



## Multi-Instrument Observations of MSTIDs and Source Determination

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### Abstract

A multi-day (6-8 May 2013), apparently medium-scale traveling ionospheric disturbance (MSTID) event with an ~1 hour period was recorded using both the vertical-looking and steerable Millstone Hill incoherent scatter radar (ISR) systems during quiet geomagnetic activity. The dense network of Global Positioning System (GPS) total electron content (TEC) receivers has allowed the horizontal imaging of this event across a far larger scale than is possible with the ISR(s) alone. This MSTID event was identified in the GPS-TEC dataset on the mesoscale centered at Haystack. However, GPS-TEC imaging also revealed that this event was coherent across the United States. The GPS-TEC imaging also revealed that similar events occurred globally. We conclude that this MSTID event was actually a coherent ionospheric pulsing structure (CIPS) that, when viewed locally, masqueraded as an MSTID event. The GPS-TEC images reveal that, on a global scale, the CIPS were stationary in longitude, but moved southward in the Northern Hemisphere—imaging of the southern hemisphere was not possible. The CIPS originated in high latitudes and at one instance were coherent across 23,000 km. The large-scale coherence, ubiquity, and source location of the CIPS points to an unidentified auroral zone source with sufficient energy to continually force the observed MSTID-like structures.

### 1. Introduction

Medium-scale traveling ionospheric disturbances (MSTIDs) are a common, longer wavelength and period manifestation of acoustic gravity waves (AWGs, [1]). Here we report (highly local) ISR observation of a long-lived ionospheric wave structure that appears to be an MSTID. However, GPS-TEC imaging on mesoscale to global scales reveals that the phenomenon is not a freely propagating MSTID but rather a continually forced, global scale “wave” we refer to as CIPS in Section 4. However, we refer to it as an MSTID in the bulk of this work.

The particular MSTIDs being investigated here seem to occur over many geographic areas and have several common features: (1) ~1 hour period, (2) ~200 km horizontal wavelength, (3) exhibit vertical wavelengths that can reach over 150 km, (4) occupy the altitude range

centered at 250 km (F-region base), and (5) are seen for days at a time [1, 2]. These MSTIDs have been observed using the ISRs at Arecibo Observatory (AO), Millstone Hill, and Poker Flat [3]. While usually observed with ISR systems [4], all-sky imagers and the GPS-TEC network have also been used to detect these waves [5].

Proposed MSTID sources have ranged from ocean tides [1], to winds over the ocean, to auroral zone heating, to solar wind oscillations [3]. The proposed source diversity demonstrates the difficulty in observing MSTIDs over sufficient horizontal scales for long enough that their full characteristics emerge.

MSTID occurrence has been found to increase in quiet solar periods [6]. The observations herein occurred during a quiet and steady period with the Kp index ranging from 0.5 to 3. Solar wind and other solar parameters were steady as well.

The MSTID event discussed here was observed using the Millstone Hill (MA, USA) two-beam ISR system as a follow-on to AO observations that introduced this phenomenon [3, 4, 5, 6]. High-resolution horizontal imaging using GPS-TEC was developed using the data collected and archived in the Madrigal system at Millstone Hill. The ISR observations reported here extend over 12:42 UT May 6<sup>th</sup> until 19:47 UT May 8<sup>th</sup>, 2013.

The Millstone Hill ISR system consists of two radar dishes. One dish is fixed pointing with a beam elevation of 88° (the Zenith beam) and the other (the Millstone Hill Steerable Antenna; MISA) was pointed parallel-B (azimuth angle = 165.8°, elevation = 66.26°) at an altitude of 250 kilometers. At 300 km altitude, the beams have a 132 km separation. The single transmitter is switched between antennas on a 6 minute 32 second cadence with data taken over ~100 km to ~980 km range.

