Comparison of Digital Beamforming Techniques for Enhanced Ice Sounding Radar Data Processing

Rolf Scheiber German Aerospace Center (DLR), rolf.scheiber@dlr.de, Germany
Pau Prats-Iraola German Aerospace Center (DLR), pau.prats@dlr.de, Germany
Matteo Nannini German Aerospace Center (DLR), matteo.nannni@dlr.de, Germany
Michelangelo Villano German Aerospace Center (DLR), michelangelo.villano@dlr.de, Germany
Keith Morrison Cranfield University, k.morrison@cranfield.ac.uk, United Kingdom
Nico Gebert European Space Agency (ESA), nico.gebert@esa.int, The Netherlands

Abstract

Ice sounding radar from high altitudes is compromised by off-nadir ice surface reflections (clutter), which overlays the nadir signal of interest originating from the bedrock and/or internal ice layers. Multi-aperture antenna radar systems were developed to mitigate the impact of surface clutter allowing spatially variant digital beamforming (DBF) processing of the data received from the individual spatially separated apertures. This paper investigates four different beamforming algorithms: conventional beamsteering, nulling of clutter angles, optimum beamformer and the MVDR beamformer. Comparisons are performed based on simulations for an airborne ice sounding scenarios. In addition, real echograms are computed from data acquired by the P-band POLARIS sensor. Relevant conclusions are drawn with respect to the implementation of a future space-based ice sounding mission.

1 Introduction

Recently, new airborne ice sounding radar systems were extended to include multi-aperture antenna systems. On the one hand multi-channel data allow for the suppression of surface clutter signals and on the other hand the extension from profile depth measurements towards the swath mapping of the ice bed. Ice sounding tomography has first been demonstrated in [5] using 12 and 16 virtual antenna phase centers with a 150 MHz radar of CReSiS/Kansas University. An upgraded radar, MCoRDS/I operating at 195 MHz with a 5 antenna array has been used in [4] to demonstrate improved surface clutter cancellation by means of an adaptive MVDR beamforming technique for profile measurements. In parallel ESA and DTU developed the POLARIS system at P-band [1], aiming at investigating the feasibility of ice sounding from space. The radar antenna has been extended in 2011 to operate with four spatially separated apertures cross-track and first surface clutter suppression results were reported independently in [2] and [3], employing the optimum beamformer (OBF) and maximum likelihood (ML) approach, respectively. The importance of knowing and/or estimating the ice surface topography has been discussed in these contributions.
In this paper POLARIS data are employed to compare clutter nulling, optimum beamformer and MVDR techniques, all of them aiming for improved profile measurements. The ASTER GDEM and a preliminary TanDEM-X digital elevation model of the test area Jutulstraumen glacier, Antarctica, are used as input for the clutter nulling and OBF techniques. Section 2 presents the different beamforming techniques and discusses their properties. Simulation results for the airborne geometry are shown in section 3 and POLARIS results on a track acquired over sloping ice surface in cross-track direction are discussed in section 4. Section 5 summarizes some implications for a potential spaceborne ice sounding mission at P-band.

2 Digital Beamforming Algorithms

This section briefly describes the characteristics of the adopted beamforming algorithms for ice surface clutter suppression.

2.1 Conventional Beam Steering

Beam steering is implemented as simple relative phase shifts applied to the antenna array elements in across-track direction. The aim is to synthesize a narrower beam pointing towards nadir. It thus considers and compensates for roll variations of the aircraft. The complex weights for antenna aperture i are computed as:

$$w_{BS}(i) = \exp(2\pi/\lambda \cdot i \cdot d \cdot \sin\rho), \qquad (1)$$

where ρ is the aircraft roll, λ is the wavelength and d is the spacing between the antenna apertures. Since nadir echoes are summed up in phase, this approach optimizes the SNR of the resulting ice profile. However, it does not suppress the left and right clutter signals in an optimum way.

