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Remote sensing lower thermosphere wind profiles using non-specular meteor echoes

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[1] This article describes a new method of measuring wind velocity profiles between 93 km and 110 km altitude by tracking non-specular meteor echoes as neutral winds transport the plasma trails. This requires a large VHF radar with interferometric capability able to point nearly perpendicular to the geomagnetic field. A small data sample from the Jicamarca Radio Observatory allows the measurement of horizontal wind speeds and directions with a range resolution of a few hundred meters. These observations show speeds reaching 150 m/s and sometimes changing by as much as 100 m/s over a 6 km altitude range. At the best times, these measurements can be made with only a few minutes of data. With some refinement of the data collection and analysis techniques, this technique should produce high resolution images of lower thermospheric winds as they change in both altitude and time. **Citation:** Oppenheim, M. M., G. Sugar, N. O. Slowey, E. Bass, J. L. Chau, and S. Close (2009), Remote sensing lower thermosphere wind profiles using non-specular meteor echoes, *Geophys. Res. Lett.*, *36*, L09817, doi:10.1029/2009GL037353.

1. Introduction and Background

[2] In order to understand energy and momentum transport by tides, planetary waves, and gravity waves, researchers need accurate knowledge of winds in the lower thermosphere (LT) [*Clemesha*, 2002]. Over the past six decades, over 400 rockets released chemical tracers to measure winds in the LT [*Larsen*, 2002]. This represents an enormous investment in obtaining these wind profiles. This article describes how one can obtain similar measurements using radar tracking of non-specular meteor trail echoes. By measuring winds between 93 and 110 km, this approach explores a region that overlaps the highest altitudes monitored by specular meteor radars but extends considerably higher. This technique does not require the temporal and spatial averaging typically used when obtaining winds from specular meteor radars or LIDARs, but instead measures detailed wind profiles with an altitude resolution of less than a few hundred meters. Further, between midnight and dawn, we expect that this method could be used to monitor winds on a nearly continuous basis.

[3] Specular meteor radars detect plasma trails when their paths lie perpendicular to the radar beam [*Ceplecha et al.*, 1998]. By measuring the average Doppler shift, the observer can infer neutral wind speeds in the line of sight direction from the radar. Using multiple receivers and observing many meteors, researchers can monitor wind velocity profiles on a nearly continuous basis [*Holdsworth et al.*, 2004]. This inexpensive method has been used for decades at many stations to develop models of neutral winds [*Hedin et al.*, 1996]. The wind measurements extend from ~75 km to ~100 km altitude and have, at best, around a 1km altitude resolution.

[4] Our new method also takes advantage of the billions of meteors that enter the atmosphere every day, leaving behind plasma trails which the neutral wind carries along. However, instead of using a small radar to track the entire trail, this method uses large radars to follow reflections from plasma irregularities that develop in or near many trails [*Oppenheim et al.*, 2000]. This requires that the radars have interferometric capabilities and can point roughly perpendicular to the geomagnetic field.

2. Data Collection and Analysis

[5] Data for this experiment was collected by the primary antenna array at the Jicamarca Radio Observatory (JRO) located near the geomagnetic equator (11.95 S, 76.87 W, 1 dip angle) in July 2005 and July 2007. Details about meteor observations with this high-power large-aperture (HPLA) radar are given by *Chau and Woodman* [2004]. The same data have been used here as in the experiments described by *Oppenheim et al.* [2008]. These experiments were unusual in that we used only a short uncoded pulse of 1μs and an inter-pulse period spanning 60 km. We transmitted with the entire array and received the return signal with 3 quarter sections of the array, enabling us to use interferometry to find a meteor's position within the beam. Since the radar collected 5000 measurements per second per altitude bin, a 25s meteor will have 125,000 data points per altitude bin. Figure 1 shows one of the longest and strongest meteors with a persistent trail.

