Remote Sensing of Sea Ice Thickness by a Combined Spatial And Frequency Domain Interferometer: Formulations, Instrument Design & Development

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ABSTRACT

The thickness of Arctic sea ice plays a critical role in Earth's climate and ocean circulation. An accurate measurement of this parameter on synoptic scales at regular intervals would enable characterization of this important component for the understanding of ocean circulation and the global heat balance. Presented in this paper is a low frequency VHF interferometer technique and associated radar instrument design to measure sea ice thickness based on the use of backscatter correlation functions. The sea ice medium is represented as a multi-layered medium consisting of snow, sea-ice and sea water, with the interfaces between layers characterized as rough surfaces. This technique utilizes the correlation of two radar waves of different frequencies and incident and observation angles, scattered from the sea ice medium. The correlation functions relate information about the sea ice thickness. Inversion techniques such as the genetic algorithm, gradient descent, and least square methods, are used to derive sea ice thickness from the phase information related by the correlation functions. The radar instrument is designed to be implemented on a spacecraft and the initial test-bed will be on a Twin Otter aircraft. Radar system and instrument design and development parameters as well as some measurement requirements are reviewed. The ability to obtain reliable phase information for successful ice thickness retrieval for various thickness and surface interface geometries is examined.

Keywords: Interferometer, correlation functions, genetic algorithm, sea ice, sea ice thickness measurement

I. INTRODUCTION

Recent studies indicate that the Arctic sea ice cover is undergoing significant climate induced-changes resulting in reduction in ice extent and also a net thinning of the sea ice cover. These changes can have profound impact not only on the Arctic itself but on the global climate system and ocean thermohaline circulation. Thermodynamically, the sea ice and overlying snow cover reduce heat exchange between the ocean and the atmosphere, which strongly impact the ice-albedo effect and the fresh water flux out of the Arctic Ocean. Hence, it is important to continue and improve long-term observations of these changes on broad, synoptic-scales at regular intervals to better understand the role of the sea ice cover in the Global climate system and its utility as an indicator of the climate change [1-6].

Currently, remote sensing instruments such as IceSAT (laser altimeter) and EnviSAT (radar altimeter) and the upcoming CryoSAT (radar altimeter) measurement systems provide estimates of the sea ice freeboard, i.e. that portion of the ice that is above the sea level. The thickness estimates inferred from freeboard have uncertainties due to unknown snow depth and ice density. In this paper, we present a new instrument technology, Cryospheric Advanced Sensor (CAS), developed under the NASA instrument incubator program (IIP) for the remote sensing of sea ice thickness. This technology utilizes a combined spatial and frequency domain interferometric radar, providing angular and frequency correlation functions (ACF/FCF) between two radar waves with slightly differing VHF-band frequencies and incidence and observation angles (Figure 1). The sea ice thickness is derived from the interferometric phase of the ACF/FCF functions [7]-[8]. The use of two narrow band radar signals with slightly offset center frequencies for characterizing the ACF/FCF may alleviate VHF frequency allocation restrictions that preclude the use of very wide-bandwidth radar, e.g. as in wide bandwidth sounding radars. This technique also allows suppression of volume scattering effects (from brine inclusions and air bubbles in sea ice), which can interfere with ice thickness retrieval. The initial prototype radar test-bed has been developed for operation on a Twin Otter aircraft (Figure 2) for technology demonstration, and investigation of the ice thickness retrieval techniques.

