Characterizing traveling ionospheric disturbances using passive HF observations from lightning sources

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Abstract

Mathematical data assimilation algorithms (MIDAS, IDA) have been used for over 15 years to retrieve accurate three dimensional (3D) time evolving maps of the large scale, slowly varying global ionospheric electron density distribution. However, data assimilative techniques to retrieve accurate 3D time evolving maps of the electron density distribution due to traveling ionospheric disturbances (TIDS) have only recently been developed. The most accurate methods of estimating the 3D time evolving maps of bottom-side TIDS make use of multiple known HF transmitters. The observations available for analysis are angles of arrival (AoAs), group delay (GD) and Doppler. While these methods have shown great promise, the requirement of having known transmitters as well as a receive array available limits their usefulness for both scientific studies and operational applications.

Purely passive methods of characterizing TIDS would be useful for a variety of reasons. One passive source of data, which is ubiquitous and found over most of the globe, is RF Lightning data. New methods of registering the coordinates of lightning events are available to the research and applied communities in near real-time, making the use of lightning observations as a source to characterize TIDS an attractive option.

This paper takes a comprehensive approach to determining the feasibility of using low earth orbiting (LEO) satellites with broadband HF receivers capable of receiving lightning signals to characterize bottom-side TIDS. A computer simulation of a TID-rich bottom-side ionosphere is generated. The TID parameters are derived from previous work estimating TID parameters from bottom-side HF observations, and thus represent a realistic TID environment. Then we simulate HF time delay versus frequency observations at a LEO satellite from a ground transmitter over the time period of the satellite pass.

We use these simulations to investigate the feasibility of the system by studying different possible system configurations, and their impact upon the ability to first detect the presence of bottom-side TIDS and then reliably estimate wave parameters. The system configurations to be studied include: configuration of the satellite orbit; HF/VHF frequency range, number of frequencies and frequency resolutions; trade-off between bandwidth and resolution of time-of-arrival measurements; and number of lightning events per minute.

1. INTRODUCTION

Recently there has been renewed interest in being able to accurately geolocate HF emitters, particularly during periods of dynamical time-varying ionospheric conditions. Dynamical ionospheric conditions at mid-latitudes can be due to geo-magnetic storms, TIDS, sporadic-E and mid-latitude spread-F, as well as other daily variability.

Various methods can be used to specify the dynamically varying ionospheric electron density. First principle predictive models and empirical models of the ionosphere can be used to predict the bottom-side electron density. However, such models are not able to accurately predict the dynamical state of bottom-side density on few-minute time scales, and are only useful in understanding the average state of the ionosphere. Tomographic imaging and data assimilative methods that ingest data to specify electron density are able to characterize the current state of the ionosphere, but typical data sets that are ingested contain little signal information about the bottom-side ionosphere, and the resulting electron density does not accurately specify the bottom-side.

Good results have been obtained by using ground-based bi-static angles of arrival (AoA) to accurately specify the three-dimensional time-evolving TIDS on the bottom-side of the ionosphere. However typically only one frequency is available. Furthermore, HF bi-static signals are not always available where they are required.

Thus, there is a need for purely passive observations that are generally available over most of the globe, and are sensitive to the bottom-side ionospheric variability. One such source of data is broadband HF from naturally occurring lightning. The Los Alamos FORTE satellite demonstrated the capability of a broadband HF/VHF receiver upon a low-earth orbiting (LEO) satellite to accurately measure the time of arrival (TOA) response of ground-based lightning emissions over a wide band of frequencies in the HF and VHF domain. Lightning occurs over a large portion of the globe. Often lightning strikes are recorded at several per minute with a local region.

