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PASSAT: Passive Imaging Radar Constellation for Near-Persistent Earth Observation

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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 to 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, the emphasis is on the PASSAT concept, the space segment investigation and the experimental results of passive SAR imaging with DVB-T transmissions undertaken at the University of Birmingham using a local DVB-T transmitter.

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

Acronyms/Abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>CNES</td>
<td>Centre National d'Études Spatiales</td>
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<tr>
<td>DAB</td>
<td>Digital Audio Broadcasting</td>
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<tr>
<td>DGA</td>
<td>Direction Générale de l’Armement</td>
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<td>DSTL</td>
<td>Defence Science and Technology Laboratory (UK)</td>
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<td>DVB-T</td>
<td>Digital Video Broadcasting – Terrestrial</td>
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<td>EIRP</td>
<td>Effective Isotropic radiated Power</td>
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<td>FM</td>
<td>Frequency Modulation</td>
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<td>GEO</td>
<td>Geostationary Earth Orbit</td>
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<tr>
<td>GPS</td>
<td>Global Positioning System</td>
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<tr>
<td>ISS</td>
<td>International Space Station</td>
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<tr>
<td>LANL</td>
<td>Los Alamos National Laboratory</td>
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<td>LEO</td>
<td>Low Earth Orbit</td>
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<tr>
<td>NESZ</td>
<td>Noise Equivalent Sigma Zero (NEσ₀)</td>
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<td>OD</td>
<td>Odessa (Ukraine)</td>
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<tr>
<td>PASSAT</td>
<td>Passive Receiver SAR Satellite</td>
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<td>PCL</td>
<td>Passive Coherent Location</td>
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<tr>
<td>RF</td>
<td>Radio Frequency</td>
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<td>RTK</td>
<td>Real-Time Kinematic</td>
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<td>SAR</td>
<td>Synthetic Aperture Radar</td>
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<tr>
<td>SC</td>
<td>Sutton Coldfield (UK)</td>
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<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
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<tr>
<td>SSC</td>
<td>Surrey Space Centre</td>
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<tr>
<td>SSTL</td>
<td>Surrey Satellite Technology Ltd.</td>
</tr>
<tr>
<td>TE</td>
<td>Tehran (Iran)</td>
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<tr>
<td>TV</td>
<td>Television</td>
</tr>
<tr>
<td>UHF</td>
<td>Ultra-High Frequency</td>
</tr>
<tr>
<td>USAF</td>
<td>United Sates Air Force</td>
</tr>
<tr>
<td>USRP</td>
<td>Universal Software Radio Peripheral</td>
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<tr>
<td>VHF</td>
<td>Very High Frequency</td>
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1. Introduction

There is a current drive to provide a spaceborne, persistent near real-time global imaging capability by means of very large constellations of small, relatively low-cost satellites, e.g. CubeSats. A prime focus has been on using optical imaging systems, given that the required digital camera technology is mature, small in volume and mass, low power and inexpensive. However, such technology can only image the Earth’s
surface during sunlit and cloud-free periods.

For truly persistent monitoring of large areas, a spaceborne Synthetic Aperture Radar (SAR) system would be desirable, as this would be able to image day or night and through cloud. However, traditional SAR payloads are large, expensive and power-hungry – all of which mitigates against deploying large constellations of SAR satellites.

Whilst 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 interval. For example, even COSMO-SkyMed, a constellation of 4 satellites, has an update rate (not the revisit cycle, which is needed for SAR applications such as repeat pass interferometry) which is up to half a day [1]. Geostationary Earth Orbit (GEO) SAR missions have been proposed, but here there are major engineering issues due the severe radio-frequency (RF) path loss across the distances involved. Indeed, path loss is even more severe in radar systems than it is in radio communications, due to radar’s two-way nature.

To provide persistent (or near persistent) monitoring from LEO, a large number of satellites would be required, and whilst this may be technically possible, a satellite constellation of the required scale would not be economically viable with current SAR satellite technology.

The PASSAT project was therefore proposed and undertaken by the University of Birmingham, with support from the Surrey Space Centre (SSC), under the sponsorship of the UK Defence Science and Technology Laboratory (DSTL), to analyse the concept of a fully passive (receive only) spaceborne SAR system based on a constellation of microsatellites – by which we mean satellites in the 10-100kg class.

