

Phase and pattern calibration of the Jicamarca Radio Observatory radar using satellites

B. Gao and J. D. Mathews[★]

Radar Space Sciences Lab, Pennsylvania State University, University Park, PA 16802, USA

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ABSTRACT

The Jicamarca Radio Observatory (JRO) main 50-MHz array antenna radar system with multiple receivers is being used to study meteors via two interferometric receiving modes. One of the major challenges in these studies is the phase calibration of the various receiver (interferometric) channels (legs). While investigating some ambiguous features in meteor head-echo results, we developed a ‘new’ calibration technique that employs satellite observations to produce more accurate phase and pattern measurements than were previously available. This calibration technique, which resolves head-echo ambiguities, uses the fact that Earth-orbiting satellites are in gravitationally well-defined orbits and thus the pulse-to-pulse radar returns must be consistent (coherent) for an entire satellite pass through the radar beam. In particular, the satellite yields a reliable point source for phase and thus interferometry-derived range, Doppler and trajectory calibration. Using several satellites observed during standard meteor observations, we derive satellite orbital parameters by matching the observed and modelled three-dimensional trajectory and Doppler results. This approach uncovered subtle phase distortions that led to interferometry-derived trajectory distortions that are important only to point targets such as meteor head-echoes. We present the array calibration and radar imaging of satellite passes from our meteor observations of 2010 April 15/16. Future observations of a priori known satellites would likely yield significantly more accurate calibrations, especially of distant side lobes.

Key words: techniques: radar astronomy – meteorites – meteors – meteoroids.

1 INTRODUCTION

Meteoroids are responsible for thousands of kilograms of mass flux into the Earth’s upper atmosphere annually (Mathews et al. 2001; Janches & Chau 2005) where, among many effects, their ions form ionospheric sporadic-E and intermediate layers (Tong, Mathews & Ying 1988; Morton, Mathews & Zhou 1993; Mathews 1998; Raizada et al. 2004). Radar meteor echoes have now been observed and studied for decades (for a review, see Mathews 2004). However, detailed observations of meteor head-echoes are only possible using high-power, large-aperture (HPLA) radars (Pellinen-Wannberg & Wannberg 1994; Mathews et al. 1997; Close et al. 2000; Chau & Woodman 2004; Mathews et al. 2008) such as the Jicamarca (Peru) Radio Observatory (JRO) 50-MHz radar system, which has the additional advantage that interferometry is enabled because this is an array antenna system that has separate antenna/receiver modules (Chau & Woodman 2004). Further details concerning the JRO radar

system and on these observations are given in our companion paper, Gao & Mathews (2015), hereafter [Paper I](#).

One of the main challenges in extracting information from point targets such as meteor head-echoes is to know the phase and amplitude offsets between different receiver channel pairs. Several phase calibration approaches for radar interferometry at the JRO have been discussed previously (Chau et al. 2008). These include the use of a common signal, such as a beacon, point radio astronomical sources and calibration against known features such as the equatorial electrojet (EEJ). The EEJ typically occurs over an altitude of 95–120 km and exhibits strongly aspect-sensitive scattering centred on the locus where local radar pointing direction is perpendicular to the geomagnetic field, $\mathbf{k} \perp \mathbf{B}$ (for details, see Lu, Farley & Swartz 2008, and references therein). However, our study on high-altitude meteor events (see [Paper I](#)) necessitates a more precise methodology that specifically applies to fast moving point targets, which might traverse all or most of the antenna beam including several side lobes. Because all of the parameters of a meteor head-echo (and thus of the progenitor meteoroid) remain unknown until they are observed by radar, there is no a priori information available to compensate for interferometer amplitude and phase errors (offsets). Incidental

[★] E-mail: JDMathews@psu.edu

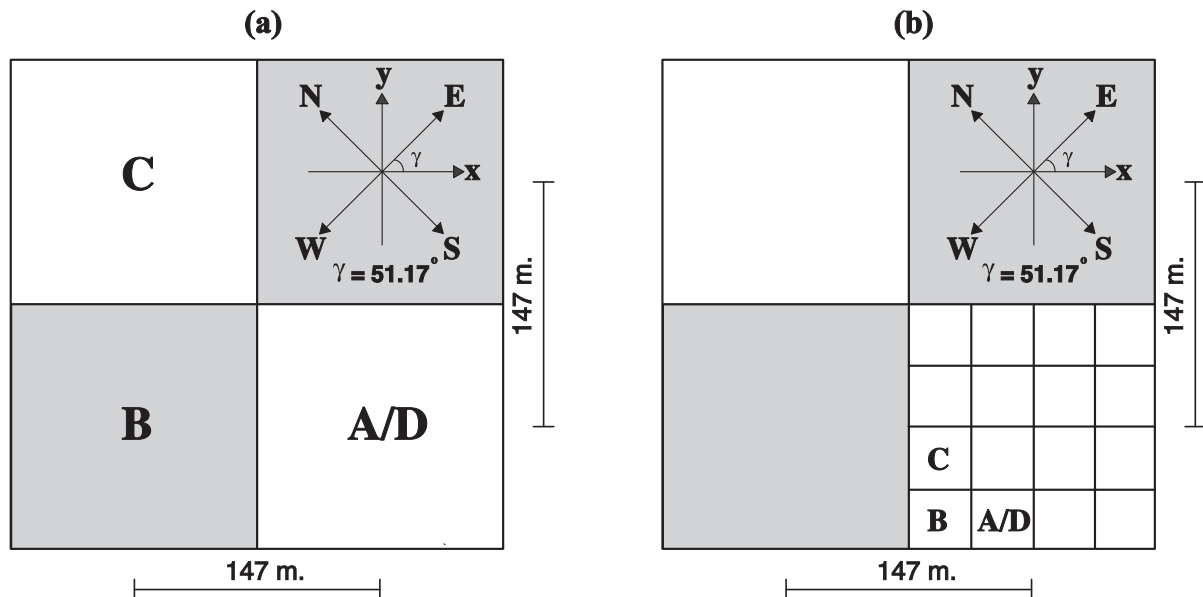


Figure 1. Antenna configuration for interferometric observations of meteors on (a) 2010 April 15 and (b) 2010 April 16. The transmission quarters are indicated in grey and remained the same for both nights. The first night used quarter sections for receiving while the second night used 1/64th module sections. Note that the subarrays labelled A, B and C use NE polarization, while the subarray labelled D uses SE polarization.

observations of low Earth orbit (LEO) satellites offer an ad hoc calibration source, because these orbits, and thus the satellite trajectory through the radar beam, are well-defined gravitational orbits whereby the radar return from each radar pulse is predictably related to all radar pulse returns from that event. Additionally, many satellites – but none of those reported here – have publically available orbital parameters, which, in principle, further constrain the derived calibration results, especially when mapping distant side lobes. The radar return from these satellites is that of a point target that is likely not highly aspect sensitive because the total JRO beamwidth for even a high-peak signal-to-noise ratio (SNR) target is likely no more than a few degrees; this determination is a major point of the research described in this paper. That is, the satellite returns resemble those of a meteor head-echo in many respects. This motivated us to study satellite signals in detail, leading to the new calibration technique reported here.

The calibration technique we report here is significantly different from the satellite technique reported by Sullivan et al. (2006) whereby optical (all-sky imager) satellite observations were used to correct the interferometric observations of the same satellite using the two 500-MHz EISCAT Svalbard Radar (ESR) antennas (a fixed, field-aligned 42-m dish and a steerable 32-m dish). In this case, the interferometer vector baseline was adjusted so that the radar path was coincident with the optical path of the satellite. They note that application of this approach to multiple satellites would refine the baseline calibration. Their technique does not include finding the precise orbital parameters of the satellite. Beyond this, it is certain that various military radars are calibrated using satellites with precisely known orbits.

