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Assigning the causative lightning to the whistlers observed on satellites

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Abstract. We study the penetration of lightning induced whistler waves through the ionosphere by investigating the correspondence between the whistlers observed on the DEMETER and MAGION-5 satellites and the lightning discharges detected by the European lightning detection network EUCLID. We compute all the possible differences between the times when the whistlers were observed on the satellite and times when the lightning discharges were detected. We show that the occurrence histogram for these time differences exhibits a distinct peak for a particular characteristic time, corresponding to the sum of the propagation time and a possible small time shift between the absolute time assigned to the wave record and the clock of the lightning detection network. Knowing this characteristic time, we can search in the EUCLID database for locations, currents, and polarities of causative lightning discharges corresponding to the individual whistlers. We demonstrate that the area in the ionosphere through which the electromagnetic energy induced by a lightning discharge enters into the magnetosphere as whistler mode waves is up to several thousands of kilometres wide.

Keywords. Ionosphere (Ionosphere-atmosphere interactions; Wave propagation) – Meteorology and atmospheric dynamics (Lightning)

1 Introduction

Whistlers were first observed on the Earth as whistling sounds of unknown origin heard on long-distance telephone lines, and they were, for the first time, unambiguously reported by Barkhausen (1919). Based mainly on the observation that whistlers sometime followed impulsive atmospherics, Barkhausen (1930) put forward the theory that they are associated with lightning discharges. Eckersley (1935) formulated the mathematical expression for the dispersion of whistlers. The detailed explanation was developed by Storey (1953), who showed that whistlers originate in normal impulsive atmospherics which travel through the ionosphere and magnetosphere, following the magnetic field lines and crossing the equator at a great height, and arriving to the ground at a magnetically conjugate point on the opposite hemisphere. During their journey they become dispersed, so as to arrive as whistling tones decreasing in frequency – "whistlers". Their dispersion is consistent with the right-hand polarised plasma waves propagating at frequencies both below the electron cyclotron frequency and below the plasma frequency. The whole branch of these plasma waves is now called whistlers or whistler-mode waves. The origin of whistler mode waves observed in the ionosphere and magnetosphere is not always connected with lightning discharges. In this paper, we will use the term whistlers only for waves that originate in lightning discharges. A significant contribution to the investigation of the propagation of whistlers in the magnetosphere was later done by Helliwell (1965). Since the dispersion of whistlers depends on the plasma density, measurements of whistler dispersion were used to deduce the electron/plasma density profile in the magnetosphere.

New possibilities in whistler investigation emerged with the era of artificial satellites. The wave measurements by satellites showed a much higher occurrence rate of whistlers than was observed on the ground, and revealed other types of lightning induced whistlers that are not observable on the ground. Gurnett and Shawhan (1965) presented and explained ion cyclotron whistlers. These are observed on the frequency-time spectrograms as a tone which starts immediately after the reception of a fractional-hop whistler (whistler with low dispersion that did not yet cross the equator). After an initial rapid rise in frequency, these waves asymptotically approach the proton cyclotron frequency. Smith

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and Angerami (1968), using measurements on OGO 1 and OGO 3 satellites, first reported Magnetospherically Reflected (MR) whistlers predicted by Kimura (1966). The MR whistlers are highly oblique (with respect to magnetic field lines) propagating waves that undergo a reflection in the region where their frequency is close to the local Lower Hybrid Resonance (LHR) frequency. Thus, the highly oblique propagating MR whistlers could not be observed on the ground. To become sufficiently oblique, the waves have to travel a relatively long trajectory, which means that they have to cross the equator. Additionally, there should be no distinct field-aligned density gradients that ensure the so-called ducted or field-aligned propagation, which prevents the magnetospherical reflection. The ducted whistlers that reach the ionosphere may penetrate through and be received at the ground. Note that only the whistler waves having a small wave normal angle with respect to the vertical direction can transform into "free space" mode because the refractive index in the non-ionised atmosphere is $\sim$1, which is much lower than the refractive index of whistlers in plasma medium. All other waves are reflected from the bottom-side of the ionosphere. Thus, the best conditions for the whistlers to penetrate the ionosphere and to arrive at the ground are at higher latitudes, where the magnetic field lines are approximately vertical. Indeed, Manoranjan et al. (1974) reported the low-latitude cutoff for whistlers observed on the ground, despite the fact that most of the lightning activity is in the tropics and/or in the subtropics (see, e.g. Rycroft et al., 2000).

