A Spaceborne Snow Mission Concept Using P-band Signals of Opportunity

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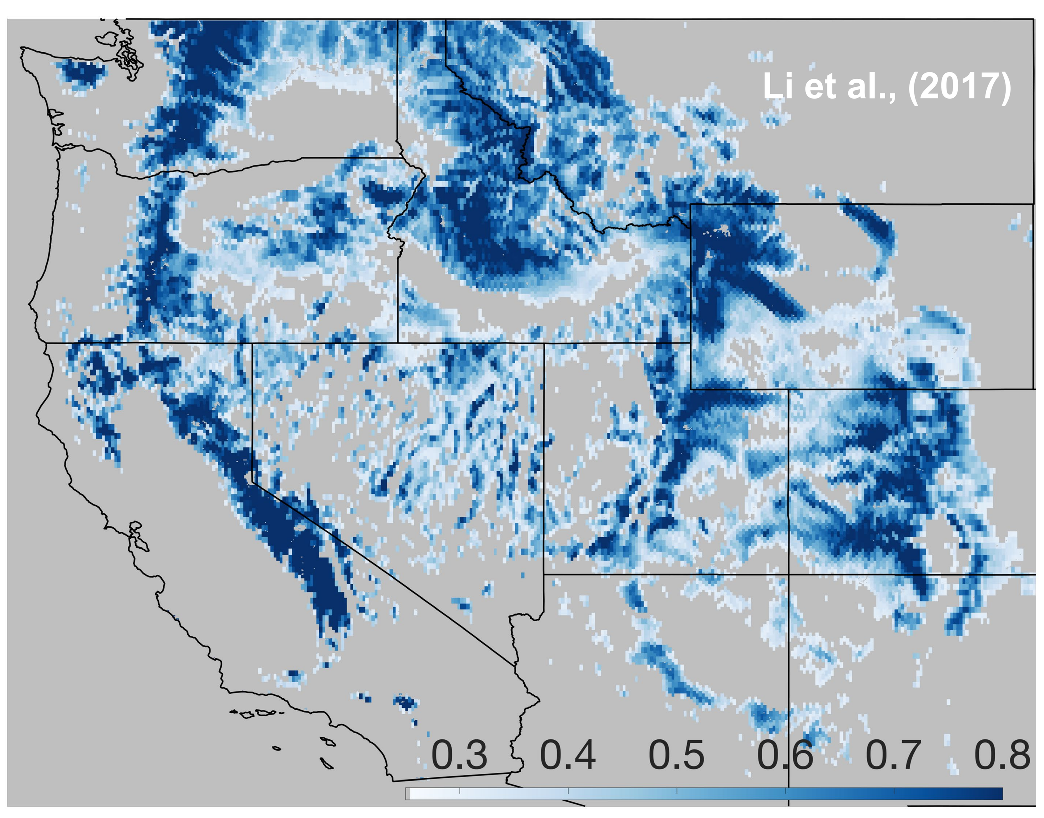
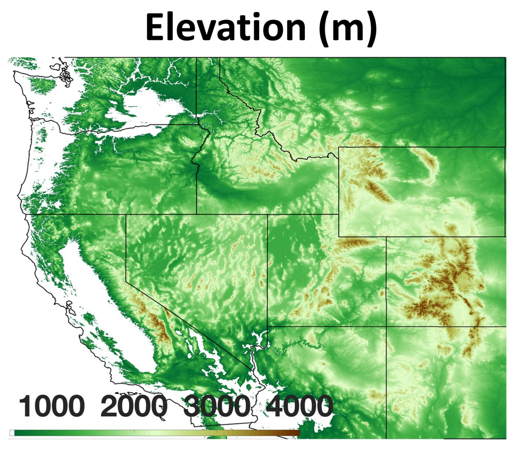
Need for Mountain Snow Water Equivalent (SWE) Measurements

➢ Seasonal mountain snowpacks provide a virtual reservoir commonly used for human water supply

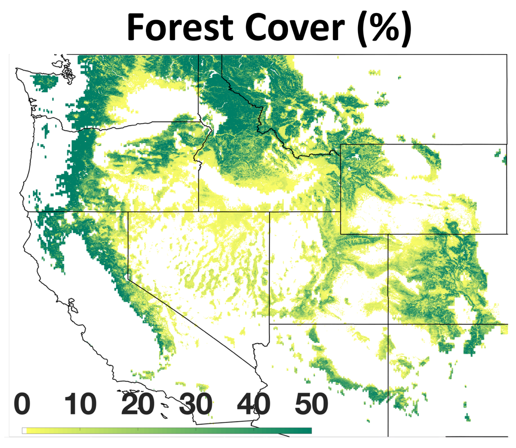
Fraction of runoff from snow over Western U.S.