The measurements presented here have been performed using an uncoded long pulse (see Section 2 for details). The reason for using this pulse mode is that meteor head-echoes are usually weak and with large Doppler shifts. Additionally, this mode parallels one commonly used at the Arecibo Observatory (e.g., Mathews et al. 2010).

This paper is organized as follows. First, we describe the experimental set-up. We then discuss the issues encountered and solutions chosen during analysis of the satellite signals on the way to calibration of the JRO interferometric observing modes. A summary and conclusions follow.

2 EXPERIMENTAL SET-UP

The results presented here all derive from observations carried out on 2010 April 15 and 16 using the JRO 50-MHz radar. Details are given in Paper I.

Meteor observations have been made using the east and west quarter-sections of the Jicamarca array ($\sim 144 \times \sim 144$ m²) for transmission and the north, west and south quarter-sections for reception on the first night (April 15). Three adjacent 1/64th array modules (see the lower-right quadrant of Fig. 1b) were used for reception on the second night (April 16). The same linear polarization (NE) has been used in both modes. Receiver D is an extra receiving channel that employs the perpendicular-dipoles in one array module to observe the orthogonal polarization of the received signals.

The JRO array was phased to point the antenna central axis off-vertical by $\sim -1^\circ 488$ in the y-direction. Although complex voltages (raw data) from four quarters could be recorded simultaneously, in principle we only need the information of three non-collinear antennas with the same polarization in order to locate the meteors inside the transmitting beam, albeit with 2π phase ambiguity. For the major results we present in this paper, we have used quarters A, B and C to obtain the angular positions of meteors with respect to the x- and y-axis. Note from Fig. 1 that the x-axis is rotated with respect to the east–west baseline by $\sim 51.17^\circ$.

The actual transmitting half-power beamwidth is $\sim 1.1^\circ \times 2.2^\circ$. The main radar parameters for the meteor mode are summarized in Table 1. The radar has until now been regularly calibrated using a beacon located on a nearby mountaintop and by aligning to the $\mathbf{k} \perp \mathbf{B}$ region of the EEJ (Woodman 1971; Kudeki & Farley 1989; Lu et al.

Table 1. Radar parameters used in observing meteor-head echoes at the JRO.

Parameter	Value	Units
Inter-pulse period	300	km
Pulse width	3	km
Code	No	
Sampling rate	0.15	km
Initial range	75	km
Number of samples	1300	
Number of complex channels	4	
Bandwidth	1	MHz
Transmitter peak power	1.1	MW

Table 2. JRO coordinates.

Latitude	11°95 S
Longitude	76°87 W
Altitude	533.25 m
Antenna tilt angle	1°488
Antenna diagonal angle	6°167
On-axis declination	12°88 S
On-axis hour angle	4.76 min W

2008). Other methods are given in Chau et al. (2008). In practice, these methods, including the use of radio astronomical sources, are not sufficiently accurate for our purposes. Table 2 lists the various coordinates of the JRO.

3 HIGH-ALTITUDE METEOR EVENTS OBSERVED WITH THE JRO

Fig. 2 shows the prototype high-altitude meteor event that led us to this investigation. It was captured at an apparent beginning height of 170 km (Fig. 3a) with a weak trail-echo recorded at ~ 160 km. As described in Paper I, this apparently extraordinary event type has in the past been largely attributed – with some justification (Vierinen, Fentzke & Miller 2014) – to ‘normal’ meteor returns seen in the side lobes of the antenna beam. The possibility of side-lobe contamination led us to carefully calibrate the system as described here. Note that, unlike the EISCAT 224-MHz radar, the Jicamarca array radar does not exhibit any strong spillover side lobes. Also note that we are expecting to implement more complete calibration modes as we, and others, develop them.

The ranges of the event shown in Fig. 2 were determined via peak-searching within the ambiguity function (Mathews et al. 2003) where the 2π ambiguity was removed from interferometric location results such that all of the trajectory (phase) points would produce a nearly straight-line trajectory, as shown in Fig. 3(b). Furthermore, the meteor SNR to beam-pattern matching technique was employed to locate the meteor head-echo within the beam (Chau et al. 2008), as shown in Fig. 3(c). No other trajectories resulting in beam-pattern matching – ignoring side-lobe attenuation – were found out to $\sim 60^\circ$ zenith angle where, again, we note that array imperfections likely dominate the pattern at large zenith angles. However, we do find some phase distortion (bias) in the interferometry results. This issue has been raised as a symptom of side-lobe contamination. In order to address this issue, we studied the interferometric characteristics of satellites observed during the meteor campaign in search of a satisfactory explanation of the phase distortion.

4 CALIBRATION USING SATELLITES

As mentioned in Section 1, and as provoked by the potential high-altitude meteors introduced above and in Paper I, we have developed a technique using the satellites observed during meteor observations to calibrate the Jicamarca main radar array system. The advantages of employing satellite radar returns are as follows.

- (i) Satellites can be treated as point-target scatterers.
- (ii) Because the JRO beam is relatively narrow, the observed radar trajectory of the satellite is linear and of nearly constant radar (scattering) cross-section (RCS). Satellites stay in the beam for a few seconds, yielding very accurate trajectories.
- (iii) The orbital parameters of a satellite are gravitationally well defined by simple Newtonian orbital mechanics yielding pulse-to-pulse (phase/Doppler) coherence across the entire event.
- (iv) Because the orbital elements of many satellites (although none of those reported here) are available in various tracking data bases, it is possible to precisely predict flybys for use in future observations. This will, in principle, provide even more precise calibration results, especially in the distant side lobes.

We observed a total of 20 orbital objects – 16 on the first night and four on the second night – during the two short observation periods reported here. The range-time-intensity (RTI) of one of these events is given in Fig. 4. Satellites have highly distinguishable characteristics relative to meteors. In particular, they exhibit a much longer duration than meteors and have a clear SNR-modulation pattern as the satellite passes through various lobes of the net antenna-beam

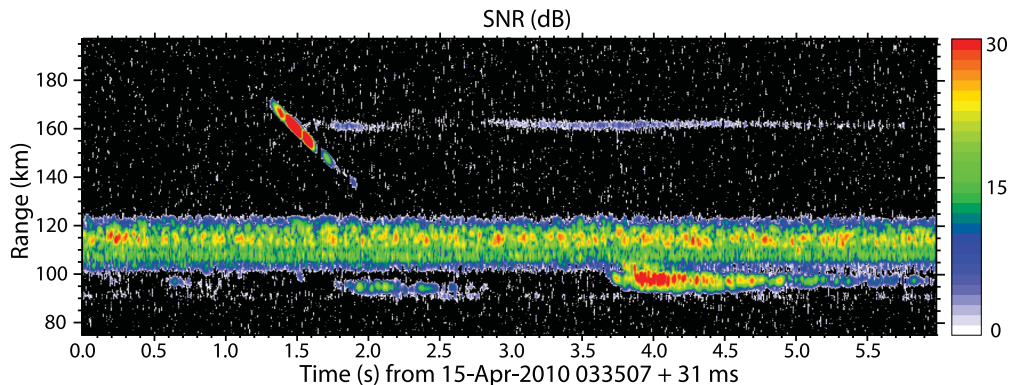


Figure 2. The prototype high-altitude meteor event observed with the JRO 50-MHz radar. The head-echo was first observed at a height of approximately 170 km along with a trail-echo at about 160 km. The SNR (colour bar in dB) is enhanced via convolution to show the weak trail-echo.

