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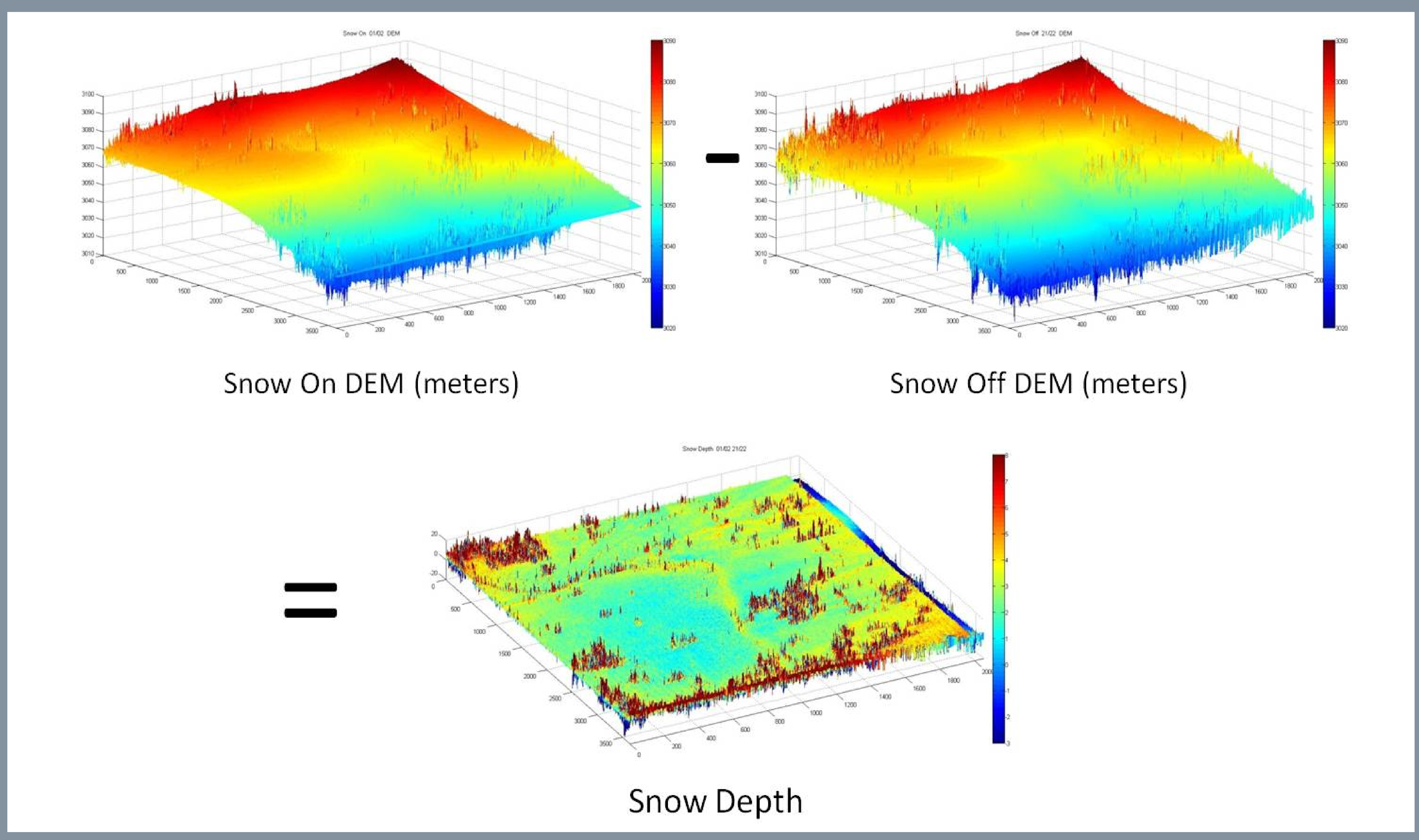
Synthetic Aperture Radar Research

SNOW DEPTH RETRIEVAL USING KU-BAND INTERFEROMETRIC SYNTHETIC APERTURE RADAR (INSAR)

- Monitoring seasonal snow accumulation is important as a factor required for evaluation of snow models, short- and long-term snow cover monitoring, and for both military and civilian operations
- Current snow depth measurement methods fall short of requirements
- A new approach uses InSAR-derived Digital elevation models (DEM) from Multi-pass (monostatic) Single Look Complex (SLC) airborne Ku-band SAR
- InSAR DEMs for Snow-Off and Snow-On cases are differenced to determine elevation change from accumulated snow

InSAR DEMs allow derivation of snow depth and volume



A site at Mammoth Mountain, California was used to test the airborne InSAR approach for snow depth estimation

Google Earth 3D perspective view of the Elysian Fields collection area looking north towards Mammoth Mountain, CA. (Google Earth, 2012).

