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## The Meteor Event of January 17, 2004 Observed by the Swedish Infrasound Network

Ludwik Liszka

*A spectacular meteor event occurred over Northern Sweden on January 17, 2004 and was recorded by 4 stations of the Swedish Infrasound Network. The preliminary results of the data analysis and the possible trajectory and yield of the bolide are discussed.*

A spectacular meteor event occurred over Northern Sweden on January 17, 2004 at approximately 1405 UT. The impact area was located about 50 km NW of the village of Jokkmokk, north of the Arctic Circle. During the following days local newspapers reported a number of eyewitness observations of the event (although the impact area is very sparsely

populated). It was clear from all reports that what has happened on January 17 was a major event. At this time of the year the area in the neighbourhood of the meteor event is very close to darkness: yet, the inhabitants of this area reported that at the time of the impact the landscape was illuminated briefly as during full daylight. A number of loud explosions were also

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Inframatics is an informal series to make available in a timely fashion information about the science of infrasound that any of us might develop. It is provided via our organization's website [www.inframatics.org](http://www.inframatics.org). We expect contributions to *inframatics* to be short and cover only one distinct subject. Figures can be hand-drawn. Lengthy formulae can be stated without derivation. Contributions should be sent to any member of the editorial board by electronic mail. We will assemble all contributions received during a quarter into a single newsletter. The information may be duplicated in the website. We expect that all of us will publish papers that use the material we have previously forwarded to *inframatics*. Everyone is encouraged to do so. To avoid having the material used by someone else in earlier publication, we require that permission to use the material contained in the *inframatics* newsletter by anyone other than the author requires permission by the *inframatics* editorial board. For the time being, Michael Hedlin will act on behalf of the editorial board in such matters.

reported and there was, apparently, an eyewitness standing just below the bolide trajectory about 30 km NNE of the impact area.

An interesting fact about the event is that the impact area was close to the triangle formed by the northernmost stations of the Swedish Infrasonic Network. The approximate impact area is shown in Figure 1 as the centre of the map. All four stations (Kiruna, Jamton, Lycksele, Uppsala) are indicated on the map with letters K, J, L and U, respectively. The list of stations and their distances from the impact area are shown in Table 1.

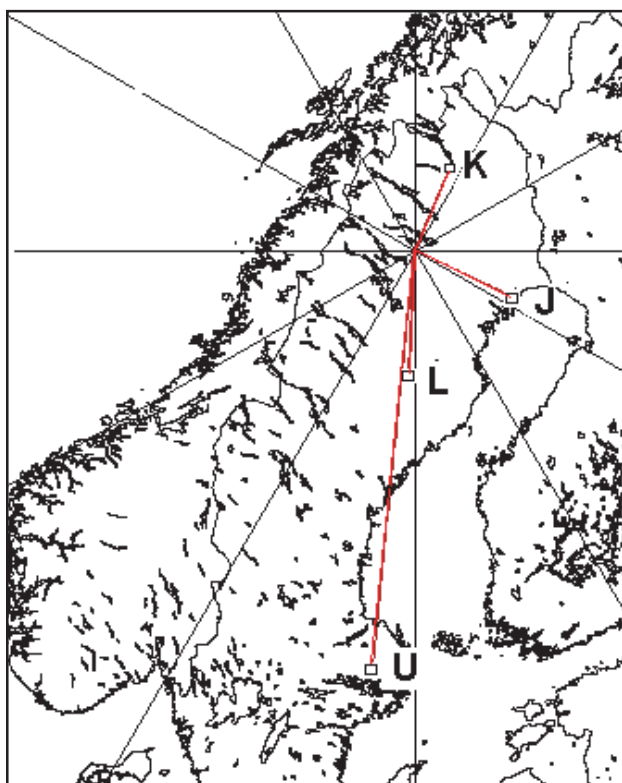


Figure 1. The approximate impact area in the centre of the map. The four stations are indicated on the map with letters: K, J, L and U.