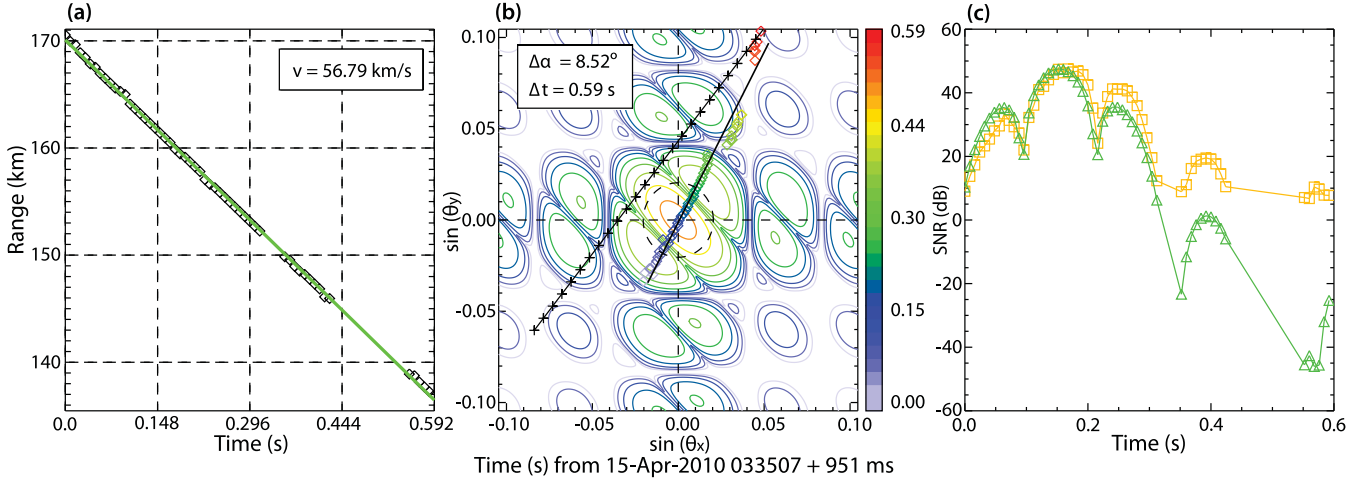


Figure 3. The Fig. 2 meteor head-echo characterization: (a) range versus time; (b) $\sin(\theta_x)$ versus $\sin(\theta_y)$; (c) SNR versus time. In (a), the range-fitting line is presented in green. The fitted slope corresponds to a 56.79 km s^{-1} line-of-sight speed towards the radar. Panel (b) gives the unwrapped phase-fitted interferometric trajectory (thick black solid line). The 2π ambiguity circle is shown as the dashed circle. A thin solid line overlaid with plus signs indicates the radar $k \perp B$ region at an altitude of 100 km (for details on finding this region, see Lu et al. 2008). The theoretical two-way radiation pattern (dB) is plotted in the background. Different colours along the observed trajectory indicate the unwrapped phase evolution with respect to time. The systematic distortion of the trajectory relative to the linear fit has been cited as evidence that the meteor is in a distant side lobe. In (c), the measured SNR versus time is plotted in yellow, while the expected relative SNR based on the theoretical antenna pattern and phase information, is denoted in green.

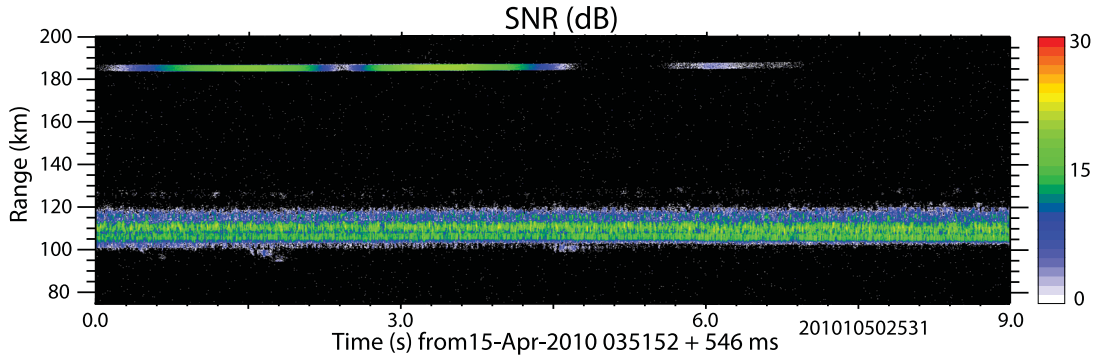


Figure 4. RTI plot of a satellite signal. The SNR pattern (dB colour scale) indicates that this particular satellite flew through three lobes within ~ 7 s. The vertical spread of the satellite return signal reflects the transmitted pulse width ($20 \mu\text{s}$, 3 km).

pattern. The actual range of suspected satellites was determined by estimating the angular speed across the beam using interferometric results and then matching that with the apparent range plus 300 km times the number of aliased range to find an acceptable circular orbit. Once the actual range is established, the detailed orbit is obtained using the range rate and Doppler matching. A typical satellite RTI return is given in Fig. 4, while its major radar characteristics are given in Fig. 5. In order to fully utilize satellite trajectories through the net (transmit–receive) JRO beam for calibration purposes, we must first carefully understand the trajectory information. We next outline the detailed analysis steps employed.

4.1 Orbital speed determination and range de-aliasing

The method we employ to determine the point-target ranges is to search for peaks in the ambiguity function of the uncoded long rectangular pulse (Mathews et al. 2003). In pulsed radar, the ambiguity function $\chi(\tau, f_D)$ is a two-dimensional function of time delay τ and Doppler frequency f_D showing the distortion of the return

pulse due to the Doppler shift of the return from a moving target. The ambiguity function is

$$\chi(\tau, f_D) = \int_{-\infty}^{\infty} s(t)s^*(t - \tau)e^{j2\pi f_D t} dt, \quad (1)$$

where $s(t)$ is a given complex baseband pulse (in our case, a $20 \mu\text{s}$ uncoded rectangular pulse) and $*$ denotes the complex conjugate in equation (1). In practice, instead of calculating the convolution in the time domain, we compute the fast Fourier transform (FFT) of the return signal and of the transmitted code. Then, we find the inverse FFT of their product.

The SNR of observed satellites is usually weaker than the net return from the EEJ region, as shown in the example in Fig. 6. Therefore, we set the complex voltage values to 0 for the range window over which the EEJ occurs (~ 95 – 120 km). Then, the local peak of the satellite return becomes the global peak, and the relatively simple peak detection method within the ambiguity function works well to determine the heights of the target satellite as seen from Fig. 6.

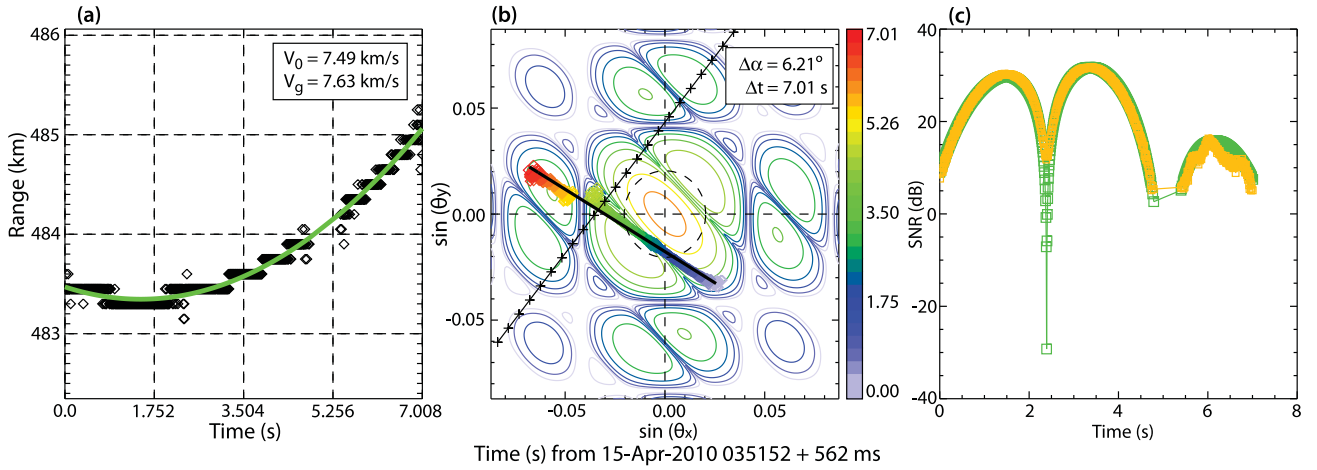


Figure 5. Characterization of the Fig. 4 satellite: (a) range versus time; (b) $\sin(\theta_x)$ versus $\sin(\theta_y)$; (c) SNR versus time. In (a), the range polynomial fitting line of degree 2 is presented in green. In (c), the green curve is the theoretical pattern along the trajectory shown in (b).