InSAR Approach

- SAR interferograms are produced and unwrapped to determine total phase (distance to terrain)
- A flat earth correction is applied using a best-fit-plane perturbation model
- Phase is converted to absolute height using linear regression to known elevations
- Determination of the Snow-Off and Snow-On DEMs and subsequent subtraction provides an estimate of elevation change caused by snow accumulation for specific locations
- Manual snow depth measurements used to validate the SAR results

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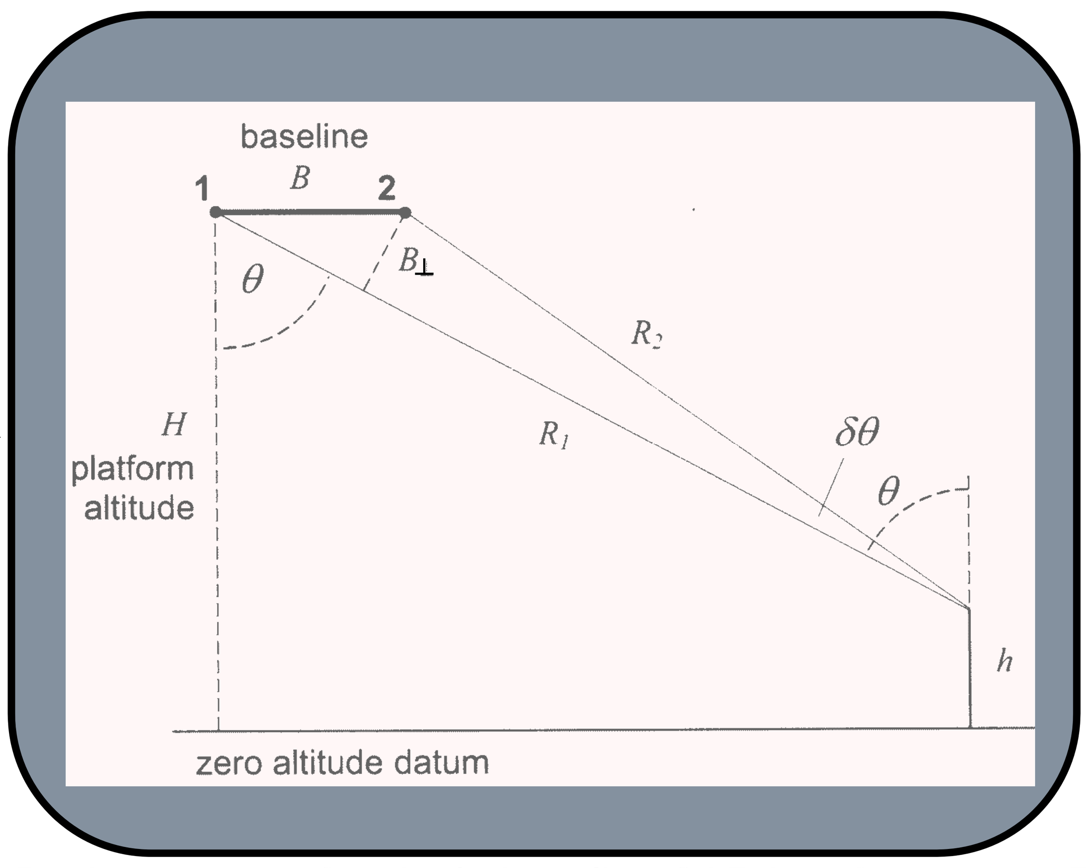
InSAR Digital Elevation Models