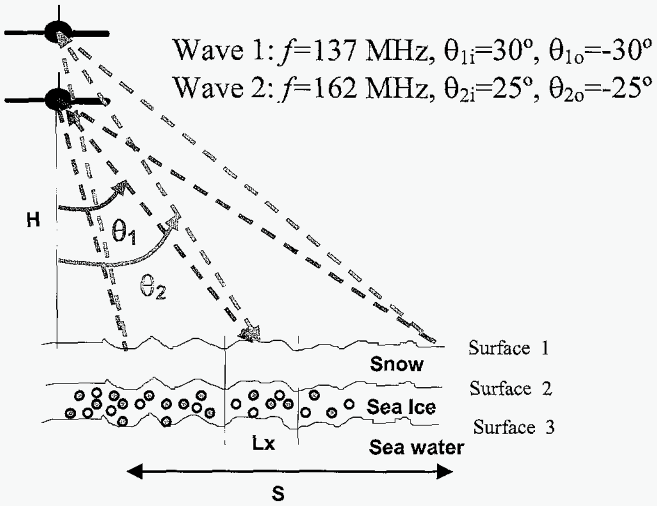


Figure 1. Geometry of combined spatial and frequency domain interferometer. Lx represents the resolution cell, and S the width of the illumination swath.

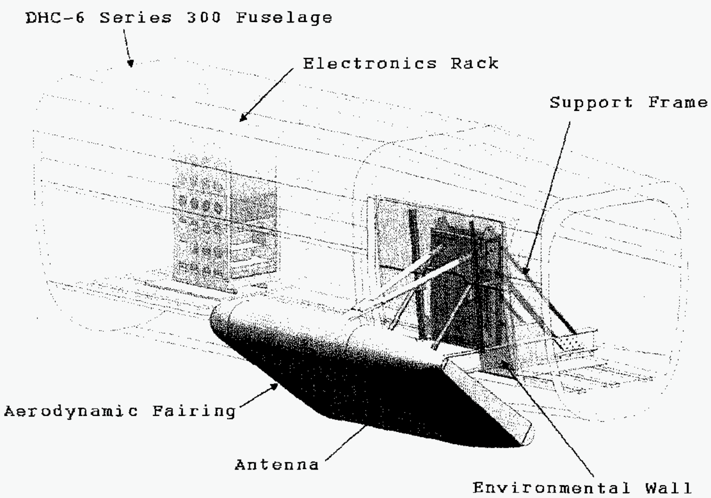


Figure 2. Cryospheric Advanced Sensor (CAS) instrument configuration for technology demonstration on-board a DHC-6 Series 300 Twin Otter aircraft.

II. MODEL

We have derived the angular and frequency correlation functions (ACF/FCF) of the electromagnetic wave scattered from sea ice using small perturbation and Kirchhoff rough surface scattering and Rayleigh volume scattering models (3D geometry). The medium is modeled as multi-layered stratification consisting of snow, sea ice (including spherical particles of air bubbles and brine inclusions), and sea water (Figure 3). The interfaces between layers are modeled as rough surfaces. The characteristics of each layer and surface applied in our calculations are given in Table 1 and 2.

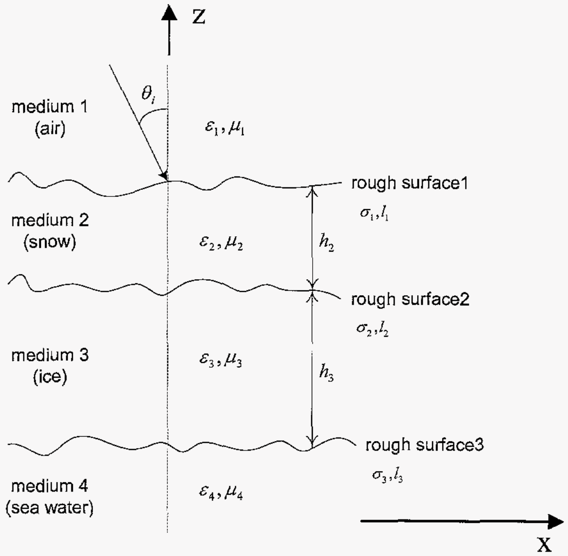


Figure 3. Geometry of the multi-layer model employed for formulating the radar backscatter model.

