The FORTE VHF instrument as a high-energy cosmic ray detector

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ABSTRACT

The FORTE satellite records bursts of electromagnetic waves arising from near the Earth's surface in the radio frequency (RF) range of 30 to 300 MHz with a polarization-selective antenna. We investigate possible RF signatures of ultra-high energy cosmic rays (UHECR), including Cherenkov radiation in ice, UHECR-triggered lightning emission, incoherent bremsstrahlung of the ionization trail, and direct geomagnetic synchrotron radiation from the high-energy particles in the shower. The FORTE database consists of over 4 million recorded events to date, and may include a significant number associated with cosmic rays near or beyond the Greisen-Zatsemin-Kuzmin (GZK) cutoff. As a first stage of investigation, we search for FORTE events in the period from September 1997 to December 1999 which can have been produced by Cherenkov VHF radiation from a UHE neutrino shower in the Greenland ice sheet. After application of several background rejection methods, one event is left that requires further investigation.

Keywords: FORTE satellite, radio detection of ultra-high energy cosmic rays, neutrino

1. INTRODUCTION

The understanding of the ultra-high energy cosmic ray neutrinos (UHE ν) represents one of the most challenging problems of modern physics. To date a couple of tens of cosmic ray events, presumably protons, have been observed with energies in excess of 10^{20} eV. The origin of this flux represents a puzzle since above $\sim 5 \times 10^{19}$ eV the cosmic ray flux is expected to be reduced to Greisen-Zatsemin-Kuzmin (GZK)[1, 2] mechanism. The primary particles inevitably generate the UHE ν in cosmic beam dumps. The weakly interacting neutrinos, unlike gamma photons or protons, can reach us from distant sources and therefore are a possible invaluable instrument of high-energy astrophysics.

1.1. Electromagnetic Emission Mechanisms

In the early 1960's Askaryan[3] hypothesized a coherent electromagnetic emission mechanism in the radio frequency (RF) range from an electromagnetic shower, which is due to excess negative charge. However, it was later realized[4] that in extensive atmospheric showers (EAS) the dominant mechanism of emission is due to charge separation in geomagnetic field, which also can be understood in terms of coherent synchrotron emission.[5] Another potential coherent emission mechanism is the transition radiation when the shower crosses a dielectric interface, e.g., the ocean surface.

In the atmosphere, there is also an incoherent bremsstrahlung emission[6] mechanism that can potentially produce detectable radio emission. It is due to collisions of ionization electrons produced the shower with atmospheric molecules. The incoherent bremsstrahlung emission is suppressed at frequencies below the electron-atom collision frequency,[7] which makes difficult its practical use for detection in VHF radio frequency range.

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There is an interesting possibility of interaction of a cosmic ray shower with a thundercloud. The shower causes excess ionization that in a high electrostatic field can trigger an electrical breakdown (intracloud lightning), and control its development. This "frustrated" lightning can have characteristics that differentiate it from a regular intracloud lightning. For example, it is expected to have a channel made by the cosmic ray shower whose shape is different from a random-walk channel produced by regular lighning.

While UHECR-triggered lightning emission, incoherent bremsstrahlung of the ionization trail, and direct geomagnetic synchrotron radiation from the high-energy particles in the shower in the atmosphere can be used to detect UHE cosmic rays via radio methods, the non-atmospheric detection radio of a shower, e.g., in polar ice sheets can be used to differentiate a UHE neutrino.

The Askaryan mechanism for a neutrino shower in ice was further theoretically investigated by Zas *et al.*[8] Experimentally, the Cherenkov emission mechanism in solids was studied in accelerator beam tests,[9] and it was used for Goldstone Lunar Ultra-high energy neutrino Experiment (GLUE)[10, 11] and Radio Ice Cherenkov Experiment (RICE).[12, 13] The search for Cherenkov emission from polar ice sheets is the basis of a baloon experiment ANITA (Antarctic Impulsive Transient Antenna),[14] and we use the same mechanism as the basis of UHE ν search of this paper.

