Detecting low earth orbit (LEO) satellites using UK-based atmospheric radars

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1 Introduction

A dedicated space surveillance radar network already exists for the purpose of tracking objects in the near-Earth space environment. This is motivated by a number of factors, including the potential for hazardous collisions between operational spacecraft (including satellites) and orbital debris or other spacecraft. There is an ever-increasing number of objects which must be tracked. Consequently, there is considerable interest in how radars that are primarily used for other purposes might contribute to the network. This extended abstract will examine the suitability of two UK-based atmospheric radars for this purpose: the Chilbolton Advanced Meteorological Radar (CAMRa) [*Goddard et al.*, 1994] and the Natural Environment Research Council (NERC) MST Radar at Aberystwyth.

2 The Chilbolton Advanced Meteorological Radar (CAMRa)

CAMRa is a 700 kW peak power, 3 GHz radar system that has been used predominantly for atmospheric research [*Goddard et al.*, 1994]. It has a fully-steerable, azimuth-elevation mount, 25 metre diameter, parabolic dish. This gives it a one-way half-power full-width of 0.28°. The dish can slew at up to 3° s^{-1} in azimuth and 1° s^{-1} in elevation. This allows the radar to continuously track LEO objects, based on their known orbits, as they move across the sky. The dish is typically programmed to begin tracking when the target is 1.0° below the horizon. However, the data acquisition system does not start to record until the target is a few degrees above the horizon. This allows the target to come within the maximum unambiguous range of 2100 km, which is determined by the inter-pulse period of 14 ms. It also reduces the distorting effects of atmospheric refraction for signal paths at very low elevation angles. The receiver signal is sampled at 75 m range gate intervals.

During a recent observational campaign, which was funded by the European Space Agency (ESA), the radar successfully tracked over 40 satellites in LEOs [*Eastment et al.*, 2011]. This was conducted during November/December 2010, April 2011, and May 2011. The missions of these satellites included: communications (IRIDIUM), weather observation (METOP-A, FENGYUN-3A, FENGYUN-3B), remote-sensing (ADEOS, AQUA, TERRA), Earth-observation (ENVISAT, RADARSAT-1, SPOT-5), and military/intelligence (COSMOS_1346, COSMOS_1782, GEO-IK-2).

The ease with which a target can be detected is quantified by its radar cross section (RCS). This is the cross-sectional area of a perfectly-reflecting sphere that would give the same radar return signal strength. This does not necessarily bear a direct relationship to the target's physical cross-section. Moreover, for a given target, the RCS can vary as a function of time owing to glints as the aspect angle changes with respect to the radar. CAMRa has been able to detect objects with RCSs as low as 2 m^2 (+3 dBsm) - e.g. CRYOSAT-2, shown in Figure 1 - at ranges of up to 1000 km. The International Space Station (ISS), by contrast, has one of the largest RCSs at 312 m^2. This allowed it to be tracked out to the maximum unambiguous range of 2100 km. This also makes it a good test target for the MST Radar - see next section.

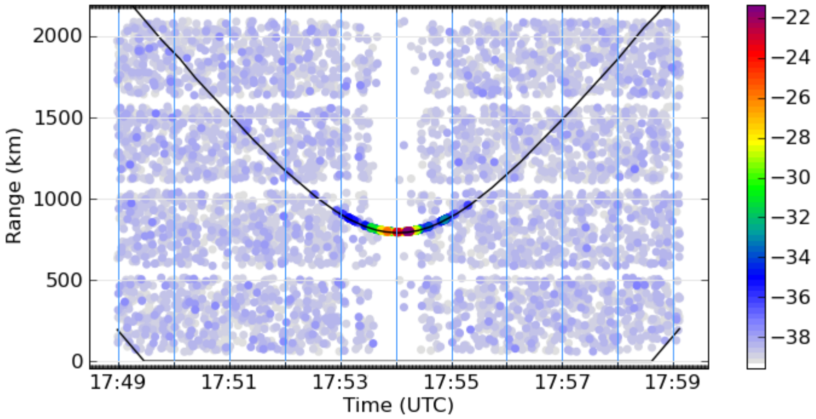

Figure 1: CAMRa signal power (dB), as functions of range and time (UT) on 1st December 2010, whilst tracking CRYOSAT-2

CAMRa can be used to do more than simply detecting an LEO object. It also has the potential to reveal whether or not an object is tumbling. Reports within the aerospace community indicated that the geodesy satellite GEO-IK-2, which was launched on 1st February 2011, had failed to reach its planned orbit. This was a result of the failure of its final stage rocket to ignite. Moreover, the satellite's orientation systems malfunctioned on 1st March 2011, which led to it moving out of alignment with the Sun. Owing to the subsequent loss of solar power, the satellite began to tumble. The spectrogram of CAMRa's co-polar receiver signals in Figure 2 shows evidence of this. The prominent peaks are at frequencies of 0.47 Hz/28.2 revolutions per minute (RPM) and of 0.24 Hz/14.1 RPM. This suggests that the satellite was tumbling at a rate of 14.1 RPM or a sub-multiple of this.

