Land and Ocean Remote Sensing Using Signals of Opportunity Reflectometry

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Committee on Radio Frequencies (CORF) Virtual 2022 Spring Meeting

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Outline

- Signals of Opportunity Concept
- Snow and Soil Moisture Remote Sensing Using SoOp
- Ocean Remote Sensing Using SoOp
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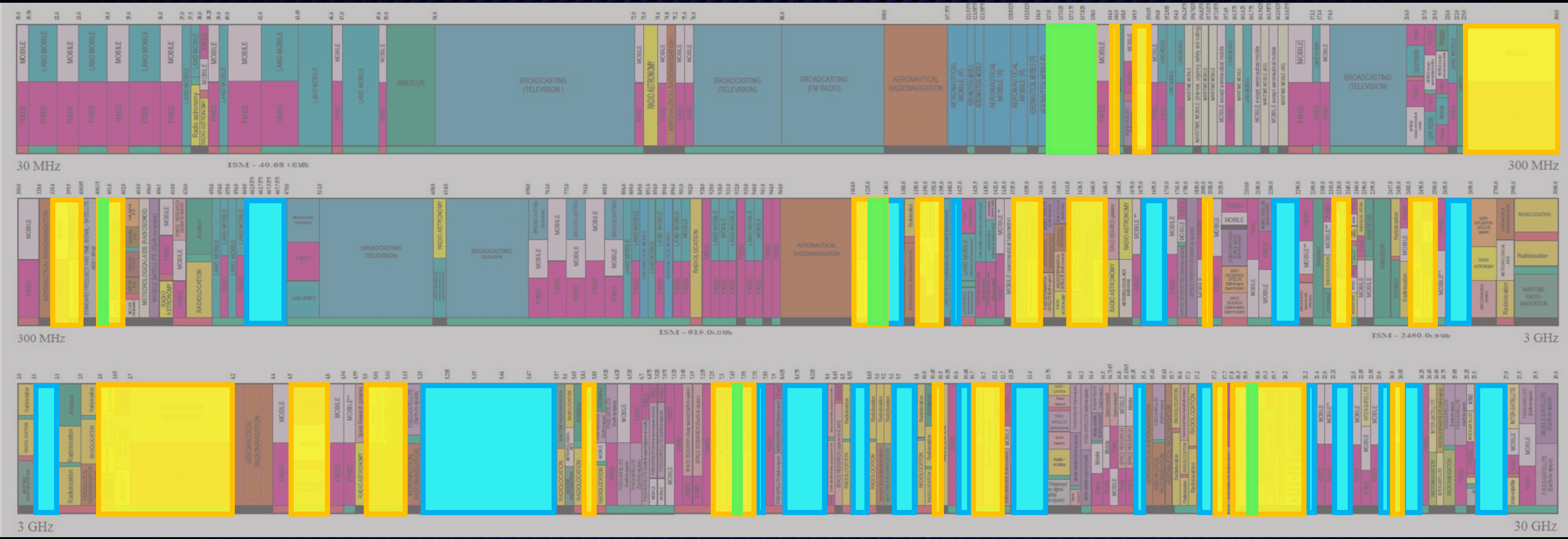
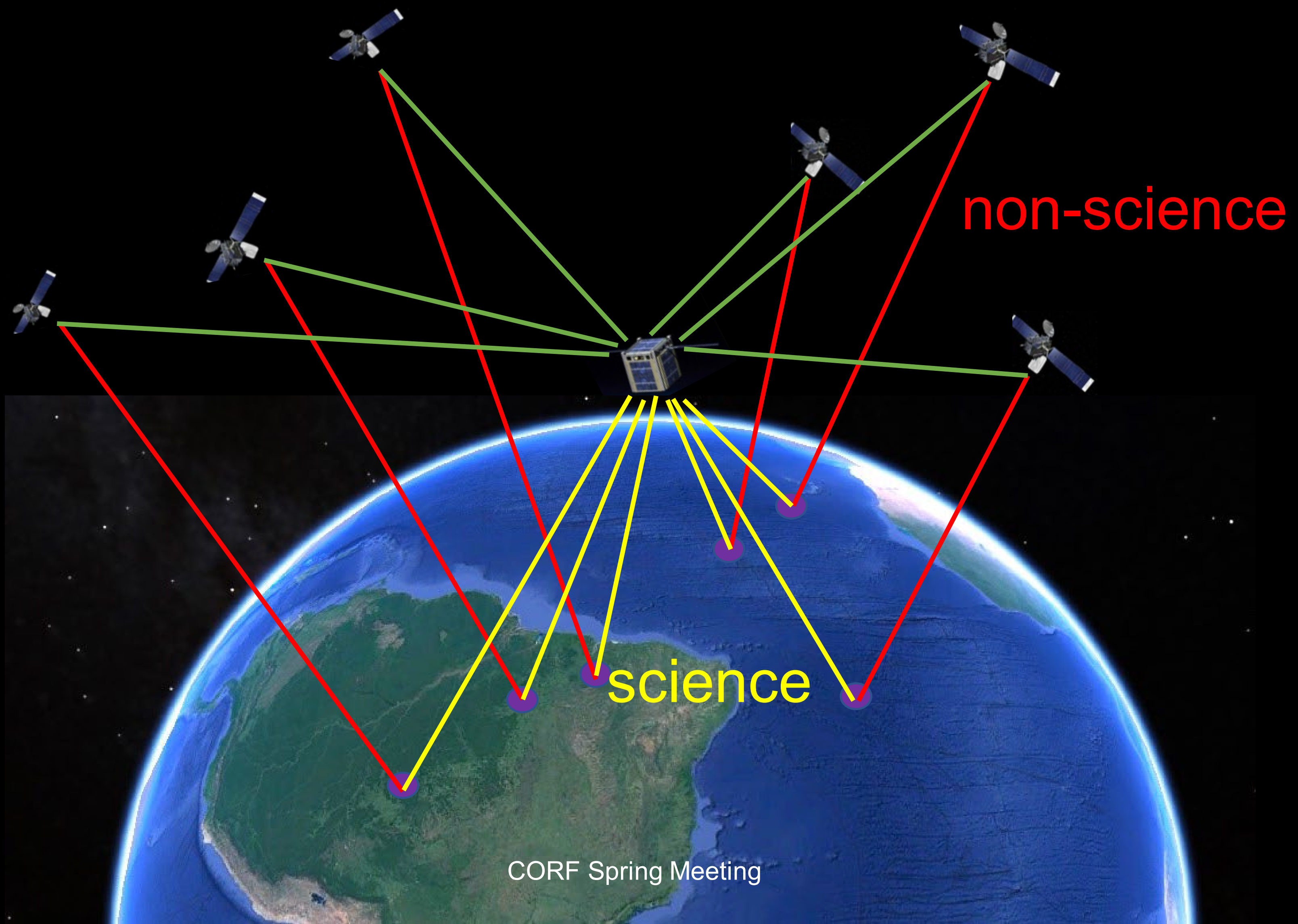
The Electromagnetic Spectrum: *Valuable Real Estate*
Two Windows on the Earth



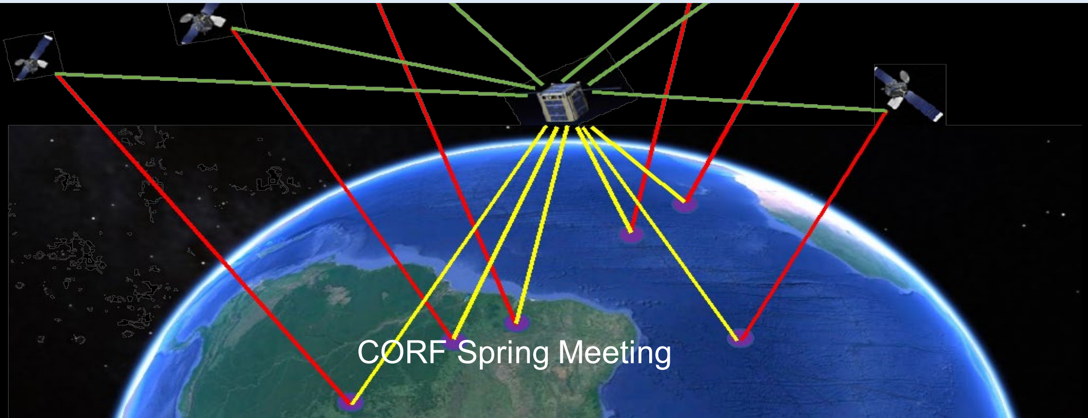
Science
Optical Window
Comm/Nav
Microwave Window
Shared

Signals of Opportunity (SoOp)
Reflectometry



Signals of Opportunity (SoOp)
Advantages

- **Operate on any frequency where a transmitter exists**
- Strong, coherent transmitted signal (in a sense "active")
- Forward scatter - high SNR
- Low SWaP enables small satellite constellations
- Resolution set by transmitting signals' bandwidth or transmitting signals' frequency
- Fundamental observation is time/frequency/phase (not radiometry) or power (requires radiometric calibration)



