Modeling and Simulation Analysis of an FMCW Radar for Measuring Snow Thickness

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Outline

- Snow cover over sea-ice
- KU snow radar
- Research goal
- Approach
  - System modeling
  - Propagation modeling
  - Simulation methodology
- Results
- Summary and future work

Snow Cover Over Sea Ice

- Sea ice extent and thickness
  - Important indicator of global climate change
- Snow layer affects sea ice thickness
  - Low thermal conductivity – insulates sea-ice
  - High Albedo – reflects energy
- Snow layer thickness measurement - important
- Properties of snow
  - Mixture – air, ice and water
  - Forms dielectric contrast with sea ice layer
  - Measurable by radar

Measurement of Snow Thickness

- Usually measured using in-situ measurements.
- Not practical over large areas like polar regions.
- Solution – satellite based measurements.
- Validation of satellite measurements needed.
- High resolution needed.
- KU snow radar.
  - 2-8 GHz FMCW radar ~ 3 – 4 cms resolution.
- Prototype radar – ground based.
- Next step – airborne radar.

FMCW Radar

- Transmits sweep

$$f(t) = f_0 + \alpha \cdot t \qquad \forall \quad t < T$$

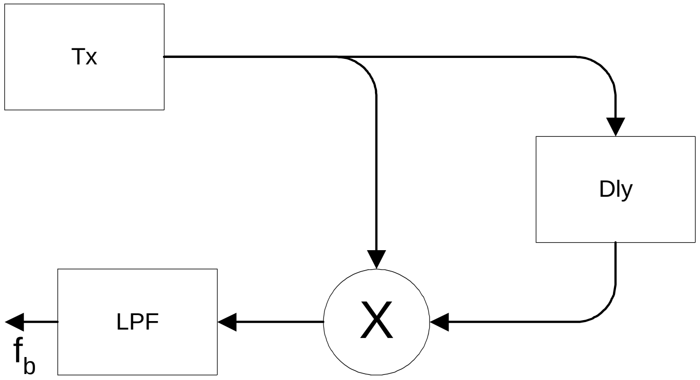
- Transmit wave phase

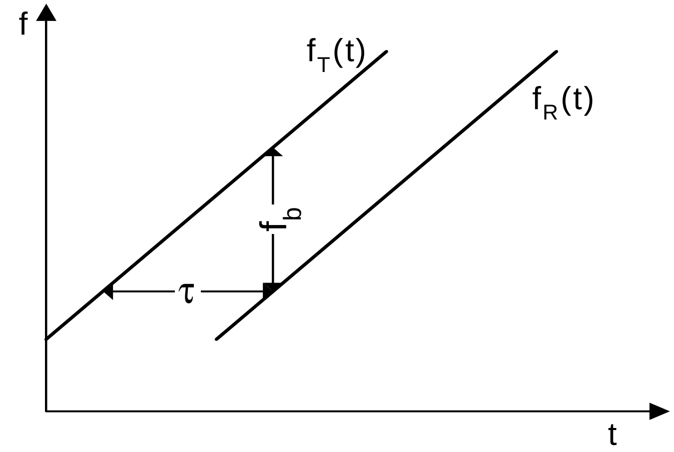
$$\phi(t) = 2\pi \int f(t)dt = 2\pi \cdot (f_0 t + \frac{1}{2}\alpha \cdot t^2)$$

