CROME Radar Instrument aboard the COMPASS Mission

Aurélien Fourmault [a], Isaac B Smith [b], The CROME Team
[a] MDA Corporation, 21025 Trans-Canada Highway, Ste-Anne-de-Bellevue, Québec, Canada
aurelien.fourmault@mdacorporation.com, +1 (514) 457-2150 #3513
[b] York University, 4700 Keele St, Toronto, Canada

Abstract

COMPASS is a mission concept aiming to determine the recent climate history of planet Mars. Aboard this mission, there would be a dual mode radar instrument capable of acting both as a Synthetic Aperture Radar (SAR) and a Subsurface Sounder for mapping shallow ice. The COMPASS Radar Observer for Mars Exploration (CROME) instrument would help advance science and exploration. First, the COMPASS mission is described. Then, the CROME instrument concept and its implementation are presented. Finally, the procedure used to predict the performance is detailed for both the Side-Looking SAR and the Nadir-looking Sounder modes.

1 COMPASS Mission

In recognition of the high priority of Mars climate science to the Decadal Survey [1], and more specifically in the Mars Exploration Program Analysis Group (MEPAG) goals document [2], the Climate Orbiter for Mars Polar Atmospheric and Subsurface Science (COMPASS) mission is a proposal to the Discovery competition that addresses many high priority science questions on the subject of the presence of near surface ice by investigating present day atmospheric-ice interactions and inventorying icy deposits across the planet. This mission has not yet been selected.

COMPASS will have a low-eccentricity sun-synchronous 3PM orbit with 93° inclination during its one-Mars-year (2-Earth-years) primary science mission. Such an orbit is naturally concentrated in the ice-rich higher latitudes and provides near-global coverage. An equator-crossing local time of 3PM allows integration of the infrared (IR) sounder and wide-angle imaging data with the legacy datasets of Mars Reconnaissance Orbiter (MRO), Mars Odyssey and Mars Global Surveyor. An orbital altitude of 255–320km enables high-resolution observations and low atmospheric drag over the course of the primary mission.

1.1 Science Context

The COMPASS science goals build upon previous Mars missions and provide an unprecedented new view of the planet's atmosphere, surface, and subsurface. Ice is the key to understanding past climate variations on Mars. Surface and subsurface ices interact with the atmosphere on different timescales and the atmosphere acts as a rapid conduit between these ice reservoirs under changing conditions.

With COMPASS, for the first time a mission will quantify shallow (< 15m) near-surface ice deposits distributed across the globe, and measure their internal layering to place the current climate in the context of past climate variations. Simultaneous measurements of active processes (e.g. winds, clouds, water vapour, dust, and temperature) in the atmosphere and their influence on ice deposits will thus reveal the underpinnings of Mars' recent climate evolution.

1.2 Overview of the Mission Capability

The COMPASS mission will resolve ice layer properties that record historic climate variations on Mars. Atmospheric, surface, and subsurface measurements are taken with four instruments to achieve COMPASS's focused science goals.

1.2.1 Advanced Mars Climate Sounder

The Advanced Mars Climate Sounder (AMCS) is a thermal-IR limb sounder (see **Figure 1**). It will retrieve temperature and abundances of water vapour, dust and condensates globally as a function of height in the atmosphere, to constrain the fluxes of volatiles, dust, and heat between icy reservoirs and the atmosphere.

1.2.2 Wind And Vapor Experiment

The Wind And Vapor Experiment (WAVE) is a sub-millimeter limb sounder (see Figure 1). It will make the first systematic global measurements of winds in the Martian atmosphere. Two antennas observe the limb to retrieve both horizontal velocity components as a function of height. Water vapour and temperature profiles will be retrieved under higher optical depth conditions than suitable for AMCS.

1.2.3 Mars Atmosphere Volatile and Resource Investigation Camera

The Mars Atmosphere Volatile and Resource Investigation Camera (MAVRIC) instrument comprises two wide-angle cameras with multi-band stereo imaging capability (see Figure 1). It will map evolving seasonal frost, clouds and dust storms with daily global coverage. Short-wave IR bands allow the discrimination of CO_2 and H_2O frosts, while multiple visible bands allow discrimination of dust and condensate clouds. Stereo capability allows the tracking of dust and condensate clouds from day to day in three dimensions.

