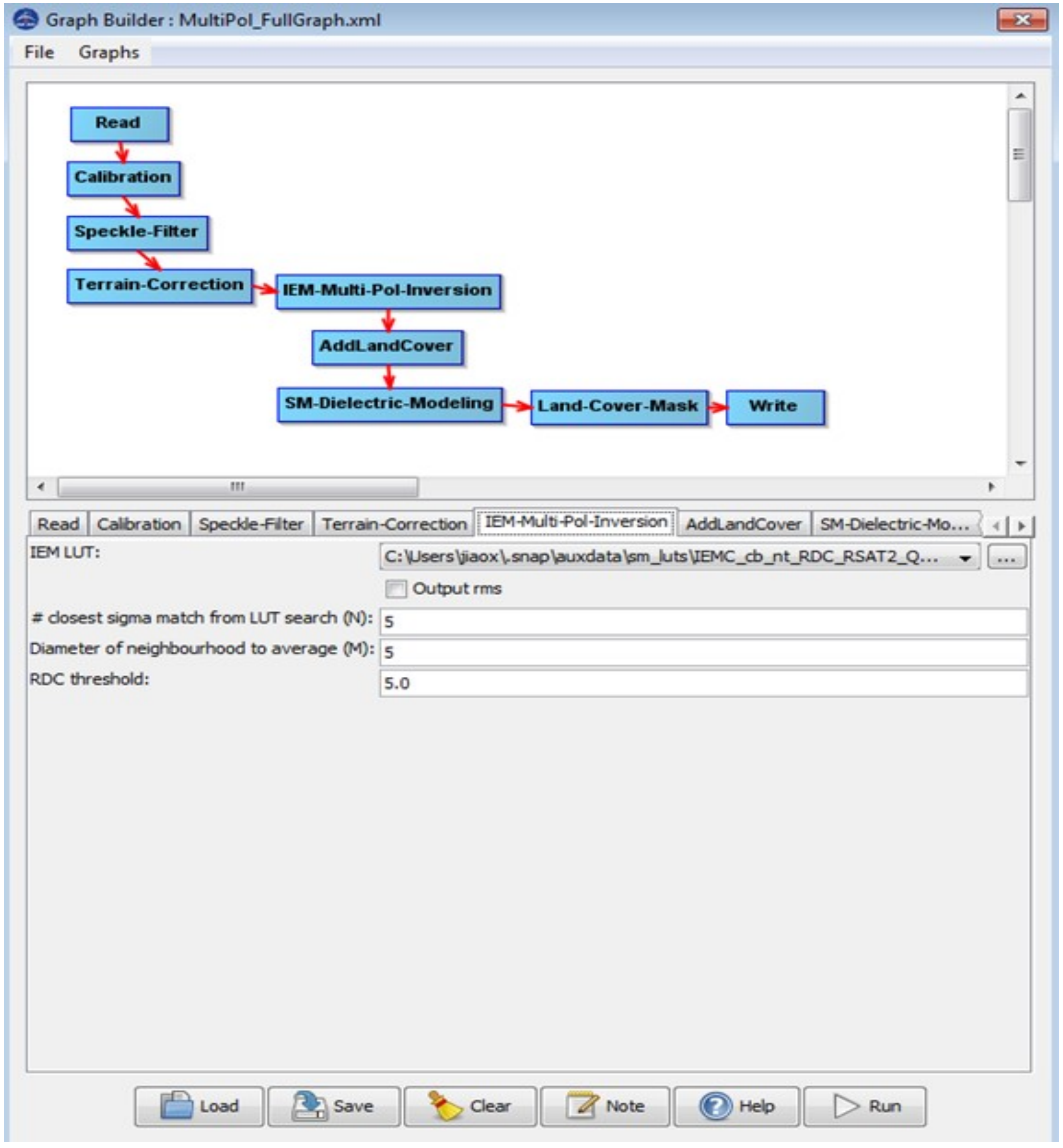
1. Select "Auto Download" for the DEM
2. Use the default setting for the other parameters



Soil Moisture Processing in SNAP: Multi-pol Method (7)

IEM Multipol Inversion:

