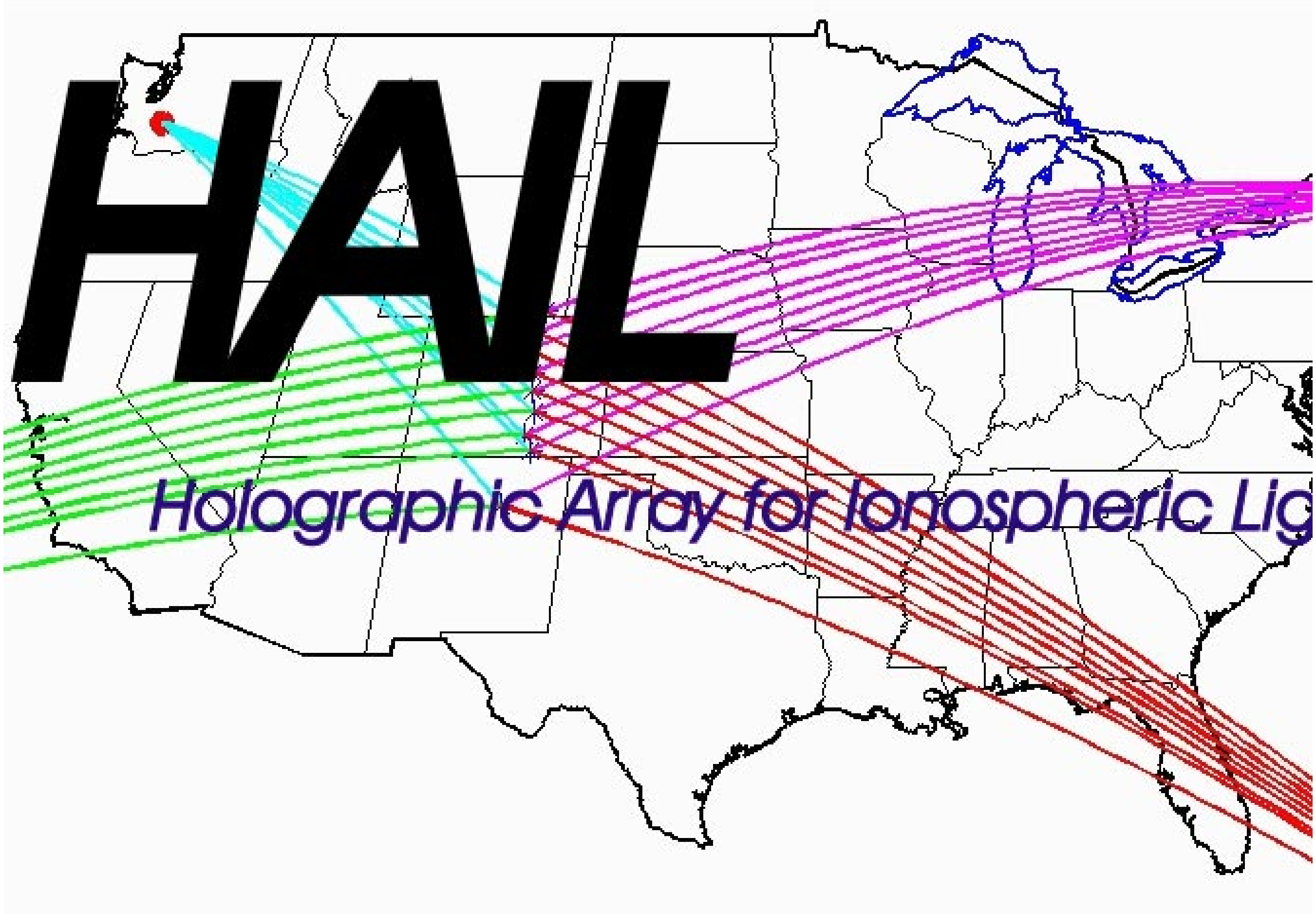


Umran S. Inan

Outline

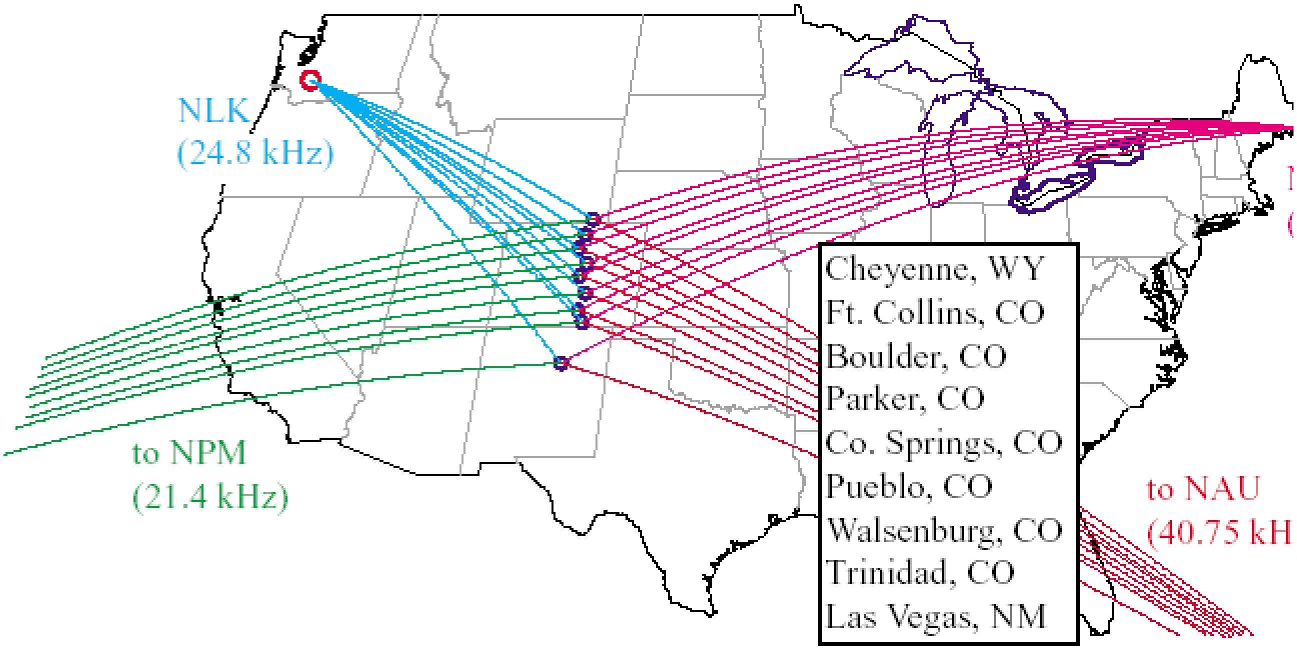
Bibliography

More on HAIL

A. INTRODUCTION

The HAIL project investigates:
(i) the physical nature of quiescent and transient changes in mesospheric/lower ionospheric (60 to 100 km altitude) conductivity produced by underlying electrified tropospheric thunderstorms and associated lightning activity (<15 km altitude)
(ii) effects of lightning discharges on the radiation belts. These questions address key topics in space physics research recommended for the next decade in the National Research Council 1995 report ‘A Science Strategy for Space Physics", namely, the middle and upper atmospheres and their coupling to regions above and below, specifically dealing with the electrodynamic coupling between the troposphere, mesosphere, and the lower ionosphere, driven by lightning and thunderstorm systems.

The primary tool to be used is the Holographic Array for Ionospheric Lightning (HAIL) (Figure 1), consisting of fully digital very low frequency (VLF) receivers deployed at nine high schools. HAIL provides sufficient spatial coverage of the active mid-western thunderstorm regions while facilitating holographic imaging [*Chen et al.*, 1996] of the spatial extent of ionospheric disturbances.



