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Optimising Estimates of Mesospheric Neutral Wind Using the TIGER SuperDARN Radar

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Abstract

Super Dual Auroral Radar Network (SuperDARN) HF backscatter radars scan 16 beam directions over a field of view of \(\sim 52^\circ\). Application of a beam-swinging algorithm permits mesospheric neutral winds to be estimated from the line-of-sight (LOS) Doppler velocity of meteor echoes detected at near ranges (<600 km). Larger meteor echo detection rates increase the accuracy of wind estimates, and also permit them to be estimated with better time and height resolution. In this study, meteor echo detection rates were increased by running dedicated radar control programs on the Tasman Geospace Environment Radar (TIGER) (147.2\textdegree E, 43.4\textdegree S). The Doppler characteristics of different echo types at meteor echo ranges were identified. The echoes were then filtered according to these characteristics, and their suitability for estimating neutral winds investigated. One echo type was clearly of ionospheric origin, forming thin, continuous traces decreasing in group range from \(\sim 1200\) km to \(\sim 300\) km before midnight. These “descending plasma streams” (DPS) merged into and disappeared at the group ranges of meteor echoes. Their behaviour resembled sporadic E associated with proton aurora as observed by other SuperDARN radars.

1. Introduction

The mesosphere-lower thermosphere (MLT) is a relatively inaccessible atmospheric region because it is too high to be probed using \textit{in situ} radiosondes, yet too low to be probed using \textit{in situ} satellites. However, understanding the dynamics of gravity waves, tides, and planetary waves within the MLT region has important implications for the chemistry and dynamics of the stratosphere (Viereck, 1991). Although dedicated VHF meteor radars provide measurements of winds within the MLT, opportunities exist to extend the spatial coverage around the planet using other radar systems, such as ionosondes (MacDougall et al., 2001), and via the use of remote sensing satellites such as the Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED) mission.

The Tasman International Geospace Environment Radar (TIGER) is a SuperDARN radar located in Tasmania, Australia (147.2\textdegree E, 43.4\textdegree S) (Dyson and Devlin, 2000). SuperDARN radars were designed to detect ionospheric backscatter and were deployed to study the dynamics of the high-latitude ionosphere (Greenwald et al., 1995). However, SuperDARN radars also detect echoes from other sources such as the ground and the sea, and from meteors. The radars will be upgraded with hardware and software to facilitate simultaneous data acquisition for the study of these phenomena.

Hall et al. (1997) identified Grainy Near Range Echoes (GRNEs) in SuperDARN data. GRNEs occur at ranges less than \(\sim 500\) km and are present regardless of magnetic activity. GNRE detection rates peak near local dawn and reach a minimum near local dusk, paralleling the diurnal variation of meteors observed optically and with VHF meteor radars. Hall et al. (op cit) concluded GRNEs were due to backscattering from meteor trails. The characteristics of SuperDARN meteor echoes have

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been further investigated by various authors (e.g. Jenkins and Jarvis, 1999; Hussey et al., 2000; Arnold et al., 2001; Arnold et al., 2003).

The identification of meteor echoes in SuperDARN data is important because the Doppler shift of these echoes can be used to determine the neutral wind in the MLT region, and the number and locations of SuperDARN radars can provide a significant extension of the available observations. As Table 1 shows, meteor echoes are basically identified as echoes at short range, from D- and E-region heights, and with low line-of-sight (LOS) Doppler velocity and spectral width. However the population of echoes with these characteristics may include some ionospheric echoes as well. Furthermore, the likelihood of detecting meteor echoes will depend on the choice of radar operating parameters. These have usually been chosen to detect F-region ionospheric echoes, not meteor echoes.

The TIGER radar was used to examine the extent to which meteor echo detection rates depend on radar operating parameters including the frequency and integration time. The characteristics of the near range echoes were studied to aid separation of meteor echoes from the broader population of radar echoes. The echo detection rates were greatly improved, thereby permitting the calculation of neutral winds with better accuracy and time resolution than obtained using the standard radar operating mode and analysis.

