GeoSAR

Phase Screen Determination for the GeoSAR Interferometric Mapping Instrument

by

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Overview

- GeoSAR System Description
- Onboard Baseline Metrology Measurements
- Need for Phase Screen
- Calibration Methodology
- Least Estimation Specifics
- Phase Screen Results

Overview of GeoSAR

- Aircraft-based, interferometric synthetic aperture radar (SAR) system for topographic mapping.
  - Gulfstream II business jet
  - Day/night, all-weather, low-cost, commercial system
- Develop precision foliage penetration mapping technology based upon dual frequency, dual polarimetric, interferometric radar.
  - X-band radar (λ=3 cm) for bare ground and "tops" of trees
  - P-band (UHF) radar (λ=86 cm) for ground and foliage penetration (HH,HV)
- Produce true ground surface digital elevation models suitable for a wide variety of applications.
  - Combination yields "true ground surface" (TGS)
- Consortium of three agencies, initially funded by DARPA, current funding by NIMA.
  - Caltech's Jet Propulsion Laboratory (JPL), Pasadena, CA
  - Calgis, Inc., Fresno, CA
  - California Department of Conservation (CalDOC)

Calgis Department of Conservation JPL NASA

Mapping System

- Mapping System Consists of:
  - Aircraft platform to host data collection hardware (Gulfstream II)
  - Flight planning software
  - Dual frequency (X-band/UHF) interferometric SARs
    - Single polarization @ X-band
    - Dual polarization @ UHF
    - Automated radar control
  - Laser interferometric baseline measurement system augmented with embedded GPS/INU systems and differential GPS for precision reconstruction of aircraft flight trajectory and attitude history
  - SAR processors capable of producing DEMs @ X-band and UHF and a true ground surface DEM from combined X-band/UHF analysis
  - A GIS system to analyze digital data

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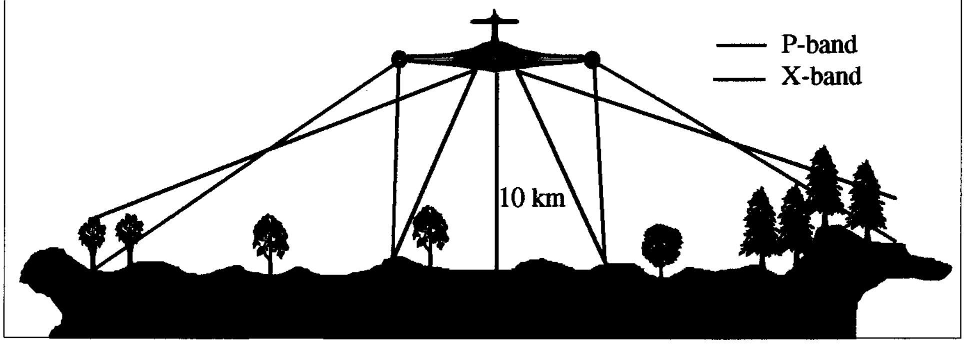
Data Collection Basics

- Nominally, GeoSAR will collect X and P-band data from both the left and right sides of the aircraft. Data is recorded on two SONY 512 Mb/s recorders.
- X-band data can be collected using either Ping-Pong or Non Ping-Pong mode depending on the amount of topographic relief.
- Data can be collected either using 80 or 160 MHz bandwidth modes. Data collected at 160 MHz is converted to 4-bit BFPQ data to reduce the data rate.



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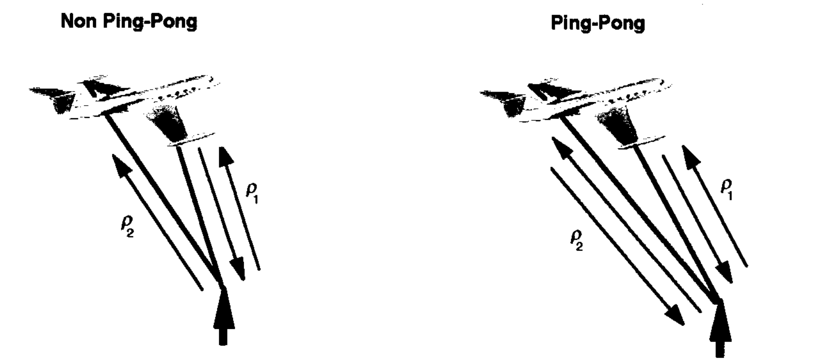
Two Methods of Data Collection