1.2. FORTE Satellite Characteristics

The FORTÉ (Fast On-Orbit Recording of Transient Events) satellite[15] was launched on August 29, 1997 into a 70° inclination, nearly circular orbit at 800 km. The satellite carries two broadband radio-frequency (RF) log-periodic dipole array antennas (LPA) that are orthogonal to each other and are mounted on the same boom pointing in the nadir direction. The antennas are connected to two radio receivers of 22 MHz bandwidth and center frequency tunable in 20–300 MHz range. Beside RF receivers, the satellite carries an Optical Lightning System (OLS) consisting of a charge-coupled device (CCD) imager and a fast broadband photometer. Although for this paper we do not report analysis of optical data, for future studies the presence of an optical instrument can be used to correlate RF and optical emissions.

The satellite recording system is triggered by a subset of 8 triggering subbands which are spaced at 2.5 MHz separations and are 1 MHz wide. The signal has to rise 14–20 dB above the noise to trigger. Typically, a trigger in 5 out of 8 subbands is required. The triggering level and algorithm can be programmed from the ground station. The multiple channels are needed for triggering because of the anthropogenic noise, such as TV and FM radio stations, or radars, which produce radio waves in narrow bands which by chance can coincide with a trigger subband. After the trigger, the RF data is digitized in a 12-bit Data Aquisition System (DAS) at 50 Msamples/s, and the typical record length is 0.4 ms. The FORTE database consists of over 4 million recorded events to date.

1.3. Possible UHE ν signatures in FORTE data

As an initial stage for a more thorough search, we considered the possibility of detection by FORTE of the Cherenkov radio emission from the UHE ν shower in polar ice sheets, since the radio emission process for these events has been studied in more detail, and is unaffected by geomagnetic or atmospheric complications. The possibility of FORTE to observe polar caps is limited due to its 70° inclination, therefore in this paper we study only the Greenland ice sheet. The results of this study can be used for other experiments, such as ANITA[14] which will specifically look for UHE ν signatures.

Other FORTE cosmic ray signatures would include the "frustrated" lightning initiated by a cosmic ray shower, and incoherent bremsstrahlung. These mechanisms are also the basis of our current and future research, but not the subject of this paper.

2. RESULTS ON CHERENKOV EMISSION FROM GREENLAND ICE

As a first stage in the analysis of FORTE data, we considered the possibility of the Cherenkov emission from a shower initiated by a UHE ν in the Greenland ice sheet.