We propose to make use of existing terrestrial transmitters of opportunity, such as Digital Video Broadcasting–Terrestrial (DVB-T), Digital Audio Broadcasting (DAB), frequency modulated (FM) radio or similar, as the RF source, and thereby avoid the problem of having to carry a high power pulsed radar transmitter on the SAR microsatellite. Instead, the satellite need only carry a suitable RF receiver, antenna and signal storage facility.

It will be noted, therefore, that this is a bi-static system, with a RF configuration which has antecedents in the very origins of radar. Indeed, a generic passive radar concept combining spaceborne and ground-based segments is also not entirely new. For example, passive SAR with navigation satellites as transmitters and ground-based receivers has been considered at length in a number of publications (e.g. [2]-[7]). In other work, the German Aerospace Centre has considered a constellation of receive-only LEO satellites, with a satellite in geostationary orbit acting as the transmitter [7]. This is essentially the opposite configuration to that proposed for PASSAT (where we have a single transmitter on the ground and multiple receivers in space). However, this work has addressed a number of key issues which are directly applicable to the PASSAT concept (such as image formation and multi-static operation).

However, this exchange of the transmitter and receiver positions introduces a number of new features. In particular, the potential use of DVB-T transmitters is very attractive, as they are one of the most popular illuminators for passive radar due to their high transmit power and reasonable signal bandwidth, and whose feasibility for Inverse SAR Error! Reference source not found. and airborne SAR [10]-[11] has recently been experimentally demonstrated. The system can therefore be used in parts of the world where there is DVB-T coverage, which includes populated (urban or rural) areas but also littoral waters.

In addition, UHF operation would be a welcome addition to existing spaceborne SARs which typically operate in the L- to X-band microwave regions, without the need for the licensing which can be problematic at these low frequencies. The long wavelengths associated with these UHF frequencies does limit the ultimate spatial resolution achievable compared to a conventional microwave SAR system, however, such wavelengths are quite penetrating compared to microwaves, and thus may allow complimentary scene information to be obtained. For example UHF bands are known for their foliage penetration and non-line of sight propagation characteristics.

Thus, the ultimate aim of PASSAT is to provide persistent (or near-persistent) large area monitoring on a global scale by means of a network of passive bi/multi-static Synthetic Aperture Radar (SAR) satellites (Fig.1).

Fig. 1: The PASSAT System Concept

It is expected that such a system would:

(i) provide all-weather day/night imaging of a monitored area with a potentially achievable
resolution of 2-3m in range and azimuth directions;
(ii) cover mainly populated parts of the Earth and, partly, littoral waters;
(iii) have a system cost which would be orders of magnitude less than that of an equivalent active spaceborne SAR constellation;
(iv) be suited to implementation on a microsatellite platform.

We envisage applications including topographic mapping; land monitoring for natural disaster and surface movement detection; infrastructure monitoring and homeland security— including the monitoring of maritime traffic in littoral waters.

2. Preliminary Estimates of SAR System Performance

For the sake of system modelling, we assume that the transmitter is a DVB-T digital television broadcast station, similar to the one at Sutton Coldfield in the UK, operating in the UHF band. We further assume that the passive receiver satellites are in a 400km altitude low Earth orbit (LEO), such as may be achieved by deployment from the International Space Station (ISS).

Sutton Coldfield is typical in having a very high effective isotropic radiated power (EIRP) (86-200kW), and its signals are centred around 650 MHz (0.46m wavelength) - with each single television (TV) channel occupying 7.61 MHz of bandwidth. We take 100kW to be the transmit power.

The SAR signal processing is complex, and we envisage this being done primarily on the ground in the first instance. Thus, for now, we require the satellite simply to record both the direct and the terrain-reflected/scattered DVB-T signals for subsequent downlinking and processing “off-line”.