Transmission from one antenna
Reception through both antennas simultaneously

Alternately transmitting out of two antennas
Reception through the same antenna used for transmission only

System Parameter Overview

UHF SYSTEM PARAMETERS

Parameter	Value
Peak Transmit Power	4 KW
Bandwidth	80/160 Mhz
Pulse Length	40 μsec
Sampling	8/4 BFPQ @ 160 MHz 8 bit for 80 MHz
Antenna Size	1.524 m x 0.381 m
Antenna Gain at Boresight	11 dBi
Antenna Look Angle	27 - 60 Deg
Antenna Boresight	60 Deg
Wavelength @ Center Frequency	0.86 m for 160 MHz 0.97 m for 80 MHz
Baseline Length	20 m /40 m
Baseline Tilt Angle	0 Deg
Platform Altitude	5000 m - 10000 m

Center Frequency 350 MHz

X-BAND SYSTEM PARAMETERS

Parameter	Value
Peak Transmit Power	8 KW
Bandwidth	80/160 Mhz
Pulse Length	40 μsec
Sampling	8/4 BFPQ @ 160 MHz 8 bit for 80 MHz
Antenna Size	1.5 m x 0.035 m
Antenna Gain at Boresight	26.5 dBi
Antenna Look Angle	27 - 60 Deg
Antenna Boresight	60 Deg
Wavelength @ Center Frequency	0.031 m for 160 MHz 0.031 m for 80 MHz
Baseline Length	2.5 m /5 m or 1.3m / 2.6m
Baseline Tilt Angle	0 Deg or 45 Deg
Platform Altitude	5000 m - 10000 m

Phase Screen Calibration Objectives

- Certain affects such as multipath or switch leakage can result in systematic phase distortions which can affect the reconstructed height in 1-10 m range.
- Phase distortions due to multi-path can be shown to be roughly sinusoidal ripples in phase with an amplitude that is range dependent.
- Provided the multipath or switch leakage signal resulting in the phase distortions is stable then it can be removed through the use of a phase screen.
- The phase screen applies a range dependent correction that to the interferometric phase using a Chebyshev polynomial expansion of the phase correction to be applied.
- Since the phase corrections are linked to the geometry of the baseline, a convenient parameter for the phase screen is the absolute phase.

$$\phi_c(\rho) = \phi_{absm}(\rho) + \Delta\phi_{ps}(\rho) = \phi_{absm}(\rho) + \sum_{i=k}^{T_4} T_k(\phi_{absm}(\rho))$$

where $\phi_c(\rho)$ is the corrected phase, $\phi_{absm}(\rho)$ is the measured phase, and $\Delta\phi_{ps}(\rho)$ is the phase screen correction and T_k are the Chebyshev polynomials of degree k.

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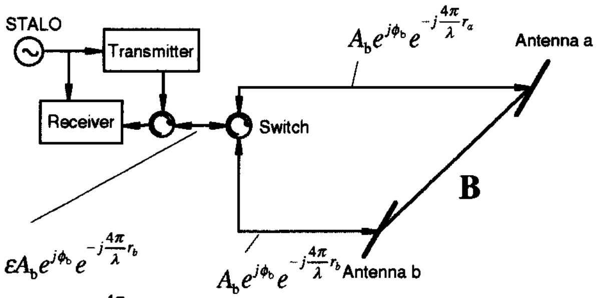
Origins of Phase Distortion-Switch Isolation



$$t_a : A_b e^{j\phi_b} e^{-j\frac{4\pi}{\lambda} r_a} + \varepsilon A_b e^{j\phi_b} e^{-j\frac{4\pi}{\lambda} r_b}$$

$$t_b : A_b e^{j\phi_b} e^{-j\frac{4\pi}{\lambda} r_b} + \varepsilon A_b e^{j\phi_b} e^{-j\frac{4\pi}{\lambda} r_a}$$

$$ab^* : A_b^2 \left(e^{-j\frac{4\pi}{\lambda}(r_a - r_b)} + 2\varepsilon + \varepsilon^2 e^{j\frac{4\pi}{\lambda}(r_a - r_b)} \right)$$

