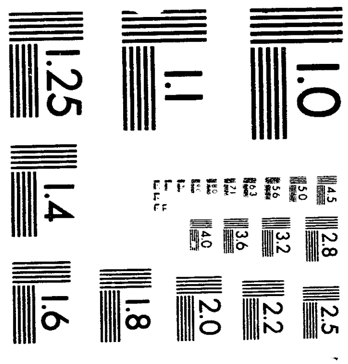
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MUSIC for Localization of Thunderstorm Cells

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Abstract

Lightning represents an event detectable optically, electrically, and acoustically, and several systems are already in place to monitor such activity. Unfortunately, such detection of lightning can occur too late, since operations need to be protected in advance of the first lightning strike. Additionally, the bolt itself can traverse several kilometers before striking the ground, leaving a large region of uncertainty as to the center of the storm and its possible strike regions. NASA Kennedy Space Center has in place an array of electric field mills that monitor the (effectively) DC electric field. Prior to the first lightning strike, the surface electric fields rise as the storm generator within a thundercloud begins charging. Extending methods we developed for an analogous source localization problem in magnetoencephalography, we present Cramer-Rao lower bounds and MUSIC scans for fitting a point-charge source model to the electric field mill data. Such techniques can allow for the identification and localization of charge centers in cloud structures.

1.0 Introduction

Lightning represents an event detectable optically, electrically, and acoustically, and several systems are already in place to monitor such activity. Unfortunately, such detection of a lightning event can occur too late, since many outdoor operations need to be protected before the lightning strikes. Additionally, the bolt itself can traverse several kilometers before striking the ground, leaving a large region of uncertainty as to the center of the storm and its possible strike regions. NASA Kennedy Space Center (KSC) and sites in New Mexico (two of the United States most active thunderstorm regions) have in place arrays of electric field mill sensors that monitor the (effectively) DC electric field. Prior to the first lightning strike, the surface electric fields rise dramatically as the storm generator within a thundercloud begins charging. Surface contours generated from these arrays can give indications of the storm centers, but interpretation in real-time by operations personnel can be difficult. For example, NASA's operational guidelines are simply to halt activities if any contour line breaks 1000 Volts/meter. However, non-threatening conditions such as ground fog and sea spray can also generate such fields, and operations are needlessly halted.

There is a pressing need for new analysis techniques for efficient and effective interpretation of this quasi-static electric field signal. We have been developing just such techniques for an analogous problem of source localization in human brain responses from the magnetoencephalogram (MEG) [1]. These MEG techniques are based on an adaptation of MUSIC, an algorithm originally developed for RF direction finding [2]. We have adapted this MEG research to the thunderstorm localization problem and applied our technique to data from the KSC field mill array.

2.0 Background

Figure 1 displays a photograph of one of the older field mills in use at KSC. KSC has begun a program to replace these older field mills with a more modern version, but the physical measurement concept remains the same. A spinning metal rotor alternatingly exposes and covers stationary metal plates (the spinning blade "mills" the field). Charges alternatingly accumulate in either the stator or rotor plates, and the sensor monitors the charge movement, which is proportional to the electric field. This older version transmitted the signal over analog land-lines to a central digitizing site; the modern mills digitize at the sensor before transmission over land-lines. Figure 2 shows the positions of the 31 field mills spread throughout the Cape Canaveral area.

The data received at the 31 electric field mills are formed into a spatiotemporal data matrix. Figure 3 displays the response of two selected mills over a time interval spanning the approach and then decline of a thunderstorm. Figure 4 displays the overlay of all mills in this same interval, a period of about four hours. Some of the key features in a thunderstorm are the onset of electrification, lightning activity, then end of storm oscillations (EOSO), during

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FIGURE 1. Electric Field Mill. This older model is being upgraded to an inverted version, which better shields the sensor from environmental conditions.

