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Studies of Wave Activity in the Thermosphere-Ionosphere System Using Dynasonde Techniques

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Abstract

Dynasonde approach to ionospheric radio sounding capitalizes on high precision of physical parameters and rich statistics of recognized echoes phase-based methods can provide. As has been recently demonstrated, the Dynasonde profiles of the electron density and of the horizontal gradients, complemented with profiles of the Doppler speed, carry comprehensive quantitative information about Atmospheric Gravity Waves, a ubiquitous feature of the space weather that has become an important objective of atmospheric modeling. Being combined into a time series, and without additional processing, the profiles allow visualization of the time fronts of the Traveling Ionospheric Disturbances (TIDs). They also provide high-resolution input data for calculating the complete set of parameters (both vertical and horizontal) of TID activity in the upper atmosphere between the base of the E layer and the maximum of the F layer. Application of the Lomb-Scargle periodogram technique to the tilt data provides unique insight into the dynamics of spectral composition of the TIDs. A similar technique applied to longer time series allows determining characteristics of thermospheric tides. Single sounding sessions allow observations of ionospheric manifestations of acoustic waves produced by ground-based sources. All the mentioned products of the Dynasonde data analysis require a common, standard ionogram mode of radar operation. Therefore, information about standard parameters of the ionospheric E, F regions, possibility to obtain vector velocities characterizing movement of plasma contours, and quantitative parameters of the km-scale irregularity spectrum are not lost and contribute into comprehensive description of wave activity in the thermosphere-ionosphere system.

1. Introduction

Recent developments in Dynasonde technique [1-7] provide solutions to many problems associated with studies of thermospheric waves. Dynasonde utilizes all capabilities of modern digital phase-based HF sounding systems and provides sensitivity and accuracy of measurements far exceeding that of obsolete image-based processing techniques. An integral part of its data analysis package, the inversion routine NeXtYZ, allows revealing wave structures from the true vertical profile of electron density, from zonal and meridional tilts, and from line-of-sight Doppler speed, all attributed to real altitudes with 1 km resolution. This is not a fitting by pre-determined functions; this is true layer-by-layer inversion procedure, entirely controlled by the data, which resolution is limited only by chosen mode of operation of the radar system. For traveling ionospheric disturbances (TIDs) both vertical and horizontal wavenumbers, as well as a complete set of propagation characteristics of AGW packets can be deduced from this information. Entire bottom-side ionosphere is covered, and observational campaigns can be virtually unlimited in time.

The same dataset, obtained in a common Dynasonde ionogram mode, can be used to measure parameters of thermospheric tidal harmonics [2], to quantify spread F phenomenon [8], to measure ionospheric drifts [9, 10]; and to detect sporadic E layers, all of this without losing information about real altitudes. This universality makes Dynasondes an optimal platform for studying complex interconnections between various processes in the upper atmosphere.

2. Dynasonde Basics

The Dynasonde is a hardware and data-analysis system of ionosphere remote sensing based on a comprehensive use of phase information in the ionospheric radio echoes [11]. With a large number of identified radio echoes and accurate estimates of their physical parameters, application of an advanced inversion procedure for plasma density, NeXtYZ is enabled. The NeXtYZ products are the true vertical profile of plasma density and the vertical profile of horizontal gradients of the plasma density [1]. It also plays a role in attributing line-of-sight Doppler speed values to real altitudes. All mentioned characteristics, when considered as functions of time, carry information about wave activities in the thermosphere-ionosphere system.

A typical modern Dynasonde hardware includes a vertex-down zigzag log periodic transmitting antenna, an eight-dipole receiving antenna array, and a digital radar system VIPIR [12, 13]. Sounding sessions are characterized by the pulse repetition interval 5-10 ms and by the number of base frequencies 500-600 in the frequency band 0.5–25 MHz. Pulses are grouped into carefully designed pattern that facilitates echo detection and application of higher-level analysis routines. The typical 2 min interval between the sounding sessions guarantees sufficient temporal resolution for the wave processes in the ionosphere.