Direct electrodynamic coupling between lightning discharges and the mesosphere/lower ionosphere is evidenced by spectacular luminous optical emissions known as red sprites [*Franz et al.,* 1990; *Vaughan et al.,* 1992; *Sentman and Wescott*, 1993; *Lyons*, 1994; *Sentman et al.,* 1995; *Rairden and Mende,* 1995; *Boeck et al.,* 1995; *Lyons,* 1996; *Winckler et al.,* 1996], blue jets [*Wescott et al.,* 1995], and elves [*Boeck et al.,* 1992; *Fukunishi et al.,* 1996; *Inan et al.,* 1997], VLF signatures of rapid conductivity changes (referred to as early/fast VLF events) [*Inan et al.,* 1988, 1993, 1995, 1996a,b; *Dowden et al.,* 1994], and radar detection of transient ionization patches above a thunderstorm [*Roussel-Dupre and Blanc,* 1997].

Identified coupling mechanisms include the heating of the ambient electrons by lightning electromagnetic pulses (EMP) [*Inan et al.,* 1991, 1996b; *Taranenko et al.,* 1993a,b; *Milikh et al.,* 1995; *Rowland et al.,* 1995, 1996; *Glukhov and Inan,* 1996; *Fernsler and Rowland*, 1996; *Valdivia et al.*, 1997], by large quasi-electrostatic (QE) thundercloud fields [*Pasko et al.,* 1995, 1996a,b, 1997a,b, 1998a; *Boccippio et al.,* 1995; *Winckler et al.,* 1996; *Fernsler and Rowland*, 1996], and by runaway electron processes [*Bell et al.,* 1995; *Winckler et al.,* 1996; *Roussel-Dupre and Gurevich,* 1996; *Taranenko and Roussel-Dupre,* 1996; *Lehtinen et al.,* 1996; 1997]. However, the physical mechanism by which early/fast VLF signal perturbations are produced is under debate [*Inan et al.*, 1996c; *Dowden et al.*, 1996; *Rodger*, 1999]. Available evidence indicates that they may be due to quiescent heating of the lower ionosphere by thundercloud electric fields [*Inan et al.*, 1996a; *Johnson et al.*, 1999a]. Such heating, persisting throughout the many hours duration of a typical thunderstorm, may lead to infrared (4.3 μm) glow at 80–120 km altitudes [*Picard et al.*, 1997], and may affect the nighttime ionospheric density via temperature dependent changes recombination and attachment rates [*Rodriguez and Inan*, 1994], its global significance needs to be evaluated in view of the fact that ~2000 thunderstorms may be active at any given time [*Volland*, 1984].

Lightning discharges *indirectly* affect the lower ionosphere via precipitation of bursts of energetic (>50 keV) particles by whistler waves [*Inan et al.*, 1990, and references therein; *Voss et al.*, 1998]. VLF signatures of these lightning-induced electron precipitation (LEP) events exhibit onsets delayed (with respect to the causative lightning) by ~0.5–1 s (Figure 2b) [e.g., *Burgess and Inan*, 1993, and references therein]. Recent evidence indicates that LEP events may be occurring on a much wider scale than previously believed [*Lauben et al.*, 1999; *Johnson et al.*, 1999b, also see Figure 7], underscoring questions (Section B) concerning the role of thunderstorms in the global loss rates of radiation belts.

The target of our proposed investigation is the ‘ignorosphere’ (40-100 km altitudes) so named due to the difficulty of making systematic measurements. Subionospheric VLF provided the earliest evidence of *indirect* ionospheric effects of lightning discharges [*Helliwell et al.*, 1973; *Burgess and Inan*, 1993, and references therein]. During the 1980s, VLF remote sensing revealed the very first evidence of the *direct* disturbance of the nighttime lower ionosphere by lightning [*Inan et al.*, 1988 and references therein]. Since the serendipitous recording of the first video images of sprites [*Franz et al.*, 1990] and many others that followed [e.g., *Sentman and Wescott*, 1993; *Lyons*, 1994], the region above thunderstorms has reached a point where it is regularly observed by a range of optical sensors based on the ground (1995–98) and aircraft (1995,1998), and balloons (1999), typically during summer Sprites campaigns in the mid-western United States. Among the many techniques used, VLF remote sensing is particularly and uniquely suited for measuring conductivity in the lower ionosphere [*Seschrist*, 1974].

The program benefits from resource sharing with an ONR sponsored Stanford effort involving novel high-speed photometric [*Inan et al.*, 1997] and telescopic imaging [*Inan et al.*, 1998] of sprites and elves and VLF measurements [*Reising et al.*, 1999]. HAIL (Figure 1) was established with substantial contributions from the ONR grant, which also supports Stanford participation in annual Sprites campaigns conducted from Yucca Ridge, Colorado [e.g., *Reising et al.*, 1999] and Langmuir Laboratory, New Mexico [e.g., *Barrington-Leigh and Inan*, 1999]. Resource sharing will continue during the proposed program, as we implement carefully targeted extensions of the HAIL network (see Figures 4 and 8). The hardware costs for three of six VLF systems and the cost of a system to acquire commercial lightning data from the National Lightning Detection Network (NLDN) will be borne by the ONR program.

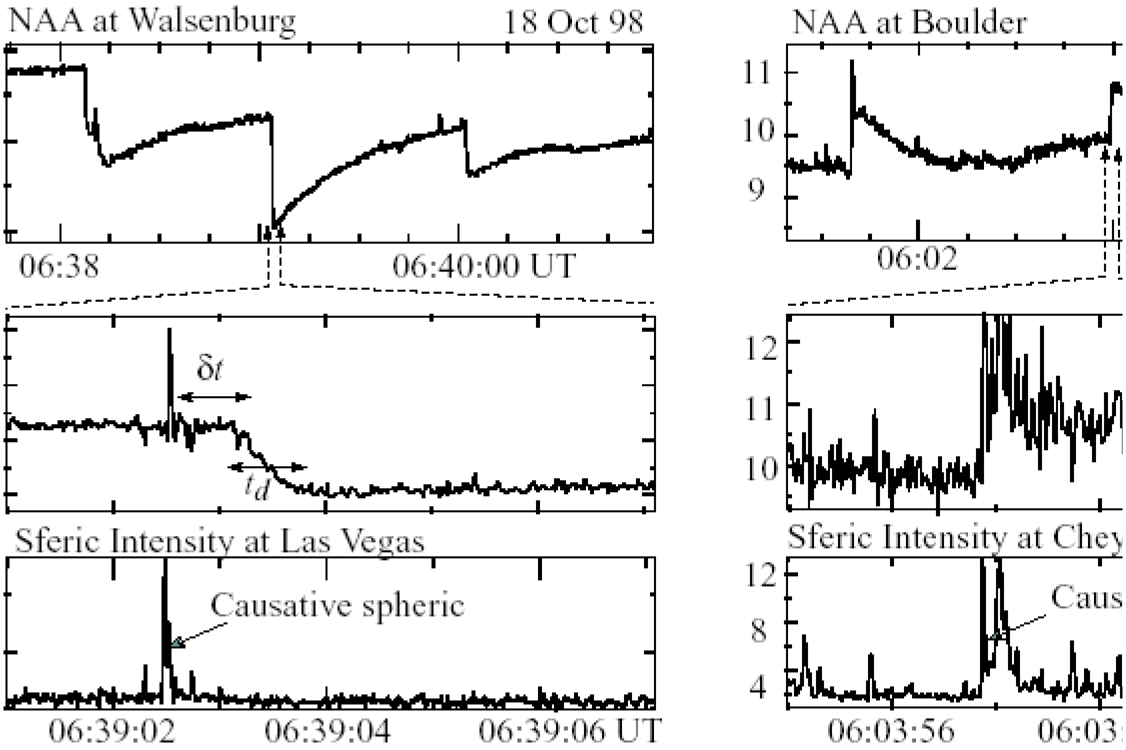
The proposed program provides substantial opportunities for scientific collaboration and educational outreach. In terms of collaborative investigations, the availability over the Internet of *all* of the data collected allows scientists at large to their own analyses in conjunction with other data (e.g., lightning location data or optical imaging data). In terms of educational outreach, our program is closely coupled at all levels with nine high schools constituting the HAIL array sites. During the past two years, the PI and his students have given more than 40 lectures (many in the classrooms) at these schools and have hosted (with AGU support) a number of teachers and students during Fall AGU meetings. At the Fort Collins high school, for example, we have had extremely fruitful interactions with the Technology teacher Mr. Russ Oliver, and the HAIL project is actually part of this school's official curriculum. We will continue to involve students and teachers from these institutions in all aspects of this program, including data analysis and interpretation. Since the data is available over the Internet, educational outreach possibilities are not just limited to the schools at the observation sites. As an example, teacher Ms. Lisa Matthews from Gadsden High School New Mexico visited Stanford during the Fall 1998 AGU meeting and has shown a keen interest in having her students work with the HAIL project.