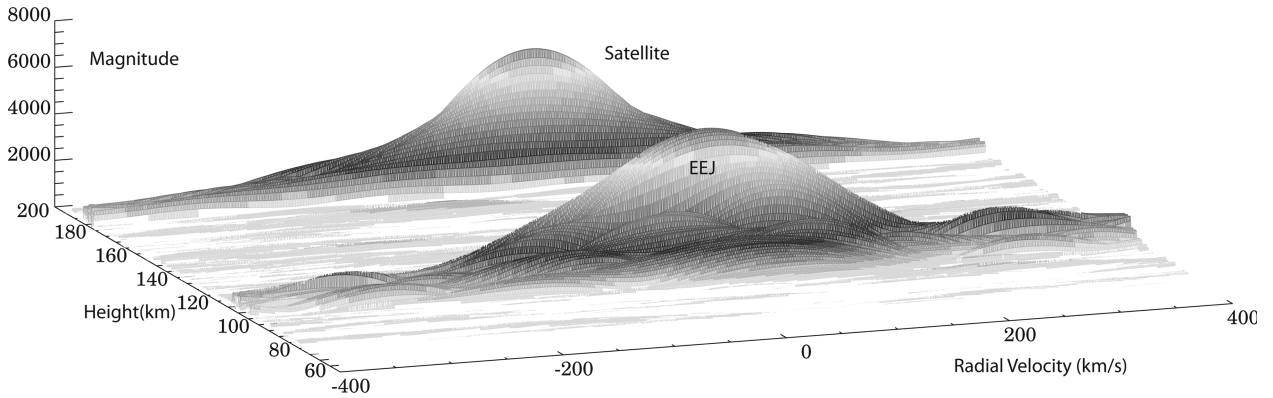


Figure 6. Ambiguity function of actual data in which both the EEJ and the satellite returns are present. The local peak at a height of $\sim 180 \text{ km}$ is the range-aliased satellite return, which is actually smaller in magnitude than the EEJ at a height of $\sim 110 \text{ km}$.

Because the inter-period pulse (IPP) for the observations reported here is 300 km , it is nearly certain that the satellite return signal is from one of the previous pulses. The satellite orbital speed is the key to estimating the actual range of the satellite. As a first guess, the speed of the satellite is estimated as

$$v_{\text{est}} = r \frac{\Delta\alpha}{\Delta t}, \quad (2)$$

where r is the radar range determined at near zenith and $\Delta\alpha$ is the total observed angular trajectory of the satellite through the JRO beam over the duration, Δt , of the event. If we assume a circular gravitational orbit, then the speed is

$$v_{\text{grav}} = \sqrt{\frac{GM}{a}} \cong \sqrt{\frac{GM}{(r + R_E)}}, \quad (3)$$

where G is the gravitational constant, M is the mass of the Earth and a is the semimajor axis for the satellite. For a circular orbit $a \cong (r + R_E)$, where R_E is the mean Earth radius. Because the r -dependence in equations (2) and (3) is r versus $\sim(1 - 2r/R_E)$, it is easy to identify which 300-km range-alias is correct. The range versus time trajectory is then further refined, as described in Section 4.2.

The result of this range determination method for the Fig. 4 satellite is shown in panel (a) of Fig. 5. The quantized steps in the range in Fig. 5(a) are the result of the basic range resolution that

is determined by the sampling interval of $1 \mu\text{s}$ (150 m). Notice the range oscillations that occur when the satellite is near the nulls of the antenna beam resulting in low SNR. This approach can be made more robust by using the pulse-to-pulse coherence of the satellite return combined with iteratively refined satellite orbital parameters yielding orbits (trajectories through the radar beam) that are much more accurate than the sampling interval.

4.2 Range rate and Doppler convergence

The peak-searching technique introduced previously does not always produce satisfactory results, especially as the satellite passes through nulls in the antenna pattern. The low SNR often results in small range-bin ambiguities or event total ‘drop-out’, as seen near 5.2 s in the Fig. 5 event. When second-degree polynomial fitting of the range is applied, this issue is reduced but often not eliminated. To further refine the range (and to converge to an orbit), we compare the range rate calculated from the resultant polynomial-fitted line to the radial Doppler speeds derived from pulse-to-pulse correlation. These discrepancies are seen in the Fig. 7 results and form the basis for refining the range to a much higher (super) resolution than range sampling alone offers. That is, we combine both the amplitude and phase information of the signal to best effect in establishing an accurate trajectory and thus location within the beam pattern.

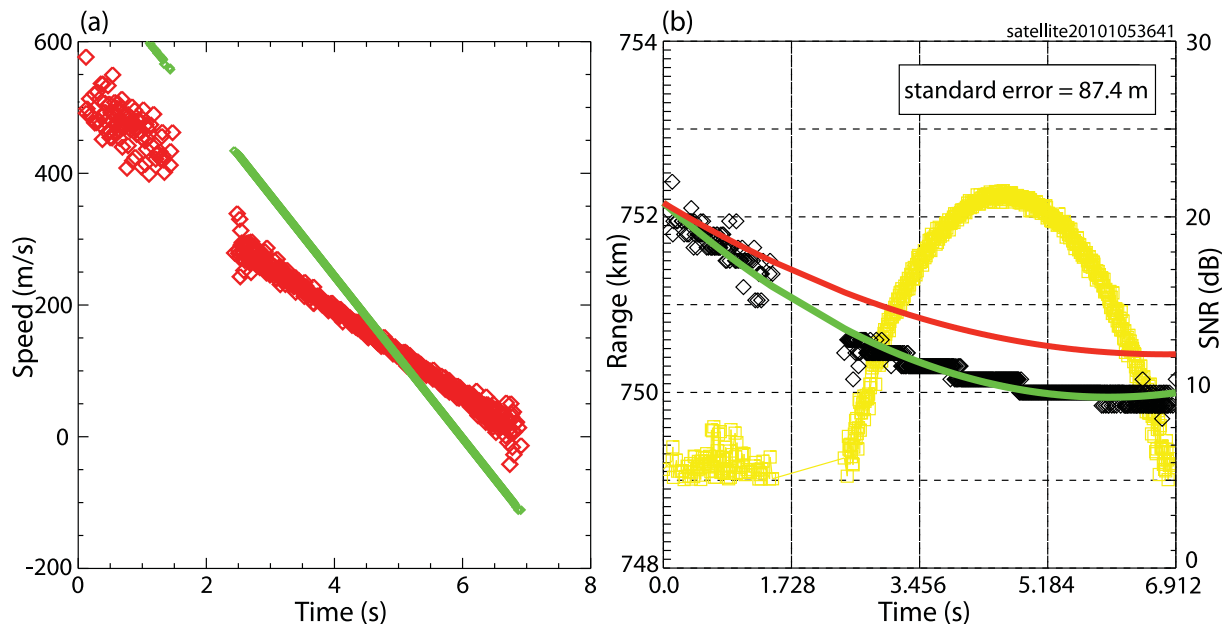


Figure 7. (a) Doppler velocities derived from pulse-to-pulse correlation (red diamonds) and the rate of range-change calculated using a second-order polynomial range fit (green). (b) Observed ranges (black diamonds) and the fitted polynomial (green) plus SNR (yellow). The red curve demonstrates what the expected ranges (using the fitted $t = 0$ range as a starting point) should be, according to the Doppler velocities in (a). The SNR is plotted in yellow in the background. The standard error is between the green fitted parabola and the observed ranges. Note that the slopes of the two Doppler segments in (a) are different. We ultimately realized that these are two separate events.