Table I. Parameters of the background media for parameterizing the backscatter model

	Index of refraction	Layer thickness	Rms Height (cm)	Correlation length (cm)
Layer 1 snow	$\varepsilon_2 = 3.15 - j0.001$	$h_2 = 8cm$	$\sigma_1 = 0.024$	$l_1 = 0.12$
Layer 2 ice	$\varepsilon_3 = 4.0395 - j0.4329$	$h_3 = 2$ m	$\sigma_2 = 0.28$	$l_2 = 1.8$
Layer 3 sea water	$\varepsilon_4 = 57.9 - j39.8$		$\sigma_3 = 0.9$	$l_3 = 24$

Table II. Constitutive parameters of the inclusions within the sea ice layer

	Radius	**Fractional volume**	**Dielectric constant**
Air bubbles	**0.5044 mm**	**4.3%**	**1**
Brine inclusions	**0.1276 mm**	**1.39%**	**60-j40**

The correlation of two fields scattered at different angles and frequencies is given by:

$$\Gamma = \left\langle E_t(\theta,\phi,k)E_t^*(\theta',\phi',k')\right\rangle = \left\langle E_{s1}E_{s1}^*\right\rangle + \left\langle E_{s2}E_{s2}^*\right\rangle + \left\langle E_{s3}E_{s3}^*\right\rangle + \left\langle E_{v1}E_{v1}^*\right\rangle + \left\langle E_{v2}E_{v2}^*\right\rangle \quad (1)$$

where the total scattered waves are a combination of rough surface scattering from all the surfaces and volume scattering from inclusions in the layers (Figure 3). The symbol <...> denotes ensemble averaging, and s1, s2, and s3 denote the rough surface 1 (air-snow), rough surface 2 (snow-ice), and rough surface 3 (ice-seawater). The v1 and v2 denote the volume scattering from air bubbles and brine inclusions, respectively (Figure 3). The parameters (θ,ϕ,k) denote the observation angle of wave 1 with wave number k. Prime quantities are for wave 2. We assume that the volume and surface scattering components are uncorrelated. Thus, the correlation of the scattered waves is the summation of the correlation of the wave scattered from each rough surface and the correlation of wave scattered from the volumes [7], [8]. When the interfaces between layers are smooth relative to the radar wavelength, as is typical for first year ice, the small perturbation method (SPM) is employed to model the contribution of surface scattering processes to the correlation function. Detailed mathematical formulation for the SPM analytical model and expressions for the each term in equation 1 are given in [7] and [8] for the one dimensional and two dimensional models, respectively. For cases where the surface rms height and correlation length are large relative to the wavelength we apply the Kirchhoff approximation for surface scattering [9]. The inclusions in the ice volume are very small compared to the wavelength. Therefore, we apply the Rayleigh approximation for volume scattering [7-9].

III. ACF/FCF RESULTS

There is an important distinction between the rough surface correlation function and the volume scattering correlation function [8]. The rough surface correlation function has a *memory line* feature, while the volume scattering correlation function exhibits a *memory dots* feature. They are the result of the phase matching conditions [8]. The phase of the surface correlation function provides information about the thickness of the layer. Figure 4 shows the results of the ACF/FCF for the two-dimensional SPM model using the following parameters: Wave 1: 137 MHz center frequency with incident angle of 30 degree and observation angle at backscattering direction. ($\theta_{1i} = 30^\circ$, $\theta_{1o} = -30^\circ$, $f_1 = 137$ MHz); Wave 2: 162 MHz center frequency with varying incident angle and observation angle.

