Infrasound observations of sprites associated with winter thunderstorms in the eastern Mediterranean

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Abstract

Sprites are transient luminous events (TLEs) that occur at mesospheric altitudes between 50 and 90 km. They last up to several milliseconds, and are caused mostly by positive lightning discharges from the thunderstorm cells below. Infrasound from sprites was first observed in detail a decade ago by a team from the French Atomic Energy Commission (CEA), as part of a renewed international interest in infrasound measurements brought about by the Comprehensive Nuclear Test Ban Treaty (CTBT) [1]. They used optical images of sprites obtained during the EuroSprite observation campaign in order to form the temporal and azimuthal basis necessary for searching for the infrasound signatures from these events, which appear as unique "chirp" or "inverted chirp" signatures depending on the sprite's distance from the infrasound array. In this paper we follow this methodology to see if the nascent Israeli infrasound arrays can detect these signals from sprites in the Eastern Mediterranean, for which there are nearly 8 years of winter-time optical observations. We calculated the expected arrival time of the infrasound from optically observed sprites, and then used a basic ray-tracing method in order to confirm that we were in fact able to observe several of these sprites, at various distances, exhibiting both "chirp"

and “inverted chirp” signals. We then compared these observations with observations of lightning activity made by the World Wide Lightning Location Network (WWLLN).

Introduction

Sprites are transient luminous events (TLEs) that occur at mesospheric altitudes between 50 and 90 km. They last up to several tens of milliseconds, and are triggered by positive lightning discharges from the storm cells below. They are usually described as a group of visible columns, sometimes with branching features that make them appear jelly-fish or carrot-like, and many images have been taken of them all over the world [2]–[4]. Israel is an ideal place to observe these phenomena, owing to the fact that thunderstorms in the eastern Mediterranean occur in winter-time, when the nights are longest, and because the sea provides few viewing obstructions [5]. This allows for a much greater chance of imaging the sprites, which are virtually impossible to see when there is any daylight at all [6].

That sprites produce detectable pressure waves was first theorized by Bedard et al [7]. Later, Liszka [8] observed signals in his infrasound data that he attributed to sprites. These were pressure pulses of between 0.01 and 0.1 Pa, lasting several tens of seconds, and with lower frequencies arriving first. He described these changes in frequency content with time as “chirps.” Farges et al [1] confirmed this with extensive infrasound observations of optically-imaged sprites, observing these chirps originating from sprites occurring about 400 km away from their infrasound array. The chirps are explained by a combination of the sprite’s size and location. Sprites at 400 km produce infrasound that reflects off of the atmosphere at higher altitude—where the effective sound speed increases with the increase in temperature—before traveling to the infrasound arrays. During this reflection, the waves are damped slightly, and there is attenuation of higher frequencies that increases with altitude. Therefore, signals coming from the higher-altitude parts of sprites (~ 80 km) arrive depleted in their upper frequency ranges. Signals from the lower altitude parts of sprites (~ 50 km) are reflected from lower altitudes, making their frequency spectrum more complete and their arrival slightly delayed, resulting in an infrasound signal that begins with lower frequencies and ends with all frequencies, including the higher ones [1], [9], [10]. Depending on the size of the sprite and the distance to the receiver, these "higher" frequencies can be anything from 2 to 10 Hz, with the "lower" frequencies being less than 2 Hz. Liszka and Hobara [8] then further studied this phenomenon through an automatic search for these signals within ten years of their data.

Upon further review of the 2005 study, Farges and Blanc [10] reported seeing even more signals of appropriate length and frequency content, only this time, the high frequencies arrived before the low frequencies, in what they called "inverted chirps." This was explained intuitively by de Larquier and Pasko that same year. Because of the closer distances, the infrasound interceptions are direct, and the closer, lower altitude signals arrive before the farther, higher altitude (and higher-frequency-depleted) ones [11].

In this paper, we will show our infrasound interceptions of both a "chirp" from a distant sprite and an "inverted chirp" from a closer range sprite, which occurred in winter thunderstorms over the eastern Mediterranean Sea.