Elevation (m)



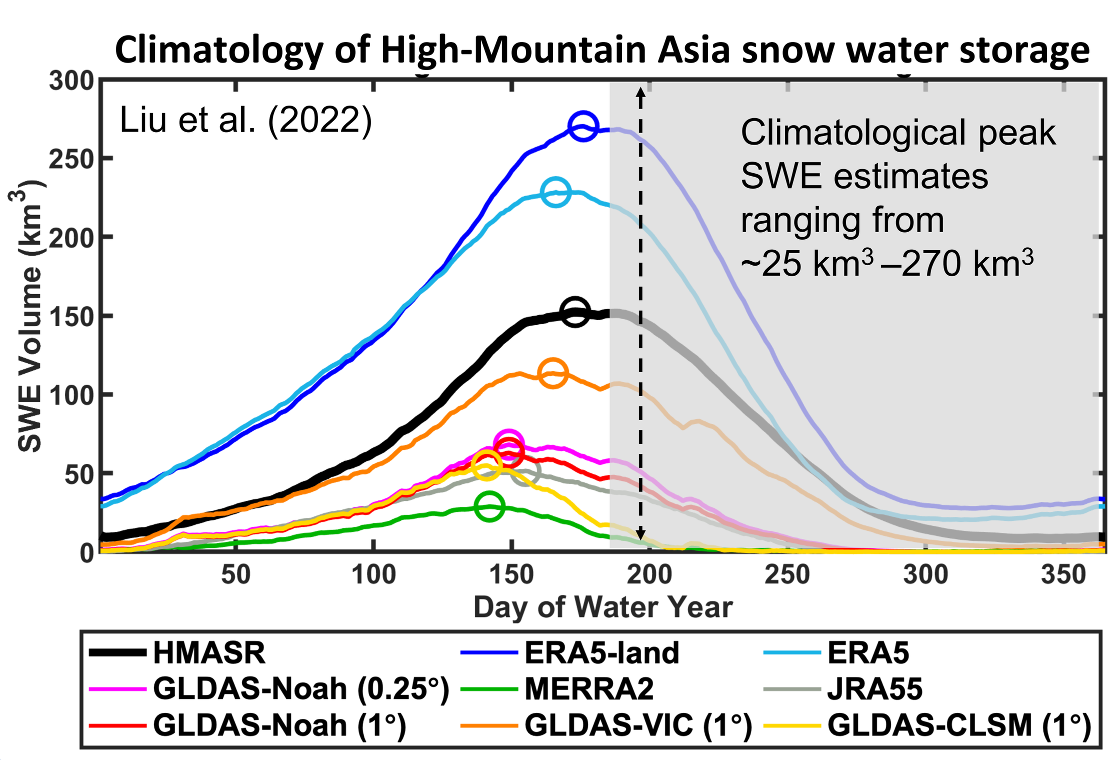
Forest Cover (%)



Mountain snow is challenging to characterize because of its spatial heterogeneity and deep snow, some in forests.

➢ Current estimates of mountain snow storage are highly uncertain

Intercomparison of global SWE products to High-Mountain Asia snow reanalysis (HMASR; Liu et al., 2021)



