Abstract
Persistent monitoring of large areas using spaceborne Synthetic Aperture Radar (SAR) is a challenging problem for various defence and civil applications. Despite the fact that spaceborne SAR from low Earth orbit (LEO) is a well-developed technology, in practice it cannot provide persistent monitoring of any particular geographical region, as any single satellite has a rather long revisit time. Geostationary Earth Orbit (GEO) SAR missions have been proposed, but here there are major engineering issues due the severe path loss across the distances involved. Indeed, path loss is even more severe in radar systems than it is in radio communications. To provide persistent (or near persistent) monitoring from LEO, a very large number of satellites (~100) would be required to detect short-lived events. However, even though such a solution may be technically possible, a satellite constellation development of this scale may not be economically viable. The PASSAT project was proposed and undertaken by the University of Birmingham, under the sponsorship of the UK Defence Science and Technology Laboratory, to analyse the concept of a fully passive (receive only) spaceborne SAR system based on a constellation of microsatellites. By making use of terrestrial transmitters (we propose to use ground-based broadcasting systems, i.e. DVB-T, DAB, FM radio and similar as transmitters of opportunity), the problem of having to carry a high power pulsed radar transmitter on a microsatellite is eliminated. Instead, the satellite only need carry a suitable receiver, antenna and signal storage facility. It is expected that such a system will: (i) provide imaging of a monitored area with a potentially achievable resolution of 2-3 m in either direction; (ii) cover mainly populated parts of the Earth and, partly, littoral waters; (iii) its costs will be orders of magnitude less in comparison to an equivalent active spaceborne SAR constellation. In addition we may expect more information-rich images, as we are dealing with a multi-static, multi-frequency (VHF/UHF) system which effectively has no equivalent at present.

In this paper, we report the results of a series of ground-based and airborne trials of the system, around Birmingham, Coventry and Bruntingthorpe Airfield, which make use of DVB-T transmissions from the Sutton Coldfield transmitter at ranges up to 46km. In the processed images, roads, wind turbines, hedgerows and trees are all clearly identified. We also discuss a proposed spaceborne demonstrator, based on a 12U CubeSat platform with a deployable high-gain UHF helical antenna.

Keywords: (Satellite Constellations, Passive Bi/Multi-Static SAR, CubeSats)
1. Introduction

Space-borne Synthetic Aperture Radar (SAR) has proven itself to be a highly capable remote sensing technique, with a plethora of applications [1–3]. The great advantage of SAR is that it provides day or night imaging, independent of weather conditions. However, this comes at the cost of needing to provide the “illuminating” radiation, which hitherto has required SAR satellites to carry high power radar transmitters. As a result, existing space-borne SAR systems typically require large and/or complex spacecraft platforms, which come at substantial financial cost: 10s-100s of millions of dollars per mission. This, in-turn, puts practical restrictions on the number of instruments that can be orbited, and this is problematic given the increasing demands for persistent or near-persistent monitoring applications, which would require a large number of SAR satellites to be effective.

One potential solution to this problem could be to make use of passive, rather than active, spaceborne SAR systems. These would utilise existing transmissions from other sources for imaging purposes, thus forming a bi-static or multi-static arrangement. Our proposal concerns such a system: the Passive SAR Satellite constellation (PASSAT) [4, 5]. Here, rather than using large and expensive satellites carrying an active transmitter, passive SAR satellites would utilise ground-based transmitters of opportunity to reduce the size and cost of the spaceborne element. Due to the passive nature of the satellites, the receiver, storage, and data downlink components would require only a small volume, and the power requirements would be modest, thus the passive SAR payload could be accommodated on a nano-satellite (e.g. a CubeSat) in the 10-20kg class, enabling multiple satellites to be deployed from a single launch. The smaller size, as well as the smaller power requirements of a receive-only system means that the PASSAT system concept would be much cheaper and less complex than a constellation of active SAR satellites – even SAR micro-satellites (100-500kg) – in a similar low Earth orbit (LEO). To further reduce cost and complexity, the data collected by the satellites would be stored on-board, then transmitted to the ground for post-processing into an image. A visualization of the concept is shown in Fig. 1.

Passive SAR satellites could, of course, fly in tandem with existing active SAR satellites to extend their coverage, however this would not address the issues of the cost and relatively small numbers of the active satellites.