2.1 Signal Levels, Antenna gain and SNR Requirements

The direct DVB-T signal is necessary as a coherent reference for image formation in much the same way as in Passive Coherent Location (PCL). Traditionally, this signal could either be correlated with the reflected signals directly, or correlated after decoding, which can suppress multipath effects and unwanted DVB-T modulating signals such as pilot carriers. All the techniques above, however, require a sufficient direct Signal-to-Noise Ratio (SNR), say >13 dB, to give reliable decoding without matched filtering. The satellites would therefore need to carry a relatively high gain antenna to ensure adequate SNR. However, the greater the gain, the larger the antenna, and therefore the more difficult it will be to deploy from a small satellite. Thus, the gain must be kept within reason. Also, the beamwidth of the antenna must be sufficiently wide to allow direct and reflected/ scattered signals to be received from the entire coverage region around the transmitter – which may be an area ~100km to ~200km across.

From these considerations, we select a desired antenna gain of 15dBi, which gives a beamwidth of 36° (~260km swath at 400km altitude). Such a gain is similar to that of a typical domestic UHF digital TV antenna, used in a weak signal area.

The passive receiver SAR payload on the satellite would essentially be a software-defined radio linked to a signal capture and storage system. A typical receiver noise figure would be 2-5dB. It would need to have a high dynamic range (~100dB) to cope with the difference in signal strength between the direct and reflected/scattered signals.

From these requirements, we can estimate the initial system parameters for the SAR (see Table 1):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Effective Isotropic Radiated Power (EIRP)</td>
<td>$P_T$</td>
<td>100 kW</td>
</tr>
<tr>
<td>Radar wavelength</td>
<td>$\lambda$</td>
<td>0.46m</td>
</tr>
<tr>
<td>Signal bandwidth (single DVB-T channel)</td>
<td>$B$</td>
<td>7.61 MHz</td>
</tr>
<tr>
<td>Receive antenna gain</td>
<td>$G_r$</td>
<td>15 dB</td>
</tr>
<tr>
<td>Receiver noise figure</td>
<td>$N$</td>
<td>5 dB</td>
</tr>
<tr>
<td>Receiver altitude</td>
<td>$r_d$</td>
<td>400km</td>
</tr>
<tr>
<td>Receiver orbital speed</td>
<td>$v$</td>
<td>7672 m/s</td>
</tr>
</tbody>
</table>

One problem with taking the EIRP to be 100kW is that the vertical profile of the transmit beam is not well documented. Indeed, the signals from the DVB-T transmitter may be assumed to be directed towards the horizon, but slightly downward, so as to link to TV receivers on the ground. Thus, we may expect that the assumption of 100kW EIRP directed vertically (i.e. to space) is optimistic and therefore we should allow an adequate design margin (although the fact that the power is beamed towards the horizon is useful in overcoming the extra path loss when the spacecraft is not directly overhead).

The SNR at the receiver is given as (Eqn.1):

$$SNR_D = \frac{P_T G_r k^2}{(4\pi)^2 r_d^2 k T B N}$$ (1)

where $k$ is Boltzmann’s constant and $T$ is the receiver noise temperature.

From the parameters in Table 1, we get a $SNR = 43$ dB, giving a good 30 dB margin for other system losses due to beam pattern, atmospheric and ionospheric propagation and polarisation miss-match, if we take the required SNR to be 13 dB.
2.2 Signal Processing Requirements

One problem associated with the altitude of the satellite (400km) is that the 15 dB gain antenna will have a ground swath ~260km across. Whilst this is good in terms of potential imaging area, it does mean that it is almost certain that multiple transmitters will be in the antenna’s “field of view” at any one time.

Even with a multi-frequency network there will be a number of transmitters operating on the same frequency in that swath, thus, in order to ensure that the SAR image corresponds to a known area (i.e. around a known transmitter), the system has to be able to separate the reflected signals from different transmitters on the same frequency. The following characteristics are, in general, available to help achieve this:

- Differences in Doppler shift versus time due to differencing cross-range positions of the transmitters
- Differing relative range delays due to the differing down-range positions of the transmitters and
- Differing transmitter identification data.

It is believed that, in combination, these distinctive features are sufficient to resolve the potential confusion between the transmitters, although this is still the subject of on-going research.

One particular issue is that of decoding the direct signal when it is received from a fast-moving platform.

This is easier for a spaceborne SAR than for some other systems, since the (land) targets are not moving with respect to the Earth and the motion of the receiver with respect to the Earth is known with high precision.