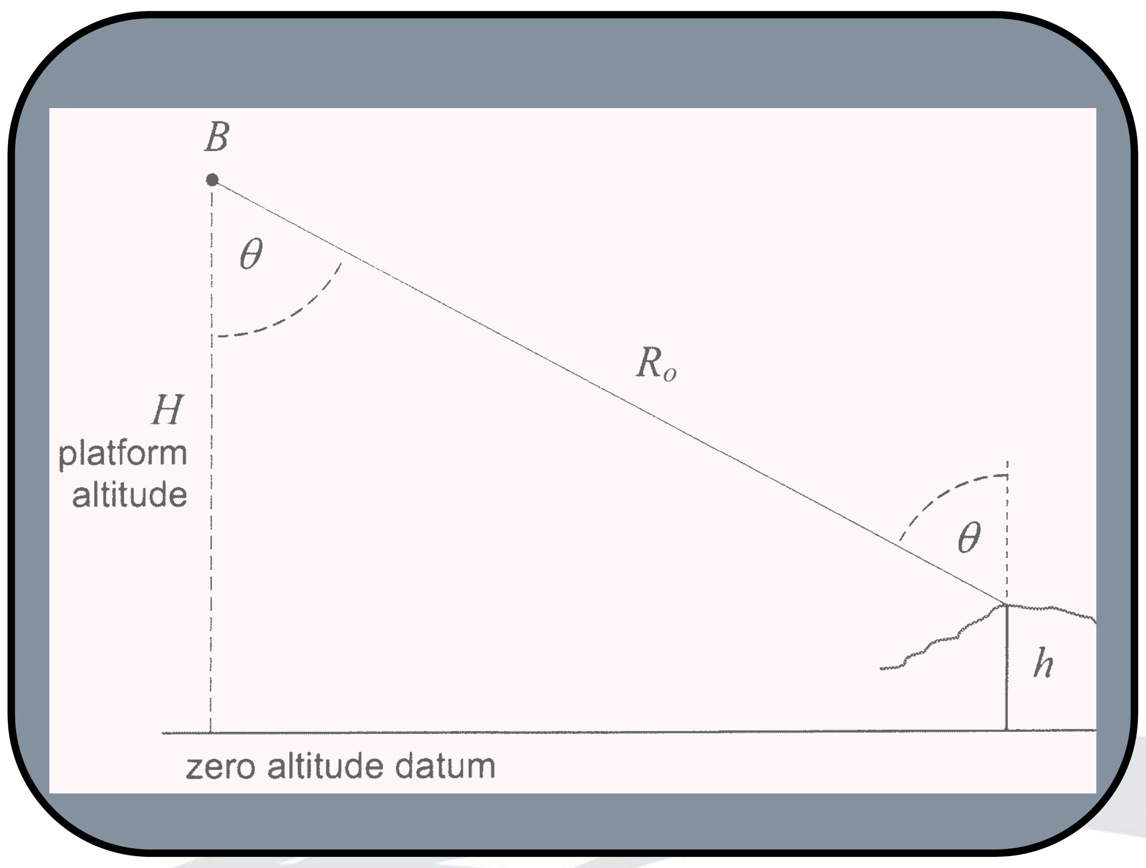
High Resolution Digital Elevation Models (DEMs) determined using multi-pass interferometric SAR (InSAR)

- Radar uses radiation emitted from an antenna in the microwave region of the electromagnetic (EM) spectrum. This emitted energy travels to a target and is reflected back to the antenna
- InSAR capitalizes on the capability to measure the phase angle of the SAR return. The transmitted phase is known and the return phase can be measured. This allows high accuracy determination of relative distances from the sensor to the ground.
- When these distances are measured from two different locations (a change in the radar's position), then topography or topographic displacement can be determined. This is the basis of InSAR.

InSAR measures phase to determine distance to the terrain



Basic geometry for single baseline SAR interferometry. "R_1" and "R_2" are the respective ranges from antennas 1 and 2. "B" is the baseline between the two antenna locations. "$B_\perp$" is the orthogonal baseline. "θ" and "$\delta\theta$" are the incidence angle and the change in incidence angle respectively (Richards 2009).