2.2 Clutter Nulling

Alternatively, a sparse array pattern can be synthesized, characterized by deep nulls towards the directions of surface clutter. This requires the (pseudo-)inversion of the

ISBN 978-3-8007-3607-2 / ISSN 2197-4403

steering matrix $\mathbf{A}$, whose columns are decribed by the steering vectors $\mathbf{a}$ with elements:

$$a(j,i) = exp(2\pi/\lambda \cdot i \cdot d \cdot sin(\rho + \theta(j)), \qquad (2)$$

whith $\theta \in \{\theta_0, \theta_l, \theta_r\}$, corresponding to nadir, and left and right clutter directions (parallel ray approximation is assumed). The weights vector is computed as:

$$\mathbf{w_{NULL}} = \mathbf{A^{-1}} \cdot [1,0,0]^T. \qquad (3)$$

Alternatively, the weights can also be obtained by pattern synthesis, e.g. by convolution of excitation coefficients of aperture pairs. Assuming a narrowband system and precise knowledge of the sounding geometry, in particular the ice surface topography and sensor orientation, in theory the clutter can be cancelled perfectly. However, the noise level cannot be controlled and noise amplification might distort the result under certain circumstances. In the POLARIS case under investigation, the unitary gain constraint, imposed towards the nadir direction, leads to strong scaling in case when nulls are steered towards the ambiguous angles (grating lobes) of the sparse array, i.e. towards $+/-45^o$, corresponding to a depth of 700m in the case of 3000m flight altitude (see simulation results in section 3).

2.3 Optimum Beamformer

To circumvent undesired noise scaling, the optimum beamformer (OBF) has been proposed. In principle it attenuates clutter signals only down to the noise level. Its weights are computed from the covariance matrix of the distortion (i.e. clutter plus noise), excluding the signal:

$$\mathbf{w_{OBF}} = \frac{\mathbf{R_{c+n}^{-1}} \cdot \mathbf{a}(\theta_0)}{\mathbf{a^H}(\theta_0) \cdot \mathbf{R_{c+n}^{-1}} \cdot \mathbf{a}(\theta_0)}. \qquad (4)$$

The denominator ensures unitary gain in the nadir direction. The main challenge is the correct estimation of the covariance matrix. In [2] a deterministic approach has been taken, based on the knowledge of the system parameters, antenna gains, sensing geometry and the assumption of a clutter model. In the present paper the covariance matrix (but for a constant) is estimated from the knowledge of the sensing geometry and an estimate of the clutter-to-noise ratio CNR from the data:

$$\mathbf{R_{c+n}} = \sigma_{c,l}^2 \mathbf{a}(\theta_l)\mathbf{a^H}(\theta_l) + \sigma_{c,r}^2 \mathbf{a}(\theta_\mathbf{r})\mathbf{a^H}(\theta_\mathbf{r}) + \sigma_n^2 \mathbf{I} \equiv \frac{CNR}{2} \cdot (\mathbf{a}(\theta_l)\mathbf{a^H}(\theta_l) + \mathbf{a}(\theta_\mathbf{r})\mathbf{a^H}(\theta_\mathbf{r})) + \mathbf{I}.$$

where $\sigma_{c,l}^2$ and $\sigma_{c,r}^2$ are the left and right clutter power and σ_n^2 the power of the noise. Clutter plus noise is estimated for each fast time instant and the noise power from the last echo lines, assuming they are free of clutter and signal. Also left-right symmetry of clutter strength is assumed. The OBF suppresses optimally only the signals from the two assumed clutter angles. Contributions from other directions are considered as signal of interest and partially remain superimposed to the nadir signal of interest.

2.4 MVDR Beamformer

Although the OBF can be regarded as a special type of MVDR beamformer, the most general implementation of MVDR is when using the covariance matrix $\mathbf{R}$ of the received signals for the computation of the weights. In this case the MVDR is usually denoted as Capon beamformer. When the signal from the nadir direction is desired, the weights are computed according to:

$$\mathbf{w_{MVDR}} = \frac{\mathbf{R^{-1}} \cdot \mathbf{a}(\theta_0)}{\mathbf{a^H}(\theta_0) \cdot \mathbf{R^{-1}} \cdot \mathbf{a}(\theta_0)}. \qquad (5)$$

Similarly, the direction of interest can be changed to point off-axis. Note that in this implementation the signal of interest is limited to the selected direction (nadir) and all other (off-nadir) contributions are considered as disturbance and will be suppressed. This beamformer has recently been applied successfully to MCoRDS/I data [4]. As a drawback one may consider the effect of self-cancellation, i.e. the case when the direction of the signal of interest does not originate from the assumed angle. For ice sounding this might occur in case of slight off-axis reflections in case of cross-track slopes at the bedrock level or in case of inaccurate consideration/knowledge of the sensor orientation.

