Processing Techniques for Topographic Mapping Using Interferometric SAR

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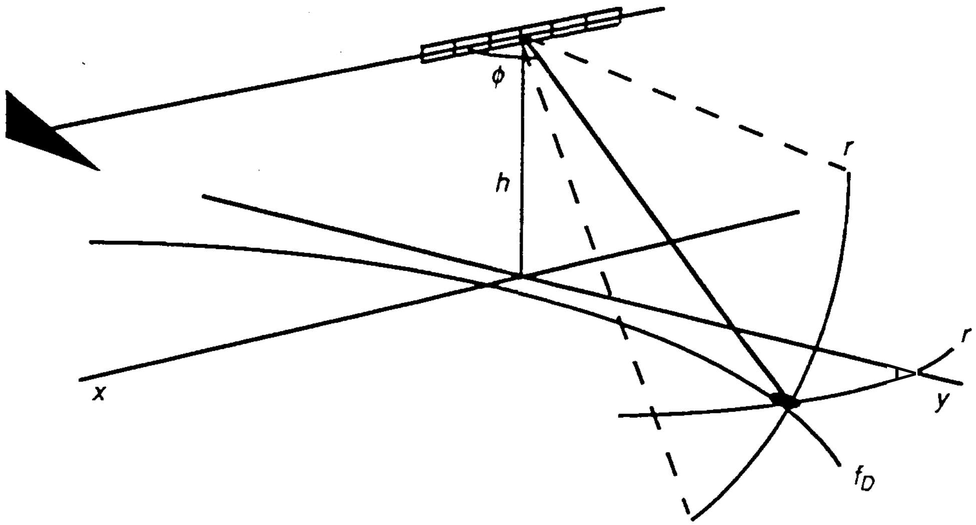
SPATIAL DISCRIMINATION MECHANISMS



$$r(x) = \left|\vec{r}_{tgt} - \vec{r}_{plt}(x)\right| \quad \Leftrightarrow \quad \vec{r}_{tgt} = \vec{r}_{plt}(x) + r(x)\hat{n}_{los} \tag{1}$$

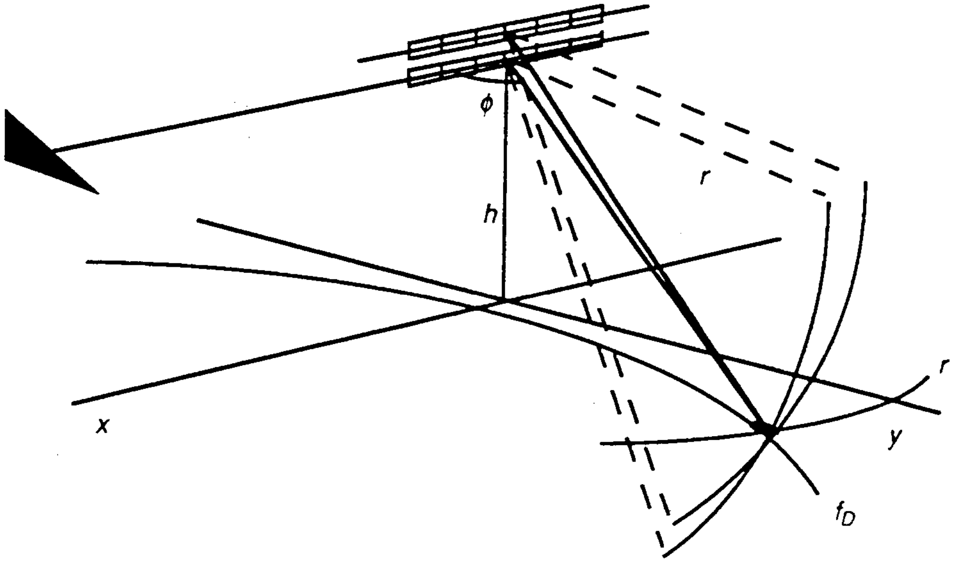
$$\delta r_d = ct_d = 2\hat{n}_{los} \cdot \delta\bar{x} \quad \Rightarrow \quad f_D = \frac{2\hat{n}_{los} \cdot \bar{v}}{\lambda} \tag{2}$$

δr_d is the differential range delay from array element to array element

$\delta\bar{x}$ is the array element spacing

SPATIAL DISCRIMINATION MECHANISMS (2)

Introduce a second parallel track!