Besides the new phenomena, the satellite and rocket measurements also brought the possibility to compare measurements on the satellites with measurements carried out on the ground and to measure the wave normal directions in the topside ionosphere. The measurements of wave normal angles can either be performed for downgoing waves or for upgoing waves. Wave normal angles of downgoing waves were investigated, for example, by Iwai et al. (1974), using measurements on the K-9M-41 rocket at heights between 130 and 270 km. These measurements were performed at relatively low latitudes. They also correlated whistlers recorded on the rocket with whistlers observed at ground stations located at 24° N and 20° N of geomagnetic latitudes. They showed that the wave normal angles with respect to the magnetic field were mostly between 20° and 50°, and the wave normal angles of whistlers observed simultaneously on the ground were small with respect to the vertical. Regarding the upgoing waves, these are strongly refracted when they enter the base of the ionosphere, and their wave normal angles are brought close to the vertical in the maximum of the ionisation, due to a rapid increase in the refractive index. In the topside ionosphere, the wave normal vectors can be significantly diverted from the vertical, due to large-scale density gradients, as was shown by James (1972). The large-scale density gradients are present mainly in the mid-latitude ionosphere. Most of the upgoing fractional-hop whistlers seem to be unducted (Hughes and Rice, 1997). The whistler-mode waves might also be scattered from small-scale, field-aligned plasma density irregularities. Bell and Ngo (1990) showed that this scattering may lead to the excitation of electrostatic LHR waves.

The whistler waves have also been studied due to their influence on radiation belt electrons, owing to wave particle interactions (Kennel and Petchek, 1966; Brinca, 1972; Abel and Thorne, 1998a, 1998b, etc.). The overall significance of lightning-generated whistlers to inner radiation belt electron loss rates is still an open question, and the approach to the problem and published results of various authors differ in some details. Rodger et al. (2003) assumed ducted propagation and concluded that whistler-induced electron precipitation dominates in the L-shell range with L=2–2.4. Lauben et al. (2001) and Bortnik et al. (2003) assumed obliquely propagating and MR whistlers. They came to the conclusion that the whistler energy in the magnetosphere has a flat peak at $L\sim$2.8, and argue that obliquely propagating whistlers may be responsible for the formation and maintenance of the slot region in the electron radiation belt, a subject studied previously by many authors (see, e.g. Lyons et al., 1975; Imhof et al., 1986; Abel and Thorne, 1998a, b, and references therein). All these authors had to deal with an estimation of the area through which the lightning energy enters the magnetosphere.

The electromagnetic waves generated by a lightning discharge propagate away from the source within the Earth-ionosphere waveguide. An interesting experimental evidence of this propagation are "tweek" atmospherics, which exhibit remarkable dispersions near the cutoff frequencies of the first and higher modes of the Earth-ionosphere waveguide (Yamashita, 1978; Hayakawa et al., 1994, and references therein). At the bottom-side ionosphere a portion of the energy of atmospherics leaks upwards into the ionosphere where it starts to propagate in the whistler mode. The effectiveness of this leakage and transformation to the whistler mode depends on ionospheric conditions.

Despite the relatively long history of the investigation of whistlers, there is a lack of information on the effectiveness of the free-space mode to the whistler mode conversion and on the size of the area in the ionosphere in which this conversion takes place. In this study, we will try to estimate the characteristic area through which the lightning energy enters the magnetosphere. We will use observations of fractional-hop whistlers on satellites. We will compare the times of the whistler arrivals to the satellite with the times of lightning discharges detected by the ground-based lightning detection network. We will show that it is possible, with high probability, to find causative lightning discharges to the observed fractional-hop whistlers. In a statistical approach, we are able to estimate the area in which the free-space lightning induced electromagnetic waves transform to whistler mode waves and enter the magnetosphere.

2 Experimental data

In the following, we will give a short description of the experimental data used in the analysis. These are data from the ground-based lightning detection network and satellite measurements of one component of the electric field in the VLF frequency range.

2.1 The lightning detection network EUCLID

EUCLID (EUropean Cooperation for LIghtning Detection) is a collaboration among national lightning detection networks with the aim to identify and detect lightning all over the European area. Operation of the EUCLID network started in 2000 and currently, the complete EUCLID network consists of 125 sensors contributing to the detection of lightning.