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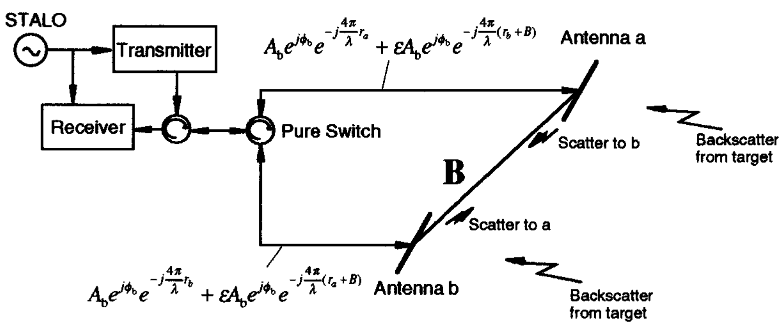
Origins of Phase Distortion - Multipath



$$ab^* : A_b^2 \left(e^{-j\frac{4\pi}{\lambda}(r_a - r_b)} + 2\varepsilon \cos\frac{4\pi}{\lambda} B + \varepsilon^2 e^{j\frac{4\pi}{\lambda}(r_a - r_b)} \right)$$

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Aircraft Position Determination & Measurement Systems

- High accuracy platform position and orientation required
  - Position to ~ 10 cm, altitude to ~ 25 cm.
  - Attitude (yaw, pitch, roll) to ~ 15 arc seconds.
- Honeywell Embedded GPS Inertial Navigation Units (EGI) (twin units)
  - 5 channel GPS system, high-quality INU, internal Kalman filter.
  - Precise attitude and velocity, rough GPS-only positions, smooth blended positions.
- Ashtech Z12 GPS receiver
  - Precise positions in differential mode with nearby ground station.
  - PNAV software.
- Laser Baseline Measurement System
  - Interferometric baseline length to < 1 mm and attitude to < 15 arcsecs.
- Surveyed relative positions of GPS systems on aircraft
  - Accurate to several centimeters or better.
- Kalman Filter used to estimate aircraft state
  - Combines position and velocity data.
  - Accounts for varying uncertainties and temporal spacing.

