Bistatic/Monostatic Synthetic Aperture Radar for Ice Sheet Measurements

John Paden
MS Thesis Defense
April 18, 2003

Committee Chairperson: Dr. Chris Allen
Committee Members:
Dr. Prasad Gogineni
Dr. Glenn Prescott

Topics

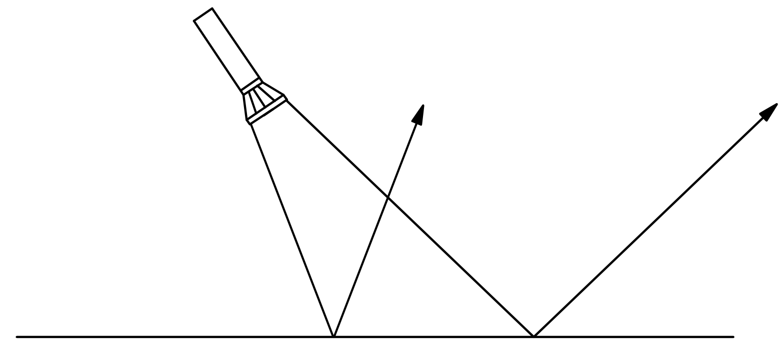
- Overview
- EM Model
- Sensor Geometry
- Antenna Array
- Position Errors
- Sandbox Tests

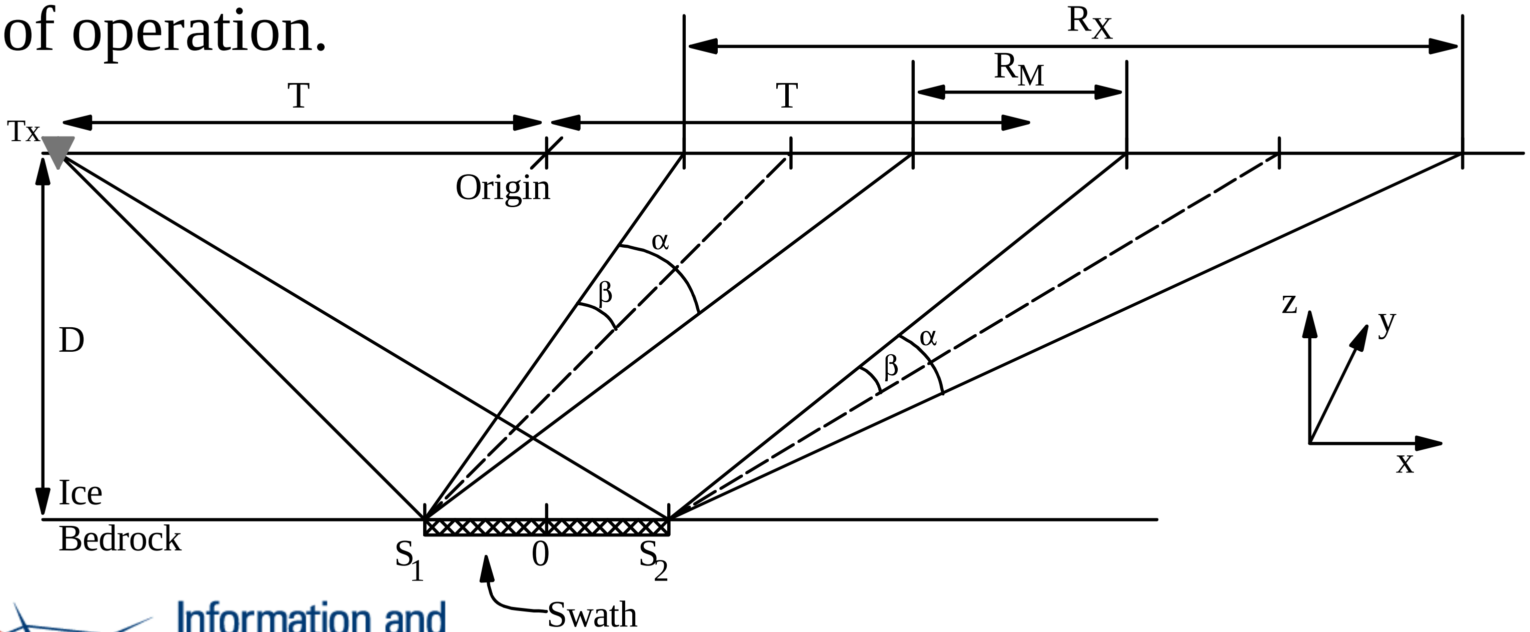
Overview – Motivation

- Global sea level rise threatens coastal regions
- Contributions from an ice sheet are measured by finding the mass balance of the ice sheet.
- Create ice flow model to predict mass balance
- Basal conditions needed for ice flow model
- We can drill boreholes in a few places, but not all over the Arctic and Antarctic regions à RADAR.

Overview – Basal Scattering

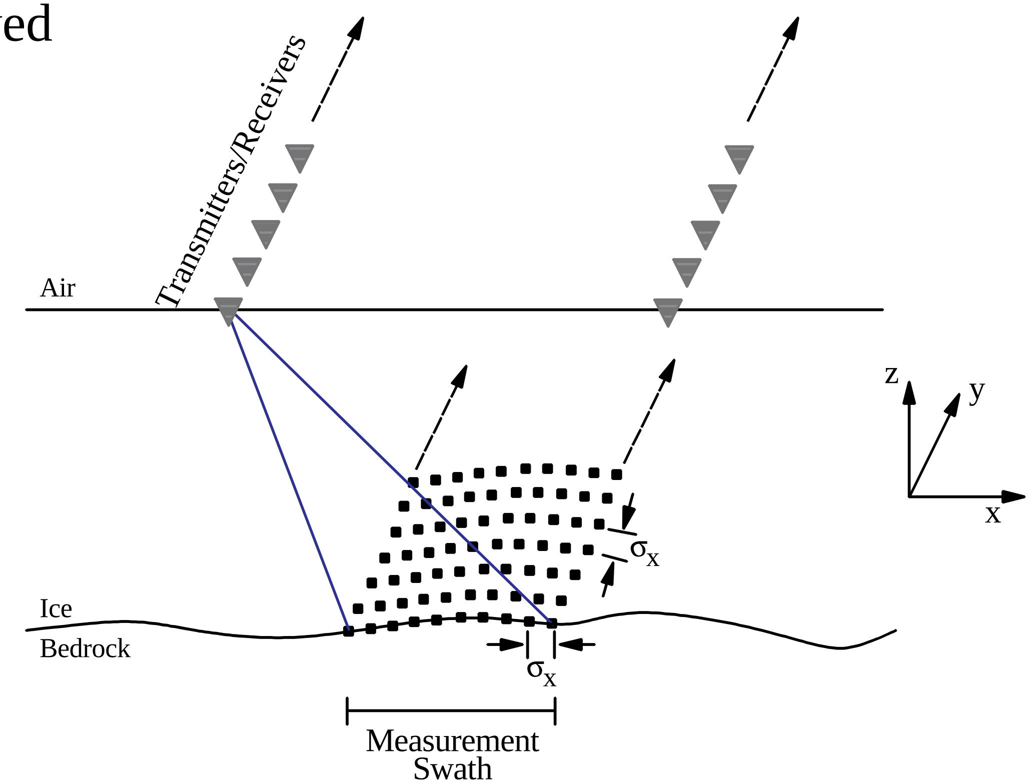
- The bedrock is thought to be smooth with respect to wavelength.
- Therefore it looks like a mirror at our frequencies of operation.





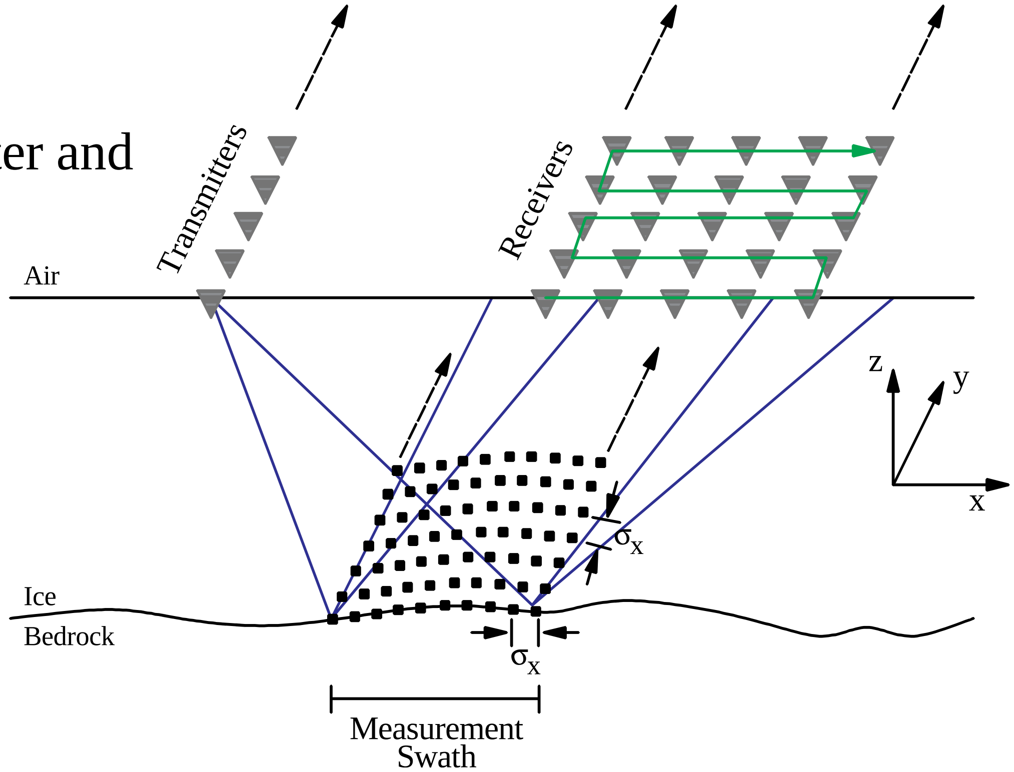
Data Collection Geometries

- Monostatic Arrangement
  - Used when the *surface is rough* and side-looking radar techniques can be employed