All the lightning data are detected by means of electromagnetic sensors in the LF frequency range (10 kHz–350 kHz), which send raw data to a central analyzer. The technology involved is provided by Vaisala (Tucson, AZ). Each sensor detects the electromagnetic signal emitted by the lightning return stroke, and GPS satellite signals are used for precise time stamping. For each lightning stroke, the main parameters are calculated and recorded, namely the time of the event, the impact point (latitude and longitude), the peak current and polarity. As in the NLDN (National Lightning Detection Network) in the United States, strokes are grouped into flashes using a spatial and temporal clustering algorithm (Cummins et al., 1998). The data of all the sensors throughout the network are processed in two Euclid central operational centres and provide a complete picture of lightning activity in real time. In parallel, data are archived for post-storm analysis, as used in this study.

The operation of EUCLID started in 2000, and since that time the network has undergone several extensions by integrating additional national networks, sensor upgrades and hence the detection efficiency and area of coverage of the EUCLID network has increased over the years. A model-based projection of the EUCLID network detection efficiency is shown in Fig. 1. Note that the detection efficiency falls off rapidly as the sea coast and borders are approached, as a result of a lack of sensors.

The type of sensors employed in the EUCLID network (IMPACT, LPATS) and the configuration setting of the EUCLID central processor are primarily designed for best performance in detecting cloud to ground lightning (CG). Only a small fraction (a few percent) of intra/intercloud (IC) discharges is detected by EUCLID, and detection efficiency of IC is not uniform across the area of coverage.

The output format of the lightning data used in our analysis contains the times of the detected lightning strokes in a millisecond resolution, location of these lightning strokes (geographic latitude and longitude), peak current estimate (including the polarity), and information about the lightning type (CG or IC discharges).

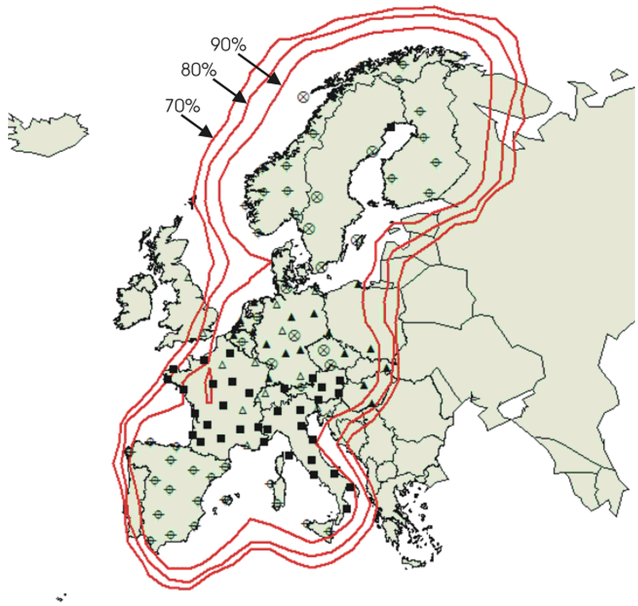

Fig. 1. Projected Flash Detection Efficiency for the EUCLID Network (Network status October 2005) for peak currents greater than 5 kA.

2.2 Satellite VLF data, and the whistler time determination

In our analysis, we have used data from two satellites: DEMETER and MAGION-5. DEMETER is a French satellite launched at the end of June 2004, and orbiting at an altitude of about 710 km along approximately a circular orbit with an inclination of 98.3°. We use the waveform of one component of the electric field measurement in the VLF frequency range by the ICE experiment (Berthelier et al., 2006). The waveform is available when the satellite is in the burst mode. The sampling frequency is f_s=40 kHz. The data are transmitted to the Earth in digital form. MAGION-5 was a Czech satellite that was in regular operation from June 1998 to July 2001. It orbited at a highly elliptical orbit with perigee ∼1200 km and apogee ∼19 000 km, with an inclination of 63.3°. VLF data transmitted to the Earth in analogue form were recorded and digitised with a sampling frequency of f_s=44.1 kHz. The analysed data cover altitudes from ∼3000 km to ∼7000 km.