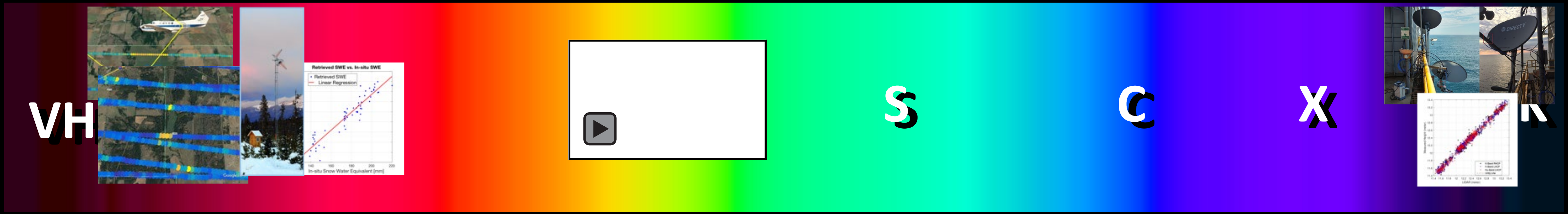
Passive Re-use of Existing Transmissions

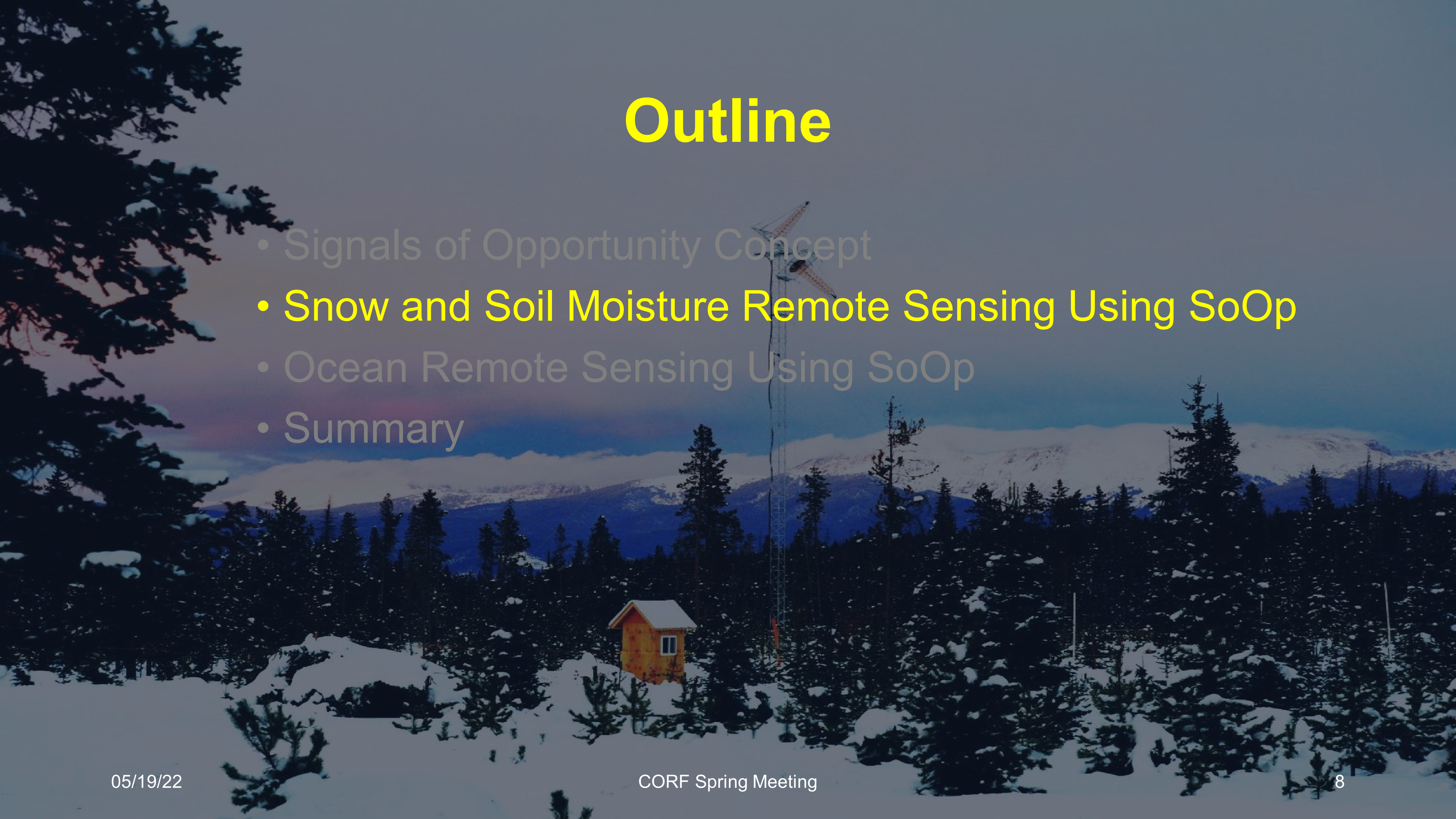
P-band (SATCOM) | L-band (GNSS) | K/Ku-Band (DBS)

RZSM & SWE

High-revisit ocean winds (CYGNSS)

Ocean Altimetry





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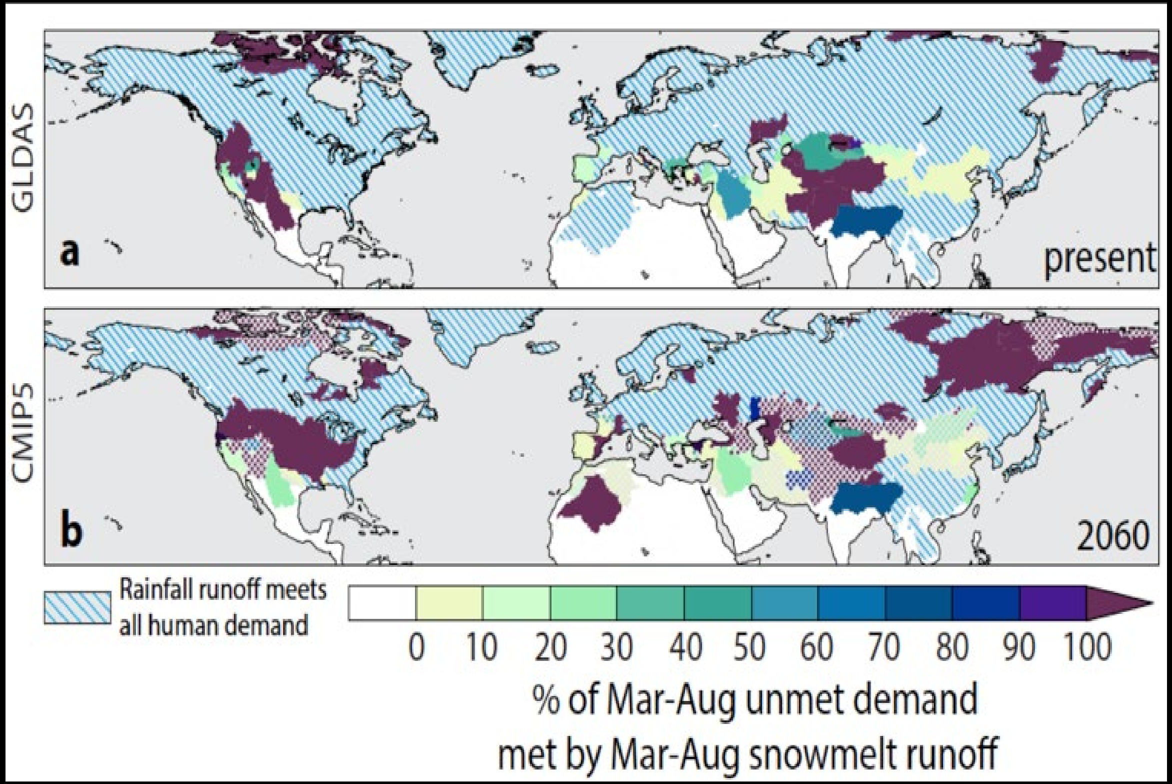
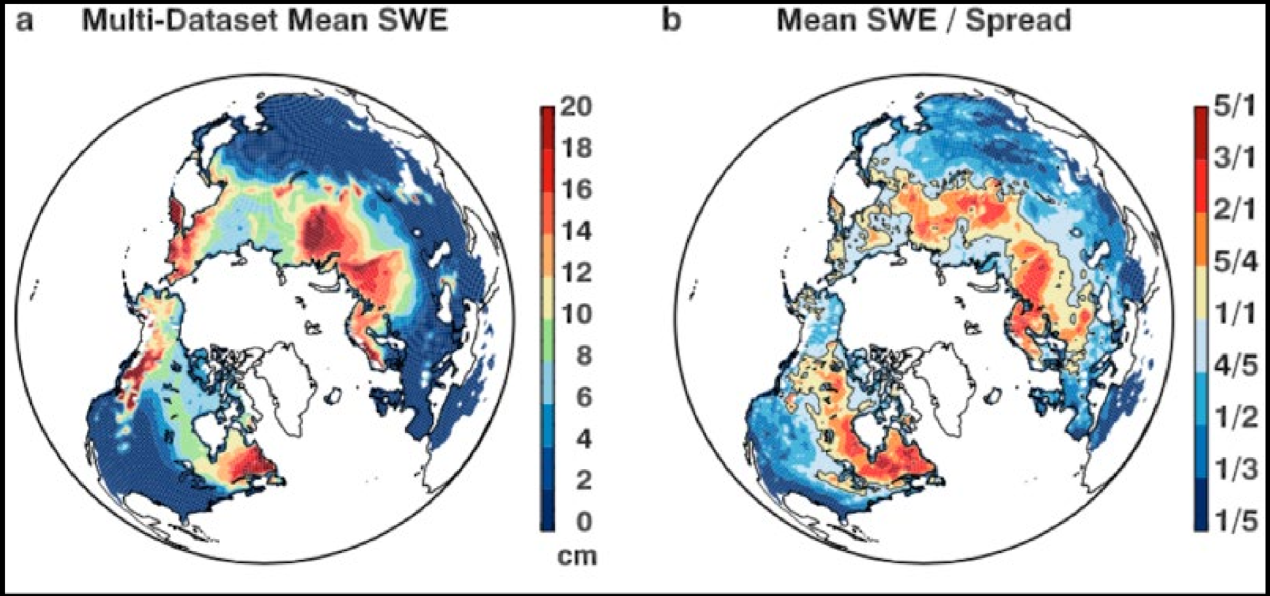
Snow-derived water supply