Table 1: Swedish Infrasonic Network and the impact area

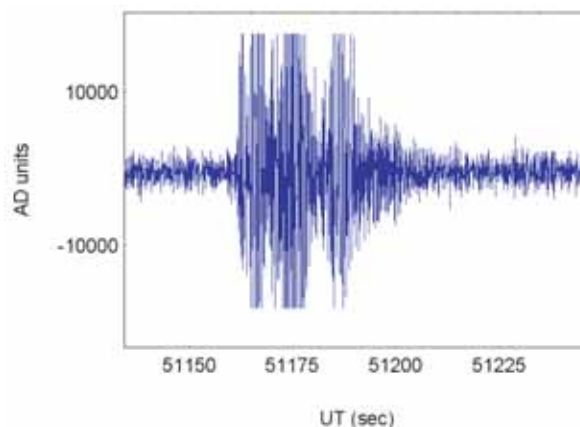
Name	Latitude	Longitude	Distance from the impact area (km)
Kiruna	67.80°N	20.40°E	160
Jamton	65.87°N	22.51°E	182
Lycksele	64.61°N	18.71°E	212
Uppsala	59.85°N	17.61°E	740

As shown in Figure 1, the bolide trajectory was close to the NS direction: therefore, the stations Kiruna, Lycksele and Uppsala were aligned with the direction of its trajectory, while the station Jamton was approximately perpendicular to it.

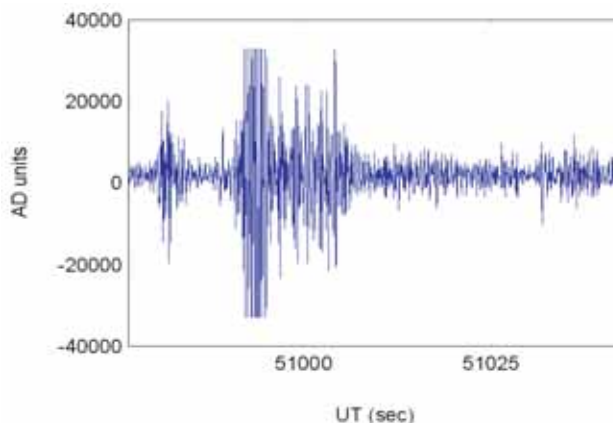
### Signal characteristics

The infrasonic signal produced by the entry of the bolide into the atmosphere and the subsequent explosions were recorded at all four stations: the recordings are shown in Figure 2.

It can be observed that the signal amplitude at the 3 northernmost stations is clipped. Only in the records of Uppsala, 740 km distant from the impact area, is it possible to make an accurate reading of the maximum signal amplitude: this amplitude corresponds to 0.056 Pa.

