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All-Sky Interferometric Meteor Radar Observations of Zonal Structure and Drifts of Low-Latitude Ionospheric E Region Irregularities

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Abstract All-sky interferometric meteor radar has been operated worldwide for the measurements of neutral winds in the mesopause region. In this paper, we employ an all-sky meteor radar and an ionospheric radar, which are situated at Ledong (18.4°N,109°E) and Sanya (18.3°N,109.6°E), respectively, and both have the interferometry capability, to study the zonal structure and drifts of ionospheric E region irregularities producing continuous and quasiperiodic echoes. We use the collocated optical meteor observations to calibrate the radar system phase offsets for interferometry measurements. A good correspondence between the irregularity measurements from both radars was found. The observations show that the quasiperiodic striations with both negative and positive slopes in radar range-time-intensity maps were produced by spatially separated irregularity structures, which drift through the radar field of view. The continuous echoes were due to irregularities generated locally. Specifically, comparing with ionospheric radar, all-sky meteor radar has a much wider field of view that can provide E region irregularity information over a large zonal region of more than 300 km. It is suggested that all-sky meteor radar provides a capability to probe ionospheric E region irregularities and to trace their movements.

Plain Language Summary The interferometry observations of ionospheric E region irregularities from a conventional all-sky meteor radar and an ionospheric radar are reported. The results show the feasibility of making ionospheric E region irregularity measurements and tracing their movements over a large zonal field of view of more than 300 km with conventional meteor radars. Since there are tens of such meteor radars continuously operated at middle and low latitudes, the interferometry observations with these meteor radars would contribute to a better understanding of worldwide ionospheric E region irregularities.

1. Introduction

Ionospheric E region field-aligned irregularities (FAIs) have been widely observed at middle and low latitudes using ionospheric radars. Based on the radar range-time-intensity (RTI) observations of E region irregularity echoes, two types of echoes were classified, including the quasiperiodic (QP) echoes and continuous echoes (e.g., Yamamoto et al., 1991). The QP echoes appearing mainly at altitudes of 100-130 km after sunset, with positive, vertical, or negative slopes in radar RTI maps, were firstly observed at middle latitude (e.g., Ogawa et al., 1995; Yamamoto et al., 1991) and then at low latitude in different longitude sectors (e.g., Chau et al., 1999; Li et al., 2013; Patra, 2008). Based on the periodic behavior of QP echoes in space and time, several mechanisms responsible for the generation of QP echoes have been proposed, including the Es layer instability modulated by gravity waves (Tsunoda et al., 1994; Woodman et al., 1991), the Kelvin-Helmholtz (KH) instability driven by neutral wind shear (e.g., Larsen, 2000), and the QP plasma cloud-associated polarization processes (e.g., Venkateswara Rao et al., 2008). The continuous echoes can occur on both day and nighttime sectors at altitudes of 90-100 km (Ogawa et al., 1995; Patra et al., 2004). Under the effects of neutral wind and electric field, the irregularities producing continuous echoes can be generated (Kagan & Kelly, 1998; Patra & Rao, 2007).

Besides the ionospheric radar, Xie et al. (2019) discussed the possibility of E region irregularity observations by using an all-sky meteor radar at middle latitude. Based on the Wuhan all-sky meteor radar and ionosonde...
data during March–June 2018, they reported that the occurrence of E region FAI echoes detected by the meteor radar was closely correlated with strong Es layer with critical frequency more than 5 MHz. Due to the wide beam width of meteor radar, backscatter echoes from different directions (where radar line of sight is perpendicular to geomagnetic field) could be detected. This may cause the difficulty to explain the echoes, which could be messed up through contributions from spatially separated different scatterers. They suggested that by employing the interferometry capability of meteor radar to estimate the arrival angles of scatterers, the spatial locations of irregularities could be obtained.