DVB-T signals are, however, not particularly robust against motion of the receiver, because the Doppler shifts mean that the individual carriers are no longer orthogonal, although ‘stretching’ or compressing the entire signal (for example by slightly changing the sampling rate of the analogue to digital converters to compensate for the radial speed of the receiver) can correct for this. This means that what destroys the sub-carrier orthogonality is not the Doppler, but the Doppler spread of the different signal replicas at the receiver (namely the direct signal and ground reflections). Since each of these comes from a different direction, even assuming one single transmitter in the frequency of interest, they will be Doppler shifted with respect to each other, leading to inter-carrier interference.

However, despite this complexity, DVB-T transmitters are still preferred as illuminators because of their very high effective radiated power levels.

Sophisticated signal processing techniques may resolve some of these difficulties, but this would almost certainly entail transferring the raw captured signals to the ground, thereby increasing the load on the satellite data link compared to performing the correlations onboard the satellite.

In some circumstances, however, a simpler, or perhaps the only, way of resolving the ambiguities would be for the reference (e.g. direct) DVB-T signal to be received by the ground station, although this might be difficult in some scenarios. These are issues for further research.

2.3 Range and Azimuth Spatial Resolution

The expected spatial resolution of the SAR is complex to calculate, given the variable bi-static geometry inherent in the PASSAT concept.

The range resolution is given by (Eqn.2):

$$\delta r = \frac{c}{2B \cos(\beta/2)}$$  \hspace{1cm} (2)

, where $c$ is the speed of light and $\beta$ is the bi-static angle between the transmitter-target and the target-receiver lines-of-sight at the midpoint of the synthetic aperture.

In the best case of a quasi-monostatic arrangement ($\beta=0^\circ$), the signal bandwidth of 7.61 MHz, gives $\delta r = 19.7$ m. This could be improved by coherently combining adjacent DVB-T channels, or combining data coherently from multiple satellites flying in formation. Range resolution is further degraded as the bi-static angle increases, falling to no resolution at all at $\beta=180^\circ$1. However, the fact that there are multiple satellites, means that the diversity in satellite-transmitter-target geometries should enable good viewing angles to be achieved for each target. To this end, ultimately, a small formation of satellites at each orbital slot would be helpful, so as to allow multi-static operation.

Whilst the range resolution is rather poor for single TV channel operation, the azimuth resolution (\(\delta_{az}\)) can be very good – ultimately determined by the effective angular speed of the satellite (\(\omega_{s}\)) and its dwell time (\(T_d\)) on the target (Eqn. 3):

$$\delta_{az} = \frac{\lambda}{2\omega_s T_d}$$  \hspace{1cm} (3)

Again, in the quasi-monostatic case, this becomes (for stripmap SAR mode):

$$\delta_{az} = \frac{\lambda}{\theta_{az}}$$  \hspace{1cm} (4)

, where $\theta_{az}$ is the beamwidth of the antenna, which, for a 15 dB antenna (36°) gives a best-case azimuth resolution of 0.74m. It is not unreasonable then to expect that an ultimate spatial resolution of 2-3m could be achieved for this system. Whilst this is relatively poor compared to what can be achieved by the best microwave space SARs, it would still provide very useful spatial detail.
2.4 Sensitivity

The sensitivity of PASSAT can be assessed by the noise-equivalent normalised backscatter coefficient (NE$\sigma_0$), which can be derived as:

$$NE\sigma_0 = (4\pi)^2 r_t^2 r_r^2 kT_v N / (P_x A_e \delta \lambda)$$

(5)

where $r_t$ is the transmitter-target range, $r_r$ is the receiver-target range, $v$ is the effective satellite velocity and $A_e$ is the effective area of the receiving antenna.

Setting $r_r$ equal to the altitude of the satellite (400km), $A_e = 0.4$ m$^2$ (that is the effective area of the 15 dBi gain antenna including a 20% antenna efficiency loss, range resolution equal to that of a single DVB-T channel i.e. ~20m, $v$ equal to the satellite orbital speed, and keeping all other calculation parameters the same as before, the NE$\sigma_0$ can be shown to be very small (less than -40dB at 100km distance from the transmitter), thus long range operation looks to be feasible (Fig. 2).