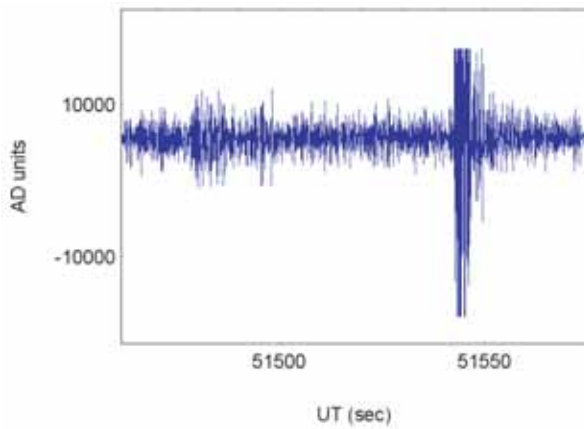


2a. Station Kiruna: max. amplitude > 0.2 Pa

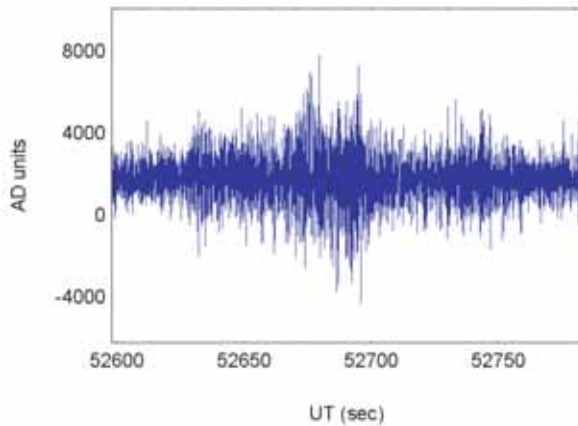


2b. Station Jamton: max. amplitude > 0.2 Pa

Figure 2. Amplitude recordings from all stations in the Swedish Infrasonic Network.



2c. Station Lycksele: max. amplitude > 9.2 Pa



2d. Station Uppsala: max. amplitude=0.056 Pa

Unfortunately, on the date of the event there was an offset problem at the Lycksele station. However, the offset didn't bias the estimation of the direction of arrival of the signal and the phase velocity readings.

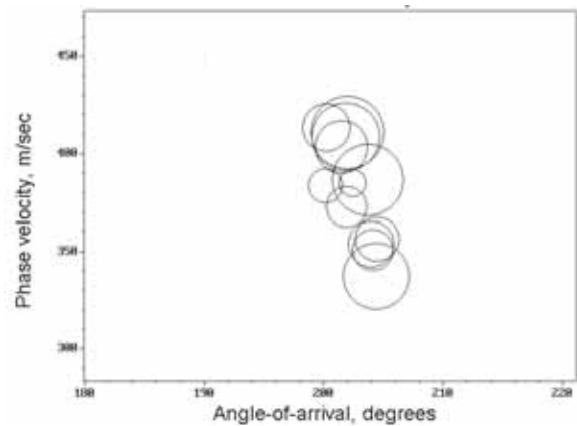
On the basis of the observed signal amplitudes, of the signal duration and of the spectral content, Dr. Douglas ReVelle, at Los Alamos National Laboratory, estimated that the energy release of the main explosion corresponded to about 1.7 tons of TNT. He also estimated that the energy at the source before it entered the atmosphere could have been 10 to 100 times bigger.

It is interesting to observe how the phase velocity of the incoming signal varies according with the distance of the recording stations from the source. For the three northernmost stations, close to the impact area, the phase velocity should be directly related to the height of the source: due to the short source-to-station distance, only a direct ray should reach the stations. However, a

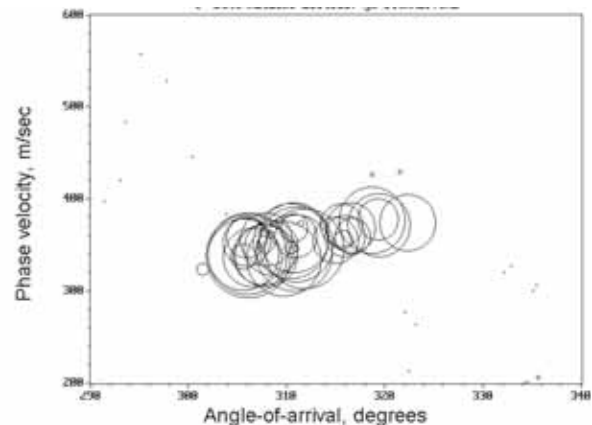
reflection in the upper atmosphere should be expected before the signal reaches the sensor at Uppsala. Figure 3 shows the phase velocity as a function of the angle-of-arrival of the signal.

It can be observed that there is a considerable difference between the phase velocities observed at Kiruna and Jamton stations: this is probably due to the corresponding aspect angles which differ with respect to the atmospheric wind system along the bolide's trajectory. However, it is assumed that the start of the infrasonic signal observed at both stations corresponds to the same point of the trajectory.