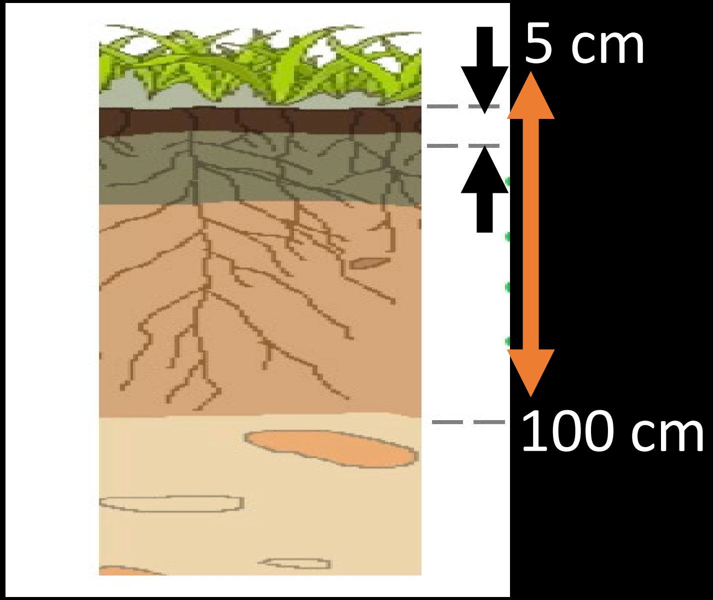


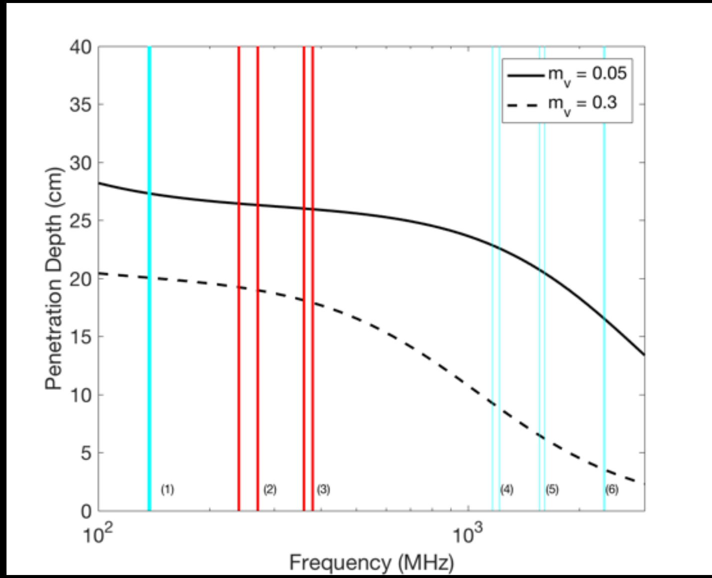
- Snow's Role in Northern Hemisphere: (a) Present (b) Future

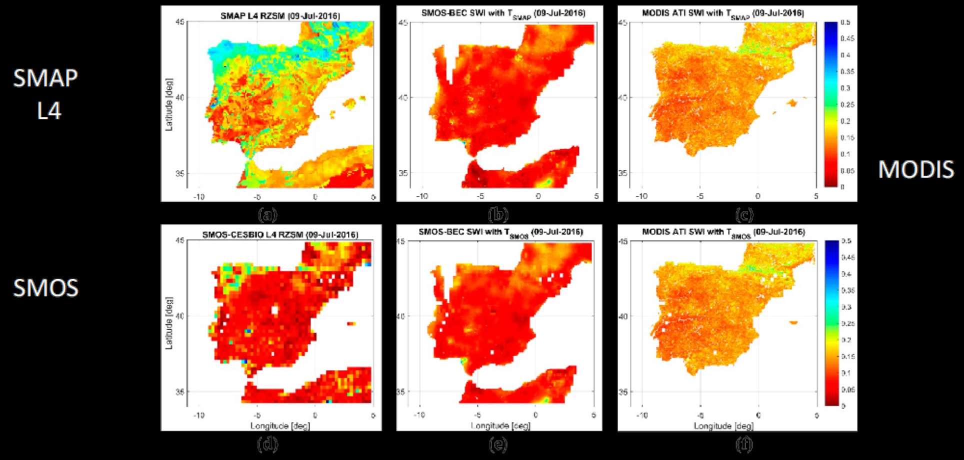
- Current state-of-the-art SWE assessments are highly uncertain
- Model spreads of -50% to 250%, relative to the mean, are common across middle-latitude regions *(Mudryk et al., 2015)*

Root-Zone Soil Moisture

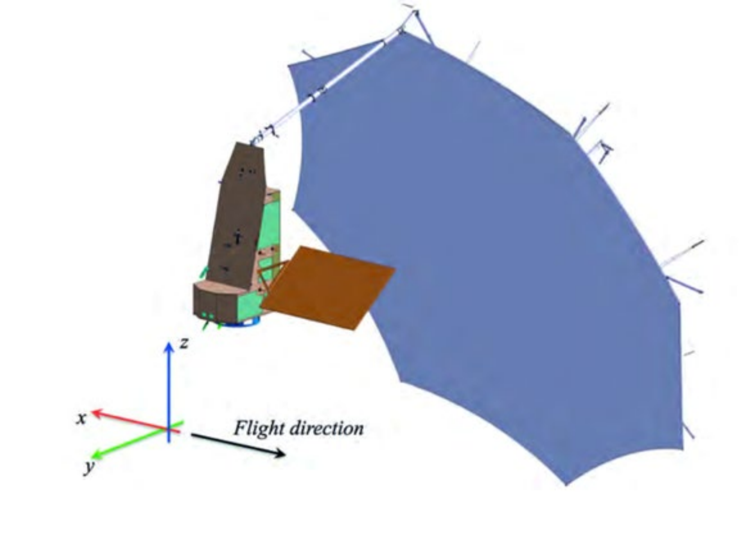
- Water content in 0-1 m of soil => Depth of absorption by plants
- L-band penetration ~5 cm => P-band penetrates deeper ~25 cm
- L4 RZSM data products from assimilation models => Large variability