1.2.4 COMPASS Radar Observer for Mars Exploration

The COMPASS Radar Observer for Mars Exploration (CROME) shown in Figure 1 is a dual-mode L-band radar that can be operated as a SAR (default reflector orientation is 40° off nadir) or as a Sounder (spacecraft roll points the beam to nadir).

In SAR mode, CROME will gather near-global SAR data at 60 and 30m horizontal resolution to locate shallow ice deposits in polarimetric mode. Higher resolution modes (better than 10m) with be used for identifying smaller features and for tracking surface changes with Interferometric SAR (InSAR).

In Sounder mode, CROME will characterize sub-meter scale vertical layering within ice deposits on Mars. At an order of magnitude higher vertical-resolution, a much smaller footprint and with shallower near-surface layer detection capability than MRO's SHAllow RADar (SHARAD) [3], these sounder data will allow the detailed correlation of stratigraphic beds with oscillations of Mars' obliquity and orbit and detection of the top of the ice table shallower than 15m.

Figure 1 AMCS Thermal-IR Sounder Overview (Top Left), WAVE Sub-mm Sounder Overview (Top Right), MAVRIC Camera Overview (Bottom Left), CROME Instrument Overview (Bottom Right)

2 CROME Instrument

CROME Instrument consists of a multi-polarization L-band SAR/Sounder Radar Instrument illuminating a six-meter diameter deployable mesh reflector procured from Harris®. CROME Feed Array is located on the COMPASS spacecraft deck facing the parabolic reflector antenna (see **Figure 2**) while CROME Radar Electronics boxes are mounted on the Nadir deck.

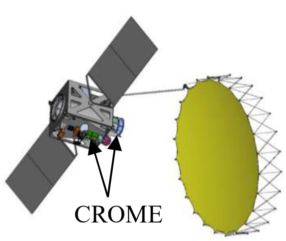

Figure 2 COMPASS Spacecraft Overview with deployed Perimeter Truss Reflector

2.1 CROME Requirements & Capabilities

In order to support the COMPASS mission science objectives, the CROME Instrument needs to include the capability to act as a SAR or a Sounder. Both pulsed modes of operation require flexibility in the instrument configuration such as variable or selectable Pulse Bandwidths, adjustable Receive Echo timing as well as Pulse Repetition Frequency (PRF) with varying ground incidence angle achieved by Spacecraft motion.

The CROME Instrument has the ability to store and process the data generated by the radar for transmission to Earth and includes the facility to identify when the data were collected to allow the final image product to be areo-located. The CROME instrument is multi-polarization capable with Hybrid Compact-Polarimetry implementation in order to allow scientists to assess the Coherence Backscatter Opposition Effect (CBOE) typical of ice backscatter, as well as applying various Science techniques to identify ice layers. A summary of the CROME Instrument capability is provided in **Table 1**.

Multiple SAR modes are available. The instrument can transmit in HP, VP, or CP and receive HP, VP, or HP+VP. This permits the design of various investigations and surface material characterization. The PRF can be adjusted to maintain the correct transmit-receive timing to account for spacecraft altitude variations.

The Sounder operates in two modes. The default mode is to transmit and receive in one of two polarizations, VP or HP. A second mode transmits CP and receives both orthogonal linear polarizations; a form of compact polarimetry. Compact polarimetry provides an additional "look" at the reflections from the surface and subsurface and enables circular polarization for transmit and receive both in co-pol and cross-pol to be synthesized. Opposite hand circular polarization has the potential to improve identification and mitigation of some off-nadir clutter returns. In Sounder mode, the required average power is generally lower than the SAR mode as backscatter is higher at normal incidence. The return echo duration in sounder mode (receive and record window) is relatively short and when combined with the pulse duration, corresponds to the upper 1km in low permittivity materials such as CO_2 ice. The radar design provides the flexibility to adjust the echo sampling times (range-gate) as well as the transmit pulse duration to record returns only in the upper 1 km of the subsurface. Data volume is reduced by not collecting noise above the surface.