In PASSAT, the transmitters of opportunity are ground-based broadcasting stations, e.g. Digital Video Broadcasting – Terrestrial (DVB-T) transmitters. These were chosen as, globally, DVB-T coverage of populated areas is quite extensive (e.g. in the UK nearly 90% of the land is within DVB-T coverage, not to mention littoral waters [6]). We also found DVB-T provides the best signal properties, including a relatively high transmission power (10-250kW), thus reducing the required satellite receiver antenna gain, as well as providing a sufficient bandwidth (7.6MHz) to give a reasonable range resolution: approximately 20m for an ideal geometric scenario. Additionally, DVB-T SAR has been shown to be fundamentally possible [7–10].

Bi-static passive/active SAR concepts that combine space-borne and ground-based segments are not new, however, to-date most have explored the opposite configuration to PASSAT. For example, passive SAR using Global Navigation Satellite System (GNSS) satellite signals and ground-based receivers has been considered at great length [11–16]. In other work, the German Aerospace Centre (DLR) has considered a constellation of receive-only LEO satellites, with a satellite in geostationary Earth orbit (GEO) acting as the transmitter [17].

While conventional orbital SAR systems operate in the L- to X-band, DVB-T operates in the VHF/UHF region, which is known for its foliage penetration and indirect propagation properties. Furthermore, the PASSAT concept, as a bi-/multi-static system, can take advantage of bistatic scattering effects to increase the available scene information, however, this can also result in unfavourable imaging geometries which result in a loss of spatial resolution. Thus, PASSAT would seem to offer the opportunity to provide large numbers of SAR imaging satellites at economic cost, with imaging potential complementary to existing SAR systems. However, an appropriate study needs to be done to confirm its validity and explore its potential.

In a recent paper, preliminary calculations on the system sensitivity, resolution, and robustness to unfavourable imaging geometries were made [18]. In this paper, we will describe the next steps in the study of this system, which has focused on the development of a DVB-T SAR technology demonstrator and its validation through an experimental campaign with a moving ground vehicle platform and an airborne platform, and a first analysis of the results obtained. We have also
developed a prototype deployable high-gain UHF helical antenna that fits into a ~4U CubeSat volume, which would form the SAR system receive antenna. These steps are a springboard for the development of a spaceborne demonstrator, which could be launched out of the International Space Station (ISS) as early as 2021.

2. PASSAT Demonstrator Ground Trials

The PASSAT passive SAR payload essentially comprises a dual channel DVB-T receiver capable of simultaneously receiving both the direct transmissions from the DVB-T transmitter and the indirect (scattered) signals coming from the area of the ground to be imaged. By sampling the signals against an accurate clock signal (provided by a Global Positioning System (GPS) receiver), the direct signal can be used as a heterodyne source in the SAR signal processing chain – thus taking the place of the coherent transmission signal in a conventional active SAR.

To test and verify the concept, in 2015 a relatively crude “proof-of-concept” trial was carried out from the roof of the University of Birmingham using a 40m long “railway track” (Fig. 2). The receiving hardware was based on National Instrument’s two-channel Universal Software Radio Peripheral (USRP).

The first channel had a standard commercial Yagi digital TV antenna pointed towards the transmitter location, to record the direct “heterodyne” signal. The signal recorded in this channel was used as the reference for range compression in the image formation algorithm. The second channel, called the “radar” channel, had a similar Yagi antenna pointed towards the imaging scene for image formation. A professional GPS receiver was also used to record the receiver’s position and speed with high accuracy (Real-Time Kinematic - RTK specifications) and update rate (20 Hz).

The transmitter was located ~17.7km away from the receiver and its GPS co-ordinates are given as 52°36′2″N 1°50′2″W. The transmitter height is 433m above mean sea-level (AMSL). The signal captured for image formation was the 650 MHz DVB-T channel, which is UHF#43.

Both the scattered and direct DVB-T transmissions were received and processed, however, the experiment was not expected to obtain high-quality imagery, as the baseline was small (40m with targets over 1km away) and the imaging geometry was poor (near forward-scan and near grazing altitude, at 60° squint angle). None-the-less, after signal processing, strong echoes were obtained (Fig. 3), which could be associated with buildings in the neighbourhood of the University.