Measurement Program of Record

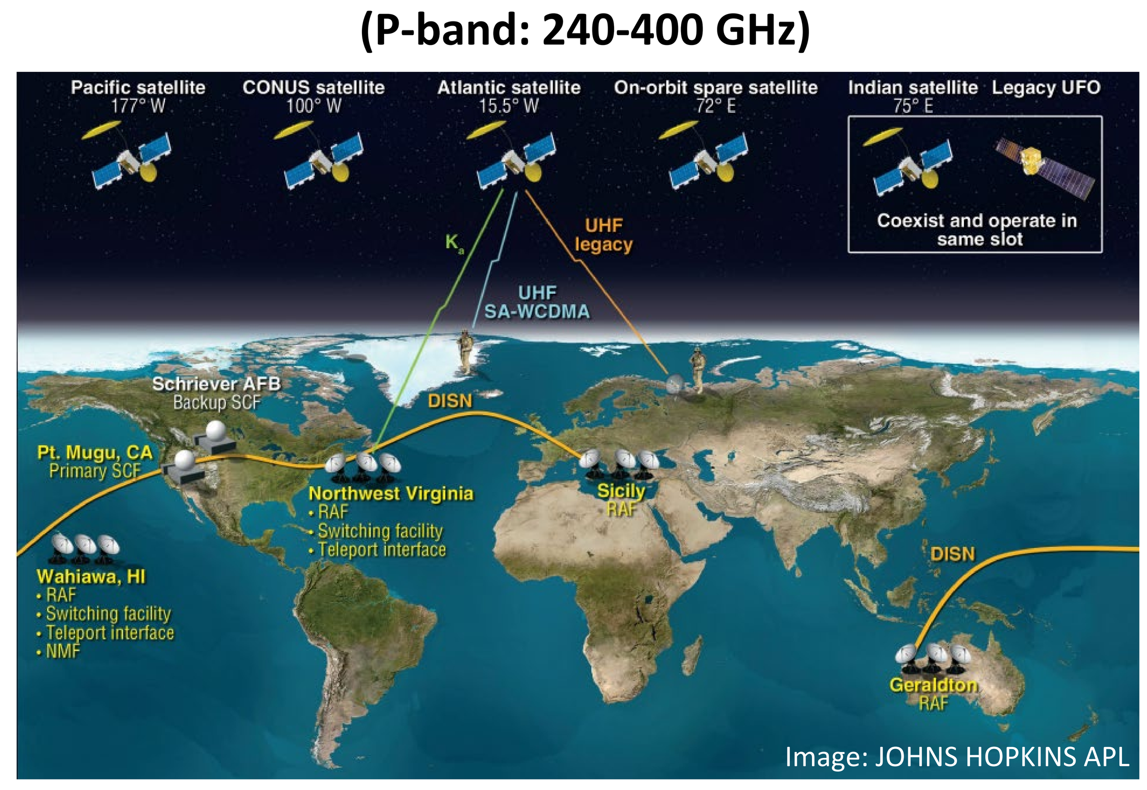
Ongoing missions (synergistic, but not SWE)	Planned future missions (Snow Depth and/or SWE)	Possible Future missions (Snow Depth and/or SWE)
Optical:	**RADAR:**	**RADAR:**
Landsat, Sentinel-2, MODIS, VIIRS	ESA Radar Observing System for Europe at L-band, ROSE-L (**L-band** SAR)	CSA Terrestrial Snow Measurement Mission, TSMM (**Ku-band** SAR)
RADAR:	NASA-ISRO SAR, NISAR (**L-band** SAR)	**X-/Ku-band** SAR
Sentinel-1 (**C-band** SAR)		**P-band** Signals of Opportunity (SoOp) SAR

P-band SoOp provides new, promising approach for mountain snow

P-band Signal of Opportunity (SoOp)

➢ An existing constellation of U.S. Military communication satellites provides a free nearly global signal at a frequency that is difficult to use for Earth science because of cost, mass, and power

MUOS (U.S. Military) Signal of Opportunity (P-band: 240-400 GHz)