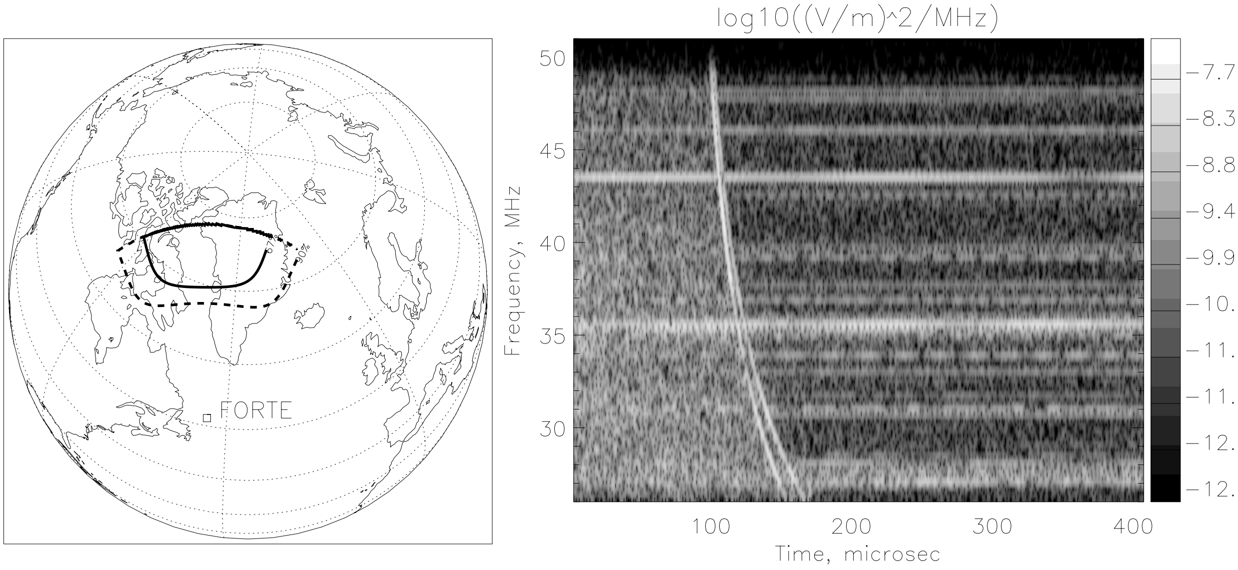

Figure 1. An example of a highly-polarized impulsive event detected by FORTE. The confidence levels for event location 67% and 90% determined using equation (1) are shown in the map. The spectrogram shows the dispersion of the pulse in ionosphere and splitting due to Faraday rotation in geomagnetic field. The horizontal lines are due to anthropogenic noise (TV and FM radio stations).

2.1. Geographic location of FORTE events

The geographic location of the signal source can be done using the dispersion of the short electromagnetic pulse in HF range going through ionosphere. Two important parameters that can be used in geolocation of the source can be determined from the data from a single FORTE antenna. The first parameter is the total electron content (TEC) along the line-of-site between the source and the satellite. It is proportional to the group time delay, which has f^{-2} frequency dependence.[16] The second parameter is determined from the Faraday rotation of a linearly polarized signal,[17] due to birefringence in magnetoactive ionospheric plasma. The Faraday rotation frequency turns out to be equal to the "parallel" electron gyrofrequency $f_{\|,ce} = eB_{\|}/m_e = f_{ce}\cos\theta$, where θ is the angle between the geomagnetic field $\mathbf{B}$ and the ray trajectory at the intersection with ionosphere. Both frequency-dependent delay and frequency splitting due to Faraday rotation are well seen in Figure 1. The Cherenkov radio emission is expected to be sufficiently short and linearly polarized, which enables us to make use of the second parameter for geographic location.

We calculate the probability distribution of the source location using Bayesian formula:

$$p(\{\lambda,\phi\}|\mathrm{TEC}, f_{\|,ce}) = Cp(\mathrm{TEC}|\{\lambda,\phi\})p(f_{\|,ce}|\{\lambda,\phi\}) \tag{1}$$

where $\{\lambda,\phi\}$ are the latitude and longitude of the source, $p(\mathrm{TEC}|\{\lambda,\phi\})$ and $p(f_{\|,ce}|\{\lambda,\phi\})$ are conditional probability distributions for the measured parameters given the location of the source, and C is a normalization constant. Here we assume that the measurements of parameters are independent, and the *a priori* distribution of the source location is uniform in the field of view of the satellite.

To estimate TEC between the source and the satellite (for given locations of both), we use the Chiu ionosphere model,[18] adapted to IDL from a FORTRAN source code found at NASA ionospheric models web site. This model gives electron density as a function of altitude for given geographic and geomagnetic coordinates, time of year, time of day and sunspot number. By integrating it over altitudes, we find the vertical TEC. To convert it to TEC along the line-of-sight, we must divide it by the cosine of the angle with the vertical. Due to the curvature of the Earth, this angle is not constant along the line-of-sight, and we make an approximation of taking this angle at the point where the line-of-sight intersects the maximum of the ionosphere (F-layer), at altitude of ∼300 km. The Chiu model, due to simplifying assumptions, does not account for stochastic day-to-day variability of the vertical electron content. The standard deviation can be as large as 20–25% from the monthly average conditions.[19] Thus, we assume a Gaussian probability distribution for $p(\mathrm{TEC}|\{\lambda, \phi\})$ with the center value calculated using Chiu model and variance of 25%.