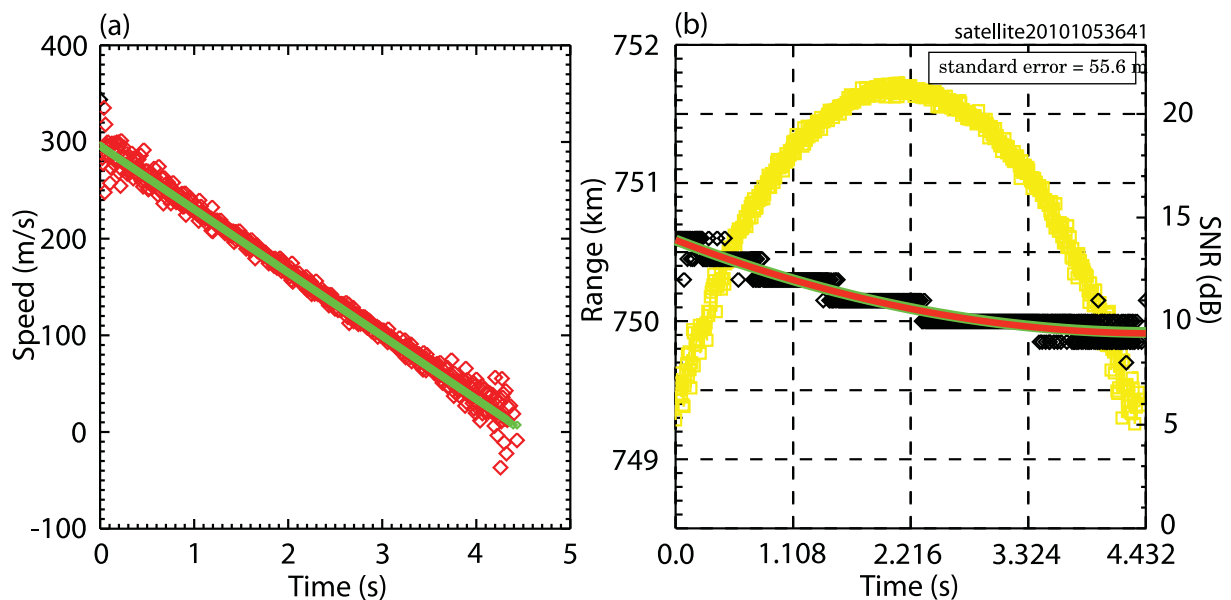


Figure 8. Adjusted ranges relative to the Fig. 7 values yield consistent range-rate and Doppler results. Note that removing the spurious side-lobe feature in Fig. 7 results in a very good range-rate and Doppler overlap, indicating that the range versus time trajectory is coherent across the event. (a) Doppler velocities (red diamonds) now agree with the rate of range-change (green). (b) The expected ranges (red) overlap the range-fitted parabola (green). Additionally, the rms variance drops substantially from the Fig. 7 result.

Fig. 7 shows a relatively short-duration satellite (also shown in Fig. 11c) observed on April 15 with the more sensitive JRO receiving configuration. This event appeared to have two components, as shown in Fig. 11(c), and was initially analysed under this assumption, as shown in Fig. 7. As described above, this process involved fitting a second-order polynomial to the observed range versus time trajectory and then finding the range rate to compare with the observed Doppler speed. This process is presented in Fig. 7(a) where we find that the range rate is larger than the radial Doppler speed and

thus that the implied line-of-sight accelerations are also different. Additionally, the range-fitting parabola (green) and the expected range changes (red) in Fig. 7(b) are not in agreement. These differences were initially thought to point to errors in finding the range in the low-SNR side-lobe portion of the event, thus emphasizing the limitations of power-only peak-searching results. However, we ultimately realized that we were seeing two nearly coincident but independent events. The final result is given in Fig. 8 where convergence between the range rate and the Doppler results is excellent;

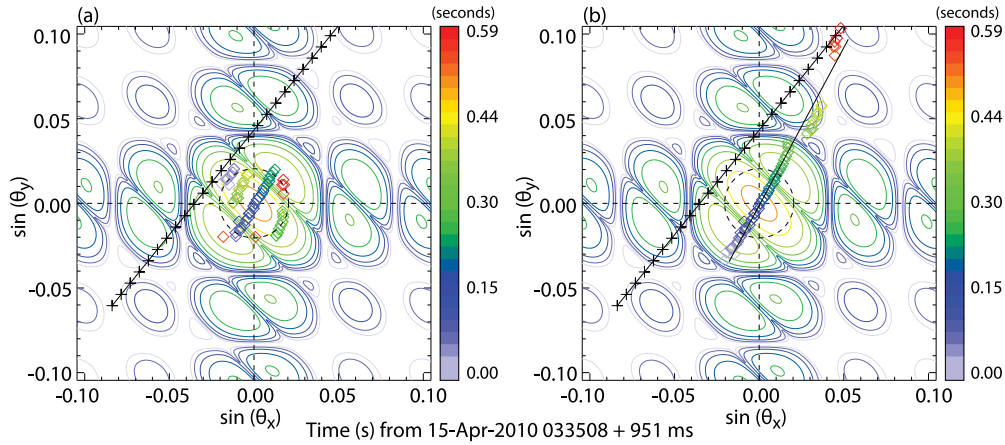


Figure 9. Interferometric results (a) phase-wrapped and (b) phase-unwrapped for the prototype high-altitude meteor event shown in Figs 2 and 3. The absolute location in the beam is established with event SNR and beam-pattern matching. Note the systematic curvature of the trajectories relative to the straight-line fit.

note that the weak event cannot be analysed because of its short duration. The revised range results shown in Fig. 8 yield a more consistent description of the satellite trajectory and firmly locate the trajectory through the beam.

This technique – i.e. separately matching the independent measurements in range (power only) and Doppler (phase) speed – provides a method to cross-check whether the determined trajectory needs further adjustment or not. The most consistent matching of these results will yield the best overall phase corrections along with the best orbital parameters.

4.3 Ambiguity removal in phase

The angular positions of the satellites, as well as meteor head- and trail-echoes, are calculated using the interferometric technique introduced by Farley, Ierick & Fejer (1981). However, we extend this to two dimensions because we employ two orthogonal baselines to pinpoint target angular position within the beam or rather within the primary 2π phase-alias circle of the technique.

The traditional method of determining the phase positions of a meteor head-echo along one baseline in interferometry is to calculate the cross-correlation function (CCF) between two receiving channels first, and then to derive the phase of this complex number. Taking receivers A and B here as an example to illustrate this technique, we have

$$CCF_n = V_{A_n} \times V_{B_n}^*. \quad (4)$$

Here, subscript n indicates the n th IPP, V_{A_n} is the complex voltage received from channel A and $V_{B_n}^*$ is the conjugate complex voltage received from channel B. Then, we find the relative phase difference between the two channels as

$$\phi_n = \angle CCF_n = \angle(V_{A_n} \times V_{B_n}^*). \quad (5)$$

The phase difference ϕ_n combined with the baseline distance between the phase centres of the A and B antennas together yield the projected angle of the target on the baseline direction. That is,

$$\sin(\theta_n) = \frac{\lambda}{d} \frac{\phi_n}{2\pi}, \quad (6)$$

where θ_n is the angle between the detected target and the on-axis pointing direction in the baseline AB direction, λ is the wavelength of the transmitted signal, ϕ_n is the phase difference between the two receiving channels calculated from the CCF and d is the distance

between the phase centres of the two receiving channels A and B. Note that while the actual phase difference could be any value, the resultant phase ϕ_n of the CCF is wrapped into the interval $[-\pi, \pi]$, thus introducing the 2π ambiguity (aliasing) issue in target angular location determination. That is, the drawback of this method is that the angular positions θ_n of the target are wrapped into the 2π ambiguity circle. The advantage of this method is that each phase position is calculated individually within one IPP. There is minimum concern that one outlier determination (because of a noise spike) will seriously contaminate the entire determination. Also, this approach can be applied to both point and volume targets.