$$\vec{r}_{tgt} = \vec{r}_{plt,1}(x_1) + r_1(x_1)\hat{n}_{los,1} = \vec{r}_{plt,2}(x_2) + r_2(x_2)\hat{n}_{los,2}$$

$$(\hat{n}_{los,1})_x = (\hat{n}_{los,2})_x = (\hat{n}_{los})_x \text{ and } \vec{r}_{plt,i}(x) = (x, y_i, z_i) \Rightarrow x_2 - x_1 = (r_1 - r_2)(\hat{n}_{los})_x \quad (3)$$

$$\vec{r}_1 = r_1\,\hat{n}_{los,1} \text{ and } \vec{r}_2 = r_2\,\hat{n}_{los,2} \text{ and } \vec{r}_1 = \vec{r}_2 + \vec{r}_{21}$$

$$r_1 - r_2 = \frac{\vec{r}_1 + \vec{r}_2}{r_1 + r_2} \cdot \vec{r}_{21} \approx \hat{n}_{los,av} \cdot \vec{r}_{21} \quad (4)$$

SPATIAL DISCRIMINATION MECHANISMS (3)

The fundamental location equations of SAR interferometry:

$$\vec{r}_{tgt} = \vec{r}_{plt,1}(x_1) + r_1(x_1)\hat{n}_{los,1t\,2}(x_2) + r_2(x_2\,)*1OS,2$$

$$\hat{n}_{los,x} = \frac{\delta r_d}{2\,\delta x} \text{ and } X_2 - xl = (r_1 - r_2)\hat{n}_{los\,,x} \qquad \textbf{(5)}$$

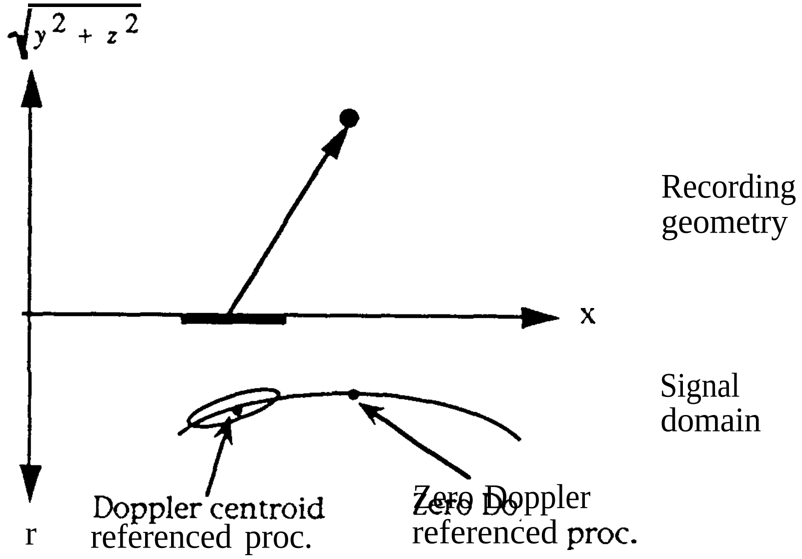
$$r_1\,, r_2 >> |\vec{r}_{21} \Rightarrow$$

$$\text{‘target} = \vec{r}_{\text{radar}} + r_{sl}\,\hat{n}_{los} \qquad \textbf{(6)}$$

$$f_D = \frac{2}{\lambda}\hat{n}_{los} \cdot \vec{\,} \Leftrightarrow \hat{n}_{los} \cdot \vec{v} = \frac{\lambda f_D}{2} \qquad \textbf{(7)}$$

$$\hat{n}_{los}\,\mathbf{721} = r_1 - r_2 = \frac{\lambda\,\phi_{intf}}{2\pi} \qquad \textbf{(8)}$$

SPATIAL DISCRIMINATION MECHANISMS (4)



- Note that the processor can apply Doppler centroid or zero Doppler referencing - both will work as long as matching values for platform position, range, Doppler are applied

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PHASE UNWRAPPING

- SAR interferogram provides complex numbers.
  Only ϕ modulo 2π is measured directly!

- To solve for topography the differential range must be determined. The appropriate number of 2π must be added to the interferogram phase measurement

- The problem can be broken into two parts:
  – Phase unwrapping
  - Absolute phase determination

- Satellite radar interferometry: Two-dimensional phase unwrapping, [Goldstein et al., 1988]

PHASE UNWRAPPING (2)

- **The unwrapping issue, example:**

Clean data:

Absolute phase in cycles

19.0	19.3	19.6
19.3	19.6	19.9
19.6	19.9	20.2

Measured

0.0	0.3	0.6
0.3	0.6	0.9
0.6	0.9	0.2

Unwrapped

0.0	0.3	0.6
0.3	0.6	0.9
0.6	0.9	1.2

Noisy data:

Absolute phase in cycles

19.0	19.3	19.6
19.3	19.6	19.9
19.6	19.6	20.2

Unwrapped (col. 1 fret)