Table 1 CROME Radar Instrument Parameters

Parameter	*Capability*
Center Frequency	930 MHz
Resolution Bandwidth (RBW)	SAR: Up to 100MHz (Selectable) Sounder: Up to 160MHz (Selectable)
Tx Polarization	HP (Horizontal Pol.) or VP (Vertical Pol.) or CP (Circular Pol.)
Rx Polarization	HP and VP
Peak Tx RF Power	1kW HP (Horizontal Pol.) 1kW VP (Vertical Pol.) 2kW CP (Circular Pol.)
Pulse Length	10 - 40 µs (Selectable)
Tx Duty Cycle	Up to 15%

The nominal SAR operating mode is Stripmap, with ground incidence changed by rotating the platform. Spotlight imaging is envisaged for extended mission phases by steering the platform during an imaging period. CROME will gather data for generating various multi-looked image products with examples presented in **Table 2**.

Table 2 CROME Image Product Examples

Data Product	*Resolution*	*Looks #*	*Geometry*
SAR Multi-Looked Wide Swath, Medium Resolution Product	30-60m	10	Swath: 25-35km
SAR Multi-Looked High Resolution Product (Spotlight)	6m	8	Spot size: 25-35km (width) x 15-22 km (length)
Sounder Multi-Looked Profile Product	1m Vertical after Range Migration; 30m Along-Track	8-64 (Selectable)	Subsurface Profile

The Instrument will be calibrated both radiometrically and polarimetrically. Radiometric calibration considers changes in the instrument that will affect the accuracy of any backscatter measurements. This calibration will use a previously characterized distributed target (similar to what was done for SHARAD). Identification of a suitable distributed target area for the relative radiometric calibration will use a combination of SHARAD, MARSIS [4], and Arecibo surface-reflectivity maps [5]. This known backscatter model will be used to generate a calibration correction factor that will be applied to images of other areas.

The absolute radiometric level normally requires a point target with known reflectivity to act as a reference. As such a target is unavailable on Mars, COMPASS will use the reflectivity maps mentioned above to act as the absolute reflectivity reference. Note that the sounder mode can be used for calibrating the instrument transfer gain for absolute calibration purposes.

Polarimetric calibration will be limited to a relative correction offset between the hardware channels in the instrument using a flat area of the planet's surface in the sounder mode of operation. Performing measurements by transmitting with VP and then HP, and receiving on both polarizations, the surface return can be used to determine the channel imbalances for the four combinations and will be applied as correction factors in both Sounder and SAR modes.

2.2 CROME Instrument Concept

Considering feasibility, complexity and performance with respect to the desire measurement objectives, the concept of operation has been designed to be as simple as possible. The operation of CROME Instrument is planned to be controlled by the Spacecraft. CROME includes a real time clock that can be synchronized to the mission time by command from the Spacecraft.

An imaging session is executed by loading a settings table into the Radar Electronics (part of the CROME Instrument) that defines Start Time, End Time, Pulse Bandwidth, Transmit Pulse Length (TPL), Echo Start Time, Echo Duration, Receiver Filter selection as well as Block Adaptive Quantization (BAQ) compression setting.

The SAR antenna concept is to have a single beam used for both SAR and Sounder modes. The CROME Instrument comprises a Feed Array illuminating a deployable parabolic reflector (see **Figure 3**)

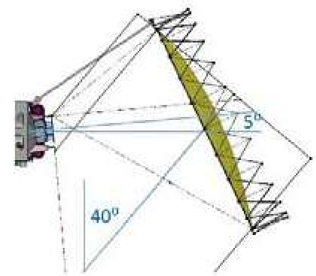

Figure 3 CROME Single-Offset Reflector-based Antenna Geometry, in Standard Flight Mode

The Radar Electronics contains all hardware necessary to implement the major functionality of the CROME Instrument: Timing Control, Pulse waveform generation with selectable duration & bandwidth, Radar echo digitization and filtering with interface to the communication subsystem.

The CROME Instrument will handle some on-board processing for low resolution SAR image generation, performing Range Compression and Sounder along-track incoherent integration followed by BAQ compression (2 to 8 bits) with packetization.