The geomagnetic field is estimated from a simple dipole model.[19] The error is assumed to be 10% according to the estimates for experimental determination of $f_{\|,ce}$ from the RF waveform, in Figure 6 of Ref. 17. However, this uncertainty can be greater for signals that are only partially linearly polarized. Again, we use a Gaussian distribution for $p(f_{\|,ce}|\{\lambda, \phi\})$ with corresponding central value and the standard deviation of 10%.

2.2. Background rejection

The pulse generated by a UHE ν shower in ice is expected to be highly polarized and essentially band-limited up to a few GHz. In these aspects, it is similar to the electromagnetic emission from the "steps" in a stepped-leader lightning.[20] However, the pulses corresponding to lightning steps are accompanied by similar neighbors before and after, within a time interval from a fraction of a ms to ∼0.5 s. The signal grouping can thus be used to distinguish UHE ν signatures from most lightning events. Also, the lightning activity must be present, which is extremely rare in areas of the Earth covered by ice, and thus can be excluded using the method described in Section 2.1.

There is a special type of intracloud lightning which produces isolated events which are called compact intracloud discharges (CID).[21] However, these events are usually randomly polarized and have several-μs pulse durations.[20]

Another rejection method uses the fact that the lightning discharges occur above ground, and therefore there is a large probability for FORTE to detect also the signal reflected from the ground. This phenomenon is known as Trans-Ionospheric Pulse Pairs (TIPPs).[22–24] The presence of a second pulse, therefore, excludes the possibility of the signal to be a UHE ν signature.

Finally, an energy spectrum analysis can be performed. In this analysis, one can employ differences between Cherenkov radio emission spectrum[8] and the spectrum of a lightning discharge, which is expected to be the electromagnetic emission from streamers.

2.3. Expected FORTE Sensitivity

The typical natural background noise level in FORTE data is $\sim 10^{-12}$–10^{-11} $(\mathrm{V/m})^2/\mathrm{MHz}$ (as can be seen, e.g., from spectrograms in this paper's Figures). In a typical 1-MHz trigger subband this corresponds to RMS value of 1–3 μV/m. The trigger level is set 14–20 dB above the noise, giving the ability to trigger on impulsive signals with frequency domain values of 5–30 μV/m in each 1 MHz trigger subband.

We use the parametrization of Cherenkov emission in ice by a neutrino-generated shower[8] to estimate the sensitivity of FORTE to the UHE ν flux. The product of the electric field E of Cherenkov emission in ice and distance to observation point R is

$$RE = 1.1 \times 10^{-7} \frac{y\mathcal{E}_\nu}{1\ \mathrm{TeV}} \frac{f}{f_0}\ \mathrm{V/MHz} \tag{2}$$

where $\mathcal{E}_\nu$ is the neutrino energy, f is the electromagnetic wave frequency and $f_0 = 500$ MHz, and y is the fraction of energy going into the hadronic shower. The theoretical value for UHE ν is[25] $\langle y \rangle \approx 0.2$. We constrain ourselves to the hadronic part of the shower, because the leptonic part is elongated for ν_e due to Landau-Pomeranchuk-Migdal (LPM) effect[26–29] and for ν_μ, ν_τ due to the smallness of interaction cross-section. Thus the Cherenkov cone produced by leptonic shower is too narrow for detection. If we take the minimum distance equal to satellite alitude, 800 km, equation (2) gives $\mathcal{E}_{\nu,\min} = 1.5 \times 10^{22}$ eV and $\mathcal{E}_{\nu,\min} = 5 \times 10^{21}$ eV correspondingly for the two typical central frequencies of the FORTE, the low ($f = 38$ MHz) and high ($f = 130$ MHz) bands.