Detailed frequency-time spectrograms were computed from the waveforms. To obtain a high frequency-time resolution, a waveform was multiplied by a Gaussian window in the time domain before computing Short Time Fourier Transform (STFT) using an FFT algorithm. We use the 7/8 overlapping of the time intervals on which the FFT is applied. Thus, in the case of a 4096-point FFT, one column in the spectrogram represents a $\sim 512/f_s \sim 12$ ms time interval.

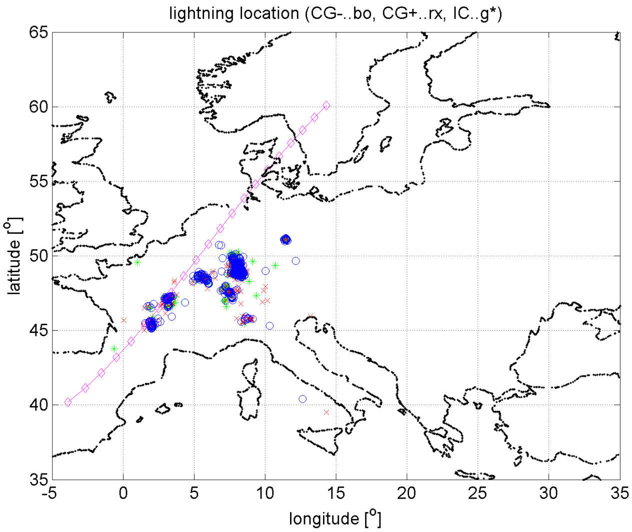

Fig. 2. Lightning discharges and the magnetic footprints of the MAGION-5 satellite from 00:15 UT to 00:35 UT on 5 June 2000. Circles (blue) correspond to −CG discharges, crosses (red) to +CG discharges and asterisks (green) to IC discharges.

We have manually (by eye) searched for the fractional-hop whistlers on detailed spectrograms. Since the dispersion of fractional-hop whistlers is low, we have not evaluated it. We determine the time of whistler arrival at the satellite by "clicking" the data cursor on individual fractional-hop whistlers at the frequency of 5 kHz in the electronic version of spectrograms.

2.3 Example of lightning activity-satellite orbit configuration

To characterize the position of a satellite with respect to the lightning discharges, we trace the satellite position along the magnetic field line to the bottom of the ionosphere, where we stop the tracing at an altitude of 110 km. We will call these points magnetic footprints of the satellite from now on. Figure 2 shows a sequence of magnetic footprints along the orbit of Magion-5 satellite, and the locations of detected lightning discharges by the EUCLID network. Different types of lightning discharges are distinguished by different symbols. Note that if during a given satellite pass the magnetic footprints do not cross the centre of the lightning activity and/or the lightning activity is located on one side of the line of the footprints, then this satellite pass does not cover all possible distances and azimuths between the magnetic footprints and the locations of the lightning at the times corresponding to the individual flashes.

3 Data processing and obtained results

In order to find the correspondence between the whistlers observed on the satellites and the lightning discharges detected by the ground-based EUCLID network, we have computed a matrix containing all the possible differences $t_{wi}-t_{lj}$, where t_{wi} is the time of the i-th detected whistler (i=1..M), and t_{lj} is the time of the j-th detected lightning discharge (j=1..N) in the analysed time interval. The length of the analysed time interval depends on the orbit of the given satellite, and it is about 5 min for DEMETER satellite and about 20 min in the case of the MAGION-5 satellite. It can also be limited by the length of the VLF record, e.g. by the length of the burst mode on the DEMETER satellite. Note that the number of detected whistlers M is usually different from the number of detected lightning discharges N. If predominantly the whistlers corresponding to the lightning discharges detected by the EUCLID network arrive at the satellite, we can expect that a certain narrow interval of time differences will occur most frequently in the matrix. These time differences would correspond to the propagation time of the waves from the discharges to the satellite and to a possible small time shift between the clock used by the EUCLID network and the clock used in the VLF record. We suppose this time shift between the clocks to be constant during the analysed time interval, which is obviously true. Concerning the propagation times from the discharges to the satellite, we suppose that they do not change significantly for 5-kHz waves during the analysed part of the orbit. This is true for the observation of fractional-hop whistlers by DEMETER. In the case of MAGION-5, small differences in propagation times comparable with the time resolution of whistler detection are observed when we divide the analysed part of the orbit into several time intervals (not shown). This variation of propagation time is caused both by the variation of length of the wave trajectory and by variation of whistler dispersion. The change in the whistler dispersion along the orbit was studied in more detail by Hughes (1981), and Hughes and Rice (1997), who measured the dispersion on the ISIS-2 satellite at an altitude of ∼1400 km and showed that the dispersion varies from ∼5 $s^{1/2}$ at a magnetic latitude of 25° to ∼12 $s^{1/2}$ at the equator. Since our observations concern middle latitudes, these variations are negligible in our case.