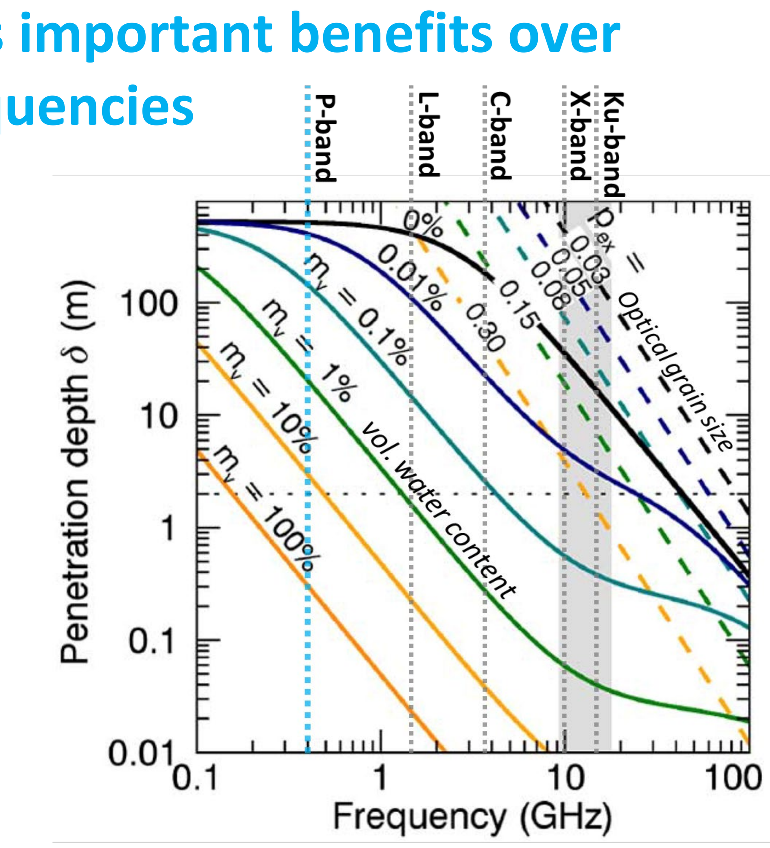
Four geosynchronous satellites with global coverage to ±60° latitude with stable long-term signal since 1978

➢ P-band has important benefits over higher frequencies

Ability to penetrate deep snow and forest canopy

Insensitivity to grain size (p_{ex}) and snow stratigraphy

Less sensitive to liquid water content (m_v)



modified from Leinss et al. (2015)

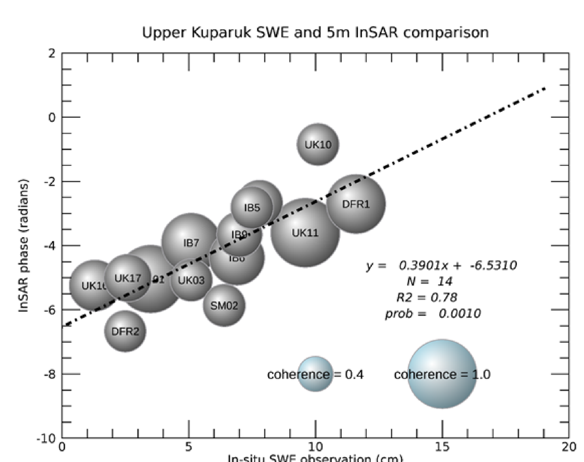
Proof-of-Concept: Spaceborne, Airborne, and Tower

➢ Microwave InSAR technique for SWE/SD retrieval has been demonstrated at L-band and P-band