Fig. 2. Proof-of-Concept System

Sutton Coldfield DVB-T broadcasting station was selected as the transmitter, both because it is located towards the North (so the full aperture length could be used) and because of its high transmit power (~200 kW Effective Isotropic Radiated Power – EIRP), which would help in testing our image formation algorithms.

Fig. 3. DVB-T SAR Image Superimposed on a Photograph of the Imaging Scene (obtained from Google Earth), for Ranges up to 1.5km. The Colour Scale shows Relative Signal Return in dB with 0 dB Being the Highest Echo Intensity Returned

To more completely verify the concept, in January 2018, a series of road trials were conducted to obtain further DVB-T data sets for the production of passive SAR imagery [19]. Bartley Reservoir, close to the University of Birmingham, was chosen as a location as it presented a near quasi-monostatic geometry, as well as a straight road to provide a linear aperture. Figure 4 shows an aerial view of Bartley Reservoir, with the vehicle path shown in yellow, the imaging direction indicated by the green arrow, and the Sutton Coldfield transmission station indicated by the red lines.
The same 650 MHz DVB-T channel was used for the experiment, with the transmitter now located 21.63 km from the centre of the aperture, at an angle of 73 degrees from the direction of motion of the receiver.

The full length of the road was 500m, however, for a typical measurement a roughly 400m aperture was produced in which the vehicle was travelling at a relatively constant speed of 8.94 m/s (20 mph) for approximately 40 seconds per measurement. The receiver was mounted on the University of Birmingham’s mobile laboratory, a Land Rover Discovery (Fig. 5).

![Fig. 5. Land Rover Discovery Vehicle Used for Ground-Based Measurements, with Two Patch Antennas Mounted on 1.5m Long Poles on the Roof of the Car](image)

The receiver was based on the same USRP used in the proof-of-concept test, and similarly two antennas were used, however, this time they were patch antennas with a 50 degree beam-width, custom-made at the University of Birmingham for ultimate installation onboard an airborne platform. These were mounted on 1.5m poles attached to the roof of the vehicle, placing them a total of 3m above ground level. The antennas had band-pass filters for interference rejection. The USRP streamed I and Q samples (10 MHz bandwidth) from both channels to a laptop computer.

Simultaneously to the radar measurement, a high precision SpatialFog Inertial Measurement Unit (IMU) and GPS receiver record the position of the vehicle with a high update rate [20]. The SpatialFog unit was connected to the same control laptop as the USRP and the position data was recorded to the same Solid State Drive (SSD). The IMU, USRP, and antenna front-ends were mounted securely within a vibration resistant box, along with batteries to provide power, so that the configuration matched that for the future airborne demonstrator.

2.1 Ground Demonstrator Results

The results shown here are from a single measurement, with the receiver travelling in the direction shown by the yellow line in Figure 4.

A back-projection algorithm was used to produce the SAR imagery for this measurement on a pulse by pulse basis. Range compression was performed by cross-correlating the reference and radar channels from the recorded data [20].

Figure 6 shows an image generated from this measurement, with a ground truth satellite image overlay. The area imaged is 4km is cross-range and 5km in range, spanning a total area of 20km squared. The colour scale is in dB, with 0dB representing the highest echo intensity in the image.

![Fig. 6. Reconstructed SAR Image of Bartley Reservoir Target Scene from Road Measurements, Overlaid with Ground-Truth Satellite Imagery](image)

The image is plotted on a local reference frame, where the origin is at the receiver location at the midpoint of the aperture. It should be noted that at a distance of 21.63km and 433m height, the transmitter is at near-grazing angle, while the receiver, at 3m ground elevation, is also at near-grazing.

In a microwave SAR, we would expect the front face of targets at near range to be imaged, with large parts of the target area behind them in shadow. However, such an effect is not shown here. On the contrary, the image looks to be more similar to that of an airborne SAR system, with typical grazing angles around 20 degrees. This is accredited to the indirect propagation effects that low-frequency radar systems possess – UHF in this case.

Also, immediately obvious are the strong returns at zero range and a repeating pattern of strong returns running across the image in a straight line. These returns are artefacts due to the main-lobe and side-lobe detection of a wall that runs parallel to the road used by the car, with an approximate height of 2m. While the mounting of the antennas atop long poles attempted to mitigate these returns, the wide antenna beam-width...
combined with the proximity to the wall made them unavoidable.

