Processing of wide-band non-stationary bistatic airborne SAR signal from the Lorambis experiment

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Abstract: This paper describes the processing at ONERA of part of the signals acquired during the Swedish-French bistatic airborne SAR experiment Lorambis. Though this campaign had for primary objective of assessing the interest of stationary bistatic configurations in UHF wide-band SAR imaging, the opportunity was taken to explore some innovative non-stationary configurations. This paper focuses on the processing of the signals acquired during these explorative acquisitions. Geometries of the acquisitions are described, specific SAR processing difficulties encountered are described and resulting images are shown.

1. Introduction

The Lorambis Swedish-French SAR campaign in 2010 was the third cooperative acquisition campaign between the FOI and ONERA, after the Ramcar campaign in 1998 with the VHF radar Carabas and the L-band radar RAMSES[1] and the Loram campaign in 2004 with the CARABAS, LoraSAR and P, L & X-band RAMSES radars[2]. This time, the two radars used -LoraSAR and Sethi- shared a common frequency band (220-460 MHz) allowing for bistatic acquisitions.

Bistatic acquisitions have already been experimented at X-band but with narrow band in both stationary configurations (Biram 2003 campaign[3][4] with the DLR E-SAR system) and in non-stationary configurations (2008 campaign[5] with RAMSES and Bu$SAR$ systems). By “non-stationary” it is meant that the nominal trajectories correspond to relative positions of the two aircraft that vary with time. As a matter of fact, even with stationary configuration (e.g. parallel tracks with same velocity) the real effective geometry is time varying due to the independent disturbances on the two aircraft trajectories. These disturbances, however, are assumed to be small (some meters), whereas for nominally non-stationary configurations, the relative displacement between the two aircraft may be kilometers.

But, since non-stationary configurations at wide band were expected to raise specific difficulties
in SAR signal processing, the opportunity was taken to include at the end of each acquisition flight a few acquisitions with more innovative configurations. The Sethi system calibration flights performed in France, prior to the departure to Sweden, were also completed with a few monostatic explorative acquisitions (for example, imaging of flying aircraft or rotating windmills at high-resolution X-band).

2. Acquisitions geometry and SAR images

The exploratory acquisitions at the end of the flights in Sweden tested 5 configurations. Three of them are nominally non-stationary: parallel tracks with 100 kt (35 %) velocity difference (Fig. 2), concentric circular trajectories (Fig. 3), and mixed linear + circular trajectories (Fig. 4). The first configuration is similar to second configuration described in [5] but with a wide-band waveform (70% versus 0.5% relative bandwidth).

The two remaining stationary configurations are parallel tracks with the same velocity, but with 20° across-track (Fig. 5) or 10° along-track (Fig. 6) separations. The former is very similar to one of the configurations of [3] with wide-band waveform (70% versus 1%), hence only the latter is illustrated here.

3. processing issues

3. 1. SAR synthesis

The time-domain processing compulsory for flashlook geometry images (see Fig. 1) and optional for stripmap geometry images needs no adaption from stationary to non-stationary bistatic SAR, however, it is considerably slower than frequency-domain processing and yields lower image quality in wide relative bandwidth cases (chromatic aberration).

The frequency-domain processing of bistatic SAR has two pitfalls: The first one is the larger displacement of the range band across the swath compared to monostatic case. Indeed in the monostatic case, the range band is offset proportionally to the baseline between the reference and the true trajectories. As this baseline varies with incidence angle across the swath and along the processing block, the variation of the offset imposes an extra padding around the signal range spectral band (i.e. a smaller range cell during processing) when the true trajectory deviates strongly from reference trajectory. In bistatic case, the range band is also offset proportionally to the cosine of half the bistatic angle which varies significantly across the swath even without any trajectory deviation (and along processing block in non-stationary cases). This may impose a narrower range cell during processing (though this effect is less severe with wider relative bandwidth) which may even practically bound the swath width that can be processed in a single run.

The second difficulty is specific to non-stationary cases: The mapping from signal frequency space to image frequency space (the Stolt interpolation) requires an image coordinate space during synthesis distorted with respect to the final image coordinates space (Fig. 1: A). This distortion has both a non-uniform nature in range (the “range” coordinate is the bistatic range
instead of the range $R$ to the reference trajectory) and a varying angular component (a squinting related to the bistatic angle which varies both with range and along track, and is further dependent on terrain elevation). This means that image needs a non-uniform resampling both in range and in azimuth before output. For comparison, in monostatic case, range resampling is optional (required when the range cell size is different during processing) and linear. Monostatic azimuth resampling (the image skewing) is both linear and proportional to range, hence it is done in frequency domain before the azimuth FFT back to space domain by a simple linear phase modulation (hence a negligible contribution to computation time).