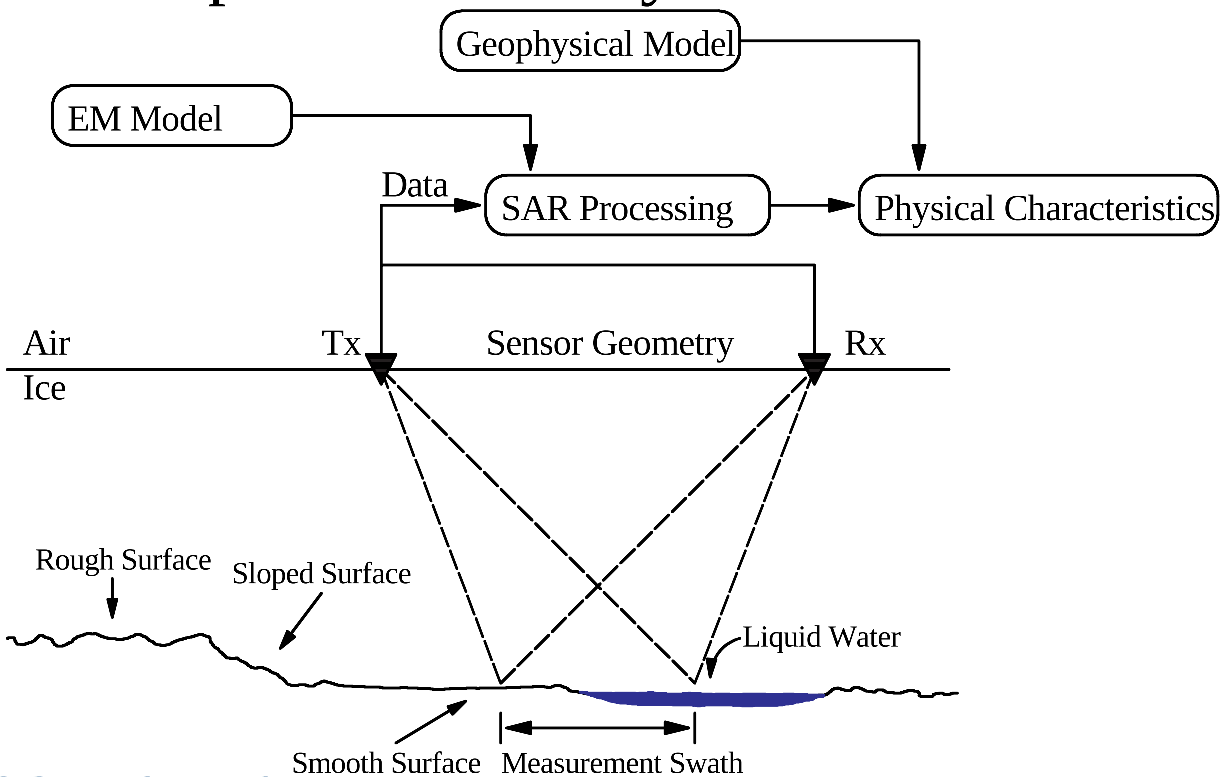
Data Collection Geometries

- Bistatic Arrangement
  - Used when the *surface is smooth* and exhibits specular (mirror-like) characteristics
  - New variable: separation distance between transmitter and receiver



Overview – System Model

- Modes of operation: monostatic and bistatic
- Broadband operation: nearly three octaves



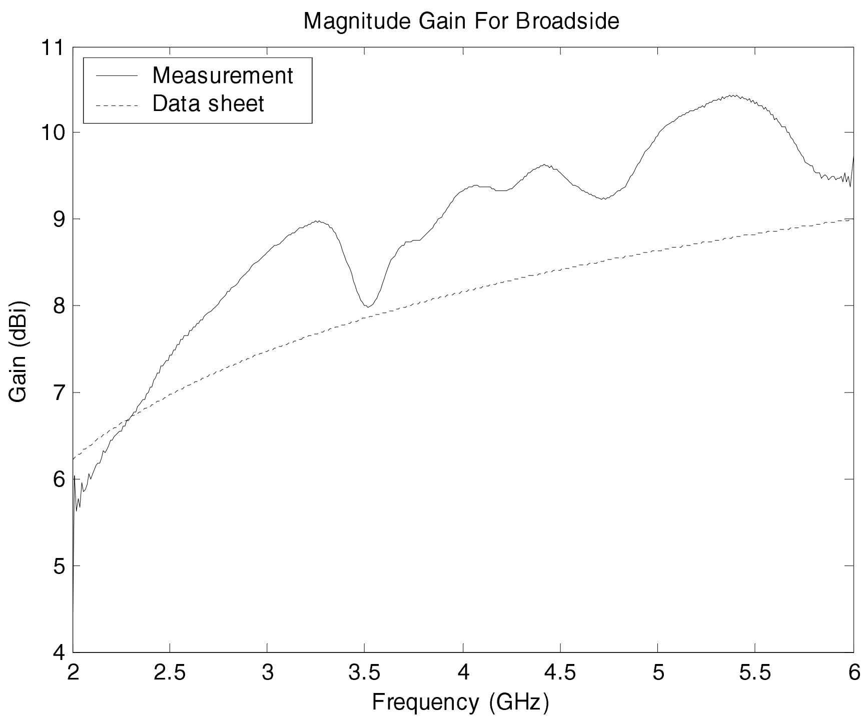
EM Model

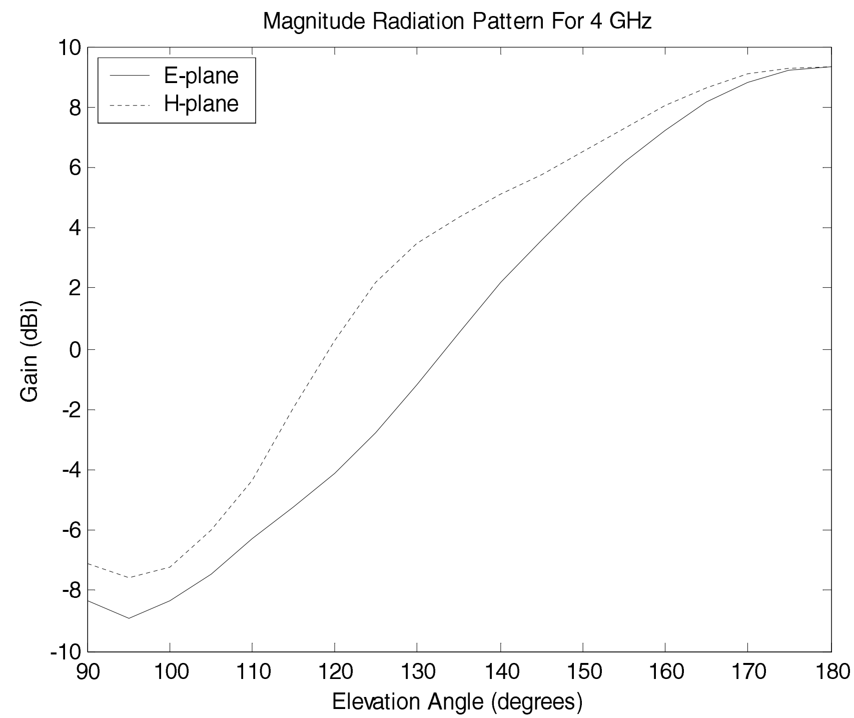
- Magnitude of Transfer Function
  - TEM Horn Antenna Measurements
  - Radar System Transfer Function
  - Spherical Spreading

$$P_R = P_T H_T \eta_{Teff} D_T \frac{\sigma_{bs}}{4\pi R_T^2} \frac{A_R}{4\pi R_R^2} \eta_{\mathrm{Re}\,ff} \left| H_R \right|$$

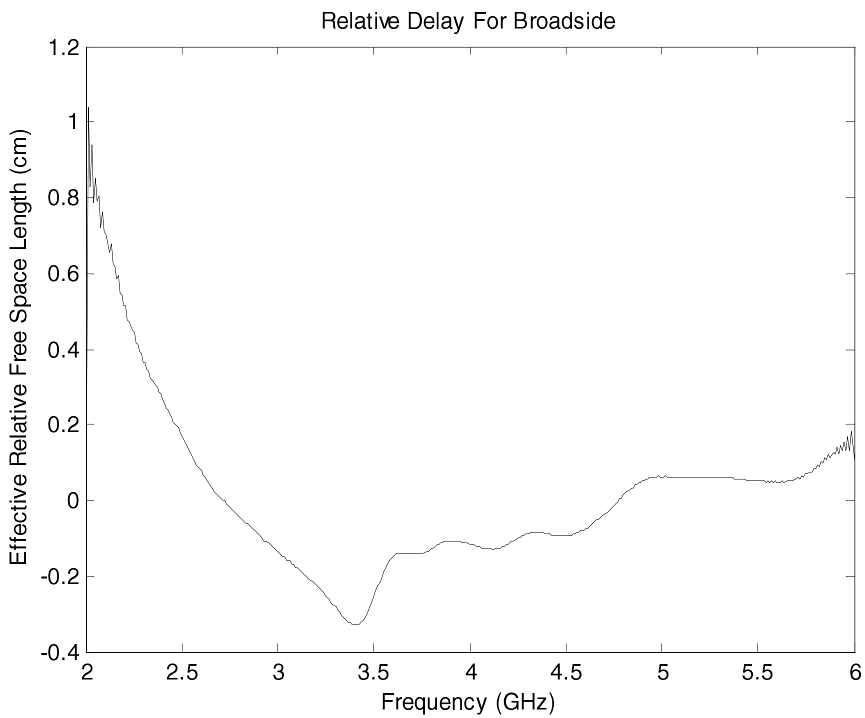
- Phase of Transfer Function
  - TEM Horn Antenna Measurements
  - Radar System Transfer Function
  - Path length, phase velocity, and refraction

