ASSESSING THE SUITABILITY OF THE CHILBOLTON RADARS FOR SPACE DEBRIS AND SPACE SURVEILLANCE APPLICATIONS

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ABSTRACT

The Science and Technology Facilities Council (STFC) operates several radars installed on its fully-steerable 25-metre diameter dish antenna at the Chilbolton Observatory in southern England. In the past, these radars have successfully detected a variety of satellite targets. High range resolution (HRR) radar profiling of ground-based targets has also been conducted. Recently, as part of the in-orbit testing activity for the EU 'Galileo' programme, the Chilbolton antenna has demonstrated highly accurate satellite tracking. This combination of satellite detection, HRR radar profiling and high-fidelity antenna tracking represents a useful capability for space debris and space surveillance work. Here, we describe the Chilbolton site, the 25-metre dish, its radars, and the results obtained in past experiments. Plans for future Space Situational Awareness (SSA)-related work at Chilbolton Observatory are outlined. The potential for Chilbolton, and other STFC assets, to contribute to the radar element of a European SSA network is discussed.

1. INTRODUCTION

Within the European Union, there is a growing interest in the development of a Space Situational Awareness (SSA) capability (see, for example, [1], in which the prospective use of Chilbolton in a future European space surveillance network is mentioned). SSA is necessary both to characterise the space debris environment and to obtain intelligence on foreign satellites by means of orbit-determination and imaging of the satellite structure (which often gives clues as to the intended mission).

Ground-based optical telescopes (eg: the USAF 'GEODSS' network) are capable of imaging large satellites in low earth orbit (LEO), but are less effective in characterising the new generation of tactically-useful small military satellites which are currently proliferating. From open-literature sources, it is thought that ground-based telescopes can only detect, but not characterise, satellites in geostationary orbit. Furthermore, the optical detection and characterisation of the space debris field is a difficult challenge.

Consequently, there is much interest in employing radar techniques for space object detection and characterisation. Several systems currently exist worldwide. These include (i) the American MIT Lincoln Laboratory Space Surveillance Complex, which includes (amongst other sensors) an X-band imaging radar; (ii) the German TIRA facility of FGAN, an L-band mono-pulse tracking and Ku-band imaging radar; and (iii) the French GRAVES facility, a bistatic VHF / UHF orbit-determination (non-imaging) radar.

In addition to the above-mentioned systems, the Rutherford Appleton Laboratory (RAL) of the UK Science and Technology Facilities Council (STFC) has initiated a study to investigate several different options for using its 25 m dish at the Chilbolton Observatory, and its associated radars, to implement a facility for (i) space debris population characterisation; (ii) satellite orbit determination; and (iii) range-Doppler imaging of selected satellites using inverse synthetic aperture radar (ISAR) techniques. Specific scenarios to be studied are discussed in section 6 below.

Chilbolton has extensive experience in the design and operation of advanced radar systems. In 2001, under funding from the UK Defence Evaluation and Research Agency (DERA), the 'CAMRa' (Chilbolton Advanced Meteorological Radar) S-band radar was successfully used in beam-park mode to detect 6 different satellites at slant-ranges up to 1300 km.

Subsequently, RAL worked with QinetiQ to install a wideband transmitter and associated signal processor, demonstrating high range-resolution profiles of terrestrial targets. It was planned to extend this work to space-borne targets, but the UK Ministry of Defence (MoD) suspended funding of the project.

More recently, through collaborations with ESA and Surrey Satellite Technology Ltd. (SSTL) on the Galileo programme, RAL Chilbolton has developed proven capabilities for high-accuracy (better than 0.1 degree error) tracking (eg: as demonstrated on the Giove-A, Giove-B, Compass-Beidou, GPS and Artemis satellites).

The fusion of RAL Chilbolton's expertise in radar technology, high-fidelity space-object tracking, and data acquisition and analysis makes the organization well-placed to pursue future space debris and space surveillance work.

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The aim of this paper is to alert the community to the capabilities and potential of the Chilbolton site in the SSA role. We hope to initiate collaborations with other European workers in this field. We also seek funding partners to continue, and to greatly expand, the use of the Chilbolton 25-metre dish for SSA work, and to develop new radar systems specifically tailored for this area of application.