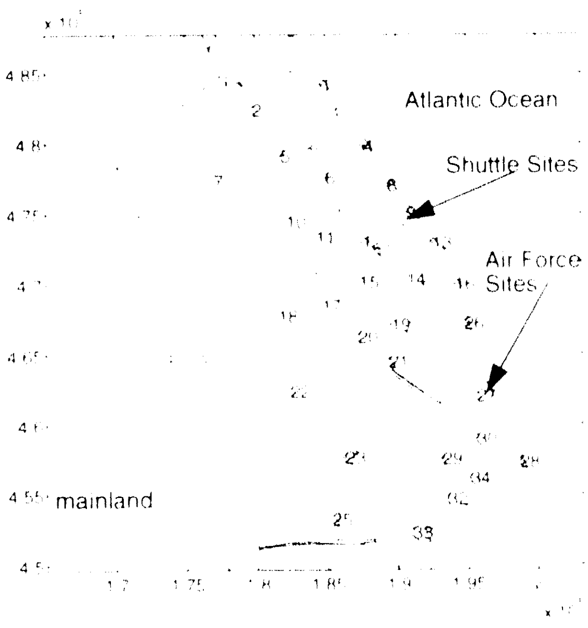

FIGURE 2. Locations of field mills throughout the Cape Canaveral area. The 31 sensors are numbered from 1 to 34, with some sensor numbers retired.

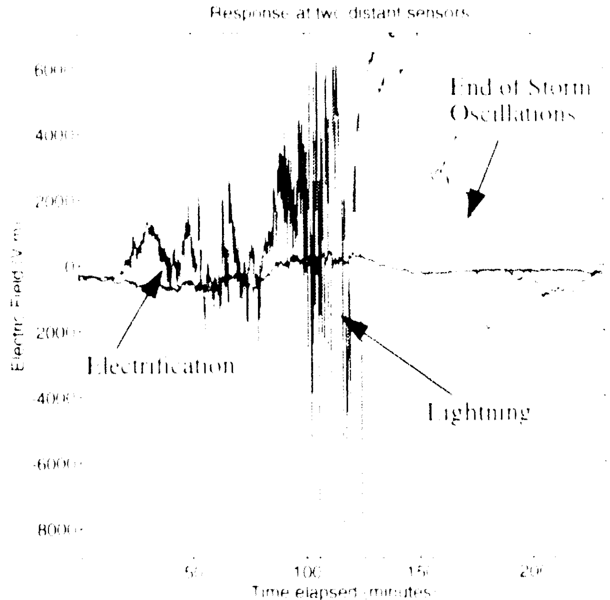

FIGURE 3. Two selected responses of field mill sensors to thunderstorm activity. The larger response is from a sensor adjacent a storm cell. The smaller response was from a sensor roughly 15 km distant.

which little lightning activity is observed as the electric fields decrease in a somewhat oscillatory manner.

3.0 Cramer-Rao Lower Bounds

In time regions before the first strike and then between the lightning strikes, the thunderstorm is modeled as a simple point charge above a reflecting ground plane. Using this model, we calculated Cramer-Rao lower bounds for the KSC array, to determine the suitably of the array pattern in localizing sources. We adapted our approach from the MEG problem [3], which was in turn an adaptation of the work of [4].

Figure 5 and Figure 6 display a map of Cape Canaveral, with sensor locations indicated by a plus "+". Overlaid on the maps are the one standard deviation error contours (in meters) for the location of a single point charge located at an altitude of six kilometers. The source intensity was assumed to be 10 Coulombs, and the noise at each sensor was assumed to be 100 volts/meter RMS. Figure 5 displays the scalar error in the horizontal plane, and Figure 6 displays the error in locating the altitude. Here the two error figures are comparable, but in many situations the altitude has greater error than the horizontal location; hence, we generally separate the two analyses. We see in this situation excellent lower bounds within the KSC array, but the logarithmically drawn error curves indicate that the error rapidly rises outside of the array. Hence the array pattern is better suited for locating cells within the Cape, but its performance rapidly degrades if we try to use it for locating cells inland or offshore.

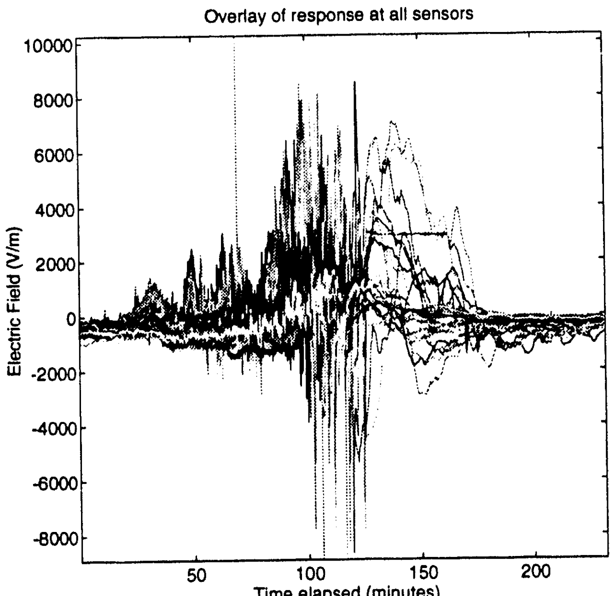

FIGURE 4. Overlay of all the sensors for the same storm observed in Figure 3.