- Beat frequency

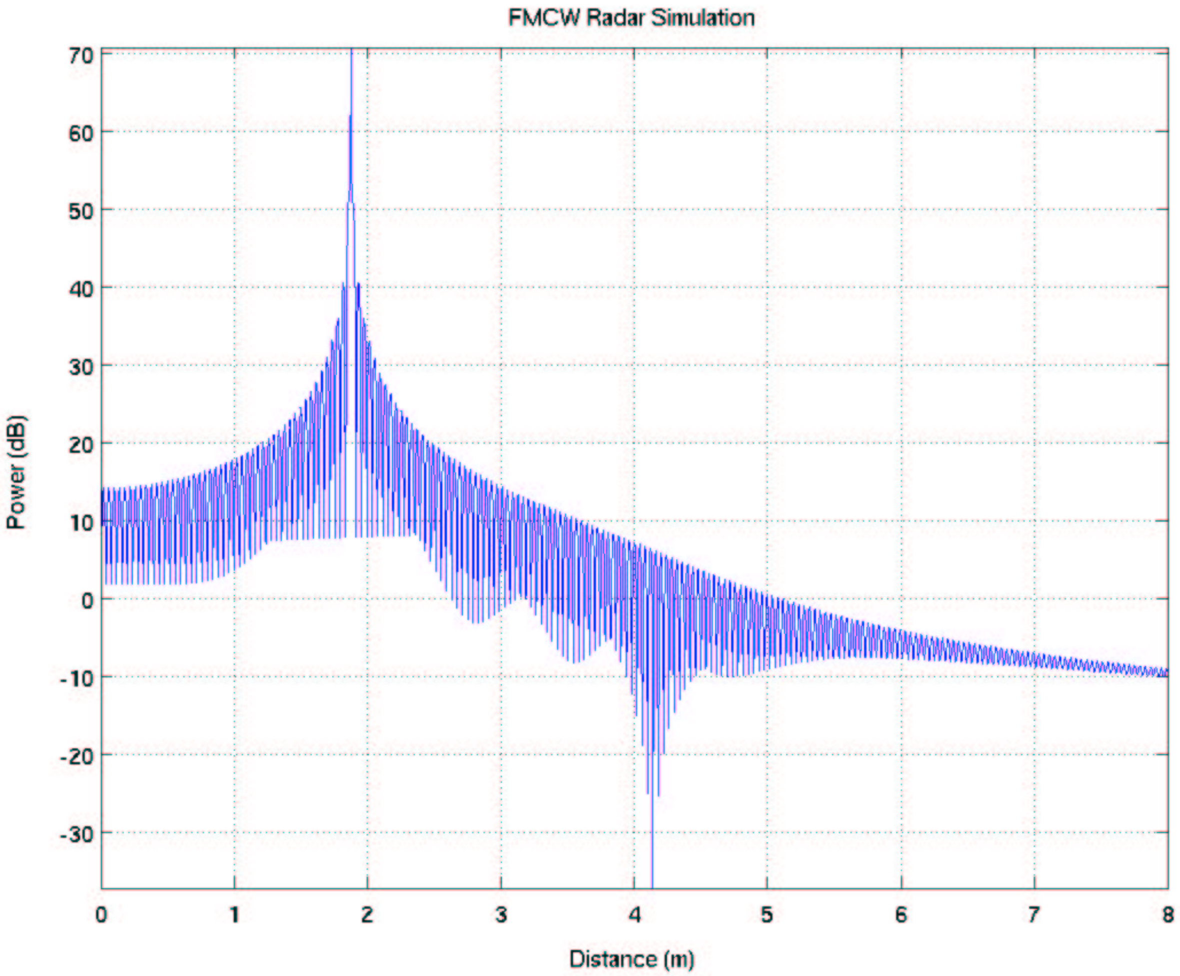
$$f_B \quad = \frac{2RB}{cT}$$

- Plotted in freq domain
- One peak = one target



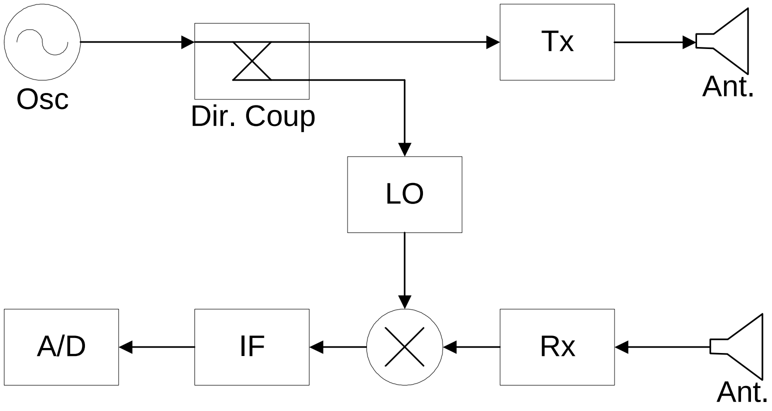


Simulated Ideal FMCW Radar Data



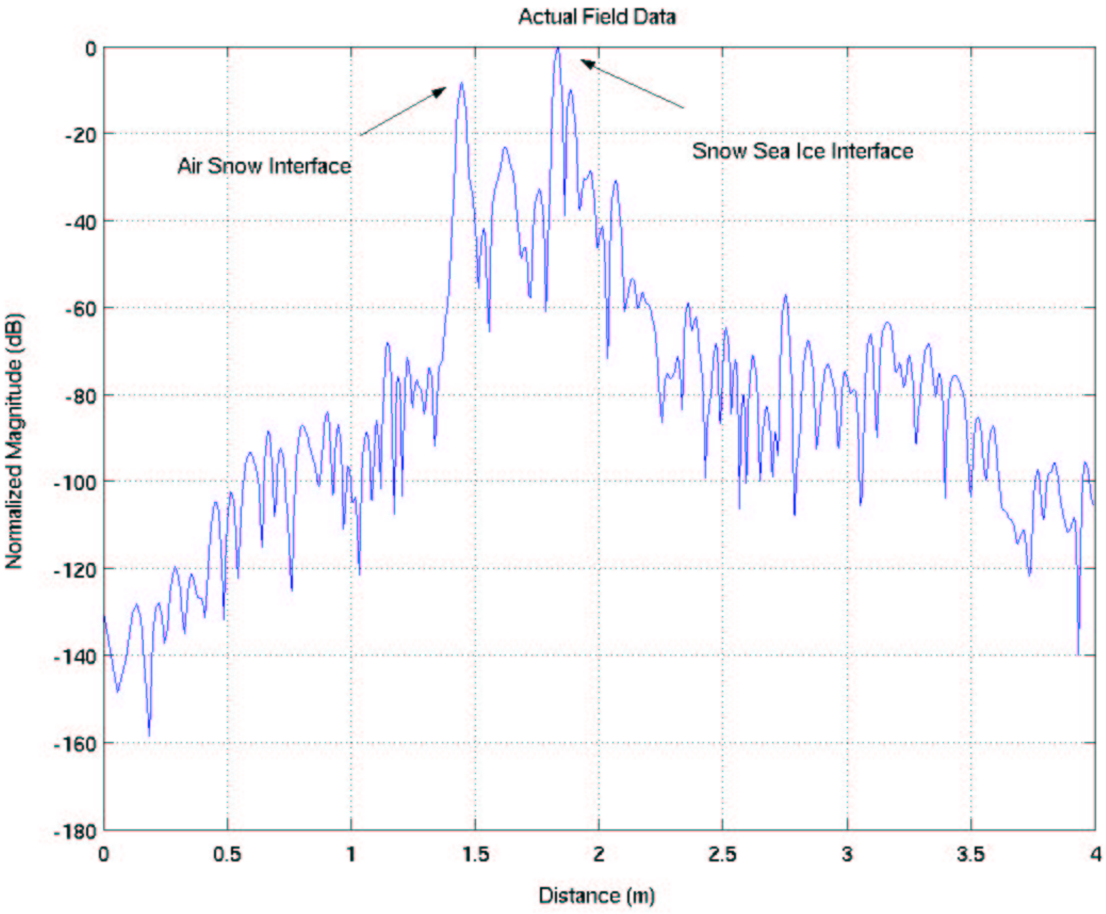
KU Snow Radar

- Radar specifications
- Frequency choice
- Bandwidth choice
- Functional block diagram



Characteristic	**Value**	**Unit**
Radar Type	FMCW	
Sweep Frequency	2 – 8	GHz
Range Resolution	≅4	cm
Sweep Time	10	msec
Transmit Power	13	dBm
PRF	25	Hz
A/D Dynamic Range	12 bit, 72	dB
Sampling Rate	5	MHz

KU Snow Radar Data



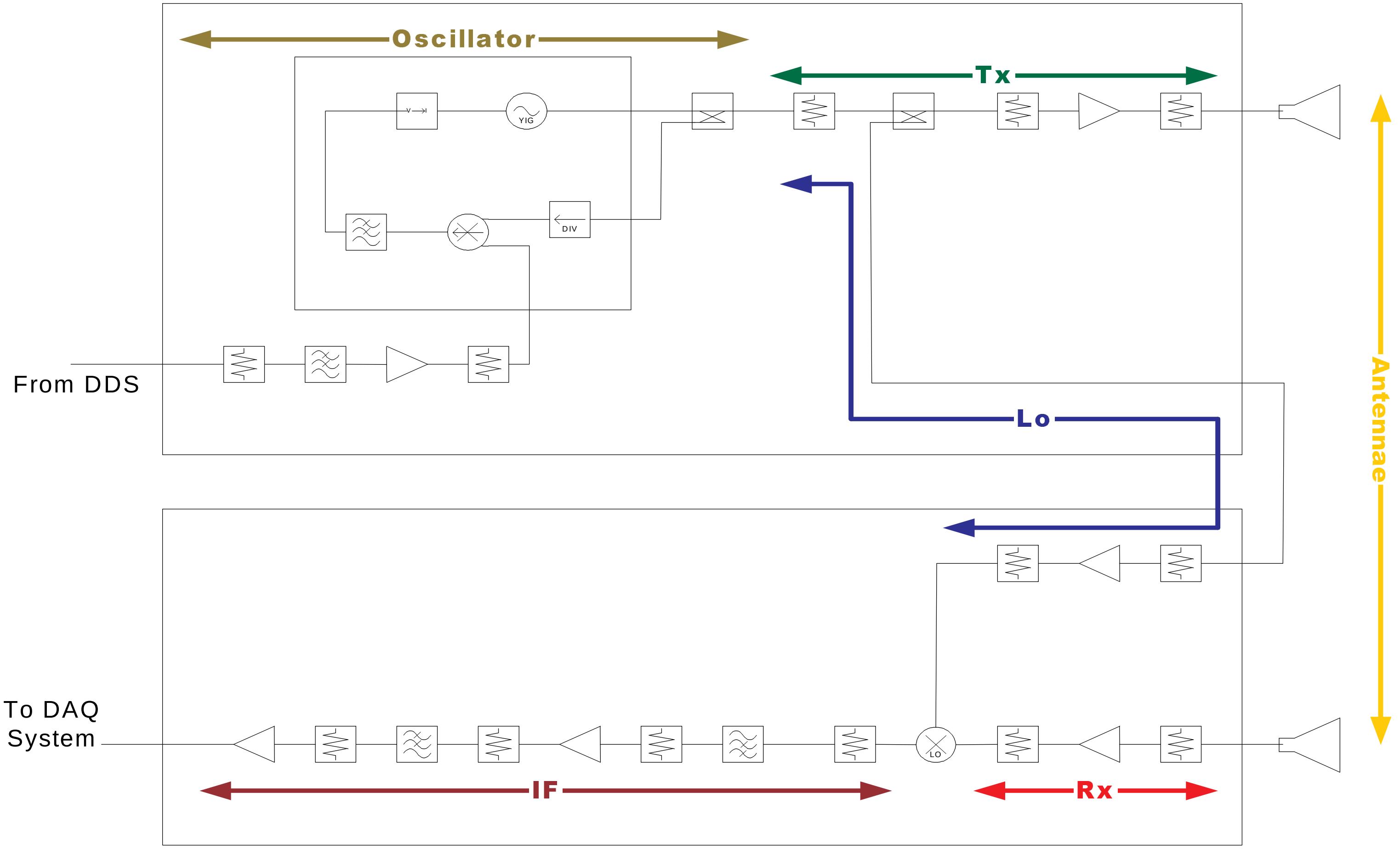
Research Goal

- Snow radar return is not ideal.
- Affected by.
  - System effects – radar components.
  - Propagation effects – surface and volume scattering.
- Goal.
  - Simulate radar.
  - Include system effects.
  - Include propagation effects.
- Helps in understanding and removing effects.