Also notable in the SAR image, when overlaid with the ground truth image (Fig. 6), is that the main reservoir and the smaller reservoir are dark and clearly outlined. A walkway runs across the smaller, semi-circular, reservoir, and this is clearly visible in the SAR image, as also shown in Figure 7.

![Fig. 7. Enlarged Subsection of the SAR Image and Ground Truth with the Walkway over the Smaller Reservoir Highlighted by the Red Outlines.](image)

Careful inspection of Figure 6 reveals that many of the strong returns are from trees, bushes and forested areas. However, along the motorway towards the bottom of the image, there can be seen a series of strong, almost point-like returns, which, after inspection of the ground-truth image, are found to be from a series of electricity pylons (Fig. 8).

Figure 6 also shows a noticeable gap in the returns beyond approximately 2500m range, despite this being within the antenna main lobe. It transpires that this can partially be explained by the terrain. Figure 9 shows the SAR image overlaid on the ground-truth and then mapped to a 3D topological map of the scene, where the z-axis represents the vertical height of the terrain map, relative to sea level. The presence of a large hill, approximately 80m higher than the SAR receiver’s road level at its highest point, goes towards explaining why large areas behind the hill are not visible to the receiver. The exception to this being a set of three high-rise buildings, shown more closely in Figure 10, and the pylons described previously, shown in Figure 8. It is crucial to highlight here that while the high-rise buildings may or may not be taller than the height of the hill, the pylons certainly are not. This is therefore another preliminary, but encouraging result showing the potential of the system for “beyond the hill” vision.

![Fig. 9. Topographic Map of the Bartley Reservoir Area, Overlaid with a Satellite Image of the Area and the SAR Image Shown in Fig. 6.](image)

![Fig. 10. Enlarged Subsection of the SAR Image and Ground Truth Showing Three High-Rise Buildings, Highlighted by the Red Outlines.](image)

3. PASSAT Demonstrator Airborne Trials

Following the success of the ground-based demonstrator, the hardware was re-packaged ready for flight in an airborne demonstration [21]. The same USRP receiver and twin patch antennas were used, only this time the antennas were mounted behind the (RF transparent) windows of carrying aircraft. The antennas each had a measured beamwidth of approximately 50 degrees and a gain of around 8dBi. As before, the antennas were connected to a radio-frequency (RF) front-end chain for amplification and band-pass filtering to reject out-of-band interference, built from off-the-shelf (Mini-Circuits) components.

The USRP down-converted incoming signals to baseband, storing digital I/Q samples to the internal, high-speed SSD of a portable workstation. The position of the aircraft was recorded by the Advanced Navigation SpatialFog – a high-precision GNSS aided Inertial Measurement Unit (IMU) which is capable of high update rates. The Spatial Fog unit was connected to the same control computer and recorded the positional data to the same SSD.
Synchronisation of the USRP with the SpatialFog was done during post-processing, as both instruments have their own GPS-disciplined oscillators (GPSDOs) and provide measurement timestamps.

Figure 11 shows a block diagram of the hardware involved. The radar electronics were mounted within a shock-proof case. A photograph of the receiver system is shown in Figure 12.

The airborne platform was a 4-seat Cessna 172N Skyhawk aircraft (Fig. 13). The two receiving antennas were placed on either side of the aircraft. As before, one was used to record the direct signal from the transmitter, whilst the other was pointed towards the target area. Due to shortage of space, the GPS antenna of the IMU was positioned at the back of the aircraft, and the distance between that and the radar antennas was taken into account during image formation. The arrangement of the equipment within the aircraft can be seen in Figure 14.

Fig. 14. Equipment Layout During Flight

3.1 Target Areas and Acquisition Geometry

As before, the DVB-T transmitter used was the Sutton Coldfield broadcasting station near Birmingham, UK, which is based on a 270.5 m tall mast mounted on top of a hill giving a transmitter height of 433m AMSL. The primary target area (Bruntingthorpe) was located nearly 46 km away from the transmitter, although other targets were imaged during the flight. The location of the transmitter, the target areas and the ground track of the aircraft are shown in Fig. 15. The total distance from the transmitter to the furthest target investigated was slightly over 51 km.