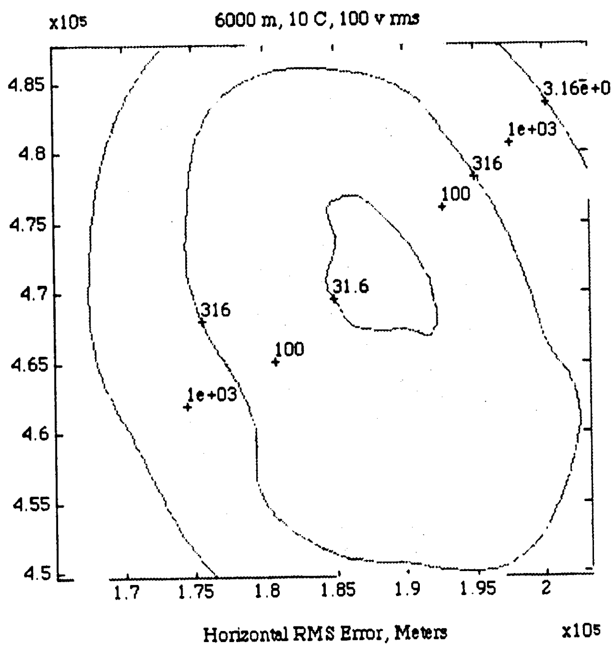

FIGURE 5. Cramer-Rao bounds for the NASA Kennedy Space Center - Cape Canaveral Air Force Station sensor array of 31 electric field mills. Source is 10 Coulombs point-charge 6 km over the Cape, with 100 volts/meter RMS noise assumed at each sensor. This figure is the scalar horizontal error.

4.0 Contour Generation

The existing KSC technique for processing the field mill data is to model the observed fields with 31 point charges placed 6 km directly over each sensor, then solve for the

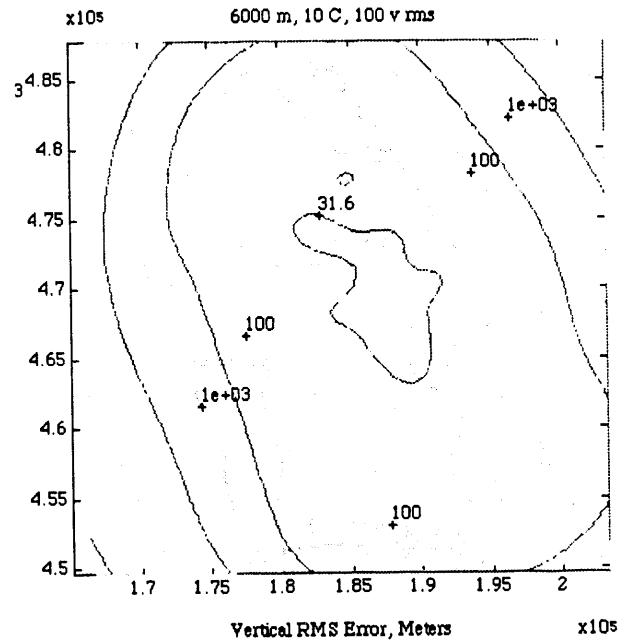

FIGURE 6. Error bounds for the altitude error. Contours are logarithmically drawn here and in Figure 5, and they represent the one standard deviation error bounds in meters.

unknown charges. These 31 charges form a relatively well-behaved exactly constrained system of 31 equations. Once the inverse is found, these 31 solutions are then used in a forward calculation over a regular grid projected onto the Cape surface, in order to effectively estimate the fields everywhere at the Earth's surface. This estimation is then used to generate contour lines on the earth's surface.

This model has the benefit that the total transformational matrix can be calculated once off-line, then applied easily in real-time as data "snapshots" from the array become available; however, this model does suffer from sensitivities to relatively small perturbations in some sensors. Additionally, some of the apparent field patterns can appear quite contrived, apparently indicating multiple storm sources that do not coincide with other expert knowledge and modalities, such as weather radar. This model, however, has been in use for two decades at KSC, and a heuristic interpretation of its output has been acquired by KSC personnel. Thus this method of contour generation will be used as a comparison test against the Thunderstorm MUSIC.