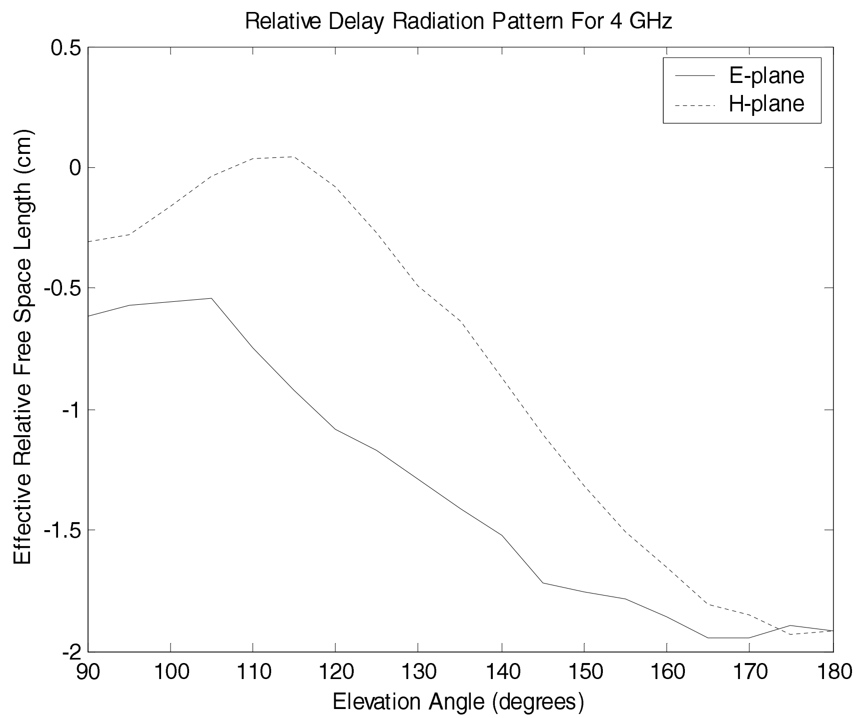
EM Model – TEM Horn Antenna





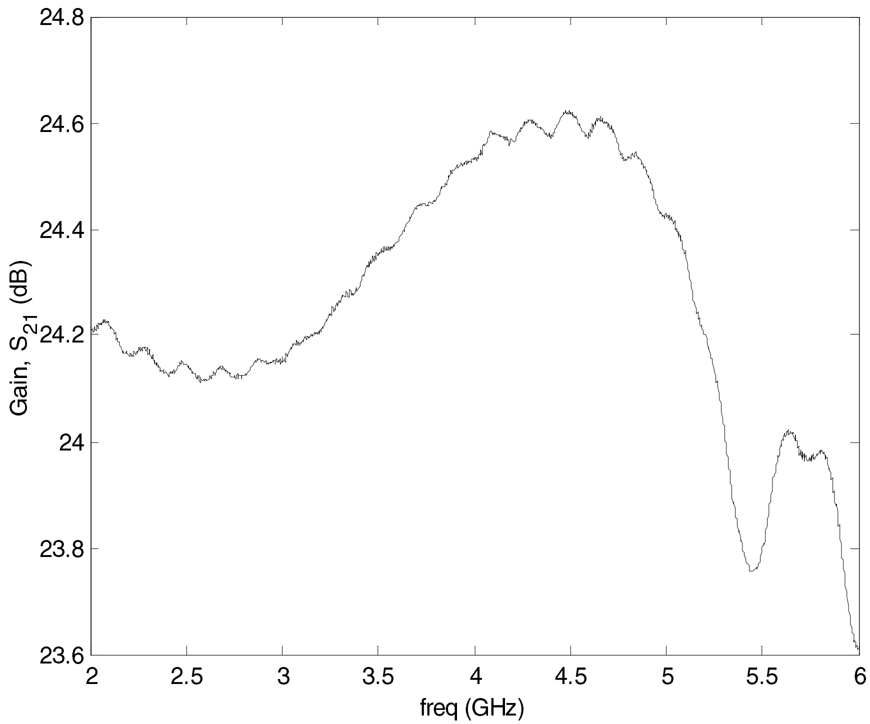
EM Model – TEM Horn Antenna

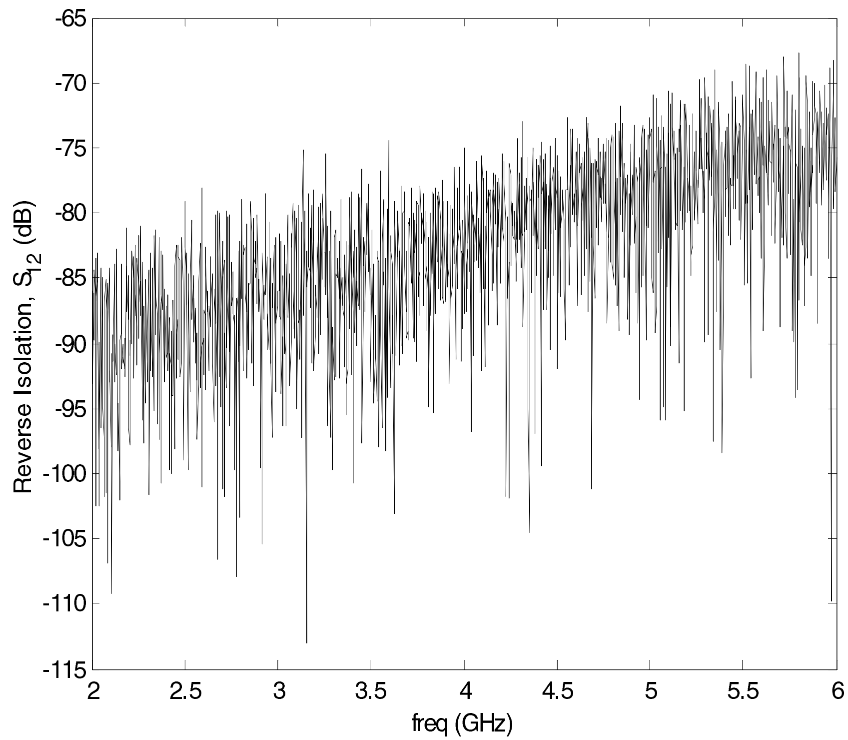




Radar System Transfer Function

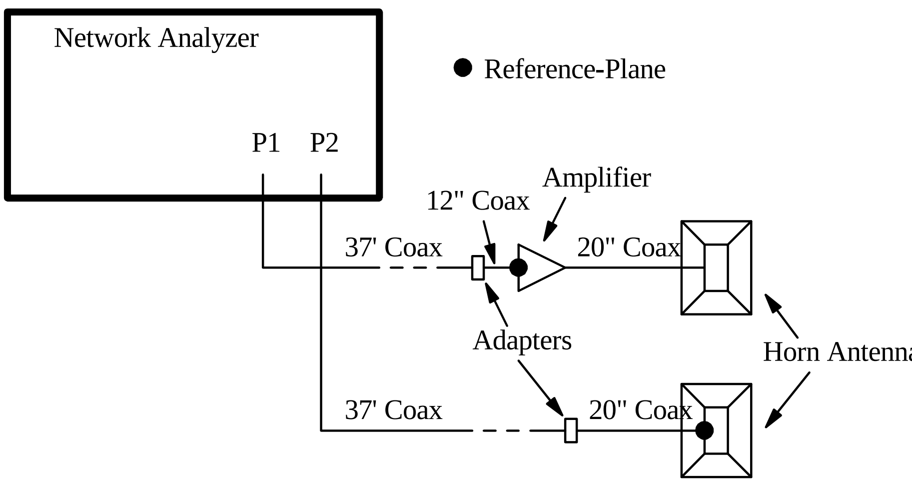
- NA Calibration and Amp/Cable Assembly

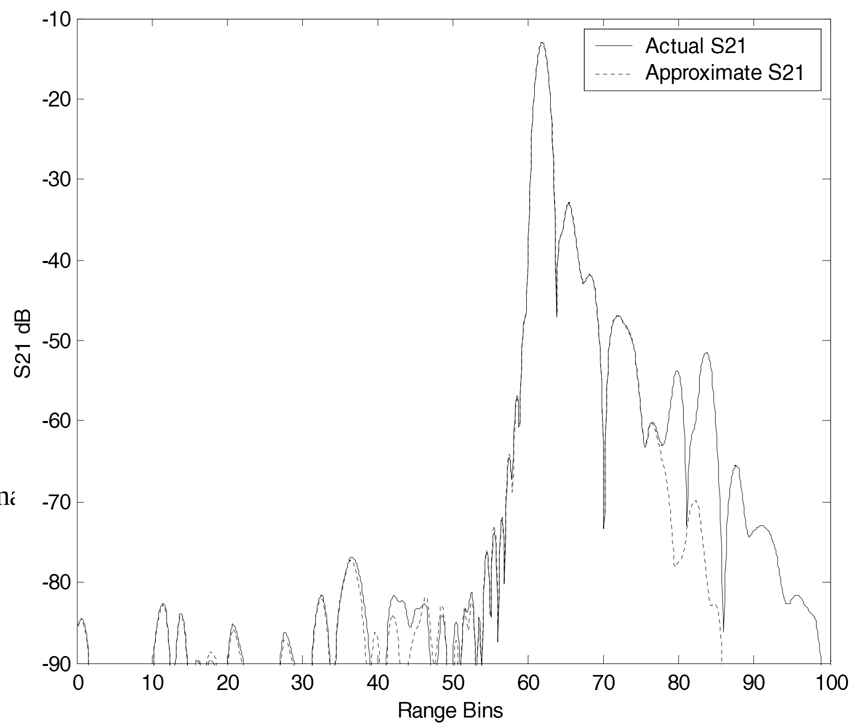




Radar System Transfer Function

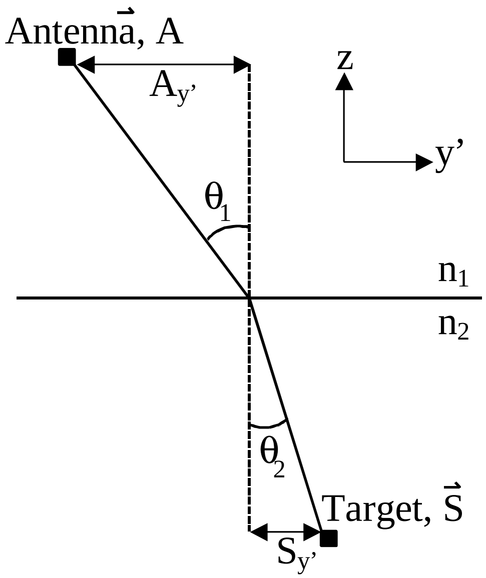
- Calibration and Amp/Cable





Dielectric Half-space Model

- Three-dimensional geometry of refracted ray can be projected onto the plane of incidence (two-dimensional)



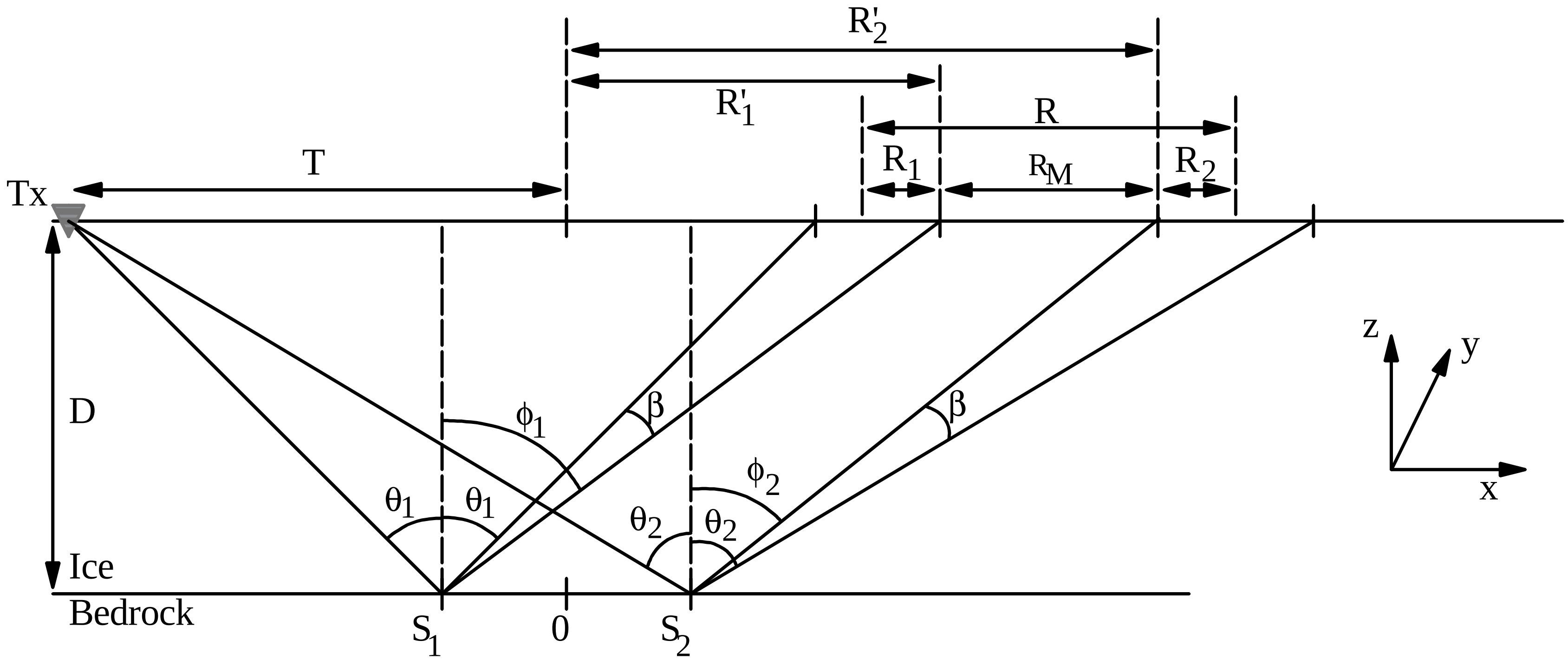
$$y' = \sqrt{(A_x - S_x)^2 + (A_y - S_y)^2}$$

$$\hat{a}_{y'} = \frac{\left((S_x - A_x)\hat{a}_x + (S_y - A_y)\hat{a}_y\right)}{\left|(S_x - A_x)\hat{a}_x + (S_y - A_y)\hat{a}_y\right|}$$

$$\left(n_1^2 - n_2^2\right)S_{y'}^4 - 2y'\left(n_1^2 - n_2^2\right)S_{y'}^3 + \left(n_1^2\left(y'^2 + S_z^2\right) - n_2^2\left(y'^2 + T_z^2\right)\right)S_{y'}^2 - 2y' n_1^2 S_z^2 S_{y'}^1 + y'^2 n_1^2 S_z^2 S_{y'}^0 = 0$$