The flux sensitivity for $\mathcal{E}_\nu \geq \mathcal{E}_{\nu,\min}$ is

$$F = (V_{\mathrm{eff}} N_{\mathrm{nuc}} \sigma \Omega T)^{-1} \tag{3}$$

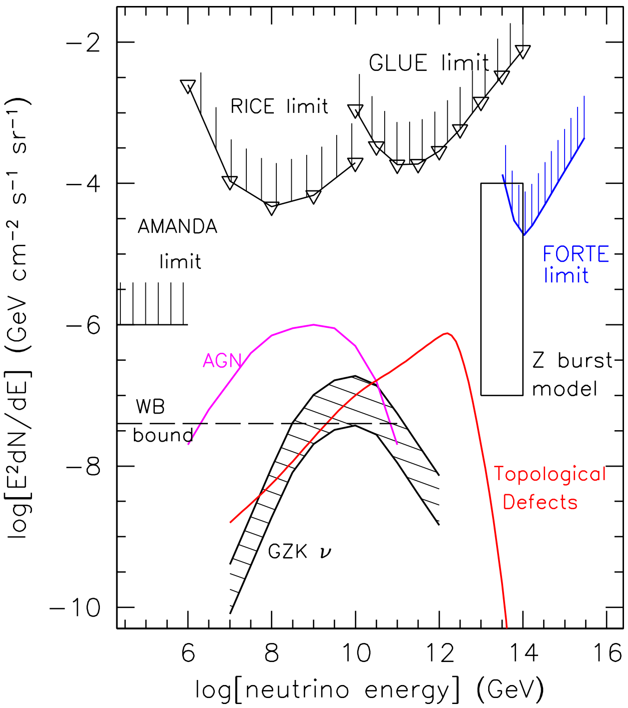

Figure 2. The estimated minimum UHE ν flux detectable by FORTE using Greenland ice sheet.

where V_{eff} is the effective detector volume, N_{nuc} is the nucleon density, σ is the theoretical neutrino-nucleon interaction cross-section,[30] $\Omega \approx 2\pi(2.4^\circ f_0/f)\sin\theta_c$ is the solid angle of Cherenkov emission,[8] and T is the observation time. The area of the Greenland's ice sheet is 1.8×10^6 km^2, and the depth is $\sim$3 km at the peak. However, the available depth is limited by RF losses[31] to 1 km. Thus we assume the available volume of Greenland ice to be $V_{\text{eff}} \approx 1.8 \times 10^6$ km^3. The time T is the total time when the satellite is close enough to see the events in the period of observation from September 1997 to December 1999. It depends on the neutrino energy, because the electromagnetic emission level depends on it. The observation time is further reduced by the fact that RF triggering system is not switched on all the time. This time is estimated to be at least $\sim$6% of time in orbit.

The results of our estimate for $f = 38$ MHz, along with limits of other experiments,[10–13, 32] are plotted in Figure 2. It also takes into account the decrease of the flux of upward neutrinos at higher energies as they get absorbed by the Earth.

2.4. Results

We searched for events recorded while FORTE was inside a circle of radius of 20° with a center at 70°N, 40°W, in time period from the start of FORTE in September 1997 to December 1999, when both 22-MHz-bandwidth receivers were lost.[33] We estimate that the satellite spent a total of 38 days inside this circle, with at least $\sim$6% of it being the time in trigger mode. We found a total of 2523 events. From these, only 77 are highly polarized. These 77 events can be geolocated using both parameters described in Section 2.1, i.e. Of these, only 16 events have intersection of the 90% confidence level with Greenland's ice sheet. Out of the remaining 16 events, 11 are rejected for being a TIPP, a pulse pair with a ground reflection that testifies the origin location above ground. An example of a rejected TIPP event is shown in Figure 3. Another two events were rejected because of the presence of a precursor before the pulse, which is characteristic of certain type of lightning and cannot be present in a neutrino shower signal. An example of such event is shown in Figure 1.