Equipment

In 2003 the ILAN (Imaging of Lightning and Nocturnal flashes) project was started, named after the late Israeli astronaut Ilan Ramon, with the mission of imaging and cataloguing as many eastern Mediterranean sprites as possible. The ILAN team set up two observation sites, with two panchromatic CCD cameras at each site: one at Tel Aviv University (32.5N, 34.5E), with a view of sprites occurring up to 400 km off the Mediterranean coast, and one at the Wise Observatory in Mizpe Ramon (30.6N, 34.76E), better at capturing sprites closer to the coast and above northern Israel . The systems were equipped with UFO-capture software in order to isolate events automatically, therefore allowing the team to delete event-free data and avoid the need for data compression. The pan-and-tilt unit (PTU) recorded the azimuth with 0.1 degree accuracy. The field of view (FOV) of the primary camera was 14 degrees in the horizontal direction, and 10.5 degrees vertical [2], [12].

The Israel Infrasound Network consists of two arrays of MB2000 micro-barometers attached to Quanterra Q330 digitizers. One array, with four elements, is in the Negev desert, near the town of Dimona; the other, with five elements, is near the northern town of Meron, close to the border with Lebanon. The arrays have been functioning nearly continuously since 2011. The Meron array has a much smaller aperture (1km as compared with nearly 5km for the Dimona array), making it much more appropriate for studying signals with wavelengths corresponding to the frequency ranges of sprites, and thus, this is the array we used for this study [13].

The World Wide Lightning Location Network, or WWLLN, is a worldwide network of about 70 very low frequency - VLF (3-30 kHz) detectors [14], organized by the University of Washington in collaboration with many other universities. WWLLN works by using ground-based detectors to intercept the VLF emissions from lightning known as sferics, localizing them using the time of group arrival (TOGA) technique. It takes advantage of the fact that these waves travel thousands of kilometers in the Earth-ionosphere waveguide without significant attenuation [15]. As with infrasound, WWLLN only sees a representative fraction of the total lightning activity, about 11% on average [16], though the location error of these detections is within 2.9 km, on average [17].

Methods

We received the complete list of optical sprite observations from the ILAN science team. These data include time, azimuth, elevation, distance, physical description (for example, "carrot" or "column"), and number of elements (meaning the number of optically distinct structures)[18].

Infrasound waveform analysis was performed using Progressive Multi-Channel Correlation (PMCC) [19]. In order to determine which time periods to analyze in the infrasound data, we calculated arrival windows, by determining how long the infrasound transit time would be if it traveled only at the lowest and highest possible sound speeds it could encounter, taken to be 250 m/s at 90km and 340 m/s at sea level. Subtracting the two gave us a window of up to 10 minutes (and in most cases much less) during which the infrasound wave from the sprite could have arrived at the micro-barometer array. Because each sprite infrasound signal is tens of seconds long, we expected it to be well isolated in our arrival window. Indeed, in almost every case where an infrasound signal appeared, only one signal of appropriate length was visible in the arrival window.

We repeated this process for all ~330 sprites observed by the ILAN science team in the years 2011-2013. In most cases, we were not able to see any signals at all in the infrasound. This we attributed to the fact that most sprites observed were optically small, listed as having only a single discernable element. While the average sprite deposits a few to tens of MJ into the atmosphere [20], a sprite must deposit hundreds of MJ into the atmosphere in order to produce even a 0.1 Pa pressure wave observable at a distance of hundreds of km [21] [22]. This means that the likelihood of any individually-imaged sprite being detected in infrasound is not very high [21]. However, we were able to observe the majority of the sprites with more than 8 observed structural elements, which themselves were just 5% of the sprites observed by the ILAN team.

In cases where more than one sprite occurred in close enough succession so as to cause infrasound arrival windows to overlap, we used ray tracing to determine which specific photographed sprite caused the observed infrasound signal. We used a 3D ray tracing model based on a modified Eikonal for a moving medium [23] solved by using the Hamiltonian representation of the system, using the short distance of the sprites from the observation points in Israel in order to neglect the curvature of the Earth [24]. This model requires two atmospheric parameters: the speed of sound profile and the wind profile. We used local averaged profiles for the winter time, consistent with other infrasound modeling studies done in the same geographical region [25]. Local radiosonde measurements enabled us to update the first 20 Km of both speed of sound and wind profiles.