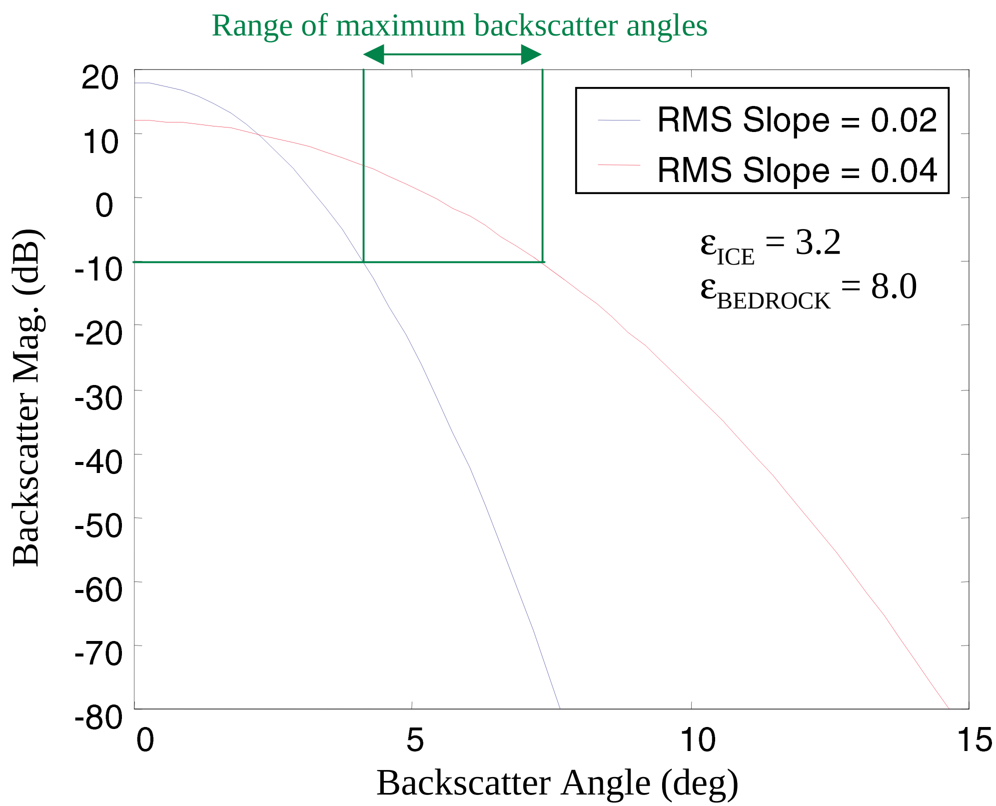
Sensor Geometry

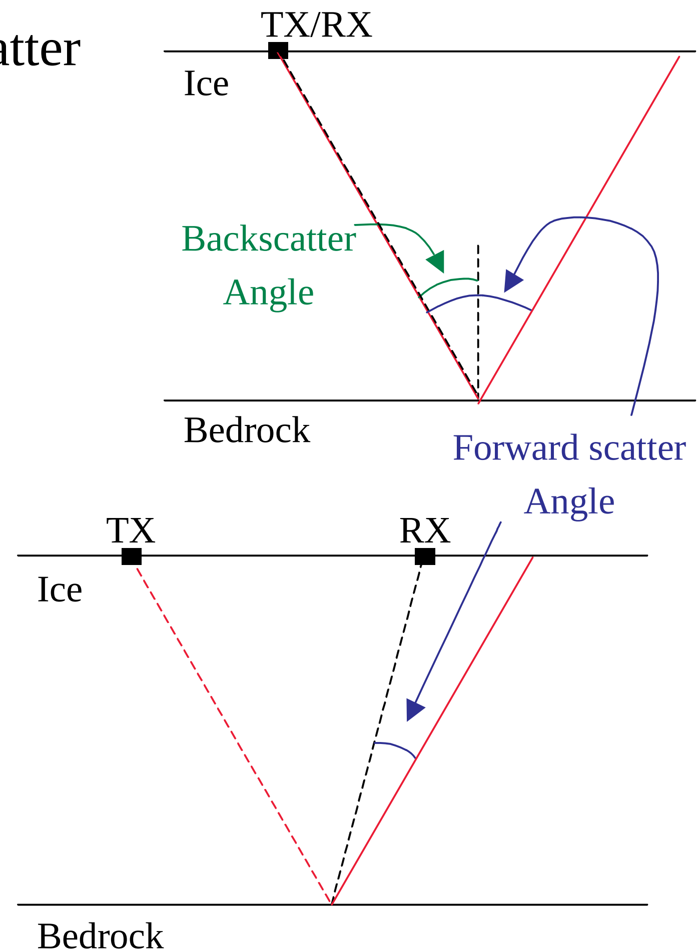
- Find the optimal transmitter position that minimizes the cross-track aperture size, R.



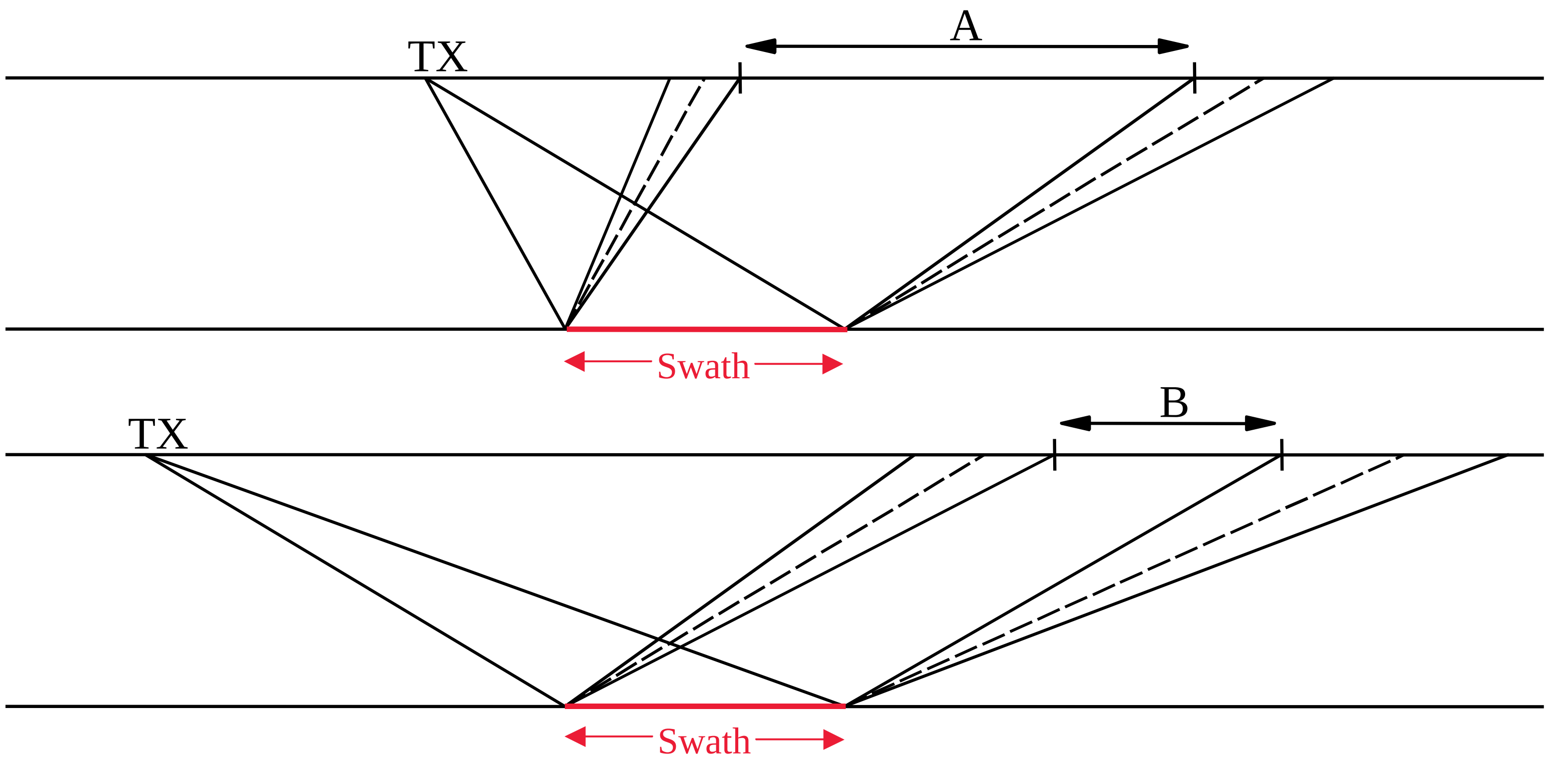
Backscatter Characteristics

- Bistatic forward scattering characteristics are approximated with our knowledge of backscatter characteristics.