In the next step, we construct an occurrence histogram of time differences $t_{wi}-t_{lj}$ in the matrix. It is convenient to do it only for reasonable time differences. We have constructed the occurrence histogram with a time step of 25 ms. Two examples of these histograms are presented in Figs. 3 and 4. Different symbols distinguish various types of lightning discharges. The curve corresponding to the highest occurrence rate represents all types of lightning. Figure 3 stands for MAGION-5's orbit during the nighttime conditions on 5 June 2000; the map with lightning activity and satellite orbit was presented in Fig. 2. Figure 4 shows the results for the orbit of the DEMETER satellite during daytime conditions

Table 1. Analysed time intervals and selected orbital parameters during the analysed periods.

Date	Time [UT]	Satellite	MLT	L	Altitude [km]
29 May 2000	00:24:00–00:44:00	MAGION-5	1.25–3.15	1.55–3.38	3190–6910
5 June 2000	00:15:00–00:35:00	MAGION-5	0.65–2.57	1.56–3.47	3210–6930
4 Aug 2000	18:50:00–19:10:00	MAGION-5	19.33–21.26	1.66–3.76	3600–7320
21 Aug 2004	10:19:32–10:24:32	DEMETER	11.52–10.82	2.41–1.41	704–702
14 Sep 2004	10:19:02–10:25:02	DEMETER	11.90–10.98	2.50–1.34	718–719
16 June 2005	20:54:02–20:58:58	DEMETER	22.62–22.70	1.34–2.30	706–709
29 June 2005	22:01:02–22:04:30	DEMETER	22.58–22.61	1.29–1.77	706–708

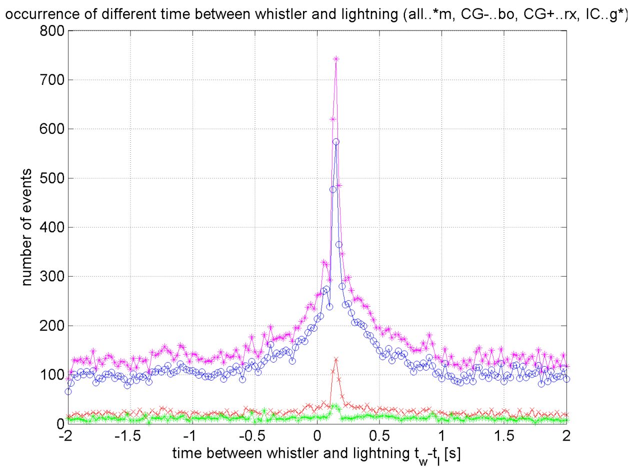

Fig. 3. Occurrence histogram of time differences $t_{wi}-t_{lj}$ between whistler observation (t_{wi}) and lightning discharge detection (t_{lj}). The histogram corresponds to the analysed period from 00:15 UT to 00:35 UT on 5 June 2000 and to the VLF record by MAGION-5 during the nighttime conditions. Asterisks (magenta) correspond to all discharges, circles (blue) to −CG discharges, crosses (red) to +CG discharges and asterisks (green) to IC discharges.