$$\mathcal{H}(q_i,p_i) = \frac{1}{2}\left[p_i^2 - u(q_i)^2(1 - p_i v(q_i))^2\right]$$

p_i is the slowness vector, q_i is the position in space and $u = \frac{1}{c}$ .The differential equations for the slowness vector, position and propagation time are:

$$\frac{dq_i}{d\tau} = \frac{\partial\mathcal{H}}{\partial p_i} = p_i + u^2(1 - p_i v_i)v_i$$

$$\frac{dp_i}{d\tau} = -\frac{\partial\mathcal{H}}{\partial q_i} = u^2(1 - p_i v_i)p_l\frac{\partial v_l}{\partial q_l} - \frac{1}{2}(1 - p_i v_i)^2\frac{\partial u^2}{\partial q_i}$$

$$\frac{dT}{d\tau} = p_i\frac{\partial\mathcal{H}}{\partial p_i}$$

Results

An example of a sprite from the ILAN database that we were able to observe occurred on 9 November, 2012 at 02:25:49 UTC. We received the infrasound pressure pulse at approximately 02:36:50 UTC at the Meron station. Figure 1 shows the spectrum of this signal, and the acoustic waves incident on the micro-barometers have been stacked so that the pressure signal is more clearly visible. Figure 2 shows PMCC analysis of the intercepted waveform. Visible is the "inverted chirp" signal typical of sprites observed from distances of less than 200 km [10], in which the end of the signal arrives depleted of its higher frequencies.