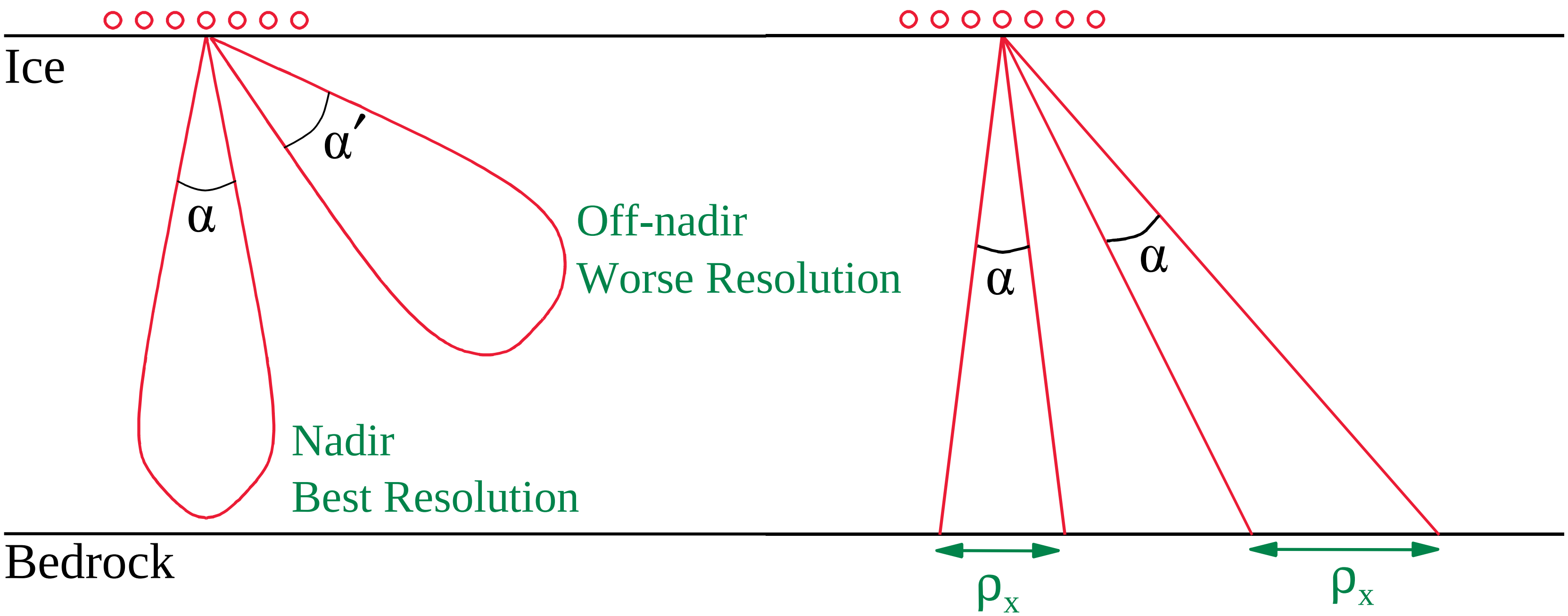
Advantage of Separation



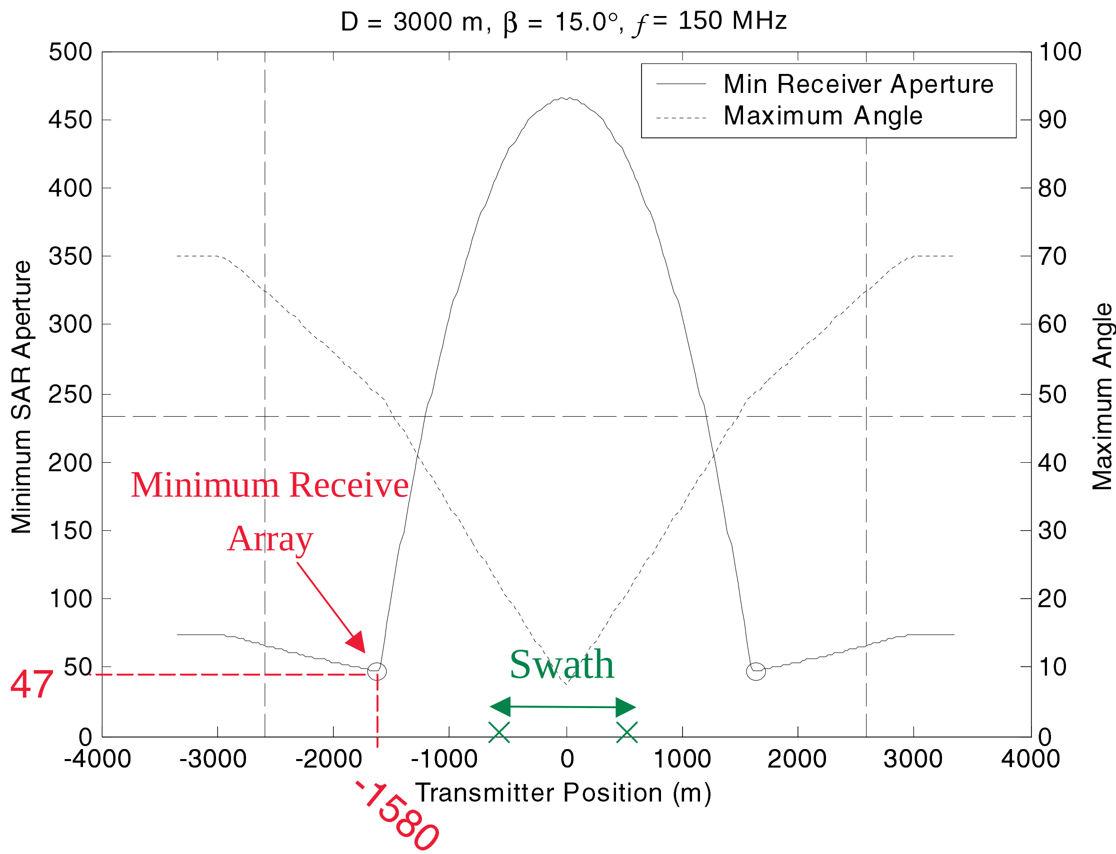
- As the transmitter moves away from the swath, the ice surface illuminated by the forward scatter cones grows.
- In turn, the minimum required receiver movement decreases (i.e. B < A).

Disadvantages of Separation

- As the transmitter-receiver separation is increased, the angular resolution decreases.
- The bedrock surface subtended also increases for the same angular resolution.



Plot of Receiver Array Size



- The minimum receive aperture occurs when the transmitter position is 1580 m from the center of the swath.
- The minimum receive aperture is 47 m.

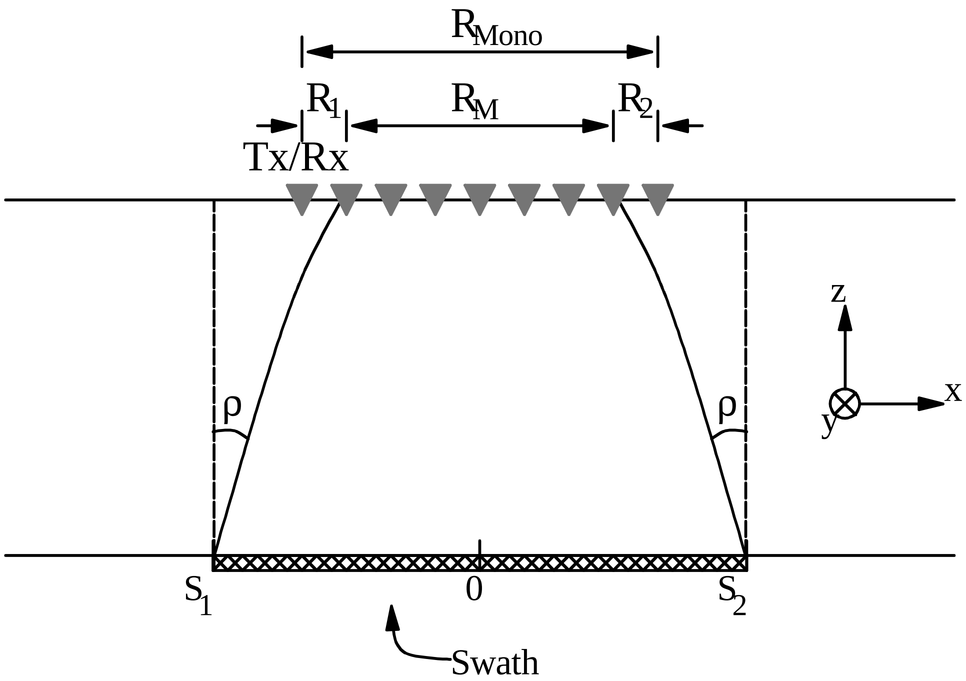
Across-track resolution: 100 m
Ice thickness: 3 km
Frequency: 150 MHz
Swatch Width: 1 km
Backscatter: 7.5 deg

Results for 3000 m thick ice

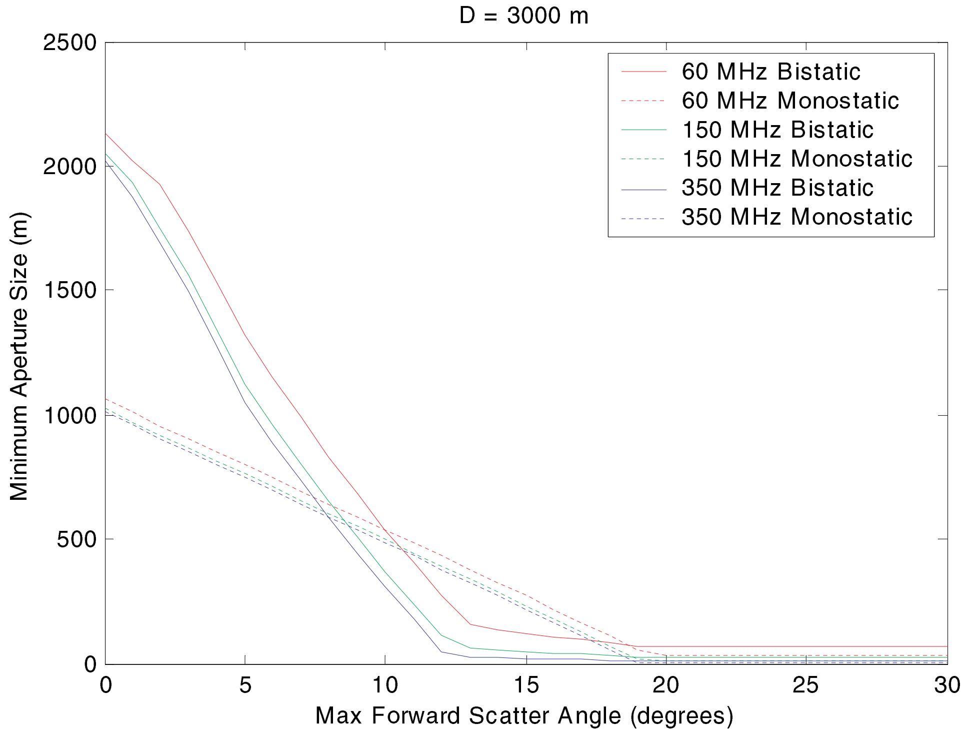
Frequency (MHz)	Max forward-scatter angle (deg)	Tx Position (m)	Min. Receiver Aperture (m)	Min. Monostatic Aperture (m)
60	5	2831	1323	799
60	**10**	**2435**	**538**	**535**
60	15	1710	121	273
60	20	0	66	32
150	5	2831	1125	762
150	**10**	**2435**	**371**	**498**
150	15	1610	47	234
150	20	0	26	13
350	5	2831	1049	748
350	**10**	**2435**	**307**	**484**
350	15	1580	20	219
350	20	0	11	6

Monostatic Mode

- For comparison.
- Using a cross-track spatially sampled monostatic array.

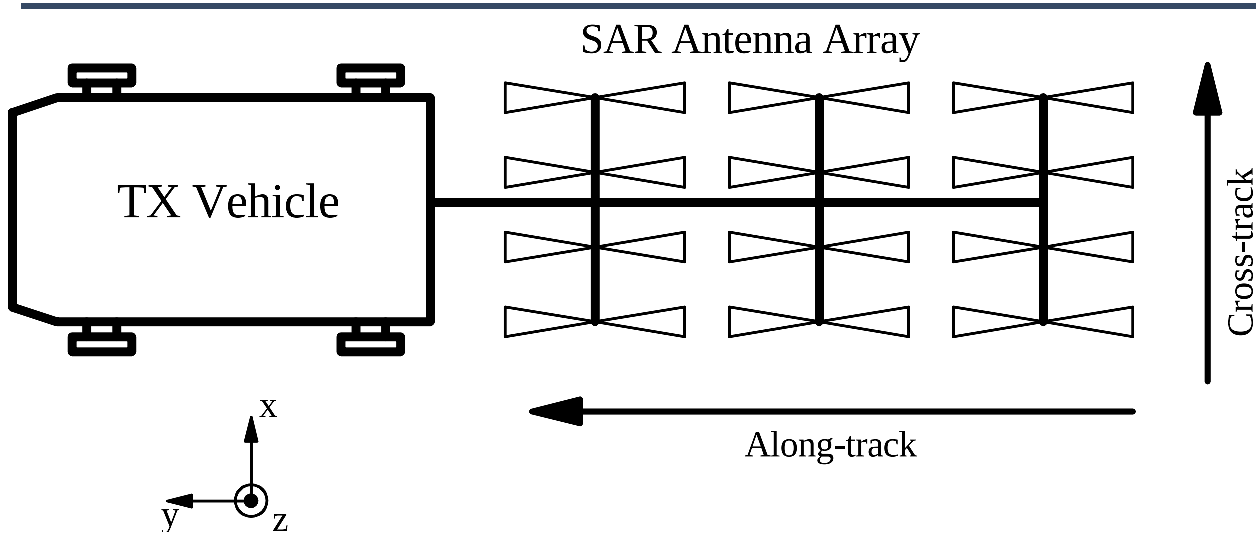


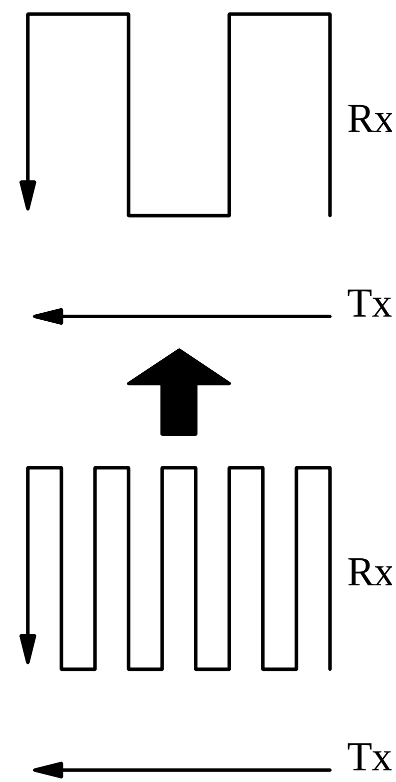
Monostatic vs. Bistatic



- Minimum SAR aperture required using a bistatic configuration (also compared to monostatic).

