Technique Evaluation for Calibrating the COBRA Meteor Radar System

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Abstract

The South Pole COBRA meteor radar system is a quasi all-sky system designed to study meteors and measure the horizontal wind field in the MLT region at 46.3MHz. The radar is composed of four six-element Yagi antennas pointing along the 0\degree, 90\degree W, 180\degree, 90\degree E meridians, respectively at a 30(deg) elevation angle, and the Yagis transmit power in time-division controlled by the transmitter. In this way, the system performs as a quasi all-sky meteor radar system. A co-located interferometer is used to achieve accurate meteor echo directions. The interferometer includes five dipoles that is configured as a cross geometry (Jones’s configuration) with four arms aligned along 0\degree, 90\degree W, 180\degree, 90\degree E meridians, respectively. In this paper we present a technique that uses meteor echoes to calibrate the phase offsets of the interferometer. Meteor echoes impinged on the interferometer are divided into four groups, depending on the Yagi beam from which the echoes are collected. Each group of echoes are used to calibrate the Dipole pair that is oriented perpendicular to the corresponding Yagi beam. The interferometer can thus be calibrated pair by pair, which significantly reduces the computational complexity that can be severe when using meteor echoes to calibrate an all sky radar system. This technique is implemented with a constraint that maxima number of the meteor echoes are received in the direction where the Yagi beam is directed, with that and the special configuration of the interferometer the phase offsets can be determined without phase aliasing problem. The accuracy of this technique is dependent upon well aligned Yagi antennas, and this can be achieved by using a radio star.

1 Interferometric Calibration Techniques

Phase calibration techniques for interferometric meteor radar system can be categorized into two types according to recent reports and publications. The

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first type requires source at a known location. The phase difference between the receiver output for a signal produced by this source is measured and compared with the expected phase difference between the antenna pairs, the difference between each pair provides an estimate of the phase offset. The sources can be low elevation ground mounted antenna (Valentic et al., 1997), unmanned aerial vehicle (UAV) (Pisano et al., 2005), or a stellar source (Palmer et al., 1996). The second calibration method uses the expected statistical distribution of meteors (Holdsworth et al., 2004). The angle distribution of the meteors over the sky are assumed to be known at a priori. Systematic phase offsets result in the estimated arrival angles of the meteor echoes showing a biased distribution characteristic, comparison of which with the priori knowledge gives an estimate of the phase offsets. Although these techniques have been implemented in particular interferometric meteor radar system, there is still difficulty in producing efficient and reliable results. The main problems encountered are limited accuracy and phase aliasing. These problems will be addressed accordingly for each method thereafter. Feasibility of applying these techniques for calibrating the COBRA system will also be discussed.

1.1 Low Elevation Ground Mounted Antenna and UAV

The use of a low-elevation ground mounted antenna was reported by (Valentic et al., 1997) as a method for calibrating an all sky meteor radar system. The calibration antenna can be easily moved to a range of azimuths. Measurements from these positions can thus be averaged to increase the accuracy of the estimated phase offsets. However, the Cramer-Rao Bound (CRB) calculated for the specific array presented in (Valentic et al., 1997) shows significantly larger angle estimation error at low elevation angles than at high elevation angles (See Figure 1), which degrades the performance of this technique. The CRB, which varies with array configurations, Signal-Noise-Ratio (SNR), arrival angles and length of echo, is a criteria that determines the lowest bound of the variance that an unbiased estimator can achieve on the angle estimates (Stoica and Nehorai, 1989). Phase wrapping about multiples of $2\pi$ is also a severe problem at low elevation angle since the receiving antennas are more than 0.5 wavelength apart and initial estimates of the phase offsets are required to solve this problem.

An alternate technique is to use UAV as calibrating source, which because of the low cost and operating flexibility, have received more consideration recently, and are under development for autonomous antenna calibration (Pisano et al., 2005). The vehicles require a robust navigation system in addition to GPS for system stabilization and operation is dependent on weather conditions. While this approach is promising the technique is not yet proven, and requires additional refinement. Therefore it will not be considered in any more
1.2 Stellar Sources

Besides man-made sources, using a radio star as natural source has also been attempted to calibrate the interferometer. The position of the radio star can be determined from an astronomical catalog. (Palmer et al., 1996) published experimental results using Cygnus A to calibrate the Middle and Upper (MU) Atmosphere radar. Three Yagi antennas were combined to form a narrow beam (3.6° for 3-dB beam width) interferometer. However, there is still difficulty to apply this technique to an all-sky meteor radar system due to the lack of directionality.