0.0	0.3	0.6
0.3	0.6	0.9
0.6	0.6	0.2

Measured

0.0	0.3	0.6
0.3	0.6	0.9
0.6	0.6	0.2

Unwrapped (row 1 frost)

0.0	0.3	0.6
0.3	0.6	0.9
0.6	0.6	1.2

PHASE UNWRAPPING (3)

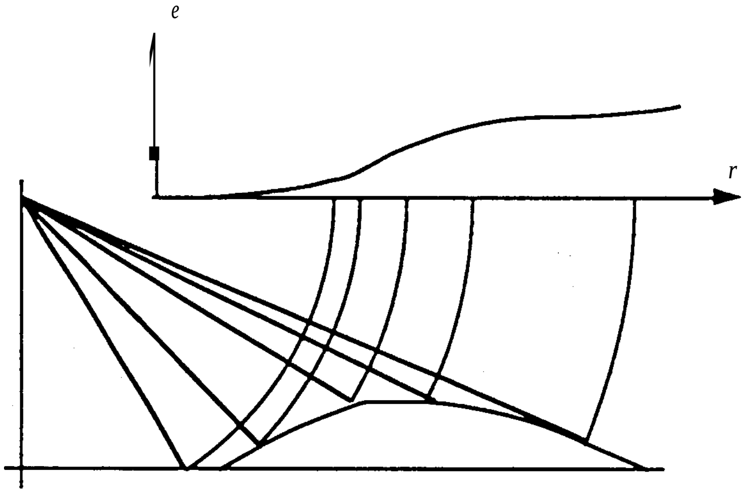
- Residues/Changes
  Unwrap the phases of four neighboring points (2 x 2).
  Net phase increment of loop= +1 cycle => residue with charge +1.
  Net phase increment of loop = –1 cycle => residue with charge –1.

- Cut lines/Three building
  Charges are connected by cut lines to form neutral trees.
  Any closed integration path not intersecting cut lines will enclose an accumulated charge of zero. Phase unwrapping not crossing cut lines will thus be consistent- but not necessarily right!

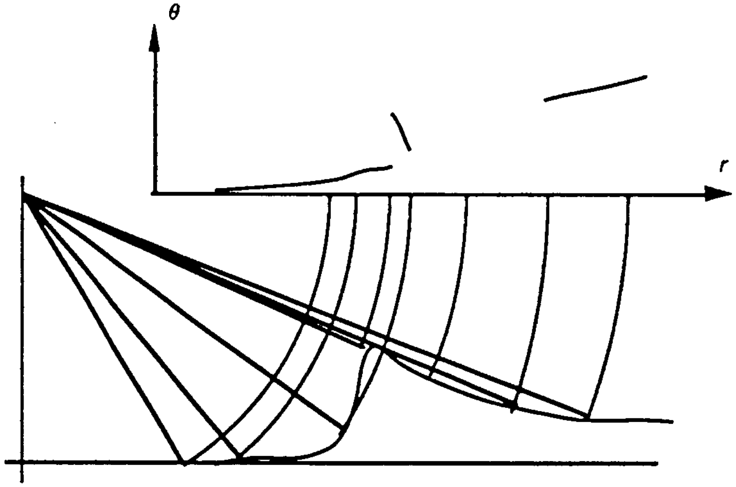
- Neutrons
  Points that by some criteria has been determined as likely cut line locations. Possible criteria: non monotonic phase variation with range, large phase variance, high contrast edges in amplitude image. Neutrons are only used for “guiding” cut lines.

- Phase flooding
  Phases are unwrapped in a consistent fashion without intersecting cut lines.

PHASE UNWRAPPING (4)



- Well behaved phase history with monotonic phase



- Discontinuous phase history (lay-over) with non-monotonic phase

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PHASE UNWRAPPING RESIDUES ONLY

