Towards a polarimetric SAR processor for airborne sensor

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Abstract — True polarimetric SAR imaging with an airborne radar is difficult due to carrier fluctuations in attitude during acquisition that modify the polarisation axes through the integration time. Even worse, at lower frequency, the wide antenna pattern (and wide angle of integration) results in an interaction between the radiated waves and the surrounding aircraft cell, causing a significant deviation of the illumination pattern from the “centre of phase” (point-like) model, and yielding non linear effective polarisation off-axis.

Here are described improvements in frequency domain SAR processing that should allow to include time-varying factor in the azimuth integration thus compensating for antenna pattern beyond the centre of phase hypothesis. This factor can be complex (already implemented today) and even a complex matrix (work in progress) thus allowing true polarimetric SAR image synthesis.

An example is given with SETHI, the airborne Radar developed at ONERA for which a UHF/VHF (two linear polarised) antenna is attached in a pod under a Falcon 20 jet aircraft wing. The far field radiation including both the antenna itself and the aircraft cell interactions has been modelled by finite elements, and the resulting illumination field (during the effective integration time) for one of the linear polarised channel can be simulated. From this simulation, we can evaluate the backscattering matrix error made by ignoring the aircraft attitude motion and depolarisation (i.e. simple channel calibration and per channel SAR image synthesis) or by including only rotation of the polarisation axes for compensating attitude changes.

1. INTRODUCTION

As ONERA recently added an UHF/VHF (222 to 470 MHz) component to its airborne SAR system Sethi (which replaces the former RAMSES system), investigations were conducted in order to determine the most appropriate location and design of the antenna inside the two pods under the carrier aircraft wings (a Falcon 20). The proposed antenna is made of two dipole pairs (for polarimetric measurements) with a cylindrical reflector on its back, either positioned in the front of the pod partially beyond the leading edge of the wing, or positioned just below the wing. A set of angles of incidence was also considered (for the trade-offs between left-right ambiguities and the reflections on the wing surface).

Due to the proximity of the wing and the large wavelength, the antenna pattern is highly distorted compared to that of the naked antenna. Furthermore, as we wish azimuth resolutions similar to attainable range resolution (60 cm), a wide integration angle (around 32 degrees) is required. Finite elements modelling of the antenna including the surrounding aircraft with the program ELSEM3D allowed to compute the far field radiation of the antenna in various candidate operating positions. Simulations showed that the “centre of phase” approximation does not hold to the accuracy required by SAR processing in any case.

However, the forward antenna position was discarded because the phase variation along azimuth angle (mainly due to strong reflections on the tilted leading edge) is strongly frequency dependent, while this effect is mostly confined to the elevation angle in the central antenna position. Since the integration for SAR image synthesis is mostly along the azimuth angle, a strong frequency dependency would have made the focusing during the synthesis more difficult and more sensitive to the unavoidable modelling error of the pattern computation.

The phase variation with squint during integration must be corrected for (in a similar manner to motion compensation) and is more or less comparable to a complex value for the antenna pattern. This algorithmic improvement, decisive even in focusing non polarimetric SAR image synthesis will be described below.

Finite elements modelling also showed that the radiated waves from each of the two antenna feeds could not be approximated as a linear polarised light with axis in the direction of the excited
Previously, polarimetric images were obtained by computing 16 single look complex images (combined later into the 4 polarimetric single look complex images). Each image is computed for one transmit and one receive antenna ports and during the azimuth integration, its signal was multiplied by the cosine or sinus of the angle between the antenna axes and the terrain vertical. This angle varies during integration due to both attitude fluctuations and motion nonlinearities of the aircraft trajectory. Due to the difficulty of including this time-varying factor in the frequency domain processor, this polarimetric processing was done in time domain (2-stage factored, but still slow compared to frequency domain processing). The new frequency domain algorithm allows this type of processing, but the elliptical component would require to synthesise simultaneously the 4 channel images, and, instead of a scalar complex antenna pattern, apply a complex polarisation restoration matrix. Design of such a processor will be sketched at the end of the paper.

2. ANTENNA PATTERN MODELLING AND DEPOLARISATION SIMULATION

Antenna patterns (Fig. 1) obtained by a mesh of the aircraft and the antenna with the rear position at 45 degree incidence (the configuration eventually used for acquisitions) show strong variations in elevation angle, but slow variations in azimuth (though the variation in phase should be compensated for). At the lower end of the bandwidth, the strong reflection on the wing causes a near blind spot slightly above antenna axis and a strong over-Nadir transmission. This results in a strong left-right ambiguity that triggers the investigation in progress on more grazing (or even upwards) angle steering of the antenna in order to use the wing as a reflector for the antenna.

The low accuracy of the polarimetric quality of the SAR images synthesised from the raw sensor
Figure 3: Principle for the frequency domain processing, the signal component for a given bandwidth and Doppler frequency for perfect linear uniform acquisition corresponds to a single space frequency of the image in cylindrical or slant-range coordinate (left). If the trajectory deviates from linear uniform, the $0^{th}$ and $1^{st}$ order motion compensation is made by range migration $R - R_0$ and azimuth migration $\Delta Z$, while higher order compensation requires to locally alter the “nominal processing phase” $\Delta R$ function of the squint angle $\delta$ by the “quadratic phase” $d\Delta R$ (right).