Image acquisitions were made in a nearly quasi-monostatic configuration so as to make analysis of the obtained images easier. The primary target area was in the vicinity of the Bruntingthorpe Aerodrome and Proving Ground, near Leicester, UK, and off the M1 motorway. Apart from the airfield itself, the area is rural and contains farmlands surrounded by tree lines and hedge rows.

The measurements were made at an aircraft altitude of 600 m above mean sea level, which is ~167 m above the top of Sutton Coldfield transmitter’s aerials and ~500 m above ground level.

As before, the measurements were done by recording a single DVB-T channel, centred at a frequency of 650 MHz. The experimental parameters are summarised in Table 1.
Note that the bistatic angle is defined as the angle between the transmitter and receiver lines-of-sight and the centre of the target area. The imaging geometry at Bruntingthorpe is shown in Figure 16.

Table 1: Experimental System Parameters

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
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<td>Carrier Frequency</td>
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<td>MHz</td>
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<tr>
<td>Bandwidth</td>
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<td>MHz</td>
</tr>
<tr>
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<td>kW</td>
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<td>Transmitter Mast Height</td>
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<td>m</td>
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<tr>
<td>Transmitter Distance</td>
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<td>km</td>
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<td>degrees</td>
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<tr>
<td>Receive Antenna Beamwidth</td>
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<td>degrees</td>
</tr>
<tr>
<td>Bistatic Angle</td>
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<td>degrees</td>
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<tr>
<td>Dwell Time</td>
<td>8</td>
<td>s</td>
</tr>
<tr>
<td>Average Ground Speed</td>
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<td>km/h</td>
</tr>
<tr>
<td>Aircraft Heading</td>
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<td>Degrees</td>
</tr>
<tr>
<td>Aircraft Altitude (above mean sea level)</td>
<td>600</td>
<td>m</td>
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Fig. 16. Satellite Image (Bing Maps) of the Bruntingthorpe Target Area with the Flight Path of the Aircraft (black line), Distance and Direction to the Transmitter (white line), and the Distance to the Airfield (yellow line) Shown

3.2 Image Formation

Bistatic SAR image formation typically involves the use of the direct signal from the transmitter to the receiver as a reference function for compressing radar echoes in range. However, for DVB-T, methods for providing this signal can vary. The optimal method is to decode the direct signal [22], and then locally reconstruct it without DVB-T pilot signals, which in passive coherent location applications can otherwise introduce false detections. However, to perform this operation is computationally expensive.

In airborne DVB-T SAR work so far, two different methods for providing range compression have been used. In the first one, the direct signal is recorded from a separate antenna pointed towards the transmitter, and is directly cross-correlated with radar data [7]. This can provide a cleaner version of the direct signal, but requires an additional RF channel.

The second method is based on the assumption that the direct signal is inadvertently collected by the radar antenna itself (most likely through its side-lobes, but that depends on the bistatic geometry). Therefore, range compression can be implemented simply by auto-correlating the radar data [9]. This method relies on the direct signal having a sufficient Signal-to-Noise Ratio (SNR) however it eliminates the need for an extra receiving channel. In addition, using such a method, artefacts in the imagery could be possible since all radar echoes would be correlated with each other.

Crucially, the latter method is especially relevant to PASSAT, and might be the only option for providing range compression. First of all, decoding the direct signal from a fast-moving platform such as a satellite is not a first option due to multipath Doppler spread [23].

Secondly, it has been calculated that for a sufficiently high SAR sensitivity, a receiving antenna of 15 dB gain can be deployed from a nano-satellite [4]. At a satellite altitude of 400km, the footprint of the antenna on the ground is so large that it is not possible to use separate antennas for direct and echo signal reception.

For the reasons above, range compression was tested during the trials for the cross-correlation and auto-correlation cases (Fig. 17), implemented in the frequency domain. This allows us to assess any artefacts arising from auto-correlation, since to evaluate this at the theoretical level would be a formidable task due to the number of possible targets in a target area. After range compression, azimuth compression was performed with a standard back-projection algorithm, taking the transmitter location and aircraft positional information from the IMU as inputs. In addition, the back-projection algorithm took into account the topography of the scene, which was obtained via free online Digital Elevation Maps (DEMs) of the terrain.