2. Observations and Analysis

In normal operations, SuperDARN radars scan 52° of azimuth by electronically stepping the radar beam through 16 steps or beam directions separated by 3.24°. The transmitter pulse width usually corresponds to 45 km in space, and the first range gate is 180 km, with 70 more ranges separated by 45 km. The transmitter frequency is often ~12 MHz or less, and the integration time is typically 7 s. The backscatter power (dB), LOS velocity (m s\(^{-1}\)), and spectral width (m s\(^{-1}\)) of echoes are estimated in real time using a standard pulse set scheme and analysis algorithm. This way of running the radars is appropriate for the measurement of ionospheric scatter out to great ranges.

Several special campaigns were run using the TIGER radar to specifically investigate meteor echoes. Beam 7 points near to geographic south and Figure 1 shows results obtained along this beam for a campaign conducted from 1400 UT, 23 May to 22 UT, 25 May 2003 (i.e. for 56 hours). During an integration period, the radar takes measurements along a single beam and one set of echo parameters can be measured at each range gate along the beam. Because more than one meteor echo might occur in each observation cell, the first range gate was reduced to 120 km and the transmitter pulse width and range gate separation were set to 15 km. Ideally, the first range gate should be reduced even further, but a software limitation precluded this in this initial study. The choice of a range separation of 15 km limited the maximum range to 1170 km. The integration time was also reduced from 7 s to 2 s, since meteor echoes have life times in the order of 0.5 s.

Figure 1 shows meteor echoes are evident as the GNREs at ranges less than about 700 km. There is a clear diurnal variation in echo occurrence, with very few echoes observed at dusk (LT\(\approx\)UT+10 hours). The top panel displays echo power, and it is apparent that the meteor echoes are generally weaker than the sea echoes observed via 1.0-hop propagation at greater ranges. The leading edge of the sea scatter oscillates in range because of the passage of medium-scale gravity waves through the intervening region of ionospheric refraction. There is also a strong band of ionospheric echoes overlapping the meteor echoes at the beginning of the plot, and a tendency for bands of ionospheric echoes to expand equatorward at dusk and extend into the region of meteor echoes.

The middle panel of Figure 1 shows the LOS Doppler velocity of the radar echoes. Most of the echoes within the reduced range window of 1170 km shown in the Figure have relatively low velocities and on the basis of velocity alone, meteor echoes do not stand out as a distinctly different
population. In contrast, in the bottom panel showing the spectral widths, the meteor echoes are a mixture of echoes with low spectral width and unusually high spectral width. These characteristics will be examined further later.

A campaign was run on 1 to 3 March 2003 to examine the dependency of meteor echo detection on the operating frequency of the radar. The radar was stepped through 18 licensed frequency bands between 9 and 20 MHz. The results are shown in Figure 2 which is a plot of the number of meteor echoes per sounding, as a function of the start frequency of each band. These results are for the first 8 hours of the campaign when there was no evidence of contamination by ionospheric scatter. It is evident that the radar was most sensitive to meteors at lower frequencies. The maximum occurrence rate was 10.0 ± 0.4 echoes per 2 sec integration. If it were not for small dead-time intervals between integrations, the peak occurrence rate implies it is possible to detect >432,000 meteor echoes per day, though concentrated in the dawn sector.

The sensitivity of the radar to meteor echoes will depend on many factors, such as the frequency dependence of the scattering cross-section of meteors, and the variation of the radar antenna beam width which increases with decreasing frequency. The average backscatter power only decreased slightly with frequency. The main beam width becomes significantly broader in both azimuth and elevation at frequencies of 8 to 10 MHz; hence a greater volume of space will be sampled for the presence of meteors. However, the ratio of the antenna back- to forward lobes is also larger, so directional ambiguities become a problem. A frequency of 12 MHz was chosen for the campaign of 23 to 25 May (Fig.1) because (1) it is an excellent working frequency for most night side ionospheric experiments, (2) it moderates the back lobe problem, (3) the echo detection rates are nevertheless satisfactory, and (4) it corresponds to the peak gain of the radar electronics.

A specific example comparing observations made at 12.05 MHz and 19.80 MHz is shown in Figure 3 where the number of meteor echoes, which occur at ranges less than ~700 km, is very much less at 19.80 MHz. At the time of these observations, the ionosphere supported HF propagation at 12.05 MHz much better, so there is also significant ionospheric and sea scatter, mostly at ranges greater than the meteor echoes. However, there are excursions of 0.5-hop ionospheric scatter into the meteor echo region from 12 to 20 hours and from 36 to 42 hours. At 19.80 MHz, the ionosphere did not favour one-hop propagation, so there were fewer sea echoes. However, direct half-hop ionospheric backscatter from the most intense irregularities persisted at the highest frequencies.