Radar System Modeling

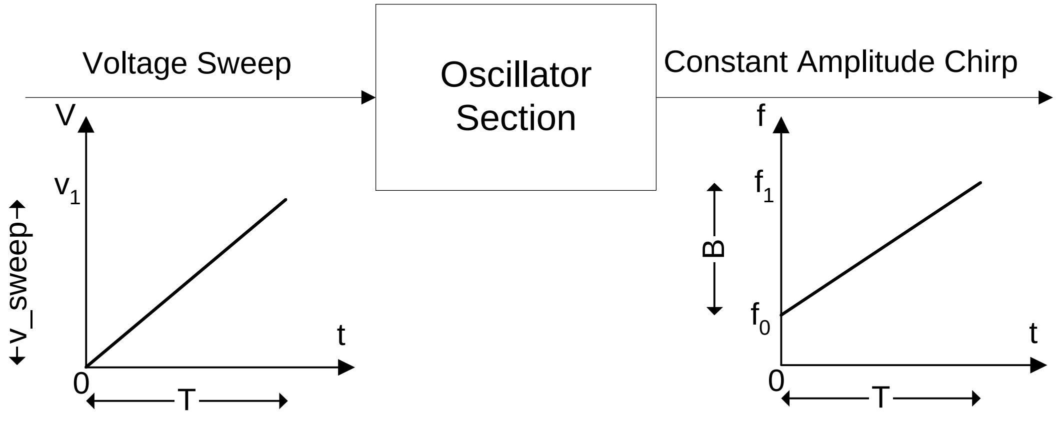
- Goal: to include effects of system into simulation
- How? Determine point spread function
  - By measurement
  - By calibration
- Modeling by measurement
  - Source modeling
  - System transfer function modeling
- Modeling by calibration
  - Calibration target

Modeling by Measurement



Modeling by Measurement

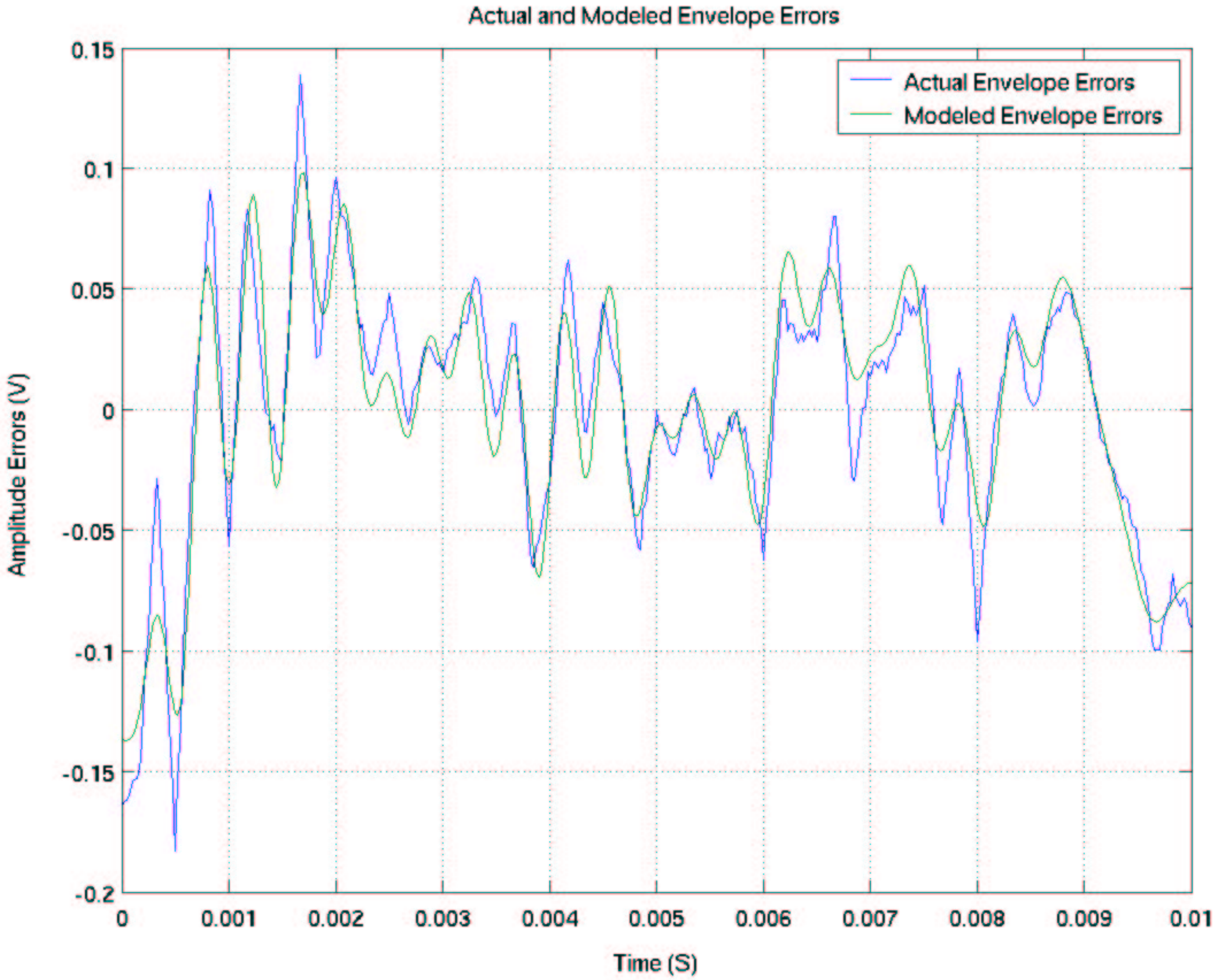
- Source modeling
  - Modeling amplitude and phase errors of sweep
- Amplitude vs. Frequency – non constant
- Frequency vs. Time – non linear



Amplitude Error Modeling

- Output power vs. Sweep voltage measured
- No amplitude errors – output power a constant
- Output power not constant
- Choose significant components as model
- How?
  - Determine DCT of the amplitude errors
  - Select significant peaks (amerr)
  - Compute IDCT