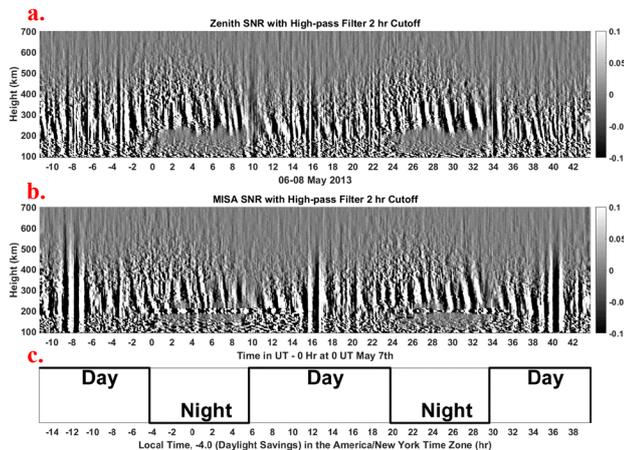
The unprocessed global GPS data used here was collected and archived at Millstone Hill. The GPS-TEC dataset consists of the slant-path TEC (sTEC) in TECU ( $10^{16}$  electrons/m<sup>2</sup>), the latitude and longitude of the propagation path at 325 km altitude, and the corresponding time. The entire available GPS sTEC dataset was processed over the ISR observing period. The processed TEC dataset was produced using an algorithm

that will soon be detailed in a publication by A. Coster et al. Their algorithm employs a high-pass filter with a 3-hour cutoff period along with a de-biasing procedure. The processed delta-sTEC data and the original sTEC data both share a time interval of 30 seconds for each GPS satellite at each receiver.

In Section 2 we introduce the ISR results and discuss the apparent MSTID feature. The ISR data is correlated with the “local” GPS-TEC data in Section 3. Finally, in Section 4, the GPS sTEC data is used to image the MSTID waves on the mesoscale centered Millstone Hill and then extended to global scales leading to the re-identification of the phenomenon as a CIPS. Section 5 summarizes our results and suggests a source for the CIPS event.

## 2. Incoherent Scatter Radar (ISR) Results

Figure 1 gives the range-time-intensity (RTI) plots from the Millstone Hill Zenith and MISA ISR systems. In Figure 1, the SNR data which was processed through a finite impulse response (FIR) high-pass, zero-phase (order 43) Hanning window filter with a 2-hour cutoff period. This high-pass filter has been shown to not introduce artificial features [4]. The time reference for this figure and all succeeding figures is based on 0 hours at 0 UT on May 7<sup>th</sup>, 2013.



**Figure 1.** The above RTI plots show the high-pass filtered results for the Zenith and MISA beams. The altitude is limited to 700 km and the SNR is limited to +/- 0.1. The Zenith beam (a.) shows coherent structures with very few interruptions throughout the nearly 3 day viewing period. The MISA beam (b.) has similar structures, but also has solar interference at local noon (hours -8, 16, 40) as well as nighttime 200 km interference streaks. The local day/night periods for the Haystack Observatory are also shown. The coherence of the “MSTID” wave structure is similar to that observed at Arecibo Observatory [3].

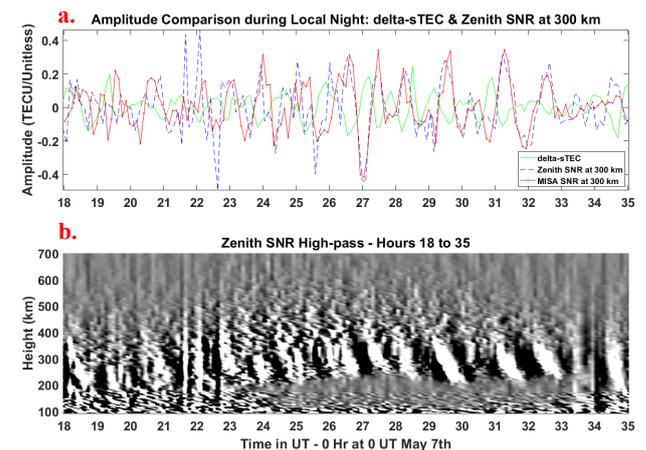
A constant wave-like pattern is seen throughout the all three days in Figure 1. Other than the solar interference in the MISA beam, the ~300 km altitude range is unaffected by major noise sources in both the Zenith and MISA beams.