The interferometers of the South Pole COBRA system, which uses the Jones’s configuration (see Figure 2) (Jones et al., 1998), are also not capable of receiving any stellar signals. However, a radio star is observed from continuously monitored background noise of the Yagi antennas. This information can be used to correct the alignment of the Yagis, and is addressed in Section 2.

1.3 Meteor Echoes

Recently, Holdsworth et. al. presented results using meteor echoes to calibrate system phase offsets (Holdsworth et al., 2004). This technique can be implemented during routine observations, so no additional sources or scheduled down time are needed to make the measurements. Phase offsets estimated over a four month period for the Buckland Park meteor radar, which has similar configuration as the South Pole COBRA system shown in Figure 2, show a standard deviation of less than 3°. This technique estimates a combination of the two phase offsets for the Dipole pairs that lie on the same baseline first, then performs an exhaustive search on one of the phase offsets, and solve for the other one. The phase offsets pair is determined by finding the one that minimizes the number of bad echoes, which are DOA unresolvable, height unresolvable, and height ambiguous. This technique is computation intensive, and after implementation of the algorithm we found that the combination of the phase offset pair produced in the first step is also an aliased result and extra care is needed to resolve the problem of aliasing.
2 Calibration of the South Pole VHF Meteor Radar System

The South Pole VHF meteor radar system is located approximately 1km from the geographic South Pole. Four Yagi antennas point along the 0°, 90°W, 180°, 90°E meridians, respectively at a 30(deg) elevation angle, and are used for both transmitting and receiving selected via a Transmit/Receive (T/R) switch. The transmitter is time-division multiplexed to each of the four Yagi antennas. The beam pattern (54° and 32° for 3-dB beam width in the azimuthal and vertical plane, respectively) of the Yagi antennas provide coarse direction information about the meteor trail. Accurate estimation of the meteor echo direction is determined by the co-located interferometer that is used in conjunction with the Yagi antennas. The configuration of the interferometer is shown in Figure 2. Four arms of the cross are lined up along the 0°, 90°W, 180°, 90°E meridians, respectively. This alignment enables us to take advantage of the geometric relation between the Yagi beam and the perpendicular arm of the cross to correct the phase offsets. Echoes illuminated by a particular Yagi antenna and measured at the perpendicular arm of the cross will show a 0 phase difference on average, equalling 90° incident angle at that arm. As mentioned above, CRB at larger incident angle shows better precision on angle estimates (see Figure 1 as reference). Therefore, unlike the low elevation ground mounted antenna accuracy of the measured DOA using this method can be assured. If there is a system phase offset for one arm of the interferometer, the statistical characteristics of the incident angles of the echoes will be biased from 90°, this provides the basis for the phase offset estimation.

The proposed method is based on the assumption that the Yagi is aligned along the correct azimuth direction, and this can be accomplished using the Stellar source as previously discussed. The COBRA system at the South Pole continuously monitors the background noise level on each Yagi. The noise data show a clear peak each day at nearly the same UT time. We extracted the UT time of each day when the maximum background noise value was observed for each day and plotted these as UT time vs. day (Figures 3 and 4). These plots show a 4 minute delay in the appearance of peak time in adjacent days for the same Yagi, and a 6 hour delay between adjacent Yagis. This result indicates that the increased noise level is due to a radio star. By looking up maps of a 45MHz southern hemisphere radio sky survey, which are given in equatorial coordinates, the detected radio star can be precisely located (Alvarez et al., 1997). The uncertainty of the measurements that were used to make the map is 4.6°(α)×2.4°(δ). The observed stellar source has a declination angle δ = −27.3° and a right ascension α = 17.8h. From the location of the star and the time when the star crosses the beam, the azimuth angle of the Yagi beam can be computed, and detailed azimuth offset values are shown in Table 1. We see that all directions except 90°E appear to have a 2-3 degree systematic offset for both years, which indicates that the transmit array is
slightly skewed. The Yagi antenna that is directed at 90° E is noisy and shows more variability.