Amplitude Error Modeling



Phase Error Modeling

- Output frequency vs. Sweep voltage measured
- Sweep voltage proportional to sweep time
- Express frequency as a function of time

$$f(t) = a_3 t^3 + a_2 t^2 + a_1 t + a_0$$

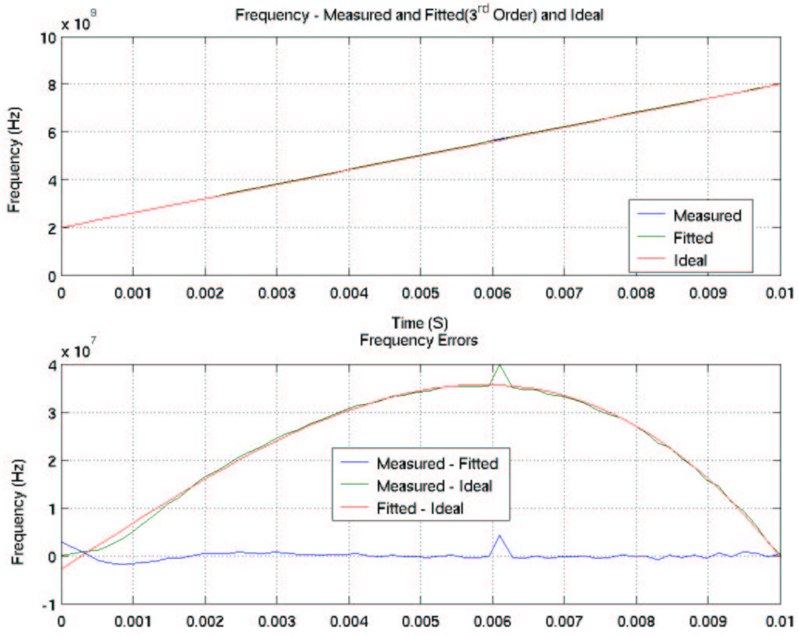
- The phase is then given by

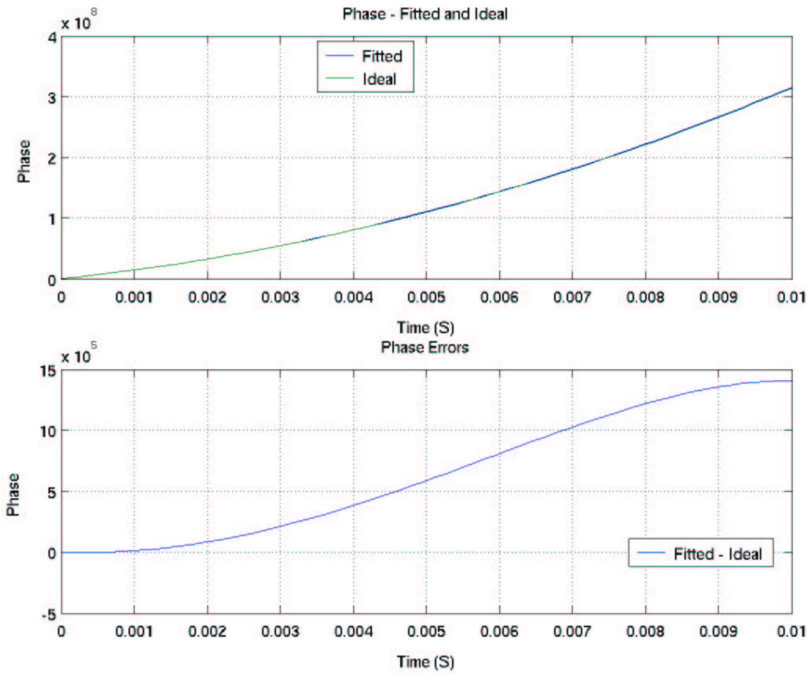
$$\phi(t) = 2\pi \int f(t)dt = b_3 t^4 + b_2 t^3 + b_1 t^2 + b_0 t$$

- This phase includes phase error
- To generate chirp with amplitude and phase errors

$$x(t) = \left(1 + idct\left(amerr\right)\right)\cos\left(\phi(t)\right)$$

Phase Error Modeling





Transfer Function

- Other section characterized by transfer function
- Transfer function determined from s-parameter (s_{21})
- S_{21} determined using network analyzer and interpolated
- System modeled as a input output relationship
- Output is the product of input and transfer function

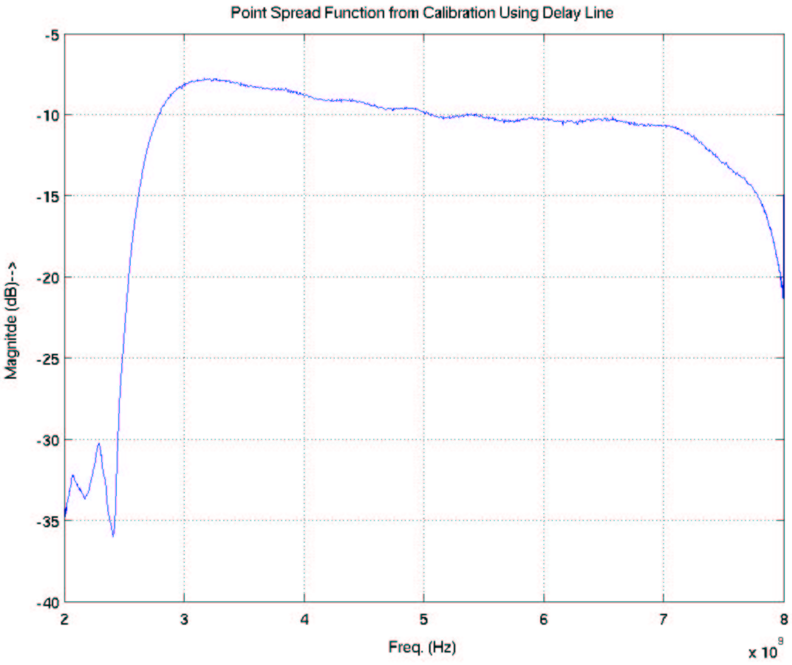
$$H(f) = \frac{V_o(f)}{V_i(f)}$$

$$S_{21} = \left. \frac{V_2^-}{V_1^+} \right|_{V_2^+ = 0}$$

$$\begin{aligned} Y(f) &= X(f) * H(f) \\ &= X(f) * S_{21}(f) \end{aligned}$$

Modeling by Calibration

- Calibration target is used – usually screen
- The return should ideally be a single peak in Freq. domain
- IFFT of obtained peak => Point Spread Function



Propagation Modeling

- Goal: determine return given transmit waveform and geophysical data
- Transmit waveform simulated from source model
- Modeling involves
  - Determining reflected power
  - Determining backscattered power
  - Combining the two and introducing noise
- What is geophysical data?

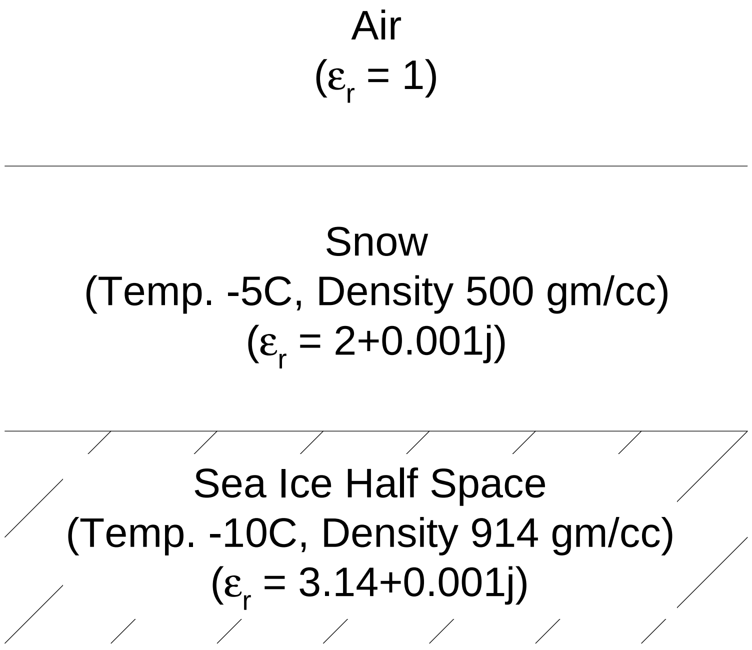
Geophysical Data

- Geophysical data: defines the medium.
- Constituent media, depth, density, temperature etc.
- Roughness information also included.