We call the bands of ionospheric scatter which descended in group range and merged into the meteor scatter “descending plasma streams” (DPSs). At further ranges (>1000 km) the ionospheric scatter probably emanated from 10-m scale F-region irregularities detected via 0.5-hop propagation. However, the DPSs approached to within meteor echo ranges and probably represent scatter from irregularities located in the E-region and lower F-region. The DPSs commenced at dusk, and expanded equatorward in magnetic local time, implying they were echoes associated with proton aurora located at the equatorward edge of the auroral oval. Thus DPSs are probably close relatives of the so-called “slow long-lived E-region plasma structures” (SLERPS) (Jayachandran et al., 2000).

All the echoes obtained for the campaign of 23 to 25 May 2003 at ranges less than 600 km were analysed to determine the characteristics of the echo population and to examine criteria used to resolve the subset of meteor echoes. Figure 4 shows plots of the echo population distributions (a) and the normalised echo population distributions (b) for echoes selected using four sets of criteria. The first (black solid line) is simply all the echoes detected within ranges of 120 to 600 km, where 120 km was the first range for the campaign. The second population (green dotted line) consists of echoes with powers, LOS
velocities and spectral widths from 3 to 24 dB, \( \pm 50 \text{ m} \text{s}^{-1} \), and 0 to 50 ms \(^{-1} \) respectively, were considered. These criteria probably selected the meteor echoes with the most accurate LOS velocity.

The lower panel of the probability distribution plots clearly shows a separate distribution of high spectral width echoes. These spectral widths are unusually large for meteor echoes and they probably arise because the standard real-time analysis algorithm does not always give correct results for echoes with modest signal-to-noise ratio. However, the middle plot of Figure 4 (b) shows that the distributions of LOS velocities is equivalent for all three categories of echoes. Hence, in the unlikely circumstance the large spectral width echoes were not meteor echoes, they probably drifted with the same velocity as meteor echoes, and the neutral winds derived from all three populations should be the same.

Figure 5 shows plots of the neutral winds calculated for the 23 to 25 May campaign. First, the top panel (a) shows the total number of meteor echoes detected every 15 minutes for all echoes. The large number of meteor echoes detected permitted estimates of neutral winds using 15 minute bins, as opposed to the hourly bins used in previous studies. The middle panel (b) shows the meridional wind (positive equatorward) and the bottom panel (c) zonal winds (positive eastward) calculated for separate echo populations following the criteria used in Figure 4. The black dots represent the unrestricted data, and the green stars the low powered echoes (3 to 10 dB). The blue triangles represent the echoes with unusually high spectral width (300 to 600 m s\(^{-1} \)), and the purple squares the meteor echoes identified using the most restrictive criteria.

The neutral winds were derived as follows. First, the horizontal component of the LOS Doppler velocities were calculated assuming that all meteor echoes had a reflection height of 95 km. This projection was performed at all ranges between 120 and 600 km and for all sixteen beams. Next the LOS horizontal components were averaged across all ranges but separately on all sixteen beams. The standard errors were also calculated. The meridional winds (middle panel) were estimated by calculating the weighted average horizontal velocity on beams 7 and 8 because geographic south lies half-way between these two beams. In order to estimate the zonal wind (bottom panel), a beam-swinging algorithm was applied if horizontal components were available on at least 5 beams. The best-fit curve to the horizontal velocities on all sixteen beams was constrained by the aforementioned estimate of the meridional wind, as well as the corresponding standard errors.

The estimate of the meridional wind assumed homogeneous meridional flow across beams 7 and 8 and all ranges between 120 and 600 km, whereas the estimate of the zonal wind assumed homogenous meridional and zonal flow across all 16 beams and ranges. The estimates of both components assumed the homogeneous flows had zero vertical winds, and the winds were stationary for 15-minute intervals. The estimates of the meridional winds (middle) show less scatter and are more accurate because they were closer to a direct measurement. However, because of all the assumptions made, both wind components are considered “synoptic scale” estimates.