2.3 CROME Instrument Implementation

A top-level block diagram of the CROME Instrument is shown in **Figure 4**. The CROME Instrument comprises the Feed Array (with radiating elements, power dividing network, Tx/Rx active units) and the Radar Electronics (Prime + Redundant) with the Reflector. The 6m diameter reflector provides a nominal 3dB beamwidth of about 3.5° suitable for the imaging scenarios for a mass of ~30kg.

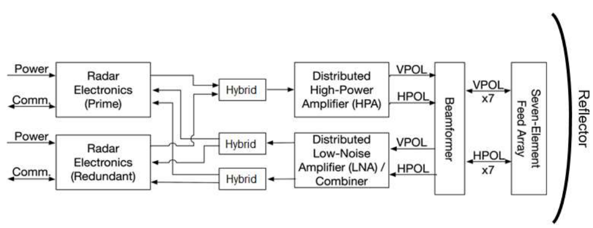

Figure 4 CROME Top-Level Block Diagram

The Feed Array comprises 7 Dual-polarized L-band elements. The Feed Array sub-assemblies are built as an integrated Radio Frequency (RF) assembly that contains the transmit and receive amplifiers with Electric Power Converters (EPC) and RF combiners/splitters mounted directly behind the feed array as shown on **Figure 5.** The overall mass of the Feed Array is ~125kg.

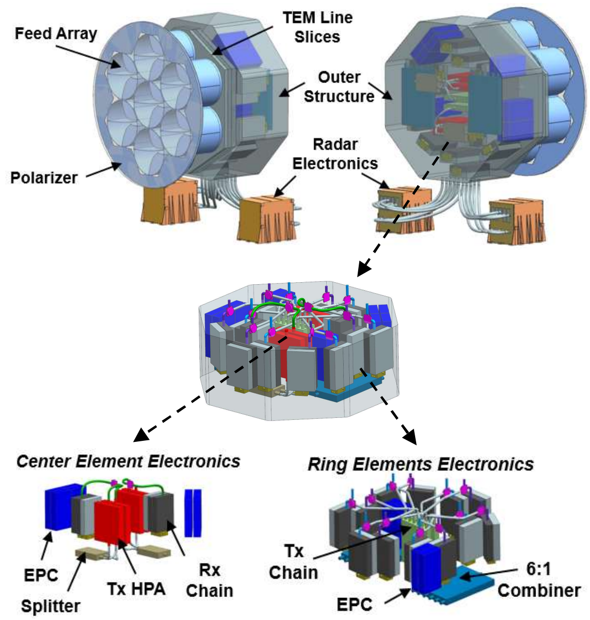

Figure 5 CROME Feed Array

The Radar Electronics are separate redundant units. The Radar Electronics implementation is divided into 5 hardware modules: the Pulse Generator, the Power Amplifier, the Receive Processor, the Local Oscillator / Intermediate Frequency (LO/IF) Conditioning and Electronic Power Conditioning. Each of these modules are interconnected as required via coaxial cables for RF signals and multi-pin harnesses for digital/power connectivity. Radiation requirements are met using radiation tolerant parts. The redundant system exhibits a mass of ~20kg in total.

3 CROME Performance Modeling

The purpose of modeling is to verify that the Instrument will satisfy the science objectives (understanding ice deposits geographic distribution, thickness, composition, depth, extent, spacing, etc.). There are 3 major modeling steps accomplished.

First, an Instrument model based on concept/hardware capability is built considering the antenna model with Feed Array properties and Radar Electronics parametric functionalities.

Then, nominal Imaging and Sounding scenario models are built with surface material properties and characteristics as well as subsurface layers with boundaries, thicknesses, geometry, etc. The Surface and Subsurface constituents are assumed to be stratified in superimposed homogeneous layers of various composition (following the radius of curvature of the planet). The SAR imaging scenario model is presented in **Figure 6**. Reflection and transmission coefficients are evaluated at each interface. Attenuation is computed through each layer.