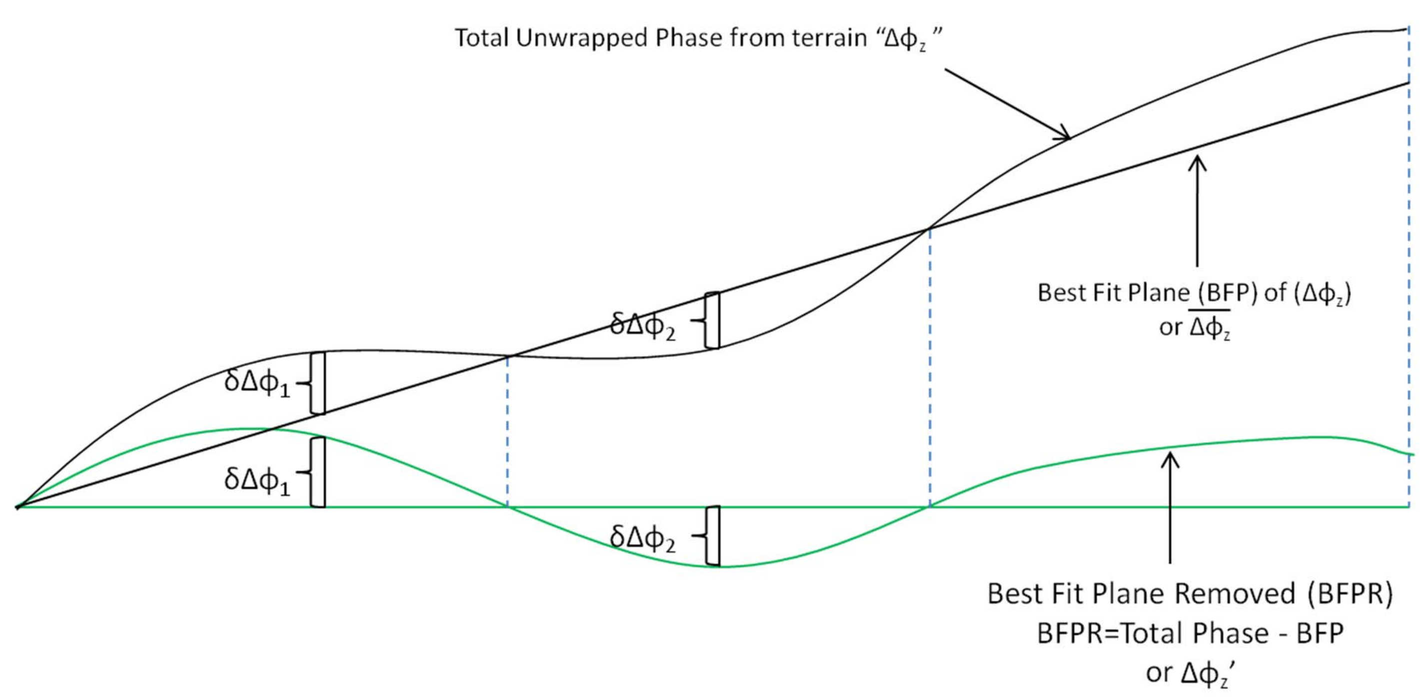
Determining the relationship between topographic height "h" and incidence angle "θ" with a platform altitude of "H" and range to the target of "R_0"
Richards, J.A., 2009, Remote sensing with imaging radar : Springer-Verlag, 361 p.

Derivation (equations from Richards, 2009 with some modifications)