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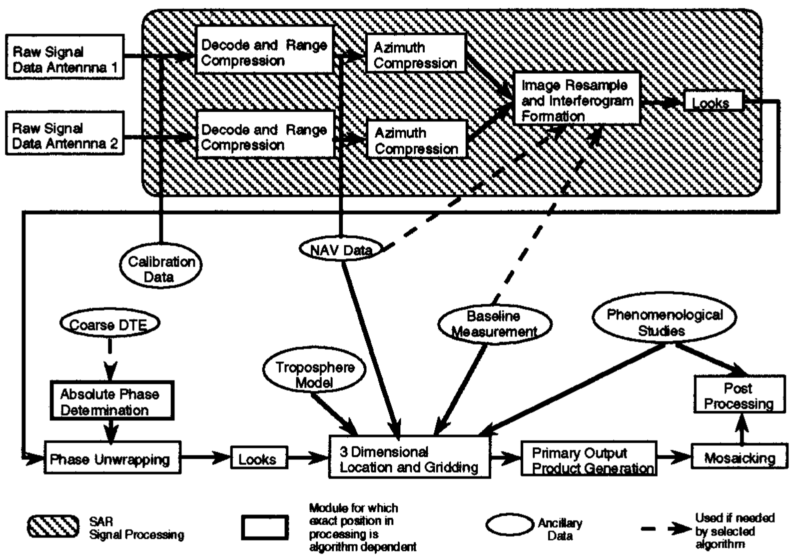
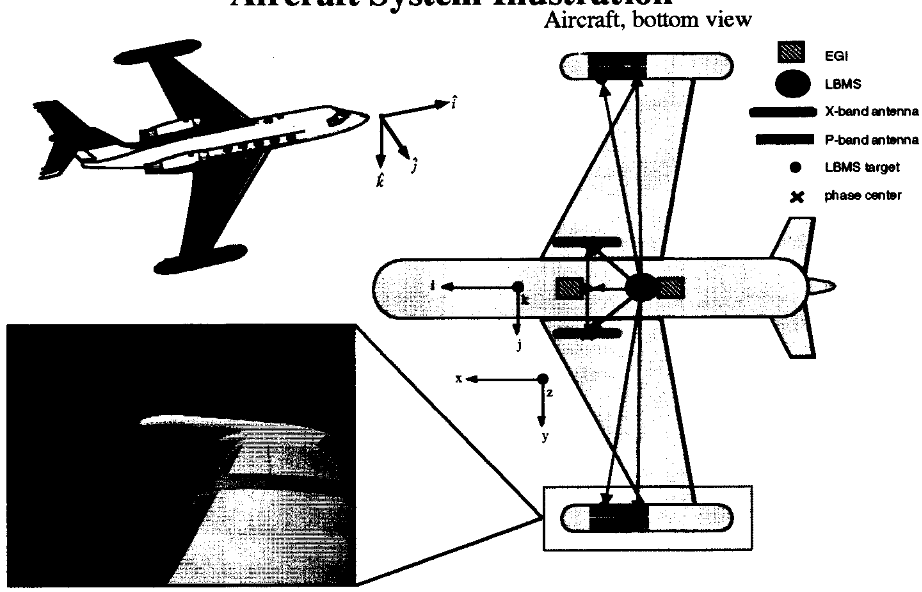
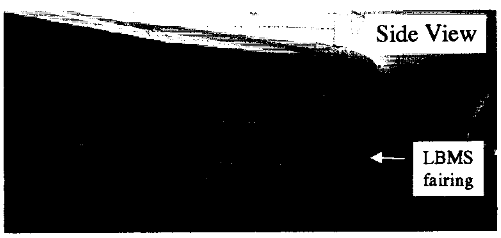
Interferometric Processing