UNWRAPPED PHASE

RESIDUE/CUT MAP

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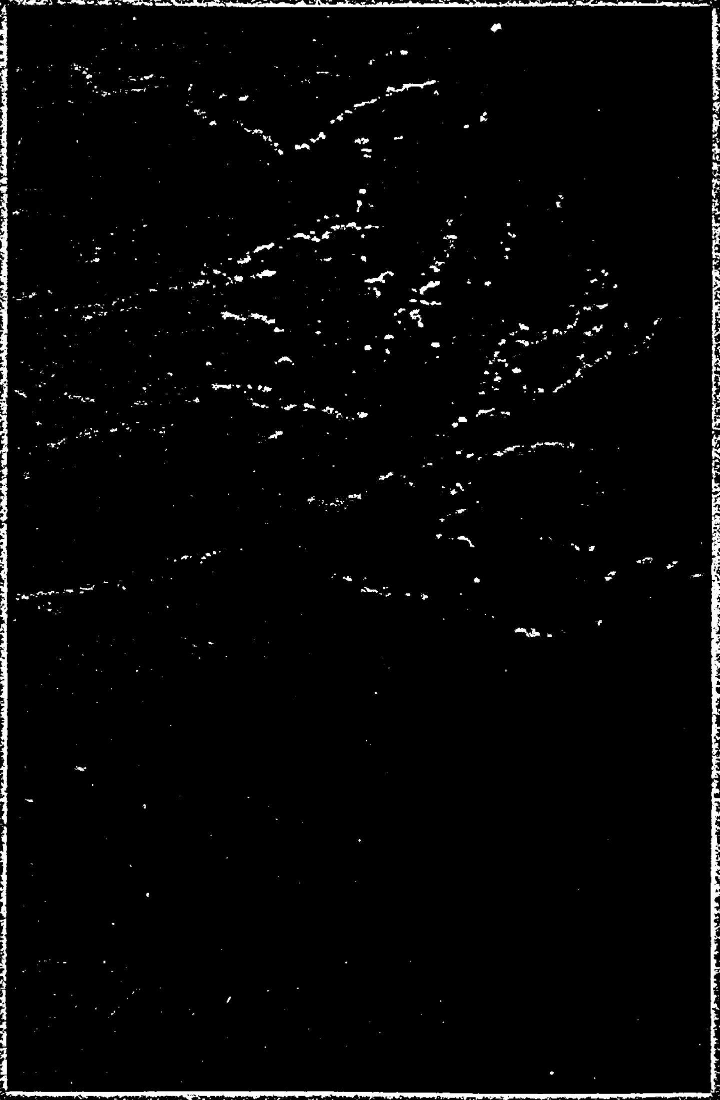
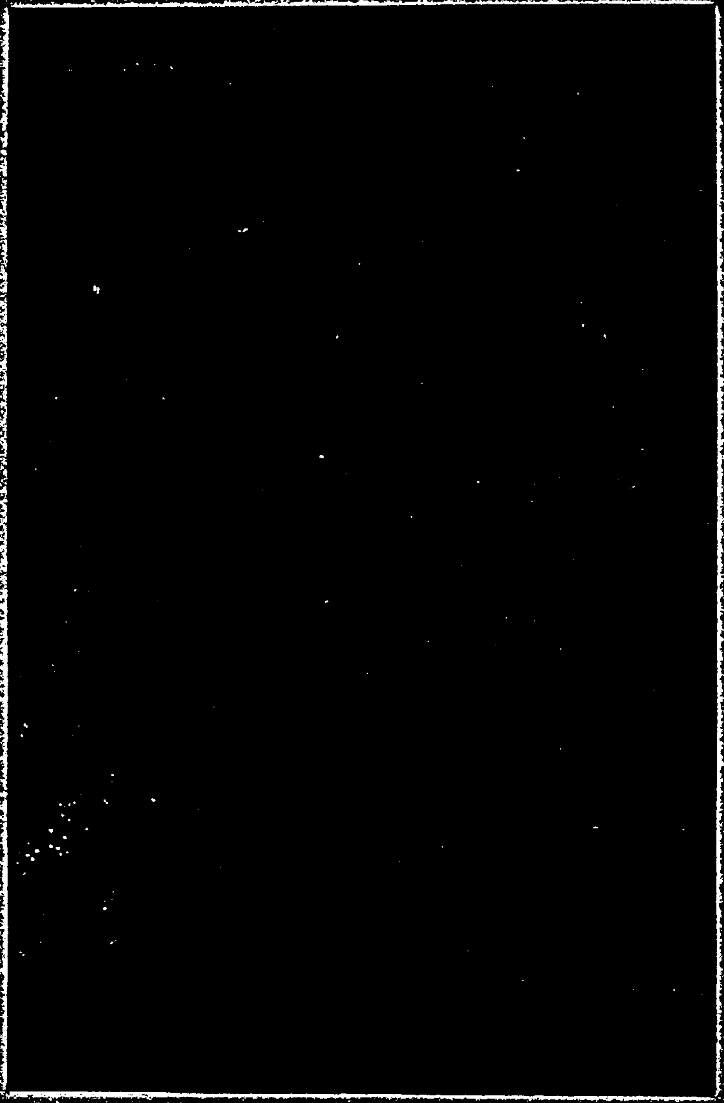
PHASE UNWRAPPING WITH NEUTRONS