B. SCIENTIFIC BACKGROUND

The two primary types of lightning-associated characteristic subionospheric VLF signal changes are shown in Figure 2. The continuous high time resolution (10 ms) data allowing unambigious identification of these two different event types. The scientific questions concerning each event class are discussed below, together with additional opportunities for quantification of ionospheric variability.

Fig. 2. Two primary types of lightning-associated VLF events. Left: Typical LEP VLF event,

with event onset delayed (from causative lightning, i.e., the impulsive radio atmospheric) by δt0.5–1 s, and with the onset duration t_d representing the duration of the precipitation burst. Right: Early/fast VLF events, with onset within 20 ms of the causative lightning (i.e., early δt<20 ms), and often fast (i.e., t_d<20 ms).



1. Thunderstorm Coupling to the Mesosphere and the Ionosphere - Early/fast VLF events

'Early/fast' VLF events exhibit a rapid onset (<20 ms, i.e., fast) followed by a relatively slow recovery (typically 10 to 100 s) and occur within 20 ms of a causative lightning discharge (i.e., early) [*Inan et al.,* 1993], as illustrated in Figure 2a. The underlying physical mechanism is under debate [*Inan et al.,* 1996c; *Rodger*, 1999], and may involve quiescent heating of the *D* region by thundercloud fields, with individual discharges leading to localized heating/cooling about the quiescent level [*Inan et al.,* 1996a], broad ionization regions produced by lightning-radiated EMP [*Dowden et al.,* 1996a] or ionization columns associated with Sprites [*Dowden et al.,* 1996b; *Rodger et al.*, 1998]. VLF scattering patterns of individual early/fast disturbances were recently measured directly with the HAIL array, revealing disturbed ionospheric regions with horizontal extents of 9030 km, with largely forward scattering patterns (15 dB beamwidths of <~30.) [*Johnson et al.*, 1999a].

Figure 3 shows two different episodes of early/fast events [*Johnson et al.*, 1999a], one of which was shown in expanded form in Figure 2a. The causative discharge, as identified by the National Lightning Detection Network (NLDN), is located nearest the HAIL paths with the largest perturbations. Between 05:00 and 05:30 UT on 2 August 1998 fourteen early/fast events (marked A,B,C,. . .,N in Figure 3) were observed at Pueblo (PU), with some also seen at the adjacent sites. The causative lightning discharges all lie 500 km to the east of HAIL within 50 km of the NAA–PU path. The average amplitude and phase (not shown) changes were respectively ~0.5 dB and ~1.. That perturbations are only observed at two HAIL sites indicates a largely forward scattering pattern with a 15 dB angular beamwidth of 18.. Between 06:00 and 06:30 UT on 15 August 1998, lightning activity existed along HAIL paths in Nebraska, with the events shown originating from lightning located near the north-east corner of Colorado within the circled region. Event O at 06:07:25 UT, shown in high resolution in the rightmost panel was typical of the sequence and perturbed the NAA–FC and NAA–BO signals with a 15 dB angular beamwidth of <~30..

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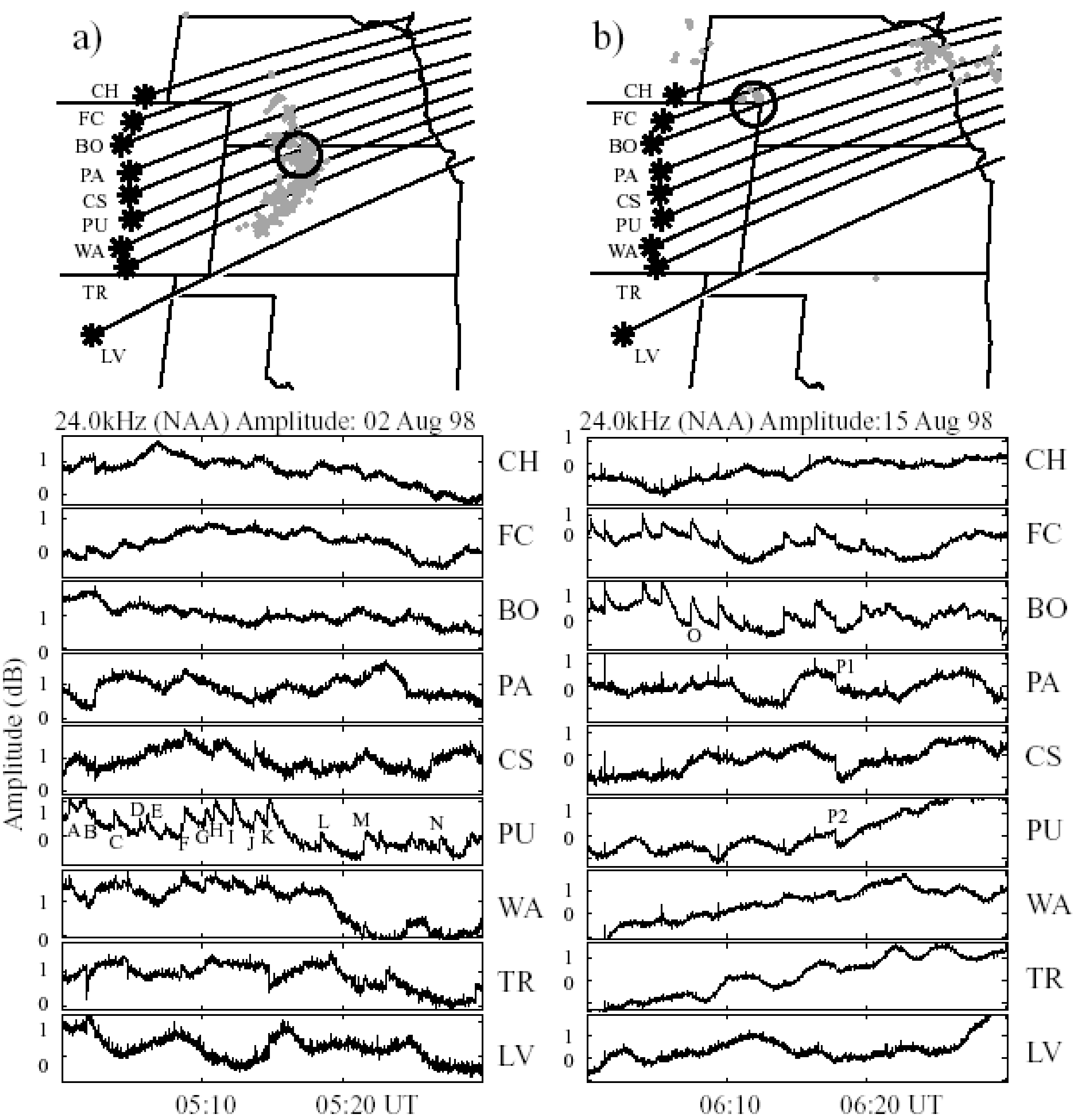