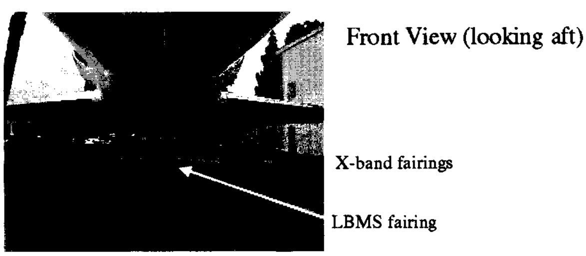


Aircraft System Illustration

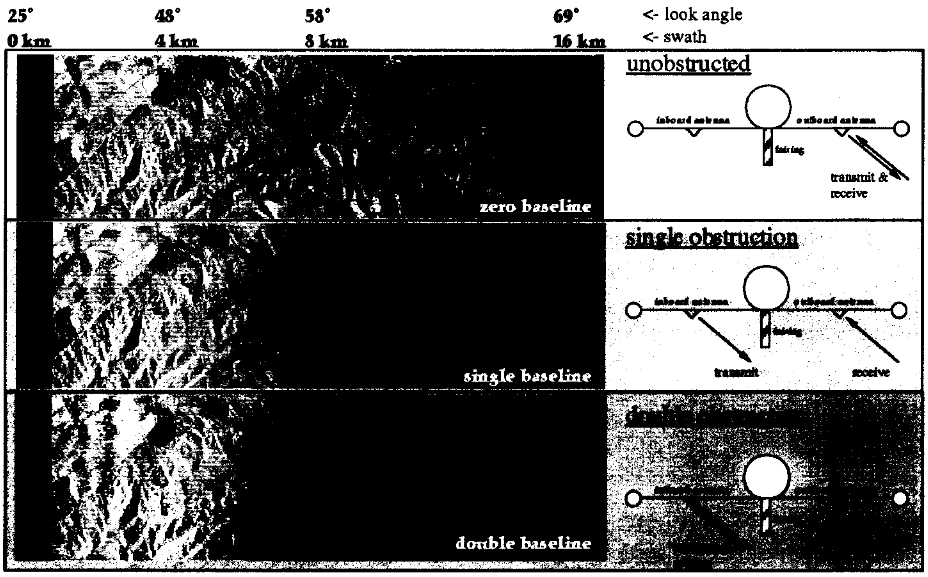


X-band LBMS Fairing Obstruction

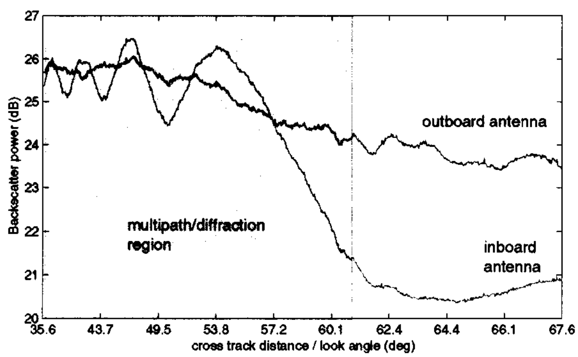




Impact on Imagery

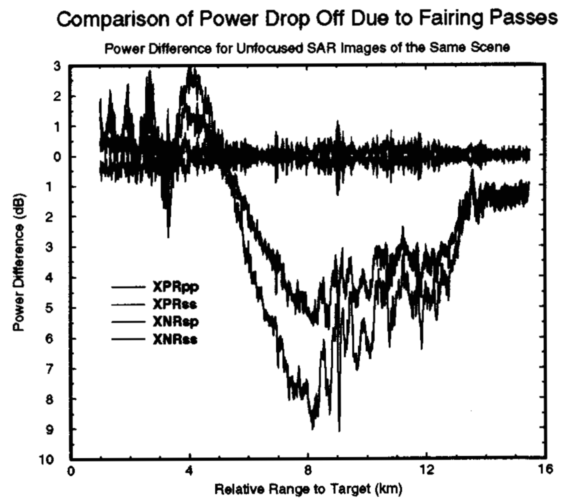


Comparison between outboard and inboard antenna performance



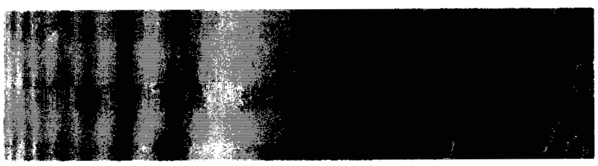
note: look angle scale may be slightly offset

Impact on Imagery (cont'd)



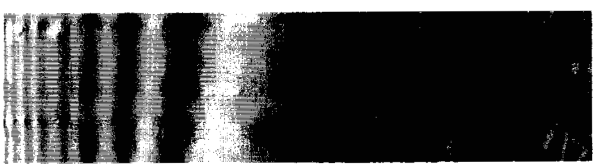
Correlation and Amplitude Ratio

Non Ping-Pong Ratio Map



Non Ping-Pong Correlation Map

Ping-Pong Ratio Map



Ping-Pong Correlation Map

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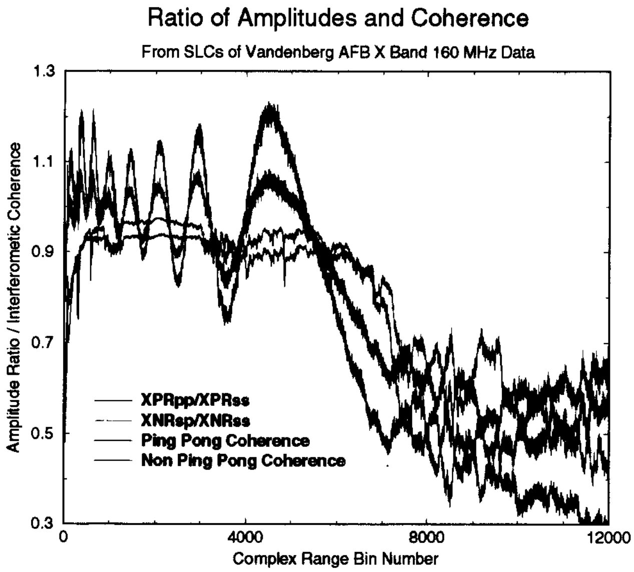
Correlation and Amplitude Ratio Plots