Radar system phase offset calibration is critical to the interferometry analysis. The phase calibration techniques are mainly based on the artificial or natural scatterers at known location, for example, the aircraft (e.g., Chen et al., 2002) and the injection of test signals into various system components (e.g., Holdsworth, Reid, et al., 2004). On the other hand, some assumptions are employed to calibrate the radar system phase offsets, for example, that the mean scattering position of lower and higher mesospheric returns over a suitably long observation period is centered on the zenith (e.g., Kudeki et al., 1990) and that the number of meteor occurrences with varying height range satisfies the Gauss distribution (e.g., Holdsworth, Tsutsumi, et al., 2004). Solomon et al. (1998) reported the use of meteor echoes for phase calibration of an over-the-horizon radar. Michell et al. (2015) used simultaneous optical meteor and radar specular meteor echoes to calibrate the phase offset of the Southern Argentina Agile Meteor Radar (SAAMER) system. Li et al. (2018) used simultaneous optical meteor and radar nonspecular meteor echoes to calibrate the Sanya radar phase offset.

Comparing with ionospheric radar, all-sky meteor radar has a much wider field of view (FOV) where ionospheric irregularities could be detected over a larger longitude range. Further, all-sky meteor radar is generally equipped with the “JWH antenna configuration” (e.g., Jones et al., 1998). This enables the meteor radar to get spatial locations of backscatter echoes unambiguously. To investigate if all-sky meteor radar can be well employed to investigate ionospheric E region irregularities, we conducted a comparative experiment in October 2018 by employing an all-sky meteor radar and an ionospheric radar located at Ledong (18.4°N, 109°E) and Sanya (18.3°N, 109.6°E), respectively, which are separated by about 70 km. To calibrate the radar system phase offsets, double-station optical meteor common-volume observations were performed at the two stations. The spatial locations and movements of ionospheric E region irregularity producing continuous and QP echoes detected by both radars were comparatively studied.

2. Experiment and Data

The Ledong all-sky meteor radar works at 38.9 MHz with a peak power of 20 kW. The radar uses one crossed dipole antenna for transmission and five crossed dipole antennas orthogonally arranged for independent reception (e.g., Jones et al., 1998; Holdsworth, Reid, et al., 2004). The radar beam width is very wide (with 3-dB beam width of about 360 × 110° satisfying the perpendicular condition with geomagnetic field at E region altitudes over a wide longitude range. During the experiment, the radar parameters are typical for neutral wind observation. The pulse repetition frequency, range resolution, and sampled ranges are 430 Hz, 1.8 km, and 68.4-318.6 km, respectively.

The Sanya ionospheric radar operates at 47.5 MHz with a peak power of 24 kW for ionospheric E and F region irregularity observations (e.g., Li et al., 2011). The radar antenna array consists of six groups of antennas in the east-west direction for transmission and reception and one group in the north of the main east-west array for reception. Each group includes 2 × 2 five-element Yagi antennas. The radar beam is centered toward north in ~24° zenith, with a 3-dB beam width of 16 × 36° satisfying the perpendicular condition at altitudes from ionospheric E to F regions. The positions of irregularity scatterers within the radar beam can be obtained by measuring the phase differences among the signals received at any three spatially separated groups (e.g., Li et al., 2014). The radar pulse repetition frequency, range resolution, and sampled ranges are 650 Hz, 0.9 km, and 80-200.6 km, respectively.

The Sanya and Ledong optical meteor observation system consists of 15 low-lux Watec 902H2 ultimate CCD video cameras, which cover the FOV of Sanya ionospheric radar and part of the FOV of Ledong meteor radar. For each video camera, a 7- to 33-mm f/0.95 Hikvision auto iris lens is coupled. The video is digitized by Canopus A/D converters, with 720 × 576 pixel resolution and a rate of 25 frames per second stored on disk in AVI format. The optical system provides an angular resolution of about 0.02° per pixel (e.g., Li et al., 2018).
During the present experiment in October 2018, the raw complex (I/Q components) data from the Ledong all-sky meteor radar and Sanya ionospheric radar were recorded for off-line interferometry analysis. The methods for locating optical meteor through double-station common-volume measurements and then calibrating the radar system phase offsets with the known location of optical meteor have been given in our previous works (e.g., Li et al., 2018, and the references therein) and will not be present here. An example of optical bright meteor and radar nonspecular meteor echo simultaneously detected at Ledong and Sanya is shown in Figure 1. The top panels from left to right show the RTI maps of backscatter echoes from the Ledong meteor radar and Sanya ionospheric radar, respectively. The bottom panels show the spatial locations of meteor light curve simultaneously observed by the video cameras around 16:34:23 UT at Ledong and Sanya and nonspecular meteor echoes by both radars.