Raw data provided by the radar are processed by autonomous Dynasonde analysis software [14]. Initial stages of the Dynasonde analysis include a) phase-based echo recognition [15], b) echo parameterization [11, 16, 17], c) echo classification into traces, and d) trace selection for higher-level analyses. Additional details of this technique may be found in recent publications describing its applications to studies of atmospheric waves [2, 7].

The 3-D inversion procedure NeXtYZ, which was introduced above, is a component of the higher-level Dynasonde analysis. The altitude interval covered by NeXtYZ, as well as by other Dynasonde analysis products, is determined by detected radio echoes. It may span from the bottom of the E layer up to nearly the F layer maximum and depends strongly on solar UV-driven changes in ionospheric ionization and other dynamic factors. NeXtYZ is a foundation for several advanced methods for detecting and characterizing wave activities in the thermosphere.

3. Visualization of TIDs

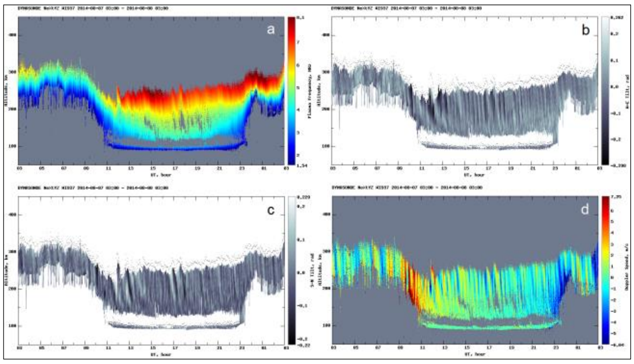

Figure 1. One of standard products of autonomous Dynasonde analysis: Temporal scans of the vertical cross-section of several ionospheric parameters as a function of Universal Time and the true altitude for one day over Wallops Island, VA. Two panels use a gray color scale to show the zonal (b) and meridional (c) tilt components; two other panels use a color scale to show the plasma frequency (a) and the vertical projection of the line-of-sight Doppler speed (d). The transition from night to day conditions happens at around 11 UT and from day to night conditions at around 23 UT.

NeXtYZ products provide a useful tool for visualization of the wave fronts at thermospheric altitudes (see Fig. 1). An important property of the images are the alternating stripes, often slightly inclined from the vertical, corresponding to variations of every parameter with a periodicity from a few minutes to a few hundred minutes. These are manifestations of the traveling ionospheric disturbances (TIDs) likely caused by gravity waves, with phase fronts propagating mostly downward. As discussed in [7, Supplementary Materials], these signatures have the same meaning as those observed by incoherent scatter radars in their vertical plasma line and line-of-sight Doppler data. Note that Dynasonde analysis is performed independently for every single time, so consistency of the overall “time vs real altitude” picture clearly visible in Fig. 1 is a powerful confirmation of validity of the methods used.

4. Results of application of spectral and other quantitative analysis techniques

As reported in [3, 4], numerical equivalents of the visualization products in conjunction with a combination of Lomb-Scargle and Welch techniques can be used to evaluate spectra of the wave processes (see Fig. 2).