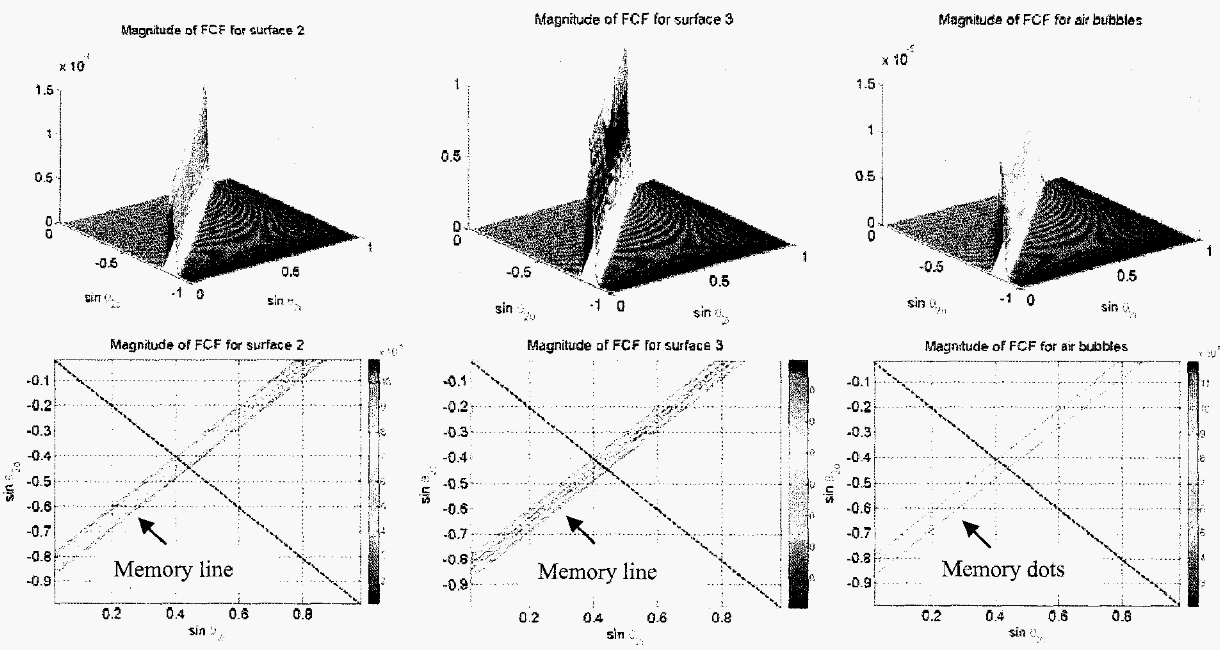


Figure 4. Correlation function for rough surface, top surface 2, middle surface 3, and bottom volume scattering (air bubbles).

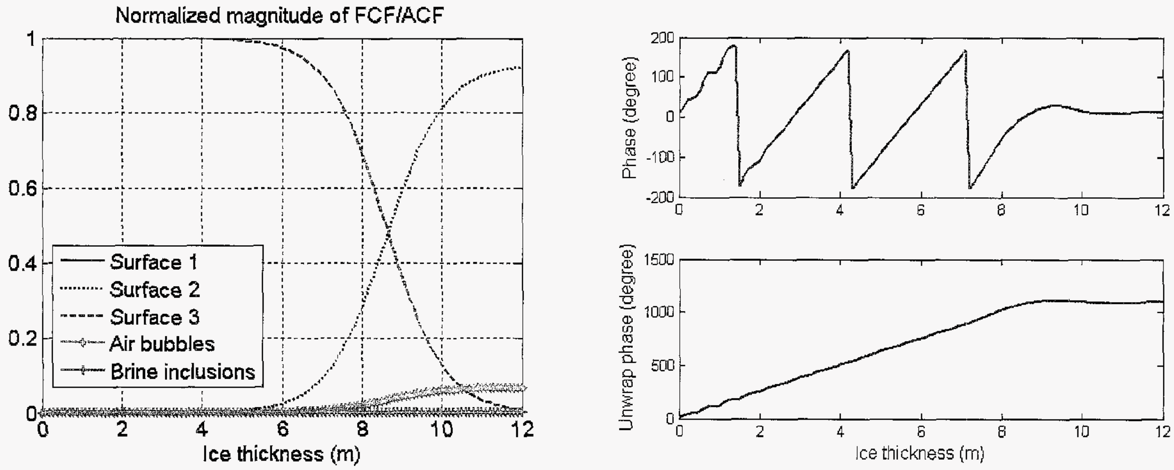
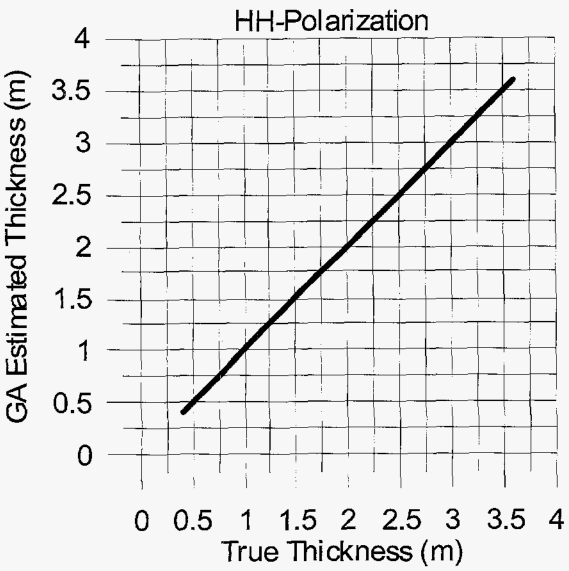