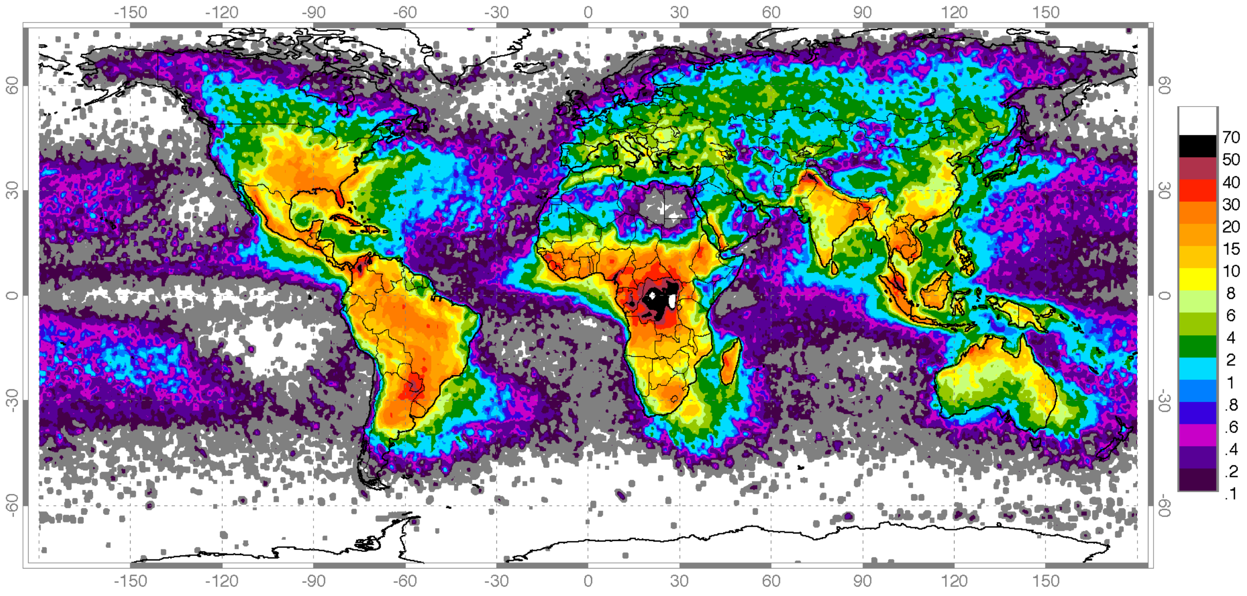

Figure 1: Global distribution of lightning in strikes/km^2/yr. Figure attributed to NASA/GHRC/NSSTC Lightning Team - http://www.nasa.gov/centers/goddard/news/topstory/2004/0621lightning_prt.htmhttp://visibleearth.nasa.gov/view_rec.php?id=2264, Public Domain, https://commons.wikimedia.org/w/index.php?curid=208039

Figure 1 presents a global distribution of lightning strikes per square km, per year. To get a sense of how this translates into strikes per minute, take as an average condition on land 20 strikes/km^2/year. Then over a 300x300 km region, we have ~ 3.5 strikes per minute, or 1 strike ~ every 17 seconds. This rough calculation is borne out by recordings from the FORTE satellite over the Caribbean and Gulf of Mexico regions. Further, new satellite missions such as the Global Lightning Mapper (GLM) on GOES –R, as well as continued advances in ground based detection/location techniques soon, will allow for near real-time detection and localization of lightning flashes.

Thus the question arises as to whether naturally occurring lightning can be used as a passive source to characterize bottom-side TIDS. In order to answer this question, we need to understand how sensitive the TOA versus frequency is to few percent wave perturbations, what sampling time is needed to characterize medium scale and large scale TIDS, and what are the best satellite altitudes? These questions are investigated in this paper through a simulation analysis.

2. SIMULATION

A computer simulation of satellite-based lightning observations through an ionosphere TID model was performed. The IRI model was used as a background and the Hooke (1968) model of TIDs was used to create the dynamic (time-dependent) perturbations. An additional computer simulation was carried out with the IRI model, but without the Hooke model TIDS as to allow an analysis of the observations to the presence of TIDs.

The lightning observations were generated by simulating a lightning source location on the ground, and a broadband HF satellite receiver on a satellite. A ray-tracer was used to trace the path of energy from the ground emitter to the receiver on board the satellite for a broadband of frequencies. For each simulated ray, overall group-delay, phase, and received angles of arrival (AoAs) were recorded. Figure 2) shows a set of ray paths through the TID ionosphere from ground source to satellite for a set of satellite positions.

For the simulation, a broadband ground electro-magnetic pulser was located at a fixed latitude and longitude, and pulsed a broadband signal at a sampling rate of 10-60 seconds. Simulations were made for the satellite low-earth orbit (LEO) satellite. These first simulations represent the best ideal condition that could be realized in a real experiment and therefore set an upper bound on how well lightning observations could be use to observe, characterize, and estimate the properties of TIDS.