![Fig. 17. Correlation Schemes for Range Compression](image-url)

(a) Cross-Correlation Scheme; (b) Auto-Correlation Scheme
3.3 Airborne Demonstrator Results

A SAR image from the target area is shown in Figure 18(b). A satellite photograph of the area (taken from Bing Maps) is also shown next to it for comparison (Fig. 18(a)). The image was formed with a dwell time of 8s, corresponding to an overall aperture length of approximately 371 m, and with the cross-correlation method described above.

The colour scale is in dB, with 0 dB representing the maximum compressed echo intensity. The dynamic range of the image was clipped to 40 dB. The x-axis represents forward ground range from the receiver, while the y-axis is cross-range and is aligned to the flight direction of the aircraft.

A good correspondence between the SAR image (Fig. 18 (b)) and the photograph (Fig. 18 (a)) can be observed. In particular, locations of high echo intensity coincide with the locations and orientations of trees, hedgerows and buildings in the image.

Figure 19, which is an enlargement of the target area up to 2km in range and within a 2km cross-range span, shows these features more clearly (e.g. as seen by comparing Fig. 19(a) and (b)). Reflections from terrain are not visible, but at the low grazing angles of the transmitter and the receiver this is expected.
Another part of the image that can be investigated is the area around Bruntingthorpe airfield itself (Fig. 19 (c) and (d)). Hedgerows follow the outline of the airstrip, which are also visible in the SAR image. Additionally, there are points of high echo intensity in the SAR image which coincide with the locations of aircraft parking spots in the middle of the airfield.

Fig. 20. Comparison of Autocorrelation and Cross Correlation Schemes: (a) SAR Images Obtained via Auto-Correlating the Radar Channel; (b) SAR Images Obtained via Cross-Correlating the Radar Channel with the Reference Channel

In Figure 20, SAR images produced with the autocorrelation and cross-correlation schemes described earlier can be seen. The dwell time is 8s. There seems to be almost no difference in image details between the two images, so both seem to be acceptable – however there is one notable exception. Figure 20(a) shows a straight line artefact across the image obtained via autocorrelation. This corresponds to the side-lobes of the compressed direct path signal, and can be seen between 0 and +500 m cross-range. This kind of effect is not new, as passive SAR images obtained with Global Navigation Satellite System (GNSS) signals also exhibit this property (see [13] or [14], for example), and some evidence of this may also be seen in other works, such as [10]. What merits further investigation is why this artefact is not seen in images obtained by cross-correlation, and, if auto-correlation is used, how this artefact can be removed without affecting information on real targets in the scene. In addition, we observe that performing range compression via auto-correlation slightly increases the background level of the image. Specifically, the mean background level of the normalised SAR image is -42.1 dB in the auto-correlated image, and -45.4 dB in cross-correlated image, i.e. an increase of about 3 dB.

Further airborne trials are planned, but the results of this first run are very promising, and bode well for a future spaceborne demonstrator.

4. Spaceborne Demonstrator Planning
Before a constellation of PASSAT satellites is established, it will be important to gain confidence by means of a spaceborne demonstrator. This would be the next logical step following the current airborne trial work.

A basic requirements analysis has demonstrated that a 12U CubeSat would be a realistic basis for forming the platform for an operational PASSAT satellite [4], however, a basic “proof-of-concept” demonstrator could be accommodated in a 6U platform.

The analysis begins by considering that for a satellite in LEO, a typical pass time over a ground station in the UK is approximately 10 mins. Let us assume as a starting point that PASSAT requires, as a minimum, that a UHF receiver of similar capabilities to the one used in the airborne trials, be flown that can store samples of the signals received over an 8 MHz bandwidth during a dwell time on target of at least 80 seconds, which would give an azimuth resolution of a few meters. It is also assumed that SAR data would be downloaded to a ground-station without any image formation processing done onboard the satellite. This is the worst case scenario in terms of data rates and volumes. Assuming 8-bits per sample, and 16 MHz sampling rate, this requires approximately 1.2 Gbytes of on-board data storage, which could easily be accommodated using flash memory storage. The receiver itself is no different to a UHF super-heterodyne receiver and can therefore be very compact, especially using modern software-define radio (SDR) techniques. From this perspective, it is envisaged that the receiver/data storage element could be accommodated in a “1U” volume (approximately 10cm × 10cm × 10cm).