[6] The primary difference between the '05 and '07 experiments was the pointing direction of the antenna array. In '05, the array pointed 1.9° off-perpendicular to $\vec{B}$ to decrease the contamination from electrojet field-aligned irregularities while in '07, it aimed perpendicular to $\vec{B}$ to see how that would affect these observations. *Close et al.* [2008] showed that radar sensitivity to meteor generated field aligned irregularities falls off by approximately ~3dB per degree (at 450MHz) as the antenna steers away from aiming perpendicular to $\vec{B}$. If that number applies for our

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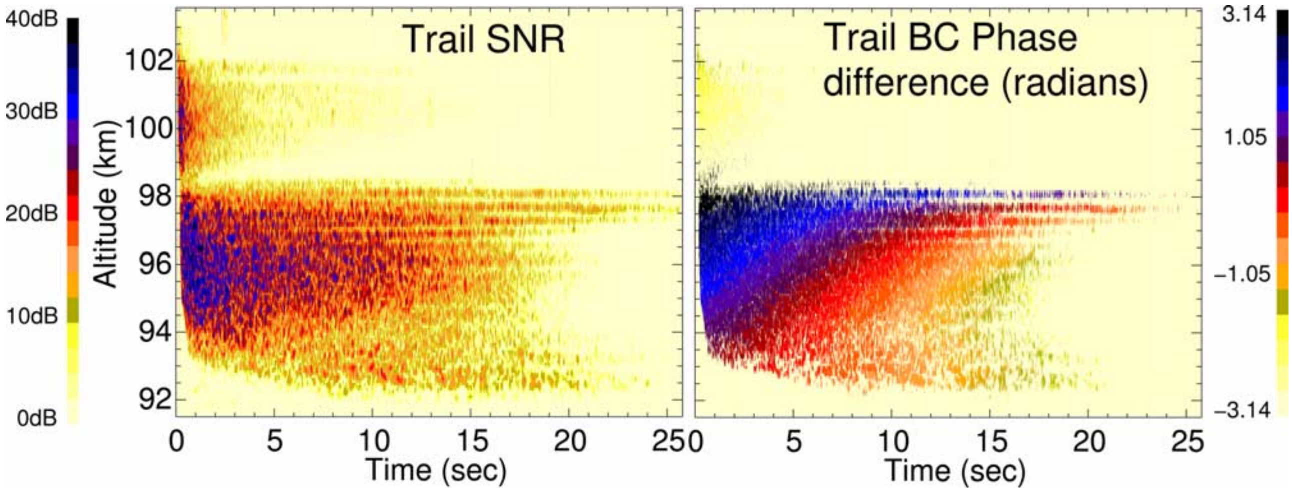

Figure 1. Long trail from July 12, '05 data set. (left) The SNR in dB and (right) the phase difference between the B and C quarters of the antenna array. Phase information is only shown for regions where the SNR exceeds 10 dB, the Doppler is less than 150 m/s, and a cross-channel coherence exceeds 95%. This meteor caused both a head and a non-specular trail echo, but the head cannot be seen on this time-scale. The data gap at 98.5km altitude occurs because the meteoroid passes through a null in the antenna pattern. This can be determined by tracking the head echo position versus the known beam pattern and because both the head and the trail vanish at this same time. The striations late in time span at least 6 pixels from peak to peak and result from unknown causes. Such striations appear only in some meteors.

50MHz measurements, then the same meteor would produce a ~6dB smaller signal in the '05 experiment compared to the '07 one.

[7] For this article, we examined meteor data from two periods: 0342 to 0429 LT, July 12, '05 and 0401 to 0437 LT, July 17, '07. During these time intervals, we have hundreds of trails with a peak SNR exceeding 10dB and a channel cross-coherence threshold greater than 0.95. Also, the electrojet did not create appreciable interference during these periods. Note that these experiments received signals from different altitude ranges: the '05 experiment spanned 90 to 119 km while the '07 one covered 80 to 130 km.

2.1. Phase Interferometry

[8] The phase difference between channels gives the meteor trail position. Figure 2 shows the positions at two times for the meteor of Figure 1. Since the radar is not aligned north-south, we rotated the resulting points 39° into a N-S/E-W coordinate system. One can infer that the horizontal wind has a strong shear in the zonal (E-W) direction, ranging from 7 m/s at 98 km altitude to 102 m/s at 96 km while the meridional (N-S) wind shows far less shear.

[9] Instead of taking snapshots of the meteor positions to obtain velocity, we fit the slope of the phase differences between channels. Figure 3 shows an example of the phase differences between two channels for the same meteor as in Figure 2. To avoid wrapping the phase angle when it reached 0 radians, we enabled the algorithm to add or subtract 2π, to maintain a smoothly changing phase angle difference. This algorithm will sometimes fail for short meteors with substantial phase noise.