Figure 4: Synoptic of the frequency domain SAR processor (present state). Black indicates mandatory steps, (red mandatory steps for bistatic case, and red background forbidden steps for bistatic case). Blue indicates optional steps, and green outputs (green background test/debug output points).

Channel signals can be assessed by computing, with a real acquisition trajectory, the rotation during integration of the sensor axes relative to the ground and by adding the contribution of the elliptical (cross-polarisation) component of the far field radiation of the antenna with its surrounding aircraft body (Fig.2). It should be emphasised that a cross-talk Hh to Vv of 10% on average is far from negligible and that the Vv component is also contaminated with the one-way cross-talk by the Hv target response (generally some 3dB below direct polarisation response). Cross-polar contamination are even worse because the one-way cross-talk applies on the stronger direct polarisation response.
3. PRESENT FREQUENCY DOMAIN SAR PROCESSOR

Frequency domain processing is based on the fact that for perfect linear uniform monostatic acquisition, a point in the 2D signal spectrum can be mapped (the map is called “stolt interpolation”) to a point of the 2D focused image spectrum. Fig. 3(left) illustrates this by representing a wavefront of a nonzero Doppler pure frequency signal radiated at half the light velocity (thus making equivalent the two-ways propagation to a single-way one). However, for an airborne acquisition, the unavoidable trajectory irregularities must be compensated for. The motion compensation (“mocomp” for short) involves range and azimuth migration i.e. time domain resampling of the signal, which are intrinsically a wide-band process for low order mocomp and, for higher order mocomp, a “quadratic phase” local correction (Fig.3 right) so called because it is roughly a quadratic function of the difference between the local and nominal squint angles $\delta - \delta_0$. Since this compensation depends both of range azimuth and $\delta$ it must be performed in range-Doppler domain as a phase correction and is thus narrow-band in nature. In our processor (Fig.4) the quadratic phase is compensated for by small azimuth sub-blocks, and in fact the average quadratic phase on the full bloc is compensated for during the nominal processing (in frequency domain, thus wide-band), and only the local deviations of the quadratic phase are compensated in the range-Doppler domain (Fig.5). Note that in Fig.3 the motion compensation is unrealistically emphasised (the true trajectory deviates by half of the nominal range from the nominal trajectory) and in Fig.5 an ultra wide band type of aperture is depicted (it is typical of the processing of the CARABAS system of the Swedish FOI).

In this processor design, it was easy to include an antenna pattern phase (as an addition to the mocomp quadratic phase) and focus SAR images acquired with our new antenna (Fig.6).

4. TOWARDS A TRUE POLARIMETRIC SAR PROCESSOR FOR AIRBORNE ACQUISITIONS

A truly polarimetric frequency domain SAR processor can be derived from the above described design. The idea is to run simultaneously 4 instances of the processor (one for each polarisation channel). The image grid must be the same for all channels, hence there should be a trajectory offset at the azimuth migration stage for compensating for the time separation because in our system each polarisation channel (both transmit and receive at UHF/VHF, only transmit at high frequency bands) are acquired on successive radar pulses. At the stage where quadratic phase is compensated for, the four range Doppler terms for the raw sensor polar channels Hh, Hv, Vh and Vv (upper case is the transmit feed, lower case is the receive port) must be corrected by a $2 \times 2$ complex matrix coordinate change to yield the polarimetric channel corrected to local (from the ground viewpoint) H and V directions.

$$
\begin{bmatrix}
H_{h_{loc}} & H_{v_{loc}} \\
V_{h_{loc}} & V_{v_{loc}}
\end{bmatrix}
= A^T
\begin{bmatrix}
H_h & H_v \\
V_h & V_v
\end{bmatrix}
A, \text{ with } A = \left( H_{loc} \right) A = \left( E_H^* \ E_V \right)^{-1}
$$

Where $E_H^*$ is the complex electrical field components radiated from feed H and $H_{loc}$ the unit vector of the horizontal direction at the aim point on the ground. Once this restauation is done, each instance of the SAR processor goes on with the signal corresponding to a ground relative linear polarisation basis.
5. CONCLUSIONS AND PERSPECTIVES

The SAR processor described above is yet to be implemented, but the work is in progress for a simpler (but less efficient) 16-pass version and comparison between full images obtained from the raw sensor polarimetry channels and obtained with corrected ground polarisation axes should be available at the time of conference.

However, the simple point computation of the polarisation channels contamination through the wide integration angle required at low frequency already demonstrated that the airborne polarimetric SAR image computed by merely calibrating the sensor (even in the accurate way described in [1]) may produce single digit accuracy for direct polarisation and irrelevant data for cross polarisation. Due to the high sensitivity of some polarimetric parameters derived from the scattering matrix, even in less critical conditions (narrower integration and antenna pattern) the careful compensation of aircraft attitude and antenna depolarising is mandatory for polarimetric airborne SAR imaging.

REFERENCES