UNWRAPPED PHASE



RESIDUE/NEUTRON/CUT MAP



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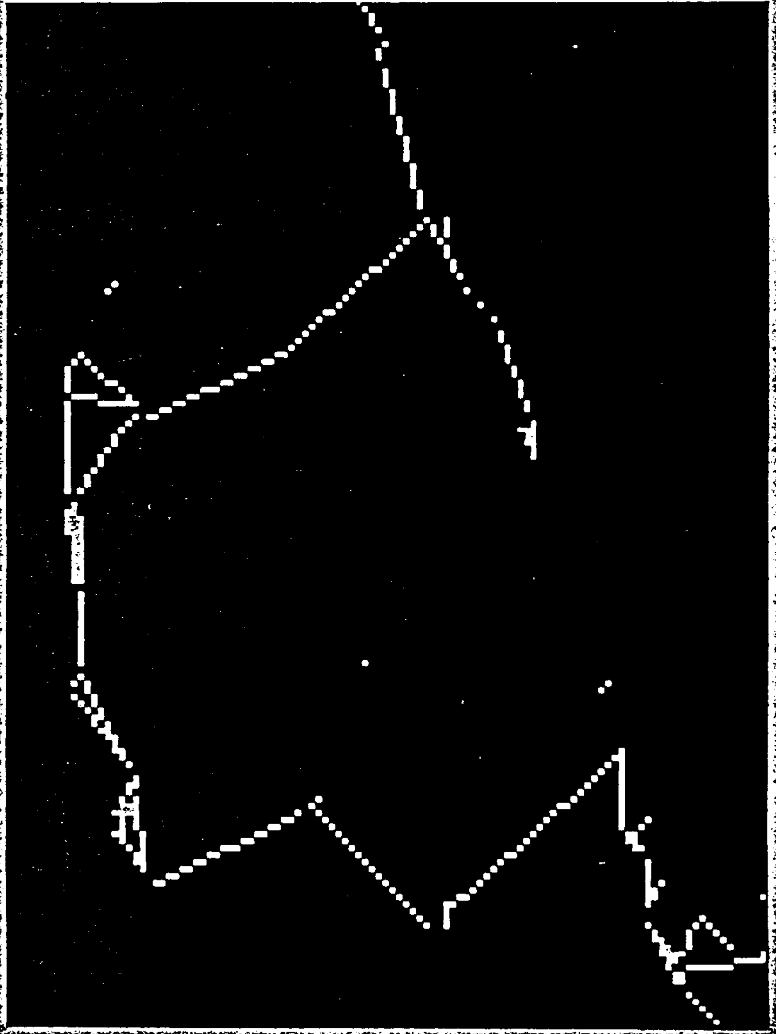
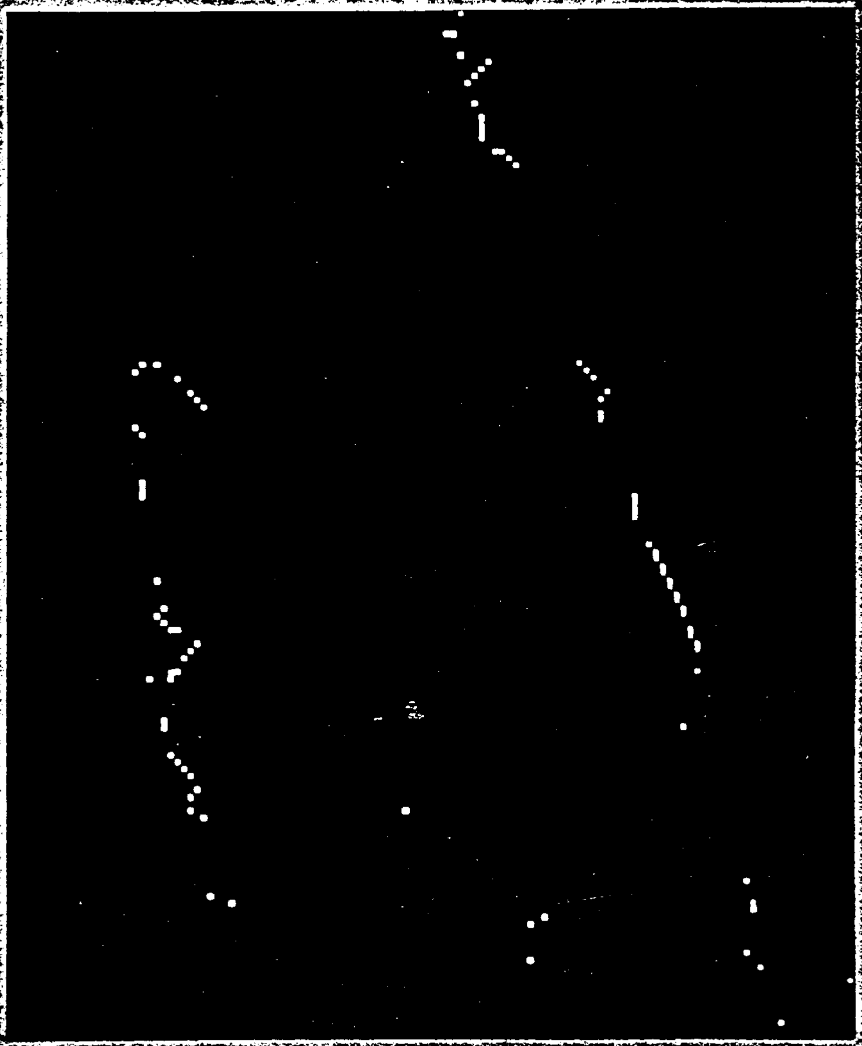
RESIDUE/CUT MAPS