3. RESULTS

3.1 Large scale TID simulations

We begin by simulating a large scale TID upon an IRI background ionosphere. The TID has a 1000 km horizontal wavelength 200 km vertical wavelength, is propagating southeast with a 1-hour period and an approximate 50% maximum perturbation at 220 km altitude. We then place a pulse transmitter at 30 degrees latitude pulsing a broad band of frequencies every 30 seconds. The frequencies used in the simulation ranged from 10-20 MHz in steps of 0.25 MHz, and then at 40 and 80 MHz A LEO satellite at 400 km altitude flies from south to north across the wave. The Figure 2 left plot shows

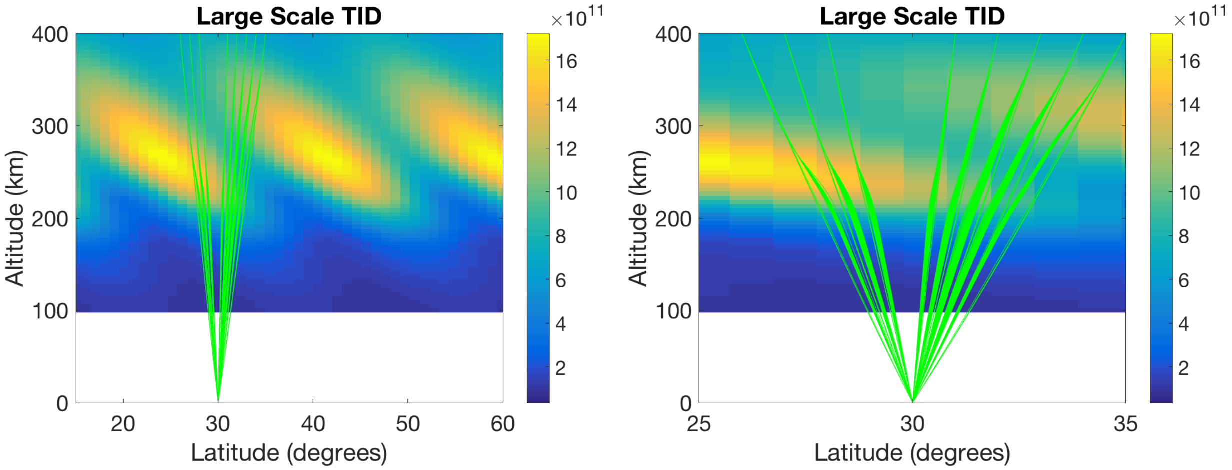

Figure 2: Large scale TID and HF propagation paths. The left hand plot shows the entire simulation region of the TID, extending from 15-60 degrees of latitude. The propagation paths between a pulser located at 30 degrees latitude and the satellite is shown for 8 satellite positions. The right hand figure enlarges the region of the observations. Variations in path versus frequency and time is clearly seen in the right hand plot

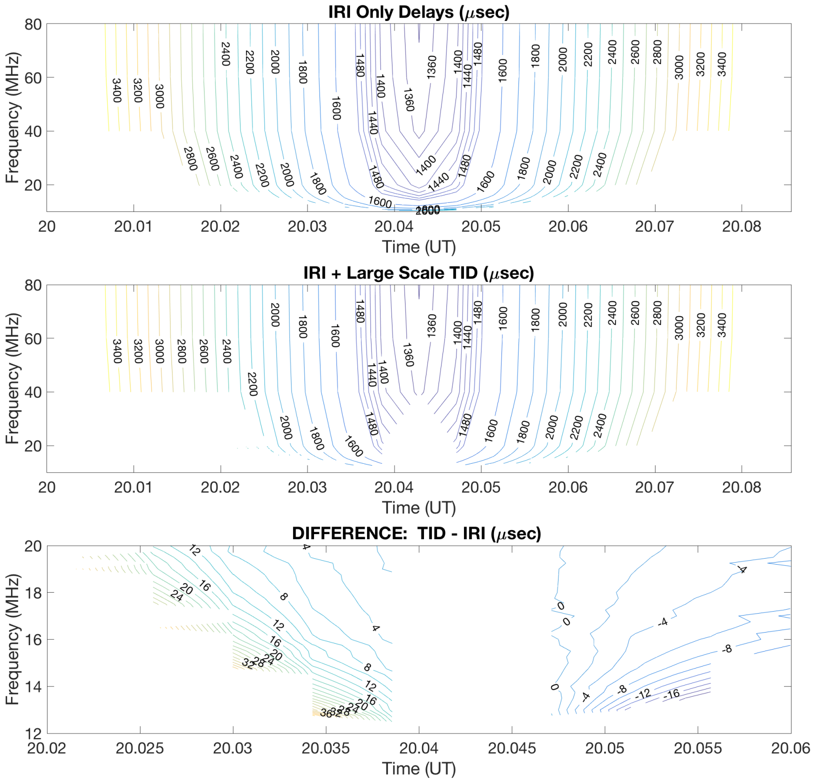

Figure 3: Comparison of delays between IRI alone (top plot), IRI with a large scale TID (middle plot) and the difference in delay between IRI+TID and IRI (lower plot)

three full wavelengths of the large scale TID from 15-60 degrees of latitude, and the propagation paths from the pulser to the satellite as it flies by. The propagation paths were obtained from the ray-trace code. The plot on the right of Figure 2 shows a blown up region where the observations were taken.