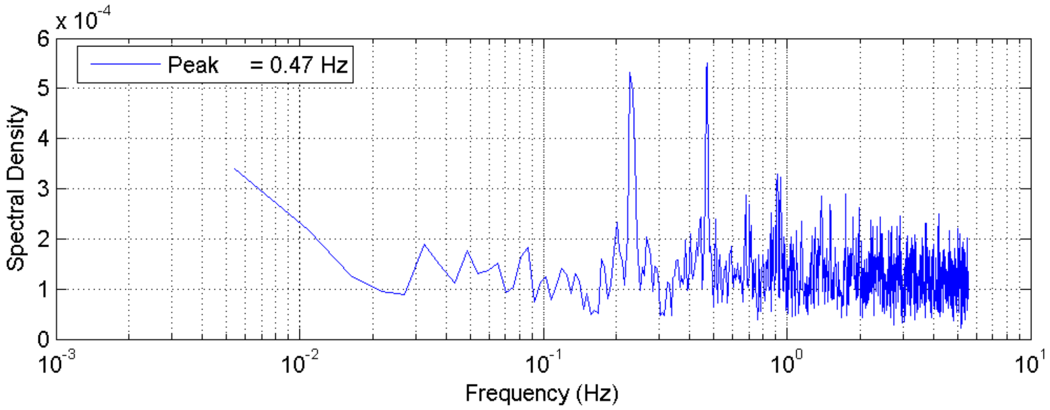

Figure 2: Spectrogram of CAMRa's co-polar receiver signal for observations made of GEO-IK-2 on 13th April 2011.

3 The NERC MST Radar at Aberystwyth

Although most of the radars used to detect LEO objects operate at UHF and above, the MU Radar in Japan has been used to demonstrate the potential of lower-VHF MST radars [e.g. *Sato et al.*, 1991; *Sato et al.*, 1992]. Initial studies used fixed beam pointing directions, a 7-bit Barker code with 64 μs sub-pulses, and coherent integration over 25 pulses. The latter corresponded to approximately 1 s.

Owing to the fact that the NERC MST radar still relies on a hardware-based radar control and data acquisition unit, it will not initially be possible to make LEO observations using an optimal configuration. Moreover, it will be necessary to modify the data acquisition software, to allow it to store the in-phase (I) and quadrature (Q) receiver samples, before a test observation can even be made. At present the I&Q samples are discarded after they have been used to derive the Doppler spectra. Nevertheless, this section demonstrates the steps required for selecting a suitable test target. Attention is focused on a particular orbit of the International Space Station (ISS), which passed over the British Isles at around 10:31 UT on 14th March 2012.

The NERC MST radar is considerably less flexible than both the MU radar and CAMRa in terms of its beam pointing capabilities. There are currently 17 available directions, which cover 5 zenith angles (0.0°, 4.2°, 6.0°, 8.5°, and 12.0°) and 8 azimuth angles (nominally N, NE, E, SE, S, SW, W, and NW, although the actual angles are 17.5° lower than the nominal ones). In fact, the new beam steering components installed during March 2011 allow up to 255 beam pointing directions to be defined - see *"Renovation of the Aberystwyth MST radar: Evaluation"* in these proceedings. Nevertheless, initial tests will concentrate on using existing beam pointing directions, which have proven reliability. Consequently, appropriate test objects must pass within approximately 12.0° of the zenith at the radar site (52.42°N, -4.01°E).

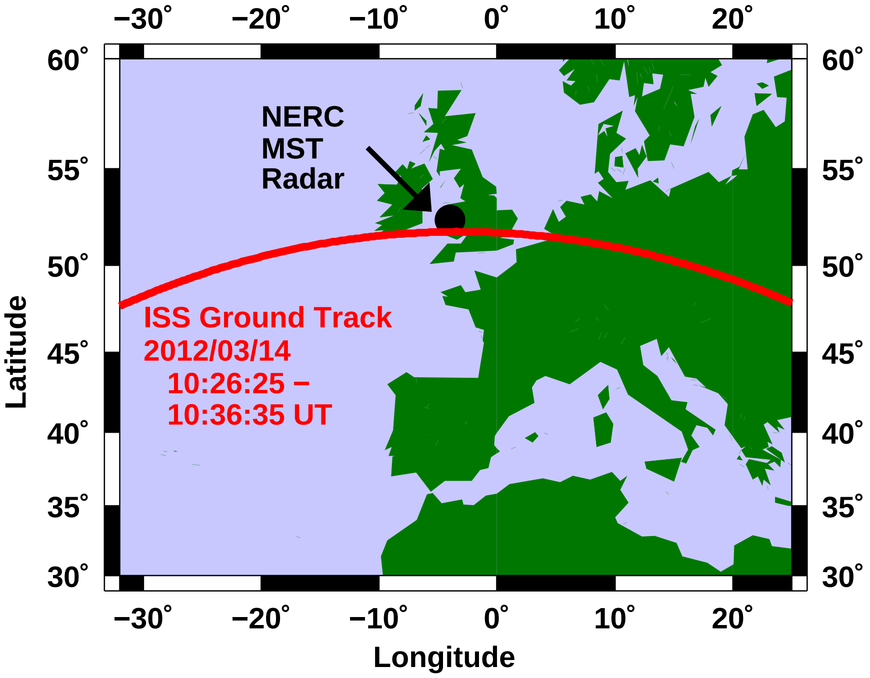

Figure 3: Ground track of the ISS for a particular orbit on 14th March 2012.

