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Short-term variability of the lower ionosphere from VLF narrowband radio observations

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Abstract

Very low frequency (VLF) radio waves propagate over long distances within the Earth-ionosphere waveguide, reflected off the Earth's surface and the ionospheric D-region. The characteristics of these signals depend on several parameters along the path, which apart from the D-region's properties, are fairly constant over short periods of time. This allows probing of perturbations in the lower ionosphere to be made using VLF measurements. In this paper, we present an analysis of VLF narrowband signals, transmitted from Sicily, Italy, and detected in Tel-Aviv, Israel. We show observations of the interaction between both pressure waves and electromagnetic perturbations from thunderstorms with the VLF waves aloft. We clearly observe long period acoustic wave signatures (up to ~4 minutes) and short period gravity wave signatures (~5-10 minutes), while also many transient events related to heating and ionization of the D-region. Comparisons with the World Wide Lightning Location Network (WWLLN) data show the possible link between tropospheric thunderstorms and D-region short-term variability. Finally, we conclude that gravity wave signatures are a common and significant feature in VLF measurements.

1. Introduction

The ionospheric D-region lies in the altitude range of ~60-95 km [1, 2]. This part of the atmosphere is highly sensitive to waves propagating upwards from the troposphere, either as pressure perturbations (gravity and acoustic waves) [3, 4], or electromagnetic perturbations from lightning discharges (resulting in sprites, elves, etc.) [5]. These disturbances can affect the temperature, the wind, the species concentration, and even the ionization in this part of the atmosphere [6, 7].

Very low frequency (VLF, 3-30 kHz) radio signals are generated by various natural and man-sources [8], and are able to propagate with little attenuation over long distances within the Earth-ionosphere waveguide, reflected off the Earth's surface and the ionospheric D-region [8, 9]. The characteristics of the received signals depend mainly on the attributes of the reflecting plates, i.e., the Earth's surface and the D-region [9]. However, the relative consistency of the surface electrical properties over short periods of time [10] makes VLF measurements a highly sensitive tool for studying perturbations of various origins in the lower ionosphere [1, 8, 11].

VLF radio wave measurements can be performed in a narrowband (NB) mode, in which the amplitude and phase of a signal generated at a constant power and at a narrow frequency band by a man-made transmitter are recorded, in order to probe the D-region [11]. In this paper, we present an analysis of VLF NB data, showing signatures of the interaction between both pressure waves and lightning-induced electromagnetic (EM) perturbations with the ionospheric D-region, as well as the plausible connection of these observed disturbances with tropospheric thunderstorms.

2. Instrumentation and Methodology

One-year-long (August 28, 2013 – August 26, 2014, ~88% complete) VLF NB signal amplitudes were used in this study. The radio signals were generated by the callsign NSY VLF transmitter located in Sicily (37.12°N, 14.43°E, broadcasting at 45.9 kHz), and recorded by the Tel-Aviv University (32.11°N, 34.80°E) VLF UltraMSK receiver [12], at 1 Hz integration frequency.

The amplitude data set was analyzed in the spectral domain using the Lomb-Scargle (LS) periodogram [13] in 30 minutes windows, with 15 minutes overlap. Data windows in which the periodogram was statistically significant (>95%) for time periods shorter than 10 minutes were then subjectively filtered (due to the high signal variability), in order to merely retain times with evident oscillations (up to periods of 10 minutes). Transient EM perturbations were detected using this analysis as well, as a result of their relatively strong amplitude change, their distinctive sawtooth shape (sudden rise with gradual relaxation), and the typical occurrence of these disturbances at a high number during a single event [1].

Finally, lightning location data detected by the World Wide Lightning Location Network (WWLLN) [14, 15] were scrutinized for collocated lightning discharges in the Mediterranean region around the transmitter-receiver great circle path (TRGCP).

It should be noted that the same methodology was performed over the VLF NB phase data, but as the results were not conclusive, this analysis is not shown in this paper.