The difference in the amount of bending and path taken as a function of frequency is clearly visible. It should be noted that for lower elevation angles (lower or higher satellite latitudes) only the 20, 40 and 80 MHz waves propagate through the ionosphere to the satellite and are not shown. It is clear that the wave causes variations in the path of propagation and the delay. The question is if the amount of delay is measurable. Any real system will have the resolution of its ability to measure time limited by the bandwidth of the received signal. A 100 KHz bandwidth provides ~ 10 microseconds of resolution, which for this study we will use as a sensitivity limit. In order to be able to detect and characterize the presence of a TID, we need to have the signal with the wave have greater than 10 microsecond variations from the background IRI ionosphere at several frequencies and several different times (or satellite positions).

Figure 3 presents a visual contour representation of the total amount of delay (in microseconds) obtained from the ray-trace for each frequency and sample time when propagating through only the background IRI ionosphere (top plot), the IRI background plus the large scale TID (middle plot), and the difference between the IRI background with the TID and without the TID (lower plot). Note that where the ray-tracer did not home, no results are presented. Note that the axis ranges have changed for the lower plot. The vertical scale only goes from 10-20 MHz, while the horizontal scale only shows the time periods close to the middle of that pass. The bottom plot shows that there are regions where the absolute value of the differential delay due to the wave is significantly larger than 10 microseconds. For the earlier part of the satellite pass (left hand part of the lower plot), where the propagation paths extend through the positive phase of the wave, the TID increases the overall delay causing a positive differential delay. For the later part of the pass, the propagation paths cross the negative phase, and the differential delay is negative. This implies that there is information in the signal not only to detect the wave, but also to be able to recover information about the properties of the wave. In order to see this effect more clearly, Figure 4 presents line plots of differential delay on the vertical axis, and frequency on the horizontal axis for 7 different satellite latitudes. The transmitter was located at 30 degrees, so for smaller satellite latitudes, the propagation path is into the positive phase of the wave, and the differential delay is positive. For larger satellite latitudes the opposite is true. Note also there are a significant amount of times (satellite positions) and frequencies that have absolute differential delays greater than 10 microseconds. However, the frequency range is between 10 and 20 MHz, which would indicate that a broad band receiver on a LEO satellite that is designed for HF wave detection and characterization should have it most sensitive reception in the 10-20 MHz band and have a bandwidth of ~ 100 KHz or larger.

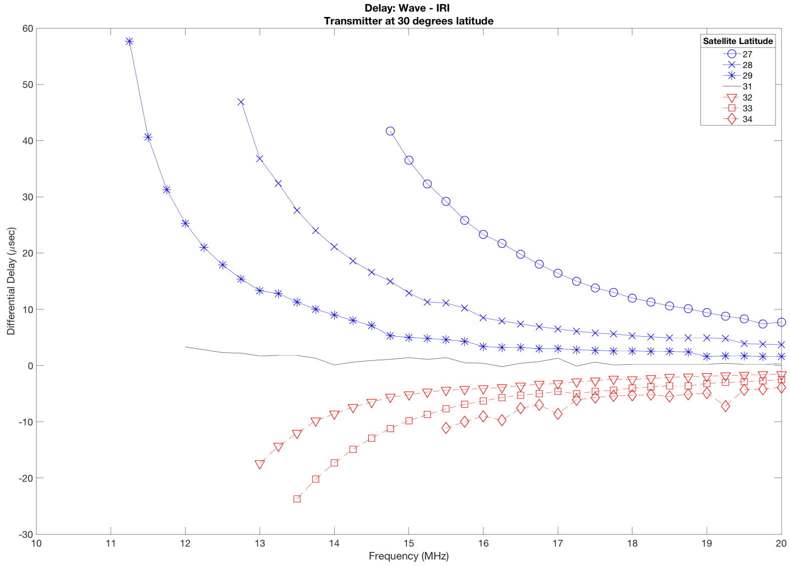

Figure 4: Plots of the differential delay versus frequency for 7 different satellite latitudes. The pulse transmitter is located at 30 degrees latitude.