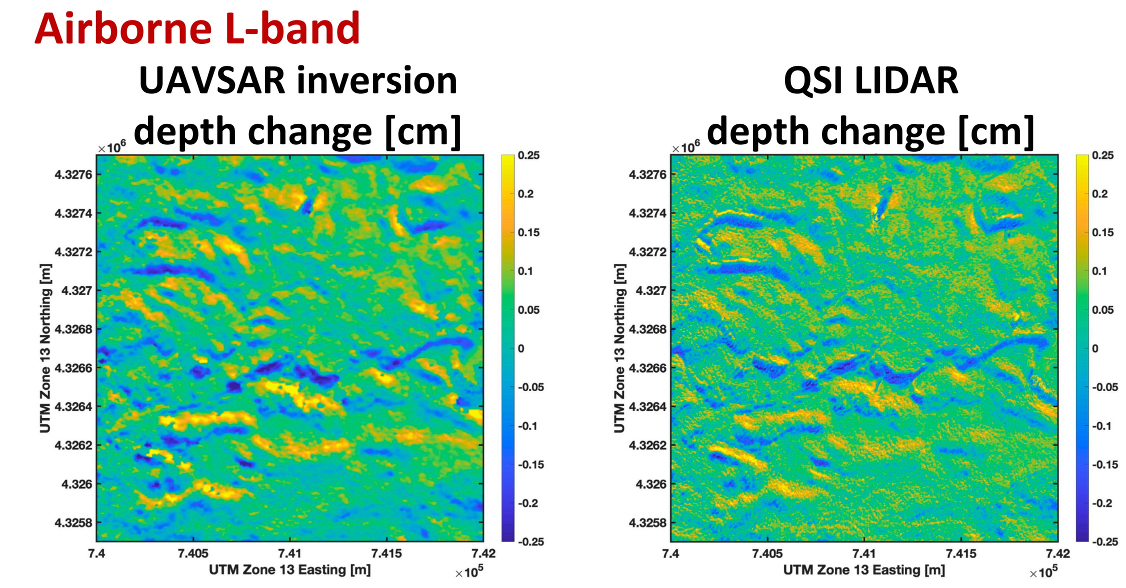
Spaceborne L-band

ALOS PALSAR phase change vs end-of-season SWE survey (184-day repeat)

Deeb, Forster, Marshall, *RSE* (submitted).

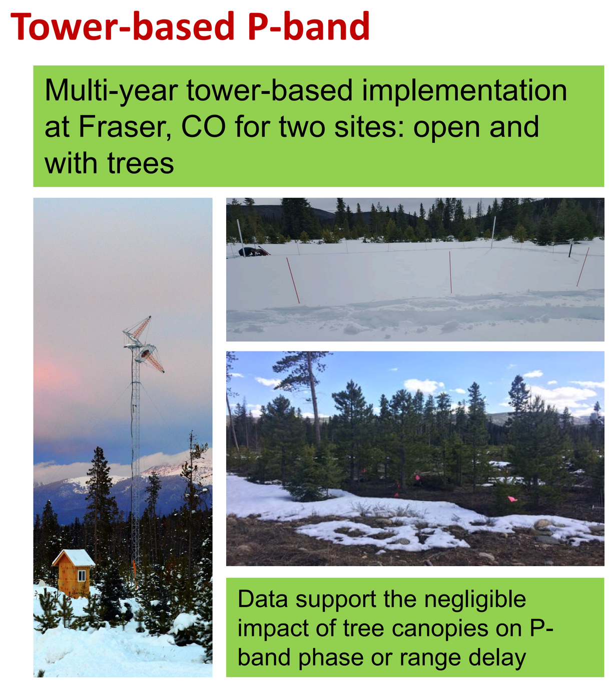


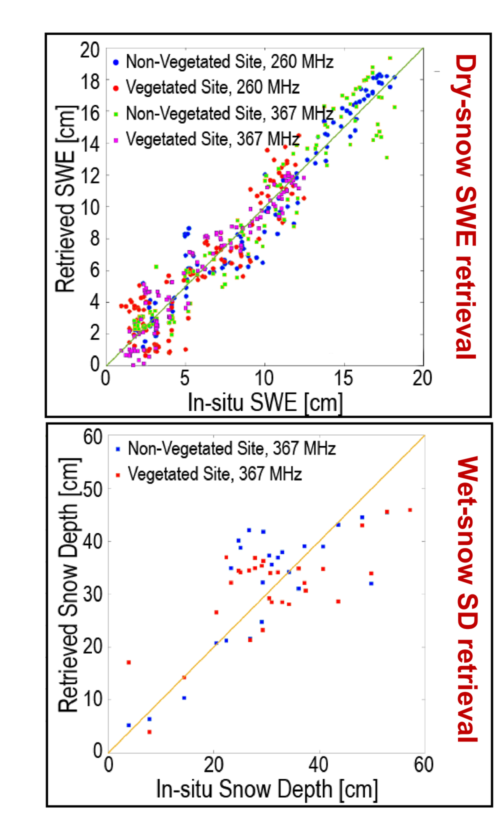
Airborne L-band



Marshall et al. (2021)

Tower-based P-band





Shah et al. (2018); Xu et al. (2018)