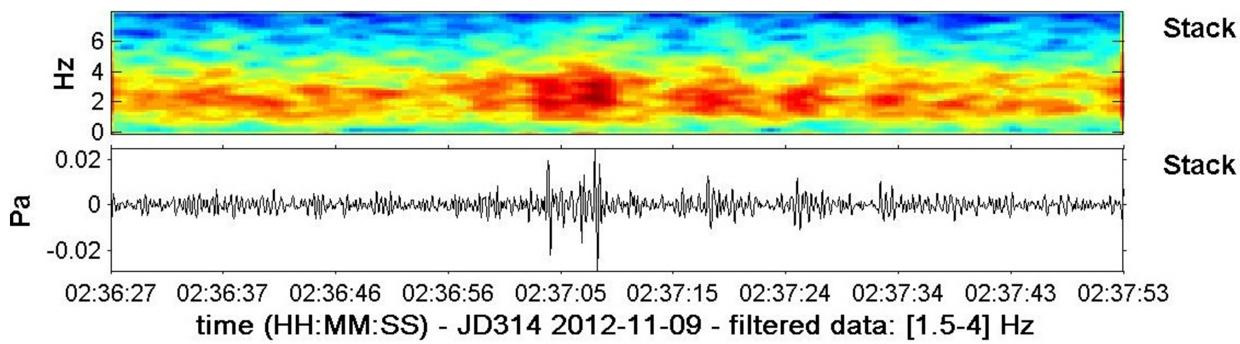


Figure 1: Pressure spectrum and stacked pressure pulse of the sprite signal

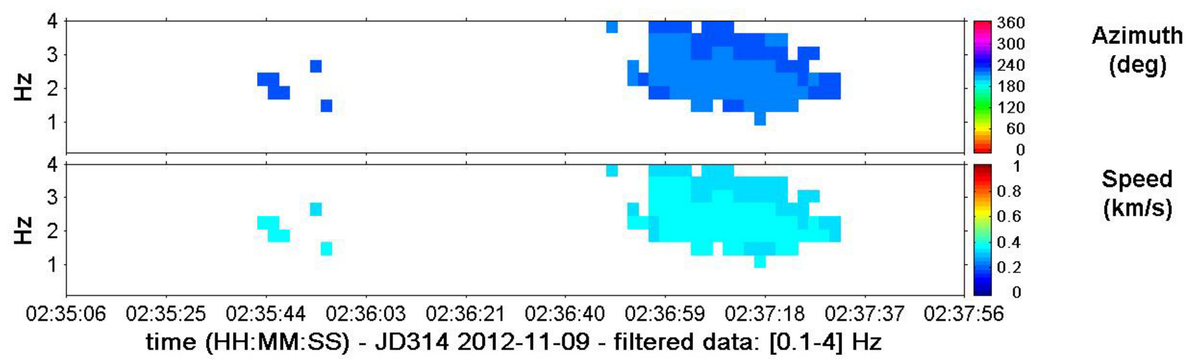


Figure 2: PMCC waveform analysis of a sprite on 9 November, 2012

This signal lay in the arrival windows of five different sprites in the optical database, all occurring within a few minutes of each other and all co-located approximately 190 km to the southwest of the Meron infrasound array, in agreement with the approximately 220-degree back-azimuth of the infrasound signal (Figure 4). We simulated the different possible arrival times using the ray tracing method described above, and determined that the sprite we intercepted was the one imaged by the Mizpe Ramon camera at 02:25:49. Although a visual image of this sprite was not saved in the database, it was described by the observer as having 10 elements, the most of any of the candidates. As seen in Figure 3, the highest altitude (70-80 km) rays were directly incident upon the infrasound detectors, whereas the lower altitude rays (65-70) made a shallower yet faster path, spending more time at lower altitude (where the sound speed is higher) and reflecting off the ground before arriving at the detector. The highest density of initial ray positions came from the area between the sprite's optically-registered location and the back-azimuth of the infrasound data (Figure 4). This slight difference between the actual back-azimuth and the PMCC-calculated infrasound back-azimuth is likely due to local winds.