3.2 Medium scale TID

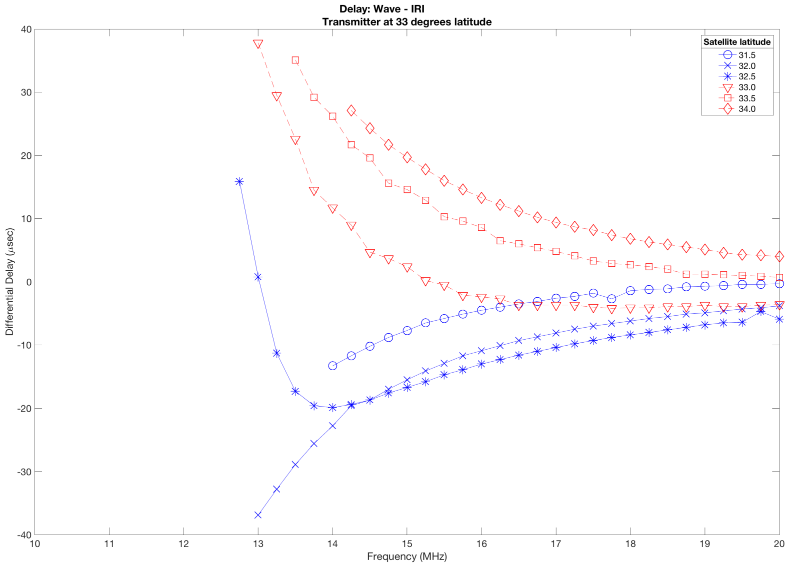

Figure 5: Same format figure as Figure 4 above. Only now for the MSTID case.

The previous analysis indicated that, indeed, large scale TIDS could be detected, and likely characterized from LEO satellite HF observations. However, that was for a large scale TID with very large amplitude. Do the same results hold for medium scale TIDS with smaller amplitudes? To address this question, a second simulation was undertaken for a MSTID. The horizontal wavelength was set to 160 km, the horizontal direction of the wave and the vertical wavelength were the same as for the large scale TID. However, now the maximum amplitude variation is only 8% at 220 km altitude. The satellite simulation is the same as before. Figure 5 is similar to figure 4, only now for the MSTID case. As for Figure 4, the results indicate that there are large number of frequencies and times where the absolute value of the differential delay is greater than 10 microseconds, implying the signature of the TID can be detected even for MSTIDS with small amplitude perturbations. In fact, in some ways the MSTID simulated observations seem to carry more information than the large scale TIDS, particularly for when the satellite is at 32.5 degrees.

4. CONCLUSIONS

The primary focus of this paper was to study the feasibility of using naturally occurring lightning flashes on the Earth as passive sources of HF signals. Such HF sources, if feasible could be used to detect, and accurately characterize the physical properties of ionospheric bottom-side TIDS. Accurate characterization and specification of TIDS is of great interest to the HF propagation community.

These HF signals could be received on LEO satellites with broadband HF receivers on board similar to the Los Alamos FORTE satellite mission in the 1990s. In order for such a set of observations to feasible, several questions must be addressed.

First, are there enough lightning strikes per minute within a geographical region to be useful to characterize and specify medium and large scale TIDS? The distribution of lightning flashes shown in figure 1 indicates that over large regions of the Earths land surface it is possible to have multiple strikes per minute over a few hundred square kilometer region.

The second question is then can these lightning strikes be detected and located quickly enough to be useful for operational systems? It would seem that advances in both space and ground based lightning detection systems will allow for near real-time detection and localization of flashes.

Given that the lightning is prevalent enough, and can be made available for operational applications, the next question is how sensitive would measurements on satellites be to TIDS, and is there enough information in the observations to be able to characterize the physical properties of TIDS? Figure 2 shows that the HF signals are sensitive to large scale TID variability, while figures 3-4 show that the ionospheric delays due to just the TID wave activity are large enough at the lower end of the frequency band to be significantly above the sensitivity limits one might expect on such a satellite system. In particular figure 4 shows a difference in the delays for different parts of the satellite pass as the propagation paths go through different parts of the TID wave. The large scale TID had a very high amplitude variability of over 50%. Thus we also simulated the case of a MSTID with a horizontal wavelength of 160 km, and a maximum variability of only 8%. Figure 5 shows that even for smaller TIDS, with less variability, the received broadband HF signals are still well above the sensitivity limit, and carry significant information on the TID over a wide range of frequencies and different satellite positions.

From this preliminary study the suggestion would be that a broad-band HF receiver on a LEO satellite that is designed to detect and characterize TIDS should focus on the lower end of the HF band from ~ 10 – 20 MHz, with bandwidths of 100 KHz or larger.