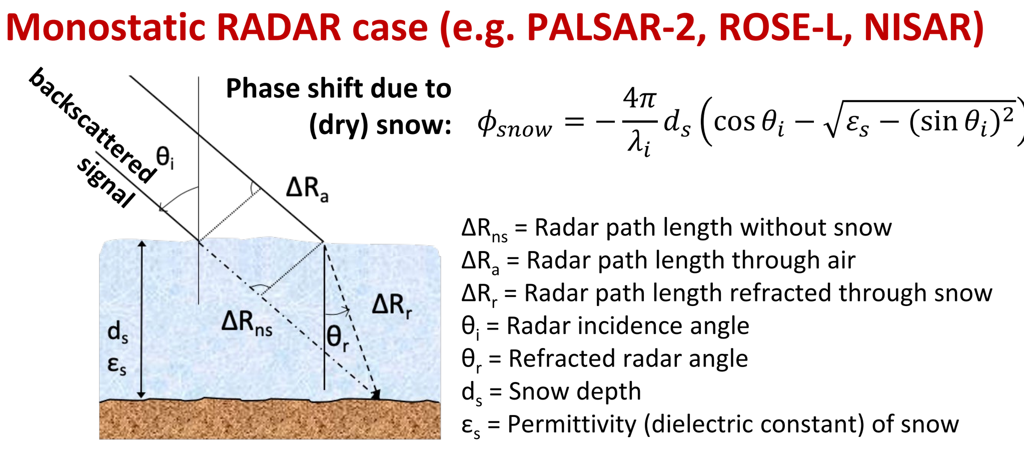
Airborne P-band SoOp campaign currently being implemented.

Retrieval Approach

➢ Repeat-pass interferometry

Monostatic RADAR case (e.g. PALSAR-2, ROSE-L, NISAR)

Phase shift due to (dry) snow: $\phi_{snow} = -\frac{4\pi}{\lambda_i} d_s \left(\cos\theta_i - \sqrt{\varepsilon_s - (\sin\theta_i)^2}\right)$

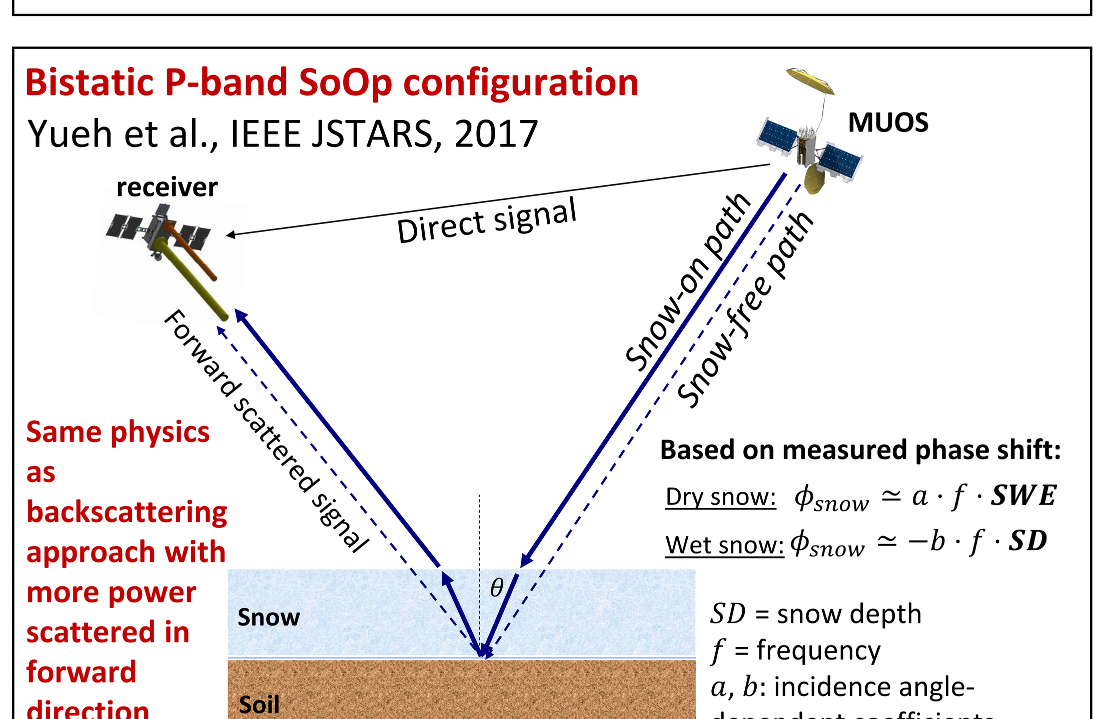


ΔR_{ns} = Radar path length without snow
ΔR_a = Radar path length through air
ΔR_r = Radar path length refracted through snow
θ_i = Radar incidence angle
θ_r = Refracted radar angle
d_s = Snow depth
ε_s = Permittivity (dielectric constant) of snow