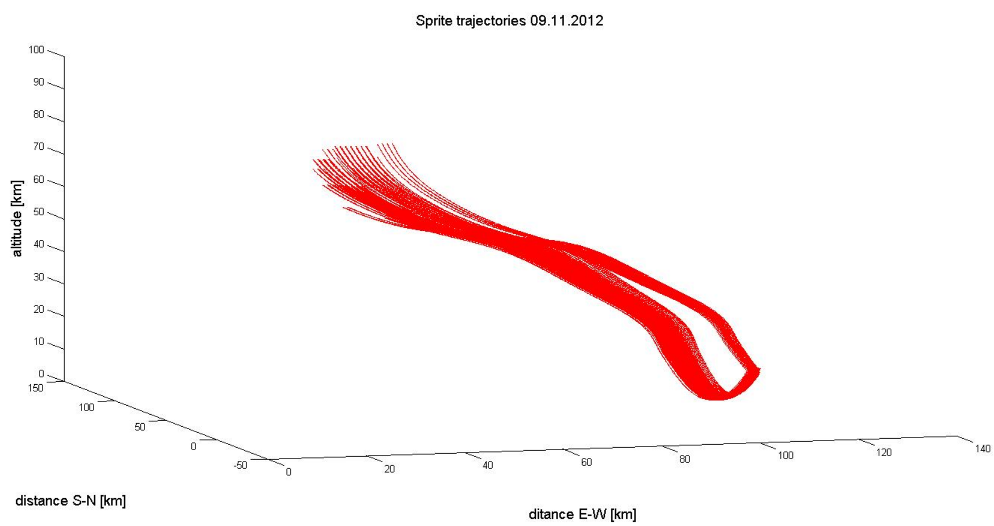


Figure 3: Ray tracing simulation for the sprite in Figure 1

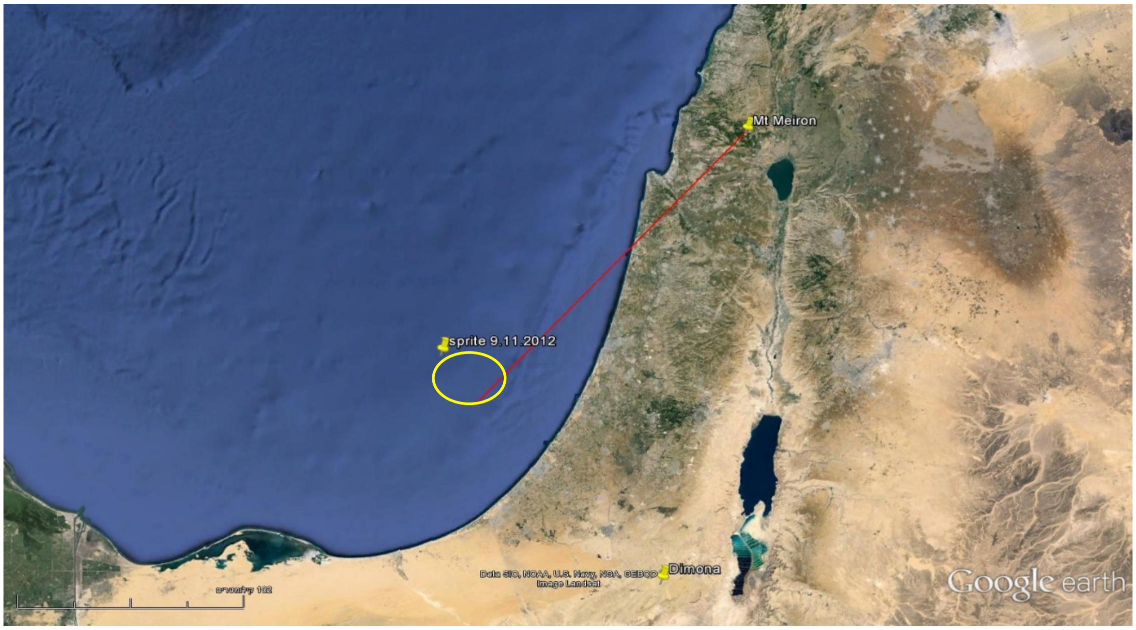


Figure 4: Oval showing the highest density area for initial ray position for the infrasound signal detected in Figure 1

When comparing this detection with WWLLN detections from the same period (Figure 5), it is readily apparent that there was lightning activity detected at the correct time from the area predicted by the infrasound interception and ray tracing model. However, as previously discussed, since neither WWLLN nor ILAN record 100% of lightning, it is difficult to say whether any of these individual flashes is associated with the specific sprite detected.

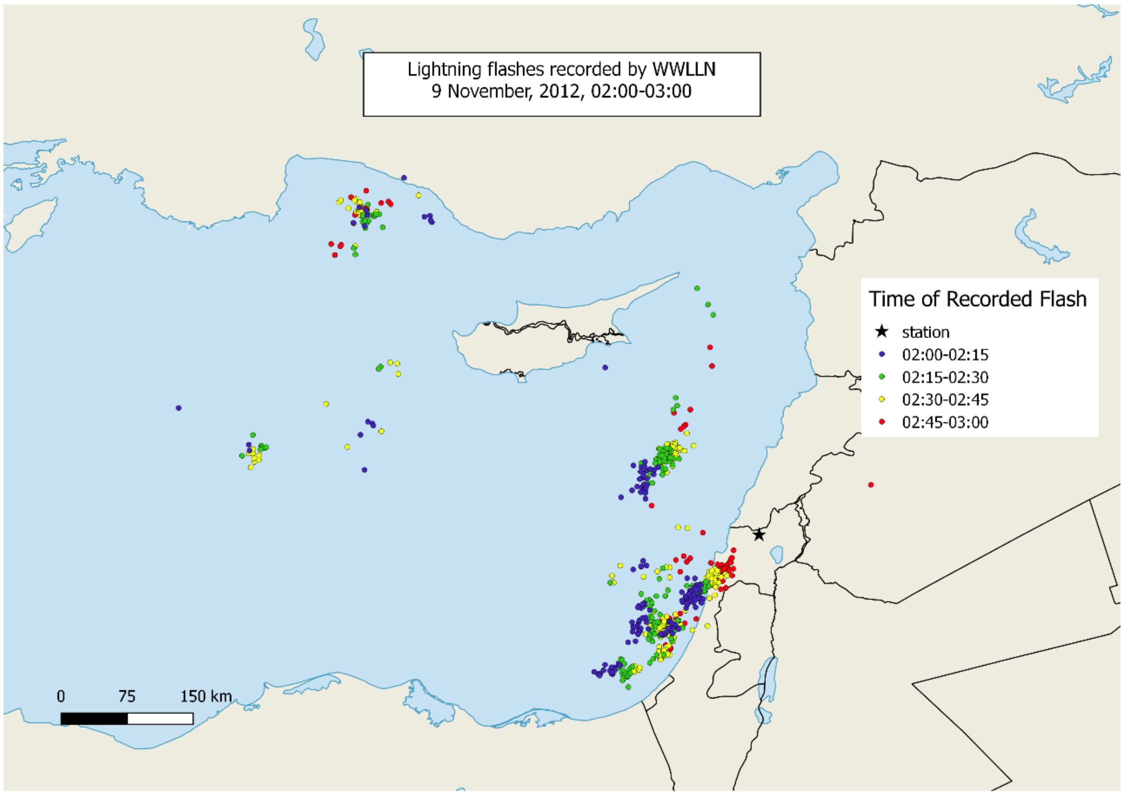


Figure 5: WWLLN Lightning Flash detections from the same time period as when the sprite was observed. There was lightning detected from the vicinity of the area predicted by the infrasound interception and ray tracing model. The sprite occurred during the time interval pictured in yellow.