NO NEUTRONS



WITH NEUTRONS



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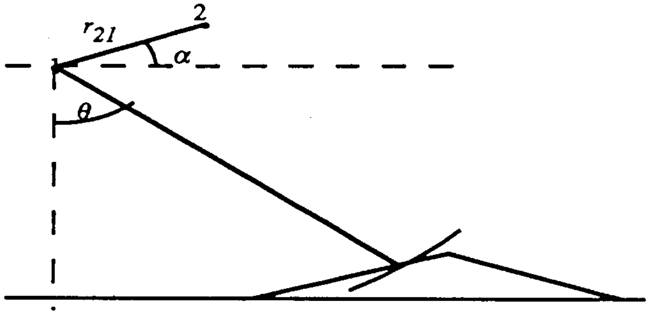
ABSOLUTE PHASE DETERMINATION

- Note that interferometric phase is a function of carrier frequency



$$\phi_1 = 2\pi \frac{f_1 r_{21}}{c} \sin(\alpha - \theta_i$$

$$\phi_2 = 2\pi \frac{f_2 r_{21}}{c} \sin(\alpha - \theta_i$$

- Differential phase is equivalent to low frequency interferometer

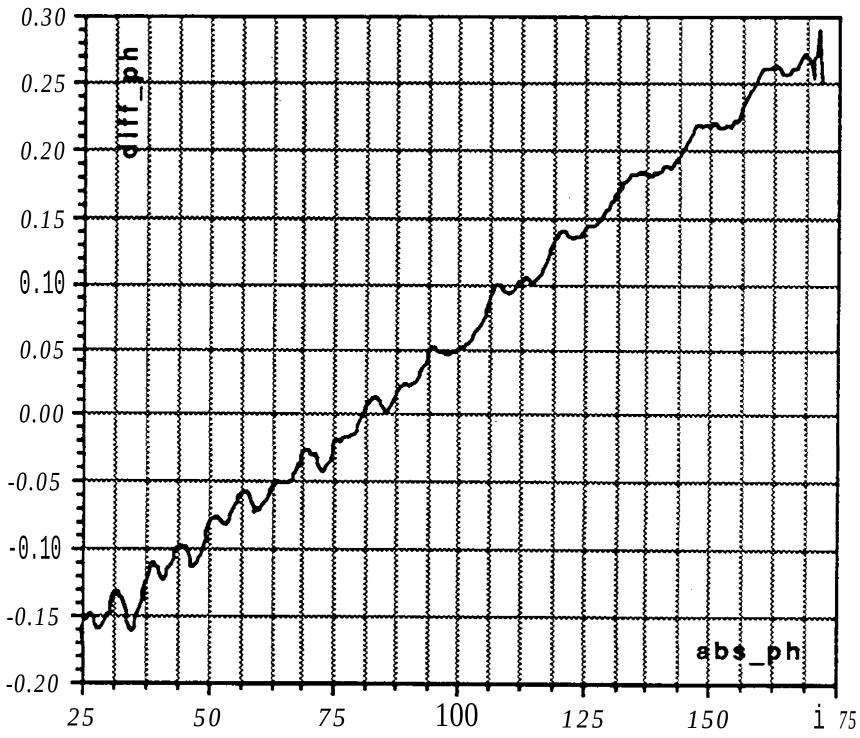
$$\Delta\phi = \phi_1 - \phi_2 = 2\pi \frac{(f_1 - f_2)}{c} r_{21} \sin(\alpha - \theta_i)$$

- No ambiguity for

$$f_1 - f_2 < \frac{c}{2 r_{21}}$$

- Split spectrum technique is not dependent on ground control points!