2. THE CHILBOLTON OBSERVATORY

RAL's Chilbolton Group comprises 10 scientists and engineers working in the general areas of radio communications, radiowave propagation, radar remote sensing and atmospheric science research. The staff are split between the RAL Chilton site and the Chilbolton Observatory, near Stockbridge in Hampshire, where the 25 metre dish is located (Fig. 1). The Observatory has a permanent staff of 5, comprising scientists, engineers and specialist electrical and mechanical support technicians for the 25 m dish.

Figure 1. The Chilbolton Observatory site

The engineers at Chilbolton are experienced in RF and microwave systems, data acquisition, computer networking and dish operations. The Observatory is connected to the Internet via a high-speed fibre-optic link, which is well-suited for transferring large recorded data-sets from radar measurement campaigns. Additionally, software has been developed to allow control of the dish, radars and associated equipment from a remote terminal, with real-time display of relevant measured parameters.

Dormitory and cooking facilities are available on-site to support dish operations outside of office hours and at weekends. The site has full telephone, fax, e-mail and web connectivity. All these facilities are available to visiting experimenters.

3. THE 25 m DISH

The 25 m dish, which is the main facility at the Chilbolton site, is shown in Fig. 2.

In Autumn 2007, this dish was fitted with a Fast Feed Changer (FFC) assembly (Fig. 3), permitting the antenna to be rapidly re-configured between meteorological radar work and the Galileo-related satellite in-orbit testing (IOT) work. The FFC has 4 feed bays, only 2 of which are currently in use. A dedicated radar feed for future space radar work could be installed in one of the presently-unused bays.

Figure 2. The 25 m-diameter fully-steerable dish at Chilbolton Observatory

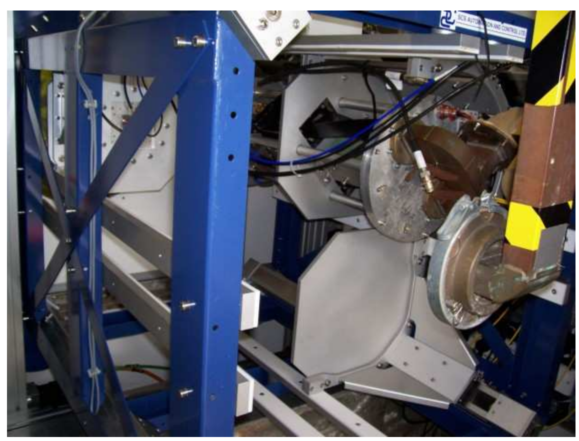

Figure 3. The Fast Feed Changer assembly

The dish is fully steerable in both azimuth and elevation, and is controlled via a PC-based system. As per our operational experience during the Galileo IOT campaigns, an orbital prediction program generates azimuth and elevation antenna pointing data from Two

Line Element (TLE) sets obtained from the NORAD Spacetrack web-site. These data are combined with locally generated GPS-derived time to facilitate real-time tracking.

Tracking system operation during the Galileo IOT campaigns has proven to be both accurate and reliable. The 25 m dish has performed reliably, with minimal down-time needed for unscheduled maintenance issues.

Very recently, a new dish drive and servo control system has been installed and commissioned. Thorough testing has confirmed that antenna tracking performance remains excellent. The electronics and mechanics of the new drive system should be much more easily maintained in the future.

4. THE RADARS

Several radars are currently installed on the 25 metre dish. The technical characteristics of these systems are briefly outlined below.

4.1. CAMRa radar

The Chilbolton Advanced Meteorological Radar (CAMRa), detailed in Tab. 1, is an S-band dual-polarisation Doppler radar employing the 25 m dish antenna, a magnetron transmitter, a dual-channel superheterodyne receiver, and a hybrid analogue-digital signal processor. The radar uses a digital signal processing scheme to achieve coherent-on-receive operation. The radar transmits alternately horizontally and vertically polarised pulses and simultaneously receives both co-polar and cross-polar returns. Full time-series measurements of I and Q are possible over a large number of range-gates and transmitted pulses.