We received another sprite-like infrasound signature on 6 January, 2011, at approximately 20:36:00, which we compared with one of four sprites imaged by ILAN between 16 and 20 minutes prior. The database entries are below in Table 1, and include the photographs, which in this case were saved.

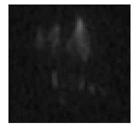
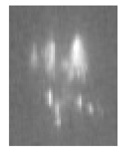
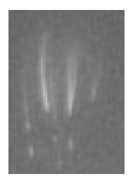
Time (UTC)	Sprite
20:16:18:040	
20:16:18:900	
20:19:05:245	
20:19:05:240	

Table 1: database entries for candidate sprites

The ILAN camera in Tel Aviv put these sprites about 380 km to the northwest of the Meron infrasound array, off the coast of Cyprus, in agreement with the approximately 285-degree back azimuth of the infrasound signal. Figure 7 shows the signal spectrum and the pressure pulse from all of the stacked micro-barometer signals. Figure 7 shows the PMCC analysis of the intercepted waveform. At this increased distance, the lower frequencies arrive prior to the higher frequencies in a “chirp” consistent with the observations made by Farges [1] from 400km.

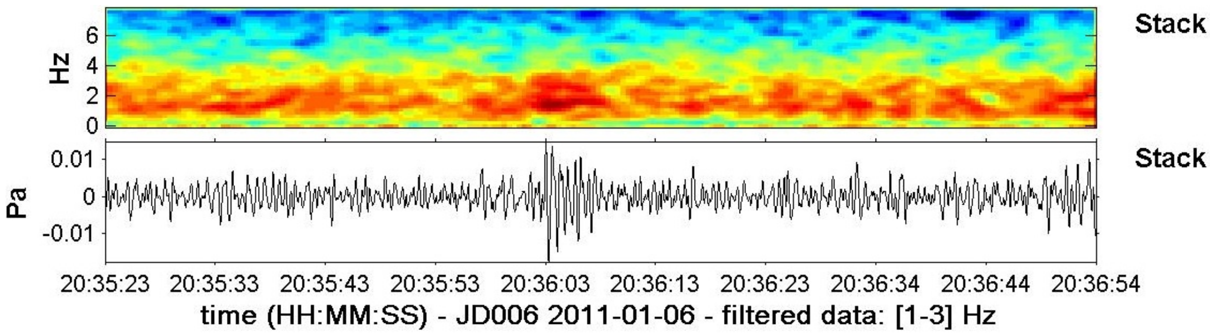


Figure 6: Pressure spectrum and stacked pressure pulse from the sprite in Figure 7

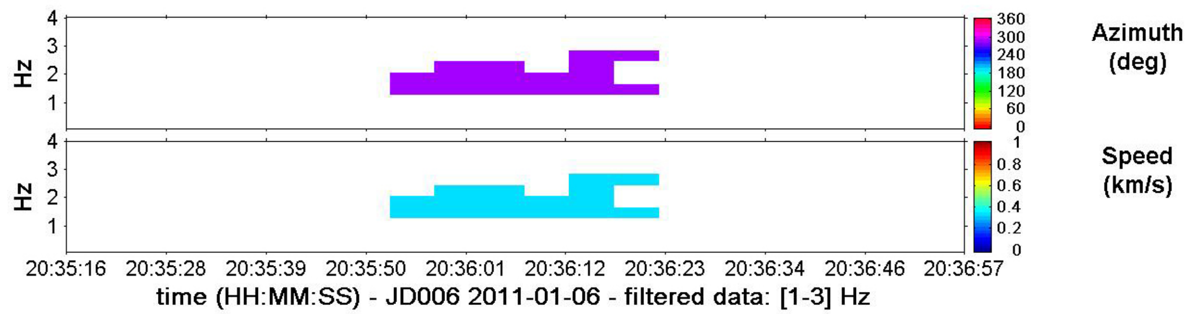


Figure 7: PMCC waveform analysis of the signal from a sprite on the night of 6 January, 2011