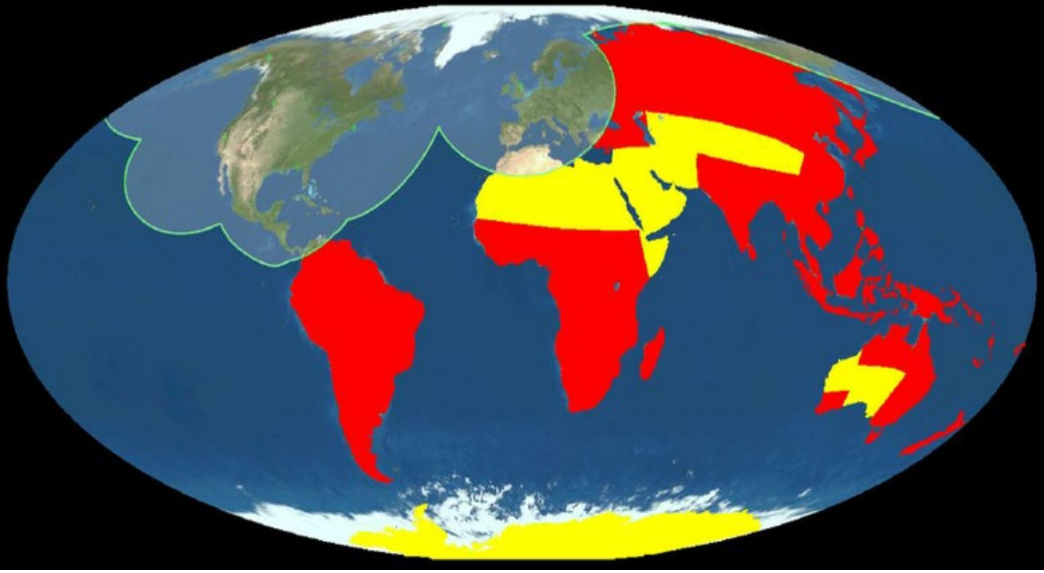


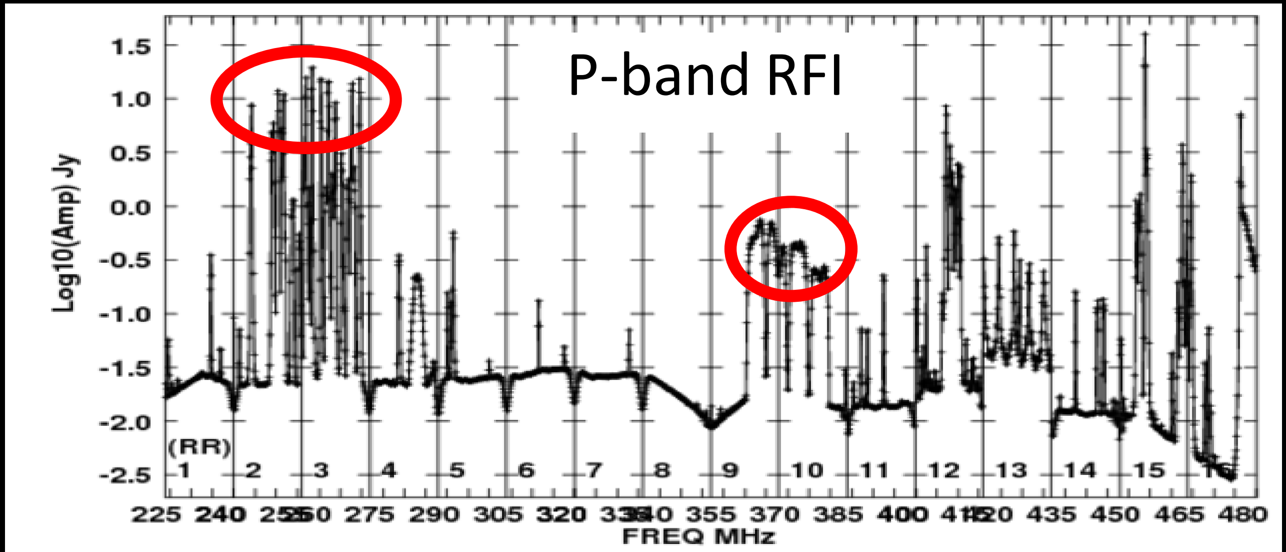




Challenges in Sensing <500 MHz



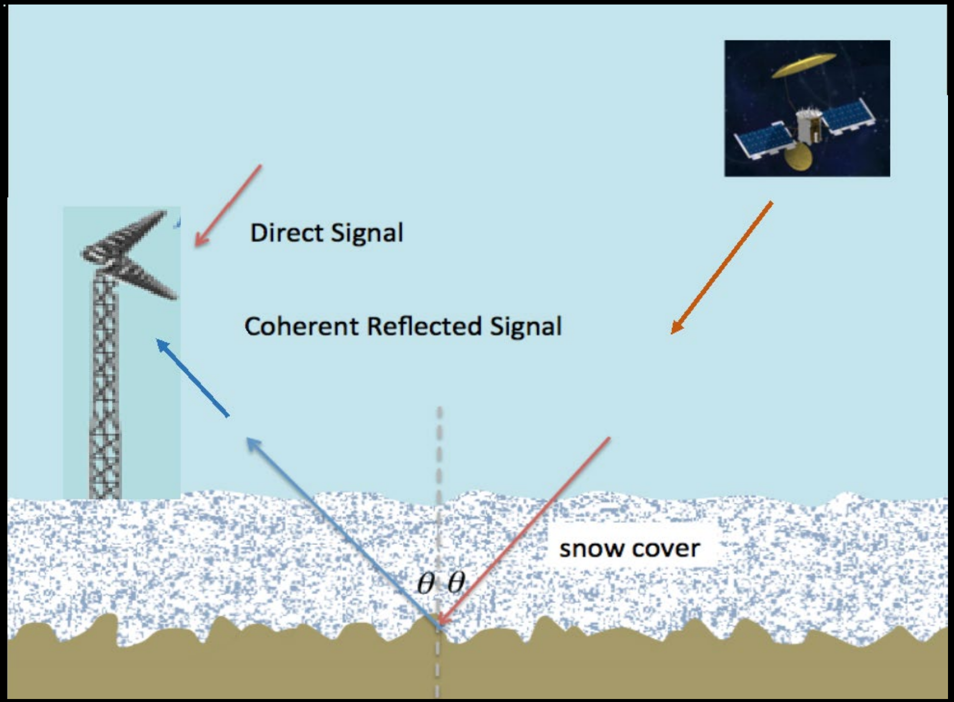




12-m Large Deployable Reflector (LDR)

435 MHz Operations prohibited over N. America and Europe due to Space Objects Tracking Radar (SOTR) [ESA SP-132, 2010]

Snow and Soil Measurement Principle



$$R \simeq R(f, \boldsymbol{Soil\ Moisture})$$

$$\phi_s \simeq \mathrm{a} \cdot f \cdot SWE$$

ϕ_s = phase change

f = frequency

a : depends on θ

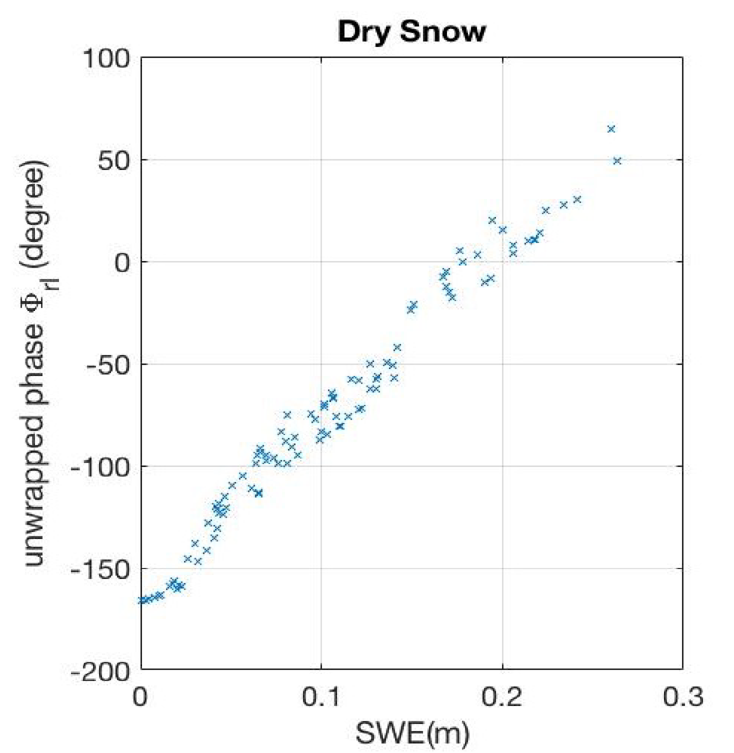
R = Reflectivity

- Long (~1m) P-band wavelength – increase phase wrapping interval
- Modeling showed phase is not sensitive to snow grain size, snow density, or snow stratigraphy

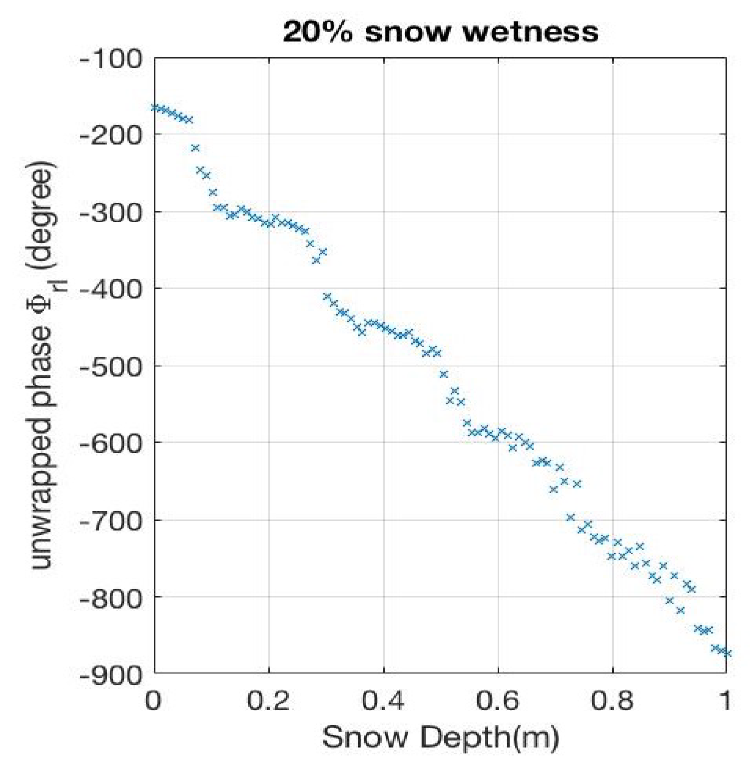
Yueh et al., 2017

Dry Snow (SWE) vs. Wet Snow (Snow Depth)

- Phase is related to SWE for dry snow
- Ground-snow interface dominates reflection



- Phase is related to snow depth for very wet snow
- Air-snow interface dominates reflection