MEASURED DIFFERENTIAL PHASE
AS A FUNCTION OF ABSOLUTE PHASE



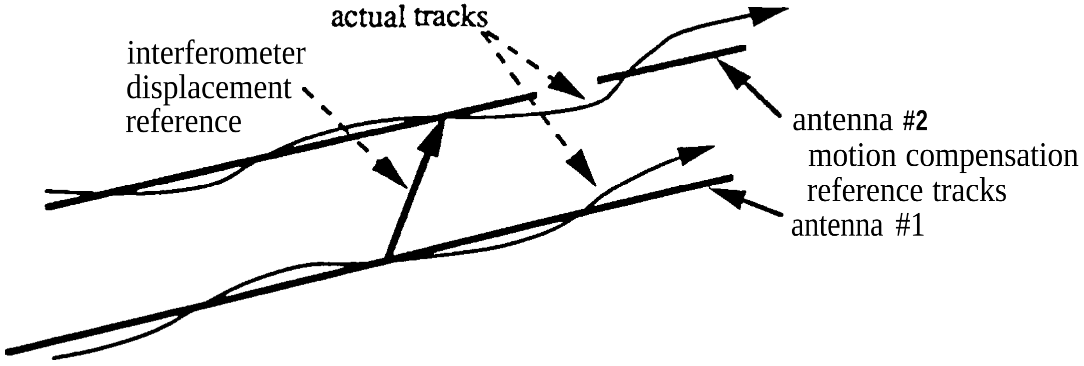
MOTION COMPENSATION

- Aircraft accelerations measured by Inertial Navigation Unit (INU) located close to radar antennae
- Accelerations are processed and combined with Global Position System (GPS) data to generate a location time-line with high update rate and small drift
- Attitude data is measured by INU
- Antenna positions are derived from INU motion and lever arm corrections
- Data are processed in small overlapped patches with locally adapted reference line

MOTION COMPENSATION (2)

- **Straight reference track selected to minimize antenna 1 deviations**

- **Antenna 2 reference off-set from antenna 1 reference by a constant baseline displacement vector; effectively making tracks parallel.**

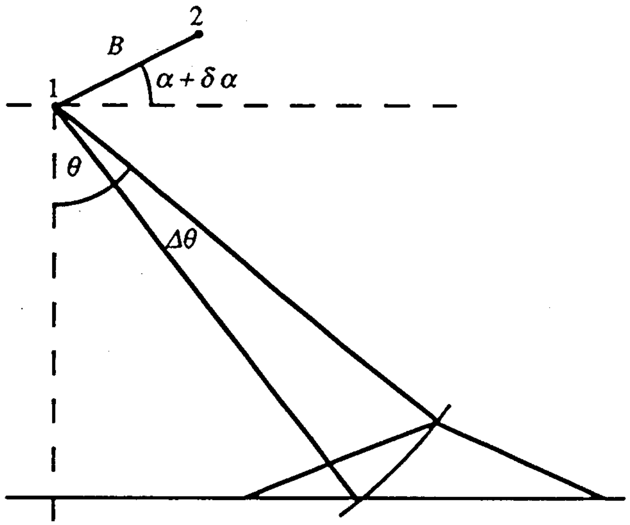


- **Antenna 1,2 signals are shifted in range and phase to compensate for any measured, $\Delta\vec{r}^{\,i}(x)$, deviation from straight line flight**

$$\Delta r^{i}_{sl}(r_{sl},x) = \Delta\vec{r}^{\,i}(x)\cdot\hat{n}_{los}(r_{sl})$$

$$\Delta\phi^{i}_{sl}(r_{sl},x) = -\frac{2\pi f}{c}\Delta r^{i}_{sl}(r_{sl},x)$$

MOTION COMPENSATION ERRORS



$$\Delta r_{21} = B\sin(\alpha+\delta\alpha-\theta-\Delta\theta)$$

$$\cong B\sin(\alpha-\theta-\Delta\theta)+B\cos(\alpha-\theta-\Delta\theta)\delta\alpha$$

$$\cong B\sin(\alpha-\theta-\Delta\theta)+B\cos(\alpha-\theta)\delta\alpha+B\sin(\alpha-\theta)\delta\alpha\Delta\theta$$

$$\alpha=63°,\delta\alpha=1°,\theta=30°,\ \ \Delta\theta=5°$$

$$\Rightarrow \delta\theta_{error}=0.046°\approx 0.0008\text{ rad}=0.8\ \ \text{m/km}$$

- **Perfect navigation data not sufficient!**
  Solutions: Iterative processing, or, inverse mocomp

RADAR PARAMETERS, TOPSAR

wavelength	0.0567 m
bandwidth	40 MHz (20 MHz)
max. squint	15°
antenna length	1.5m
baseline length	2.5 m
baseline angle (rel. her.)	63°
altitude	9 km (approx.)
look angles	30-55°
slant range	10-15 km
output size	6.4 x 30 km (12.8 x 30 km)
pixel spacing/resolution	10 m / 15 m