3.2. RFI filtering, range spectral band equalising and geocoding

Besides SAR processing, two other difficulties have to be solved: First, some of the innovative configurations (Fig. 4) were only acquired with Sethi radar transmitting and LoraSAR receiving. This imposed to process LoraSAR raw signal which features strong radio-frequency interferences internal to the digitising system with characteristics very different from that of the RFI we have on Sethi radars. LoraSAR digitises 24 sub-bandwidths down-modulated to baseband on 24 channels. Up to 8 channels are recorded simultaneously for each of the 4 transmitted subbands. Weak coupling between channels induce sharp interference peaks in the signal spectrum that must be filtered before image synthesis. Thanks to the help of the FOI team, a filter for such an RFI was added to our processing chain.

Another difficulty arises from the geometrical model, used for mapping the images to the ground (illustrated on Fig. 2 to 6), but also critical in image frequency band localisation, which is used for range spectral band estimation. Previously, the geometrical model only provided the centre of the image spectrum at a given position in the image. This position was used to pad the zeros for interpolating the complex image while geocoding it, but also for equalising the range spectral band (and seamlessly assemble the sub-bands in case of frequency agile waveforms) by analysing a point-like echo (corner reflector). Because of the nonlinear correspondence between image and signal spectra (Fig. 7), a low azimuth resolution image was used in order to keep the correspondence approximatively linear.

The main drawback of the low azimuth resolution is that the contrast between the point-like echo and the background is lower, yielding a more noisy estimate of the band distortion. In low frequency bistatic case, RCS is low even for large corner reflector because larger reflectors are more directive towards transmitter (and not towards receiver), and in the LoraSAR receiving case, we need to evaluate the registration of channels for narrower sub-bands (1/24 of the total bandwidth) hence with low SNR. This made the low-azimuth resolution approach useless, hence the geometrical model has been improved to provide the position of the range band for any position within the integration angle. With that function, the point-like echo analysis can map the echo spectrum back to range spectral band (a.k.a locally undoing mocomp and focusing) even for wide aperture (high azimuth resolution) and strong motion compensation (or bistatic compensation), thus yielding accurate range spectral band distortion estimates used for equalising spectral band and for registering sub-band channels.
Figure 1: Geometries for SAR images synthesised. A: Stripmap mode, a look corresponds to a fixed squint angle $\delta$. B: Flashlook mode (here depicted with linear acquisition track, but this mode is often used for circular acquisition track), a look correspond to a time within acquisition (centre of integration interval $T_i$). The reference trajectory is linear and is the median between the transmitter and receiver trajectories in bistatic cases.

Figure 2: Parallel track with 100 kt velocity difference. A: Trajectories, transmitting LoraSAR aircraft (red) is 270m below receiving Sethi aircraft (blue). B: Stripmap bistatic image

Figure 3: Concentric circular trajectories. A: Trajectories, transmitting LoraSAR aircraft (red) is 325m below receiving Sethi aircraft (blue). B: flashlook bistatic image.
Figure 4: Mixed linear and circular trajectories. A: Trajectories, transmitting Sethi aircraft (blue) is 1100m above receiving LoraSAR aircraft (red). B: stripmap bistatic image.

Figure 5: Parallel track with $20^\circ$ across-track separation. A: Trajectories, transmitting LoraSAR aircraft (red) is 400m below receiving Sethi aircraft (blue). B: Stripmap bistatic image.

Figure 6: Parallel track with $10^\circ$ along-track separation. A: Trajectories, transmitting LoraSAR aircraft (red) and receiving Sethi aircraft (blue) fly at the same altitude. B: Stripmap bistatic image.
Figure 7: Illustration of the image spectrum distortion for: A low azimuth resolution, B wide azimuth integration (induces aperture curvature) and C wide azimuth integration & strong motion/bistatic compensation (induces distortion from the circular curvature). The dark line corresponds to the transmission notch around the distress radio frequency. Without taking the aperture distortion into account, the range spectrum of a point echo would produce an accurate (but noisy) estimate of the range spectral band in case A, a moderately smeared estimate in case B and a totally blurred estimate in case C, which is representative of a wide band bistatic SAR image.

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