3 Airborne Simulation Results

We have simulated multi-antenna aperture ice sounding radar profiles corresponding to the POLARIS radar and antenna technical parameters (see Table 1) and an observation geometry of 3000m above the ice surface, similar to the geometry used by POLARIS during the IceGrav campaign in 2011.

3.1 Synthesized Antenna Diagrams

Figure 1 shows synthesized diagrams (array factor) generated from weights obtained by clutter nulling and by OBF. The pattern is presented for suppression of clutter signals originating from $+/-45^o$ off-nadir, which are the grating lobe angles. In this case the patterns for beam-steering, as well as for MVDR weights are similar to the one of OBF.

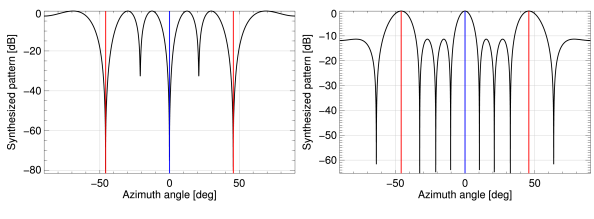

Figure 1: Synthesized patterns for (left) the nulling and (right) the OBF approaches. The clutter angle corresponds to the maximum unambiguous interval, which in the POLARIS case is at $+/-45^o$. The vertical red lines indicate the location of the clutter angles (symmetric in this case),while the blue line shows the nadir direction.

ISBN 978-3-8007-3607-2 / ISSN 2197-4403

For the nulling approach a null is present also towards nadir, responsible the extreme noise scaling at the corresponding depth. The OBF instead "knows" that these directions correspond to nulls of the receive apertures, thus being characterized by noise only (no clutter). A diagram similar to the conventional beam steering approach is the consequence.

Parameter	Value
Center frequency:	435 MHz
Antenna length:	3.9 m
# of Tx-apertures:	1
# of Rx-apertures:	4
Distance between apertures:	0.96m

Table 1: POLARIS radar and antenna parameters in the single polarisation multi-aperture antenna configuration. For further POLARIS technical parameters see [1].

3.2 Airborne Clutter Suppression Performance

Simulated sounder profiles are presented in Figure 2. The scenario includes discrete reflection horizons at the ice surface at 0m, at the bedrock at 1000m and at four intermediate depths, being the signal of interest (in red). Surface clutter is added with a linear decay of 0.2dB per degree of off-nadir angle, weighted by the Tx-Rx antenna patterns and noise at about 20dB lower than the bedrock reflection. The system bandwidth is 25MHz and a roll angle of the sensor of 3^o has been assumed.

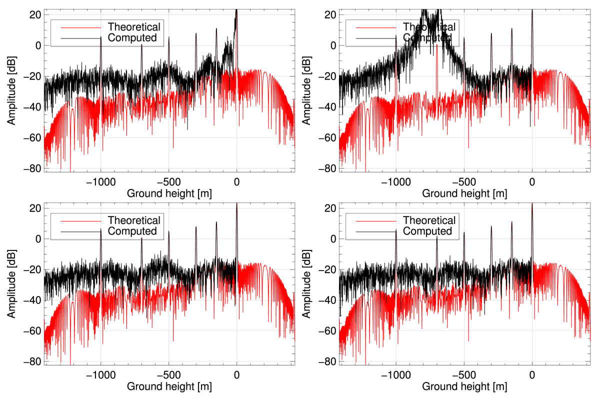

Figure 2: Simulated sounder profile in airborne geometry computed by (top left) beam steering, (top right) clutter nulling, (bottom left) optimum beamformer, (bottom right) MVDR. An aircraft roll angle of -3deg has been simulated.