[10] For each trail, we find the slope using a least absolute deviation algorithm and estimate the error via the least squares method [*Press et al.*, 1992]. We exclude all points where the SNR drops below 10 dB. For trails persisting longer than 3 seconds, these errors typically become quite small, often less than 10 m/s. We manually eliminated one trail which showed wind speeds jumping by as much as 50m/s over one range gate. A close inspection

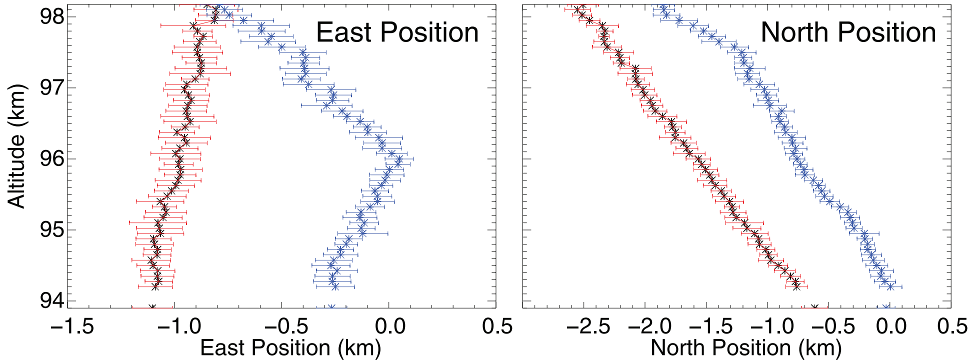

Figure 2. East-west and north-south trail positions vs. altitude at 0s–0.5s (red) and again at 10s–10.5s (blue). Phase data in these intervals were treated as statistical samples and converted to 3-D positions. The central point at altitude corresponds to the mean position, while the horizontal bars give the standard deviation.

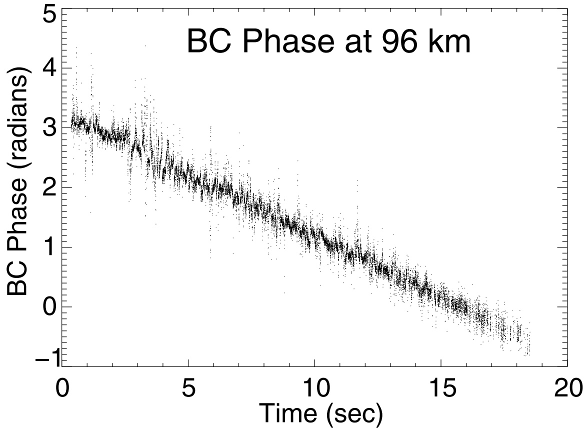

Figure 3. Difference between the B and C phase angles in radians at 96 km altitude.

showed that this data actually contained two simultaneous trails.

2.2. Wind Velocity Profiles

[11] Even long, strong meteor trails generally span less than six kilometers in altitude. However, in a 2 minute period, we will often have more than a dozen meteors lasting 10s or longer. Figure 4 shows two wind profiles obtained by combining all the meteors in our data intervals. These measurements extend from 93 km to 109 km. The east winds have less variability than the north winds. These errors will be discussed further in section 3.

[12] One can immediately see that, at a given altitude, the wind velocities are roughly consistent from trail to trail, though with an error level that greatly exceeds the statistical error level shown. The zonal (east) wind data is more consistent from meteor to meteor than the meridional (north) ones. Between 94 and 103 km all the meteors give similar velocities at a given height. Above this height, the ’07 data shows a considerably larger range of wind speeds. The ’07 zonal wind data between 103.5 and 105 km altitude derives from only one meteor and ranges between −80 m/s and +40 m/s, and shows an implausible amount of variability. Above that altitude, between 105 and 109 km, we have 2 meteors which have roughly the same mean of 35 m/s, but one meteor shows quite a lot of shear while the other indicates a relatively constant wind profile. Further experimentation and refinement of the data analysis technique should enable us to improve this consistency.