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The width of the main beam of the scattering pattern as projected along the HAIL array can be relatively wide [*Chen et al.*,1996] either for narrow disturbances (< 30 km) which scatter isotropically or for relatively large disturbances (> 500 km) which overlap more of the VLF paths. The calculated normalized scattering patterns for EventOare displayed in Figure 4 for disturbances of different Gaussian transverse profiles (i.e., $e^{-(r/a)2}$, where a is the disturbance radius). The disturbance with a=90 km hasa narrow main beam which fits the data better than the wide beam patterns associated with the larger (a=210 and 300 km) and smaller (a=30 km) disturbance widths. The comparison of the theory/data shown in Figure 4 also underscores the need to improve the spatial resolution of the holographic measurement, since data from two additional sites midway between the two sites on both sides of the peak would have allowed much better definition of the lateral extent of the disturbance. We propose to implement an extension of HAIL during the next two years by establishing two additional receiver sites at locations indicated by the red circles in Figure 4. Data from these additional sites should allow us to determine the tranverse shape of the disturbance, for example whether it is in the shape of a pill-box or has smoother edges such as a Gaussian profile. This determination will in turn illuminate the underlying physical mechanisms; for example, the quiescent heating mechanism [*Inan et al.*, 1996a] is expected to lead to a smooth variation in the lateral dimension, while we might expect sharp edges if these events involve VLF scattering from ionization columns formed by sprites or groups of sprites [*Rodger et al.*, 1998].

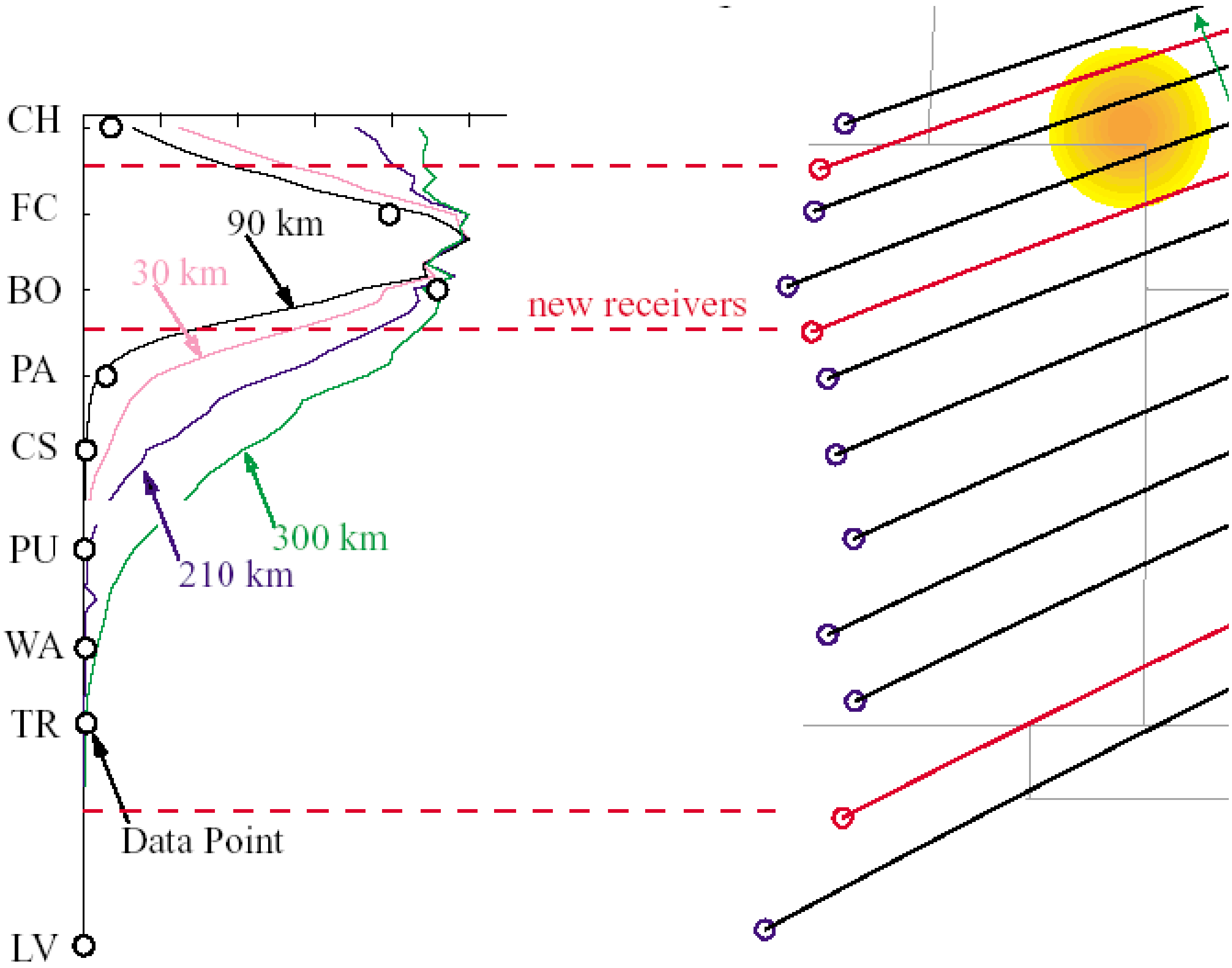
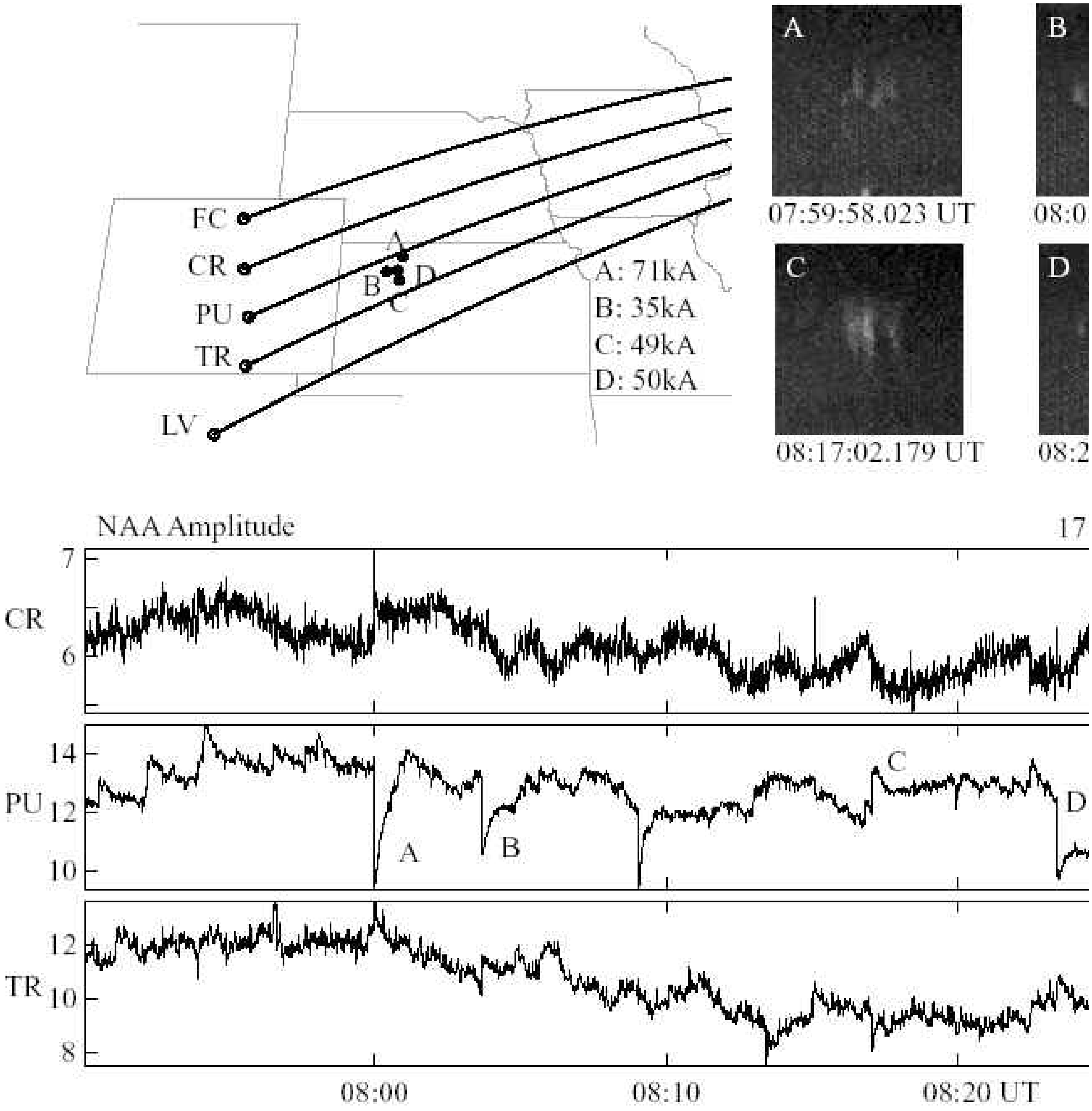