Depth (m)	**Medium**	**Density (gm/cc)**	**Temperature (°C)**	**Salinity PPT**
1	Air	-	-	-
0.5	Snow	0.500	-8	-
5	Sea-Ice	0.915	-12	40
Snow layer roughness: rms height = 1cm, correlation length = 40cm				
Sea-Ice layer roughness: rms height = 1mm, correlation length = 10cm				

Dielectric Profile

- For radar EM properties are needed
- Convert geophysical data to dielectric profile
- Determine dielectric constant of every layer
- Dielectric contrast can be seen to form 2 interfaces



Air
(ε_r = 1)

Snow
(Temp. -5C, Density 500 gm/cc)
(ε_r = 2+0.001j)

Sea Ice Half Space
(Temp. -10C, Density 914 gm/cc)
(ε_r = 3.14+0.001j)

Return Power Due to Reflection

- Assuming plane surfaces, Γ can be determined

$$\Gamma = \frac{\sqrt{\varepsilon_2} - \sqrt{\varepsilon_1}}{\sqrt{\varepsilon_2} + \sqrt{\varepsilon_1}}$$

- Then Γ is reduced to accommodate for surface roughness

$$\Gamma = \Gamma_{sp} e^{-4k^2\sigma_h^2}$$

- The return power due to reflection is determined

$$P_r = \frac{P_t \lambda^2 G^2 |\Gamma|^2}{(4\pi)^2 (2R)^2}$$

Surface Scattering Coefficient

- Surfaces not smooth – cause surface scattering
- Power reflected from various angles
- Depends on rms height and correlation length
- rms height – standard deviation of surface height
- Correlation length – autocorrelation = (1/e)
- Modeled using
  - Kirchhoff model for large roughness
  - Special case of IEM for small roughness

Volume Scattering

- Media not homogenous – volume scattering
- Scattering and extinction occurs between interfaces
- Volume scattering coefficient computed as sum of contributions of scattering and extinction

$$\sigma_v^o(\theta) = \frac{\sigma_v \cos(\theta)}{2\kappa_e}\left(1 - \frac{1}{L^2(\theta)}\right)$$

- Here σ^0_v is the volume backscattering coefficient, L the loss factor and k_e is the extinction coefficient

Backscattered Power

- Combine scattering coefficients using

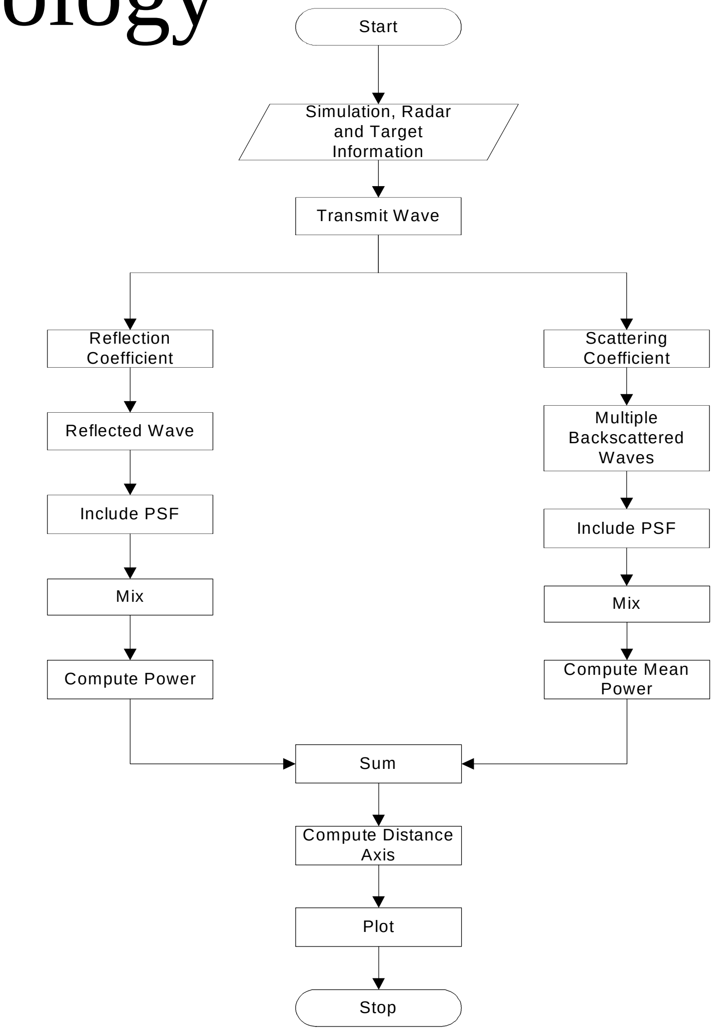
$$\sigma^0(\theta) = \sigma_{ss}^0(\theta) + T_s^2(\theta)\left[\sigma_{sv}^0(\theta') + \frac{1}{L^2(\theta')}\cdot\sigma_{is}^0(\theta')\right]$$

- Here σ_{ss} is the snow surface scattering coefficient, σ_{sv} the snow volume scattering coefficient, σ_{is} is the ice surface scattering coefficient, T_s the transmission coefficient and L the loss factor
- Using this the back scattered power is computed as

$$P_r = \frac{P_t \lambda^2 G^2 \sigma^0 A}{(4\pi)^3 (R)^4}$$

Simulation Methodology

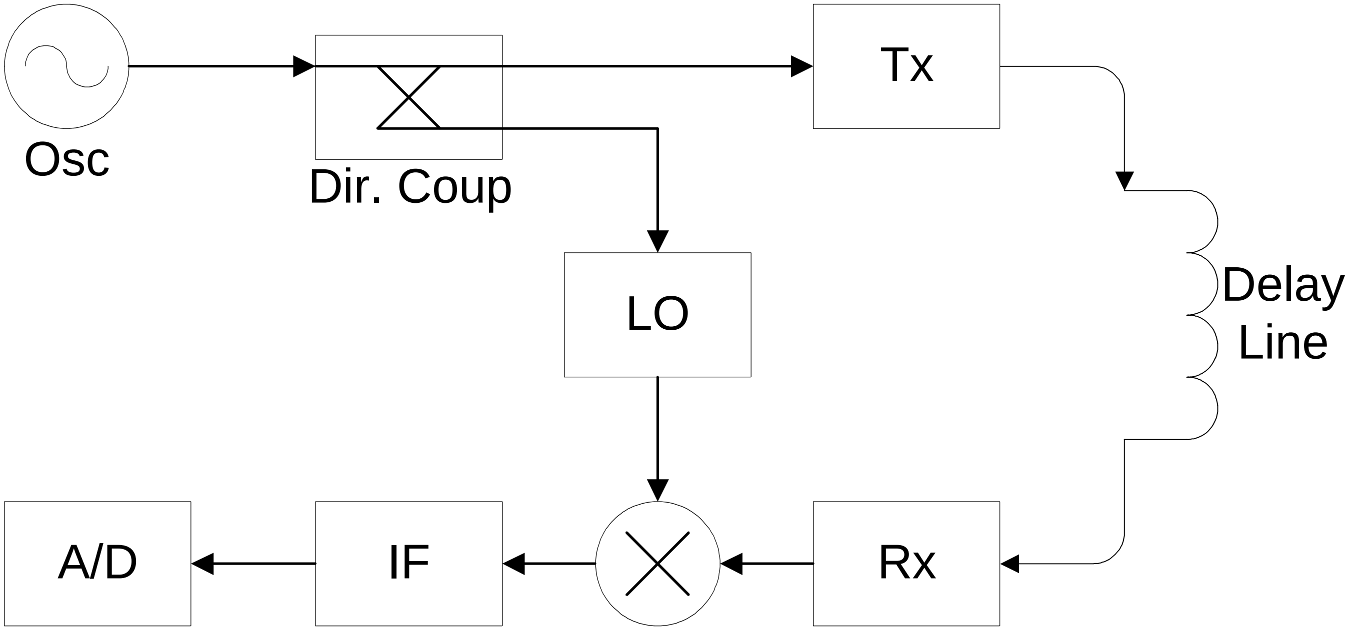
- Generate transmit wave
- Find reflection coefficient
- Determine reflected power
- Find scattering coefficient
- Determine scattered power
- Introduce noise
- Add up powers
- Compute distance axis
- Plot distance vs. Power