3. Discussion

[13] The physics of non-specular meteor trails enables us to explain many of the capabilities and limitations of this technique. Non-specular trails result from radar scattering from field aligned irregularities which, in turn, derive from instabilities evolving into turbulence [*Oppenheim et al.*, 2003; *Dimant and Oppenheim*, 2006]. This means that radars measure wave-fronts within a turbulent plasma. These wavefronts may have non-zero average phase velocities which may effect the phase of the returning signal and, potentially, add error to our results. Nevertheless, the measured results appear highly accurate and consistent from meteor to meteor.

[14] While Figure 3 shows a clear overall slope, enabling us to make an accurate determination of the horizontal wind speed, the signal includes substantial deviations from this trend (eg., see the phases changes at 6s). These deviations

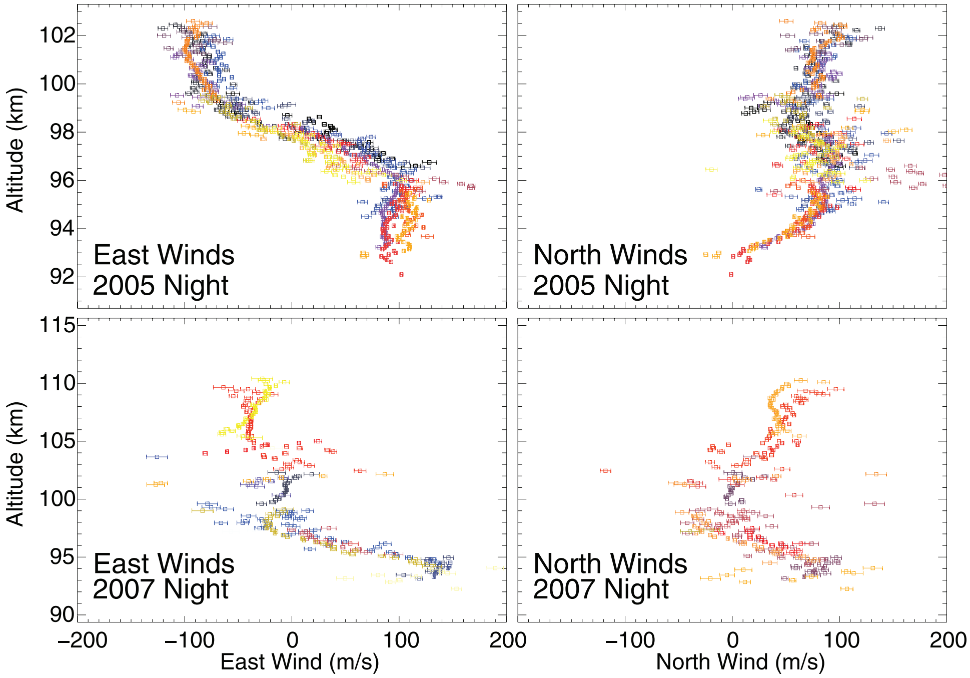

Figure 4. Horizontal wind velocities vs. altitude from 2 data sets. The zonal (east) and meridional (north) meteor winds from the time interval (top) 0342 to 0401 from July 12, ’05, and (bottom) 0401 to 0437 July 17, ’07. Each trail was assigned a distinct color. Much of the ’07 data set had a channel receiver timing offset which added a large systematic error to the BC phase data, making only the longest duration trails useful. We used all data where the error in the slope was less than 10 m/s.

make it challenging to obtain wind data from meteor trails lasting less than 3 seconds. A close inspection of these deviations shows that they result from coherent phase changes which include as many as a dozen radar pulses. If this resulted from actual motions of the meteor, it would imply that the meteor moves over a km in about 25 ms, a velocity exceeding 50 km/s, clearly an unphysical result.

[15] We can speculate about the causes of these rapid phase variations. Most likely, the radar is detecting a second signal originating in another location within the beam which temporally overcomes the primary signal. We expect that a 20 second interval at 4am will include approximately 40 secondary head echoes and 5 trails, usually at different altitudes. We use the high Doppler shifts of head echoes to eliminate those spurious signals, but occasional aliasing will cause this exclusion technique to fail. Secondary trail echoes will generally be much weaker, lasting less than 1 second. Nevertheless, they may be able to hijack the signal temporarily. We have some examples where strong trails are clearly interrupted by smaller but still substantial trails, causing the phase angle to jump around. A better data collection technique should enable researchers to minimize this problem. Also, signals from space debris could cause problems.