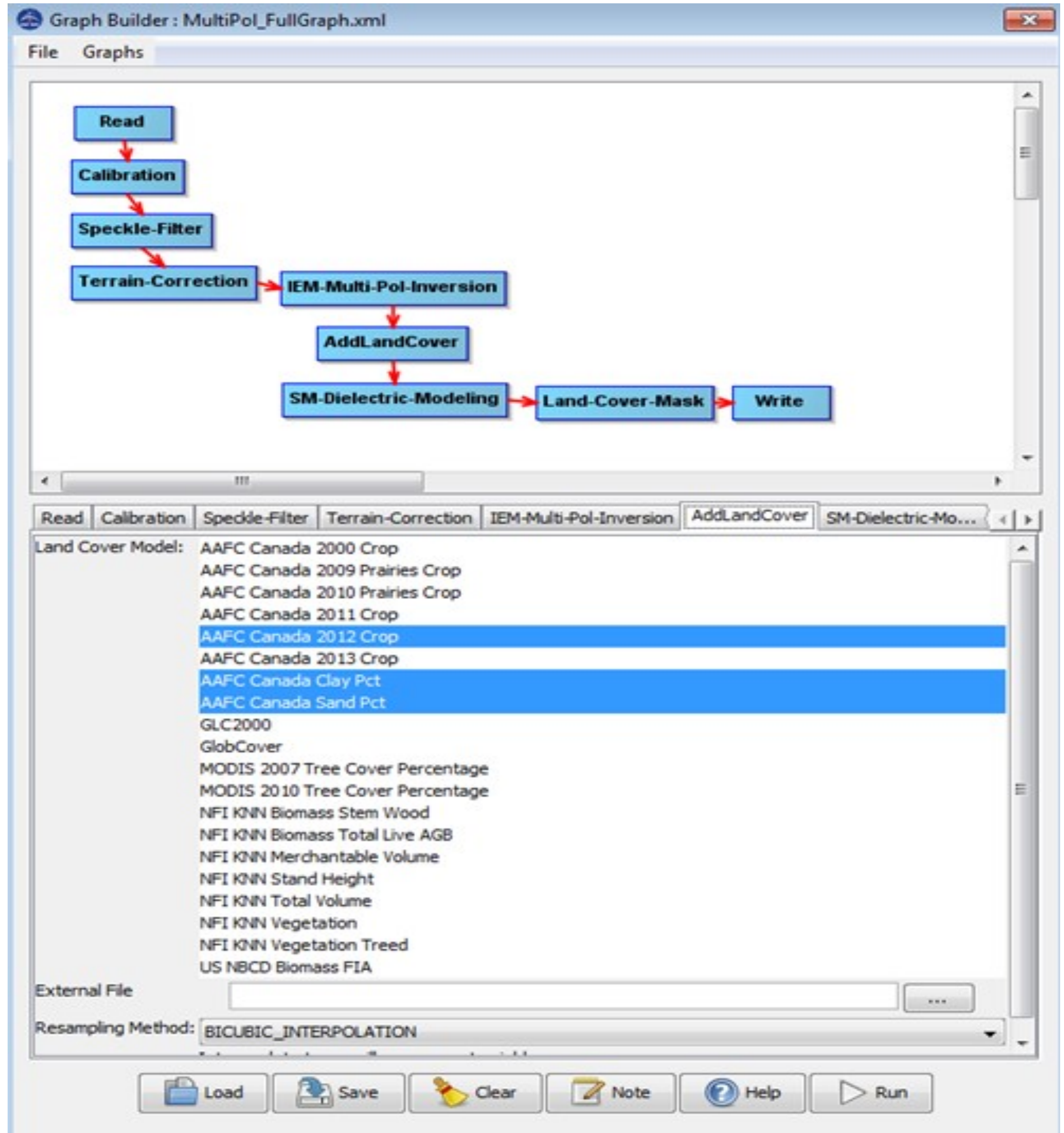
1. Select calibrated IEM LUT
2. Use the default setting for the other filtering parameters



Soil Moisture Processing in SNAP: Multi-pol Method (8)

Add land Cover:

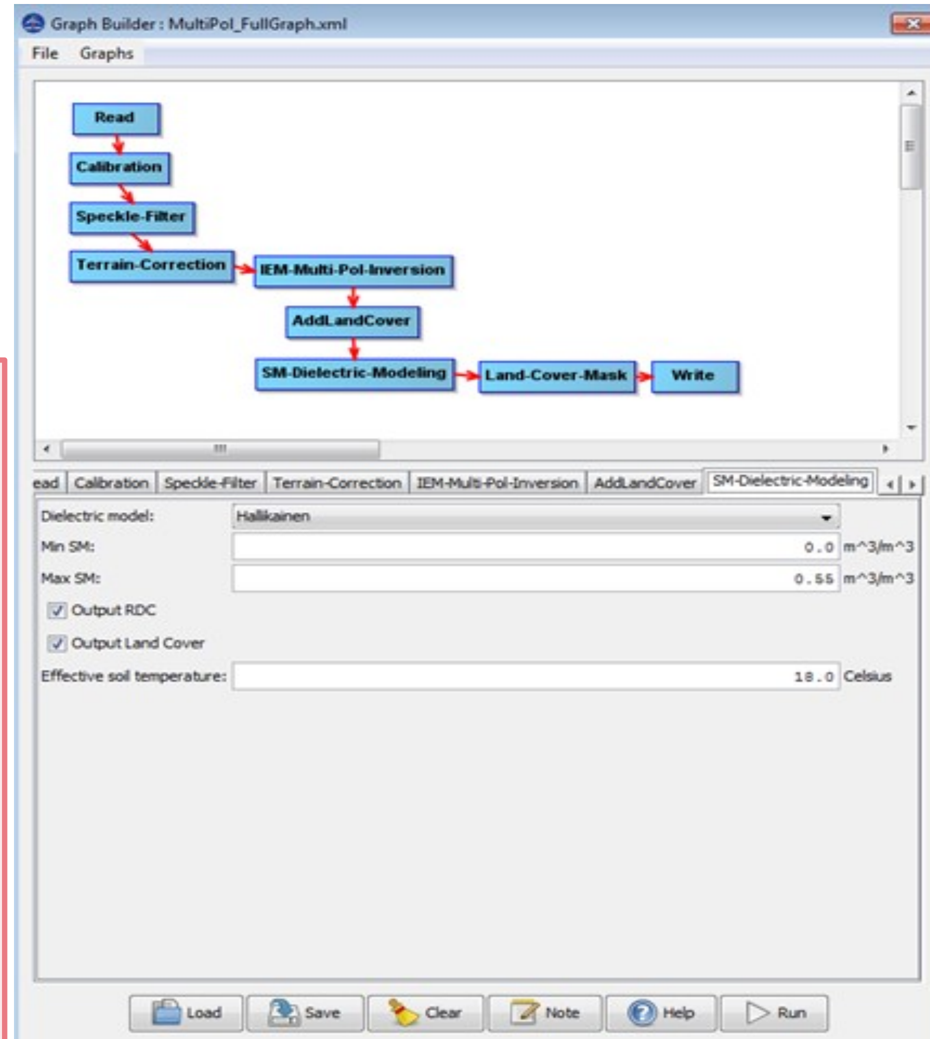
1. Select the land cover file
2. Select sand and clay fractions maps