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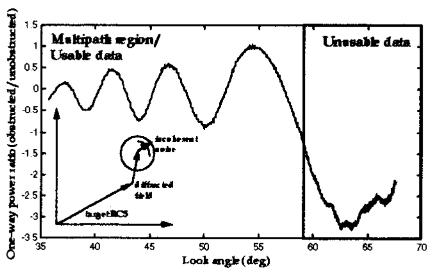
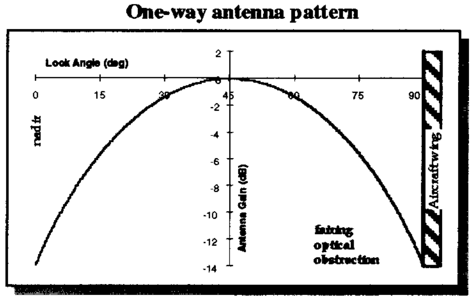
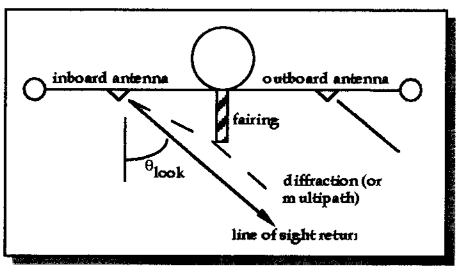
Geometry



One-way antenna pattern





- Ratio of inboard to outboard power will give a measure of the interference of the coherent field diffracting off of the LBMS fairing.
- Antenna pattern serves to illuminate the field diffracting off of the fairing.
- SNR decreases with look angle due to shadowing of fairing and incoherent interference from energy reflected off of fairing and aircraft structure.

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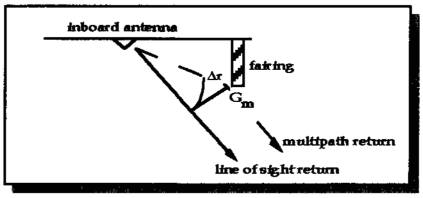
Diffraction Theory

Two ways to look at the problem(same solution)

- Form of multipath



$$E_{tot} = E_{los} + E_m$$
$$= E_0\left(1 + G_m e^{ik\Delta r}\right)$$
$$|E_{tot}|^2 = |E_0|^2\left(\left[1 + |G_m|^2\right] + 2\,\mathrm{Re}\{G_m\}\cos(k\Delta r)\right)$$

offset *fluctuation*

- Blockage of illuminating field (classical diffraction; pg 465 of Jackson)

$$|E_{tot}|^2 = |E_0|^2\left[\left(C(\xi) + 1/2\right)^2 + \left(S(\xi) + 1/2\right)^2\right]$$ C, S - Fresnel Integrals

$$\xi = \left(\frac{\pi/\lambda}{z_{fair}\sin\theta + x_{fair}\cos\theta}\right)^{1/2}\left(x_{fair}\cos\theta - z_{fair}\sin\theta\right)$$

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Phasescreen Estimation Methodology

- Calibrate system for all other interferometric calibration parameters prior to phasescreen determination.
- Generate an interferometric DEM over an area having an accurate DEM (e.g. photogrammetric derived DEM)
  - For each pixel in the output DEM output the absolute phase and derivative of height with respect to phase.
- Generate a phase differences as a function of absolute phase by converting the height differences between the interferometric DEM and the truth DEM to phase differences

$$\Delta\phi = \Delta h\left(\frac{\partial h}{\partial \phi}\right)^{-1}$$

- Make a Chebyshev fit to the delta phase data
- Estimate the source(s) of the the multi-path signature and extend domain of phase screen using analytic model.

Least Squares Estimation I

- Multi-path parameter estimation is done using least squares with a vector of observations given by the differences between the heights measured interferometrically and the truth DEM

$$\vec{O}_i = \phi_m - \phi_s = \frac{\partial\phi}{\partial h}(h_m - h_s)$$

where subscripts s,m denoted measured and truth DEM values for $1 \le i \le N$.