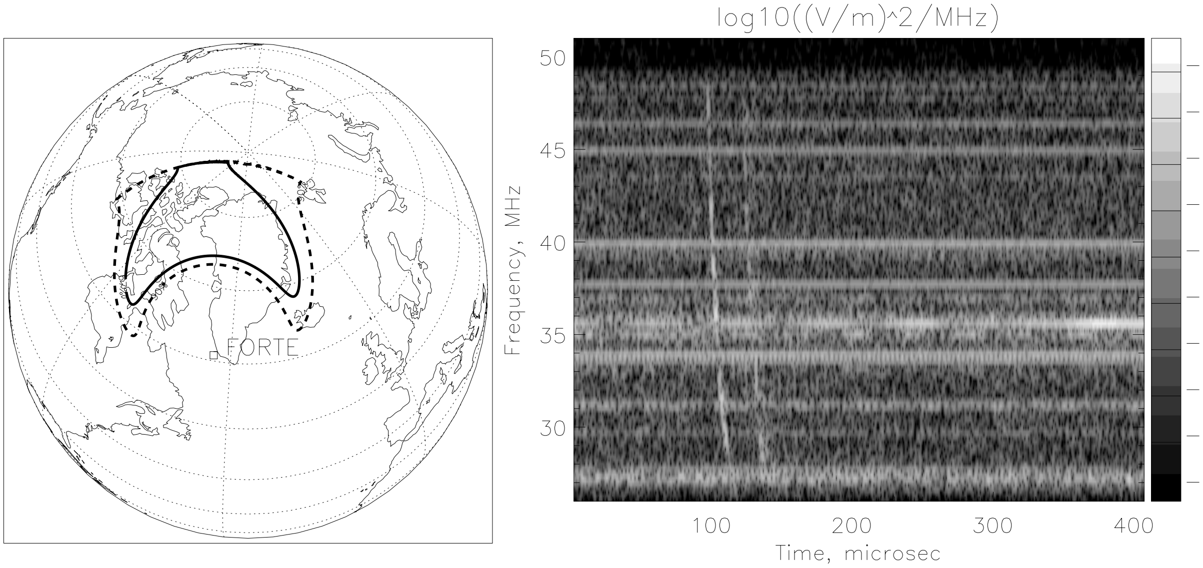

Figure 3. The confidence levels of 67% and 90% for geographic location and a spectrogram of an example event. This event that cannot be caused by a neutrino shower in ice because of being a TIPP (a pulse pair).