Figure 5. Amplitude (left) and phase (right) of ACF/FCF as a function of ice thickness.

Figure 5 shows the amplitude and phase of the ACF/FCF as a function of the ice thickness. We use correlation of wave one of frequency of 137 MHz, incident angle of 30 degree and observation angle in the backscatter direction, with wave two of frequency of 162 MHz, incident angle of 25 degree and observation angle in the backscatter direction. These frequencies and incident and observation angles lie in the memory line where the effect of the volume scattering is mostly suppressed as shown in Figure 4. Based on this theoretical model, we estimate sea ice thickness from the phase of the ACF/FCF functions. We apply several methods to the sea ice thickness estimation: gradient-descent (GD), least square (LSQ) and genetic algorithm (GA) [7], [8]. Here we present the genetic algorithm results. We employ a Genetic Algorithm [9], [10] to the estimation as a means to maximize a fitness function $fitness = e^{-(\psi_m - \psi(h))^2}$ between the phase of ACF/FCF calculated from the forward model, ψ (h), and the measured phase, ψ_m, of ACF/FCF– in this case the phase is obtained from simulated forward data using this model, and no phase noise is added to it [8]. These results show that the sea ice thickness retrieval can be done by the ACF/FCF method (Table 3 and Figure 6).

Table 3. Genetic algorithm results.

Genration #	True Thickness (m)	GA Estimated Thickness (m)	True Phase (rad)	GA Average Phase (rad)	fitness
24	0.4	0.400152593	0.876806492	0.877050684	0.9999962
18	0.800000006	0.79962157	1.927457852	1.927728711	0.99999496
75	1.200000012	1.199499496	2.961878644	2.960683848	0.99999099
68	1.600000018	1.600695822	-2.652130432	-2.649332636	0.99998884
47	2.000000024	2.000488296	-1.896338547	-1.895077318	0.99999472
83	2.40000003	2.400842311	-0.938707112	-0.937311929	0.99999119
133	2.800000036	2.799523911	-0.055901897	-0.056947825	0.99999488
29	3.200000042	3.198535112	0.7782043	0.775156393	0.99999066
25	3.600000048	3.601806696	1.673959465	1.677228174	0.99998926



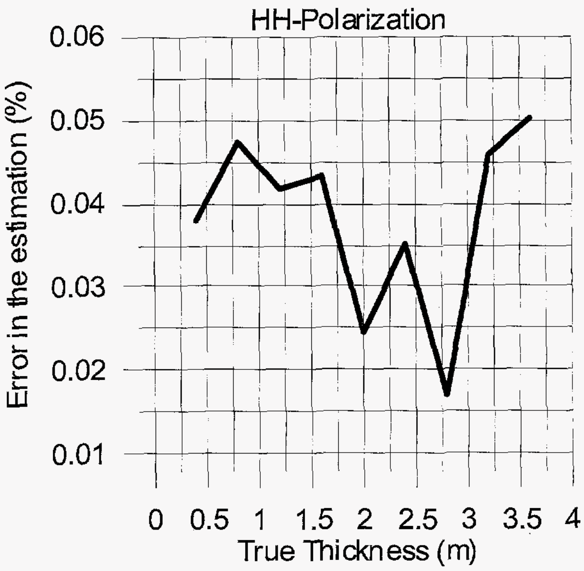


Figure 6. Genetic algorithm estimated thickness versus true thickness (left) and, error of the ice thickness estimation (%) as a function of true thickness (right).

