First Results from the Ingara L-band SAR

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Abstract—A significant challenge for Intelligence, Surveillance and Reconnaissance (ISR) systems is the detection and possible identification of concealed targets, for example vehicles and structures under foliage. Low Frequency (LF) imaging radar sensing offers a number of unique phenomenologies and modalities that can address this problem. To investigate the utility of L-band to provide a useful Foliage Penetration (FOPEN) capability the Defence Science and Technology (DST) Group has developed an 8 channel, fully polarimetric L-band SAR. This paper describes the capabilities of this system as well as results from the first engineering test flights conducted in September 2017. Key objectives of the trials were the calibration of the full 8 channel array and the demonstration of repeat-pass and along-track interferometric processing.

I. INTRODUCTION

Since the early 1990s the Defence Science and Technology Group has developed and flown an X-band multi-mode imaging radar system. The system provided the experimental capabilities to conduct research into a wide range of SAR techniques including repeat-pass and along-track interferometry, polarimetry as well as bistatics [1] [2] [3]. The system has flown on a range of aircraft including an RAAF C-47 Dakota, Beechcraft 350 Super King Air, and currently a Beechcraft 1900C referred to as the Defence Experimentation Airborne Platform (DEAP).

A significant limitation of operation at X-band is the limited foliage penetration capabilities at this wavelength. Target detection beneath canopy is limited to opportunistic “poke through” of RF energy. Robust detection of targets in hide necessitates operating at lower frequencies where the RF attenuation through the canopy, quantified by the vegetation extinction coefficient, is significantly lower. The use of lower frequency imaging radars for FOLiage PENetration (FOPEN) has been an area of on-going research for many years with many systems developed and commercially available. Operating frequencies ranging from VHF to L-band have been reported in the literature [4] [5] [6]. A key challenge for the design and operation of a low frequency SAR for research into FOPEN is achieving a sufficiently wide operating envelope (e.g. in terms of stand-off range, incidence angle range, system noise floor, antenna characteristics, bandwidth, polarimetry, RF spectrum limitations and interference) to explore target and clutter discrimination over a wide parameter space.

To conduct research into the utility of L-band for use in the land and maritime domains, an L-band version of the Ingara imaging radar has been developed at DST Group. While lower frequencies such as P-band offer more favourable extinction coefficients, L-band does offer some advantages including ready access to large contiguous spectrum allocations, mostly free of other RF interference, as well as a better fit to the Space, Weight, and Power (SWaP) limitations of the DEAP aircraft. In addition the choice of L-band has enabled a four phase-centre dual-linearly polarised antenna to be developed and installed in the DEAP radome volume to facilitate research into the utility of L-band multi-channel and MIMO concepts. This system builds upon an initial interim L-band capability based on a helical antenna design giving dual circularly polarised data [7].

This paper details results from the first engineering test flight of the Ingara L-band SAR conducted in September 2017. In particular this paper shows first images as well as the repeat-pass and along track interferometric capabilities of the system. In addition a passive continuously-sampling static ground-based receiver was deployed during the trial to measure system performance as well as facilitate bistatic imaging.

II. INGARA L-BAND SYSTEM

The Ingara L-band system is fully polarimetric and operates at 1.32 GHz with a 140 MHz bandwidth. The L-band antenna is a dual-linearly polarised patch design developed in-house. The antenna consists of 4 panels (each 0.261 m in width and 0.42 m in height) arranged in the along-track direction with each panel providing a H and V port (see Figure 1). Each panel in turn consists of 6 patches arranged as 2 columns and 3 rows. The feed network partitions the power equally between the two columns and across the rows the power is partitioned in the ratio 0.25, 0.5, 0.25 to provide a modest degree of shading to control elevation sidelobes. There is no shading employed across columns. The gain of each panel is 12.5 dB.

Each antenna panel port is connected to 8 Transmit/Receive Modules (TRMs) (TRMs 1, 2, 3 and 4 are connected to the H-polarisation ports, TRMs 5, 6, 7 and 8 are connected to the V-polarisation ports). A single Arbitrary Waveform Generator
(AWG) generates an LFM chirp waveform that is distributed across the 8 transmitters. However, a future upgrade path is seeking to incorporate additional AWGs to provide unique waveforms for each transmitter. Each transmitter includes a 500 W Power Amplifier (PA) as well as a 6-bit phase shifter to enable individual phase control of the transmit waveform to correct for array calibration offsets and provide a limited azimuthal beam-steering capability. A duty cycle limit of 10 percent is imposed by the PAs. The receivers employ direct sampling of the 100 MHz IF with 8 synchronised 2-GSPS 8-bit ADCs. Polyphase filtering is implemented on the ADC boards to facilitate sub-sampling of the data to meet data-rate and swath-width requirements. Raw ADC samples are written directly to disk in Hierarchical Data Format 5 (HDF5) for later processing and exploitation.

Coarse resolution spotlight SAR images for one receive channel are formed using a simple rectangular format algorithm in near-real-time during data collection to verify that the radar is operating correctly.