Table 1. Specification of the CAMRa radar

Parameter	Value and comments
Operating frequency	3076.5 MHz
Antenna gain	53.5 dBi
Beamwidth	0.28° (FWHM; -3 dB, 1-way)
Polarisation	Tx: H, V; Rx: H and V
Transmitter type	Cavity magnetron
Peak power	600 kW
Average power	183 W
Pulse repetition frequency	610 Hz
Pulse width and coding	0.5 μs, un-coded rectangular
Receiver type	Superhet, log and I/Q channel
Noise figure	3.5 dB, plus duplexing losses
IF centre freq. and bandwidth	30 MHz centre, 4 MHz BW
Data acquisition system	7 channels, 12-bit / channel

The radar's feed and polarizer assembly is shown in Fig. 4. A detailed description of the radar sub-system hardware, and of the signal processing scheme, is given in [2].

Figure 4. The CAMRa radar's feed and polarizer assembly

4.2. ACROBAT radar

The Advanced Clear-air Radar for Observing the Boundary layer and Troposphere (ACROBAT), detailed in Tab. 2, is a fully-coherent L-band single-polarisation pulse-compression Doppler radar. The system employs the 25 m diameter dish antenna, a travelling wave tube amplifier (TWTA) transmitter, a low-noise down-converter and a flexible, programmable waveform generator and signal processor. The radar provides real-time measurement and display of the full target Doppler spectrum. Time-series of I and Q data may also be recorded for more detailed off-line analysis.

Table 2. Specification of the ACROBAT radar

Parameter	Value and comments
Operating frequency	1275 MHz
Antenna gain	47.5 dBi
Beamwidth	0.66° (FWHM; -3 dB, 1-way)
Polarisation	Tx and Rx: Horizontal
Transmitter type	Travelling Wave Tube
Peak power	2 kW
Average power	32 W
Pulse repetition frequency	2500 Hz, typically
Pulse width and coding	6.4 μs, 8 x 800 ns BPSK chip
Receiver type	Superhet, linear I/Q channel
Noise figure	2.5 dB, plus duplexing losses
IF centre freq. and bandwidth	60 MHz centre, 4 MHz BW
Data acquisition system	3 channels, 12-bit / channel

The racks which house the radar's exciter, IF signal processing, timing and control, and data acquisition sub-systems are shown in Fig. 5. A detailed description of the ACROBAT radar hardware is given in [3].

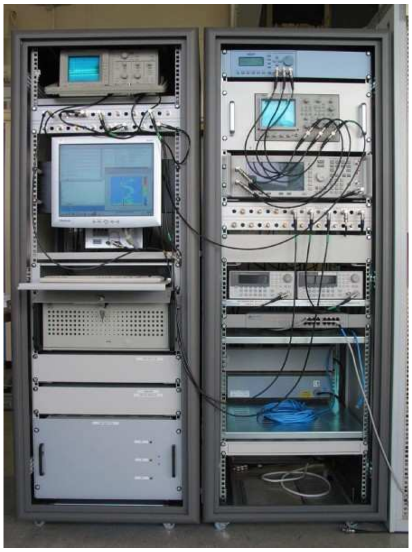

Figure 5. ACROBAT radar racks in the control room

4.3. AWS-5 radar

The AWS-5, detailed in Tab. 3, was originally a high-power, ship-borne, S-band military radar, which was subsequently modified for installation at Chilbolton. It features high average power, combined with a wide-band transmit waveform. In conjunction with QinetiQ's proprietary RPS (Radar Processing System), pulse-compression processing of the LFM (linear frequency modulated) chirped pulse yields high-range resolution in the order of 0.5 m.