[16] The meridional wind data shows more meteor-to-meteor variability than do the zonal ones. The observation of these trails depends upon the radar detecting field-aligned plasma turbulence [*Close et al.*, 2008]. If a meteor trail initially lays on the line where the radar pointing direction and the geomagnetic field are perpendicular, then, as the trail moves eastward, the radar and the field maintains a 90° aspect angle. However, as it moves north, this angle will decrease. If it moves 2km, then the angle will change by 1.1°. It cannot move much more than twice this distance before leaving the primary side-lobes of the antenna pattern. Fortunately, the signal retains sufficient strength to allow meridional wind profiles, though not with the reliability of the zonal profiles. This technique may slightly underestimate the meridional winds because as a trail moves to the north (or south), different sides of the trail may preferentially reflect due to changes in this angle.

[17] Meteor trails also diffuse, though the molecular and even anomalous diffusion rates remain quite low. *Dyrud et al.* [2001] estimated that they reached as high as 50 m^2/s above 105 km. Assuming simple isotropic diffusion, we expect a trail at this height to spread from 1m to about 13 m in radius in 10s. This may contribute a small amount to the error if the expansion of the trail caused by diffusion adds to noise in the phase data. Additionally, when a wind drags a trail plasma across $\vec{B}$ one might expect considerable spreading of the plasma not due to simple diffusion. At this time, we cannot predict this effect accurately.

4. Conclusions, Summary, and Future Work

[18] The field aligned nature of non-specular trail irregularities means that a radar must be able to point nearly perpendicular to $\vec{B}$ to detect winds. Hence, the Arecibo, EISCAT, Millstone Hill, and Sondrestrom radars cannot make these measurements but JRO, MU, and EAR can. The ALTAIR radar has 5 receiver horns, which should allow it to obtain the phase angle of a meteor echo but, because of the close spacing, we do not yet know if it has sufficient resolution to determine accurate wind velocities.

[19] At low latitudes, radars can use this method to obtain altitude resolutions better than a few hundred meters. At higher latitudes, a radar will need to point at lower elevation angles and detect more distant signals to perform this analysis. This will reduce their altitude resolution but will increase the observing volume and likelihood of detecting a strong meteor trail. Also, one will need to use the Doppler to calculate the component of the wind velocity away from the radar to obtain meridional winds. At low latitudes, Doppler data may enable radars to measure vertical winds.

[20] This technique works best between midnight and dawn. After dawn, meteor trails become substantially less frequent and less enduring because of the affects of the background ionosphere on trail formation and duration. We estimate it will require about 6–8 times as long an observing period to produce similar wind data [*Oppenheim et al.*, 2008]. Between noon and dusk, we have the added problem that the meteor rate drops. After sunset, trail durations should increase but the count rate remains quite low until we approach midnight.

[21] While the JRO is a good tool for performing this type of monitoring, we believe a far smaller radar could do this quite well. In this experiment, we used a short pulse duration (0.5–1.0 μs) signal from the main antenna. One would expect a longer pulse from a smaller radar would have sufficient sensitivity to detect non-specular echoes. We need to test this wind profiling technique with other existing radars such as the 30MHz imaging radar overlooking Arecibo [*Larsen et al.*, 2007].

[22] The horizontal wind model (HWM93) of *Hedin et al.* [1996] predicts considerably lower wind velocities between 90 and 115 km altitude, generally reaching less than 50m/s for the zonal winds and less for the meridional one. These measurements derive from MF radar wind and specular meteor radar data. Our observations and the in-situ rocket measurements show consistently higher winds, reaching twice or more the HWM93 values [*Larsen*, 2002].

[23] The wind profiles detected via non-specular trail echoes are consistent from meteor to meteor and with previous rocket data. In order to have a higher degree of confidence in this method, a validation study is needed, possibly at the Kwajalein rocket range. One straightforward method would be to use a rocket-borne chemical release at the same time a radar monitors non-specular trails. Agreement between these two methods, would give us a high degree of confidence in this new technique. We expect to continue developing this technique to enable high-resolution monitoring of lower thermospheric winds.

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