In general, it can be seen from the top two panels of Figure 1 that nonspecular meteor echoes and Es layer irregularity echoes were observed by both radars. For the nonspecular echo event starting around 16:34:23 UT, it was detected simultaneously by both radars but with longer duration in the Sanya RTI map. The difference of echo duration for the same meteor event detected by both radars could be caused by the radar sensitivity (e.g., peak power) and the magnetic aspect sensitivity of nonspecular echoes. Close et al. (2007) reported that the duration of nonspecular echo depends on the angle between the radar line of sight and the direction perpendicular to geomagnetic field line. The nonspecular echoes coming from the direction perpendicular to geomagnetic field generally have a duration longer than those from the directions off perpendicular (e.g., Close et al., 2007; Li et al., 2018; Oppenheim et al., 2014). In the bottom panels of Figure 1, the superposed dots represent the location of nonspecular meteor echo through radar interferometry analysis. It is evident that the spatial locations of nonspecular meteor echoes derived from both radars are in the same place, which correspond quite well with that of the optical meteor trail (marked with circles). The results indicate that the system phase offsets for both radars have been well calibrated.

3. Results and Discussion

Figure 2 shows a comparison of ionospheric E region irregularities obtained from the Ledong meteor radar and Sanya ionospheric radar in October 2018. The curves superposed in Figures 2a and 2b represent the occurrence rates of irregularity echoes with intensity more than 0 dB. Two notable features can be clearly seen from Figures 2a and 2b. One is that the irregularity backscatter echoes were mainly observed at nighttime, with a higher occurrence around 1300-2000 UT (2020-0320 LT) at both stations. The results are consistent with Ning et al. (2012) where E region irregularity echoes were observed mostly at nighttime, closely correlated with the presence of strong Es layer. On the other hand, the E region irregularity observations from both radars are generally consistent with each other in the day-to-day variability, except that the echo intensity from the Ledong meteor radar is apparently weaker than that from the Sanya ionospheric radar due to the difference of peak power and beam width. The sensitivity difference may cause some weak echoes being detected by the Sanya radar but not by the meteor radar. The present results together with Xie et al. (2019) indicate that the meteor radar can be employed to investigate the general occurrence of ionospheric E region irregularities at low to middle latitudes.

While looking into the irregularity echoes in radar RTI map, which are responsible for the nighttime higher occurrence shown in Figures 2a and 2b, it was found that the echo patterns at daytime and nighttime are usually different, belonging to continuous and QP echoes, respectively. Figures 2c and 2d show a typical case of E region irregularities observed by the Ledong meteor radar and Sanya ionospheric radar on 10 October 2018. There are multiple echo striations detected by both radars at a large range interval with both negative and positive slopes during nighttime 1500-2000 UT (2220-0320 LT), being classified as QP echoes. The QP echoes are likely clustered into three groups around 1500-1720, 1720-1840, and 1840-2000 UT, respectively. There have been numerous reports on ionospheric radar observations of multiple QP echoes with positive or negative slopes (e.g., Chen et al., 2005; Hysell & Burcham, 2000; Tsunoda et al., 1999), where the striations were suggested to be indication of the drifts of irregularity structures driven by horizontal wind through the radar FOV, and/or tilted sporadic E layers. During daytime around 00-05 UT, continuous echoes were observed. The short vertical streaks distributed discretely in the Ledong meteor radar RTI map are due to nonspecular meteor echoes.
To get the spatial locations of E region irregularity structures producing the QP and continuous echoes shown in Figures 2c and 2d and trace their movements, we employ the multichannel raw data from the all-sky meteor radar and ionospheric radar for interferometry analysis. Figure 3 shows the spatial locations of E region irregularity echoes during 1500-2000 UT. Considering the high magnetic aspect sensitivity of E region FAIs, the echoes from the directions off perpendicular to geomagnetic field (which could be due to nonspecular meteor echoes) have been removed. The top left panel shows that for the irregularity echoes detected by the meteor radar, they are widely distributed in the azimuth ranging between $-80^\circ$ and $75^\circ$. The echoes detected at longer ranges are from the eastern or western side where the azimuth (elevation) angles are larger (lower). The middle panels show the echo positions projecting on the vertical plane. The echoes are mostly located in the altitudes of 95-120 km. The right panels show the positions of irregularity echoes projecting on the horizontal plane. In general, the echo intensity (indicated by different colors) attains a maximum when the irregularities are just due north of the radar site. One possible cause is that these echoes are detected at shorter ranges. Comparing with the ionospheric radar, the observation by meteor radar covers a larger area of more than 300 km in the zonal direction, providing a good chance to continuously detect the occurrence of irregularities over a larger longitude region.