Along-track Array

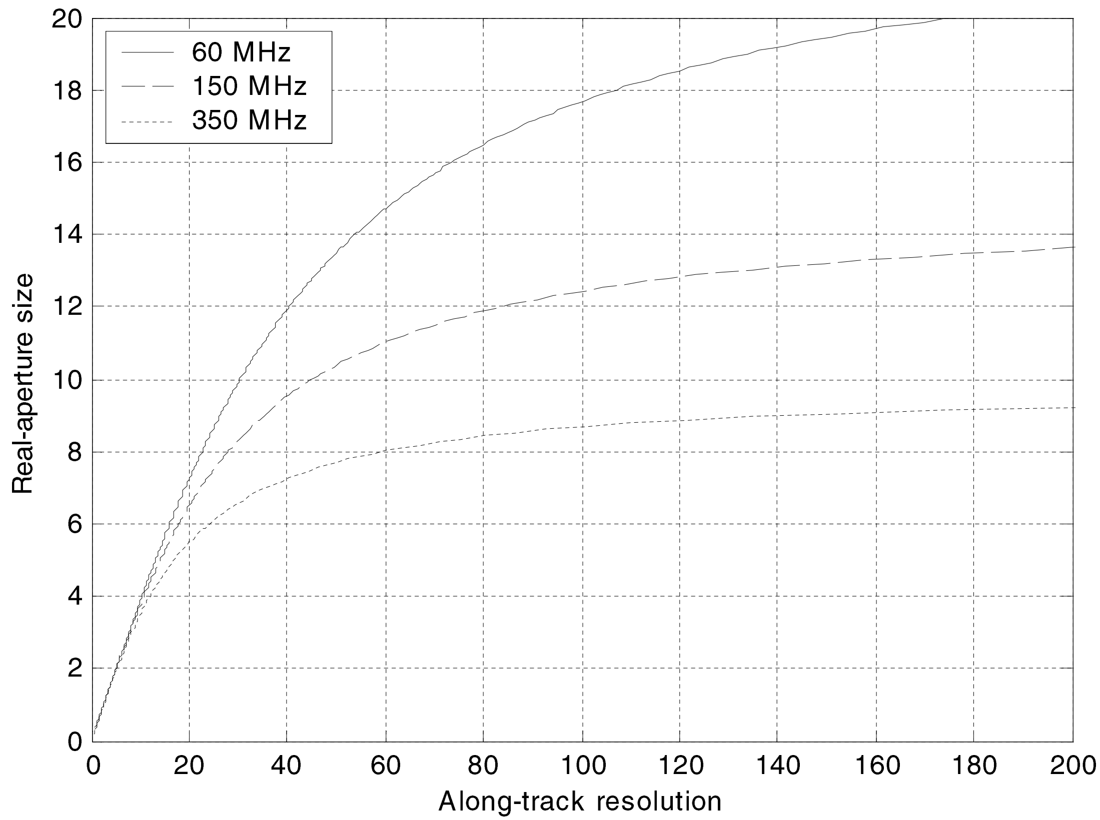




- Along-track antenna array
  - Sharpens along-track beam
  - Less frequent along-track sampling
  - Sum antenna array elements together
  - SAR focusing hindered by loss of control over individual elements

Results

- This plot shows the maximum SAR resolution attainable versus aperture size.
- One tenth of a wavelength variation across the aperture was tolerated.

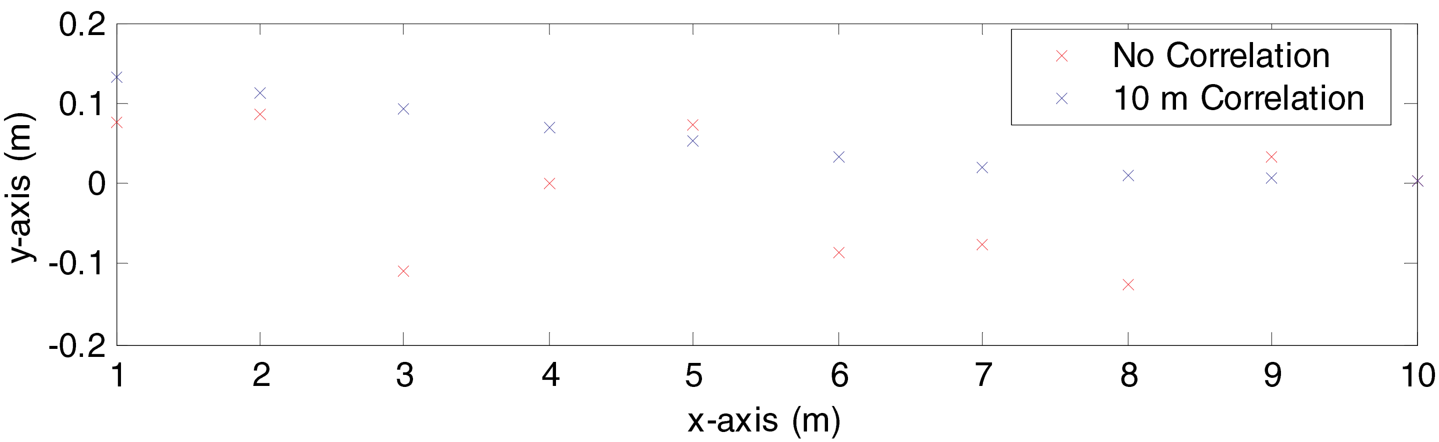


Position Errors

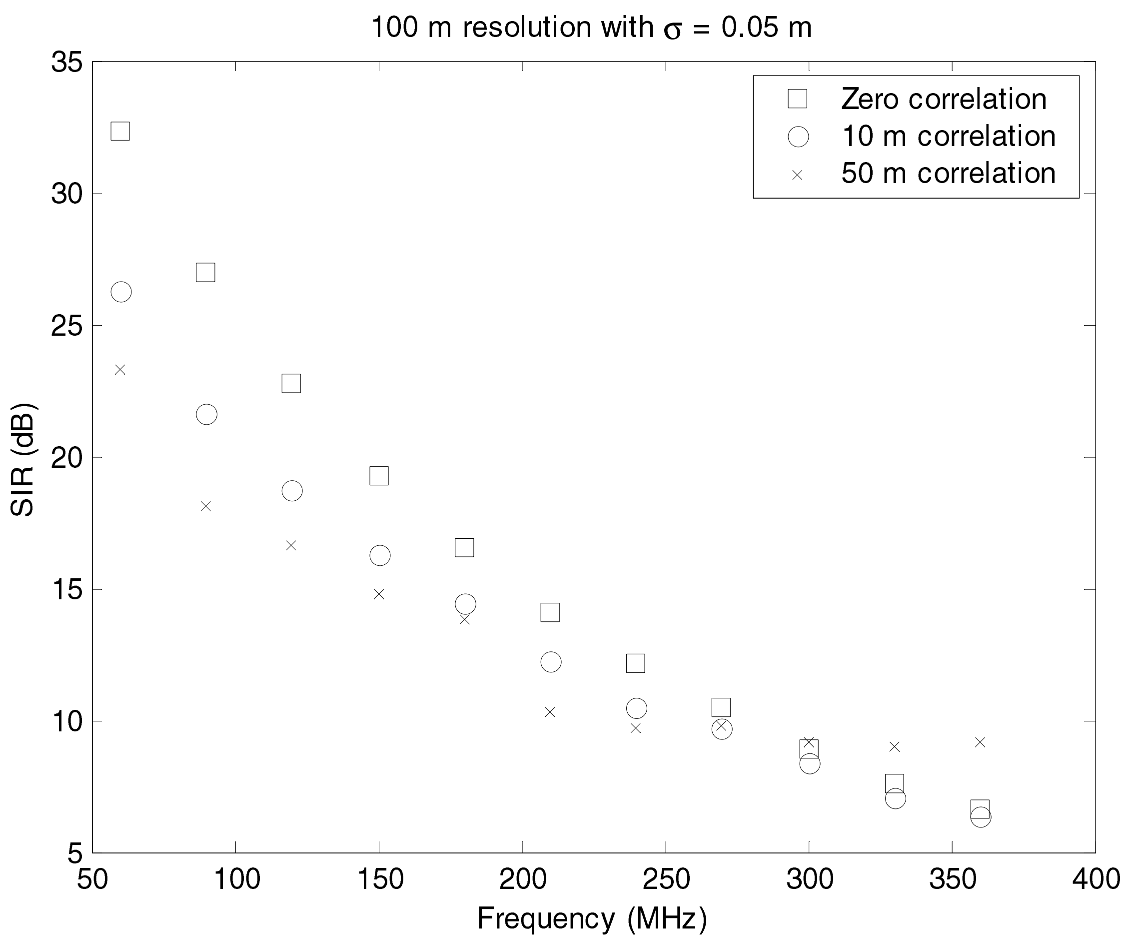
- The Radar will derive its position using the global positioning system (GPS).
- GPS's have errors that are a significant fraction of a wavelength
- Need to answer the question: How do positioning errors effect the performance of the SAR processor?

Position Errors

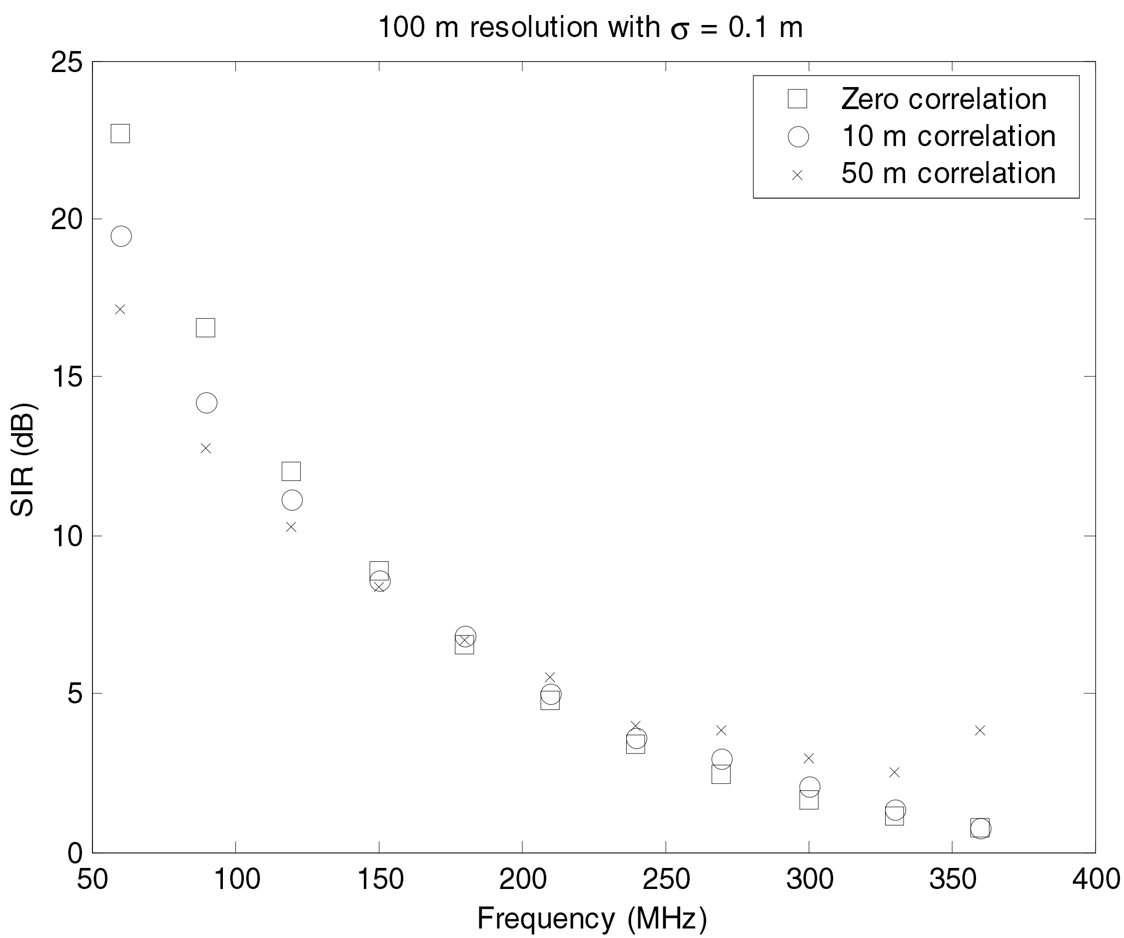
- Gaussian random process
- Correlated errors created by low pass filtering
- Topcon GPS system:
  - 0.1 m standard deviation in latitude
  - 0.1 m standard deviation in longitude
  - 0.2 m standard deviation in elevation