The energy distribution in the frequency domain can be represented through a series of scalograms, shown in Figure 4. A scalogram

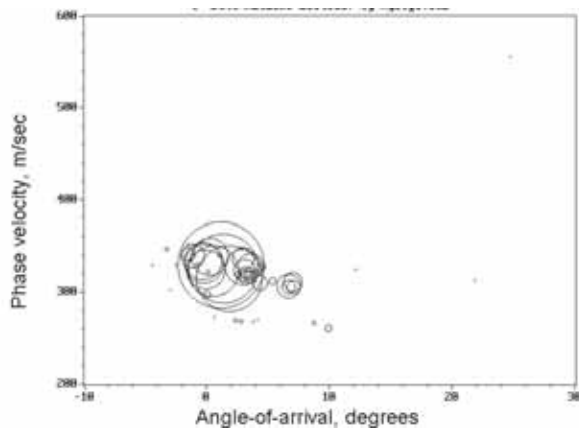


3a. Station Kiruna

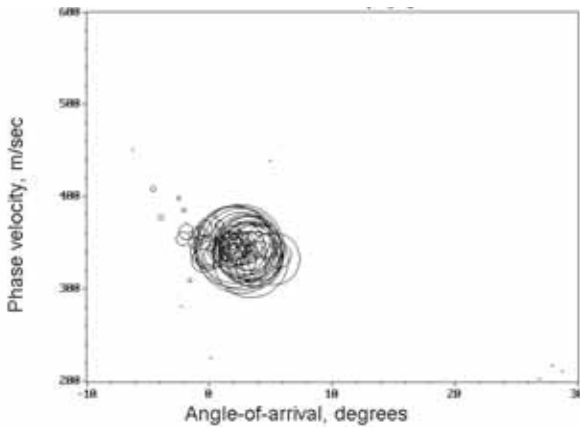


3b. Station Jamton

Figure 3. Phase velocity (m/sec) versus angle-of-arrival (Degs) for the 4 recording stations. The radii of the circles are proportional to the average cross-correlation across the array (continued next page).



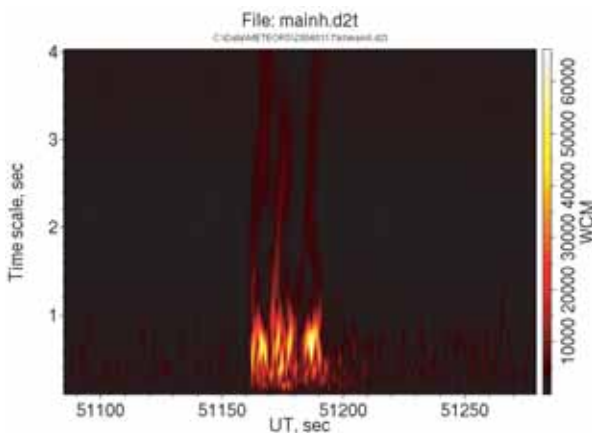
3c. Station Lycksele.



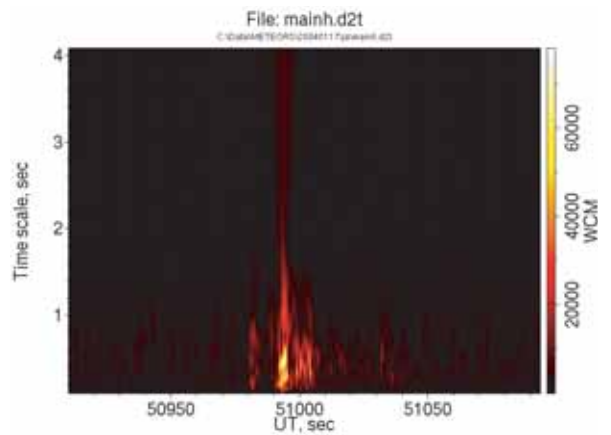
3d. Station Uppsala.

Figure 3. Continued.