The inclination of the ISS's orbit is 51.6°. On 14th March 2012, the altitude was 378 km at perigee, 402 km at apogee, and 391 km when it passed to the south of the MST radar site around 10:31 UT - see Figure 3. Figure 4 shows the projection of the 17 available beam pointing directions at this altitude to ground level. It can be seen that the ISS passed almost through the centre of the SW12.0 beam, i.e. the one directed 12.0° off-vertical along an azimuth angle of 207.5°.

The hardware-based radar control and data acquisition unit imposes a number of limitations on making LEO observations. Firstly, the maximum available inter-pulse period is 640 μs, which corresponds to a maximum unambiguous range of 96 km. Any reflections from the ISS for the demonstration orbit, i.e. at a slant-range of 400 km, would have been range aliased 4 times over before being detected at an apparent altitude of 16 km. This means that they would have had to compete with atmospheric returns from the lower stratosphere.

The second limitation is that the in-phase and quadrature receiver samples are coherently integrated over a minimum of 81.92 ms. This should not be a problem in terms of isolating the signal in the time domain.

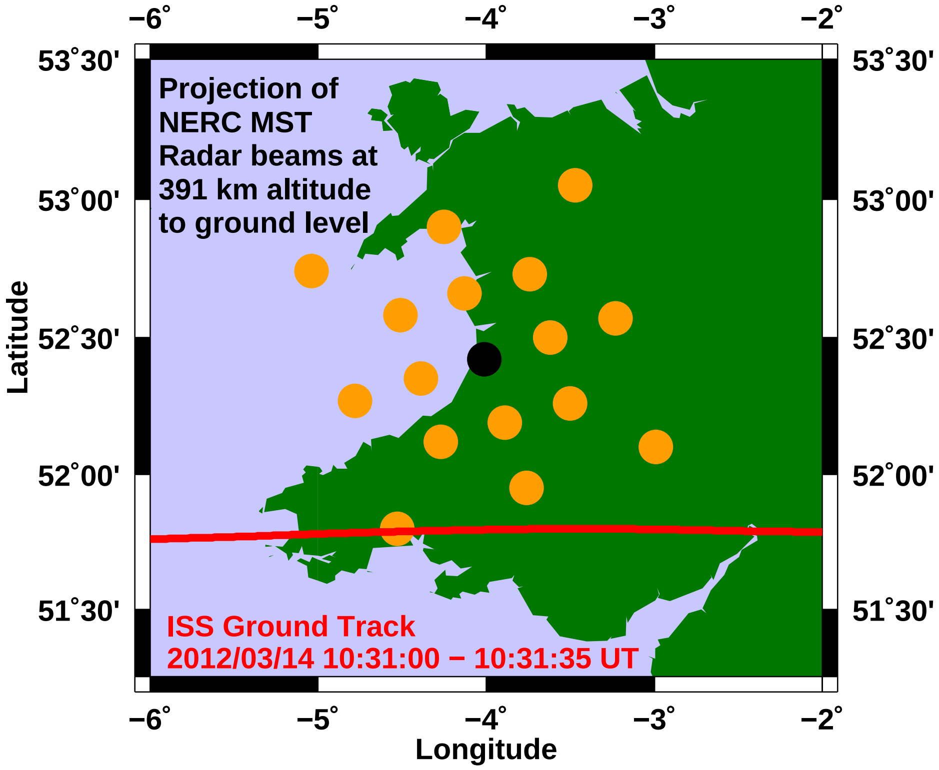

Figure 4: The ground track of the ISS passing almost through the centre of the SW12.0 beam for a particular orbit on 14th March 2012. The size of the dots corresponds to the two-way half-power full-width of the beams (2.1°). The black dot represents the vertical beam.

The orbital speed of the ISS is approximately 28,000 km hour^{-1}. The transit time through the radar beam would have been almost 2 s, corresponding to approximately 20 samples. However, the radial component of the velocity would have been in excess of 700 m s^{-1}. The 81.92 ms interval between consecutive samples results in a Nyquist Doppler velocity of just under 20 m s^{-1}. Consequently, the Doppler shift of the signal would have been aliased many times over and of no practical use.

At the time of writing this abstract (October 2012), the altitude of the ISS's orbit has been boosted by more than 20 km. This means that the exact details shown in this abstract are no longer applicable. The most significant effect will be that if an orbit passes through the SW12.0 beam, it will be range aliased to an apparent altitude of approximately 35 km. This puts it in the range between 21 and 56 km which cannot be sampled by the current hardware-based radar control and data acquisition unit. Consequently a new search for a potential target will have to be made as soon as the software has been modified to allow time series data to be recorded.

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