Analyzing the different results from the individual beamformers several observations are made. The BS does not suppress the clutter sufficiently for ice depth of few hundred meters. Residual clutter corresponds to the mainlobe and the sidelobes of the synthesized antenna pattern (see Figure 1). Clutter nulling performs well at these shallow depths, but is affected by extreme noise scaling in the vicinity of the grating lobes. Due to the roll angle, they become non-symmetric and singularities appear at the two corresponding depths. Also the OBF result is not perfect, since symmetry of clutter levels is assumed. The consequence is a slight scaling of the noise at around 500-600m depth. The best result is obtained for the MVDR case.

4 Results using POLARIS data

The data used in this section were recorded by POLARIS on February 19, 2011 during the IceGrav mission at Jutulstraumen glacier, Antarctica. The sounded ice corresponds to the ridge of a mountain located to the east of the glacier tongue.

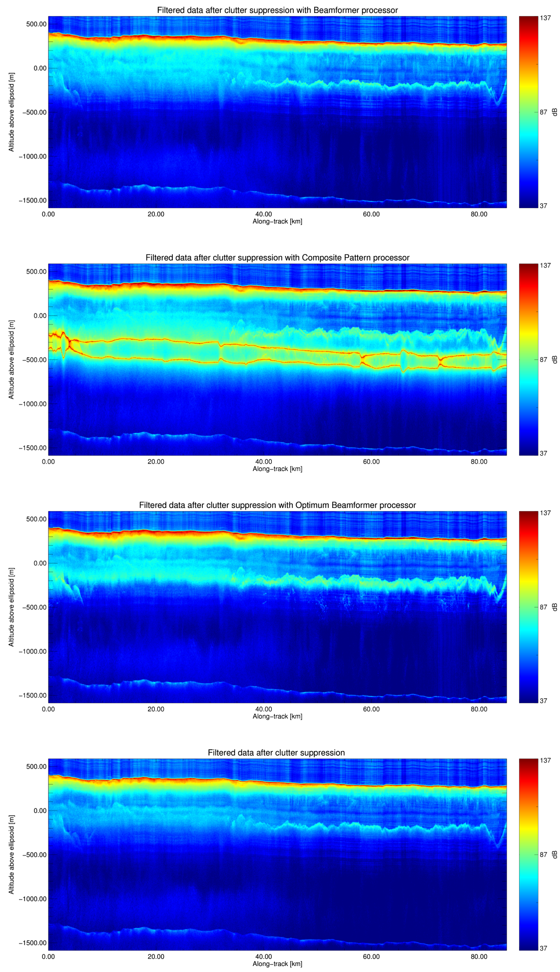

Figure 3: POLARIS echograms obtained with different methods. From top to bottom: beam steering, clutter nulling, optimum beamformer, MVDR. The flight track is on a sloping ice surface in cross-track direction (ID: jsns1, deep sounding mode at 30 MHz).

Slopes are present along the flight direction (north) and also cross-track. Figure 3 presents the echograms obtained after processing the four-channel data with the beamforming algorithms described in section 2. The bedrock is located at about 500m below the ice surface and the ice surface multiple is at 1300m to 1500m depth.

ISBN 978-3-8007-3607-2 / ISSN 2197-4403

For the beamsteering case it is noted that considerable clutter energy is still present at depth of few hundred meters, when compared to the other approaches. The regions of large noise scaling at about 700m below surface in the nulling case are broadened and exhibit two peaks due to the cross-track slope and variations are also present due to aircraft roll. However, when considering the POLARIS antenna patterns in the nulling matrix inversion scheme, the amount of noise scaling is reduced. On the other hand, OBF and MVDR results are not affected by noise scaling. Another important insight is with respect to the bedrock region, which appears widened for the reconstruction with clutter nulling and OBF. The reason is that off-axis signals close to nadir are not deliberately suppressed, when the simple left/right clutter model is adopted. The situation is different for the beam steering and MVDR, which point the maximum to nadir and leads to a sharper bedrock. Especially the MVDR considers off-axis bedrock reflections as a distortion and tries to suppress them, especially if they have more strength then the clutter signal which is attenuated by antenna pattern nulls at corresponding angles.