Soil Moisture Processing in SNAP: Multi-pol Method (9)

SM dielectric Modeling:

1. Select "Hallikainen" mixture model
2. Use default values for other parameters



Hallikainen model was used to estimate the volumetric soil moisture, which is based on retrieved dielectric values. This model requires the soil texture information (clay and sand fractions)

$$\varepsilon_r = (1.993 + 0.002\,S + 0.015\,C) + (38.086 - 0.176\,S - 0.633\,C)\,m_v + (10.720 + 1.256\,S + 1.522\,C)\,m_v^2$$

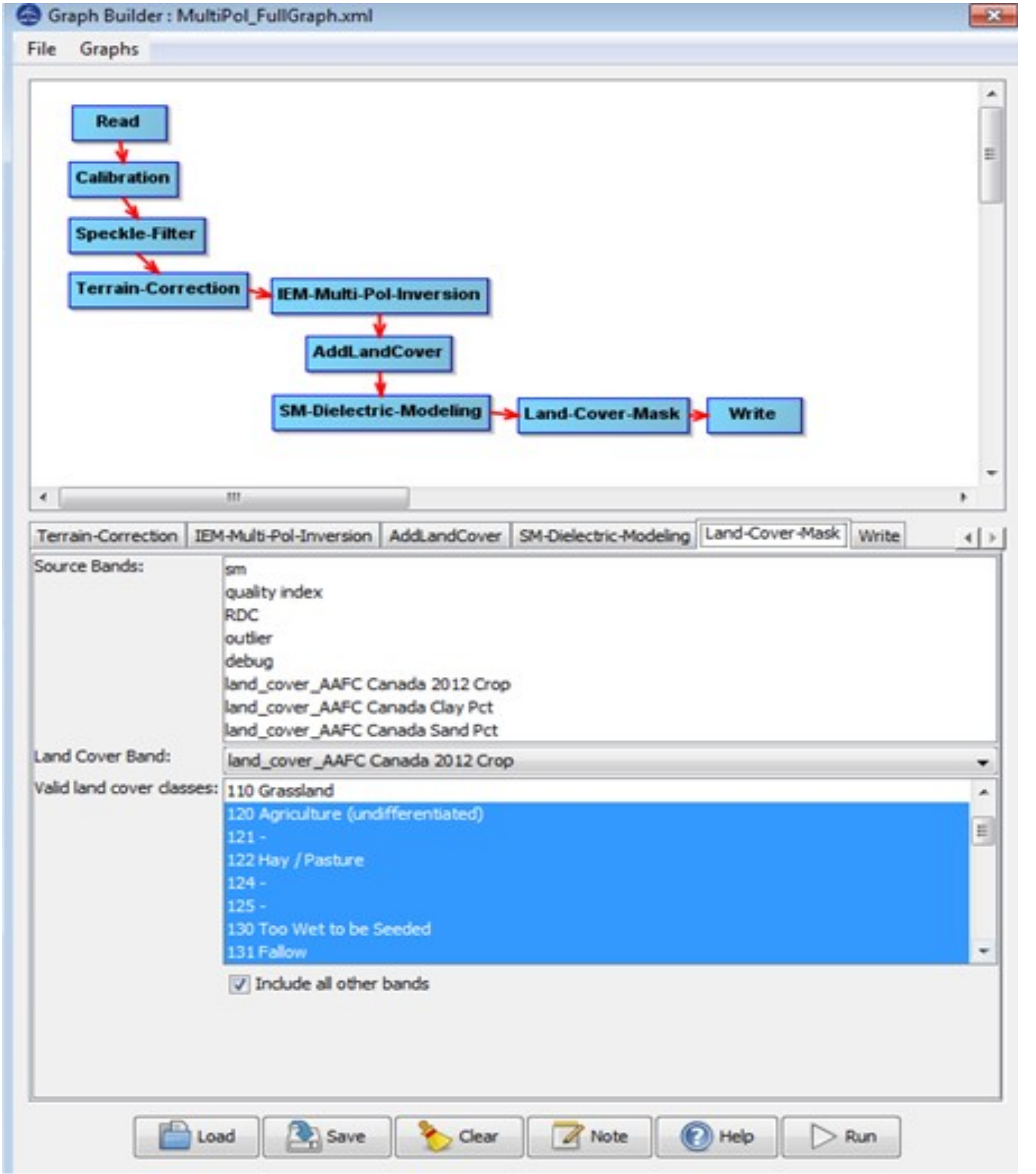
Where:
εr = real part of the dielectric constant
mv = volumetric soil moisture fraction
S = soil sand fraction
C = soil clay fraction

Information source: Hallikainen et al., 1985.

Soil Moisture Processing in SNAP: Multi-pol Method (10)

Land Cover Mask:

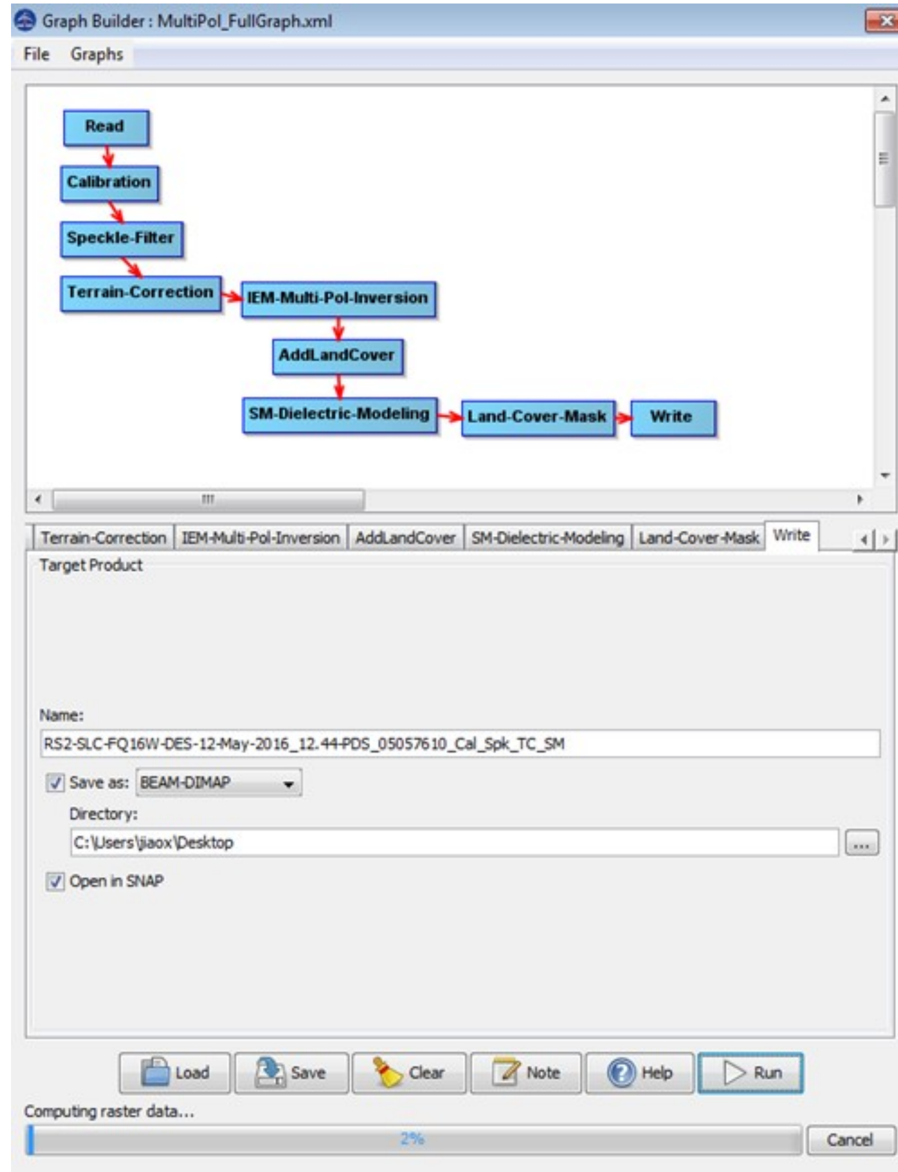
1. Select land cover valid agriculture classes.
2. Check "Exclude all other bands"



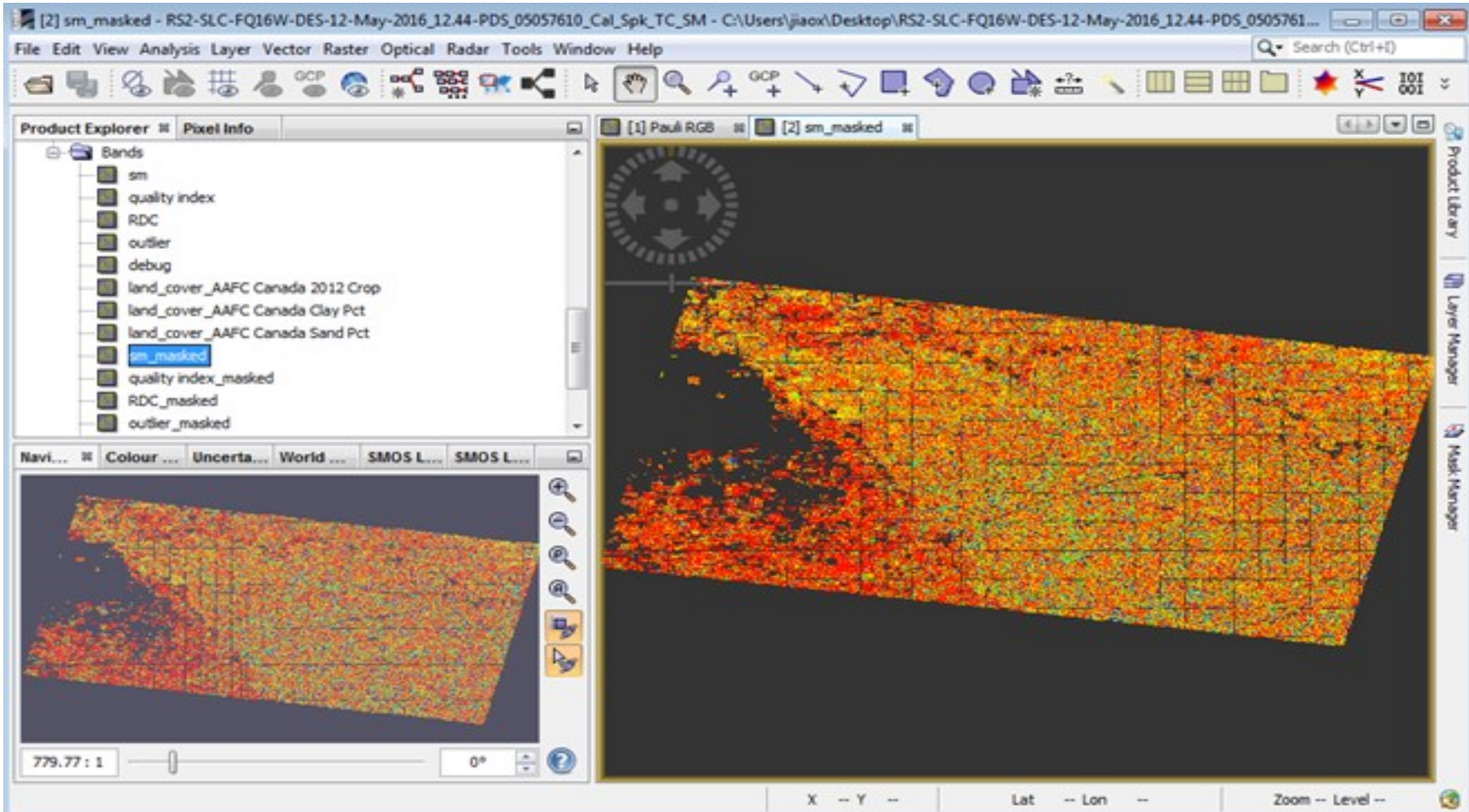
Soil Moisture Processing in SNAP: Multi-pol Method (11)