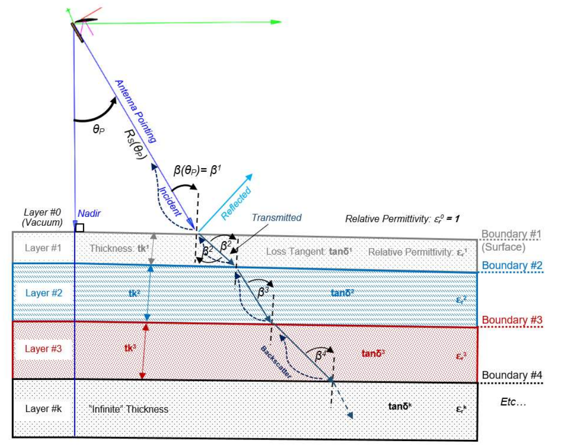

Figure 6 SAR Imaging Scenario Model

The Sounder imaging scenario model is presented in **Figure 7**. For now, the backscatter is assumed to be specular with no volumetric scattering or diffuse reflection. Attenuation and delay are computed through each layer. Subsurface power reflection coefficients are evaluated at each interface.

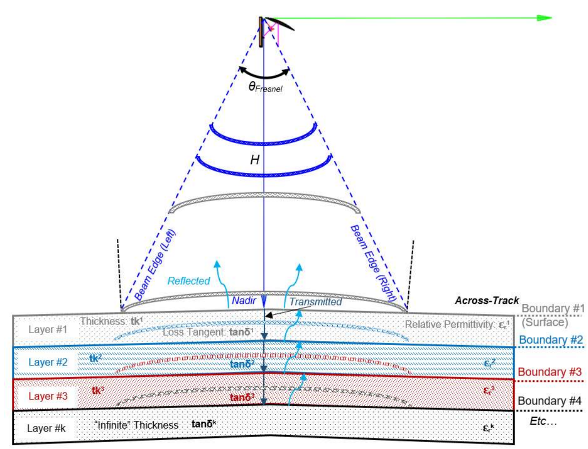

Figure 7 Sounder Imaging Scenario Model

Finally, the Instrument performance is simulated for both operation modes in terms of SAR sensitivity (NESZ/SNR), Sounder subsurface penetration capability (SNR) as well as other evaluations including resolutions, ambiguities, clutter, etc. In order to understand the effect of subsurface backscatter combined with reflection and attenuation properties, an equivalent surface backscatter model is derived accounting for any subsurface impact, dependent on all the layers located above the subsurface of interest.

4 CROME Performance

The SAR mode sensitivity is expressed by the Noise Equivalent Sigma Zero (NESZ) which is the normalized scattering cross-section coefficient (σ_0) resulting in a Signal-to-Noise Ratio (SNR) of 0dB for an area of distributed targets. This 0dB SNR is selected as being the detection level in this mode. The lowest bandwidth can be used to achieve better NESZ where range resolution is not the driver. Conversely, the highest bandwidth can be used when resolution is of most concern, and NESZ is less of a concern. For the Sounder mode, a SNR threshold of 10dB is selected. Generic performance parameters for the Radar are shown in **Table 3**.

Table 3 Generic Performance Parameters

Performance Parameters	*SAR Mode*	*Sounder Mode*
Image Point Incidence Angle	35° to 50°	0° (Nadir)
NESZ Min. / Goal	-30dB / -35dB	N/A
Min. SNR *	0dB	10dB
Range Ambiguity Ratio	< -25dB	N/A
Azimuth Ambiguity Ratio	< -20dB	N/A
Min. Signal-to-Clutter Ratio**	N/A	10dB**

** Scenario dependent*

*** Clutter modeling under development*

The following Instrument performance is computed considering a 320km altitude around Mars (~3400m/s Spacecraft orbital velocity) with a System noise temperature around 600K and a low atmospheric loss, typically 0.5dB to account for Mars ionosphere absorption and scintillation impact at L-band frequencies.

4.1 CROME SAR Mode Performance

For a surface imaging case at the lowest incidence (35° per Table 3) and minimum swath (SW) of 25km (per Table 2), a low transmit duty cycle (of 7%) is sufficient to meet the minimum NESZ performance required across the selectable resolution bandwidth of Table 1 in SAR mode for surface returns. **Figure 8** is showing the performance results with selected TPL and PRF values. Single-Look resolutions are about 30m with 10MHz bandwidth, down to 3m with the full 100MHz bandwidth. Ambiguity performance meets the requirements with comfortable margin.