- The observations are weighted by covariance estimates derived from the interferometric correlation.

$$C_i = \sigma_\phi^2(\gamma)$$

- The vector of parameters to be solved for is

$$\vec{P} = [\Delta B_1 \quad \Delta\alpha_1 \quad \Delta\kappa_1 \quad \Delta\varepsilon_1 \quad \ldots \quad \Delta B_N \quad \Delta\alpha_N \quad \Delta\kappa_N \quad \Delta\varepsilon_N]$$

where the Δb_i, $\Delta\alpha_i$, $\Delta\kappa_i$, and $\Delta\varepsilon_i$ are the multi-path baseline and strength parameters.

Least Squares Estimation II

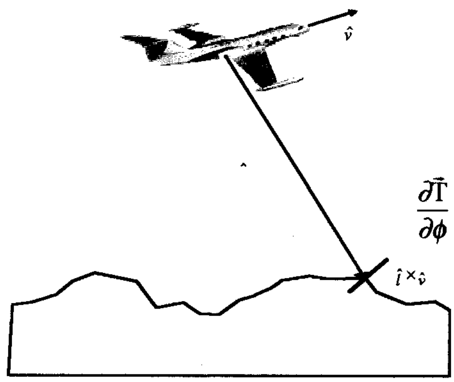
- The least squares solution is

$$\vec{P} = \left(\sum_{i=1}^{N} A_i^t C_i^{-1} A_i\right)^{-1}\left(\sum_{i=1}^{N} A_i^t C_i^{-1} \vec{O}_i\right)$$

where A is the matrix of partials of the observations with respect to the parameters to be estimated.

$$A = \left[\frac{\partial\Delta\phi}{\partial B_1} \quad \frac{\partial\Delta\phi}{\partial\alpha_1} \quad \frac{\partial\Delta\phi}{\partial\kappa_1} \quad \frac{\partial\Delta\phi}{\partial\varepsilon_1} \quad \cdots \quad \frac{\partial\Delta\phi}{\partial B_N} \quad \frac{\partial\Delta\phi}{\partial\alpha_N} \quad \frac{\partial\Delta\phi}{\partial\kappa_N} \quad \frac{\partial\Delta\phi}{\partial\varepsilon_N}\right]$$

Phase Sensitivity



$$\frac{\partial \vec{T}}{\partial \phi} = \frac{-\lambda\rho}{a 2\pi B g \cos(\theta,\alpha,\beta)\cos(\kappa)} \begin{bmatrix} 0 \\ \cos(\theta) \\ \mu \sin(\theta) \end{bmatrix}$$

- Phase errors give position errors along perpendicular to the line of sight and velocity vectors.

Derivative Correction for Spherical Earth

- Since the interferometrically derived fiducal point position measurements are in a spherical coordinate system we must correct the tangent plane position (primed) derivatives to derivatives that represent position changes with respect to the spherical coordinate system (unprimed).

$$\frac{\partial s_T}{\partial \zeta} = \frac{r_a}{s_T'^2 + (r_a + h_T')^2} \left\{ (r_a + h_T') \frac{\partial s_T'}{\partial \zeta} - s_T' \frac{\partial h_T'}{\partial \zeta} \right\}$$

$$\frac{\partial c_T}{\partial \zeta} = \frac{r_a}{\sqrt{s_T'^2 + (r_a + h_T')^2}} \left\{ \frac{\partial c_T'}{\partial \zeta} - \frac{c_T'}{(r_a + h_T)^2} \left[\left(c_T' \frac{\partial c_T'}{\partial \zeta} + s_T' \frac{\partial s_T'}{\partial \zeta} \right) + (r_a + h_T') \frac{\partial h_T'}{\partial \zeta} \right] \right\}$$

$$\frac{\partial h_T}{\partial \zeta} = \left(\frac{r_a + h_T'}{r_a + h_T} \right) \frac{\partial h_T'}{\partial \zeta} + \frac{1}{r_a + h_T} \left(c_T' \frac{\partial c_T'}{\partial \zeta} + s_T' \frac{\partial s_T'}{\partial \zeta} \right)$$

Height Map Prior to Applying Phasescreen

PLOT HERE

Height Map After to Applying Phasescreen

PLOT HERE