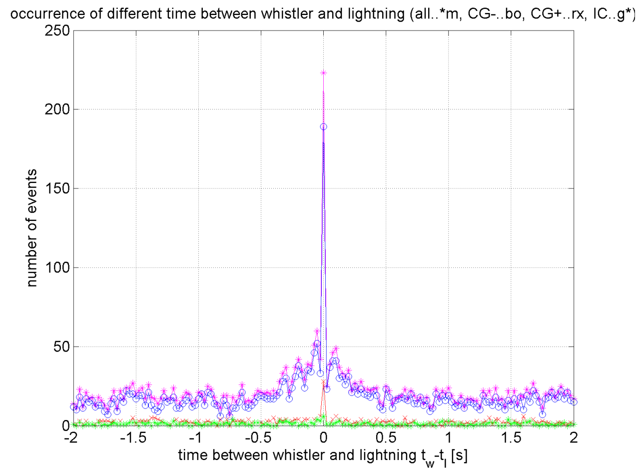

Fig. 4. Occurrence histogram of time differences $t_{wi}-t_{lj}$ between whistler observation (t_{wi}) and lightning discharge detection (t_{lj}). The histogram corresponds to the analysed period from 10:19:02 UT to 10:25:02 UT on 14 September 2004 and to the VLF record by DEMETER. The meaning of symbols and colours is the same as in Fig. 3.

on 14 September 2004. We can see a distinct peak in both occurrence histograms. This means that the satellites mainly receive the whistlers caused by lightning discharges detected by the EUCLID network in both cases. If this was not true, the time differences would be randomly distributed in the matrix and no distinct peak would occur. Obviously, a reliability of assigning the causative lightning to a whistler increases with the amplitude of the peak relative to the average occurrence rate in the histogram. We remind again that the time difference corresponding to the peak comprises both the propagation time and a possible time shift between the clocks. The possibility of the time shift between the clocks is also the reason why we have searched for the peak in the range of negative time differences, which obviously contradicts the causality and has no physical meaning.

Knowing the characteristic time difference corresponding to the peak $t_{ch}=(t_{wi}-t_{lj})_{\text{peak}}$ for each orbit, we can select only those lightning discharges for which we have found, with great probability, a corresponding whistler in the spectrogram. Once we have found the corresponding pairs "causative lightning-whistler", we can find the distance between the magnetic footprint of the satellite and the location of the lightning discharge at the given time. Thus, we can investigate the size of the area in the ionosphere trough where the waves enter the magnetosphere. We have analysed data from four orbits of the DEMETER satellite (two of them during late evening and two of them during the daytime conditions) and from three orbits of the MAGION-5 satellite during the nighttime or evening conditions. Table 1 summarizes the dates, times, magnetic local times (MLT), L-shell and altitudes of the satellite during the relevant parts of these orbits. Table 2 gives an overview of the overall number of detected lightning discharges and whistlers. We should note that apart from the fact that the EUCLID network is rather insensitive to IC discharges, the number of detected lightning strokes

Table 2. Number of detected lightning discharges and whistlers during the analysed time intervals.

Date	Time [UT]	Satellite	Number of detected Whistlers	Number of detected Lightning
29 May 2000	00:24:00–00:44:00	MAGION-5	299	751
5 June 2000	00:15:00–00:35:00	MAGION-5	1722	4093
4 Aug 2000	18:50:00–19:10:00	MAGION-5	185	292
21 Aug 2004	10:19:32–10:24:32	DEMETER	206	499
14 Sep 2004	10:19:02–10:25:02	DEMETER	512	558
16 June 2005	20:54:02–20:58:58	DEMETER	391	137
29 June 2005	22:01:02–22:04:30	DEMETER	259	573

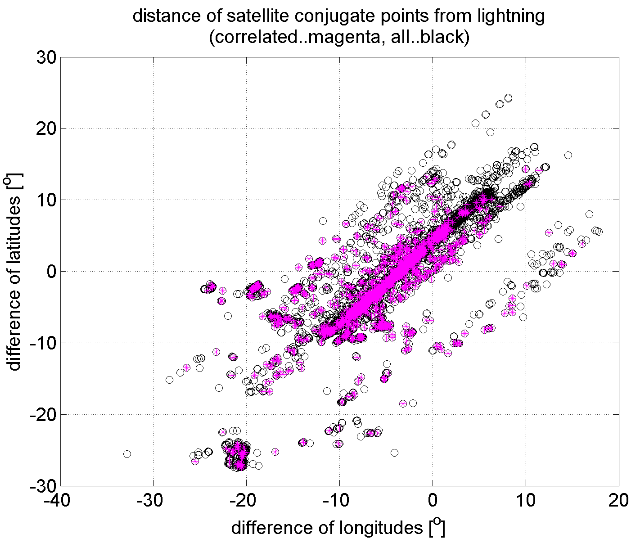

Fig. 5. Distances between the magnetic footprint of the satellite (at the altitude 110 km) and the lightning discharges. Circles (black) are used for all lightning, asterisks (magenta) for those discharges for which the corresponding whistler was found. Positive value of the difference in latitudes (longitudes) means that the footprint was northward (eastward) from the discharge.