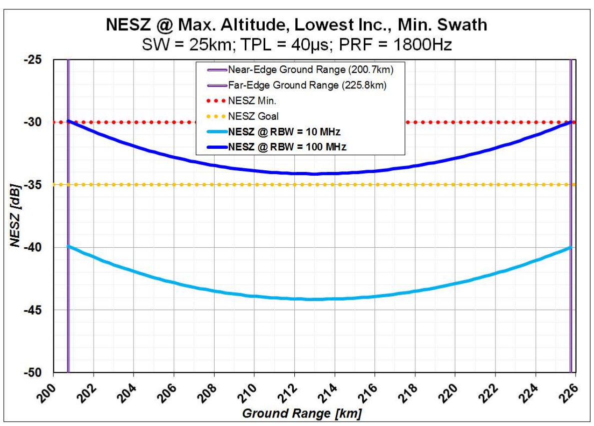

Figure 8 NESZ @ Max. Alt., Lowest Inc., Min. Swath

A similar surface imaging case with highest incidence (50° per Table 3) and maximum SW of 35km (per Table 2) would require a transmit duty cycle of 14% for similar performance.

A multi-layer case is considered in **Figure 9** where a 50m thick slab of water ice sitting on the bedrock is located beneath 0.5m of dust. With the nominal CROME look angle of 40° as shown in Figure 3 and the set of parameters identified on the figure, the SNR for a HH polarization selection is computed across the wide swath. The surface dust and the dust-ice interface returns are strong enough to be detected (SNR above 0dB) while the bedrock interface returns are below the detection threshold.

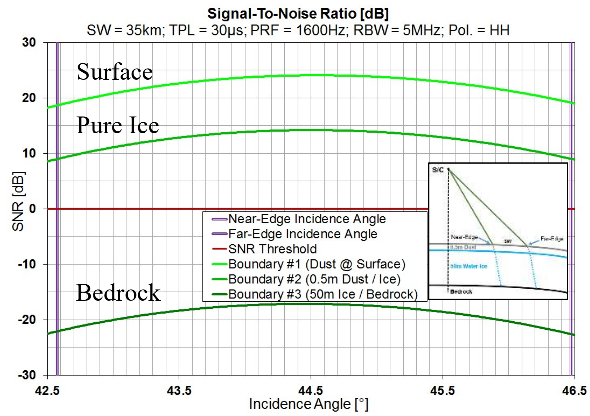

Figure 9 Modeled SNR (HH) of 50m Thick Water Ice beneath 0.5m of Dust

The backscatter being affected by the roughness and the polarization, **Figure 10** is showing the maximum depth (beneath dust) for ice-table detection as a function of ice roughness (expressed by its root mean square (RMS) slope) with the same operational parameters.

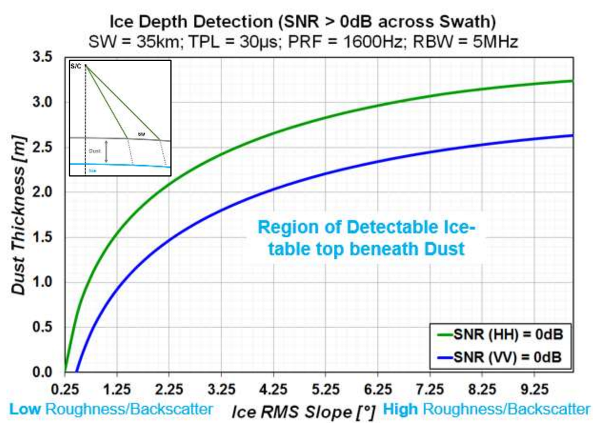

Figure 10 SAR Mode Ice Depth Detection below Dust

4.2 CROME Sounder Mode Performance

For the Nadir-looking Sounder, it is possible to select 1 or 2 Tx/Rx channels (HP, VP or both). Using a large pulse bandwidth helps improve the vertical resolution. During operation, echo traces are recorded and a selectable pre-summing is performed (from 1 to 64 traces) to increase SNR. Range compression is performed with suitable weighting functions for sidelobes reduction at the cost of decreased resolution cell.