In order to largely remove the 2π ambiguity issue, we also calculate the pulse-to-pulse phase of each CCF. That is, we autocorrelate the CCFs from pulse-to-pulse yielding a single lag of the autocorrelation function (ACF)

$$ACF_n = CCF_n \times CCF_{n+1}^*, \quad (7)$$

where the phase difference yielded by the ACF is

$$\Delta\phi_n = \angle ACF_n = \angle(CCF_n \times CCF_{n+1}^*). \quad (8)$$

The phase difference $\Delta\phi_n$ is due to the progression of the target over a single IPP and allows us to unwrap the phase ambiguities characteristic of CCFs alone by actually tracking phase progression along the point-target trajectory. An example of the original and unwrapped trajectories for the event shown in Figs 2 and 3 is given in Fig. 9. This process is combined with the target-SNR/beam-pattern matching, introduced by Chau et al. (2008), and detailed knowledge of the satellite orbit restrictions to phase-calibrate the JRO array while locating targets in the theoretical beam pattern.

The advantage of employing the method outlined above is obvious in that it makes the determination of the target trajectory across the beam much easier at least for high-peak SNR targets. However, because all the phase positions are calculated relative to adjacent points, one outlier badly contaminated by noise would affect the entire result. This is, of course, an issue, because the satellite passes through beam nulls and near the edge of the beam. Knowledge of the satellite orbit bridges these gaps, revealing previously unavailable pattern and phase information.

4.4 Distant side-lobe refutation

A satellite can generally be considered to have a large and essentially constant RCS, at least when it is nearly over the near-zenith-pointing

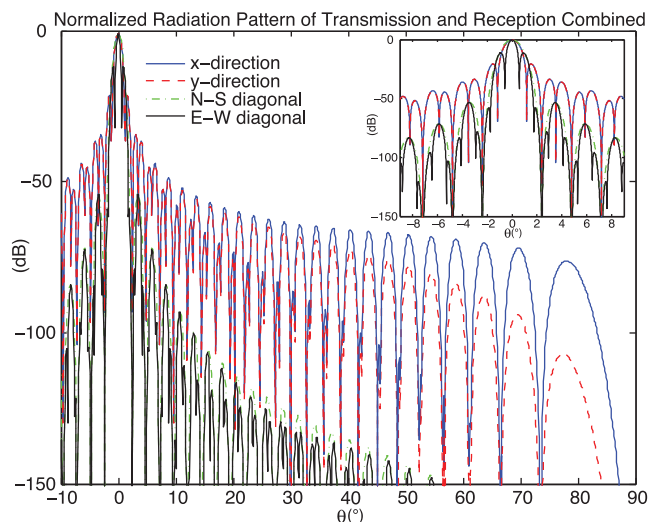


Figure 10. Theoretical JRO transmit/receive beam-patterns for the narrow-beam 2010 April 15 configuration. In reference to the Fig. 1 antenna coordinate system definitions, the patterns are given along the x - or y -axis (blue), EW diagonal (red) and NS diagonal (green). The inset shows the near-peak pattern. This model includes the coaxial, collinear (COCO) antenna elements plus ground screen effects. The net gain in any direction is simply the product of the transmit and receive gains.

JRO antenna. Using a calibrated three-antenna interferometer, the location of a satellite inside the beam can be determined with very high precision. The same is true for meteor head-echoes, except that rapid changes in the meteor SNR might be a result of meteoroid processes, and multiple fragments might be present. The question raised here – the same question as that regarding high-altitude meteor events – is whether the target was actually detected in the distant side lobes of the antenna pattern. This question was answered in the affirmative concerning the EISCAT 224-MHz radar (Vierinen et al. 2014).

The SNR patterns of the meteor event shown in Fig. 3(c) and the satellite event shown in Fig. 5(c) easily match the near-zenith JRO net beam-pattern shown in Fig. 10. The Fig. 10 pattern is the net theoretical transmit/receive pattern for the narrow-beam (2010 April 15) configuration. The advantage of modelling an array antenna is that, because of the large number of individual elements, the model is very robust near the peak. Importantly, the basic side-lobe structure or pattern is well defined and helps us to locate point targets in the beam. While the distant side-lobe structure is, in principle, equally well defined, in practice, it is likely dominated by irregularities in the array, such as missing elements. For example, from Fig. 10 we note that, theoretically, the side lobes are at least 50 dB down from the peak at beam angles greater than 10° , and we would not expect any targets to be located in these directions. However, it is these distant side lobes that are invoked to explain high-altitude (> 130 km) meteors. We have not identified any satellites in the side-lobe structure. Additionally, there is no evidence of strong returns from the night-time EEJ in the side lobes of the antenna that lie along the plane containing the magnetic equator. This is also true of meteor trail-echoes from the **kLB** region (Malhotra, Mathews & Urbina 2007); see Fig. 3 in Paper I. However, we cannot totally rely on beam attenuation to prove the case for high-altitude meteors because very large RCS, meteor-zone events (bolides) at large ranges certainly do occur in the huge volume illuminated by the full beam including distant side lobes.

4.5 Phase noise and phase bias issues

The satellite data allow us to identify two separate issues with interferometry. These are the effects of low SNR on the interferometric positioning and the isolation of a phase (and thus position) bias issue that had been attributed to returns in distant side lobes. These issues are seen in Fig. 5(b) and in all events shown in Fig. 11. These issues also occur with meteor head-echoes but cannot be separated from meteoroid phenomena because the trajectories are not known and a constant or near-constant RCS cannot be assumed. In Fig. 11, note that the satellite (phase) positions scatter more widely near the nulls of the radiation pattern and are more concentrated in the vicinity of the peaks of the pattern for both nights. This scattering is, of course, expected for lower SNR. Also note the hints of a bias, exhibited as a biased deviation from a straight-line trajectory, in the position results given in Fig. 11. Moreover, note that the satellites observed on April 16 exhibit more position-scattering than those detected on April 15. This is a result of the overall lower SNR because the wider-beam configuration was used for the April 16 observations. The meteor trajectory shown in Fig. 3(b) shows a very noticeable deviation from the best-fitting straight line. This deviation has been invoked as evidence that the event was seen in an antenna side lobe. The same phenomenon is seen in Fig. 5(b), even though the satellite trajectory is well determined.

The reason for interferometric position (phase) noise is that the complex voltage signal E_R collected by the receivers is comprised of two components, the satellite return and noise,

$$E_R = A_S e^{i\phi_S} + A_N e^{i\phi_N}, \quad (9)$$

where A_S and A_N are the amplitudes of the return signal and noise, respectively, and ϕ_S and ϕ_N are their respective phases. Assuming a constant RCS, A_S follows the antenna pattern, while A_N is a constant determined by the system temperature, etc. Additionally, ϕ_S is deterministic depending on the vector properties of the satellite orbit relative to the antenna array, while ϕ_N is (ideally) uniformly and randomly distributed on $[-\pi, \pi]$. Thus, at high SNR, the satellite trajectories shown in Fig. 11 are well defined, while near the pattern nulls we observe significant, but unbiased, trajectory spreading.