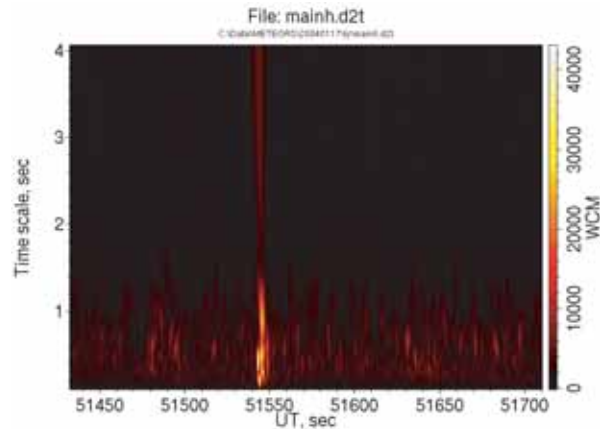
displays the wavelet coefficient magnitude (WCM) as a function of the time scale (inverted frequency, expressed in sec.) and of the elapsed time (UT, expressed in sec.).



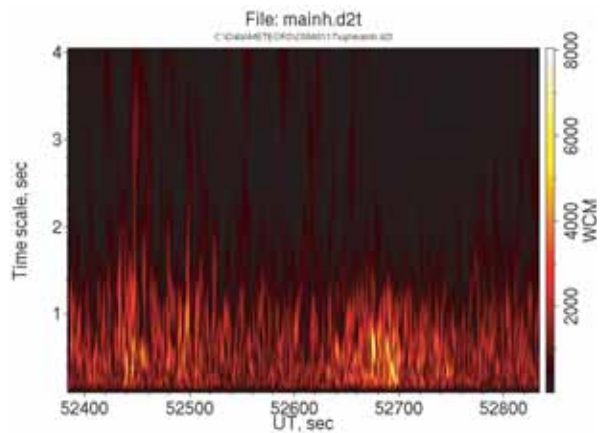
4a. Station Kiruna



4b. Station Jamton



4c. Station Lycksele.



4d. Station Uppsala.

Figure 4. Wavelet scalograms of the bolide signal recorded at all four stations.

Since the actual wind and temperature profile during the period this event occurred are not known, it is impossible to convert the phase velocity information into the absolute height of the source. However, assuming that the highest phase velocities observed at Kiruna and Jamton corresponds to the same point of the trajectory and using that as a reference, it is possible to combine the azimuths measured at both stations and to determine the horizontal projection of the

bolide's trajectory. The results of the triangulation are shown in Figure 5. The figure shows an enlarged part of the map shown in Figure 1, and it is centered at Jamton station. Kiruna and Lycksele stations are indicated by letters K and L, respectively and the horizontal projection of the bolide's trajectory is indicated by a thick line. The cross on the line shows the position of the main explosion. The length of the projection, calculated by combining the source-to-station directions from Kiruna and Jamton, is approximately of 86 km. This implies that at its entry into the atmosphere, the bolide was heading to the direction 206.9 degrees.

Given the length of the trajectory's projection A-B, a trajectory's inclination of around 40 degrees should be expected in order to obtain a

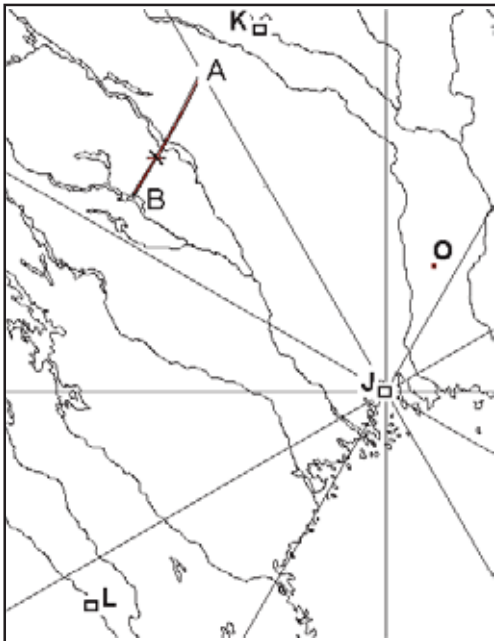


Figure 5. The northernmost stations and the horizontal projection of the bolide trajectory (thick line), as determined from directional data from Kiruna and Jamton stations. The cross on the trajectory projection marks the position (67.06N, 19.23E) of the main explosion.