In particular, Surrey Satellite Technology Ltd. (SSTL) produced a series of ~50kg “micro-satellites” in the 1990’s to support radio-frequency (RF) terrestrial signal receiver applications, including one for the French Space Agency (Centre National d’Études Spatiales – CNES) – the S/80T spacecraft, launched in 1992 [12] (Fig. 3) and one for the French Ministry of Defence (Direction Générale de l’Armement – DGA) – CERISE (Caractérisation de l’Environnement Radioélectrique par un Instrument Spatial Embarqué) launched in 1995 [13].

Radio receiver payloads were also carried by two satellites built for the United States – the 70kg PICOSAT-9, built for the United States Air Force (USAF), and launched in 2001[14] and the 163kg CFESat, built for Los Alamos National Laboratory (LANL), launched in 2007 [15], which attempted to deploy 4 inflatable log-periodic antennas to monitor the 100 MHz to 500 MHz radio spectrum via a software defined radio (Fig. 4).

However, one thing should be noted: the transmitter is at best a few 100m above the ground, and so the incidence to the (ground) target is small (e.g. 6° at 1km from a 100m tall transmitter). SAR systems generally do not work well at grazing angles of less than about 5° due to shadowing and to “layover” effects, whereby the returns from tall buildings are projected onto the ground further down range. At UHF, the problem could be mitigated by relying on indirect propagation, however such propagation effects and their effect on system sensitivity needs further research.

3. Space Segment Requirements Analysis

3.1 Platform Options for PASSAT

The UK has particular expertise in small satellite technology, and has produced a range of platforms suitable for the task of carrying passive space based radio receivers for monitoring terrestrial transmissions in the VHF/UHF bands.
Unfortunately, only one of the three antenna masts inflated correctly, potentially due to the RF cable bundle being too tightly constrained interior to the antenna masts. The other two masts inflated about half way before they stalled and vented, leaving the antenna elements in a non-optimal orientation [16].

The ~50kg satellites were stabilised using gravity-gradient booms and magnetorquer coils, giving a pointing precision of a few degrees off nadir. They rotated about the boom axis (i.e. the zenith-nadir direction) once every 10 minutes for thermal control purposes. They did not carry propulsion systems and so could not control or modify their orbits.

Their typical orbit average power was 25-30W using body mounted solar panels. With modern triple-junction cells this could be pushed to around 50W. CFESat, which had deployed panels, could generate more power – an orbit average of 110W, with 30W available to the platform. Again, with modern cells, this would be more like 150W.

CFESat was 3-axis stabilized, using a pitch momentum wheel and a yaw reaction wheel, along with dual redundant 3-axis magnetorquers as actuators. Pointing stability was maintained within ±0.5° with pointing knowledge to 0.1°, provided by dual redundant star trackers.

Since 1993, all the SSTL spacecraft have carried multi-channel GPS receivers, and so their orbit and position in space is known to relatively high precision – approximately ±15m. GPS also provides an excellent on-board timing reference.

Today, much of the capability demonstrated by these 1990’s satellites can be accomplished by much smaller platforms, taking us into the realm of so-called “nano-satellites” and in particular, CubeSats, whose size is measured in units of “U” (10×10×10cm), e.g. 1U, 3U, 6U, 12U).

PASSAT requires, as a minimum, that a VHF/UHF receiver 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 based on (2) in practice. It is also assumed that SAR data are downloaded to the station without any image formation processing done onboard the satellite as 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 an UHF super-heterodyne receiver and can therefore be very compact, especially using modern software-defined radio (SDR) techniques. From this perspective, it is envisaged that the receiver/data storage element could be accommodated in a “1U” volume of, say, a “12U” CubeSat spacecraft, which would have approximate dimensions of 20×20×30cm.

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), which would bring the data rate into the range available using the S-band high-rate transmitter (up to 10 Mbps) made by Surrey Satellite Technologies Ltd, with a size of 200 × 191 × 80 mm, and a mass of 1.8 kg. It should therefore be just about possible to accommodate it in a bespoke 12U CubeSat structure – leaving enough room for the rest of the spacecraft subsystems, payload receiver and deployable antenna.

If a slightly more capable payload becomes necessary, of course a slightly larger platform could be used.