Spectral analysis reveals the apparent period of the MSTID was 65 and 90-95 minutes at 300 km altitude for both beams.

The ionospheric “waves” seen in Figure 1 fulfill the usual definition of an MSTID. The apparent periods are in the range expected for MSTIDs, as is the large vertical wavelength. The surprise is that this MSTID structure is visible for the entire observation period. The horizontal wavelength is such that the Zenith and MISA results display very little phase difference despite the expected wavelength of about 200 km given the 300 km beam separation of about 130 km. Still the ISR results point to an MSTID event.

## 3. ISR Result Correlation to GPS-TEC

Correlating the ISR dataset to the GPS-TEC dataset will determine if the two datasets are pointing to the same F-region wave phenomenon. For the correlation study, high-passed ISR SNR data was averaged over 275-325 km altitude for both the Zenith and MISA beams to better match the vertical averaging intrinsic to the GPS-TEC results. The GPS-TEC data interval is 30 seconds, while the ISR data has an interval of about 6.5 minutes, so the GPS-TEC dataset was time averaged to match the interval of the ISR data. The GPS-TEC dataset was also high-pass filtered with the same zero-phase FIR filter used with the ISR dataset. The GPS delta-sTEC data was further processed by averaging all data points within a 50 km radius of Millstone Hill. This creates a 2D array of time and delta-sTEC that is approximately centered over the ISR beam locations. Finally, a late-afternoon/night-time period (18-35 UT) was chosen for the most consistent ISR results. Figure 2 shows the results of this approach.



**Figure 2.** (a.) Shows the delta-sTEC results as well as the Zenith and MISA high-passed SNR results at 300 km. The processing for both datasets is described earlier in Section 3. Note that both the TEC and ISR results show similar features that point to a common source despite the widely differing measurement methods. (b.) Gives the corresponding Zenith SNR RTI plot from Figure 1a. for context.

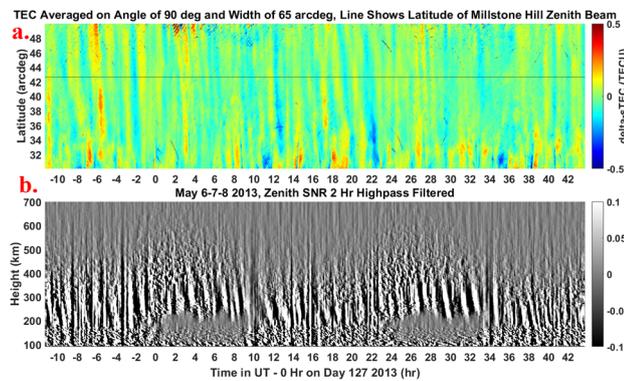
The Figure 2a time domain plot shows that strong perturbations are visible in both the ISR beams as well as the GPS-TEC. These features appear to have similar periods but the phases vary. Spectral domain analysis provides a better comparison as the period peaks are not instrument-specific and do not rely on relative amplitude between datasets. A Lomb-Scargle periodogram analysis of the time series data in Figure 2a. yielded shared 65 minute peaks and 90-95 minute shared peaks. The GPS-TEC had a peak at 80 minutes not observed in the ISR beams, but that frequency was visible in the periodogram of the entire ISR dataset.

We find that major features of the average, near-Millstone Hill GPS-TEC results are well correlated with the ISR results for 300 km altitude. Still these results are not totally convincing and so we move to GPS-TEC imaging results.