also depends on the location of discharges with respect to the sensors (coverage of the network). The number of detected whistlers partially depends on the subjective assessment. We can see that, in our cases, the number of detected lightning strokes is usually larger than the number of whistlers, with the exception of the case on 16 June 2005, when the number of whistlers is larger than the number of lightning discharges. On that day, most of the lightning activity occurred at the border of the area covered by the EUCLID network and hence in an area of a low detection efficiency.

In order to minimize the unwanted influence of the configuration “lightning activity – satellite orbit” on our results, we have superposed the results from all the analysed orbits for the time intervals presented in Table 1. The results of the analysis are displayed in Figs. 5 and 6.

Figure 5 shows the distances between the magnetic footprints of the satellites and the lightning discharges in the geographic latitude–longitude coordinates. Circles (black) represent all lightning discharges detected by the EUCLID network during the analysed time intervals, whereas asterisks (magenta) stand only for those discharges for which we have found the corresponding whistler. Figure 6 redisplays the results presented in Fig. 5 in a form more useful for the interpretation of the results. Different colours distinguish different types of lightning discharges. Thin lines stand for all detected discharges, whereas thick lines are used only for the discharges for which we have found a corresponding whistler. We present the occurrence histograms of lightning, and the ratios of lightning for which a whistler was found, to all lightning, as a function of the distance between lightning discharges and magnetic footprints of satellites. We should point out that the values of these ratios are statistically insignificant at distances larger than ∼1500 km – see the number of events in the top left plot. The absolute distances (in km) between the magnetic footprints of the satellites and lightning discharges were computed from the given latitudes and longitudes as distances on a spherical model of the Earth’s surface.

We can see that the electromagnetic energy induced by a lightning discharge can enter into the magnetosphere as whistler mode waves at distances up to ∼1500 km (occasionally even more) from the discharge. Thus, if the penetrating area is symmetric around the lightning position, its width is two times that distance, which is ∼3000 km. If the situation is asymmetric, the size of the area is less than twice that distance. The decomposition of the distances into longitudinal and latitudinal differences may indicate a certain asymmetry, which can be, however, specific to our data set. The symmetry/asymmetry of the penetrating area will be discussed in the next section.

The top right plot in Fig. 6 also demonstrates that positive and negative lightning discharges have approximately the same efficiency in producing whistlers, since the curves presenting the ratios of discharges for which whistlers have been found, to all detected discharges, are about same for both +CG and −CG discharges. We cannot say anything