realistic altitude at which the infrasound waves started to be generated. However, there is an observational evidence that apparently contradicts the above conclusion: at the point marked as O in Figure 5, almost 200 km ESE from the impact area, a photograph of the meteor trail has been taken, "shortly" (a few minutes) after the main explosion (see Figure 6). In this picture it can be clearly seen that the trail is nearly vertical. The most likely explanation is that the picture, taken some time after the explosion, shows the part of the trail diffusing along the geomagnetic field lines and not the trajectory of the bolide itself, responsible for the generation of the infrasound waves recorded at the 4 stations.



Figure 6. A photograph of the meteor trail taken some time after the main explosion from point O (cfr. with Figure 5), approximately 200 km from the impact area (Photo: H. Eliasson).

Additional studies will be carried out in order to find a higher level of constraints to the bolide's trajectory and incident angle.

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## Atmospheric Specifications for Infrasound Calculations

Douglas P. Drob

*The primary research goal of [inframatics.org](http://inframatics.org) is to coordinate worldwide research on understanding how to use low-frequency sound waves to characterize distant natural and man-made atmospheric events. There are a number of different problems being investigated. These include;*

- *Quantification of the impact of the assumptions and levels of approximations in propagation codes and atmospheric specifications.*
- *Development of remote sensing capabilities for significant natural geophysical phenomena of the solid earth (e.g. earthquakes, volcanoes, and land slides); ocean processes (e.g. microbaroms, littoral surf interactions); and atmospheric processes (e.g. stratospheric dynamics, upper atmospheric tides, and lower thermospheric heating).*
- *Operational infrasound source location including; event detection and location, interactive event screening and location, and ground-truth event location and analysis.*

The solution to any one of these problems is not mutually independent. Whatever the specifics may be, infrasound propagation calculations require specifications of the atmospheric state variables – wind, temperature, density, and pressure from the ground to 170 km. These fields are needed on a case-by-case basis for the analysis of historical events, in real-time for operational processing, and over extended periods of time for climatological investigations. Ideally these specifications should be global in nature and have as much spatial and temporal resolution as possible. Furthermore, it is important that the software tools to exploit these data for infrasound propagation calculations should be simple, reliable, easy to use, and independent of the type of atmospheric specification selected. Recent and continuing improvement in the atmospheric science community's ability to specify and provide detailed atmospheric specifications is helping to advance infrasonic research. There are several types of specifications available; a) raw atmospheric observations coincident with infrasonic events of interest, b) climatologies or empirical models, c) global and regional

operational Numerical Weather Prediction (NWP) analyses, and d) hybrid models.

The purpose of this article is to increase awareness in the infrasound community about the sources, availability, utilization, and basic aspects of the various types of specifications available. This article will provide a perspective from the point of view of an atmospheric scientist on the relative strengths and weaknesses of these different specifications for infrasound propagation calculations. The ultimate goal is to reach a point where improvements in atmospheric specifications no longer improve the performance of infrasound monitoring systems. This point has not yet been reached. To help define this issue more clearly the uncertainty and errors of any inferred infrasound source characteristics are the combination of errors and uncertainties in; 1) the measured signals from each array element, 2) array waveform processing and detection algorithms, 3) the propagation models relating the observables back to the source, and 4) the specifications of the background atmosphere. Items three and four are tied together by the fundamental physics of infrasound propagation.