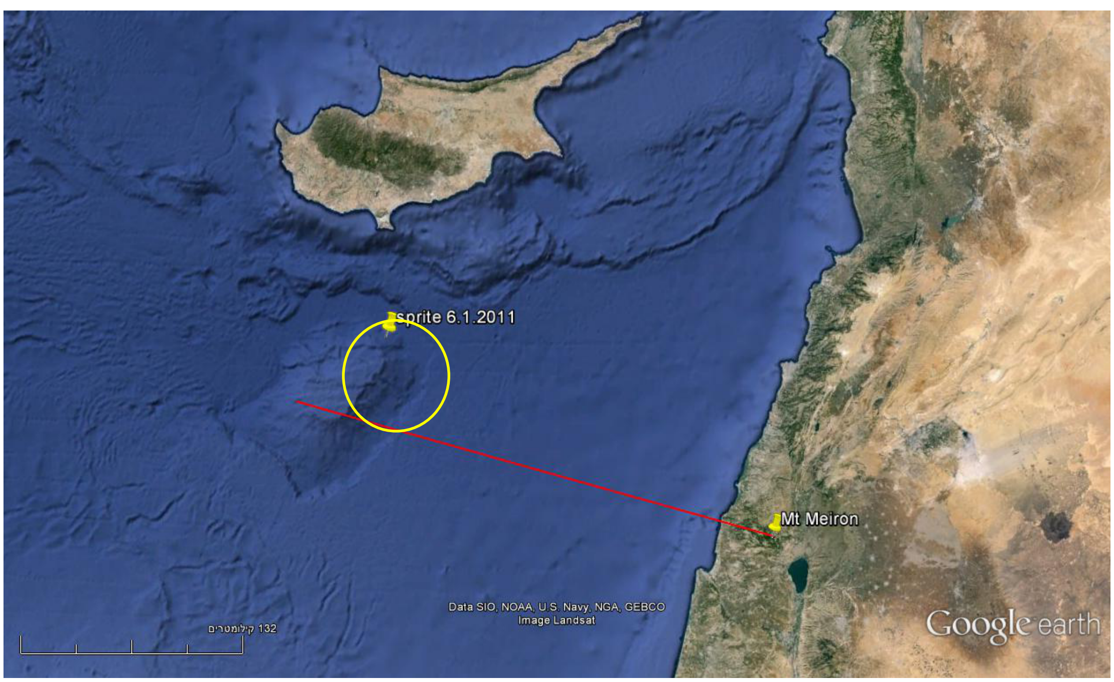


Figure 8: The location of the sprite in Figure 5, the back azimuth of the infrasound detection, and the oval in which the greatest number of rays originated.

Figure 8 shows the back-azimuth of the detected infrasound signal from this sprite, as well as the predicted location of the sprite based on the ray tracing model. The two sprites at 20:19:05 provided the best fit, with the slightly later one being larger and therefore more likely. Once again, the highest density of initial ray positions came from the area between the given center of the image and the infrasound back-azimuth. When comparing that figure with Figure 9, which shows the lightning activity detected by WWLLN in the period of time surrounding the sprite, one can again see that there was intense lightning activity at the correct place at the correct time.