Based on the results shown in Figures 2 and 3, it is very likely that the QP echoes were produced by spatially separated irregularity structures and that the negative and positive slopes for the same echo trace were

Figure 1. A case of meteor event simultaneously detected by radar and optical meteor observation system at (left) Ledong and (right) Sanya on 20 October 2018, 16:34 UT. The red lines superposed in the top panels mark the start time of optical meteor. The bottom panels show the spatial locations of radar nonspecular meteor echoes (marked with colored dots) and optical meteor trail (marked with circles).
caused by the horizontal motion of irregularity patch into and out of the radar FOV. To get more detailed information, Figure 4 plots the spatial locations of the E region QP echoes at a selected time interval 1546 UT and of a selected single QP echo trace during a long time interval from its appearance to

Figure 2. (a and b) The temporal variation of maximum echo intensity observed at the altitude interval of 100-120 km in October 2018. (c and d) A case of E region irregularity echoes observed on 10 October 2018. The curves superposed in Figures 2a and 2b represent the occurrence rates, which are defined as the number of data points with echo intensity more than 0 dB divided by the total number of data points in each time interval (15 min).
disappearance. In the top left panel, the dashed line in the RTI map highlights the time interval 1546 UT. The top middle panel shows the corresponding spatial locations of different echo striations in the vertical plane. It is clear that different echo strips at the same time interval from the meteor radar are caused by irregularity structures spatially separated by 50-100 km in the east-west direction. The true heights of different echo strips are around 100-115 km, consistent with previous observations of QP echoes (e.g., Chen et al., 2005). In the horizontal plane (top right panel), the QP echoing regions were likely elongated in the north-south direction. In general, comparison of meteor radar irregularity observations (top panels) with ionospheric radar (middle panels) shows a good correspondence, whereas only one echo strip was observed by the ionospheric radar due to its narrower beam width. The echo strips simultaneously detected by both radars correspond quite well in the echoing structure and spatial location. The results suggest that the meteor radar is capable to distinguish spatially separated E region irregularity structures simultaneously appearing in the radar FOV and trace their movements through interferometry analysis.

The bottom panels of Figure 4 show the RTI map of a selected echo strip and the spatial locations of corresponding irregularity echoes at different time intervals (marked with labels from “A” to “G”) projected on the vertical and horizontal planes. There is an evident dynamic behavior of the irregularity structure producing the echo strip. In the east-west direction, the irregularity entered into the radar FOV from the eastern side (marked with “A”) and then went out from the western side (marked with “G”), at an altitude range of 100-110 km. This explains the negative and positive slopes for the same QP echo trace in the RTI map. It is relevant to mention that in previous observations of QP echoes by ionospheric radar, the positive and negative slopes represent drifts of irregularity toward opposite directions. The present observations of negative and positive slopes by meteor radar are due to the drifts of irregularity toward the same direction (westward) over a wide region. In the bottom right panel of Figure 4, the irregularity seemed like to have a southward drift component. Interestingly, when the irregularity passed over the radar site, the echoing region was slightly aligned in the direction from northwest to southeast. In general, the results in Figures 3 and 4 indicate that the QP echo striations are mainly caused by the westward (with a small southward component) motion of irregularity structures spatially separated by 50-100 km, which are generated in the eastern of radar sites.