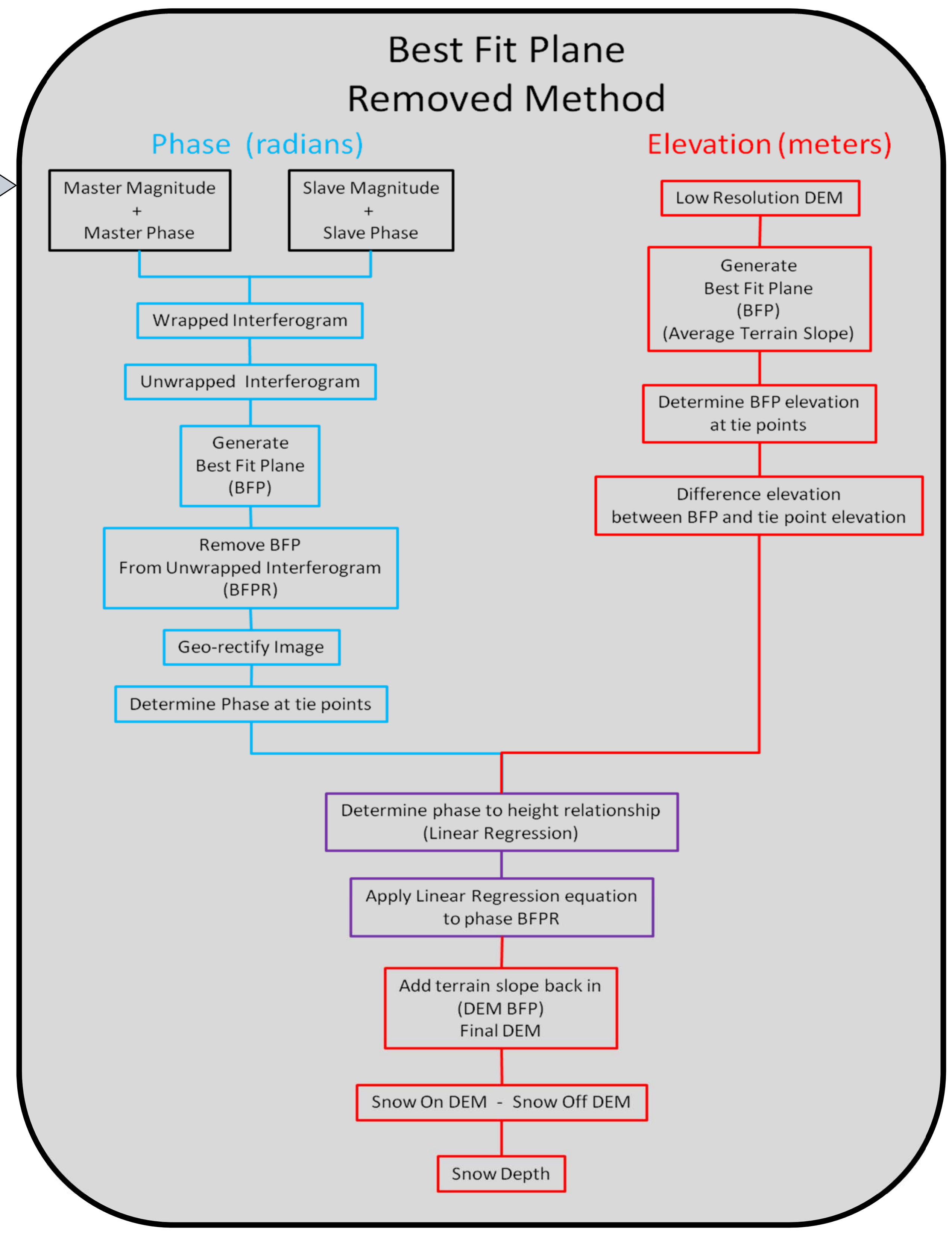
- The difference in the path lengths "R_1" and "R_2" in terms of the phase and a given baseline and incidence angle of "B" and "θ" respectively can be derived as: $R_1 = R_2 \cos\delta\theta + B\sin\theta$ (1)
- $\delta\theta$ is assumed to be approximately *0* using the plane wave approximation. The plane wave approximation considers the change in the incidence angle to approximate *0* when the target is infinitely far away when compared to the length of orthogonal baseline. This results in:
  $R_1 = R_2 + B\sin\theta$ (2) therefore $\Delta R = R_1 - R_2 = B\sin\theta$ (3)
- The difference in phase angle "$\Delta\phi$" (interferometric phase angle) associated with the change in path length "ΔR" between the two passes can then be given as $\Delta\phi = \frac{4\pi B\sin\theta}{\lambda}$ (4)
- If in the Figure above, "H" is the total height above an assumed altitude, and "R_0" is the range to the target, observe that $h = H - R_0\cos\theta$ (5)
- Taking the partial derivative of the topographic height and of $\Delta\phi$ with respect to the incidence angle results in $\frac{d(h)}{d\theta} = R_0\sin\theta$ (6) and $\frac{d(\Delta\phi)}{d\theta} = \frac{4\pi B\cos\theta}{\lambda}$ (7)
- Combining these equations results in $\frac{d(\Delta\phi)}{dh} = \frac{d(\Delta\phi)}{d\theta}\frac{d\theta}{d(h)} = \frac{4\pi B\cos\theta}{\lambda R_0\sin\theta}$ (8)
- We now have an expression for the change in interferometric phase with respect to the change in topographic height. Simplifying results in $\frac{d(\Delta\phi)}{dh} = \frac{4\pi B_\perp}{\lambda R_0\sin\theta} = \frac{4\pi B_\perp\cos\theta}{\lambda (H-h)\sin\theta}$ (9)
- The interferometric phase factor α_{IF} is defined as $\alpha_{IF} = \frac{dh}{d(\Delta\phi)}$ (10)
- and the height of a specific pixel will be given by $h(x,y) = \alpha_{IF}\,\Delta\phi(x,y) + CONSTANT$ (11)
- Equation (10) enables the generation of a DEM from InSAR image pairs