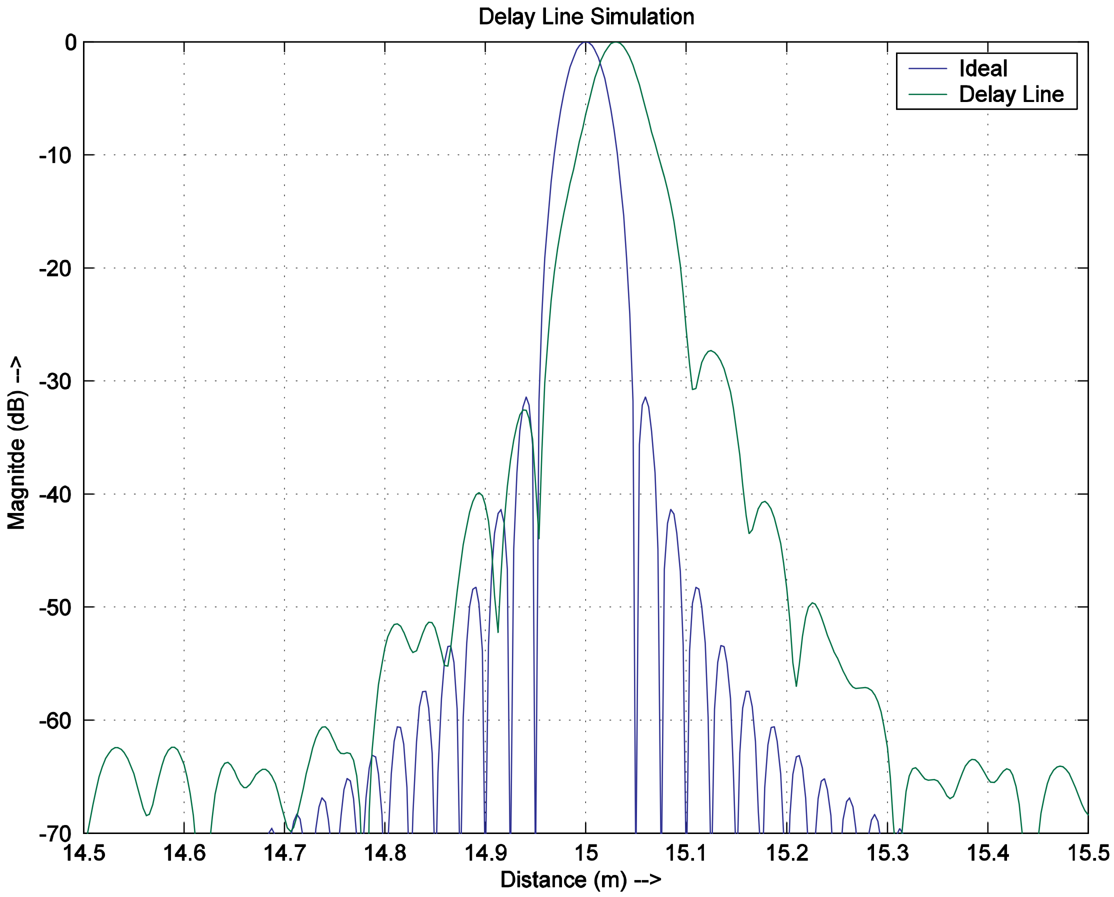
Results

- Delay line simulation and measurement setup
- Delay line simulation results
- Comparison of simulation and measurement
- Snow over sea-ice simulation setup
- Snow over sea-ice simulation results
- Snow over sea-ice measurement setup
- Comparison of simulation and measurement