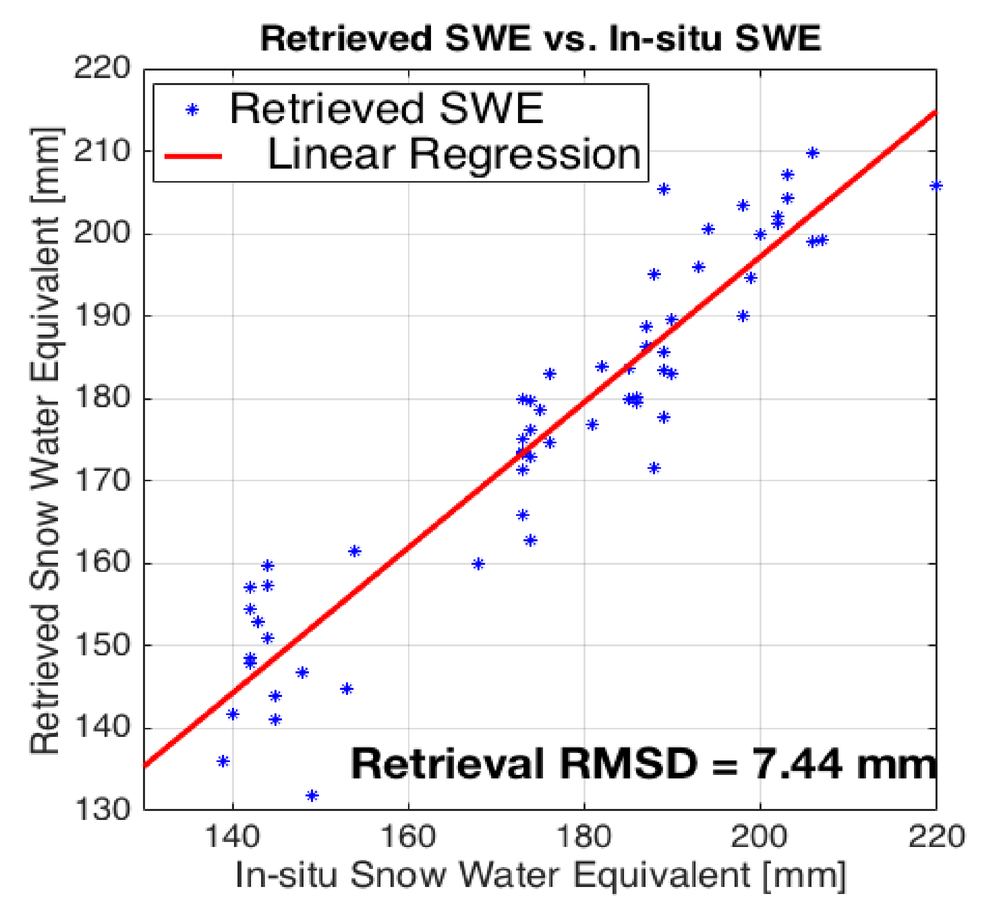


Ground Based Experiment

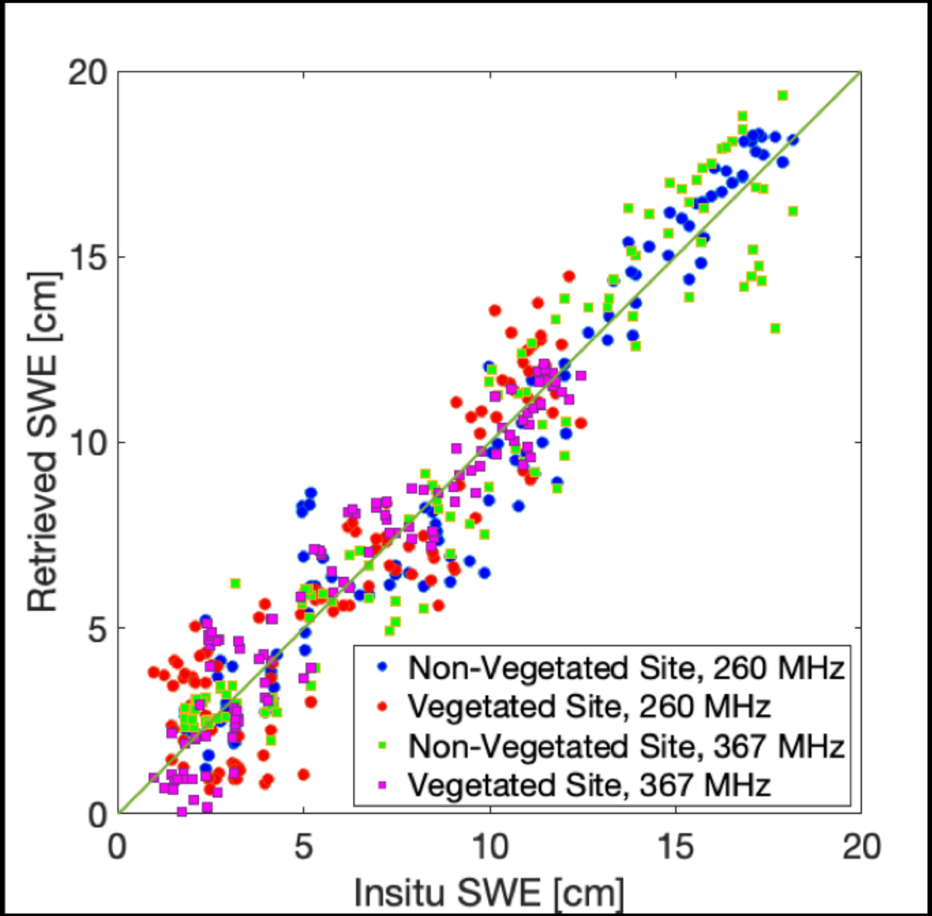
Site A (since Fall 2015):
- Almost no vegetation
- Data recording from 254-270 MHz and 360-376 MHz

Site B (since Fall 2016):
- Vegetation with trees up to 3 meters
- Data recording from 254-270 MHz and 360-376 MHz