After the Yagi alignment is corrected, meteor echoes collected on the Yagi beam can be used to calibrate the interferometer. Since underdense meteor echoes can be well modeled by a damped sinusoid (Mckinley, 1961), in this paper simulated meteor echoes of typical range and DOA distributions are used to illustrate the technique and verify its performance (Lau et al., 2006). Figure 6 shows an example of Height, SNR, and DOA distributions obtained on 90°W Yagi for one simulation realization with \( N = 10000 \), where echoes with \( SNR \leq 5 \) are discarded because of their poor DOA estimates. These simulated echoes are used to compute the phase offsets of the Dipole pair 4-0 and 3-0. Geometric relation between the meteor echoes and baseline 4-0-3 is illustrated in Figure 5. The incident angle \( \theta \) is computed through \( \cos(\theta) = \cos(\alpha) \cos(\beta) \), where \( \alpha \) is the elevation angle and \( \beta \) is the azimuth angle. Phase differences of Dipole 4-0 and 3-0 are simulated using

\[
\phi'_{40} = \phi_{40} + \delta_{40} + \xi_{40} \\
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\]

where \( \phi_{40} = 2\pi d_{40} \cos(\theta)/\lambda \) is the phase difference induced by the meteor echoes, \( d_{40} \) is the antenna separation between Dipole \( i \) and Dipole 0, here we define \( d_{40} = 2.5\lambda \) and \( d_{30} = -2\lambda \), \( \delta_{40} \) is the phase offset varying within \( \pm \pi \), we used \( \delta_{30} = -55^\circ, \delta_{40} = -40^\circ \) throughout the simulation, and \( \xi_{40} \) is a random component used to represent the experimental error. In the following analysis the error terms are neglected from Equation 1 and 2 for the convenience of illustrating the calibration technique. Since \( \phi_{40} \) is significantly aliased into \( \pm \pi \), it is meaningless to study its statistical distribution unless the problem of aliasing is already taken care. However, combination of \( \phi'_{40} \) and \( \phi'_{30} \) gives that

\[
\phi' = \phi'_{40} + \phi'_{30} = \frac{2\pi}{\lambda} (d_{40} + d_{30}) \cos(\theta) + \delta_{40} + \delta_{30} = \phi + \delta
\]

Given that \( d_{40} + d_{30} = 0.5\lambda \), Equation 3 can be implemented as though meteor echoes with incident angle \( \theta \) impinge on an array with two antennas separated 0.5λ apart, and no aliasing is induced to \( \phi \). Therefore, the statistical characteristic of \( \phi \) can be taken advantage to estimate \( \delta \). Since the peak power is transmitted out from the Yagi at 90° with respect to the baseline 4-0-3, we could expect maxima number of echoes are received in this direction, which means \( E[\phi] = 0 \), thus the expected value of \( \phi' \) is

\[
E[\phi'] = E[\phi] + \delta
\]
Notice from Equation 3 that $\delta$ can be any value within $\pm 2\pi$, so $\phi'$, which is $\phi \in [-\pi, \pi]$ shifted by $\delta$, actually falls into $\pm 3\pi$, resulting in its measurement an aliased result. Therefore, to determine an optimal value of $\delta$ and cover all its possible solutions, we produce revised distributions $[\phi' - 2\pi, \phi', \phi' + 2\pi]$, and this is shown in Figure 7(a). A Gaussian curve is fitted to one of the peaks and results in an estimate $\delta = -94.5^\circ$. Other possible values for $\delta$ are $-454.5^\circ$ and $265.5^\circ$. Subtract $\delta$, which can be any one of the three values, from Equation 3 and wrap the results into $\pm \pi$ we get phase differences $\phi$ for the meteor echoes, and those are plotted in Figure 7(b). These values of $\phi$ can be used to solve the phase aliasing induced in $\phi'_{30}$ and $\phi'_{40}$, thus yielding reliable estimates for $\delta_{30}$ and $\delta_{40}$. $\delta_{30}$ is computed in the following analysis as an example to illustrate our technique, and when this is done $\delta_{40}$ can be determined either using the same procedure or simply from $\delta_{40} = \delta - \delta_{30}$.