The different receiving configurations employed for the two nights of observations result in very different SNR profiles for the satellites, as shown in Fig. 11. Thus, while the transmit pattern and power remained the same, the quality of the interferometry results was strongly affected. This is simply because of the use of 16 times the receive area per receiver on the first night compared to the second night.

In addition to noise-related issues, we also note the trajectory bias issue seen in Figs 3(b) and 5(b). This bias issue is that the apparent trajectories are not linear. In the case of the high-altitude meteor events, this deviation from a linear trajectory was taken as evidence that the events were in distant side lobes because array phase distortion is suspected far from the beam centre. However, because we know the altitudes of the satellite events, we can eliminate the side lobes as the cause of this bias effect. In fact, we can go further and suggest the cause of the issue.

In order to understand the source of this phase distortion, we turn to the modelling of a non-ideal receiving system in which the gains of individual modules in the same receive-quarter are not identical. To this end, the complex voltage received by each quarter section, n , is expressed as

$$A_n e^{i\phi_n} = \sum_{k=1}^{16} A_{n,k} e^{i\phi_{n,k}}, \quad n = 1, 2, 3 \quad (10)$$

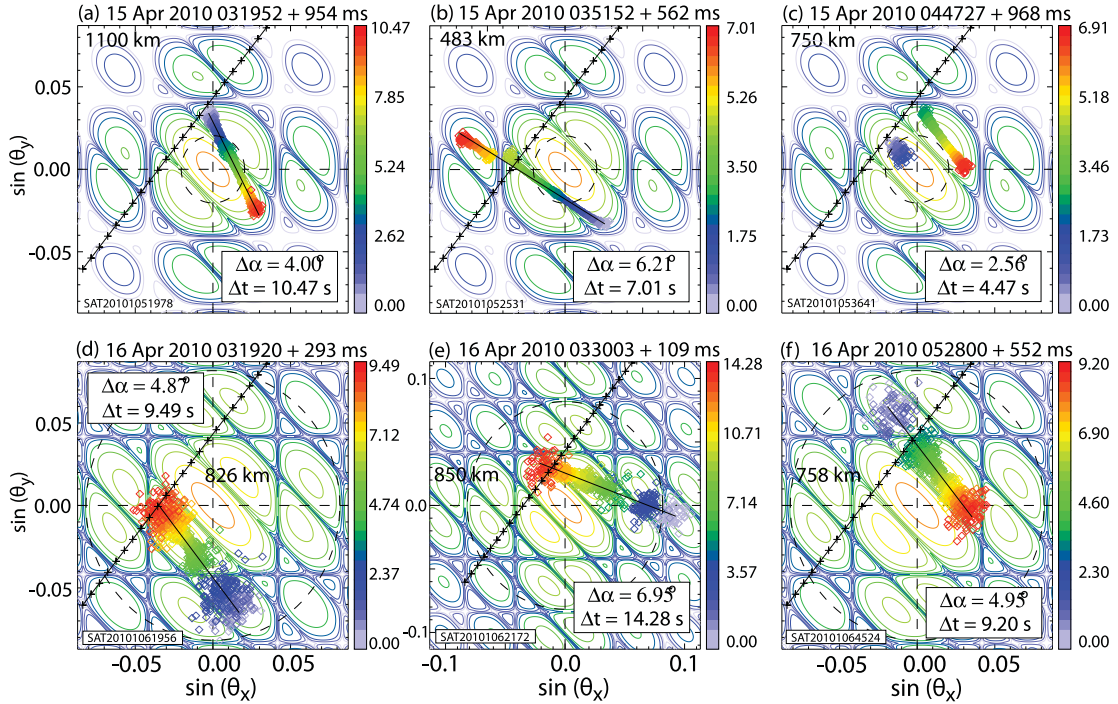


Figure 11. (a)–(c) The narrow-beam interferometric results for satellites observed on 2010 April 15 (quarter-receiving configuration). (d)–(f) The interferometric results of satellite returns detected on 2010 April 16 (module-receiving configuration). Different colours indicate position (phase) evolution with respect to time. Note that panel (e) is on a different angle scale than panels (d) and (f). Also, the narrow-beam results required phase unwrapping while the wide-beam results did not. The altitude of the satellite orbit segment during the overpass is given for each event. Note that the aliasing altitude is 300 km. The colour bar indicates the time evolution (s) of each event.

where $A_{n,k}$ and $\phi_{n,k}$ are the amplitude and phase, respectively, of the complex voltage received by 1/64th module k , part of quarter-subarray n , and A_n and ϕ_n are the net resultant amplitude and phase of the complex voltage collected by the n th quarter-subarray.

Note that the amplitude A_n in equation (10) is proportional to the gain of each receiver as well as the well-balanced amplitude and phase distribution across each 1/64th array module. That is, if all the gains of module receivers were identical, the net phase of the output complex voltages of each quarter-array would be equal to the theoretical value at the phase (and physical) centre of the quarter-array receiving section, and each quarter-array would be identical to the others. However, for various practical reasons, the net gains exhibited in the individual modules are not identical and are not equal to the theoretical value. The fact that there are these non-ideal system characteristics is verified by showing the differences of power received among different receiving channels. From Fig. 12, we can see that channels A and B are at nearly the same level, but channel C has an obvious higher power (~ 3 dB higher).

Non-identical channel properties change the apparent phases determined by application of equations (4) and (5) processing, in effect shifting the phase centres from the physical centre of each subarray.

To further test our hypothesis on the origins of the phase/path distortion, we modelled the antenna receive array with the transmit pattern also built into the model. In the model, we employed the actual meteor/satellite fitted three-dimensional trajectory to emulate the radar signal sequence as a function of time with additive Gaussian noise included. The simulation included transmitting the pulse from the east and west quarter sections of the array radar system, finding the scattered signal from the constant RCS target, and then finding the received signal at each of the three quarter-arrays (north, south and west) individually, with each quarter-array simulated as

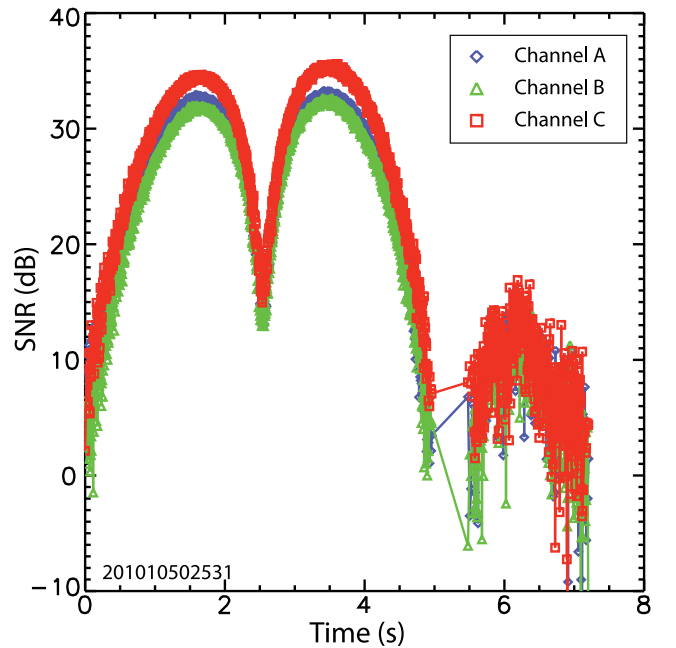


Figure 12. Power received from individual quarter-array channels for the satellite event shown in Figs 4 and 5. Note that channels A and B are at about the same level, while channel C is about 3 dB higher in SNR.

the individual modules shown in the top panels of Fig. 13. After considerable experimentation, we discovered that the observed results can be reproduced by simply weighting the gains of individual modules to either 1 or 0, as shown in the top panels of Fig. 13. Setting the