#### 4. GPS-TEC on Larger Scale

In Section 3 we analyzed the GPS-TEC dataset immediately surrounding (over a 50 km radius) Millstone Hill. We next extend the analysis to the mesoscale and larger. To present the GPS-TEC results effectively, an averaging system was employed to produce averaged in latitude/longitude vs. time “maps”. In this approach a geographical region is sliced into thin rectangles, and all GPS-TEC data points within that rectangle are averaged to one number. This is done for each time interval to create a plot that shows the wave (MSTID) coverage with time.

Ideally, averaging over a latitude/longitude-narrow but longitude/latitude-wide horizontal (or a rotated mix) area will reveal (amplify) the MSTID presence in one direction and suppress it in the other. Unexpectedly, it was found that this averaging in any direction produced strong wave features. The averaging area was increased to larger and larger regions to find wave direction. In particular, the averaging system was applied to the United States, splitting the 30° - 50° latitude by -60° to -125° longitude region into latitude strips. The approximate width of a slice was 11.1 km. Figure 3 gives these results.

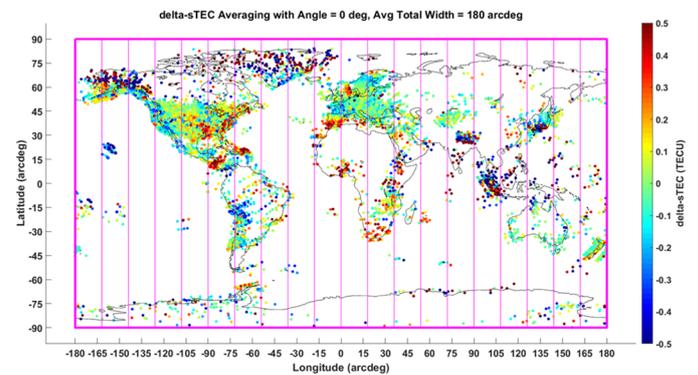


**Figure 3.** (a.) The result of the averaging system described above. The strong vertical features indicate that the wave feature is not moving with latitude. The

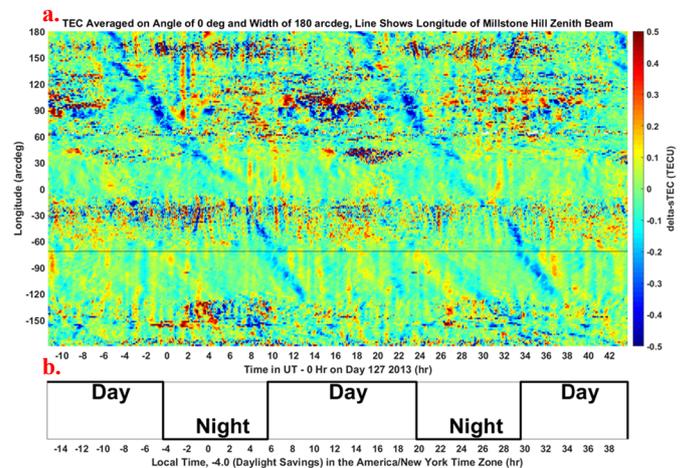
longitude plot of the same area demonstrated it was not moving with longitude, either. The black line represents the latitude of the ISR system. (b.) The Zenith ISR high-passed SNR plot is provided for reference to the local MSTID event. Note that when the MSTID loses coherency in the ISR plot, such as at hour 10, the GPS-TEC also exhibits coherency reduction.

The strong, vertical features seen in Figure 3a. suggest that the MSTID has a horizontal wavelength much larger than the United States since no directionality can be discerned. That wavelength demands a wave speed of at least 8,000 km/s for an hour period, which is physically impossible. Thus, the MSTID event observed locally with the ISR system seems to be something else.

Next, the averaging area was expanded to global scale to try to discern the direction of travel of the “wave”. Figure 4 shows the averaging grid for Figure 5. Figure 6 shows the results of averaging perpendicular to the direction shown in Figure 4.