3. Results

Figure 1a depicts an example of a short period gravity wave signature in the NSY transmitter signal amplitude, as measured on October 22, 2013. These oscillations reached an amplitude of ~0.25 dB and lasted for ~30 min. Figure 1b illustrates the LS periodogram of the amplitude time series (black curve). The dashed blue and red lines represent statistical significance thresholds of 95% and 99.9%, respectively. According to this analysis, an apparent 6 minutes oscillation, which matches the periodicity of high-frequency gravity waves, dominates the time series. Lightning discharge locations detected by the WWLLN up to 3 hours prior to the identified gravity wave signatures (Figure 1c) show a large thunderstorm ~1750 km north of the NSY transmitter. Since intense thunderstorms can produce strong gravity waves, and as the occurrence time of the thunderstorm matches the time of the observed VLF signatures (based on gravity wave phase velocity), and because high-frequency gravity waves can essentially propagate over great distances in a ducted mode [16], this thunderstorm in northern Europe might be the origin of the observed oscillations in the VLF NB data.

Similar to Figure 1, Figure 2 shows an example of an acoustic wave signature observed on September 9, 2013. The apparent oscillations had an amplitude of ~0.2 dB and continued for ~30 minutes, similar to the latter gravity wave example. The LS periodogram shows a distinct ~2.5 minutes peak. These low-frequency acoustic waves can generally be produced by lightning as well as deep convection, and propagate over large distances, both horizontally and vertically with relatively low attenuation [17, 18]. Examination of the lightning location map indicates (based on acoustic wave propagation velocity, i.e., the speed of sound), that the occurrence time of the thunderstorm ~700 km west of the NSY transmitter corresponds with the time of the observed oscillations, making it a plausible candidate for the source of the measured amplitude wave signatures.

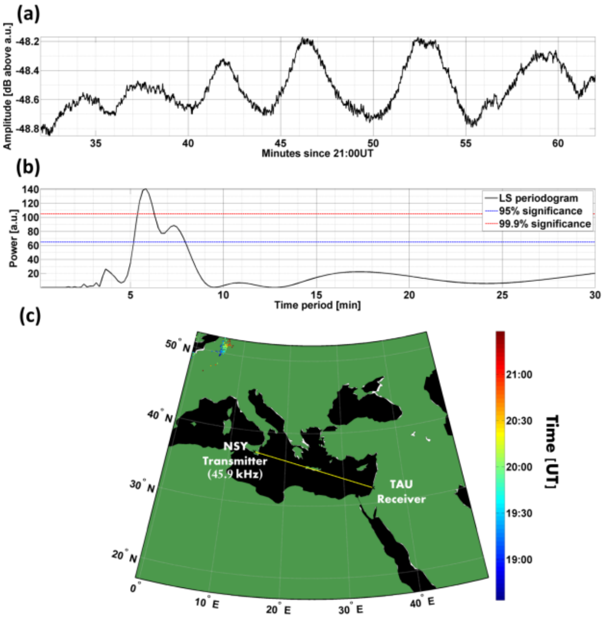

Figure 1: (a) short period gravity wave signatures in the NSY transmitter received signal amplitude on October 22, 2013, (b) Lomb-Scargle periodogram of the amplitude time series (black curve). The blue (red) dashed curves represent the 95% (99.9%) statistically significance thresholds, respectively, (c) lightning discharges' location detected by the WWLLN up to 3 hours prior to the identified gravity wave signatures (discharge location colors indicate the time of occurrence). The yellow curve depicts the NSY-TAU transmitter-receiver great circle path.