IV. INSTRUMENT DESIGN

We have developed a fully polarimetric flexible field experimental system (FES) that is to be deployed on a Twin Otter aircraft for instrument and field tests over the Arctic sea ice in the coming months, to test the measurement approach and validate and improve the inversion model (Figures 7 and 8). The FES is a chirped pulse radar system that operates in the VHF band. It is capable of an output power of 100 Watts and provides a calibration tone for direct input to the receiver. The receiver combines the return signal with the calibration tone at the front-end. The total receiver gain is adjustable in increments of 1 dB ranging from 39 to 70 dB with a total noise figure of 4.5 dB. A 9-bit, 480 MHz A/D is used to directly sample the received waveform. With the exception of power amplifier and high power switches, the radar hardware is contained within a compact PCI module (Figure 7). A lightweight microstrip antenna with multi-polarization capability and 30% bandwidth has been developed for the FES (Figure 8) for placement outside a Twin Otter Aircraft passenger door [11]. The antenna is surrounded by a fairing to reduce the aircraft drag (Figure 9). The software that controls the system is executed on a single board computer running the Linux operating system.

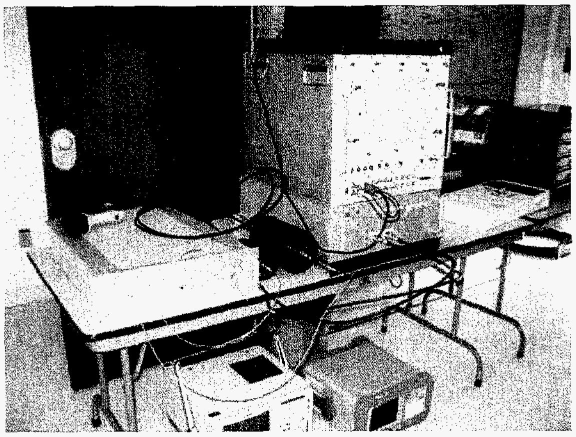


Figure 7. Cryospheric advanced sensor airborne radar

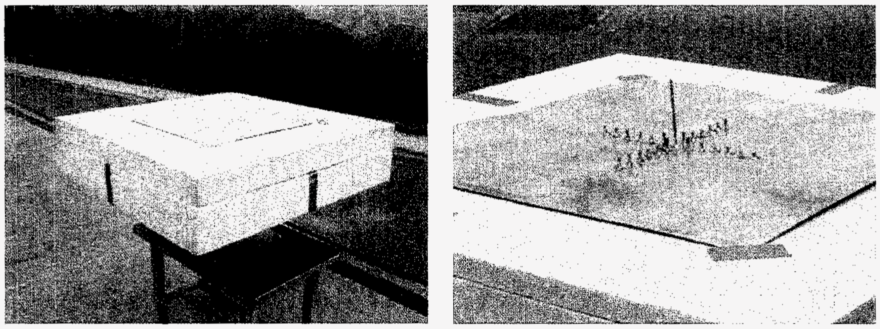


Figure 8. Dual-polarized and broadband lightweight multi-layer VHF (127-172 MHz) microstrip antenna. Left photo is the antenna system with top microstrip patch shown; the right photo showing the bottom patch with the top patch removed.