From Equations 2 and 3 it is easy to get $\phi_{30} = 4\phi$ and $-\pi < \phi'_{30} - \phi_{30} \leq \pi$. If we use $\Phi'_{30}$ to represent the measurement of $\phi'_{30}$, i.e. the aliased value of $\phi'_{30}$, we have $\phi'_{30} = \Phi'_{30} \pm 2k\pi$, where $k$ is an integer from -2 to 2. Figure 8(a) shows the distribution of $\Phi'_{30}$. To determine $\phi'_{30}$ from the measurements $\Phi'_{30}$, we compute $\phi_{30}$ from $\phi_{30} = 4\phi$, where $\phi$ is obtained in the preceding paragraph, and seek for $\phi''_{30} = \Phi'_{30} \pm 2k\pi$ that satisfies $-\pi < \phi''_{30} - \phi_{30} \leq \pi$. In the absence of phase errors $\phi''_{30} \equiv \phi'_{30}$, thus the phase aliasing on Dipole 3-0 is solved and a histogram of the resulted $\phi''_{30}$ is shown in Figure 8(b). A Gaussian curve is fitted to the peak, yielding an estimate $\delta_{30} = -52.6^\circ$, which is in good agreement with the input value $-55^\circ$. Subtract $\delta_{30}$ from $\delta$ we get an estimate of $\delta_{40} = -41.9^\circ$. Multiple samples produced on this beam, as well as on the $90^\circ E$ Yagi beam, can be averaged to increase the accuracy. The $\delta_{30}$ and $\delta_{40}$ averaged with 100 samples, each of which is produced using $N = 10000$ echoes, are $-52.4^\circ$ and $-42.55^\circ$, with standard deviation $2.28^\circ$ and $2.77^\circ$, respectively. Phase offsets of Dipole 1-0 and 2-0 can be computed using echoes collected on the $0^\circ$ and $180^\circ$ Yagi beam with the same procedure. The performance of this technique is directly dependent upon the statistical distribution of the echoes collected on the Yagi beam, which degrades if the statistical mean of the computed phase differences deviate from $0^\circ$.

3 Conclusions

Based on the special configuration of the South Pole meteor radar system, a new technique is proposed to calibrate the phase offset of the interferometer. This method uses meteor echoes as calibration source and can calibrate the interferometer pair by pair, which reduces the computational complexity as well as ambiguity problem. Simulations of typical range and angle of arrival distributions of the echoes show this technique has promises. It will be applied to the South Pole meteor data in the near future.
References


Figure 1. Cramer-Rao bound at variant elevation angles for the specific array configuration utilized in (Valentici et al., 1997).
Table 1
Azimuth offset of the Yagi beams computed using stellar source for both 2002 and 2003 data.

<table>
<thead>
<tr>
<th></th>
<th>0°</th>
<th>90°W</th>
<th>180°</th>
<th>90°E</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>2.94°</td>
<td>2.51°</td>
<td>2.79°</td>
<td>0.85°</td>
</tr>
<tr>
<td>2003</td>
<td>3.26°</td>
<td>3.10°</td>
<td>1.78°</td>
<td>-4.33°</td>
</tr>
</tbody>
</table>

Figure 2. Antenna configuration of the South Pole meteor radar system.

Figure 3. 2002 South Pole noise measurements.

Figure 4. Same as Figure 3 but for 2003.

Figure 5. Meteor echoes impinged on baseline 4-0-3.

Figure 6. (a)Height, (b)SNR and (c) DOA distribution of simulated meteor echoes on the 90°W Yagi beam.

Figure 7. Histogram of (a) revised distribution of $\phi' = \phi_{30}' + \phi_{40}'$, and (b) $\phi = \phi_{30} + \phi_{40}$. $\phi$ is computed by subtracting $\delta$, which is estimated in (a), from $\phi'$.

Figure 8. Histogram of (a) $\Phi_{30}'$ and $\phi_{30}''$. $\phi_{30}'' \equiv \phi_{30}'$ in the absence of phase errors, and a Gaussian curve is fitted to the peak of the histogram, yielding an estimate $\delta_{30} = -52.6°$. 
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