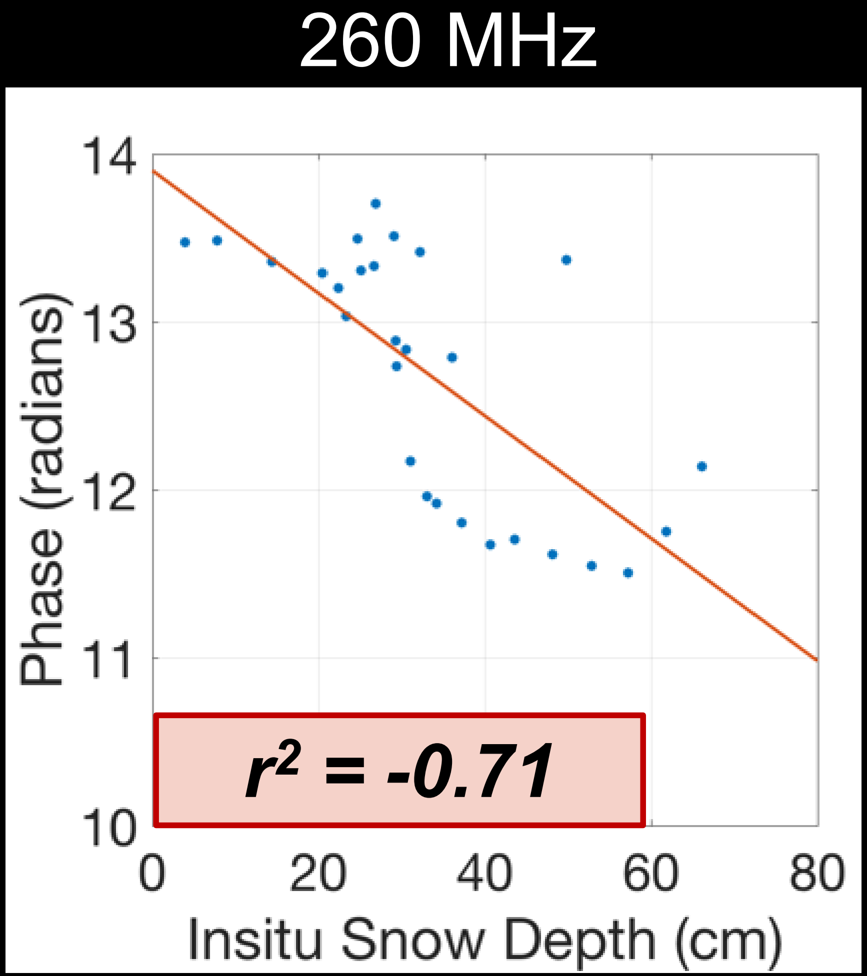
Snow Retrieval Demonstration

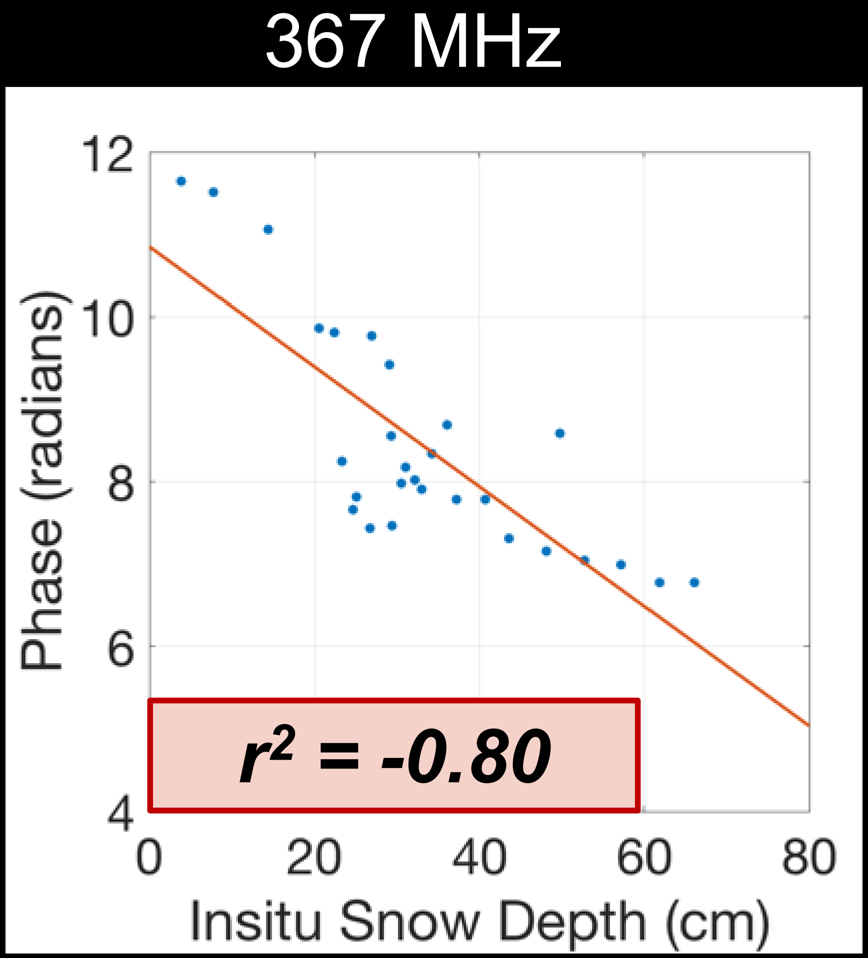


Shah et al., 2017



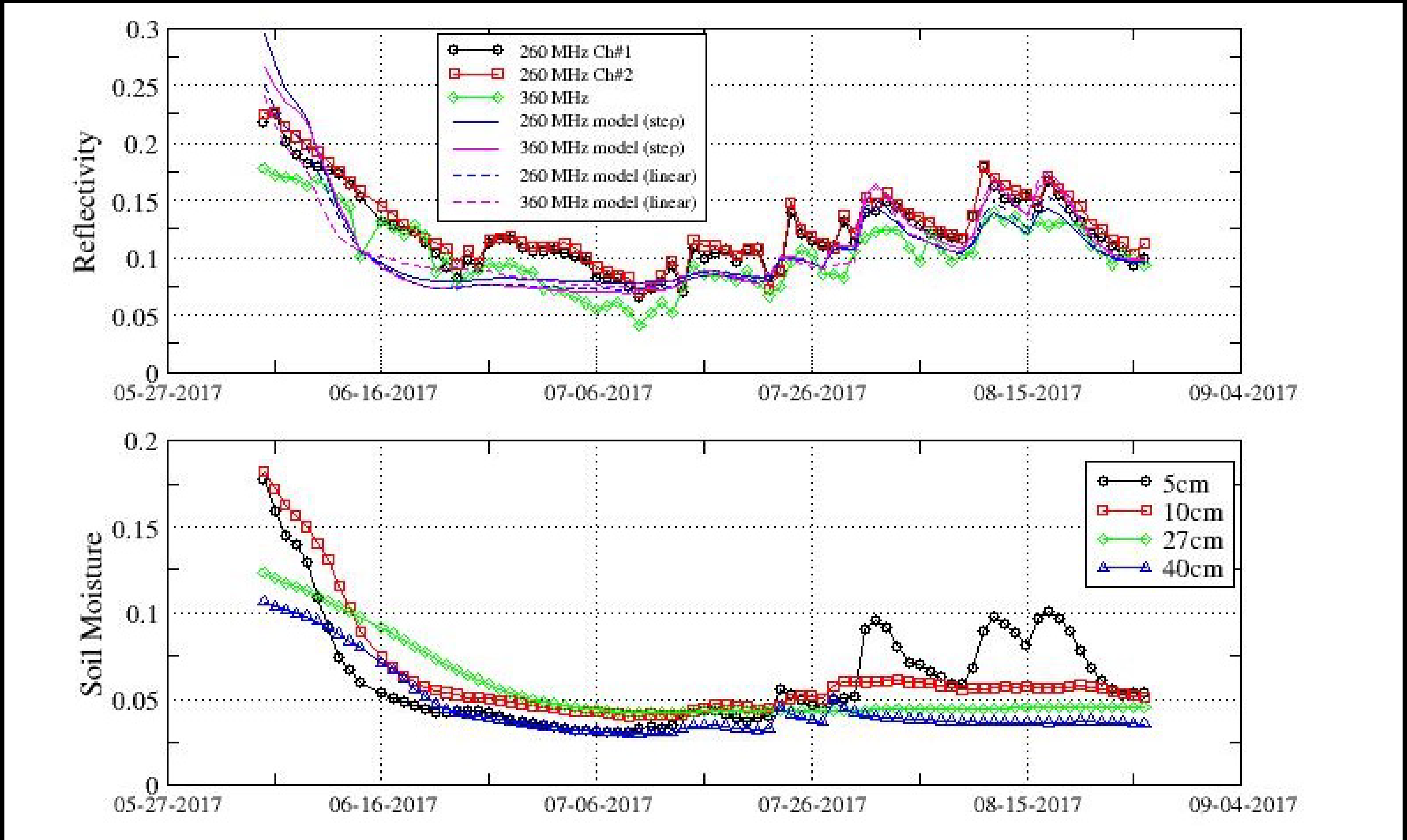
Snow Retrieval Wet Snow





RZSM from P-band SoOp

Fraser Experimental Forest

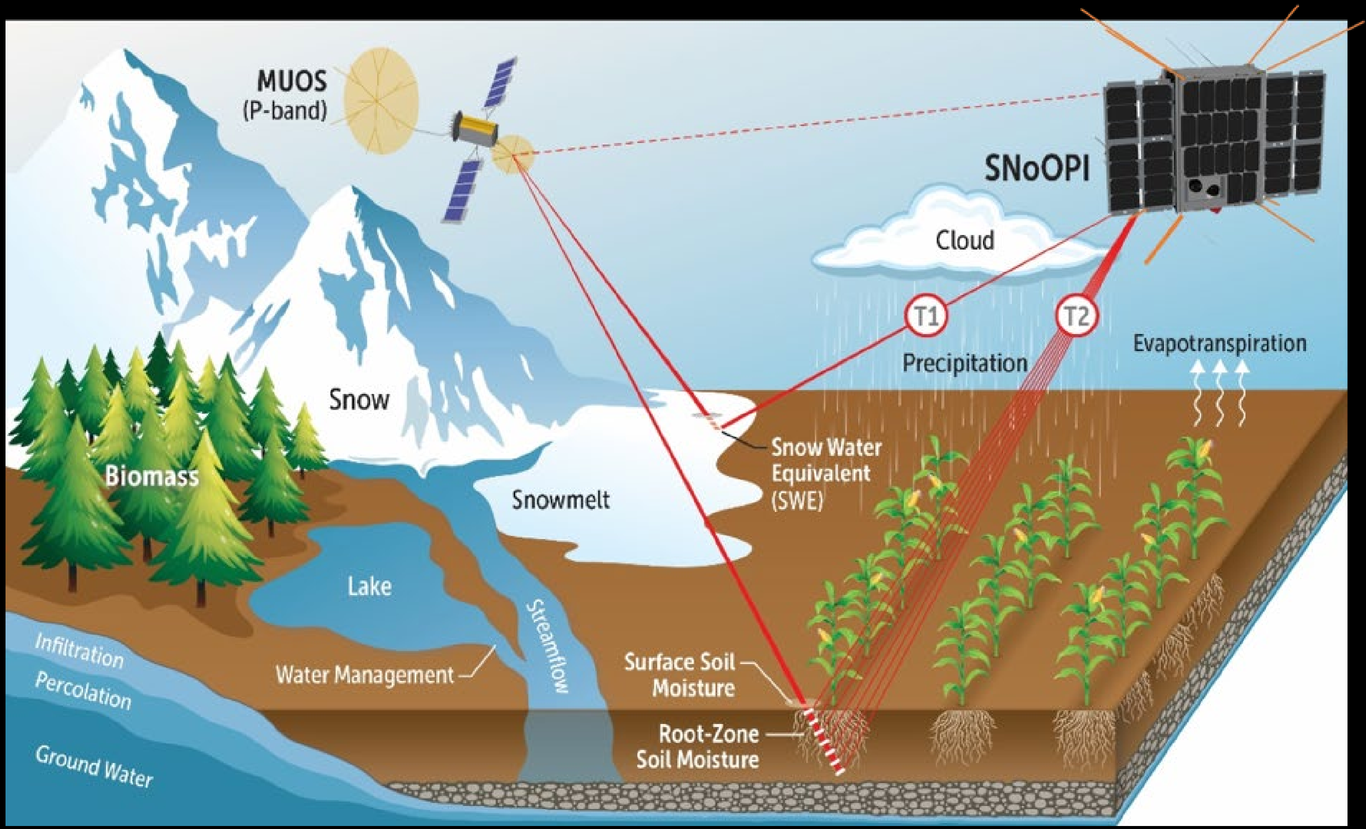


- Sensitivity to changes in soil moisture is shown

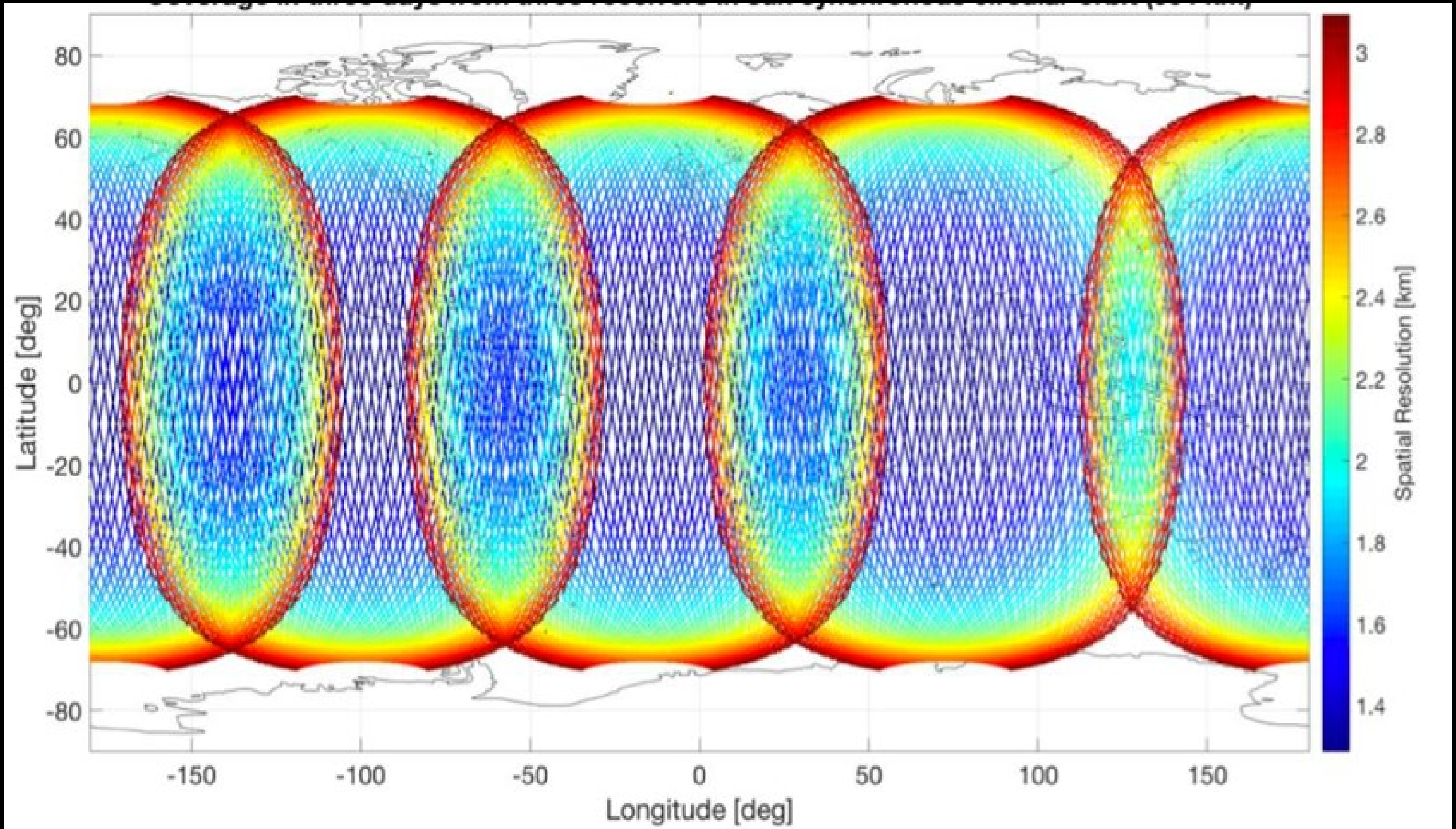
Yueh et al., 2019

SNOOPI: SigNals Of Opportunity P-Band Investigation

- Objective – In Space Validation of the SoOp ***technique*** in P-band
- Necessity of Space validation:
  1. Validate **link budget** from orbital altitudes and speeds to quantify uncertainty in reflectivity and phase
  2. Quantify **RFI effect** from space (broad field of view, global distribution of measurements)
  3. Demonstrate model prediction and instrument tracking for orbital delay and Doppler with non-cooperative transmitter



P-Band SoOp Constellation: Repeat orbit



Summary: Snow and Soil Moisture

SoOp technique can provide accurate sampling of SWE or snow depth and RZSM

- Phase directly proportional to SWE for dry snow and snow depth for wet snow