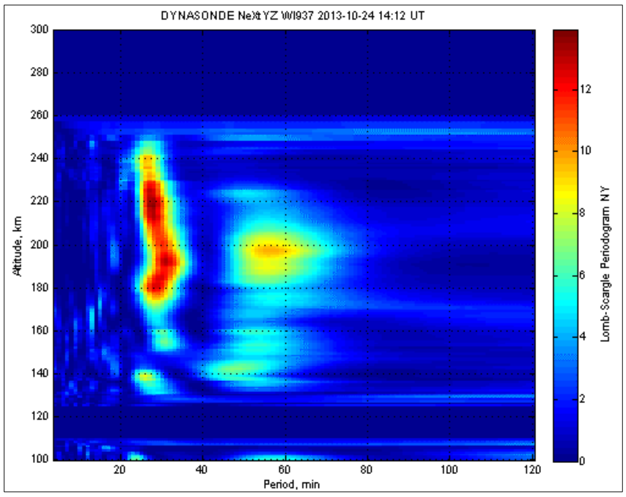

Figure 2. Normalized Lomb-Scargle periodograms of the zonal tilt characterizing wave activity over Wallops Island obtained for a single position of a 2-hour window, independently for every 1 km altitude range, shown as function of the period in min and real altitude in km. Two most energetic wave packets have in this case periods about 30 and 50 minutes.

It was shown that wave activity at any frequency seldom occupies entire observable altitude range; there are usually several outstanding wave packets at any time and at any altitude, and there is a background wave continuum. These are important factors to consider in the analysis of the wave interconnection.

In [5], the technique was used to investigate the seasonal variability of the power spectral density of TIDs. By analyzing the ionospheric tilts and Doppler speed data from Wallops Island, VA and Tromsø, Norway, the presence of two peaks in wave activity is highlighted. First, a winter peak, previously observed using other remote sensing techniques, and a second peak during summer, previously unreported in the literature.

A method for determining real-time values and statistical distributions of all propagation characteristics of the wave packets based on Dynasonde analysis results, an ability critical to any AGW-related study, has been developed in [4]. For the first time, the agreement between the TID propagation parameters and the AGW dispersion relation is successfully verified in a quantitative way. The statistical distribution of the propagation parameters is investigated, including its altitude dependence, for a month-long dataset from Wallops Island, VA.

A measurement technique for momentum deposition by AGWs at thermospheric altitudes has been described in [6]. Estimates are obtained of the single-packet and average height profiles of the momentum flux magnitude, direction, and variability, and from this, the forcing on the background thermosphere-ionosphere due to gravity wave dissipation is evaluated.

In [2], the main features of the first three tidal harmonics were investigated using electron density and tilt data from Wallops Island and San Juan, PR Dynasondes with two datasets obtained in May-June and October-November 2013 (see Fig. 3).

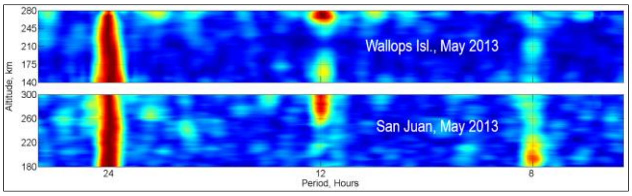

Figure 3. Diurnal, semidiurnal and terdiurnal harmonics of the atmospheric tide revealed in a broad altitude range by normalized periodograms of the zonal tilt for Wallops Island, VA and San Juan, PR, in May 2013.

A theory establishing connection between background Infragravity Waves in the ocean and Acoustic Gravity Waves (AGWs) in the atmosphere has been developed [18]. First experimental evidences for this theoretically predicted effect have been obtained based on analysis of multi-season Dynasonde dataset [18]. The spectral correlation technique was applied to the data from two Deep-ocean Assessment and Reporting of Tsunamis (DART) stations located off the US East Coast and Dynasonde system located at Wallops Island, Virginia, to confirm that infragravity waves in the ocean continuously radiate atmospheric waves and are a major source of wave activity in the thermosphere [7].

5. Conclusions

Technical capabilities for measuring spectral and correlation properties of wave motions in all geophysical media have improved dramatically in recent years. More instruments provide a possibility of studying long time series. We now can perform simultaneous precision measurements in geographically close locations with Dynasondes and other sensors. Favorable instrumental configurations exist in Northern and Southern Americas, in Europe, in Asia and in Africa. Dynasonde analysis products help to close the widely acknowledged "thermospheric gap" in available information about atmospheric wave activity.

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