JPL PROCESSOR, PHYSICAL CONFIGURATION

- Presently running on Alliant FX-800,
  - 12 proc. Intel i860
  - 512 Mbyte RAM
  - 10 Gbyte disk

- UNIX operating system

- Processor coded in Fortran 77

- Throughput:
  - input: 2 files each 81920 lines of 3072 bytes off-set video
  - output: -3000 lines of 640 samples (1 O* I O m pixels)= 192 km^2

  2 hours 20 minutes

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JPL PROCESSOR, CHARACTERISTICS

- Range-Doppler type processor
- Patch processor with local reference tracks adapted to actual track
- Doppler centroid is a function of range and is updated for each patch
- Data is motion compensated as a function as slant range
- Phase unwrapping using algorithm based on residues and neutrons
- Absolute phase determined using split spectrum technique

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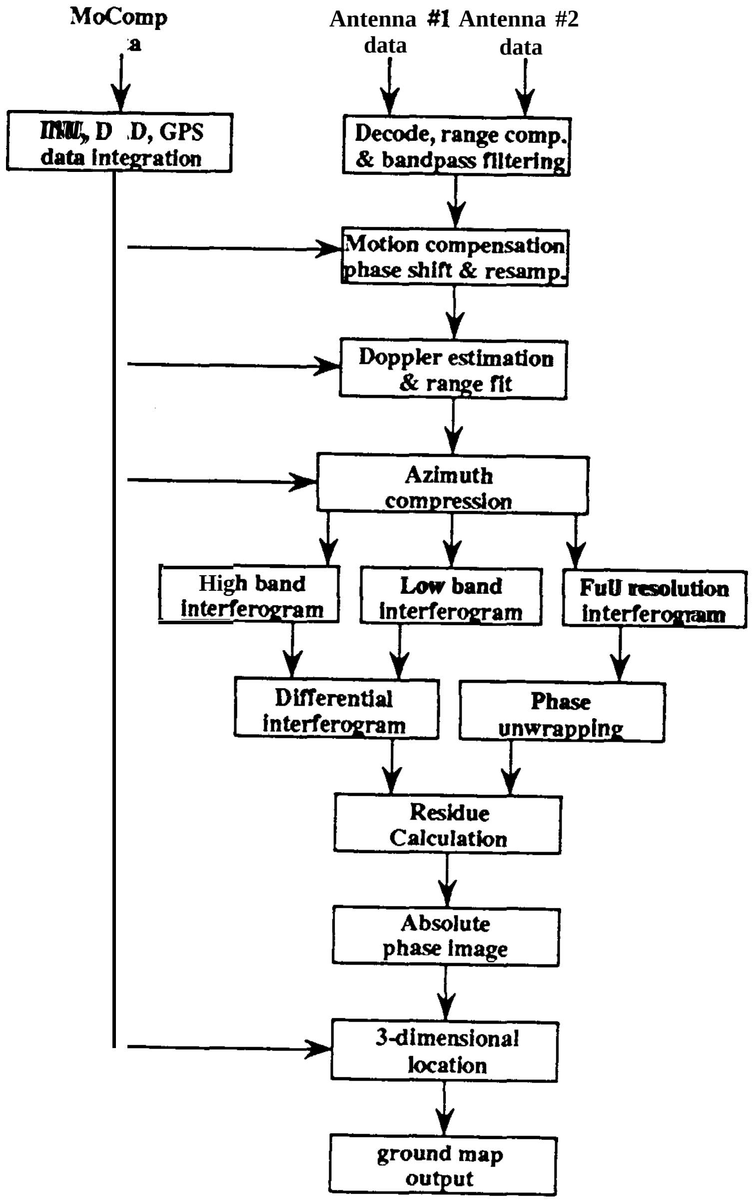
PROCESSOR BLOCK DIAGRAM



MoComp
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Antenna #1 data

Antenna #2 data

INU, D .D, GPS
data integration

Decode, range comp.
& bandpass filtering

Motion compensation
phase shift & resamp.

Doppler estimation
& range fit

Azimuth
compression

High band
interferogram

Low band
interferogram

Full resolution
interferogram

Differential
interferogram

Phase
unwrapping

Residue
Calculation

Absolute
phase image

3-dimensional
location

ground map
output

ON-GOING PROCESSOR RESEARCH RELATING TO INTERFEROMETRY

- Phase unwrapping

- Absolute phase determination

- Map resampling σ_{xyz} (*range*, *azimuth*) => $z(x, y)$ & $\sigma(x, y$