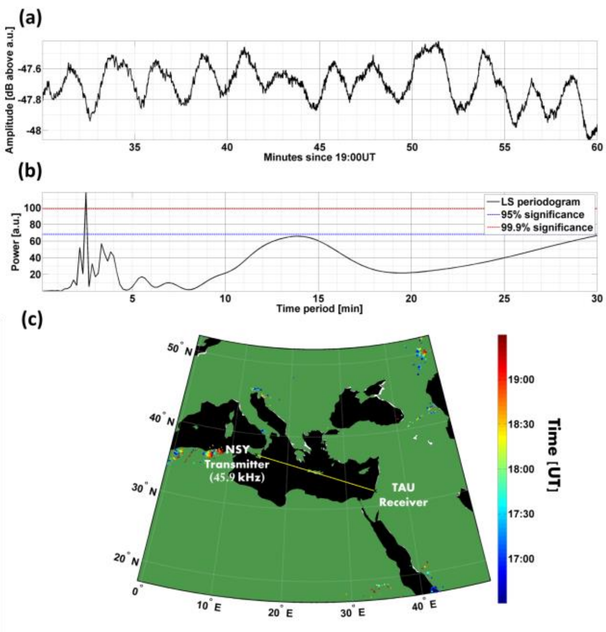

Figure 2: Same as Figure 1, but for acoustic wave signatures on September 9, 2013.

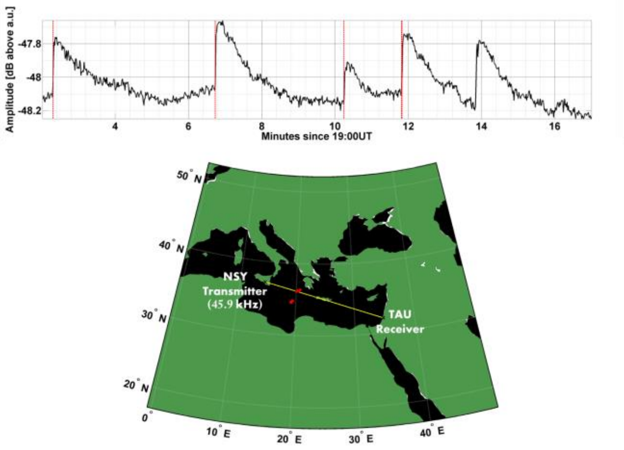

Figure 3: (Top) Lightning-induced perturbations detected on November 11, 2013, together with the associated lightning discharge occurrence times (red lines), as detected by the WWLLN, (bottom) associated lightning discharges' location (red circles).

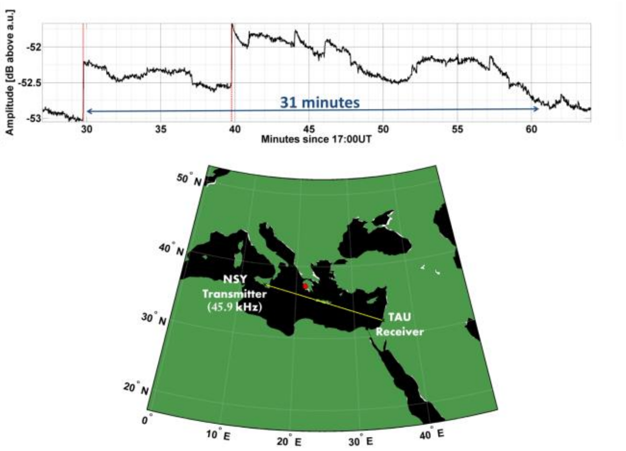

Figure 4: Same as Figure 3, but for 'long recovery early events' on November 25, 2013.

Figure 3 displays lightning-induced perturbations in the signal amplitude on November 11, 2013, together with the associated lightning discharge occurrence times. These NB perturbations had recovery times of up to ~2 min. The bottom panel shows in red circles the associated lightning discharge locations, as detected by the WWLLN. These associated discharges were situated up to ~185 km away from the TRGCP. The presented perturbations are most likely 'early' events, though it is not possible to distinguish whether they are of the 'early/fast' or 'early/slow' type, due to the relatively low sampling frequency. The absence of associated WWLLN detection in the last presented event is probably due to the limited WWLLN detection efficiency [19].