If the images are formed on the satellite they could be subject to lossy data compression to ~1bit/sample and the resulting 2 Mbps could be just about feasible which just brings the data-rate into the realm of a CubeSat S-band downlink transmitter (see [17], for example).

The data downlink is therefore one of the main engineering challenges for the mission, and this, together with the amount of signal processing to be carried out onboard the satellite, will need further study as the mission and payload characteristics are refined.

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 downlink – 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 12U CubeSat. A simple “rule-of-thumb” metric is that for typical LEO missions, the orbit average power in watts is numerically equal to the mass of the spacecraft in kg (12-15kg for a 12U CubeSat) for body mounted solar arrays. Deployed arrays can increase this, but add complexity.

The PASSAT link budget analysis (Section 2.1) indicates that a 15 dBi receive antenna gain is required on the spacecraft. We favour using circular polarization on the spacecraft so as to overcome the deep fading effects due to the Faraday rotation which occurs when an UHF radio wave traverses the ionosphere. This, however, incurs a 3 dB link penalty.

We propose 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.
We estimate that such an antenna could be stored in a 4U volume (20×20×10cm) within the 12U CubeSat. A prototype of such a deployable helical antenna is currently in development at SSC.

The 3dB beam-width of the antenna is not less than 20°, and so pointing accuracy and stability requirements are not too onerous. The CubeSat Attitude Determination and Control System (ADCS) developed by Surrey and Stellenbosch Universities [18], as used on the QB-50 mission would be adequate.

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. This requires some form of propulsion. 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, SSC has developed a butane propellant based “warm-gas” propulsion 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 Error! Reference source not found.. Combining all the elements above together, the conclusion of the space segment analysis is that the mission should be feasible with a 12U CubeSat type 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).

3.2 Constellation Design for PASSAT

In order to provide Earth monitoring at high update rates, a constellation of these satellites is needed. However, the optimization of this constellation depends on the actual update rate to be achieved, as well as the required coverage. If truly persistent area monitoring is desired anywhere in the world, including the poles, an Iridium-type Walker Star constellation of 66 satellites would be appropriate. While a 12U CubeSat mission may still be economically feasible, this is a somewhat extreme example and gives perhaps an upper limit on the number of satellites needed. We envisage that the final PASSAT design would be a fraction of that size.

Various constellation configurations have been analysed, including a single International Space Station (ISS) launched 12U CubeSat (i.e. representing an initial technology demonstration mission): an ISS launched “string-of-pearls” constellation, with 4 satellites equispaced by 90° along-track in a single plane (this is the lowest cost option); an ISS launched Walker-Delta configuration and a Sun Synchronous orbit (SSO) Walker-Star configuration.

For the sake of system modelling, 3 widely spaced DVB-T stations were chosen as target sites: Sutton-Coldfield, UK: 52°36’2”N 1°50’2”W; Odessa, Ukraine: 46°27’0.0”N 30°44’28.0”E; and Tehran, Iran: 35.7° N 51.3° E.

For a single satellite in ISS orbit, in 10 days, there are 45 passes over Sutton Coldfield (SC), 56 over Odessa (OD) and 41 over Tehran (TE). Pass times range from 144 to 384 seconds (at SC), 80 to 383 seconds (at OD) and 150 to 381 seconds (at TE). At SC, there are thus ~4.5 passes per day all in succession, with ~19 hours between each group of passes. At OD, there are ~5-6 passes per day all in succession, with ~17 hours between each group of passes and at TE there are ~3-5 passes per day with ~15 hours between each group.

For the 4 satellite “string of pearls” constellation, there are more passes over each target per day, but the maximum delay (latency) is only reduced slightly (17 hours compared to 19 hours). The best configuration for ISS altitudes was to use a Walker-Delta configuration of 3 planes of 4 satellites, where the planes are separated by 120°. This gives a maximum latency of 30 minutes at all the target sites, and a maximum delay of ~3 hours anywhere between 60° N and 60° S.

4. Initial Ground Verification Experiments

To help verify the PASSAT concept, a ground demonstrator was set up on a short (40m) “railway track” on the roof of a building at the University of Birmingham (Fig. 5).

The receiving hardware was based on NI’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 its direct signal, which we refer to as the “heterodyne” channel. The signal recorded in this channel was used as the reference signal 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.