Fig. 4. Scattering pattern of Early/fast disturbances and proposed new observation sites. The pattern was calculated usi of VLF propagation and scattering with a conductivity profile having20%enhancement at 80km[*Johnson et al.*, 1999a].

It is not clear whether conductivity changes which lead to early/fast events occur due to the same processes that cause sprites and elves [*Dowden et al.*, 1996; *Inan et al.*, 1996c], although at least some VLF events occur simultaneously with sprites [*Inan et al.*, 1995; see Figure 5]. However, only a subset of early/fast events may be accompanied by visibly luminous sprites. Even when they occur together, the two phenomena may involve different physical mechanisms initiated by the same lightning discharge. Not all lightning discharges lead to early/fast VLF events, even if they occur near a VLF path and possess peak currents that are similar to or even higher than other discharges which cause events [*Inan et al.*, 1993]. In the cases of Figure 3, the peak current magnitudes of the correlated discharges ranged from



-24 to -64 kA and from +18 to +52 kA, whereas ten other discharges with >64 kA did not produced events, despite being located within 50 km of NAA–HAIL great circle paths. Comparison of HAIL data with broadband VLF radio atmospheric data indicate that lightning discharges which lead to early/fast VLF events may preferentially occur in clusters of tens to hundreds of sferics, as illustrated in Figure 6. Such sferics clusters signify the presence of multiple channels of horizontal intracloud dentritic lightning discharges which surround certain cloud-to-ground discharges, or which occur on their own [*Shao and Krehbiel*, 1996; *Johnson and Inan*, 1999]. With this background, the following scientific questions will be addressed in the context of the proposed program:

Questions:

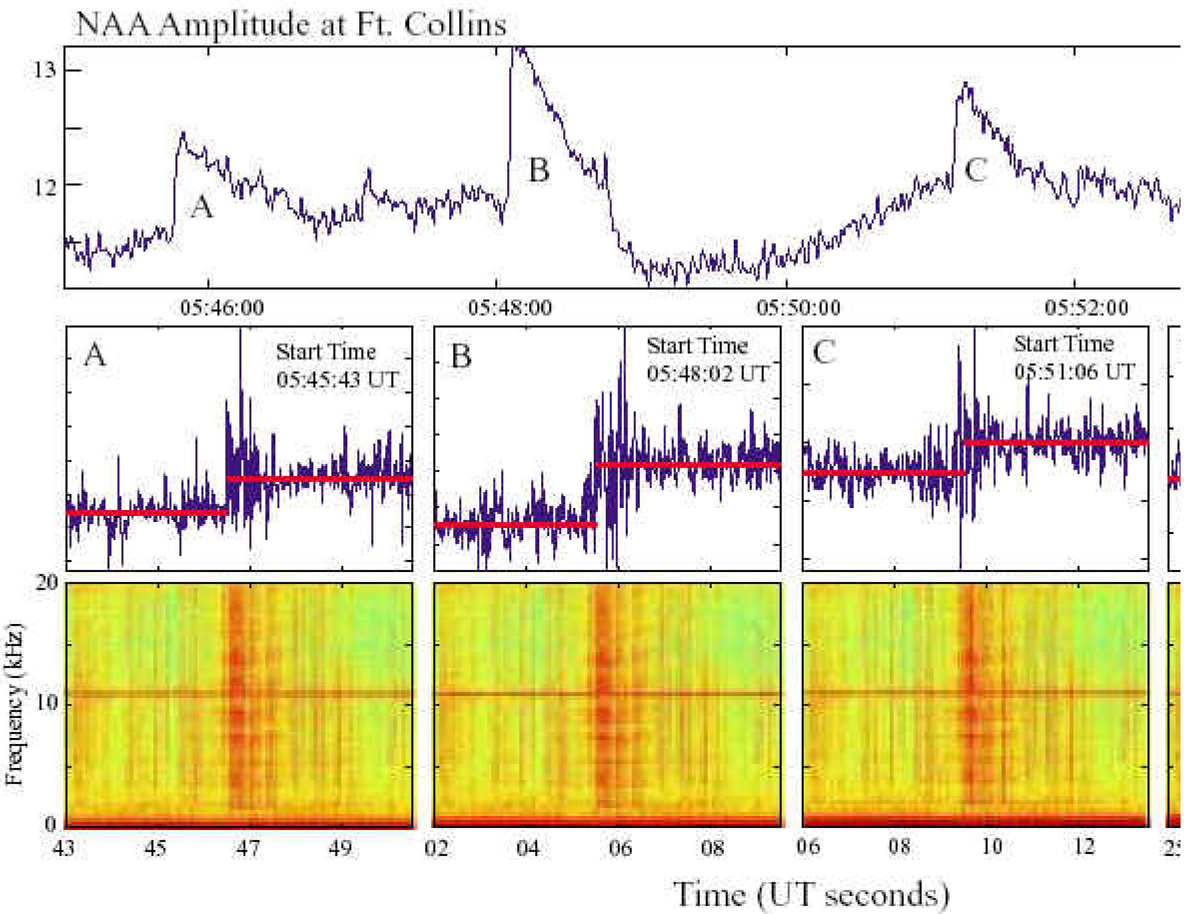
What is the transverse and altitude profile of ionospheric disturbances that cause early/fast VLF events? Are some types of thunderstorms or lightning flashes more likely to produce early/fast VLF perturbations than others? What fraction of lightning flashes lead to early/fast VLF events? How are early/fast events related to Sprites? What is the physical mechanism underlying early/fast VLF events?