Figure 4 illustrates two consecutive 'long recovery early' events (LOREs) [1], detected in the NSY transmitter signal amplitude on November 25, 2013, together with the associated lightning discharge occurrence times. The total recovery time spans a staggering 31 min. The bottom panel shows in red circles the two associated lightning discharge locations, as detected by the WWLLN. These associated discharges were very intense (based on the dozen WWLLN receivers that detected them), and were located ~150 and ~160 km away from the TRGCP,

Table 1 summarizes the VLF NB perturbations detected in the data set. The detected LOREs all had recovery times larger than 6 minutes. Their day of occurrence had only a single overlap with days in which other 'early' events were detected. All 'early' events (including the LOREs) were predominantly associated with lightning discharges located up to 200 km away from the TRGCP, similar to prior observations [11], and were detected only during nighttime.

Similarly, acoustic wave signatures were merely detected during nighttime as well. In all of these events, large thunderstorms occurred west of the NSY transmitter (see Figure 2) in times which corresponded with occurrence times of these apparent signatures. Nevertheless, due to the low number of detected events, it is hard to reach any conclusions regarding the needed location of the parent thunderstorm relative to the VLF transmitter, in order to generate a detectable VLF amplitude oscillation. Moreover, these observed locations of the plausible parent thunderstorms are not in agreement with prior observations of acoustic wave signatures in VLF data [3].

Table 1: Summary of VLF perturbations detected during one year of amplitude measurements.

	Gravity waves	**Acoustic waves**	**'Early' events**	**LOREs**
Number of days with events	28	2	14	7
Maximum peak-to-peak amplitude/ amplitude change	0.80 dB (0.40 dB during daytime)	0.45 dB	0.90 dB	0.85 dB
Nighttime events percentage	86%	100%	100%	100%

Short period (<10 minutes) gravity wave signatures were observed during significantly more days than all other types of perturbations combined. These observed oscillations, which typically lasted for ~30-120 minutes, had peak-to-peak amplitudes that are comparable to the amplitude change during the VLF 'early' events. Moreover, unlike the other types of perturbations, they were not confined to the nighttime ionosphere, and were observed 14% of the time (4 events) during daytime as well, although exhibited much lower peak-to-peak amplitudes (~0.1 dB in three of those events, and up to 0.4 dB in the fourth). Thunderstorms with a matching time of occurrence (while considering the wave propagation time) were detected in the Mediterranean region in 93% (26 out of 28) of the events. This might suggest that some or most of them were the possible source of the observed oscillations. However, the lack of matching thunderstorms during two of the events emphasizes that other sources [16] might have generated the gravity waves which produced the observed oscillations.

4. Summary and Conclusions

In this study we analyzed one year of VLF NB data. It was shown that perturbations could be characterized in more than ~13.5% of the days of the year. Future development of this study will include modeling of acoustic and gravity waves' propagation into the upper atmosphere, in combination with VLF wave propagation models, in order to confirm the thunderstorms as the source of some or most of these VLF amplitude disturbances. However, it is possible to conclude that although only a limited number of studies were focused on these VLF perturbations [11], gravity waves are a common feature in VLF amplitudes, which should be further studied in the future. Moreover, the analysis presented here demonstrate a possible use of VLF NB measurements as a remote-sensing tool to study gravity wave propagation within the ionospheric D-region and the corresponding neutral atmosphere.

5. Acknowledgements

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6. References

[1] U. S. Inan, S. A. Cummer, and R. A. Marshall, “A survey of ELF and VLF research on lightning-ionosphere interactions and causative discharges,” *J. Geophys. Res.*, vol. 115, p. A00E36, Jun. 2010.

[2] J. K. Hargreaves, *The solar-terrestrial environment An Introduction to Geospace—The Science of the Terrestrial Upper Atmosphere, Ionosphere, and Magnetosphere*. New-York: Cambridge Univ. Press., 1992.

[3] R. A. Marshall and J. B. Snively, “Very low frequency subionospheric remote sensing of thunderstorm-driven acoustic waves in the lower ionosphere,” *J. Geophys. Res. Atmos.*, vol. 119, no. 9, pp. 5037–5045, 2014.