5.0 Thunderstorm MUSIC

The sensors are recording a quasi-static electric field signal, so no time-of-arrival information among sensors is available. As in the MEG problem, we instead exploit the near-field intensity of the signal and the signal's assumed

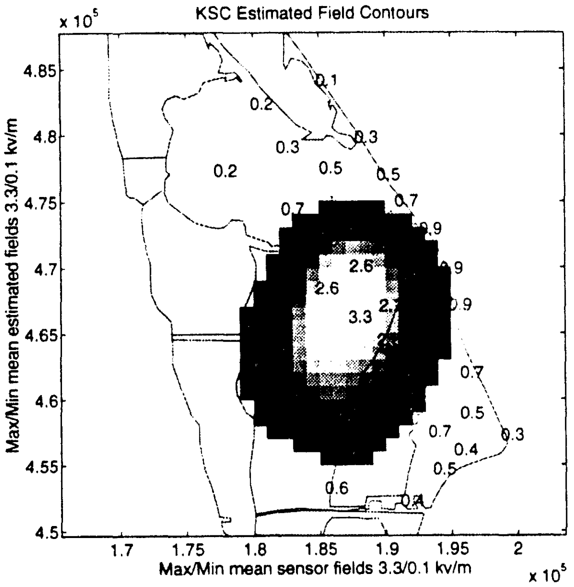

FIGURE 7. Contour generation from KSC Model for two simulated sources. Compare with Figure 8.

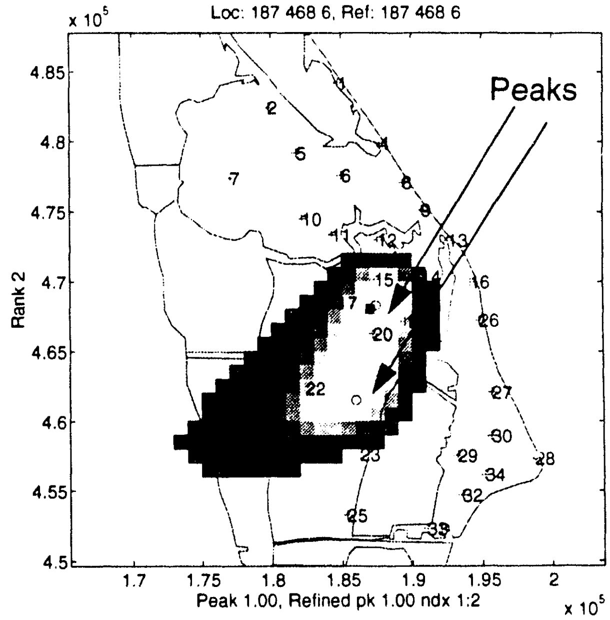

FIGURE 8. MUSIC images for two source simulation. Peaks occur at proper locations.

algebraic independence from other sources. The matrix is decomposed into signal and noise subspaces through conventional eigendecomposition approaches. An array manifold is formed for the point charge model over a conducting plane and scanned in three dimensions through the signal subspace, looking for intersections of the model and data spaces. The metric recorded at each point is the primary cosine of the angle between the model and signal subspace, such that unity indicates a perfect intersection of the primary vectors [5]. The observed rank of the signal subspace is typically less than 5.

In spite of this oversimplification of the thunderstorm model, the point-charge results are quite promising. We present a simulation and a data example to illustrate the potential of the thunderstorm MUSIC in processing KSC field mill data. Figure 7 and Figure 8 present the KSC contour model and the results of a MUSIC scan for a two source equal intensity simulation. The contours were generated from the average observed field, while the MUSIC image was generated from a rank 2 analysis of the same interval. Only the field values above 1 kv/m were imaged in the KSC model, while only MUSIC peaks above 0.9 were imaged. We see that the MUSIC scan correctly identifies the two peaks, while the KSC model results in an overall blur.

Figure 9 displays a 200 second time interval during a thunderstorm recorded on August 5, 1991, during the CAPE program. The arrow indicates the region analyzed by both the KSC model and the Thunderstorm MUSIC. Figure 10 displays the contours from the KSC model, and Figure 11 displays the MUSIC image. The two results now disagree in the apparent location of the storm cell; however, the KSC model was observed to have a large variability in the apparent peak of the field as a function of time, while the MUSIC peak was relatively stationary. The MUSIC peak of 0.98 indicates a very good fit between the model and the rank 5 subspace. Unfortunately, "ground truth" is not readily available for this data set, and future efforts will focus on data sets where other corroborating modalities are available, such as weather radar and lightning detection systems.