Another multi-layer case is considered in **Figure 11** where a 40m thick slab of ice sitting on the bedrock is located beneath 2m of dust. Sounder parameters used are indicated on the figure. The processed SNR Radargram time scale is normalized to surface return and accounts for the 2-way delay. The performance is affected by the subsurface layers thickness and the material properties (loss tangent, dielectric constant). Although the performance is theoretical, it is noticeable that the various interfaces appear distinctly on the figure above sidelobes and the noise threshold. The dust-ice interface is close to surface causing the return to merge with the surface impulse response which indicates that this transition cannot be detected if the dust layer is too thin using high sidelobe suppression. If the dust thickness over the ice is smaller than the compressed range resolution then the interfaces cannot be resolved. Data sent back to earth will be processed using different windowing functions in order to maximise sidelobe suppression or range resolution, in order to detect both the upper and lower boundaries of the ice table.

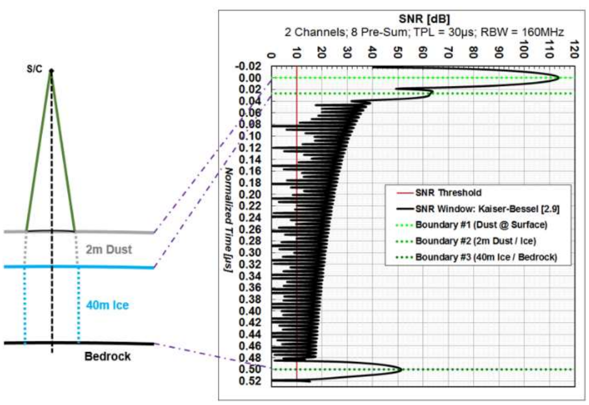

Figure 11 Sounder Mode Dust-Ice Scenario with Processed Radargram

Determining the depth to buried ice is a major goal of COMPASS. The shallowest detectable ice depth varies with ice dielectric constant. The minimum detection depth is limited by the resolution cell (main beam) and the contrast between dust and ice. **Figure 12** provides this minimum detection depth (dust thickness) to ice layer as a function of ice dielectric constant. Targeting porous dust covering ice, simulations show that the data are not noise limited and that ice table depths as shallow as 0.5m are detectable except in a narrow range of cases where dirty ice has an equivalent dielectric constant to the overlying porous dust.

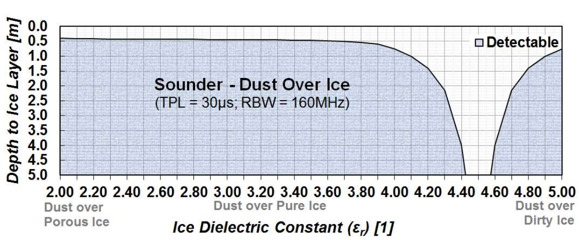

Figure 12 Sounder Mode Ice layer detection below Dust

It is also important to evaluate the penetration capability of the Sounder signal through ice as it depends of its burial depth beneath dust. The configuration is similar to the one in Figure 11 with variable dust and ice thicknesses. The ice slab is sitting on the bedrock. Simulated sounder radargrams were range compressed using Kaiser-Bessel windowing. An algorithm developed in house has been used for the for ice-bedrock boundary detection process amongst sidelobes (from surface and dust/ice interfaces impulse responses). **Figure 13** is showing results for either porous, pure or dirty ice (referring to Figure 12) beneath a dust layer thickness varying between 0.25m to 3.25m.

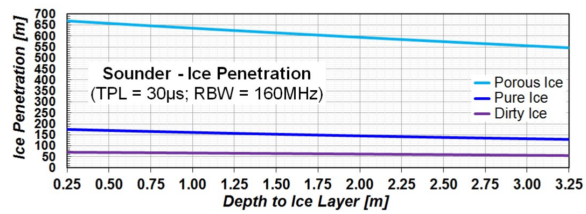

Figure 13 Sounder Mode Ice Layer Penetration

For dirty ice, the Sounder capabilities exceed 50m across the range of dust thickness. Where pure ice buried by a few meters of dust, capabilities exceed 100m. This performance exceeds COMPASS requirements.

5 Acknowledgment

The Canadian Space Agency (CSA) would provide the radar instrument for the mission. MDA Corporation would be the instrument supplier to the CSA. The authors would like to acknowledge the participation of the CSA in the development through Government of Canada sponsorship and to the COMPASS Team for their contributions.

6 Literature

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