Figure 3. The spatial locations of E region irregularity echoes during 1500-2000 UT observed by the (top) Ledong meteor radar and (bottom) Sanya ionospheric radar. The shaded region (marked with circles) in the left panel represents the direction where radar line of sight is perpendicular to geomagnetic field, which was calculated using the IGRF-2015 model at E region altitudes (90-130 km) with a magnetic aspect angle of less than 0.5°.
Figures 5a and 5b show the locations of E region QP and continuous echoes in the east-west direction as a function of time. Different colors represent the altitudes of 95-110 km. It can be seen from Figure 5a that all the QP echoes detected by the meteor radar during 1500-2000 UT have negative slopes. Here we consider each striation at the same altitude interval as a cluster and calculate the slope, which represents the drift velocity of irregularity structure producing QP echo in the east-west direction. The superposed solid curve shows that the estimated velocities range between $-70$ and $-140$ m/s (negative value means westward).

For the continuous echoes, Figure 5b shows that the echoing regions were always located over the radar site at altitudes of 95-105 km. The observations indicate that the irregularities producing continuous echoes could be generated locally over the radar site. Previous studies have suggested that the E region

Figure 4. (left) The RTI map and (middle and right) spatial locations of corresponding irregularity echoes during the selected time intervals. The vertical lines in the left top and middle panels mark the time interval 1546 UT when different echo strips were simultaneously observed. The vertical lines in the left bottom panel mark different time intervals (“A” to “G”) for a selected single echo strip. Note that the top middle and right panels show spatially separated irregularity structures simultaneously observed at 1546 UT. The bottom middle and right panels show the spatial location of the same irregularity structure during different time intervals (labeled with “A” to “G”).
Continuous echoes are caused by irregularities generated through the gradient drift instabilities. The required electron density gradient can be provided by Es layer. Both neutral wind and electric field could play roles in forming the continuous echoes (e.g., Patra et al., 2009).

Unlike the continuous echoes generated locally within the radar FOV, the QP echoes were due to irregularity structures coming from the eastern (northeastern) of radar sites, which are spatially separated by 50-100 km in the east-west direction. The irregularities drifted toward west (southwest) with velocities ranging from −70 to −140 m/s through the radar FOV. Specifically, Figure 4 shows that the irregularities producing QP echoes are likely aligned with the wavefronts north or northwest to south or southeast. In previous studies of QP echoes, the QP echo striations were suggested to be telltale of the southward propagating gravity waves or the horizontal wind-driven motion of discrete scattering structures through the radar beam (e.g., Hysell et al., 2002; Tsunoda et al., 1994). On the other hand, Yamamoto et al. (1997) and Tsunoda et al. (2004) proposed that QP echoes are associated with Es layers propagating southwestward, which is the same preferred propagation direction as the medium-scale traveling ionospheric disturbances (MSTIDs). It has been suggested that the generation of periodical irregularity structures causing QP echoes could be connected with MSTIDs through the coupling of E and F regions (e.g., Otsuka et al., 2007; Saito et al., 2007; Zhou et al., 2018). By employing the chain of meteor radars (Yu et al., 2013) and GNSS receiver network (Li et al., 2019) over China middle- and low-latitude regions, comparison studies of spatial structures of E region irregularities and MSTIDs would help to improve our understanding on the generation of QP echoes. This, however, is beyond the scope of this study and left for future work.

4. Conclusions

We conducted a comparative experiment of E region irregularity with the Ledong meteor radar and Sanya ionospheric radar. The two radars are located 70 km apart. The collocated optical meteor observations at the two stations were employed to calibrate the radar system phase offsets for interferometry analysis. In general, the irregularity measurements by the meteor radar and ionospheric radar showed a good correspondence in their statistical occurrence and dynamic behavior. Importantly, compared with the ionospheric radar, all-sky meteor radar has a much wider FOV that can provide E region irregularity information over a large zonal region. The observations by the meteor radar showed that the QP echo striations with both negative and positive slopes in radar RTI maps were produced by spatially separated irregularity structures, which were generated on the eastside of radar sites and drifted through the radar FOV over a large zonal distance of more than 300 km. Whereas the meteor radar beam width is very wide, considering the good consistency in the statistical local time dependence of E region irregularities from both radars and the well-resolved zonal structure and movement of E region irregularity, we suggest that besides the regular meteor observation, all-sky interferometric meteor radar could provide a capability to simultaneously trace the E region irregularities over a large area.
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