Best Fit Plane Removal for InSAR Topography

A perturbation or decomposition of parts (Best Fit Plane Removal, BFPR) approach was used to derive topography from InSAR Total Phase



The Best Fit Plane Removed (BFPR) method subtracts the best fit plane (BFP) from the total unwrapped phase. The BFPR isolates the portion of the total unwrapped phase that is due to the deviation of the terrain from the average slope of the terrain and is signified as "$\Delta\phi_z'$" or the equivalent "$\delta\Delta\phi$".



Derivation of Perturbation (BFPR) Method

As used in the following equations, variables with an over-bar represent the mean of that variable while the "prime" symbol represents the deviation of the value from a particular mean.

- An unwrapped interferogram is made up of both flat earth and terrain phase as is seen in (12) where "$\Delta\phi_z$" represents the phase associated with the terrain (simplified from Richards, 2009).

$$\Delta\phi_{total} = \Delta\phi_{flat\_earth} + \Delta\phi_z \quad (12)$$

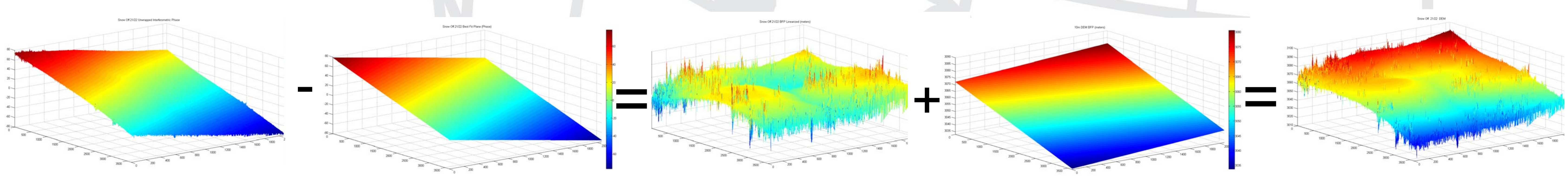
- From a perturbation perspective, the flat earth phase is $\Delta\phi_{flat\_earth} = \overline{\Delta\phi}_{flat\_earth} + \Delta\phi'_{flat\_earth}$ (13)
- The flat earth phase, however, is a plane and has no perturbation. Therefore it reduces down to $\Delta\phi_{flat\_earth} = \overline{\Delta\phi}_{flat\_earth}$ (14)
- The terrain phase from a perturbation perspective is $\Delta\phi_z = \overline{\Delta\phi}_z + \Delta\phi'_z$ (15)
- Unlike the flat earth phase, there are variations throughout the image. "$\overline{\Delta\phi_z}$" is the average slope of the terrain and "$\Delta\phi_z'$" is the variation or perturbation from that average slope.
- By substituting (14) and (15) into (13), the total phase can now be given as

$$\Delta\phi_{total} = \overline{\Delta\phi}_{flat\_earth} + \overline{\Delta\phi}_z + \Delta\phi'_z \quad \text{or} \quad \Delta\phi_{total} = \Delta\phi_{flat\_earth} + \overline{\Delta\phi}_z + \Delta\phi'_z \quad (16)$$

- Taking the best fit plane of the total phase is the same as finding the average slope of the phase image and is now given by $\overline{\Delta\phi}_{total} = \overline{\Delta\phi}_{flat\_earth} + \overline{\Delta\phi}_z$ (17)
- Subtracting the BFP or (17) from the total phase yields

$$\Delta\phi_{total} - \overline{\Delta\phi}_{total} = \Delta\phi_{flat\_earth} + \overline{\Delta\phi}_z + \Delta\phi'_z - \Delta\phi_{flat\_earth} - \overline{\Delta\phi}_z = \Delta\phi'_z \quad (18)$$

- Equation (18) represents the BFPR terrain (in phase space) and demonstrates that subtracting the BFP from the total phase results in only the terrain perturbations or terrain that deviates from the mean slope
- A best fit plane to a low resolution DEM is used to estimate the mean slope. Linear regression is then used to convert the BFPR phase to the difference between the mean slope elevation and the known elevations. Finally, the mean slope is added back into the InSAR-derived terrain to create the final DEM.