Only the antennas were physically installed on the mobile SAR platform simulator. Long cables (>40m) led from these to the USRP and the host PC, which were both located within the rooftop laboratory. The long cables introduced some losses, but due to the very high transmit signal power of the DVB-T transmitter, these losses were acceptable.

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).
In selecting the appropriate DVB-T broadcasting station, the orientation of the railway system had to be taken into account. The railway faces to the North (Fig. 6), but there is a ~13m long ventilation shaft directly behind it which is metallic. If the transmitters of opportunity in the South (Bromsgrove) or South-East (Brierley Hill) were used, our contiguous synthetic aperture length would reduce to approximately 17m.

Fig. 6: Railway System Orientation  
(image credit: Google Earth)

More importantly, looking at the coverage maps of these transmitters, none of them seem to cover the Birmingham area and that seemed to be due to a combination of local landscape and transmit power. For this reason, the only other option was to use the Sutton Coldfield transmitting station, 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 EIRP), which would help in testing our image formation algorithms. The transmitter is ~17.7km away from the receiver and its GPS co-ordinates are 52°36’2”N 1°50’2”W. The signal captured for image formation was the 650 MHz DVB-T channel, which is UHF#43.

Unfortunately, the location of this transmitter was not favourable in terms of the expected spatial image resolution. This is because the transmitter bearing is only 20° to the North from the receiver (see white arrow on Fig. 7) implying a near forward-scatter case where there is an essential loss in range resolution.

To somewhat alleviate this effect, squint-mode, rather than broadside, SAR acquisitions were made, with the radar antenna pointed at 40° and 60° relative to North.

Thus, given the necessary experimental setup, it was not expected that we would obtain high-quality imagery, as:

- We were in a near forward-scatter mode, where the range resolution is substantially degraded.
- We were operating at a 60° squint, where the azimuth resolution is degraded.
- The synthetic aperture length was only 40m, with target distances up to a few km.
- We were imaging at near-grazing due to the restricted height of the building.

Fig. 7: PASSAT Proof of Concept Imaging Area  
(image credit: Google Earth)

None-the-less, after signal processing, strong echoes were obtained (Fig. 8), which could be associated with buildings ~1-1.5 km away. Other related experiments have produced clearer imagery, which verify the operational principles of the concept.
In parallel to these experiments, and in preparation for airborne trials in 2018, it was sought to obtain other DVB-T data sets that could be used for SAR imaging. The reasoning behind this was to test the DVB-T SAR image formation algorithms developed in the first phase of the research, whose functionality could only be tested at a very basic level due to the unfavourable bistatic geometry (nearly forward scatter) of the Birmingham roof-top experiments. At the same time, having a DVB-T SAR image could allow us to have a first understanding of potentially unique imaging features.

Such a dataset was kindly provided by Fraunhofer IAF. The dataset was a by-product of a Fraunhofer experimental campaign which was not intended for SAR, but which could nevertheless be re-used for this purpose.

The measurements were conducted in Eckernforde harbour in Germany, using the DVB-T transmitter located in a neighbouring town. The receiver was mounted on a moving boat. Unlike in our roof-top experiment, this passive receiving system utilised a single antenna for simultaneously collecting direct signal from transmitter and the echo from the target area. The DVB-T transmitter mast is around 22 km from the receiver. The receiver’s movement passes a distance of around 400m within 81s dwell time, of which 20s were suitable for imaging.

As the received signal contains both the direct and reflected signals, the signal processing involves two steps. The first step requires knowing the DVB-T signal structure in advance and decodes the direct signal as the synchronisation. Based on the synchronisation results, a reference signal can be generated as a noise-free replica of the direct signal, but with pilot carriers suppressed. This reference is then used for the range compression of the reflected signal by matched filtering. FHR has done the decoding and shared the range compressed data.

In the signal processing, the data length of each range bin is 1120 μs, which is the cycle of one symbol of the DVB-T signal. Based on the range compressed data, the Back Projection Algorithm (BPA) has been used for imaging formation. The processing is achieved by firstly projecting the range compressed data to the Imaging area and then applying the coherent summation throughout the entire dwell time. No multi-looking, motion compensation, or sidelobe weighting have been applied. In the current stage, we are concentrating on applying the image formation algorithms to the data to see whether or not the algorithm essentially works. This is verified by trying to identify structures within the scene which are seen at the image level.