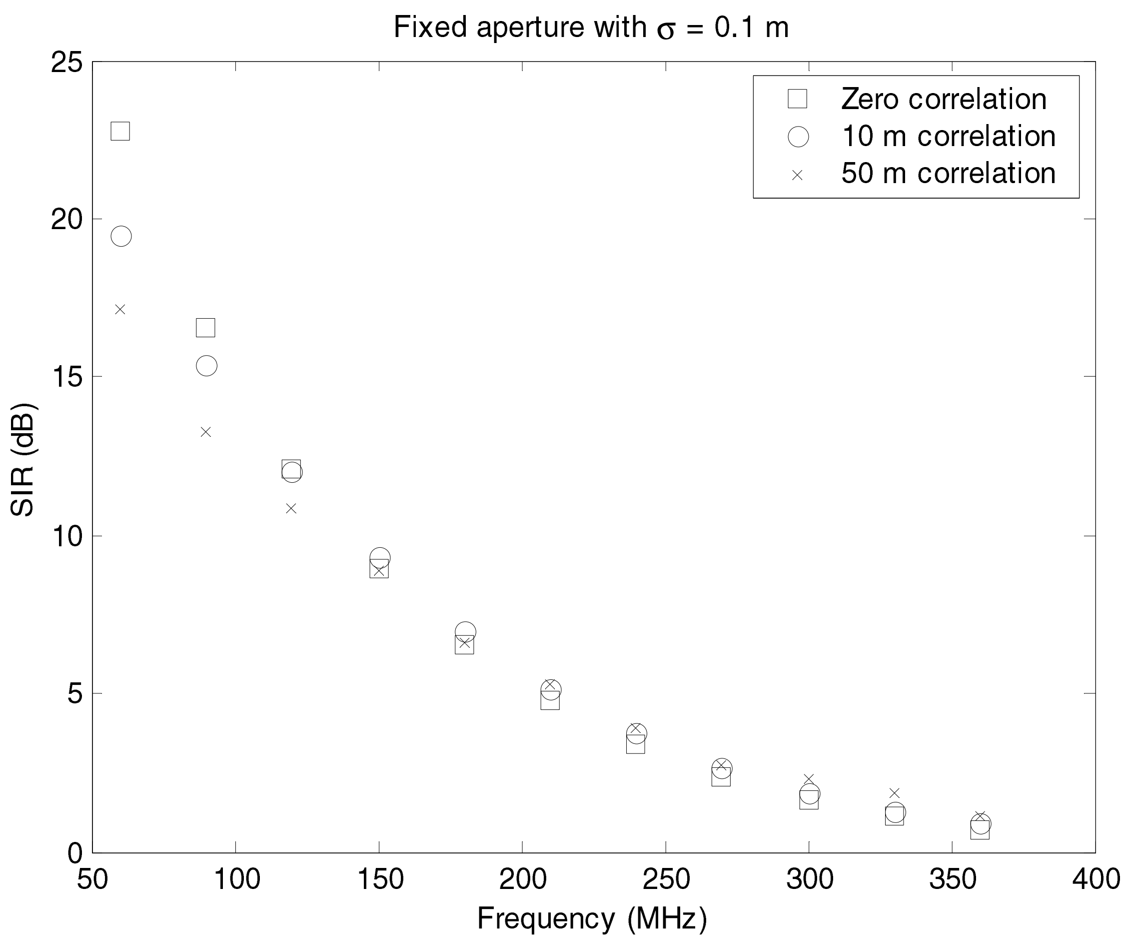
Results for σ = 0.05 m



Results for σ = 0.1 m



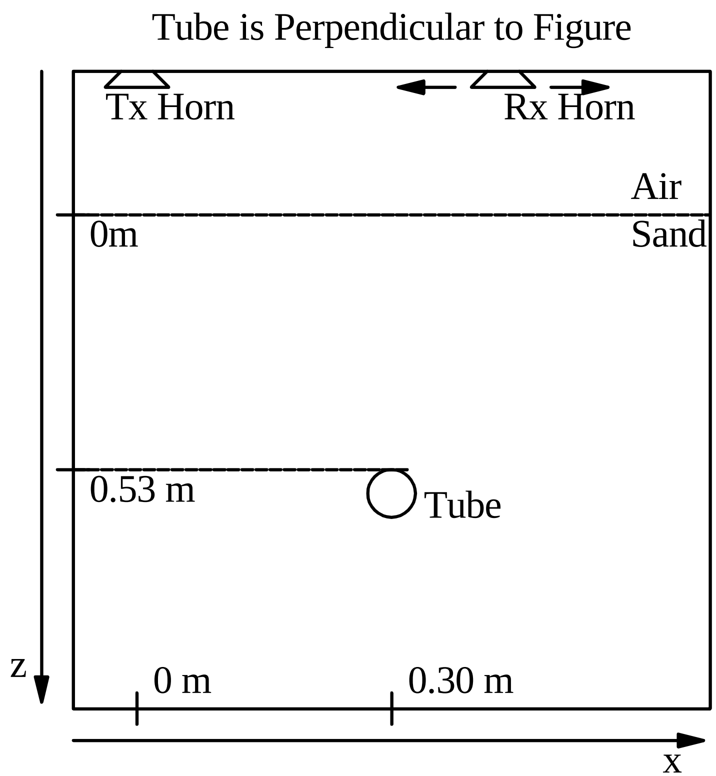
Results for σ = 0.1 m (fixed aperture)

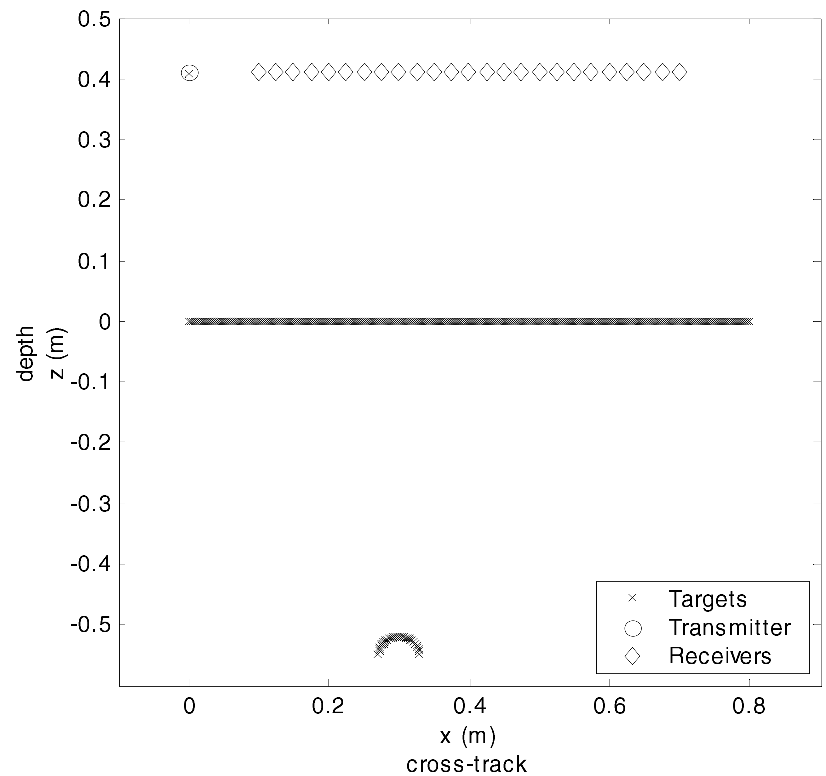


Sandbox Laboratory

- Test the EM model
- Test the SAR processing algorithm
  - Ability to determine the position of a target
  - Ability to accurately determine the target's reflectance

Measurement Setup



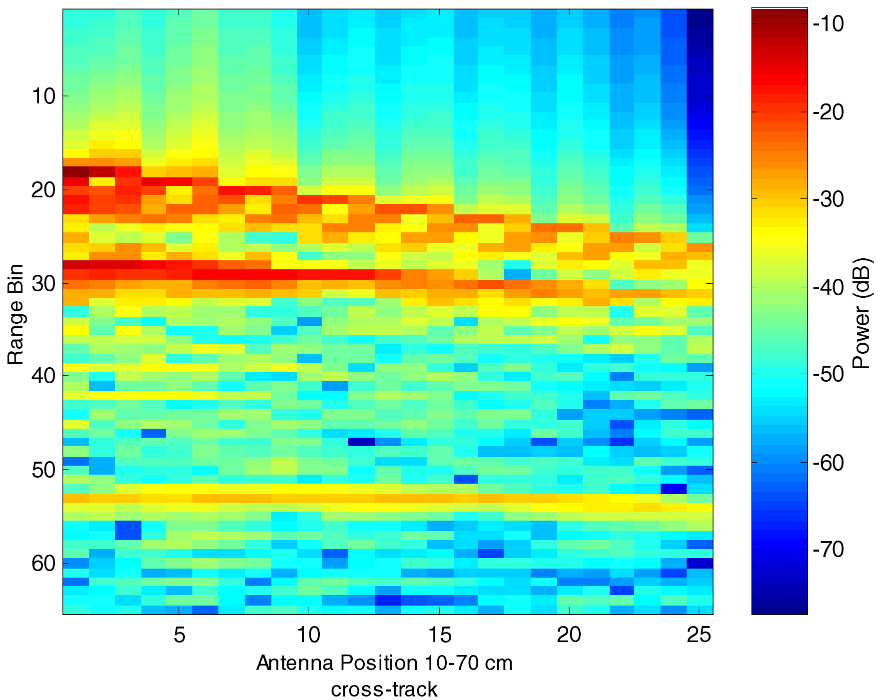


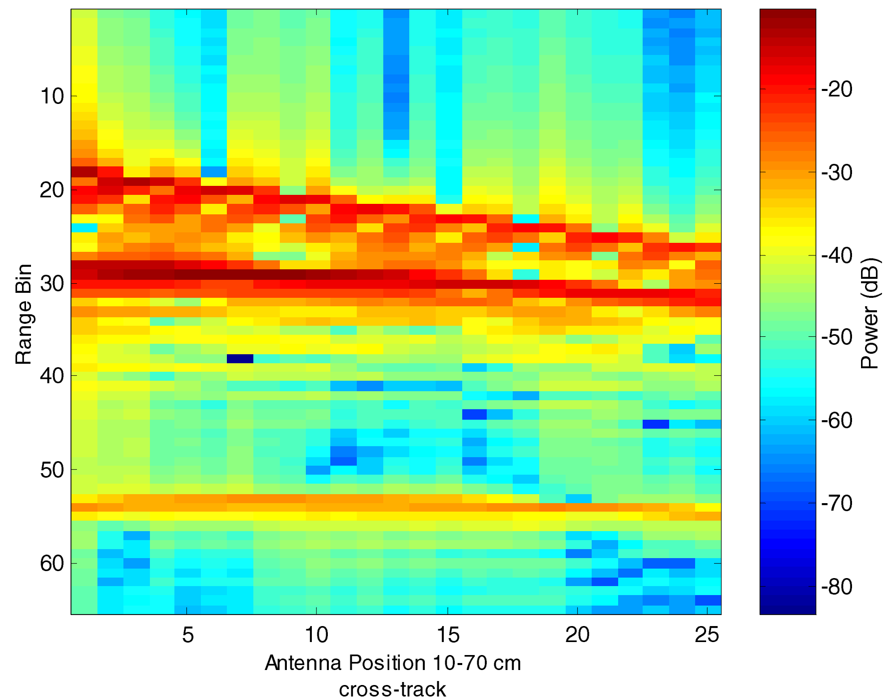
- Left side: measurement setup
- Right side: simulation setup