As expected, the scatter in the estimated winds increased (decreased) at dusk (dawn) when the number of available echoes was a minimum (maximum). However, the scatter was greatest of all for the echoes with unusually high spectral widths (blue triangles), suggesting that these were actually meteor echoes with less accurate LOS velocity and very poorly determined spectral width. Nevertheless, there is consistency in the wind values derived from each of the echo populations, and they all provided a consistent synopsis of the winds in the MLT region just south of Tasmania. The net wind direction throughout the campaign was poleward and westward, though becoming more equatorward towards the end of the campaign, and there were clear variations on gravity-wave and tidal time scales. The geophysical significance of these winds will be analysed in a separate study.

3. Recommendations
In order to optimise the detection rate of meteor echoes, we recommend the use of transmitter pulses of width 15 km and range gates separated by 15 km commencing at ranges of ~60 km. The use of shorter range sampling will also facilitate better resolution of the height variation of the winds. The integration time should also be reduced to 2 s or less. These are not the standard operating parameters used for ionospheric research, but they result in the detection of numerous meteor echoes permitting the calculation of neutral winds with greater accuracy and time resolution.

Work continues on resolving directional ambiguities in the detection of meteor echoes due to the presence of back lobes (S. Yukimatu, private communication). We recommend the use of a radar operating frequency of ~12 MHz, and even less when the back lobe ambiguities can be resolved. The latter will permit the measurement of neutral winds in two separate MLT regions displaced several hundred kilometres north and south of a radar pointing in the meridional direction, or at least an estimate of the meridional gradient.

Our analysis shows that the criteria used to identify meteor echoes are not critical for estimating the synoptic-scale meteor winds. The present approach will remain valid for the derivation of synoptic-scale MLT winds, and especially for the re-processing of SuperDARN data archives which now extend back ~20 years. However, it will be superseded by the use of a new radar operating system which permits the direct detection of the rise and decay of meteor echoes (Yukimatu 2002), combined with the use of new digital receivers and signal processing. This will facilitate better horizontal and vertical resolution of the MLT winds.

The descending plasma streams (DPS) which merged into and contaminated the meteor scatter observed by TIGER will be less of a problem for the planned network of “storm time” SuperDARN radars to be deployed at mid-latitudes for the study of major substorms and storms which occur less frequently.

4. Acknowledgments

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5. References


Table 1.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Nominal Values</th>
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<tr>
<td>Power</td>
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<td>LOS Doppler velocity</td>
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<tr>
<td>Spectral width</td>
<td>&gt;1 and &lt;50 m s⁻¹</td>
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<td>Range</td>
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Figure Captions

**Fig. 1.** Summary plot of all echoes recorded at 12,050 kHz on beam 7 during 12 UT on 23 May to 0 UT on 26 May 2003. The top panel shows the backscatter power (dB), the middle panel the LOS Doppler velocity (m s⁻¹), and the bottom panel the Doppler spectral width (m s⁻¹). Magnetic latitudes are superimposed.

**Fig. 2.** Histogram of the number of meteor echoes per 2-s sounding versus the start transmission frequency of each licensed band.

**Fig. 3.** (a) Summary plot of echoes recorded using a 12,050 kHz transmission frequency. (b) Summary plot of echoes recorded using a 19,800 kHz transmission frequency.

**Fig. 4.** (a) Distribution functions of the number of echoes recorded between ranges 120 to 600 km for the (i) backscatter power (dB), (ii) LOS Doppler velocity (m s⁻¹) and (iii) Doppler spectral width (m s⁻¹). The black solid line represents the unrestricted echoes, and the green dotted line the echoes with amplitudes of 3 to 10 dB. The blue long-dashed line represents the echoes with high spectral width (300 to 600 m s⁻¹), and the purple dot-dash line represents the meteor echoes identified using the most restrictive criteria (see text). (b) The same as part (a) except the individual distribution functions have been normalised to their peak values.
Fig. 5. (a) The number of meteors detected during each 15 minute interval of time during the 23 to 26 May 2003 campaign. (b) The corresponding meridional winds calculated using the Doppler shifts observed on beams 7 and 8. A positive wind indicates equatorward (northward) motion. (c) The zonal winds calculated using the beam-swinging technique described in the text. A positive wind indicates eastward motion. Only those meteor echoes identified using the most restrictive criteria were used in these calculations.
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Figure 4 a B&W Printed Version

(i)

(ii)

(iii)