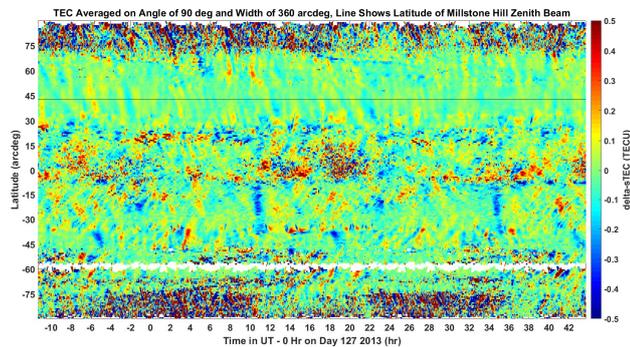


**Figure 4.** The GPS-TEC global, longitude-band, averaging scenario. The averaging angle is 0° with a width of 180° reaching pole-to-pole. The distance between the slices is 1.8° or about 200 km at middle latitudes. This averaging orientation will strongly detect the day/night transition in the ionosphere.



**Figure 5.** (a.) Demonstrates the results of the averaging systems shown in Figure 4. Substantial vertical features are visible across all longitude ranges. The strong blue diagonal features and weaker orange/red diagonal features

are the day/night shift. The black line represents the longitude of the Millstone Hill ISR Zenith beam. (b.) Shows the local day/night periods for the Haystack Observatory local time.



**Figure 6.** Figure 6 demonstrates the results of the averaging system that is perpendicular to the one in Figure 4. The vertical features now show a slight tilt indicating that as time progresses the coherent MSTID-like structures move towards the equator. From 30° to 60° latitude, consistent tilted features can be seen. The rest of the averaging area has much less data density leading to higher noise inclusions, but there are intermittent strong oppositely-tilted features in the Southern Hemisphere as well. The black line shows the latitude of the Millstone Hill ISR Zenith beam. The 30° to 60° latitude features do not seem to be day/night time dependent which is expected since the averaging range covers both.

From the Figure 5 & Figure 6 results we find that the MSTID-like features are in fact global in extent and thus not freely propagating but continuously forced “waves”. Given the Figure 6 hint of southward (northward) phase progression in the northern (southern) hemisphere, this suggests a (semi)coherent, auroral zone energy source that forces this whole ionosphere response. For lack of a better description, we call this overall “wave” response a Coherent Ionospheric Pulsing Structure (CIPS).

## 5. Conclusions

Millstone Hill ISR observations detected strong, multi-day, wave features that appear to be F-region MSTIDs with about 1 hour period as seen in Figure 1.

The global GPS-TEC dataset allows for a horizontal imaging of the ionosphere on MSTID scales. The MSTID-like wave pattern was found to be visible locally to Millstone Hill as well as across the entire United States as well as globally. Locally and at larger scales, the GPS-TEC features align with the ISR-observed wave features. But the larger scale results reveal that what we thought to be MSTIDs seen are large-scale, coherent, and ubiquitous ionospheric pulsing structures (CIPS). Any analysis on a scale less than the world showed little or inconclusive wave movement. Figure 5a shows that the pulsing structures are coherent across huge distances but do not move in longitude. Figure 6 shows that the coherent, pulsing structures move southward in the Northern

Hemisphere and likely oppositely in the Southern Hemisphere.

These “wave” features, now renamed coherent ionospheric pulsing structures (CIPS), are likely continuously forced by auroral zone (magnetospheric) processes. Figure 6 demonstrates that the structures originate from high latitudes with southward phase progression. They extend around the globe longitudinally. Other sources [1] do not have the consistency or energy to continually produce these huge structures that are coherent across tens of thousands of kilometers. Finding a magnetospheric source for these CIPS is the next step. Other previously identified long-term MSTID events may actually be CIPS events masquerading as a local MSTID.

## 6. Acknowledgements

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## 7. References

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