Total Unwrapped Phase — Best Fit Plane = Best Fit Plane Removed + Low Res DEM Best Fit Plane (Slope) = BFPR Digital Elevation Model)

Lynx II Airborne InSAR Snow Depth Results

One Snow-Off and six Snow-On Lynx II data collects were used to make snow depth estimates based on InSAR Pairs

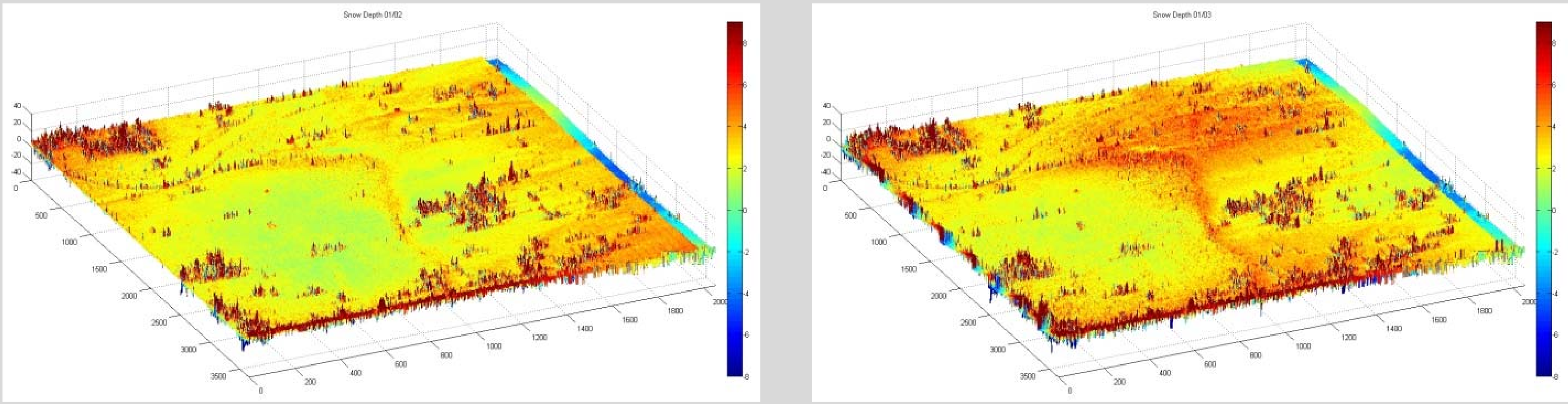
SAR Image number	Date	Time	Surface Condition
01	3 April 2012	18:47 Z, 10:47 L	snow covered
02	3 April 2012	18:55 Z, 10:55 L	snow covered
03	3 April 2012	19:04 Z, 11:04 L	snow covered
04	3 April 2012	19:00 Z, 11:00 L	snow covered
21	13 July 2012	17:58 Z, 10:58 L	bare
22	13 July 2012	18:05 Z, 11:05 L	bare