- Amplitude is related to RZSM

- Measurement principle demonstrated with field campaign
  - SWE was retrieved RMSD with linear regression is 7.5 mm
  - Relationship between phase and retrieved SWE matched theory
  - Amplitude was shown to be sensitive to changes in soil moisture
- Validation of measurement principle demonstration with from space is underway with SNOOPI

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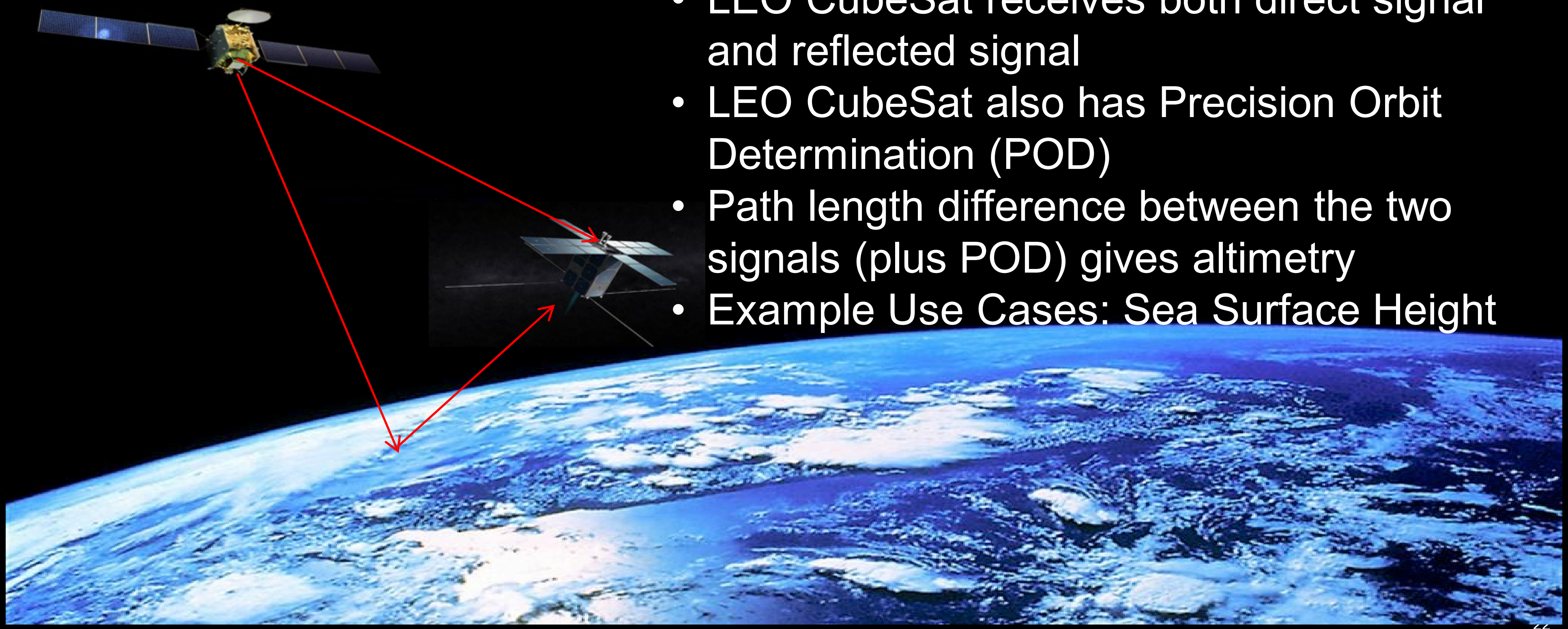
Measurement Concept for GEO SoOp

- GEO-based Comsat transmits signals
- LEO CubeSat receives both direct signal and reflected signal
- LEO CubeSat also has Precision Orbit Determination (POD)
- Path length difference between the two signals (plus POD) gives altimetry
- Example Use Cases: Sea Surface Height



Freeman and Shah, Cospar, 2018

SSH Precision from SoOp

$$\sigma_H = \frac{c}{2 \sin \epsilon \boxed{BW} \sqrt{N_{IN}}} \sqrt{\left(1 + \frac{1}{SNR}\right)^2 + \left(\frac{1}{SNR}\right)^2}$$

BW : Signal Bandwidth

SNR : Signal-to-noise ratio

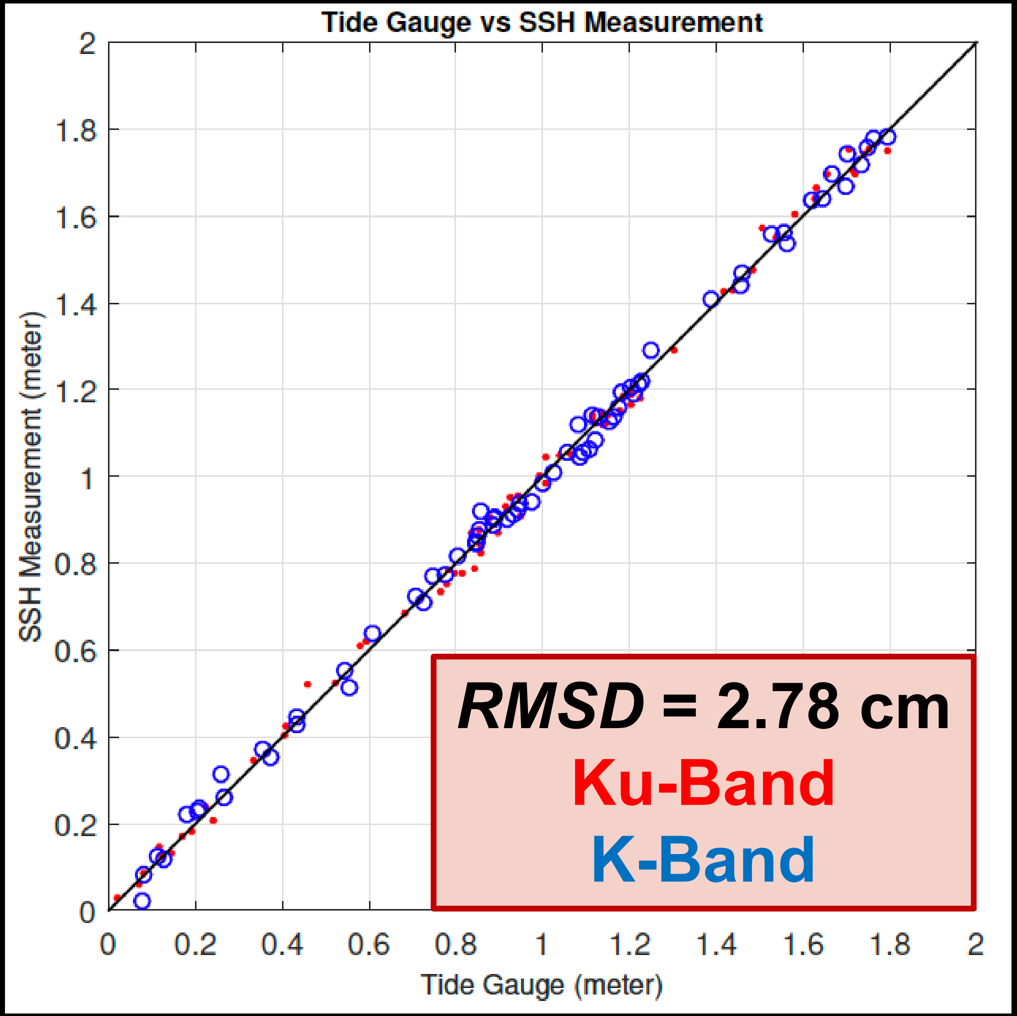
$\mathcal{E}$: Elevation Angle

N_{IN} : Number of "looks"