(modified from Guneriussen et al., 2001)

Bistatic P-band SoOp configuration

Yueh et al., IEEE JSTARS, 2017

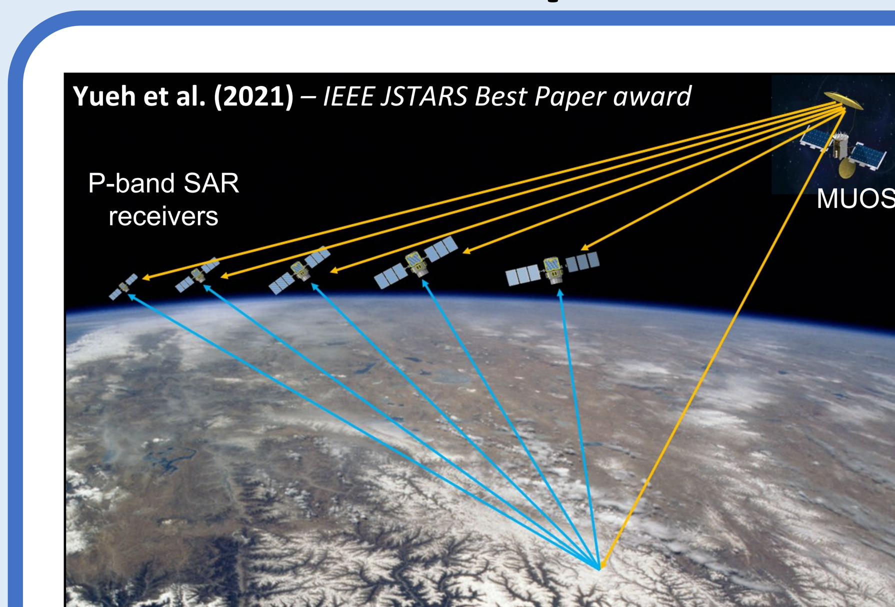


Same physics as backscattering approach with more power scattered in forward direction

Based on measured phase shift:
Dry snow: $\phi_{snow} \simeq a \cdot f \cdot \boldsymbol{SWE}$
Wet snow: $\phi_{snow} \simeq -b \cdot f \cdot \boldsymbol{SD}$

SD = snow depth
f = frequency
a, b: incidence angle-dependent coefficients

Snow SoOp SAR Concept



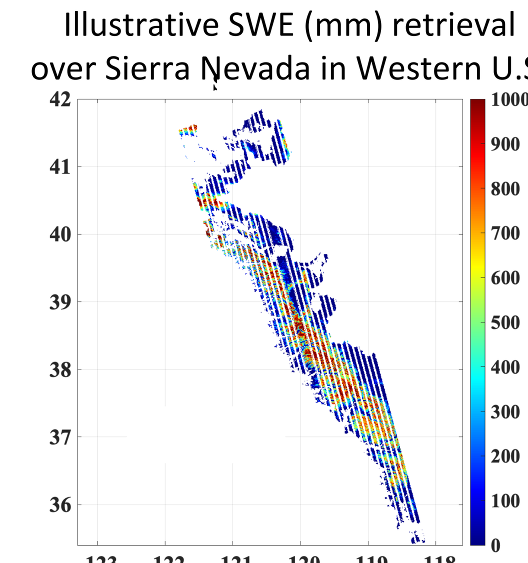
Train of SmallSats on one orbit plane

Earth rotation used to create separate ground tracks

Dual frequency P-band (240-270 MHz & 360-380 MHz) SAR receivers

P-band zenith (direct) and nadir (reflected) antennas

Illustrative SWE (mm) retrieval over Sierra Nevada in Western U.S.



- Swath created by SmallSat train: ~100-200 km
- Temporal repeat: 3-12 days
- Spatial resolution, with some gaps: ~50 m along-track to 500-1500 m cross-track
- Retrieve SWE (dry-snow) or SD (wet snow)
- Space-time continuous maps of SWE can be derived using data assimilation