Table 3. Specification of the AWS-5 radar

Parameter	Value and comments
Operating frequency	2900 MHz (2.7 – 3.1 GHz)
Antenna gain	53.0 dBi
Beamwidth	0.29° (FWHM; -3 dB, 1-way)
Polarisation	Vertical
Transmitter type	Travelling Wave Tube
Peak power	125 kW
Average power	2500 W maximum
Pulse repetition frequency	250 Hz, typically
Pulse width and coding	13 μs LFM, 400 MHz BW
Receiver type	Superhet, linear I/Q channel
Noise figure	5.5 dB system NF
IF centre freq. and bandwidth	700 MHz ctr., 400 MHz BW
Data acquisition system	Special (QinetiQ 'RPS')

The AWS-5 transmitter / receiver, together with its water-glycol cooling system, was housed in the basement of the 25 m dish. The cabinet containing the radar's transmitter, receiver, exciter, power and control sub-systems is shown in Fig. 6. The unit in the separate rack at the left of the picture is the RPS.

Figure 6. AWS-5 transceiver cabinet installed in the basement of the 25 m dish

5. RESULTS FROM PREVIOUS MEASUREMENTS

Here, we briefly describe the results of three separate pieces of work undertaken at Chilbolton for separate projects and customers. With sufficient future investment, the fusion of the capabilities demonstrated would yield a sensitive, high range resolution, satellite tracking radar for space object characterization.

5.1. Detection of satellite targets using the CAMRa radar:

With the objective of demonstrating that the radar beam could be pointed with high accuracy, a series of observations was undertaken on selected satellite targets in low-earth orbit [4], [5], [6]. Highly accurate orbital predictions for various satellites of suitable radar cross section (RCS) were obtained from the Satellite Group at DERA, Farnborough. The radar was operated in 'beam-park' mode. The antenna was directed to the predicted co-ordinates, and the data acquisition system was operated in time-series mode for several seconds around the predicted time of satellite transit through the antenna beam. Data were recorded, and processed off-line using MATLAB to generate plots such as the example shown in Fig. 7.

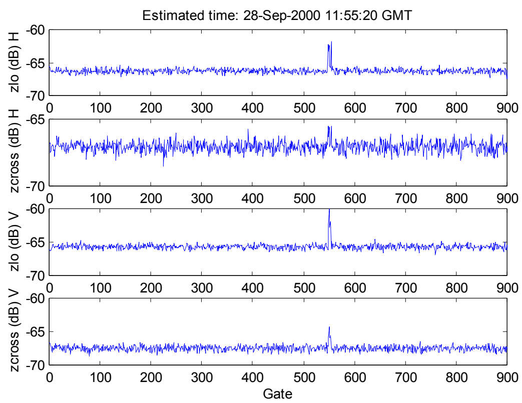

Figure 7. Radar returns from COSMOS 1346 at 1074 km range

In several cases, the target returns were sufficiently strong so as to be visible in real-time on the radar's A-'scope. A full list of the space objects observed is given in Tab. 4.

Table 4. Summary of all satellites successfully detected by the CAMRa radar

Satellite	Slant range / km	Comments
COSMOS 1346	807, 1074, 1286	3 detections
COSMOS 1782	729, 849	2 detections
COSMOS 2265	571	
COSMOS 2332	837	
METEOR 7	560, 1347	2 detections

Measurements of received echo signal levels proved to be largely in agreement with those predicted on the basis of expected satellite RCS and range.

5.2. High range resolution profiling of terrestrial targets with the AWS-5 radar

The AWS-5 system was installed at Chilbolton in 2001 with a view to its eventual use as a space object characterization radar. Although funding was not available to continue this work, early development did result in the commissioning of an operational radar on the 25 m dish. As part of the system testing phase, observations were conducted on ground targets to demonstrate the radar's HRR capability. A television transmitter mast at Hannington (shown in Fig. 8), some 22.5 km from the radar, was observed.

Figure 8. Hannington TV mast, at 22.5 km range from the Chilbolton radar site

The processed data clearly show the mast standing-out as a high-RCS target of short range extent embedded in a background of much lower-RCS ground-clutter. This measured HRR profile is shown in Fig. 9, and in greater detail in Fig. 10.