III. ENGINEERING TEST FLIGHTS RESULTS

The engineering test flights were preceded by ground based full power testing of the system in July 2017. In these tests the system was hoisted onto a 15 m high tower at the DST Group Edinburgh site and illuminated a nearby hill-side upon which a set of 2.4 m triangular trihedrals were deployed. Following on from the successful ground tests, engineering test flights were conducted over a 4 week period in September and October 2017. The main objectives of these test flights were to verify the correct operation of the radar and characterise its performance, in particular to measure and correct for transmit and receive array phase mis-calibrations, verify the phase steering capability, measure the system noise performance and measure the polarimetric calibration of the system.

A key component of the test regime was the deployment of a two-channel ground based continuously sampling receiver that was typically used to acquire the direct path signals from the airborne system. This receiver employed two spare TRMs from the airborne system with the transmitter disabled and enabled measurement of the airborne antenna patterns, polarimetric properties and estimates of the Effective Isotropic Radiated Power (EIRP).

A. Image Formation Processor (IFP)

Fine resolution imagery over wide swaths at low frequencies is generally formed using backprojection or time-domain beam forming techniques as these provide exact compensation for wavefront curvature effects. The non-Fourier-based nature of this approach however, means that many image based processing and exploitation approaches such as Phase Gradient Autofocus (PGA), sub-aperture processing and interferometric aperture-trimming, developed within a Fourier imaging framework, are no longer suitable (or indeed require re-processing of the original raw data). In order to make use of the standard Fourier domain exploitation techniques to assist in the analysis of the system calibration and image quality, the Polar Format Algorithm (PFA) was employed. The PFA provides a well understood relationship between the collected raw data or phase history domain, the scene’s reflectivity in the spatial frequency domain and the collection geometry (namely the polar angles between a scene reference point and an antenna phase centre) [8].

B. Array Calibration

The purpose of array calibration is to measure and compensate where possible the amplitude and phase imbalances of each of the TRMs on both transmit and receive. While receive channel imbalances can be corrected for in the IFP via application of appropriate calibration coefficients, transmit imbalances must be corrected for in hardware during flight. The Ingara system can correct for phase imbalances on transmit using the 6-bit phase shifters in the TRMs, but there is no mechanism to compensate for amplitude imbalances.

The array calibration model employed for each polarisation is

\[ O = R\sigma T^s \]

where \( O, R \) and \( T \) are 4 element column vectors describing, for a single polarisation the observed imagery, the receiver channel imbalance coefficients and the transmitter channel imbalance coefficients respectively. \( \sigma \) is a scalar representing the scene reflectivity and \( s \) is a 4 element column vector defining the active transmitters. Measurement of the transmit calibration vector \( T \) to within a complex scalar was achieved by toggling on a pulse-to-pulse basis between a selected transmitter pair. For example toggling between transmitter 1 and 2 gives

\[
\begin{bmatrix}
O_{11} \\
O_{21} \\
O_{31} \\
O_{41}
\end{bmatrix} = \begin{bmatrix}
R_{11}T_{1} \\
R_{21}T_{2} \\
R_{31}T_{3} \\
R_{41}T_{4}
\end{bmatrix} \sigma
\]

Selecting the imagery obtained from one of the receivers and forming the ratio

\[ C_{12} = \frac{O_{11}}{O_{12}} = \frac{T_{1}}{T_{2}} \]

gives the relative amplitude and phase imbalance between transmitters 1 and 2. Toggling between transmitters 1 and 3 and then 1 and 4 allows the measurement of the H-pol channel imbalances of each transmitter relative to transmitter 1 (and similarly for the V-pol transmitters 5, 6, 7 and 8). It is only the transmit phase imbalance that can be compensated in the Ingara hardware and so it is the phase \( -\arg(C_{12}) \) that is applied to the transmitter 2 phase shifter. While toggling through all 4 transmitters in sequence would expedite the calibration, the resulting 4-fold reduction in PRF would adversely affect the image SNR as well as significantly undersample the Doppler bandwidth resulting in significant image domain aliasing.

It is noted that recovering the calibration phase \( -\arg(C_{12}) \) is the same process as is performed in estimating the interferometric phase between an image pair. Indeed the same interferometric processing steps must be applied including aperture trimming, image registration and spatial averaging.

\[ O, R \]

\[ T \]

\[ C_{12} \]

\[ \sigma \]

\[ s \]
to obtain robust estimates of this phase. In the present case the aperture trimming process is implemented in the PFA as the along-track interferometric baseline between the effective phase centres is known and so the raw data associated with each channel may then be resampled onto the same phase history domain sampling grid. This process should eliminate the image domain phase ramps that would otherwise result where the effective phase centres have an along-track offset. An image registration step is used to measure and correct for sub-pixel timing mismatches between the TRMs. Finally the interferometric coherence can be computed over an $N$ pixel spatial window

$$
\gamma_{exp}(j\phi) = \frac{\sum_{k=0}^{N-1} O_{11k}O_{12k}^*}{\sqrt{\left(\sum_{k=0}^{N-1}|O_{11k}|^2\right)\left(\sum_{k=0}^{N-1}|O_{12k}|^2\right)}}
$$

(5)

to provide the calibration phase estimate $\phi$. Figure 2 shows the image obtained from panel 5 (V pol.) associated with the phase calibration collection toggling between TRM 5 and 6 on transmit while Figure 3 shows the interferometric phase obtained between the two channels. The central region of the interferometric phase is extracted and only phase values with an associated coherence $\gamma$ above a threshold, taken to be 0.7, were used to form the histogram shown in Figure 4 to then estimate the calibration phase.