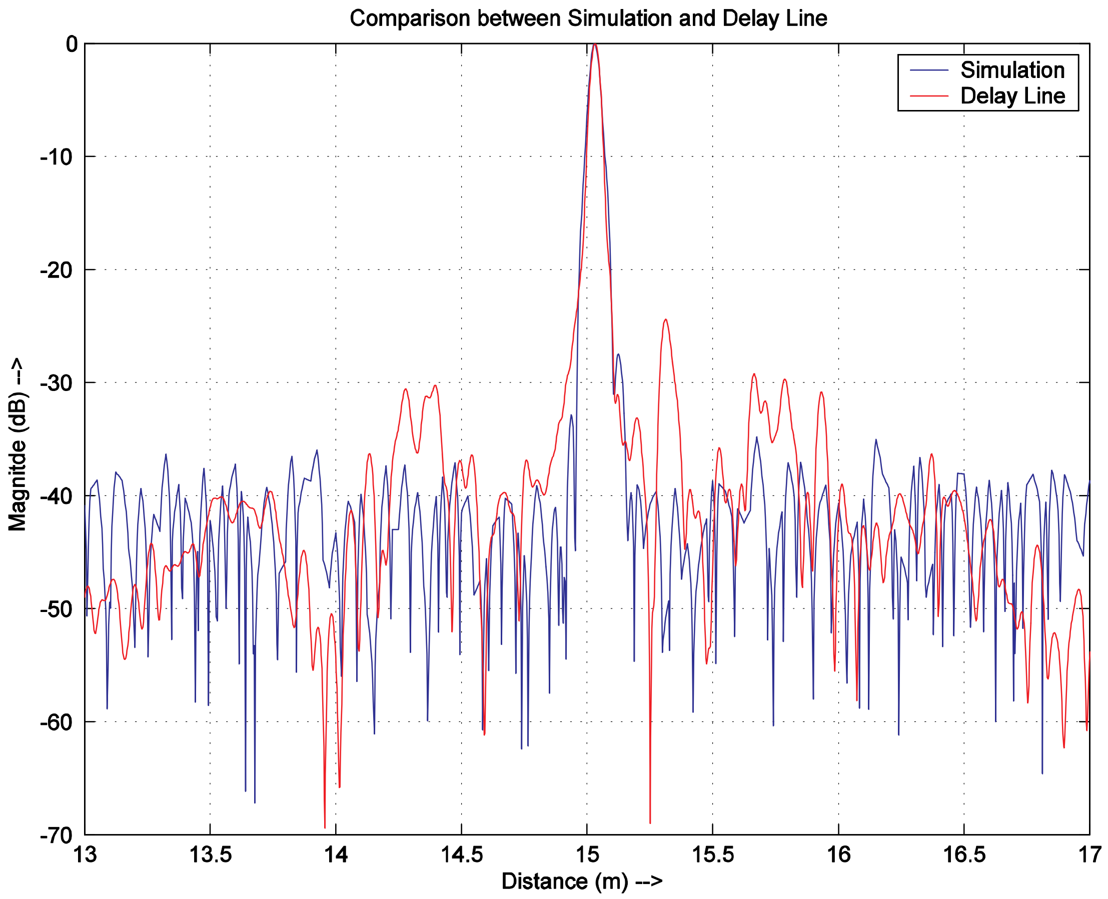
Delay Line Setup



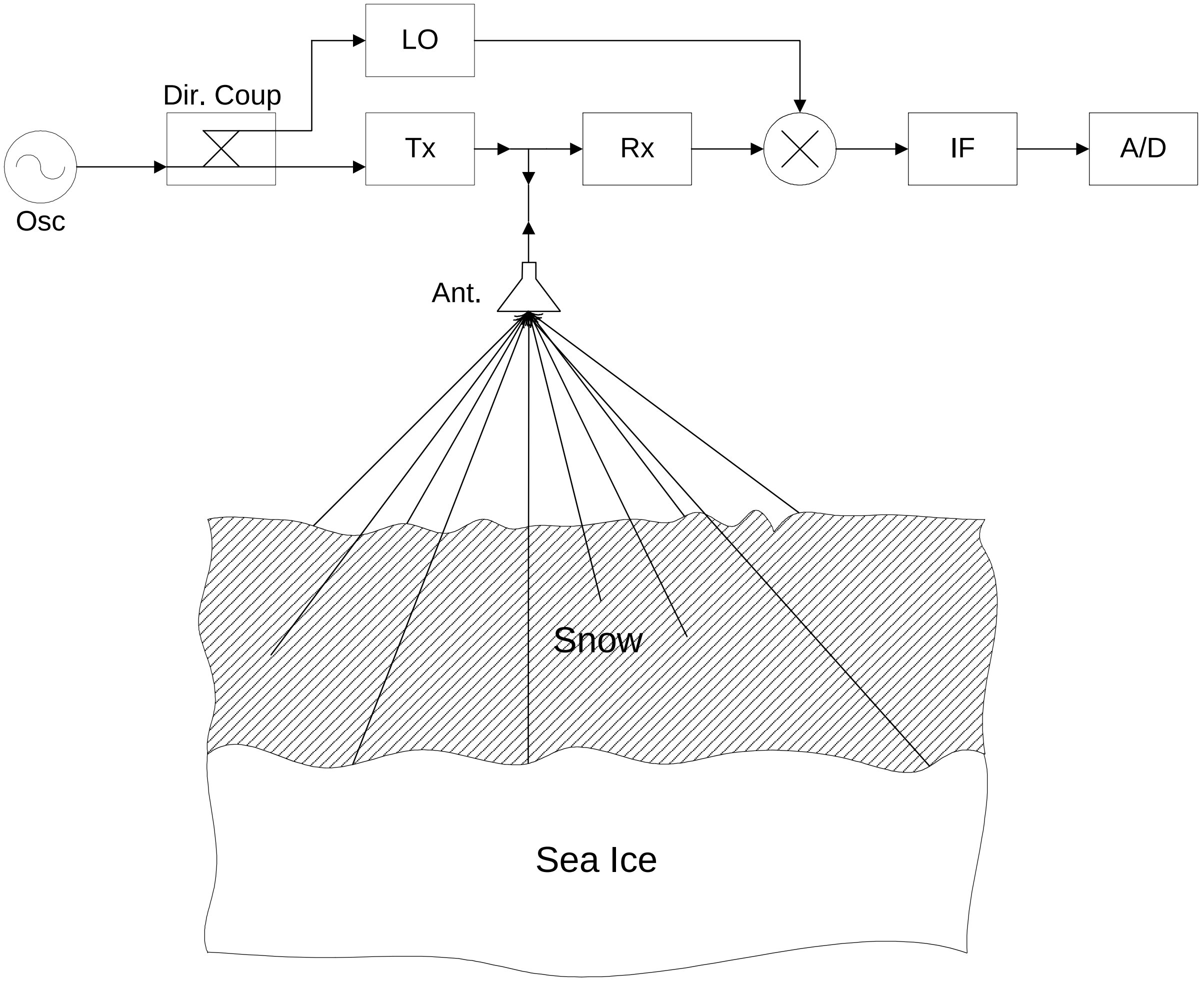
Delay Line Simulation Result



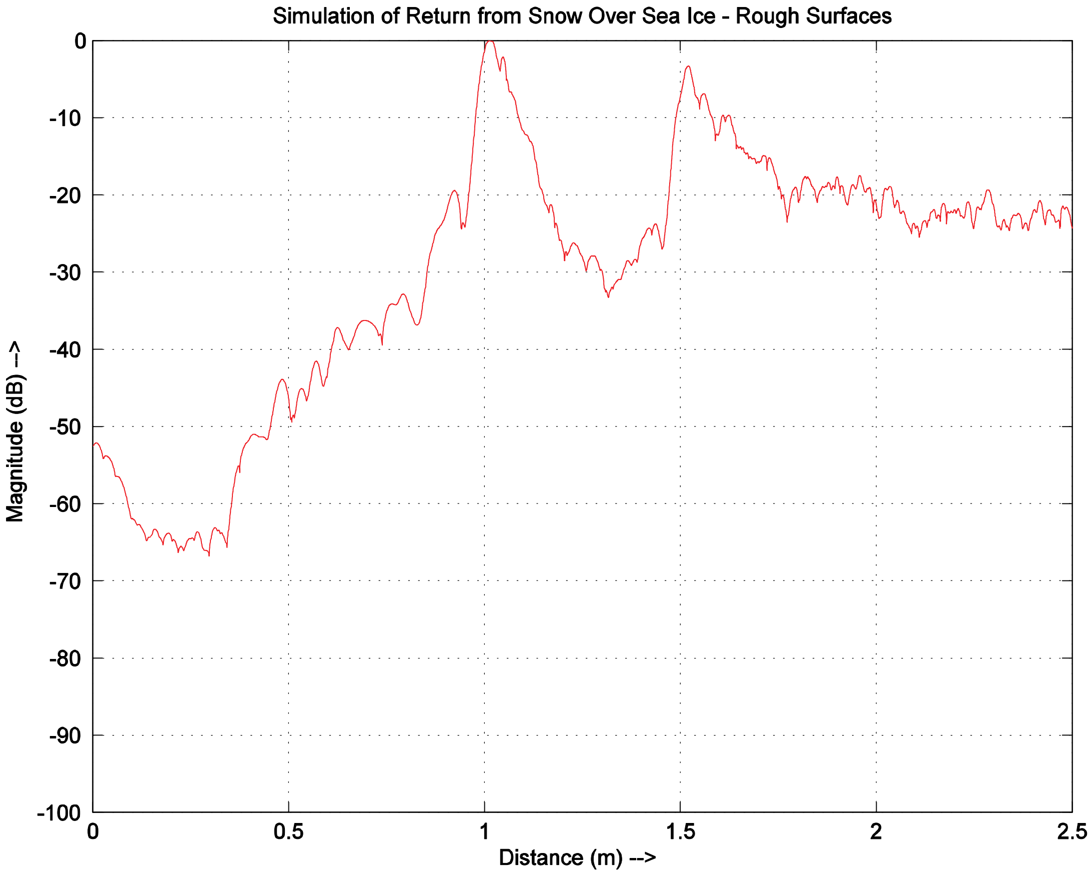
Simulation and Measurement Comparison



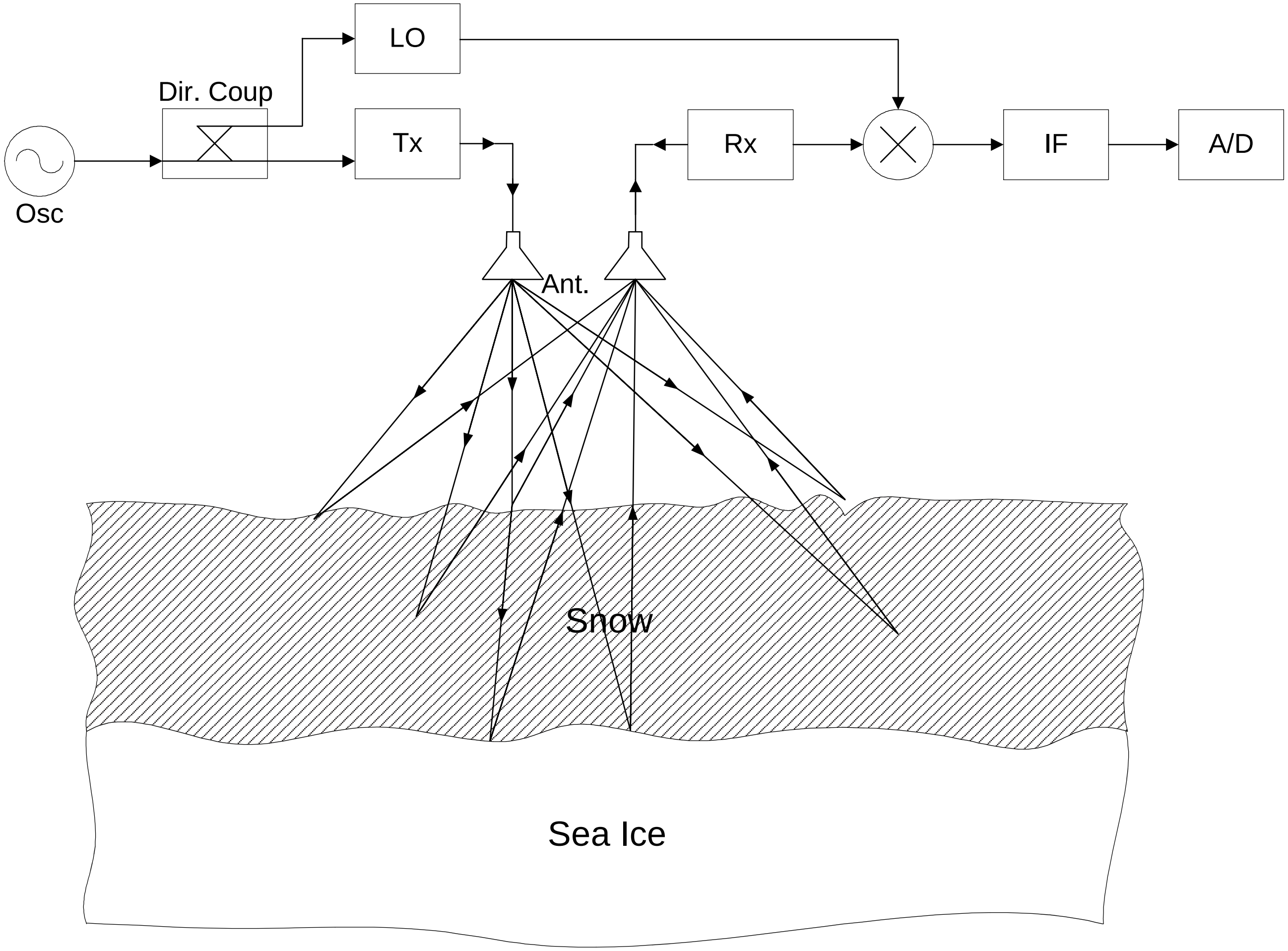
Snow Over Sea Ice Simulation Setup



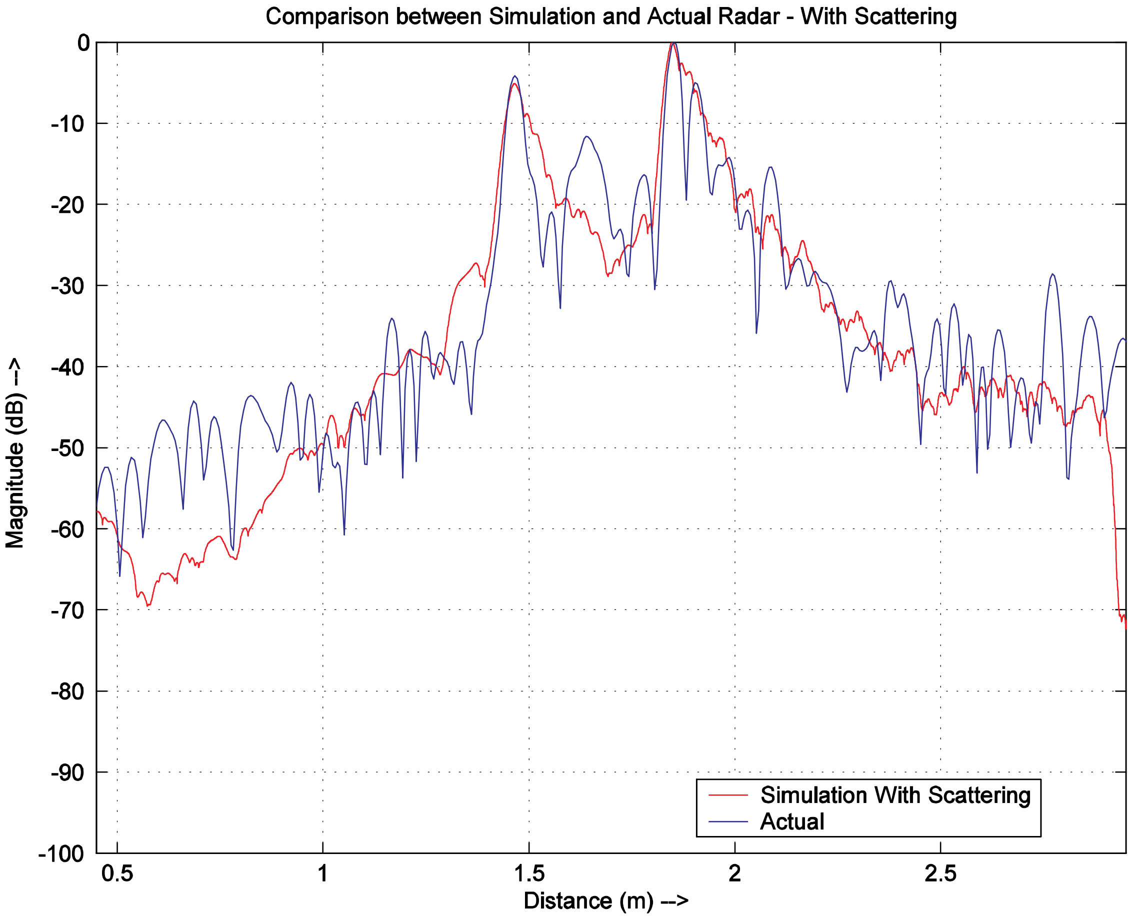
Snow Over Sea-ice Results



Snow Over Sea-ice Field Trial Setup



Simulation and Measurement Comparison



Summary and Future Work

- Simulation of snow radar
  - System model
    - By measurement with source model
    - By calibration
  - Propagation model
    - With surface and volume scattering
  - Results
- Future work
  - IF section effects need to be simulated
  - Deconvolution needs to be applied
  - Forward scattering models need to be included

Questions ??

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