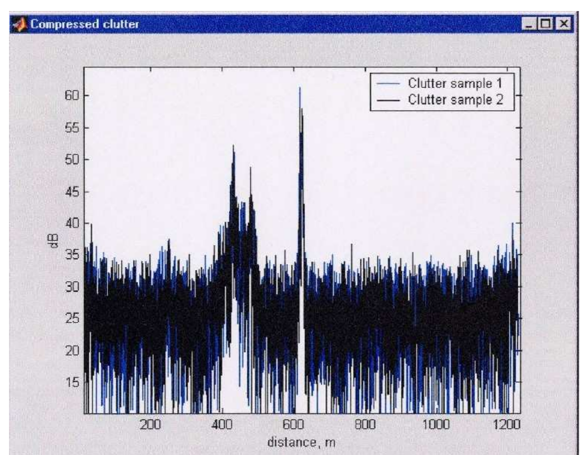

Figure 9. HRR profile showing detection of Hannington TV mast against a ground-clutter background

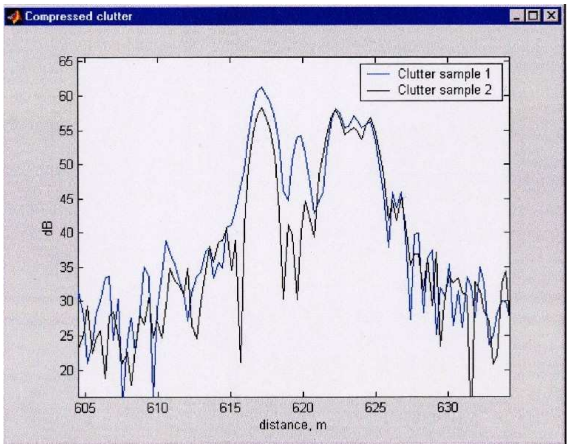

Figure 10. Expanded view of range-bins corresponding to the range interval around the Hannington TV mast

Although the AWS-5 radar is not currently operational, it could either be refurbished or replaced with an alternative wideband, high-power transmitter.

5.3. Highly accurate programmed tracking of the Giove-B satellite

As part of RAL's work [7], [8] with ESA and SSTL on in-orbit testing of the initial Galileo navigation satellites, Giove-A and Giove-B, a high-performance programmed tracking capability has been demonstrated using the Chilbolton 25 m dish.

Fig. 11 shows the results of effective isotropic radiated power (EIRP) measurements on the E5a CW transmission from the Giove-B satellite in May 2008. At this frequency of 1176.45 MHz, the 25 m dish exhibits a –3 dB beamwidth of 0.7°.

The curvature of the plot results from the shape of the satellite's transmit antenna pattern. However, the point to note is that the plot consists of 2 very closely overlapping traces, separated by only hundredths of a dB. These 2 traces represent the EIRP variation as the satellite, as seen from Chilbolton, was rising and setting, respectively. The fact that the traces match so closely is indicative of very high fidelity tracking on the part of the 25 m dish.

In the absence of a cueing sensor, such as a co-sited mono-pulse radar, such high quality programmed tracking is essential for space object characterisation work.

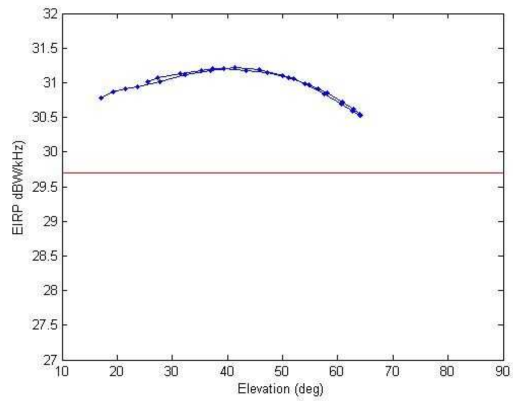

Figure 11. EIRP measurement of the Giove-B satellite, demonstrating high-fidelity satellite tracking

6. CURRENT SSA-RELATED PLANS USING THE CHILBOLTON 25 m DISH

Subject to funding support becoming available, it is hoped to pursue the following SSA-related activities using the Chilbolton dish – either as a stand-alone monostatic radar, or as a co-operative receiver in conjunction with one or more remote, bistatic transmitters:

i) Monostatic radar observations using the Chilbolton S-band and L-band systems: The potential of the CAMRa and ACROBAT radars for detection and tracking of some of the larger satellites in LEO will be assessed by calculation, and demonstrated by means of practical measurements.