Write Output:

1. Browse and name the output file.
2. Select the appropriate format for the retrieved soil moisture product.
3. Run the module



Soil Moisture Processing in SNAP: Multi-pol Method (12)

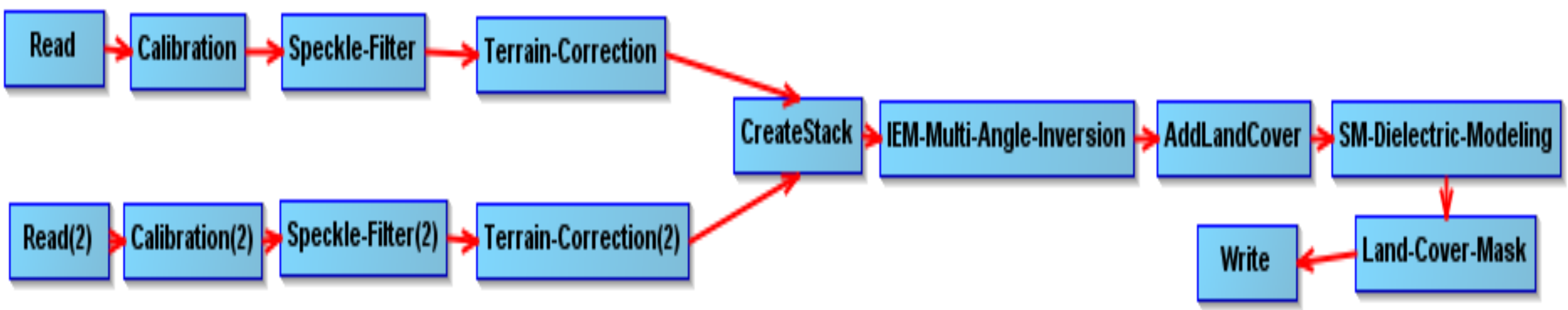


Soil moisture map obtained by inverting the calibrated IEM and using a single RADARSAT-2 image acquired in May 12th 2016 in southern Manitoba

Soil Moisture Processing in SNAP – Hybrid Method (1)

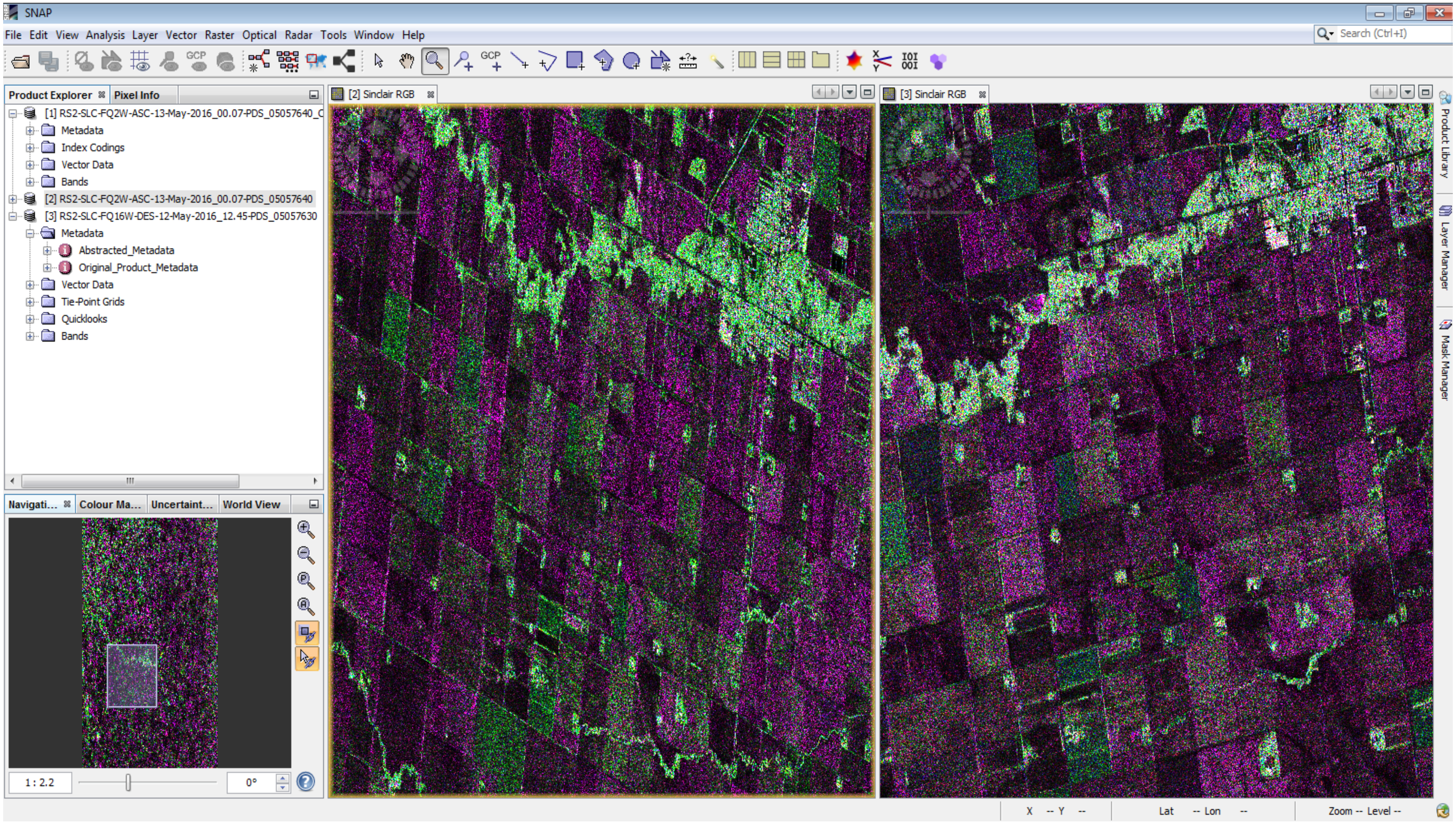
- Soil moisture map derived from 1 AM RADARSAT-2 acquisition and one PM RADARSAT-2 acquisition using multi-angles / multi-polarization approach