A-Scopes

Left side: measured dataset

Right side: simulated dataset

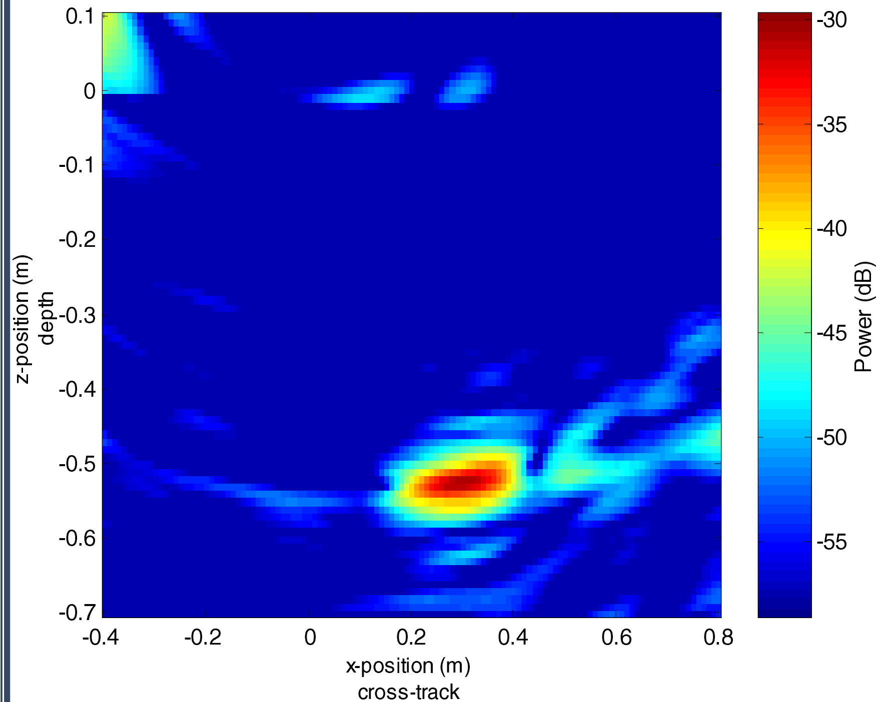


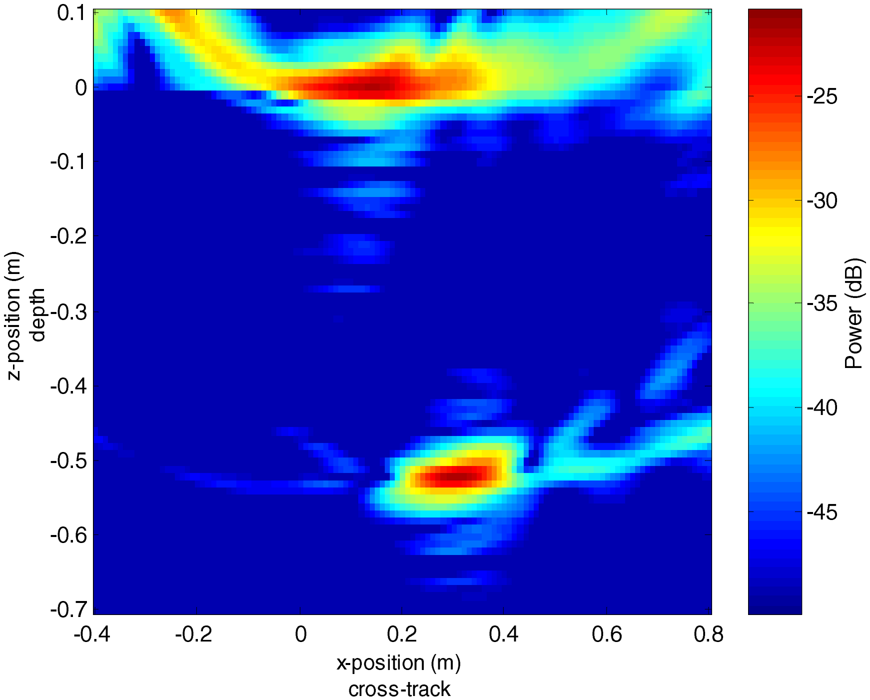


SAR Processed

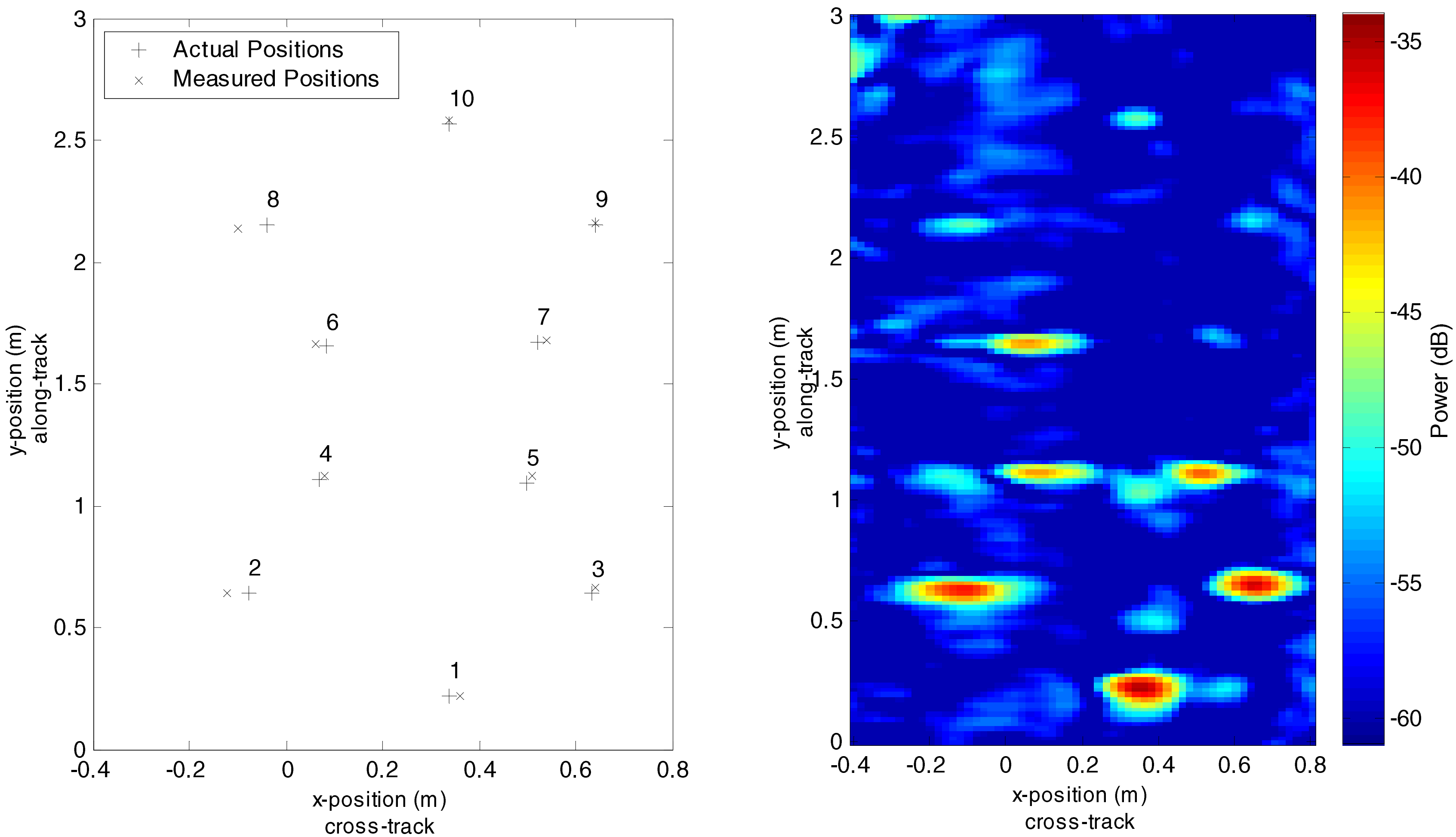
Left side: measured dataset after SAR processing

Right side: simulated dataset after SAR processing





Ten Targets



Actual Positions
Measured Positions
1
2
3
4
5
6
7
8
9
10
y-position (m)
along-track
x-position (m)
cross-track
Power (dB)
-35
-40
-45
-50
-55
-60

Table of Results

Target #	Diameter	Metal/Air	Signal Power	Position Error
1	12.5 cm	Metal	-35 dB	2 cm
2	10 cm	Metal	-38 dB	5 cm
3	12.5 cm	Metal	-35 dB	2 cm
4	10 cm	Metal	-42 dB	1.41 cm
5	10 cm	Metal	-40 dB	2.24 cm
6	10 cm	Metal	-42 dB	3.16 cm
7	11.5 cm	Air-filled	-53 dB	2.24 cm
8	15 cm	Air-filled	-49 dB	6.08 cm
9	11.5 cm	Air-filled	-52 dB	1 cm
10	15 cm	Air-filled	-49 dB	1 cm

- Max sidelobe is –49 dB
- Signal to sidelobe is at least 4 dB within the region of the target

Conclusions

- Transmitter Location (Sensor Geometry)
  - The transmitter position has a very large effect on the size of the bistatic array.
  - Depending on the type of scattering and thickness of the ice, the bistatic mode may or may not be faster than the monostatic mode.
  - The bistatic transmitter position that minimizes the receiver cross-track movement was found.
- Along-track Antenna Array
  - Along-track antenna array could be helpful in expediting the bistatic measurements.
  - For high-precision measurements (e.g. 10 m) its usefulness is limited unless each element can be controlled individually.

Conclusions

- Position Errors
  - Position errors can be very severe at higher frequencies. Increasing aperture length does not help position errors.
  - GPS errors need to be characterized in terms of magnitude of relative error and error correlation over time and space.
- Sandbox lab tests showed:
  - First-order EM Model gives results consistent with the measured results
  - Ability to position targets to within a few centimeters
  - Ability to distinguish targets with different reflectivities (with similar targets giving consistent reflectivities)