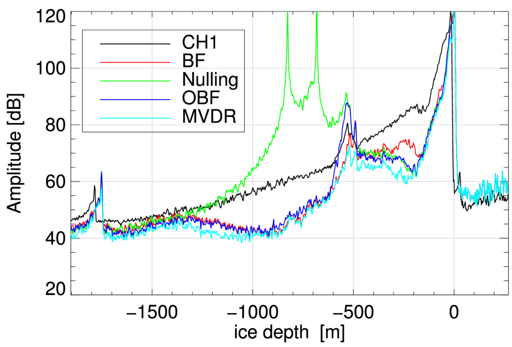

Figure 4: POLARIS sounder profile corrsponding to azimuth position 45km of the echograms in Figure3.

For a quantitative comparison Figure 4 is included, which shows the sounder profiles of the echograms corresponding to the azimuth position 45km. When inspecting the depth region from 0m to 400m, the beam steering (BF, red) is worst in terms of clutter suppression. Nulling (green) and OBF (blue) perform better by 5-10dB. However, both rely on the precise knowledge of the sensing geometry. Here the ASTER GDEM has been used, but its accuracy is limited. This explains why MVDR (cyan) achieves even better performance around the depth of 300m, suppressing the clutter by additional 5dB. Note also that the bedrock reflection of MVDR at 500m depth is limited to a narrower interval when compared to nulling and OBF. For comparison, the profile of a single aperture is also indicated (CH1, black).

5 Spaceborne analysis

A multi-phase center antenna configuration with 3 apertures of 4m length in cross-track is considered for the spaceborne case. Grating lobe angles will be at about $+/-10^o$ affecting the reconstruction for ice depths around 5500m. Opposite to airborne geometries the effect of misregistration between channels will be negligible, even for a bandwidth of several tenth of MHz. With perfect knowledge of the geometry, all investigated beamforming algorithms except for the beam steering BS will give very similar results for symmetric scenarios. In case of surface slopes the MVDR was shown to lead to superior reconstruction, being less affected by model mismatch and noise scaling. Increasing the number of apertures from 3 to 4 decreases the noise scaling giving more robust results for deep layers. Other limiting effects to be considered are the angular spread of the clutter cells (function of transmit bandwidth) and the sidelobes of the ice surface reflection (to be reduced by proper pulse weighting).

6 Conclusions

We have analyzed and demonstrated different techniques for ice surface clutter suppression for an airborne ice sounding radar. The results obtained with POLARIS data confirm the suitability of the MVDR technique for enhanced clutter suppresion performance, reducing the requirement for an ice surface elevation model with high accuracy. The investigated algorithms were shown to be applicable also for a spaceborne scenario, however being subject to further investigation concerning other system effects.

Acknowledgement The presented work has been conducted under ESA-ESTEC contract 104671/11/NL/CT.

References

[1] Dall, J. et al: *ESA's polarimetric airborne radar ice sounder (POLARIS): Design and first results* IET Proc. Radar, Sonar & Navigation, vol. 4 (3), 2010.

[2] Bekaert, D., Gebert, N., Lin, C. C., Hélière, F., Dall, J., Kusk, A. and Kristensen, S. S.: *Surface Clutter Suppression Techniques for P-band Multichannel Synthetic Aperture Radar Ice Sounding*, Proceedings of European Conference on Synthetic Aperture Radar (EUSAR), 2012.

[3] Nielsen, U. and Dall, J.: *Coherent Surface Clutter Suppression Techniques with Topography Estimation for Multi-Phase-Center Radar Ice Sounding*, Proceedings of European Conference on Synthetic Aperture Radar (EUSAR), 2012.

[4] Li, J., Paden, J., Leuschen, C., Rodriguez-Morales, F., Hale, R. D., Arnold, E. J., Crowe, R., Gomez-Garcia, D., Gogineni, P.: *High-Altitude Radar Measurements of Ice Thickness over the Antarctic and Greenland Ice Sheets as a Part of Operation Ice Bridge*, IEEE Transactions on Geoscience and Remote Sensing, vol. 51, no.2, pp.742 - 754 , 2013.

[5] Wu, X., Jezek, K. C., Rodriguez, E., Rodriguez-Morales, F., Freeman, A.: *Ice Sheet Bed Mapping With Airborne SAR Tomography*, IEEE Transactions on Geoscience and Remote Sensing, vol. 49, no. 10, 2011.