The obtained SAR image is demonstrated in Fig. 9. The image is superimposed on the optical photograph from Google Earth of a 7 km × 7 km wide scene. This is for a more convenient inspection of the target responses in the SAR image compared to the ground truth. The two dimensional map demonstrates the intensity of the reflections from the target area. The mapped values have all been normalised to the highest intensity of the target area (excluding the direct signal) as 0 dB, and the lower limit of the shown colorscale is artificially clipped to −45 dB.

In the SAR image, relatively weak signals are reflected from the water areas and forest areas. This can be expected for DVB-T signals belonging to UHF band, and its foliage penetrating characteristic is beneficial for covert target detection. Moreover, isolated targets are seen detected as far as 7 km away from the receiver. In addition to the image, four sets of sidelobes appear to be emanating from the lower right corner. It is believed these are in fact compressed sidelobes from four nearby DVB-T stations.

![Fig. 8: DVB-T SAR Image Superimposed on a Photograph of the Imaging Scene (obtained from Google Earth), for Ranges up to 1.5km.](image)

![Fig. 9: DVB-T SAR Imaging Results with the First 20s of Dataset (superimposed on the scene)](image)

Two target scenes of interest have been selected. The first one is the coastline area, shown in Fig. 9.
Comparing Fig. 10 (b) and (c), the coastline can be clearly picked up from the SAR image. Secondly, parts of the marina around \((X,Y= 2, -2 \text{ km})\) have been detected, that includes an outline of its outer walls but also its inner platforms. The pier located at \((3.3 \text{ km}, -250 \text{ m})\) is also observed as an isolated target, as well as returns from various points around the shore, which are found corresponding to isolated buildings or landmarks, e.g. the strong response near \((3.8 \text{ km}, -2.6 \text{ km})\).

The other target is a wind turbine situated at \((3.9 \text{ km}, -6.2 \text{ km})\), as shown in Fig. 11 (using 81 s dwell time), where a strong return is visible in the SAR results from almost exactly the same position.

Overall, the image looks similar to what we would expect from airborne or spaceborne images, which are normally taken around typical depression angles of 20 and 45 degrees, respectively. However, in this experiment, the transmitter mast is 22km away, so it is the transmitted signals are at near grazing angle. At the same time, the (boat mounted) receiver is practically at sea level, so it is also at near grazing angle. From a microwave SAR with these angles, we would expect to only be able to pick up an outline of the shoreline and the front face of buildings along it, with all other areas effectively being in shadow. The fact that we see more shows that passive operation at UHF exhibits indirect propagation effects, which can be evidenced (albeit at a qualitative level at this stage), in a number of areas such as the inside structure of the marina and the wind turbine which can be seen up to a distance of 7km from the receiver.

Of course these are very preliminary results under a non-conventional data acquisition scheme, but they perhaps begin to indicate the potential of DVB-T SAR imaging.

5. Conclusions

This paper has presented a new concept for passive bi-static SAR imaging from LEO, where terrestrial transmitters of opportunity, e.g. Digital Video Broadcasting (DVB-T) stations, are used as the active signal source and a LEO satellite acts as a passive receiver to form a bi-static arrangement. By recording the terrestrial reflected/scattered signals from the vicinity (~100km) of the transmitter, as well as the direct signal from the transmitter itself, and downloading this information for subsequent signal processing, SAR images with the potential for 2-3m resolution may be obtained.

Because the spaceborne payload is relatively compact and low power, it lends itself to accommodation on-board a very small spacecraft of the micro/nano-satellite class – and we believe that accommodation on a 12U CubeSat is feasible.

The resulting cost effectiveness enables the use of a constellation of such satellites to be used for near-persistent Earth Observation of populated areas. For example, a constellation of 12 satellites, operating at ISS altitudes, could give excellent, low latency (< 3 hour) coverage of the geographical region between 60° North and 60° South.

Initial ground experiments, carried out at the University of Birmingham have verified the basic principles, and we are now progressing towards a series of airborne trials over the UK. Work is also progressing at Surrey on the development of the deployable 15 dB i gain helical antenna, necessary for the space segment.

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