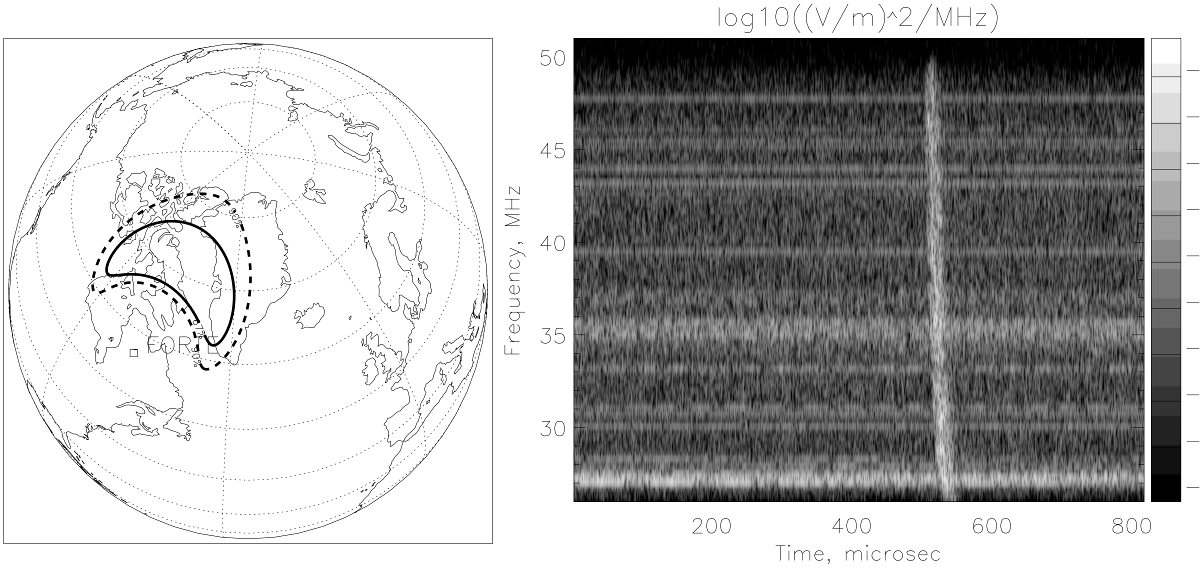

Figure 4. The confidence levels of 67% and 90% for geographic location and a spectrogram of an example event. This event cannot be generated by a neutrino due to its long duration ($\gtrsim$10 μs).

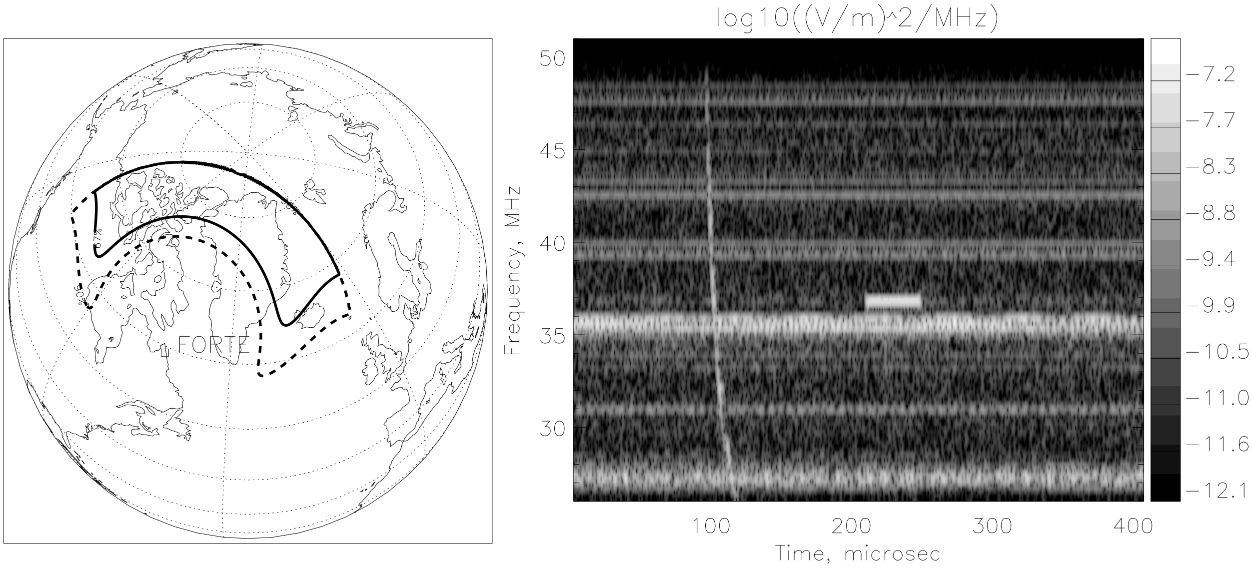

Figure 5. The confidence levels of 67% and 90% for geographic location and a spectrogram of an example event. A short horizontal streak in the spectrogram is due to anthropogenic noise (a radar). This event needs further consideration for being rejected as neutrino-generated. However, its nearest neighbor events were found at -1.4 ms and $+0.7$ ms, which makes it a probable lightning event.