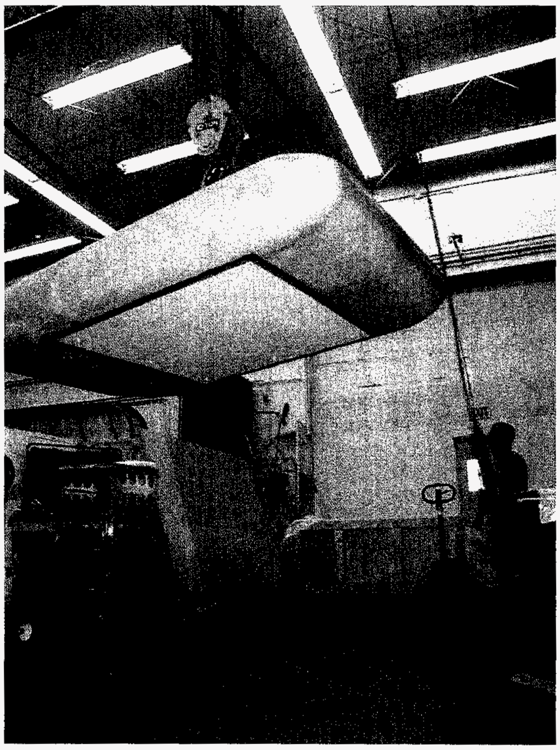


Figure 9. Shown is the fairing and antenna being loaded into a shipping crate. The antenna is covered with a radome and sealed with Kapton to prevent absorption of water.

To demonstrate the sea ice thickness measurement from the proposed combined spatial and frequency domain interferometer instrument, two separate measurements are required from different altitudes (1.0 km and 1.2 km), with measurements being at offset frequencies and correspondingly different incidence angles. The nominal central frequencies for each measurement are 137 MHz and 162 MHz with 20 MHz bandwidth each, and correspond to the following incidence angles (Figure 1): *Wave 1: f=162 MHz, incidence angle of* θ_2 *=25 degrees and observation in the backscatter direction from an altitude of 1.2 Km; Wave 2: f=137 MHz, incidence angle of* θ_1 *=30 degrees and observation in the backscatter direction from an altitude of 1.0 Km* with a measurement accuracy of better than 5 degrees rms phase noise, and a spatial resolution of 15 meters by 15 meters on the sea-ice surface. The radar system will be configured to sweep over the 127 MHz to 172 MHz frequency range in a 5 microsecond interval for each required altitude measurement. The radar data are sampled at a 480 megasample per second. During data processing, the data will be separated into two separate frequency band channels. The FES radar parameters for the 137 MHz and 162 MHz channel are given in Table 3.

Table 3. CAS radar system parameters

Instrument Parameters			
Center Frequency	137	162	MHz
Chirp Bandwidth	20	20	MHz
Altitude	1	1.2	Km
Transmit Peak Power	100	100	Watts
Pulse Duration	2.22	2.22	usec
Transmit Waveform	**CHIRP**	**CHIRP**	
PRF	700	700	Hz
Average Power Radiated	0.155	0.155	Watts
Antenna Radiation Gain	9.0	9.0	dB
Antenna Losses	2	2	dB
Antenna Width	1.1	1.1	Mtrs
Incidence Angle	30	25	Deg
Antenna Length	1.1	1.1	Mtrs
Filtering Losses	1	1	dB
Electronic Gain	70	70	dB
Receiver Noise Temperature	845.5	845.5	DegK
A/D Saturation	-24	-24	dBW
A/D Bits	8	8	Bits
Velocity	46	46	Meter/sec
Sampling Rate (MSPS)	480	480	Msps
Cross Track Resolution	15	15	Meters
Along Track Resolution	15	15	Meters
Number of Looks	7	7	
Boresight Slant Range	1.15	1.32	Km

V. CONCLUSION

We introduce the angular and frequency correlation function (ACF/FCF) method for direct estimation of sea ice thickness. The model illustrated here is a two-dimensional three-layered medium which consists of snow, sea ice and sea water. The surface scattering correlation function is based on small perturbation method and Kirchhoff rough surface scattering model. The volume scattering correlation function is based on Rayleigh scattering model. The sea ice thickness is derived from the interferometric phase of the ACF/FCF functions. Prototype instrument technology has been designed and developed for demonstration of instrument capabilities through a sea ice field experiment conducted on the ocean ice cover.

VI. ACKNOWLEDGMENTS

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