Snow Depth Estimation results

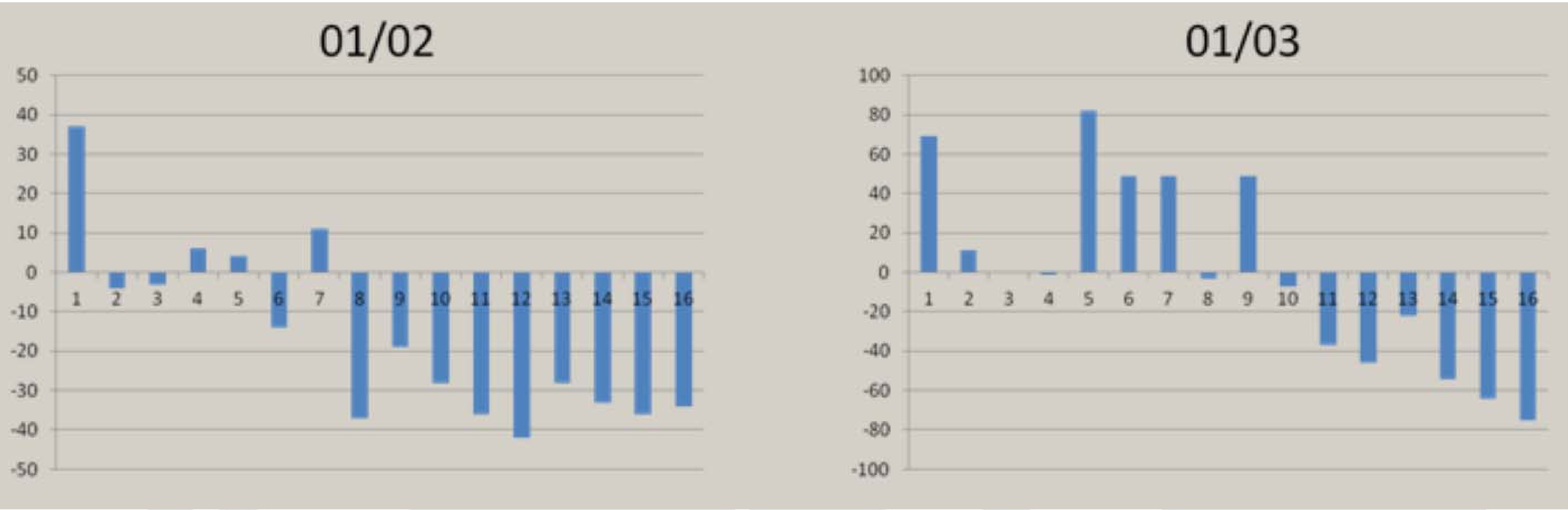
Mean Snow Depth Error by SAR image pair						
SAR Image Pair	01/02	01/03	01/04	02/03	02/04	03/04
Average Snow Depth error (cm)	-8.00	95.00	-49.06	175.69	-86.56	-41.69

- ❖ Most estimated snow depths are in the 0 – 2.5m range, with some obvious errors due to the interaction of SAR with trees and other obstacles
- ❖ Estimated snow depths were compared to individual snow depth measurements at 16 field locations and to mean snow depth error for each SAR DEM (see Tables above and at right)
- ❖ Average snow depth errors vary and each of the different SAR image pairs tend to show either a high or low average error (bias)

- ➢ Multiple passes of Lynx II Ku-band radar operating at 15.2-18.2GHz frequency (1.8cm wavelength) were flown at 0.1m spatial resolution at Mammoth Mountain, CA
- ➢ Snow-On and Snow-Off collections were flown on 3 April 2012 and 13 July 2012 respectively
- ➢ The data were processed to DEMs using a combination of standard InSAR processing and the “Best Fit Plane Removal” (BFPR)
- ➢ Results were compared to manual snow depth measurements



Two 3D perspective views of snow depth at the Elysian Fields site, Mammoth Mountain showing variability and biase. Left: InSAR Snow-On Pair 01/02, Right: InSAR Snow-On Pair 01/03.



- ❖ While it is not quite clear where these biases are coming from, it is believed that they are related to possible tilt or unresolved slope in BFP calculation and removal processes

Conclusions

- ➢ The goal of the Snow Depth Airborne Radar (SNODAR) research was to explore snow depth estimation using Multi-pass Single Look Complex InSAR
- ➢ Differencing of a Snow-Off DEM and Snow-On DEMs derived from intereferometric Ku-band airborne SAR data using a perturbation or decomposition of parts bypassed the requirement for detailed, precise InSAR baseline knowledge to isolate the interferometric phase caused by the terrain
- ➢ The snow depth results for six Snow-On SAR pairs were compared to 16 manually measured snow depth locations with varying degrees of success. The SAR image pairs showed an average error of -8cm, 95cm, -49cm, 175cm 87cm and 42cm for the respective six SAR pairs. High errors and variability most likely are related to biases resulting from unresolved tilt in some of the BFP and also the coherence of the unwrapped InSAR data. Theses phenomena bear further investigation.
- ➢ This research demonstrates that Ku-band radar is capable of discerning the snow air interface with minimal penetration and therefore is capable of mapping snow depth
- ➢ We are exploring sources of snow depth error and how to reduce their effects