[4] A. Nina and V. M. Čadež, “Detection of acoustic-gravity waves in lower ionosphere by VLF radio waves,” *Geophys. Res. Lett.*, vol. 40, no. 18, pp. 4803–4807, Sep. 2013.

[5] M. J. Rycroft, “Introduction to the physics of sprites, elves and intense lightning discharges,” in *Sprites, Elves and Intense Lightning Discharges*, Netherlands.: Springer, 2006, pp. 1–18.

[6] R. D. Hunsucker, “Atmospheric gravity waves generated in the high-latitude ionosphere: A review,” *Rev. Geophys.*, vol. 20, no. 2, p. 293, 1982.

[7] V. P. Pasko, “Theoretical Modeling of Sprites and Jets,” in *Sprites, elves and intense lightning discharges*, Netherlands.: Springer, 2006, pp. 253–311.

[8] R. Barr, D. L. Jones, and C. J. Rodger, “ELF and VLF radio waves,” *J. Atmos. Solar-Terrestrial Phys.*, vol. 62, no. 17–18, pp. 1689–1718, 2000.

[9] K. G. Budden, *The propagation of radio waves: the theory of radio waves of low power in the ionosphere and magnetosphere*. New-York: Cambridge University Press, 1988.

[10] J. P. Hauser, W. E. Garner, and F. J. Rhoads, *A VLF effective ground conductivity map of Canada and Greenland with revisions derived from propagation data*. No. NRL-6893, Naval Research Lab Washington, DC, 1969.

[11] I. Silber and C. Price, “On the Use of VLF Narrowband Measurements to Study the Lower Ionosphere and the Mesosphere–Lower Thermosphere,” *Surv. Geophys.*, pp. 1–35, 2016.

[12] M. A. Clilverd *et al.*, “Remote sensing space weather events: Antarctic-Arctic Radiation-belt (Dynamic) Deposition-VLF Atmospheric Research Konsortium network,” *Sp. Weather*, vol. 7, no. 4, Apr. 2009.

[13] W. H. Press and G. B. Rybicki, “Fast algorithm for spectral analysis of unevenly sampled data,” *Astrophys. J.*, vol. 338, pp. 277–280, 1989.

[14] R. L. Dowden, J. B. Brundell, and C. J. Rodger, “VLF lightning location by time of group arrival (TOGA) at multiple sites,” *J. Atmos. Solar-Terrestrial Phys.*, vol. 64, no. 7, pp. 817–830, May 2002.

[15] C. J. Rodger, J. B. Brundell, R. L. Dowden, and N. R. Thomson, “Location accuracy of long distance VLF lightning locationnetwork,” *Ann. Geophys.*, vol. 22, no. 3, pp. 747–758, 2004.

[16] D. Fritts and M. Alexander, “Gravity wave dynamics and effects in the middle atmosphere,” *Rev. Geophys.*, vol. 41, no. 1, p. 1003, 2003.

[17] L. Evers and H. Haak, “The Characteristics of Infrasound, its Propagation and Some Early History,” in *Infrasound Monitoring for Atmospheric studies*, A. Le Pichon, E. Blanc, and A. Hauchecorne, Eds. Springer Netherlands, 2010, pp. 3–27.

[18] E. Blanc, A. Le Pichon, L. Ceranna, T. Farges, J. Marty, and P. Herry, “Global Scale Monitoring of Acoustic and Gravity Waves for the Study of the Atmospheric Dynamics,” in *Infrasound Monitoring for Atmospheric Studies*, A. Le Pichon, E. Blanc, and A. Hauchecorne, Eds. Springer Netherlands, 2010, pp. 647–664.

[19] S. D. Rudlosky and D. T. Shea, “Evaluating WWLLN performance relative to TRMM/LIS,” *Geophys. Res. Lett.*, vol. 40, no. 10, pp. 2344–2348, May 2013.