- RADARSAT-2 AM and PM data collected only ~12 hours apart. The hybrid inversion method is performed on the overlapping geographic area.



Hybrid inversion graph using two RADARSAT-2 images

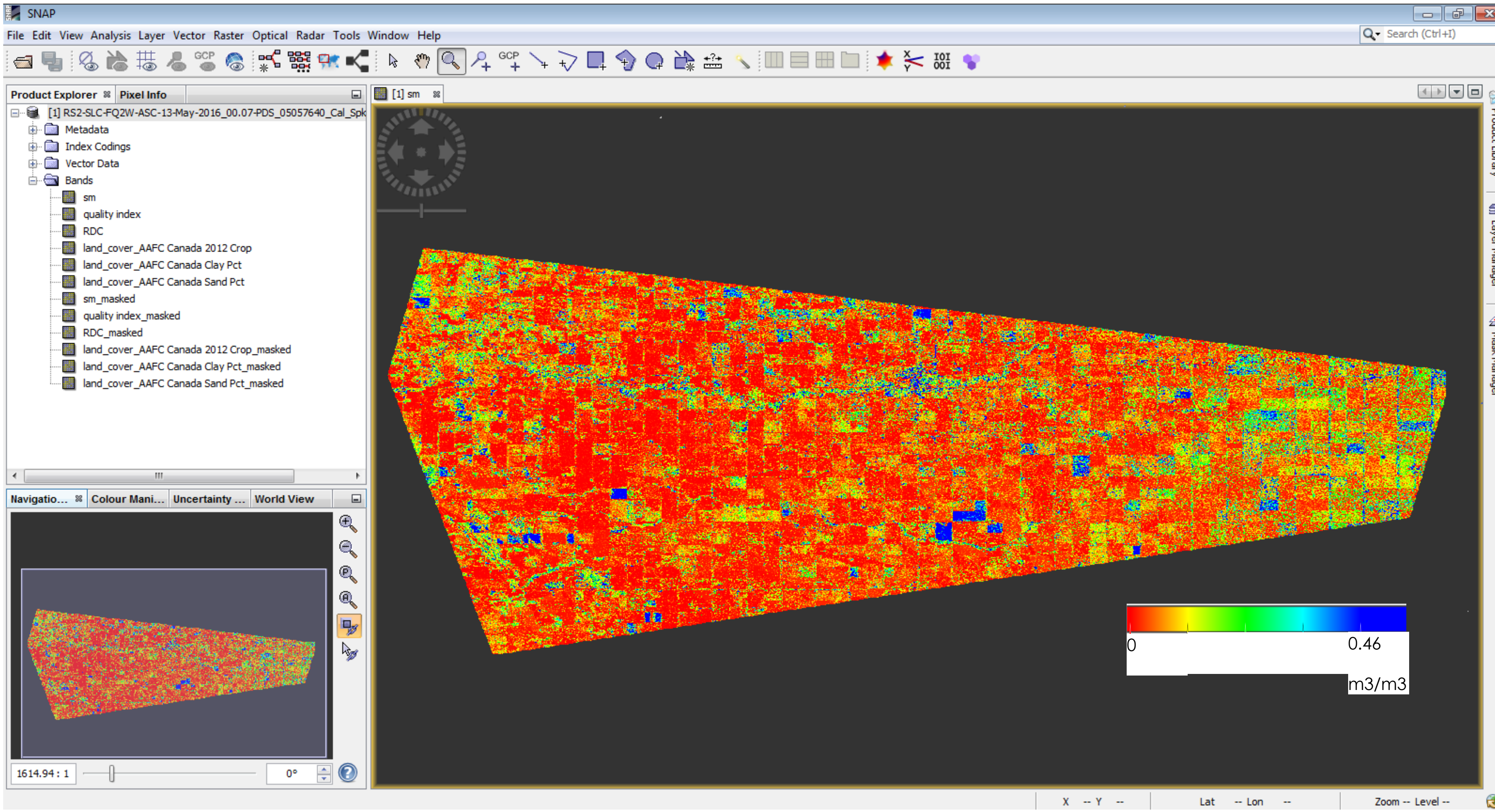
Soil Moisture Processing in SNAP – Hybrid Method (2)



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

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

Soil Moisture Processing in SNAP – Hybrid Method (3)



Soil moisture map obtained by inverting the IEM and using a pair of RADARSAT-2 images acquired in May 12^{th} / 13^{th} 2016 in southern Manitoba

How Do We Validate Soil Moisture Estimates?