ii) Bistatic radar observations using the RAL Chilton 12 m dish as an S-band CW illuminator, and the Chilbolton dish as a passive receiver: The feasibility of collecting statistical data on the space debris population passing through the common-volume of the Chilton and Chilbolton antennas will be assessed by calculation, and demonstrated by means of practical measurements.

iii) Possible collaborative bistatic radar observations with the TIRA radar as a wideband Ku-band illuminator, and the Chilbolton dish as a passive receiver: The ability of this configuration to generate bistatic ISAR imagery of satellite targets will be determined by calculation. An approach will be made to FGAN with a view to initiating a future collaborative programme of work in this area.

7. FUTURE SSA-RELATED APPLICATIONS OF OTHER STFC ASSETS

STFC owns, or has access to, two other large-scale facilities which may have applications in an SSA-related role. These are (i) the Mesosphere Stratosphere

Troposphere (MST) Radar Facility at Aberystwyth in west Wales, UK, and (ii) the proposed Low Frequency Array for Radio-astronomy (LOFAR) receiving station, to be located at Chilbolton Observatory.

7.1. The MST radar

The MST radar, described in [9], is operated by STFC on behalf of the UK Natural Environment Research Council. It is a 46.5 MHz monostatic radar, designed to investigate atmospheric dynamics – in particular, upper air winds.

This fully-coherent, pulse-compression, Doppler radar uses a bank of 5 transmitters, generating 160 kW peak-pulse power, in conjunction with the antenna array pictured in Fig. 12, comprising 400 x 4 element vertically-pointing yagis. A network of switchable phase-shifters is employed to swing the radar beam over an angle of ± 12° with respect to the zenith. A low-noise receiver and data acquisition system enable time-series data to be recorded over user-defined range intervals.

With simple modifications to the transmitted PRF and pulse-coding scheme, it is believed that this radar could be used to observe targets in low earth orbit.

Figure 12. The MST radar antenna array

7.2. The LOFAR array

The LOFAR project, described in [10], seeks to establish an international network of passive receiving stations, primarily for radio astronomy applications. Each station in the network comprises a pair of multi-element VHF phased-arrays. The low-band antenna (LBA) and high-band antenna (HBA) cover the frequency ranges 30 – 80 MHz and 120 – 240 MHz, respectively. Each comprises an array of 96 individual dipole elements. An existing LOFAR station LBA is shown in Fig. 13.

Because the output from each element of the arrays is digitized and stored locally in a high-performance computer, it is possible, using digital signal processing techniques, to form virtual antenna beams over a wide range of pointing-angles by post-processing the recorded data-set.

A LOFAR station is scheduled for installation at the Chilbolton Observatory in 2009-2010. This suggests the possibility of using the Chilbolton LBA as a co-operative receiver in conjunction with, for example, the MST radar transmitter, to form a bistatic radar for space-based target detection and characterisation.

Figure 13. Example of a LOFAR station LBA, similar to that shortly to be installed at Chilbolton

8. SUMMARY AND CONCLUSION

RAL's past work, future plans, and facilities of relevance to SSA have been presented. In particular, on the basis of successful previous projects at Chilbolton, it has been shown that:

- Radar detection of satellites has been accomplished
- High range resolution radar target profiles have been generated
- High-fidelity satellite tracking has been demonstrated

Considering likely future usage of the 25 m dish by currently-envisaged scientific programmes, it is anticipated that Chilbolton will have a high availability for potential SSA-related work. The dish also has 2 presently-unused bays available in its focus-cabin for the installation of special-purpose radar feeds. This makes the site well-placed to be included as a radar asset in the planned European SSA ground-based sensor network.

RAL is keen to collaborate with other organizations in exploiting the use of its current radar assets, and in developing purpose-built radars at Chilbolton for the SSA mission. To this end, we seek funding to support these activities, and to develop our expertise in, and facilities for, this strategically-important new area of work.

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