Applying the measured transmitter calibration phase values and transmitting over all panels provides nominally a 6 dB increase in transmit power as well as a 6 dB increase in the antenna gain. The effect on the image as a result of transmitting and receiving on the full array is shown in the HH polarisation images in Figures 5, 6 and 7. Figure 5 shows the image obtained using a single panel on transmit and receive. In the case of a spotlight SAR image the image intensity envelope across azimuth is an indication of the antenna azimuthal beampattern. The one-way -3 dB azimuthal beamwidth for a single panel is 54$^\circ$ thus in Figure 5 it is evident that the PRF is insufficient to sample the Doppler bandwidth leading to azimuthal aliasing of the scene content at the left and right sides of the image. The azimuthal image intensity envelope and the measured single panel beampattern is shown in Figure 8. Figure 6 shows the image obtained using all transmitters and a single panel on receive. In this case the -3 dB one way azimuthal beamwidth of the 4 panel array is 13$^\circ$. Finally Figure 7 shows the image obtained with using the full array on transmit and receive.

C. Repeat Pass Interferometry

The collection of multi-baseline SAR imagery to form an aperture through elevation provides an ability to resolve scatterers in height and has the potential to detect vehicles and scene disturbances or changes under canopy [9] [10] [11]. A key first step in achieving this is the ability to perform
Fig. 6. HH polarisation image obtained from with all panels on transmit and a single panel on receive.

Fig. 7. HH polarisation image obtained from with all panels on transmit and all panels on receive.

Fig. 8. Image intensity envelope across azimuth for each of the three images in Figures 5, 6 and 7 as well as the corresponding azimuthal antenna beam-patterns measured in the anechoic chamber (Red and magenta: Single Panel Tx and Rx, Blue and Cyan all panels Tx, Single panel Rx; Black and Green: All panels on Tx Rx). Good agreement between the intensity envelopes and the measured beam-patterns is observed. The flattening of the intensity envelopes with increasing azimuthal angle is a result of the worsening clutter-to-noise ratio off broadside. Note the “dip” in the intensity envelopes at an azimuth angle of $-15^\circ$ is simply due to the spectral characteristics of the polar to rectangular filters in the PFA.

repeat-pass interferometry. Figure 9 shows the first pass VV pol. image of a repeat-pass interferometric pair acquired 36 minutes apart and Figure 10 shows the associated interferometric coherence. The use of interferometric coherence to measure and detect subtle scene changes, i.e. Coherent Change Detection (CCD), at X and Ku band is well known. The utility of CCD at L-band is an area of ongoing investigation.

D. Along Track Interferometry

The use of multiple along-track phase centres to measure slow-moving targets in the land and maritime domains as well as to measure ocean and river currents is well known. The interferometric phase of a target, moving with a line-of-sight velocity of $v_L$, measured using two phase centres separated in the along track direction by distance $L$ is given by

$$\Delta \phi = \frac{4\pi L v_L}{\lambda v_a}$$

where $v_a$ is the aircraft velocity and $\lambda$ is the wavelength. Given the $1/\lambda$ dependence of the interferometric phase the use of L-band for ATI applications results in reduced sensitivity compared to higher frequency radars. The use of the additional along-track channels and the fully polarimetric capabilities of the Ingara L-band system to improve slow-moving target detection, such as via the use of generalised likelihood ratio tests [2], is an area of ongoing investigation.

The utility of the Ingara L-band system for ATI was demonstrated in the engineering trials via the detection of two slow moving targets in the interferometric phase formed...
between the first and last panels as shown in Figure 11. As all transmitters were active in this collection the along track separation of the effective phase centres of the two channels is 0.3915 m. The measured ATI phase offsets of the two targets from the zero-phase clutter were measured as 34° and 66°. Given the aircraft velocity of 85.3 m/s this gives line-of-sight velocities of 2.34 m/s and 4.54 m/s for the two targets. Given the estimated line-of-sight velocities, compensation of the resultant azimuthal displacement of the moving target places them along roads within the quarry as shown in Figure 12. Based on the 30° depression angle and the orientation of the quarry roads one can estimate a ground velocity in the vicinity of 30 km/hr for both vehicles, consistent with speed restrictions in the quarry thoroughfares.

IV. CONCLUSION

A four phase-centre, 8 channel, fully polarimetric L-band imaging radar has been developed by the DST Group to conduct FOPEN experimentation and investigate the utility of L-band in the maritime domain. The system’s first engineering test flights were conducted in September 2017 and focused on array calibration and characterisation of the radar. Key results from these trials have been demonstration of repeat-pass and along-track interferometry. Follow on trials to collect radar signatures and phenomenology in vegetation and the maritime domain are planned for early 2018.

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