Approach:

Addressing even the simplest of the questions (e.g., the occurrence statistics) require the acquisition of a substantial data base on early/fast events, which is facilitated by the high spatial resolution provided by HAIL. The mid-west U.S. region of coverage is appropriate in view of high lightning activity and also the opportunity to participate in annual Sprite campaigns, during which the HAIL VLF data can be readily compared with data from other sensors (e.g., video and photometric). HAIL VLF data is acquired on a continuous basis throughout the year in order to study seasonal variations and questions relating to dependence on thunderstorm and lightning type, and is made available to the scientific community over the Internet within 12 hours of acquisition so that some of the scientific questions (and others) can be pursued by interested colleagues. The quantitative interpretation of the HAIL data, for example to determine the lateral or the altitude profile of associated conductivity changes, will be based on the use of three dimensional VLF waveguide propagation and scattering models [*Poulsen et al.*, 1993a,b; *Lev-Tov et al.*, 1995; *Chen et al.*, 1995; *Johnson et al.*, 1999a]. Physical mechanisms underlying early/fast events will be investigated by comparing the measured profiles with predictions of theoretical lightning-ionosphere interaction models. Different models for electromagnetic [*Taranenko et al.*, 1993a; *Glukhov and Inan*, 1996], quasi-electrostatic [*Pasko et al.*, 1996a; 1998a], electrostatic [*Pasko et al.*, 1998b], and runaway electron processes [*Lehtinen et al.*, 1997] have been developed at Stanford and are thus directly available for quantitative comparison of individual cases.

Fig. 6. Early/fast events and sferics

clusters. Expanded records for all four events (A,B,C and D) show a cluster of sferics (vertical lines in the frequency-time spectrogram) in the vicinity of the event onsets.



2. Thunderstorm Coupling to the Radiation Belts-LEP VLF Events

Lightning-induced electron precipitation (LEP) is a means of loss of the radiation belt electrons caused by resonant whistler wave-particle interactions. Precipitation of individual bursts of energetic electrons in association with individual lightning discharges has been measured on satellites, rockets, and via VLF remote sensing of associated ionospheric disturbances [*Voss et al.,* 1998 and associated references therein]. Previous theoretical [e.g., *Inan et al.,* 1989] and experimental [e.g., *Burgess and Inan,* 1993] work on the LEP phenomena has emphasized interactions with 'ducted' whistler waves which propagate in field-aligned ducts of enhanced ionization. The first quantitative model of the precipitation of bursts of energetic electrons by oblique (non-ducted) whistlers launched by individual lightning flashes has only recently been realized [*Lauben et al.,* 1999]. LEP VLF events induced by ducted whistlers exhibit onset delays and duration which are quantized by the required presence of a magnetospheric duct [*Inan and Carpenter*, 1986]. In contrast, scattering by obliquely propagating whistlers (which illuminate a wide range of field lines) leads to precipitation over an extended region, with a continuum of onset delays and durations as a function of latitude [*Lauben et al.,* 1999].

HAIL data have provided the first direct experimental confirmation of several important predictions of the *Lauben et al.* [1999] model in HAIL data [*Johnson et al.*, 1999b]: (i) bursts of electrons precipitated from different field lines arrive at the ionosphere with onset delays steadily increasing with increasing *L*-value, (ii) ionospheric regions disturbed in individual events may have spatial extents of up to ~1000 km and are poleward-displaced in latitude with respect to the causative flash, and (iii) that the peak precipitation fluxes induced by oblique whistlers are at least as intense as those produced by ducted waves. Since most of the wave energy launched into the magnetosphere propagates in the nonducted mode [e.g., *Edgar*, 1972], these new observations suggest that the LEP process is very likely to be a significant loss process for radiation belt electrons on a global scale. The salient results of *Johnson et al.* [1999b] are summarized in Figure 7, showing a five minute sequence of LEP VLF amplitude events, marked A–D, observed on the NAA signal. An expanded record of Event 'B' was shown in Figure 2. Similar repeated (>10 per hour) sequences of clearly identifiable (>0.5 dB changes) LEP VLF events were observed on the NAA signal on six days during October 1998. Using NLDN data, events A–D were unambiguously associated with lightning discharges occurring near Austin, Texas.

The perturbation of all of the NAA–HAIL paths and the upper five NAU–HAIL paths (not shown) indicate a disturbance much larger than the ~90 km in extent of the early/fast event (Figure 4). The absence of events on the lower four NAU–HAIL paths (despite being closer to the causative discharge), indicates a poleward-displaced precipitation zone, as predicted by *Lauben et al.* [1999]. Astriking feature of the data is the steadily increasing onset delay with increasing geomagnetic latitude of the affected paths, as is evident from the superposed (after proper filtering and normalization) display of the VLF signatures observed on different NAA–HAIL paths (Figure 7). The distinctly different onset delays indicate that the various different VLF paths respond to ionospheric disturbance regions that become active at different times. Thus, the VLF amplitude changes seen on the different paths *cannot* be due to a single localized ionospheric disturbance, as produced (for example) near the footprint of a whistler-mode duct. Instead, the continuum of onset delays steadily increasing with geomagnetic latitude agrees remarkably well with the predictions of *Lauben et al.* [1999]. The precipitation region calculated with the *Lauben et al.* [1999] model for a source lightning discharge near Austin Texas also agrees remarkably well with the layout of the perturbed VLF paths (Figure 7) as does the energy-flux deposition as a function of time and latitude, describing the manner in which the different parts of the precipitation region appear in time. Although LEP has been known to occur for some time, its potential role on a global scale has only recently been quantified with estimates indicating that losses of radiation belt particles by lightning induced whistler waves is significant in the *L*-shell range $1.8 < L < 2.6$ [*Abel and Thorne*, 1998a,b].

These estimates did not have the benefit of the new discovery of regular precipitation induced by nonducted (oblique) whistlers, which greatly enhance the potential global role of the LEP process. The present HAIL configuration is well suited to capture LEP events occurring in this *L*-shell range, and we propose to extend the array by adding three more sites to increase its coverage up to*L*4, as illustrated in Figure 8. In this context, our goal is not to enhance the spatial resolution as is required for early/fast events (Figure 4), but rather to simply provide an ability to define the latitude extent of events and to capture LEP regions excited by both low latitude (e.g., Texas) and mid latitude (e.g., Kansas) lightning. With this background, the following scientific questions will be addressed in the context of the proposed program:

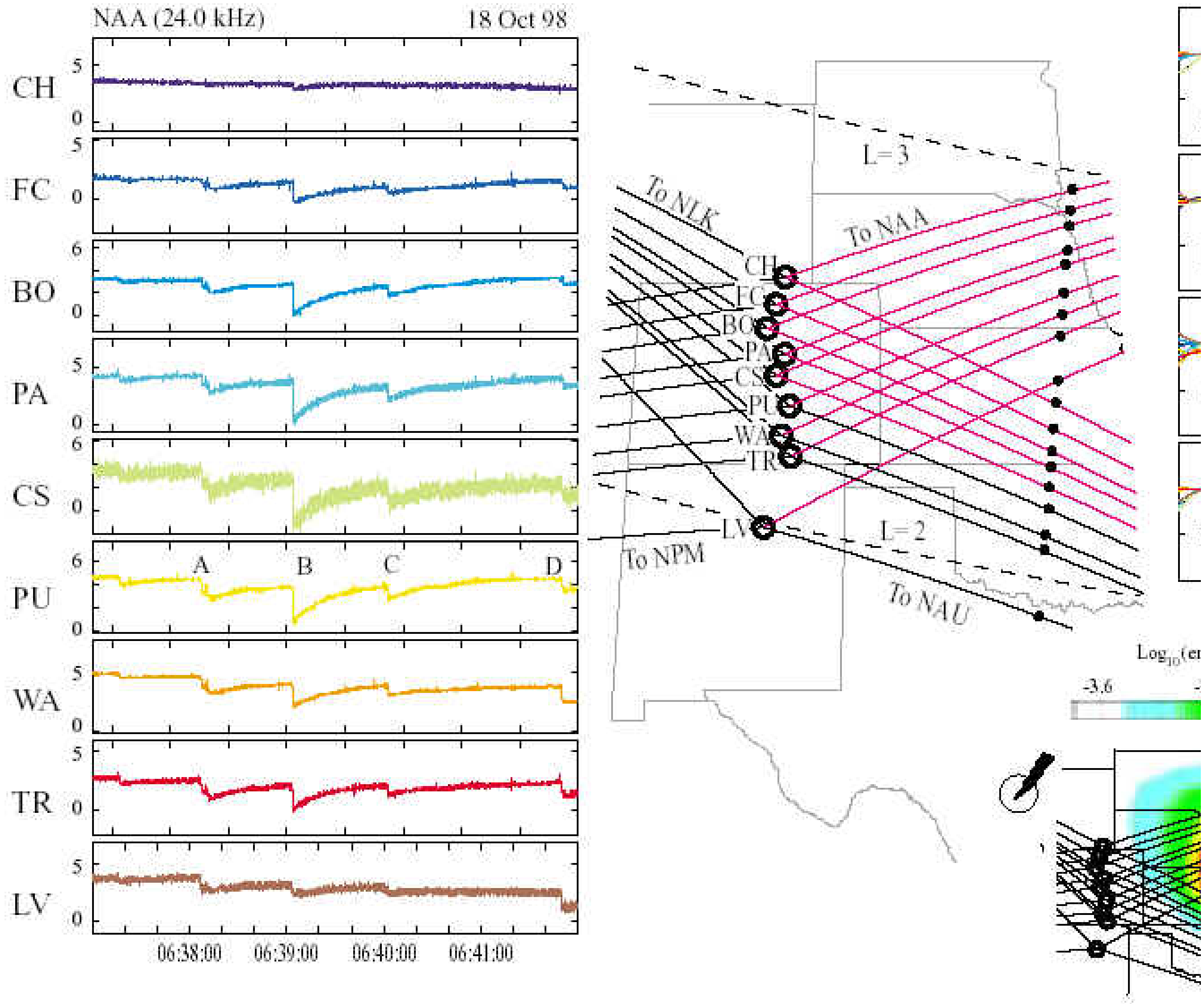


Fig. 7. HAIL evidence for electron precipitation induced by oblique (non-ductoed) whistlerwaves from lightning. Even simultaneously on the left hand panels, in fact exhibit onset delays which steadily increase with latitude of the affected great and end of the onsets measured for event B on the different HAIL paths are shown in circles in the lower right corner, with th points of intersections (shown as black dots in the middle panel) of the constant longitude line with the great circle path of int

Questions:

Under what conditions does LEP represent a significant fraction of the overall particle loss rate? What is the spatio-temporal structure of LEP regions? What is the geographic (longitude) and geomagnetic (*L*-shell) distribution of LEP event activity? What is the variability of the onset timeand duration, as well as the rise and decay times of VLF events in comparison with magnetospheric wave and particle activity? Can VLF signatures of LEP events be used to measure the altitude profile of enhanced ionization and hence the energy spectra of the precipitating particles?

Approach:

Quantification of the global significance of the LEP process requires the knowledge of the size (individual regions) and distribution (both regional and global scales) of disturbed ionospheric regions (and therefore the affected magnetospheric regions), the determination of which is a primary goal of our proposed program. HAIL provides the spatio-temporal resolution needed as well as sufficient regional coverage of continental United States region, while simultaneous data from the north (HAIL) and south (Palmer Station, Antarctica) will allow the assessment of the geomagnetic conjugacy of event activity [*Burgess and Inan*, 1993]. The relationship between temporal signatures (i.e., onset, rise, decay) of VLF events and magnetospheric parameters will be studied by comparing northern hemisphere data with ducted whistlers observed at Palmer Station, with nonducted whistlers measured in situ on the POLAR and FAST spacecraft, and with magnetospheric activity (e.g., Kp ndex) in general.

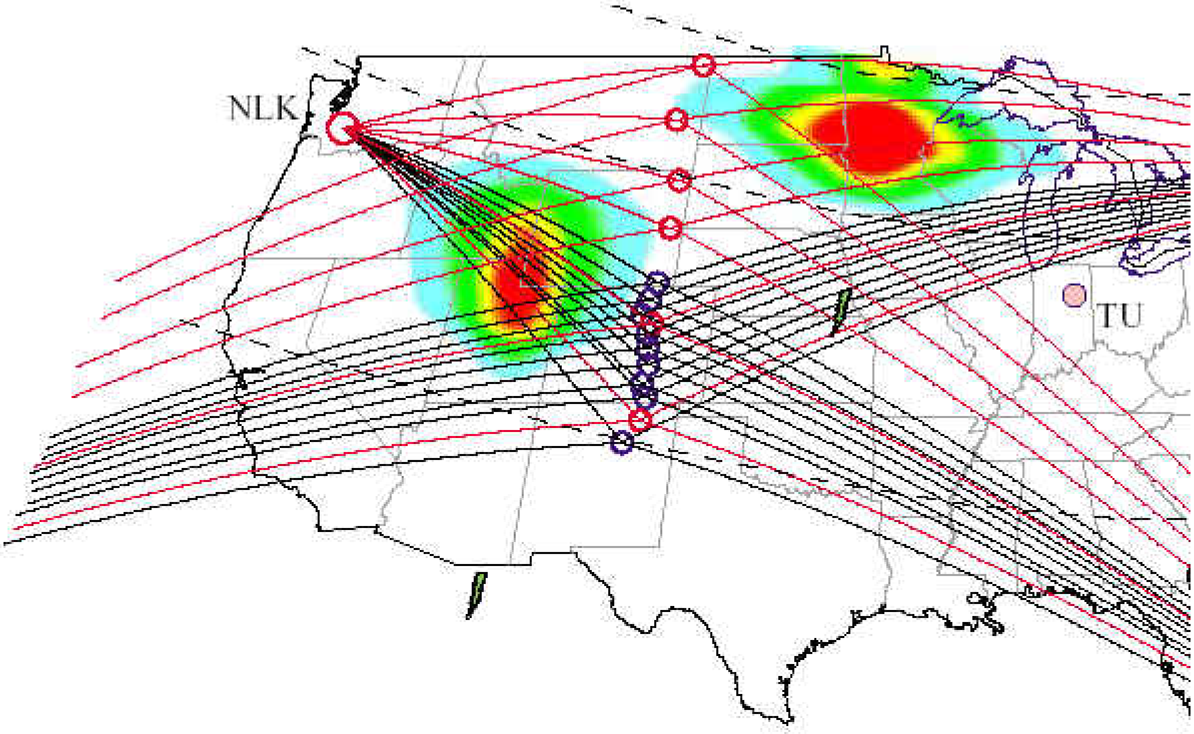


Fig. 8. Proposed targeted extension of HAIL to provide coverage of LEP regions at higher *L*-shells. Also shown are the predicted [*Lauben et al.*, 1999] nonducted LEP regions for two different lightning discharges occurring just south of Arizona–Mexico border and in northeastern Kansas. The red colored paths are the new VLF paths that will be observed by the extended HAIL,

while the black paths are the presently observed paths.

3. Quantification of Ionospheric Variability and Parameters

The continuous acquisition of HAILdata in pursuit of our scientific objectives also provides unprecedented information (in terms of resolution and coverage) on general lower ionospheric variability. An example is the recent observation (Figure 9) of the disturbance of the nighttime ionosphere by a gamma-ray flare from a *magnetar* located at the edge of our galaxy, 23,000 light years away from earth [*Inan et al.*, 1999a]. Although such events are rare, they provide benchmarks against which we can check/calibrate our lower ionospheric models, especially in terms of quantifying the chemical response of the nighttime *D*-region to suddenly introduced extra ionization. Each LEP VLF event exhibits well defined recovery signatures, which have been interpreted using a simple four constituent (consisting of electrons, positive and negative ions, and cluster ions, applicable when the quantity of interest is electron density rather than different ion constituents) model of the nighttime *D*-region [*Glukhov et al.*, 1992; *Pasko and Inan*, 1994]. Calibration of such models (for example by placing bounds on recombination and attachment rates using the measured ionospheric response to the gamma-ray flare) may allow the use of the recovery signatures to deduce the altitude profile of enhanced ionization, and hence the energy spectra of LEP bursts.