Martin-Neira et al., 2011

SSH from Wideband Ku/K Bands SoOp

Platform Harvest



- SSH = Sea Surface Height
- SSH can be computed using time delay between direct and reflected signal
- Use of 400 MHz wide DirecTV spectrum ➔ SoOp is coherent over wide bandwidth

Ho et al., 2019

SSH Precision from Spaceborne Wideband Signal

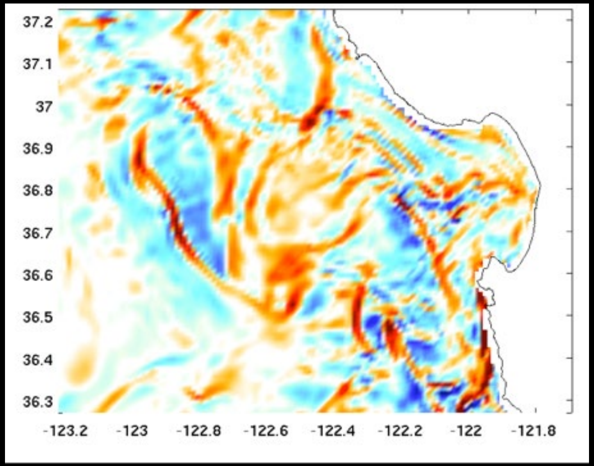
$$\sigma_H = \frac{c}{2\sin\epsilon\, BW\sqrt{N_{IN}}}\sqrt{\left(1+\frac{1}{SNR}\right)^2+\left(\frac{1}{SNR}\right)^2}$$

	Values				Units
Receiver Orbit Height	500		1380		km
Transmitting Frequency	12.5	18.5	12.5	18.5	GHz
Signal Bandwidth	400	500	400	500	MHz
c / Signal Bandwidth	75	60	75	60	cm
Averaging Time	1	1	1	1	sec
SSH Precision	**4.1**	**3.7**	**5.7**	**5.5**	**cm**

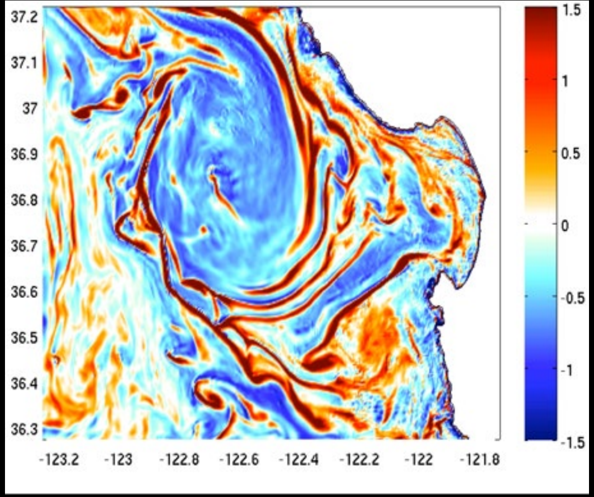
Precision from spaceborne system: ~4-6 cm

Coastal Eddies

- Coastal Altimetry can provide significant insight into:
    - *Storm surge prediction*
    - *Realistic wave models development*
    - *Improved forecast of wave setup*
- Submesoscale process in this region are highly energetic and have a short temporal scale
- Current satellite altimeter has limitation near the coast



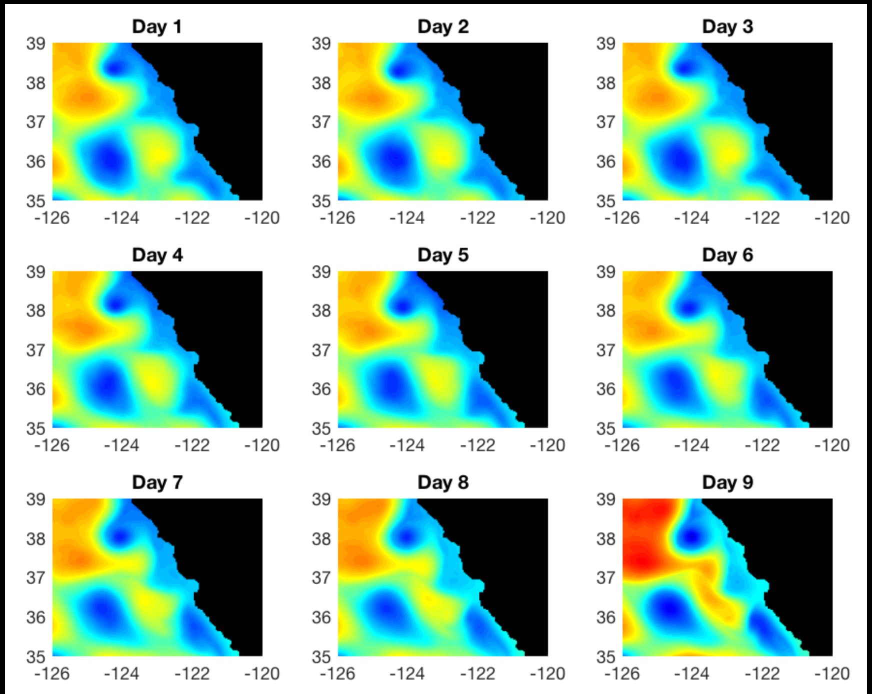
1-km ROMS



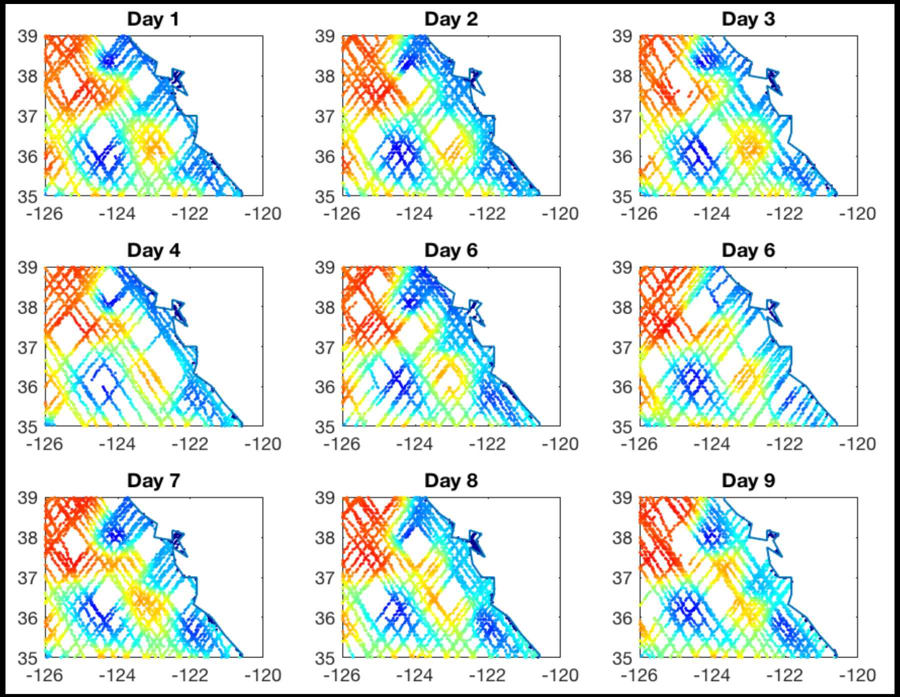
1/3km ROMS

Coastal Eddies Coverage

Simulation



SoOp Constellation



With a modest constellation of 8 receivers => the coverage of coastal eddies can significantly be improved

Summary: Ocean

SSH Wideband SoOp has the potential to provide higher temporal and spatial resolution measurements enabling coastal ocean circulation measurements down to sub-mesoscale

- ➢Improve our understanding of multi-scale circulations and thus of biological and chemical variability

Spatial and temporal coverage of SoOp has unique operational values for coastal management

- ➢Coastal zones are under serious threat from coastal erosions, storm surges, and deadly tsunamis

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Summary

- Reflectometry - combines aspects of active and passive microwave remote sensing - but is a distinct “third way”
- Navigation (GNSS) signal special properties enabled the first reflectometry demonstrations (late 90’s)
- Expansion of reflectometry broadly to “Signals of Opportunity” opens this technique to nearly all microwave frequencies penetrating the Earth’s atmosphere.

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