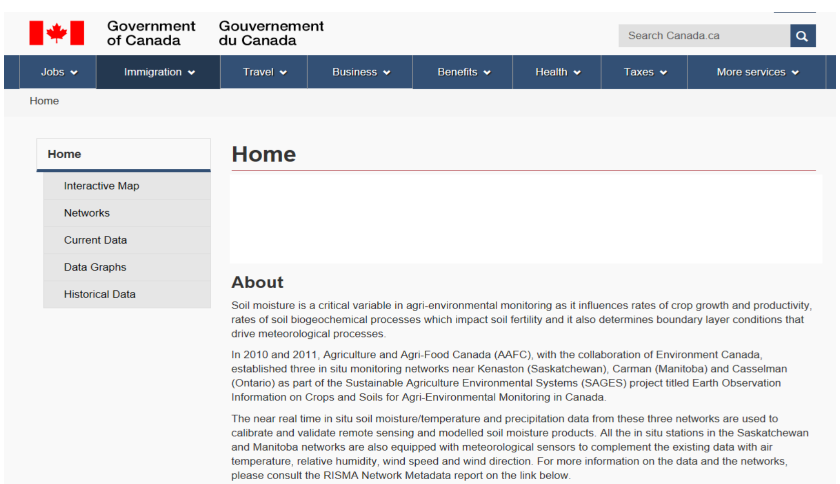
Real-time In-Situ Soil Monitoring for Agriculture (RISMA)

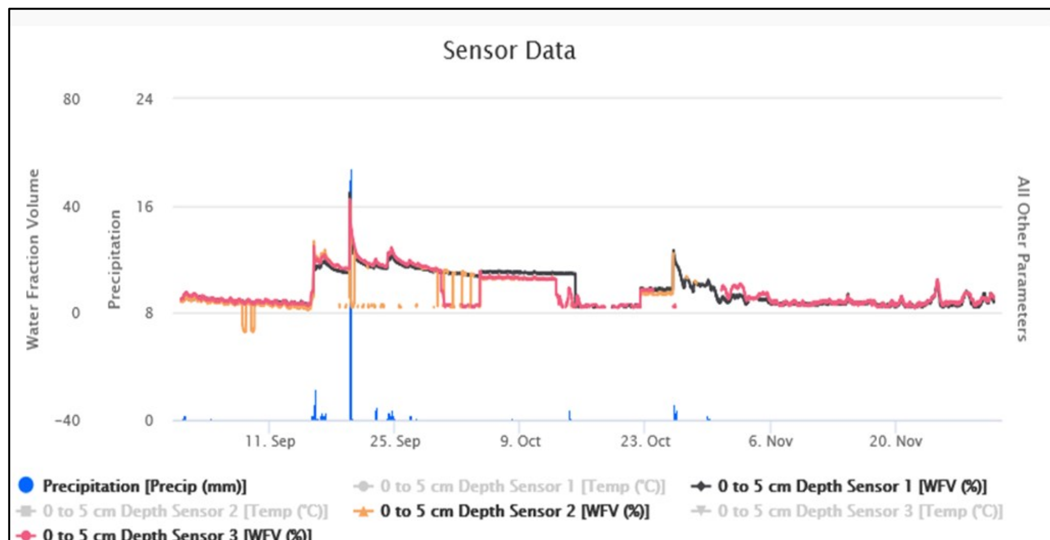
- Soil moisture and temperature: 0-5, 5, 20, 50, 100*, 150* cm
- Meteorological measurements: soil temperature, precipitation, air temperature, relative humidity, wind speed, wind direction.

Image source: AAFC

Real time delivery of quality checked and calibrated soil moisture data, as well as meteorological data