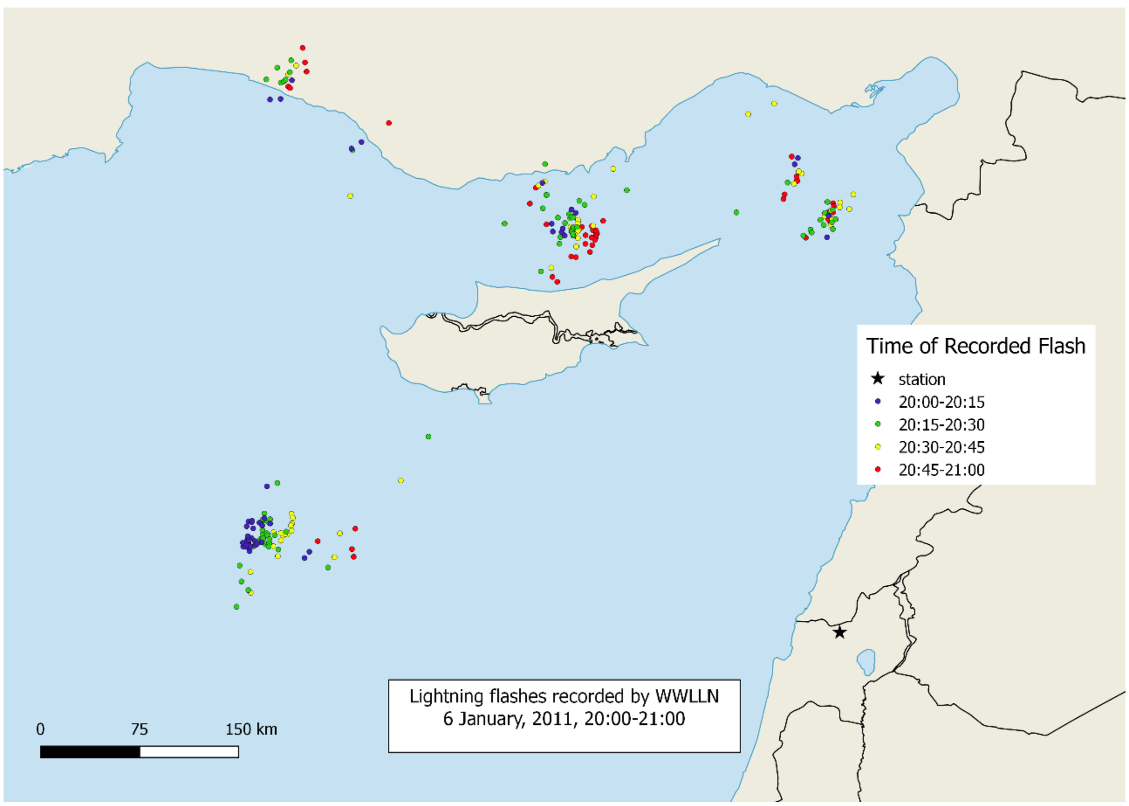


Figure 9: WWLLN flash detections from the time period surrounding the sprite detection. WWLLN detected lightning flashes from the area of the infrasound detection during the correct time period. The sprite occurred during the yellow interval.

Discussion and Conclusions

We have shown that the Meron infrasound array is capable of observing the infrasound signals from sprites occurring in Eastern Mediterranean thunderstorms. Moreover, we have associated the “inverted chirp” of a sprite at close range with a specific, photographed sprite, and confirmed this observation using both electrical activity data and ray tracing technique.

While performing this study, we discovered three potential sources of uncertainty in our observations: the large FOV of the sprite cameras, the fact that storms produce many sprites, not all of which are imaged (because of dimness), and the slight lateral deviations in propagation azimuth due to local winds. Error attributed to local winds is likely small, because of the relatively short transit time of the wave to our detector arrays. Most of the time, there was little difference between the sprite’s optical location and the infrasound back-azimuth. The next potential source of error was the camera FOV. Although potentially up to seven degrees in either horizontal direction, we found that the deviation was most of the time much less than this, since the camera is pointed at the center of sprite-producing electrical activity in the first place. Rather, what we found most often in our data were sprite-like signals missed by the cameras.

In some cases, two sprites may occur in a very short amount of time and from a very similar location. In these cases, it may not be possible to tell which sprite produced the recorded infrasound unless one sprite is markedly larger than the other. Furthermore, should both produce detectable infrasound, the pressure pulse of the first may mask that of the second.

The literature makes it clear that it takes a big sprite or a close sprite to make a detectable infrasound signal, and our results are very much in agreement with this. Most notably, we are able to provide visual confirmation that close-range sprites cause the kind of inverted chirps seen by Farges and Blanc [11]. In that paper, the authors lament that they were unable to provide such visual confirmation because their interceptions came from azimuths not imaged by their cameras.

Most of all, we verified that the Meron infrasound array is in excellent working order and able to contribute to future observations of eastern Mediterranean sprites, especially during times of low visibility when optical imaging is challenging.

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Conflict of Interests

The authors state that there are **no** conflicts of interest in publishing this manuscript, whether between authors, institutions or funding agencies.