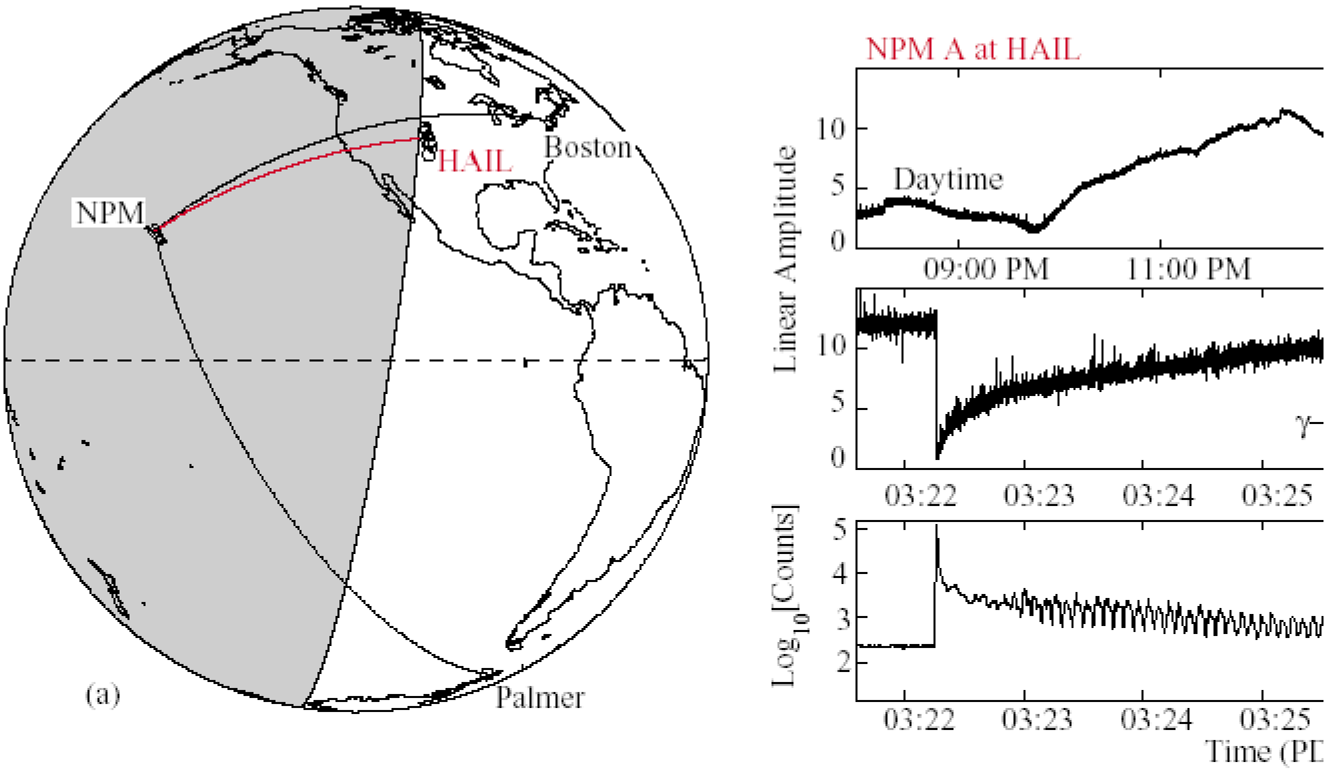


Fig. 9. Disturbance of the lower ionosphere by gamma-rays from a magnetar. (a) The VLF great-circle paths from the
receivers in Boston, Palmer, and the HAIL network. The part of the globe illuminated by the γ–ray flare from SGR 1900+14
amplitude of the 21.4 kHz NPM signal as observed in Trinidad, Colorado, over a 10 hour period. (c) Expanded record of the
~3:22 am PDT. (d) The intensity of the gamma ray burst as observed on the Ulysses satellite (from [*Hurley et al.*, 1999]).

C. THE RESEARCH

Steps:

(i) implementing an expansion of the HAIL system as described in Figures 4 and 8,
(ii) acquiring HAIL data on a continuous basis
(iii) analyzing the new VLF data as well as data in hand (acquired under the predecessor grant) and quantitatively interpreting this data to estimate the lateral and altitude profiles of lower ionospheric disturbances in the context of models of VLF propagation and scattering
(vi) using these derived estimates to assess the physical mechanisms of early/fast events and the occurrence rate and global significance of nonducted (oblique whistler-induced) LEP events

Task 1:

Develop VLF event recognition software (to be called FINDVLF) based on nonlinear-median-filter methods for removal of impulsive sferics, followed by algorithmic recognition of events based on set thresholds in terms of amplitude (e.g., >0.5 dB) or phase changes (e.g., 1.) occurring within specified intervals (e.g., 1-s). Until now, most subionospheric VLF data have been analyzed by inspection of summary plots (either on-line using JAVA or in printed form) followed by subsequent digital analysis (e.g., using either MATLAB or a specially designed and highly versatile multi-channel serial data analysis tool known as MACTRIMPI) of high resolution data. However, with continuous data acquired at nine sites, now proposed to be expanded to 6 additional ones, these methods are prohibitive in terms of the amount of time required to do statistical analysis of even short (a few weeks) epochs. At the same time, our knowledge of the phenomena has advanced to a point where we now know a lot more about the signature features of early/fast and LEP VLF events, and thus can develop sufficiently realistic criteria to capture most events.

Task 2:

Use FINDVLF to determine occurrence rates and properties [e.g., assessments of disturbed region sizes simply from simultaneous observation (or not) of events at multiple sites] of early/fast events, monthly, seasonally, and annually. The early/fast (rather than LEP) nature of the events will be assessed by comparing high-time-resolution signatures of the identified events with VLF sferics and NLDN data.

Task 3:

Once the HAIL system is expanded northward to cover*L*-shells up to*L*4, use FINDVLF to determine nonducted (oblique) LEP VLF event occurrence and latitudinal (*L*-shell) distribution, with the LEP nature of events determined by comparison of high resolution signatures with VLF sferics, NLDN lightning, or whistler data from Indiana (see Section E) or Palmer Station.

Task 4:

Once the HAIL system is extended to provide higher spatial resolution, analyze the best defined early/fast events to quantitatively determine the lateral shape (profile) and altitude profile of the associated ionospheric disturbance (see Figure 4), using three dimensional VLF propagation and scattering models.

Task 5:

Compare the lateral and altitude profile of early/fast events (from Task 4) with lightning-ionosphere interaction models to assess the physical mechanism(s) underlying early/fast VLf events, in particular determining whether these events represent ionization changes or whether they are manifested by quiescent heating of the lower ionosphere by thundercloud electric fields.

Task 6:

Analyze selected events and epochs in detail to quantitatively determine spatio-temporal structure nof ionospheric disturbances, using existing three dimensional VLF propagation/scattering models for both early/fast and LEP events. For LEP events this determination will facilitate the assessment of the importance of LEP phenomena in radiation belt loss rates on a regional scale, from which global estimates can be made based on comparative analysis of lightning occurrence rates (from other sensors, such as the Optical Transient Detector operated by Dr. H. Christian (NASA/MSFC) on a low altitude satellite. A second graduate student to be supported under the proposed program will also work on the above tasks, but he/she will be specifically responsible for managing the educational outreach component of the program, working closely with the 15 schools at which we will have equipment as well as with other schools which access the HAIL VLF data over the Internet. As described in Section G, the HAIL program offers opportunities for meaningful educational outreach, which we intend to fully cultivate.

MORE ON HAIL

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