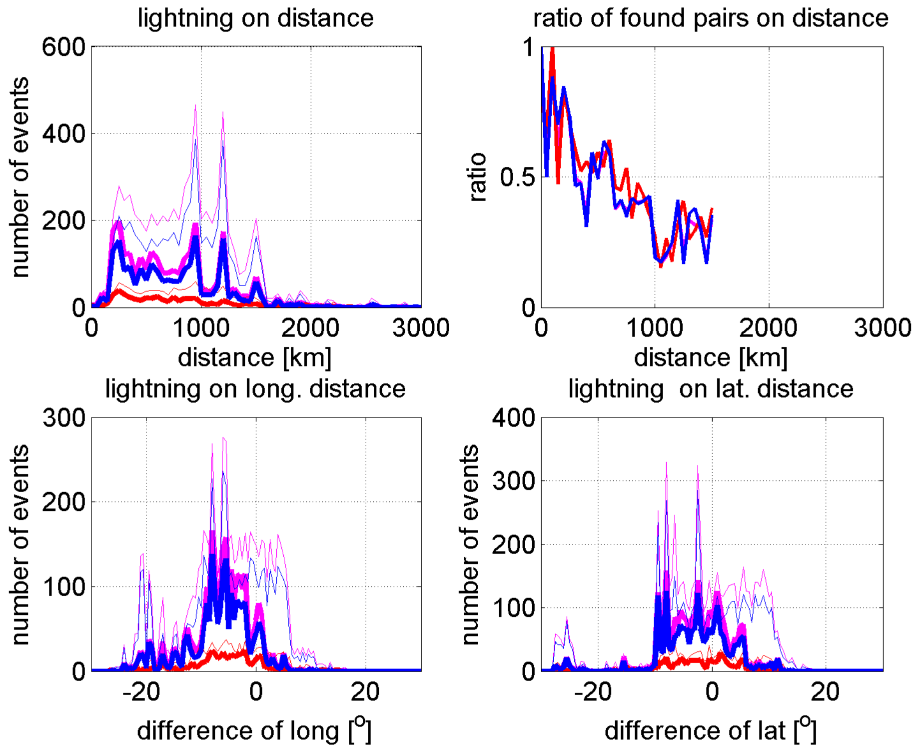

Fig. 6. Top left plot: occurrence histograms of lightning discharges on distance from the magnetic footprints of the satellites. Thick lines stand for the lightning for which the corresponding whistler was found, thin lines stand for all detected lightning. Magenta lines represent all types of discharges, blue −CG discharges, red +CG discharges.

Top right plot: the ratio of lightning discharges for which the corresponding whistler was found to all discharges. Colours distinguish different types of discharges and their meaning is the same as in the top left plot. Note that the values for distances larger than ∼1500 km are statistically insignificant – see the top left plot.

Bottom: Occurrence histogram of the distances between the magnetic footprints of the satellites and lightning discharges decomposed on longitude (left) and latitude (right). The meaning of lines and colours is the same as in the top right plot. The meaning of signs is the same as in Fig. 5.

about the IC discharges, since the EUCLID network is rather insensitive to them; the results related to IC discharges have no statistical significance and are not displayed.

4 Discussion, constraints of the analysis, future work

The plots presented in Figs. 5 and 6 indicate that the lightning-induced waves tend to penetrate the ionosphere in the south-west direction from the lightning discharge. Nevertheless, we think that this result might be influenced by special configurations "lightning activity – satellite orbit" and that more data has to be analysed before we could confirm this result. In our results, the positive values of differences are mostly covered by whistler measurements by MAGION-5 satellite at relatively high L-shells and high altitudes. We should also note that the size of the penetrating area may be slightly overestimated if the propagation of whistlers is nonducted. Thus, future studies should mainly be based on data from DEMETER or another Low Earth Orbit satellite to be sure that propagation effects do not play any important role. Nevertheless, we should remark that we have not found any remarkable difference between the size of the penetrating area when we analysed cases for DEMETER and MAGION 5 satellites individually (not shown).

In the present study, we have manually detected several thousand whistlers. An analysis of more data requires usage of an automatic or quasi-automatic whistler detection. We note that the time resolution of ∼0.1 s, which has the neuronal network instrument "RNF" detecting automatically whistlers on board the DEMETER satellite, is insufficient for this purpose. A reliable automatic detection of fractional-hop whistlers with sufficient time resolution could help us to answer the question of whether there is an asymmetry in the area through which the lightning energy enters the magnetosphere. The software for automatic whistler detection could also enrich the data by the information about the whistler intensity.

We have analysed both daytime and nighttime cases (see Tables 1 and 2). The results that we obtained for the separated daytime and nighttime cases did not show remarkable differences (not shown). Again, in order to decide whether there is a difference between the size of the area through which the waves enter the magnetosphere during the nighttime and daytime conditions, we should analyse more cases, which requires automatic or quasi-automatic whistler detection.

Despite the constraints of our work, we note that the estimated size (at least 2000 km) of the area through which the waves enter the magnetosphere is consistent with the size used in numerical simulations of MR whistlers (Shklyar et al., 2004), to obtain the best agreement with the observations of MR whistlers.

5 Conclusions

We have shown that by using a statistical approach it is possible to assign the causative lightning discharges to the observed whistlers both on the Low Earth Orbit (LEO) satellites, and to the whistlers observed at satellites orbiting at altitudes of ∼5000 km. The assignment is possible both in the nighttime and daytime conditions.

The area in the ionosphere through which the lightning energy leaks into the magnetosphere, and transforms to whistler mode waves is more than 2000 km wide.

We have not observed a higher effectiveness of any type of lightning discharge in producing whistlers. We remark that the EUCLID network is rather insensitive to the IC lightning discharges, therefore the results obtained for these types of discharges are statistically insignificant.

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