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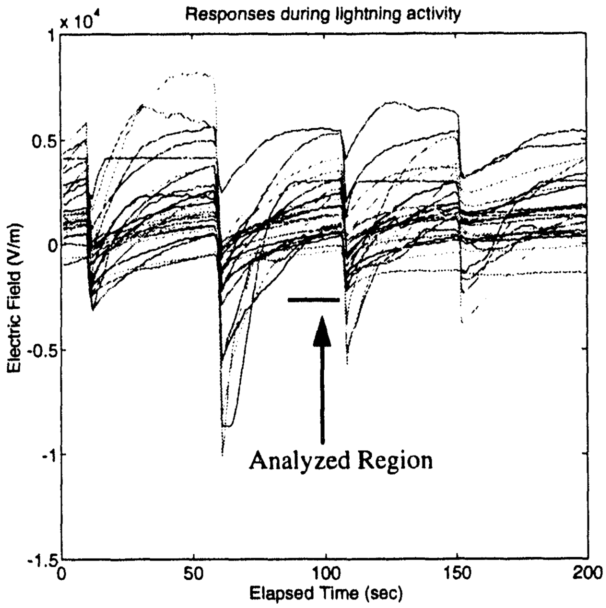

FIGURE 9. Overlay of sensor responses during 200 seconds of thunderstorm activity. Sharp changes are the response of the mills to lightning activity. The data are analyzed just prior to a lightning strike. Some other features to note are the apparent exponential clamping of the fields (a physical phenomenon), as well as some clipped sensor responses (a sensor problem).

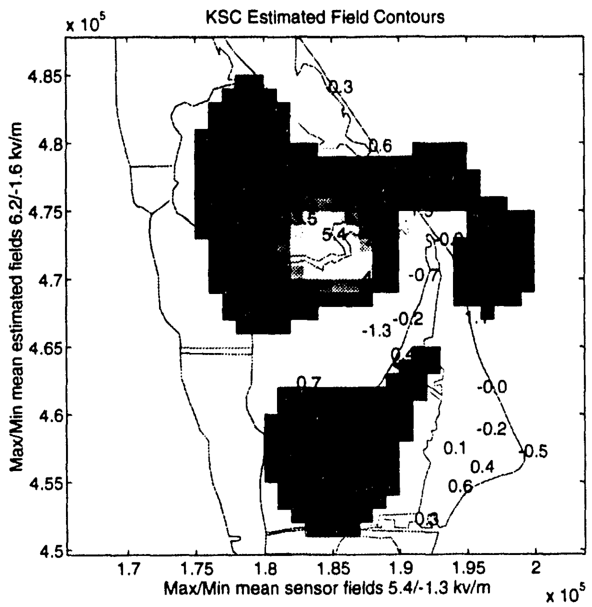

FIGURE 10. Estimated fields using KSC model for the data in Figure 9. Only fields above 1 kv/m were imaged. Compare with Figure 11

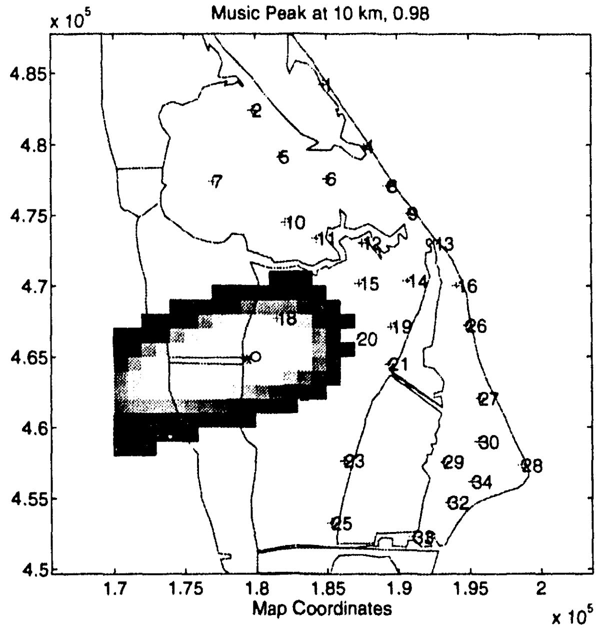

FIGURE 11. MUSIC Image for same period. This location was consistently found over many time intervals, unlike the estimated field peak in Figure 10;

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