http://agriculture.canada.ca/SoilMonitoringStations/index-en.html





Accuracy of Soil Moisture Estimates

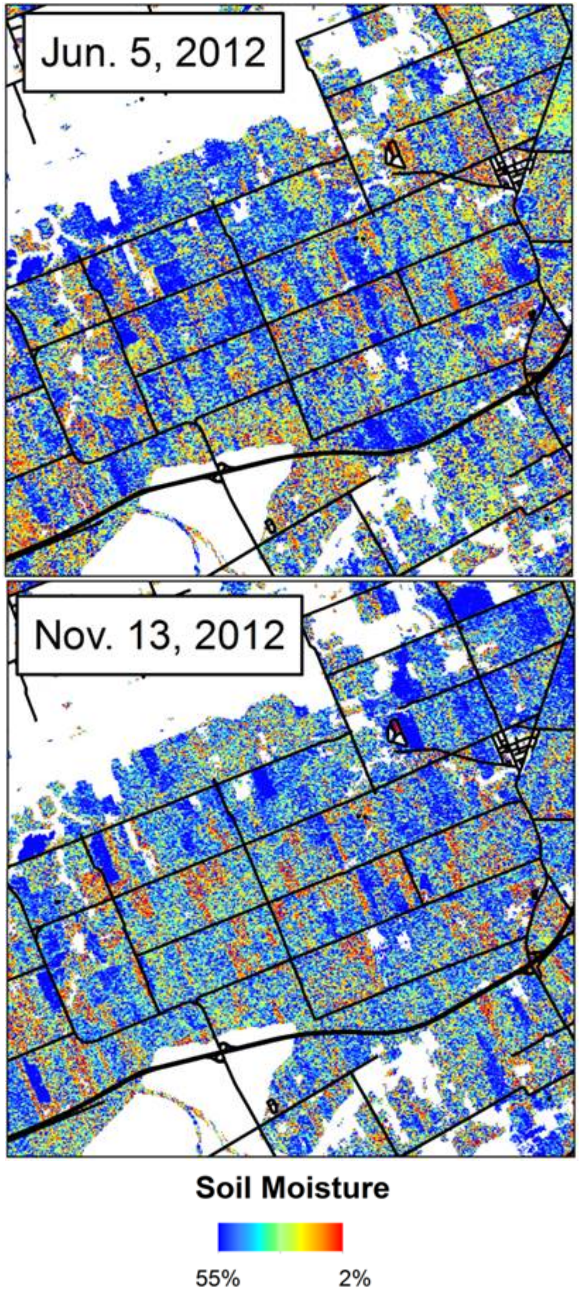
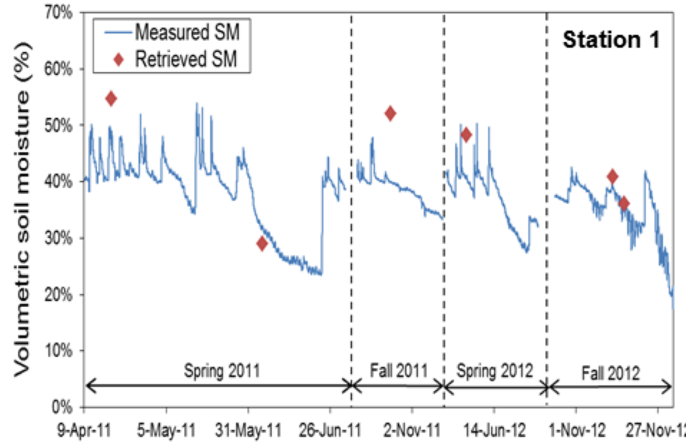
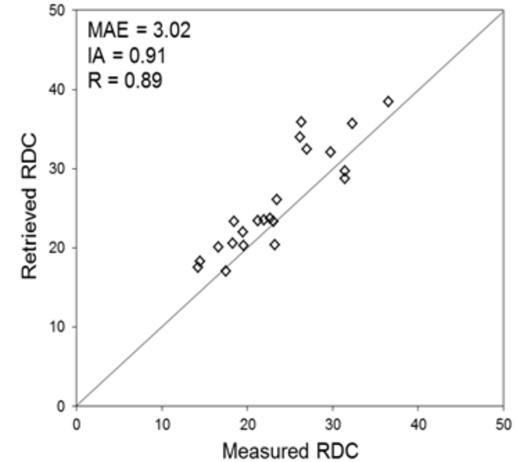
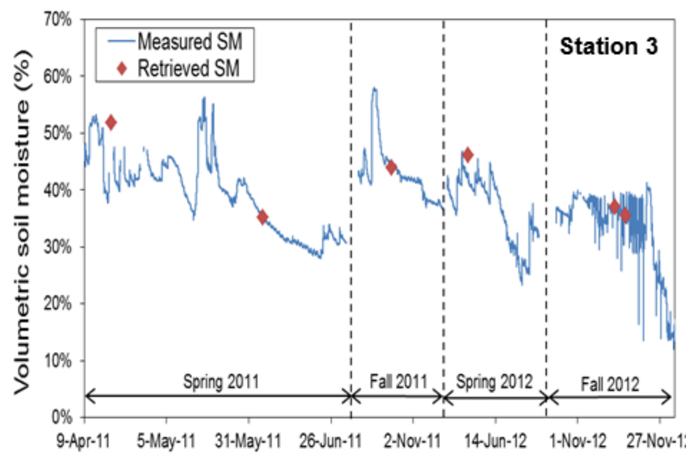
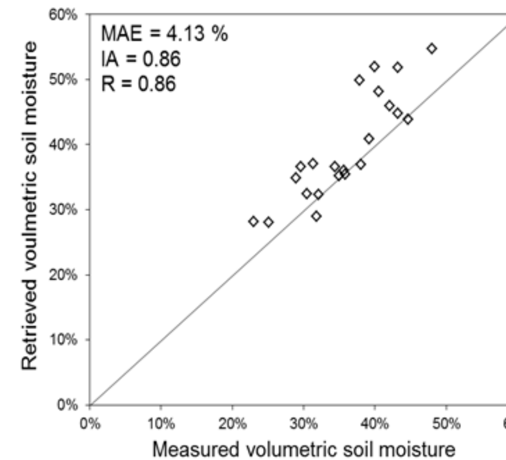


Image source: Merzouki and McNairn, 2015









Inversion method	Retrieved parameter	MAE	IA	R
Multi-polarization	RDC	5.39	0.82	0.81
	VSM	8.13%	0.76	0.81
Hybrid	RDC	3.02	0.91	0.89
	VSM	4.13%	0.86	0.86

Acknowledgment

Carleton University
Canada's Capital University

Agriculture and Agri-Food Canada
Agriculture et Agroalimentaire Canada

CSA ASC

Natural Resources Canada
Ressources naturelles Canada

PCI Geomatics

Environment and Climate Change Canada
Environnement et Changement climatique Canada

INRS
Institut national de la recherche scientifique

References

Merzouki, A. and H. McNairn. 2015. A Hybrid (Multi-Angle and Multipolarization) Approach to Soil Moisture Retrieval Using the Integral Equation Model: Preparing for the RADARSAT Constellation Mission. Canadian Journal of Remote Sensing 41(5): 1-14.

Hallikainen, M.T., Ulaby, F.T., Dobson, M.C., El-Rayes, M.A., and Wu, L.K., 1985. Microwave Dielectric Behavior of Wet Soil, Part I: Empirical Models and Experimental Observations. IEEE Transactions on Geoscience and Remote Sensing, GE-23: 25-34.