Out of the remaining three events, one (shown in Figure 4) is rejected for its long duration ($\gtrsim 10\ \mu$s). The remaining two events are shown in Figures 5 and 6. The first of them has close neighbor events, which makes it a probable part of a stepped-leader process in a lightning. The neighbors of the second event are not very close, but it still can be a lightning event. At this point, we have to use other methods for the analysis, such as the differentiation according to the pulse energy spectrum.

3. CONCLUSIONS

We performed a search of UHE ν RF signatures due to Askaryan emission in the Greenland ice sheet, using existing FORTE satellite event database. All events but one have been rejected using algorithms described in this paper.

As we see from Figure 2, if we find a way to reject these events, our estimate of the sensitivity of the described FORTE experiment is such that the results can confirm or refute some regions of parameters of the Z_0 burst model.[34, 35] This result is very preliminary due to crudeness of approximations used to derive these limits, and a better estimate of sensitivity will be available in the future. Other models plotted are AGN production,[36] gamma-ray bursts[37] (marked as WB bound), GZK mechanism (from cosmic ray intaraction with cosmic microwave background)[38] and decay of topological defects.[39, 40]

In the future, we plan to continue a search of UHE cosmic ray signatures in FORTE database which are due to other emission mechanisms described in the Introduction.

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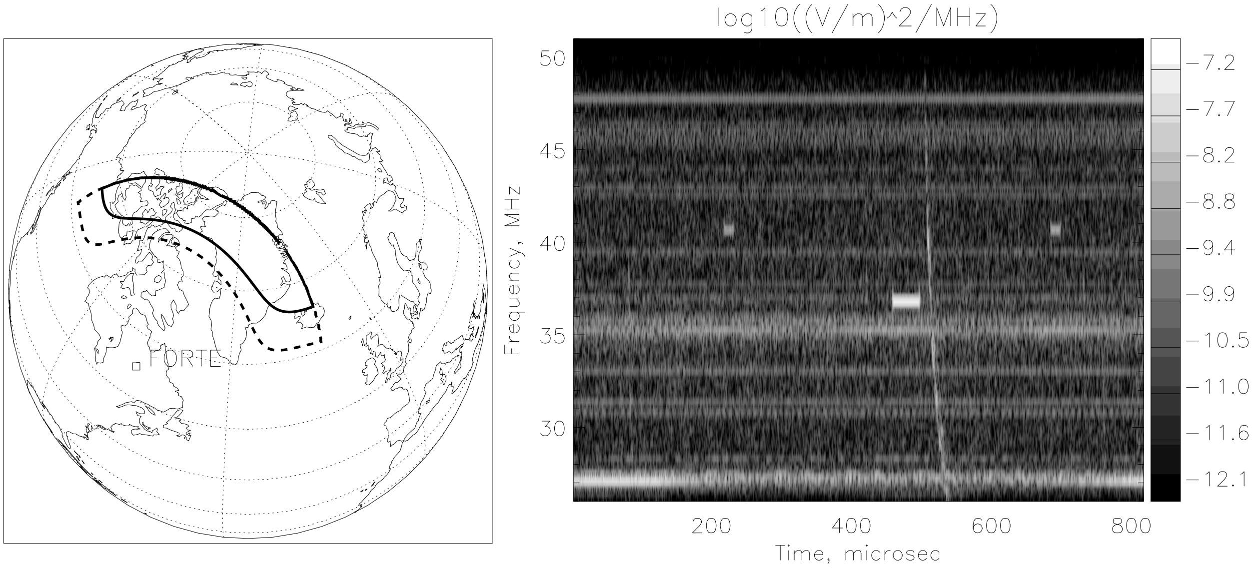

Figure 6. The confidence levels of 67% and 90% for geographic location and a spectrogram of an example event. Its nearest neighbors were found at −0.27 s and +5.55 s. This event needs further consideration for being rejected as neutrino-generated.

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