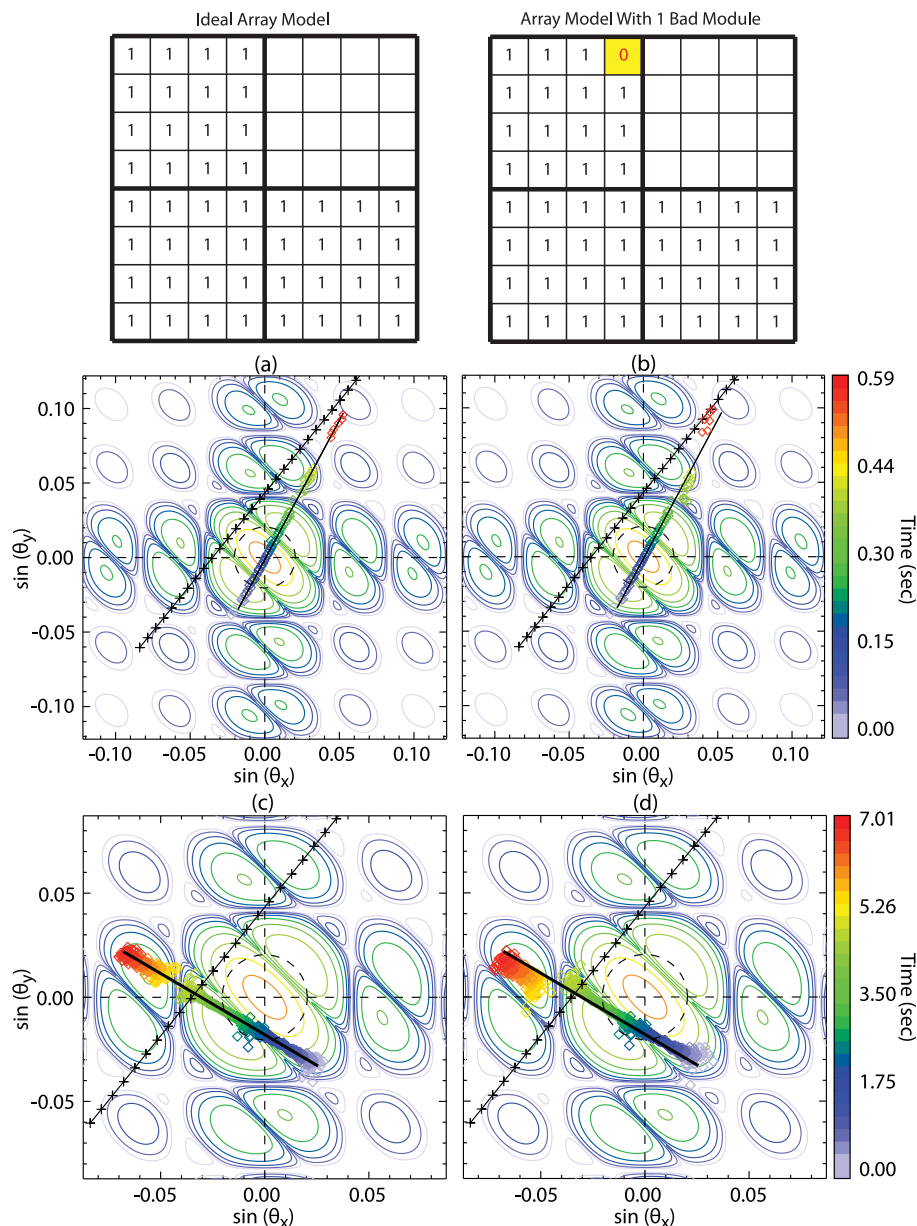


Figure 13. Point-target simulation results for a perfect quarter-array system (left) and of an array system with one absent module (right). Gaussian noise is added in this simulation. Panels (a) and (b) show the simulation comparison for the prototype high-altitude meteor event, while panels (c) and (d) show the model comparison for the satellite shown in Fig. 11(b). Note that the missing module results in trajectory distortion very similar to that which we observed.

corner-edge module, indicated in Fig. 13, to zero weight reproduces the observed path-distortion effect. That is, removing the module, in effect, moves the phase centre of that quarter-array, reproducing the observed effect. Fig. 13 compares the uniformly weighted quarter-array results with the results where the C-subarray (see Fig. 1) has a single bad module. These results are indistinguishable from the actual observed results. That is, the observed interferometric distortion is easily explained by imperfections in the individual modules that together comprise the quarter-arrays.

4.6 Radar calibration with satellites

We assume that over the JRO beam, individual satellites have a constant RCS with the added feature that we can determine the gravitational orbit very precisely from the radar trajectory of the

satellite through the beam. If we can determine which satellite we have observed (or will observe), we can in principle refine our calibration technique beyond what we describe here using published orbital data for that satellite. However, basic orbital physics combined with the apparent radar three-dimensional trajectory of the satellite through the beam completely establishes the exact radar trajectory with very high precision. This extra knowledge reveals that no satellites have yet been observed in distant side lobes, and this serves to very precisely calibrate the antenna pattern and interferometric properties. A goal for future work would include the attempt to observe, for example, the *International Space Station* at large zenith distances from the JRO. This would serve to calibrate the side-lobe structure and thereby help us better model the array.

To summarize, if we have published knowledge of a satellite orbit, then we can determine the satellite orbit parameters in terms

of latitude, longitude and altitude as it passes through the JRO beam. Then, through several coordinate conversions, we can determine the position information of the satellite in the form of $(\theta_x, \theta_y, r)_d$ with respect to the centre of the radar array and as a function of time. Because this set of satellite positions is totally independent of the JRO measurements $(\theta_x, \theta_y, r)_m$, we can compare these two sets of trajectories (angular position and range versus time) to refine the calibration of the array for interferometry. As stated above, given knowledge of a satellite orbit, we can search carefully for a return in distant side lobes.

Somewhat surprisingly, the identities of the (LEO) satellites we observed during the observations reported here remain unknown. These objects did not appear in the data bases we searched (e.g. celestrak.com). There might be several reasons for the failure to identify these satellites. These could be military satellites or space debris for which the two-line element (TLE) orbital parameters are not available. However, given their nearly polar orbits (inclination of $\sim 99^\circ$) and low altitude (< 1200 km), these are likely to be reconnaissance satellites.

5 CONCLUSIONS

We have presented a new phase and pattern calibration technique employing satellite returns found in a set of JRO meteor observations. Because the satellite passage through the antenna beam is coherent, the detailed characteristics of the satellite returns reveal considerable detail about the antenna, including the relative phase distributions that arise in the use of the array for interferometry. We also discuss the likely explanation for observed phase anomalies (i.e. mildly distorted interferometric point-target trajectories).

Besides providing accurate phase and pattern calibration of the JRO 50-MHz radar system, this technique is so sensitive to small angles that it offers a new way to calculate the on-axis pointing vector of the JRO antenna. This calibration technique enabled us to remove trajectory anomalies from the prototype high-altitude meteors reported in [Paper I](#) and to better support our conclusion that these are indeed high-altitude events rather than side-lobe events.

We have only detected a handful of satellites, none of which could be identified in the publically accessible data bases. This problem can be solved in future observations by using the data base to a priori identify satellites (e.g. the *International Space Station*) with orbital trajectories that pass near to the JRO, so that we can better determine the distant side-lobe structure of the array. That is, with thorough knowledge of overpasses, we can search for evidence – thus far not seen – of satellites in distant side lobes. Importantly, we emphasize that satellite observations have so far confirmed/refined the basic system calibration and have revealed otherwise minor, but important to point target, anomalies associated with non-uniform quarter-array characteristics. This result is not surprising in retrospect.

Thus far, this new calibration technique has been employed only at the JRO. However, it clearly can and should be employed for any radar system of sufficient sensitivity, especially where side-

lobe characteristics are of concern. We plan to continue improving this technique, while studying meteors, by using future JRO meteor observations that emphasize interesting satellite passes.

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