Based on the calculations above, to download the signal sample data in a single pass, a downlink data rate of approximately 18 Mbps would be required – assuming a 10% data packet overhead. Lossless data compression could reduce this by a factor of 3 (6 Mbps). This would require a bespoke S-band
transmitter, however, for a simple demonstrator, more time could be allowed for downlinking the images, in which case a smaller commercial-off-the-shelf CubeSat S-band downlink transmitter (see [24] for example) operating at ~ 2Mbps would be feasible, allowing one image data set to be downloaded each day. The usual CubeSat VHF or UHF downlink transmitters, operating at 9600 bps or 38,400 bps, would not be able to support the required payload data download – however, such transmitters could still be carried as a back-up, and to provide normal platform telemetry.

The peak power demand of the payload and downlink transmitter would be ~6-10W for no more than 10 minutes, which is well within the capability of a 6U or 12U CubeSat. Body mounted solar arrays should be sufficient, but deployed arrays could be used to increase the power available.

A link budget analysis of the bistatic SAR system indicates that a 15 dBi receive antenna gain is desirable on the spacecraft for an operational PASSAT system. This allows a generous 30dB margin for implementation losses and transmitter antenna pattern uncertainties. We favour using circular polarization on the spacecraft so as to overcome the deep fading effects due to Faraday rotation in the ionosphere at these frequencies – albeit at a 3dB link penalty. We propose, therefore, to mount an axial helical antenna of ~10 turns onto the CubeSat.

Basic antenna calculations show that such an antenna would be ~1.2m long at DVB-T frequencies, and therefore it would need deploying from the satellite once in orbit. To this end, a prototype 10 turn spring-loaded deployable helical antenna has been recently designed and built at the University of Surrey, which deploys from a ~4U volume (Figures 21 and 22).

If we can relax the gain requirements, then it should be possible to mount two patch antennas, similar to those used on the airborne demonstrator, as flat deployables on a 6U CubeSat. Here the gain would be ~6-8dBi assuming circular polarization.

The 3dB beam-width of a 15 dBi antenna is >30°, and so the pointing accuracy and stability requirements of the platform are not too onerous. The CubeSat Attitude Determination and Control System (ADCS) developed by Surrey and Stellenbosch Universities [25], as used on the QB-50 mission would be adequate (Figure 23).

In order to operate and maintain a controlled constellation of spacecraft, a degree of orbit control is required to phase the spacecraft around their orbits and to maintain spacecraft separation. Orbit control may also be required at the end of mission in order to dispose of the LEO spacecraft into the atmosphere within the 25 year period, post end-of-life, currently specified for UK missions. To this end, Surrey has developed a butane-based propellant system for CubeSats, designed to give 5–10 mN thrust range at ~ 80s Isp. A 1.5U volume would provide enough propellant to meet the orbit control and disposal requirements [26].

Combining all the elements above together, we conclude that a full PASSAT demonstrator should be feasible with a 12U CubeSat platform (approximately 2U for avionics, 1.5U for propulsion, 1U for the receiver payload, 3U for the S-Band downlink and 4U for the stowed deployable antenna), and that a simple proof-of-concept demonstrator, using deployable patch antennas, could be achieved with a 6U CubeSat.

Launching two 6U CubeSats together would allow multi-static SAR imaging and formation flying experiments to be carried out.

5. Conclusions

This paper has summarised progress into the investigation of the PASSAT concept. Following a ground-based trial, an airborne technology demonstrator was built and the first PASSAT airborne campaign was flown. Images were acquired and the validity of the demonstrator and the image formation algorithms was confirmed.
Aspects of SAR image formation in this configuration, such as means of performing range compression and the effects of SNR on the reference channel were considered. Shortly, a second airborne trials campaign will be undertaken, under fully bistatic acquisition geometries, to begin the interpretation of DVB-T SAR imagery, and to investigate methods of suppressing the direct signal sidelobes arising from performing an auto-correlation of the radar data for range compression. Design work on a spaceborne demonstrator is in progress.

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References