## Direct Measurements

Direct measurements in the vicinity of the source or receiver within a few minutes or hours of an event provided a way to specify the infrasound signal propagation conditions. Typically these can be radiosonde (0 – 35 km) and/or rocketsonde (35 – 75 km) wind and temperature profiles. Radiosonde measurements are being collected on a daily basis around the world by various weather services. Other direct measurements such as satellite temperature and wind profiles are also available but difficult to obtain, understand, and utilize in infrasound propagation calculations. These observations then need to be combined with climatologies and/or weather analysis products. Unfortunately, direct measurements typically include localized wave structures that may or may not be part of the larger synoptic scale structures (200 to 1000 km); i.e. observable at both the source and receiver. Furthermore, direct measurements may include unchecked calibration biases and measurement errors. This makes using raw radiosonde and other single point measurements rather dubious for some infrasound propagation calculations. In most cases, direct measurements are only useful for short to medium range propagation calculations where more than one profile is available and it is safe to assume range independence. Direct in-situ surface measurements, however, remain the best available source of wind information used for noise characterization and reduction experiments.

## Climatologies

A decent climatology can capture the main aspects of the general circulation and temperature structure of the atmosphere determining the behavior of infrasound propagation. Climatologies are convenient in that they circumvent the need to deal with direct measurements or gigabytes of operational numerical weather prediction data. As such, they are also a useful tool for developing and testing

propagation codes. They also provide a convenient resource for calculating static travel time tables. Unfortunately the represented geophysical variations in climatologies can often be overshadowed by naturally occurring stochastic variations and lead to erroneous interpretations of infrasound observations.

The most popular climatologies in today's infrasound community are the Mass Spectrometer and Incoherent Radar Model (MSIS-90, NRLMSISE-00) [1, 2] for temperatures, densities, and pressures, and the Horizontal Wind Model (HWM-93) [3] (henceforth the HWM/MSIS empirical models). These two models were originally developed at the NASA Goddard Space Flight center but are now the primary responsibility of the Naval Research Laboratory, Upper Atmospheric Modeling Section. Constructed from a 40-year historical database of upper atmospheric research measurements, the HWM/MSIS models provide a good way to obtain estimates of winds, temperatures, pressures, and major species concentrations in the mesosphere and lower thermosphere (55 to 150 km) for infrasound propagation calculations. Referenced over 750 times in the scientific literature, the empirical models are widely used by the atmospheric science research community.

There are several reasons why the HWM/MSIS models are convenient for infrasound propagation calculations. As FORTRAN subroutines with embedded empirical coefficients, there is no data management requirements associated with the models. Furthermore only minimal programming experience is required to independently run or integrate these two models directly into existing infrasound propagation codes. With interpolation in space and time intrinsically provided, the specifications are continuous functions over the full range of latitudes, longitudes, altitudes, seasons, local times, solar flux, and geomagnetic conditions.

There are however, disadvantages to using the HWM/MSIS models for infrasound propagation calculations. Other than the most cyclical or repeatable patterns, these models make no attempt to resolve of the atmosphere's random synoptic

scale weather patterns and waves. The coverage of the available historical observations is often sparse over sections of the models temporal and spatial domain; therefore they only represent the grossest salient dynamical features of the general circulation of the lower, middle, and upper atmosphere. Though the output precision is infinite, the effective spatial resolution of the modeled atmospheric variations is approximately  $10^\circ \times 10^\circ$  degrees horizontally and about 1-2 km vertically. Compared to other options the spatiotemporal resolution of these models is limited.

To understand what this implies for infrasound propagation calculations the statistical performance of the HWM wind model was evaluated [4]. Biases in the magnitude and position of the stratospheric wind jets as compared to 15-day zonal averages of stratospheric Numerical Weather Prediction (NWP) analysis is on the order of 25 m/s and can persist for several months, particularly in the southern hemisphere. The calculated geophysical variances within the 15-day zonal averages of the NWP data are on the order of 20 to 30 m/s. Within a given daily zonal average, the variances due to the synoptic scale weather patterns are an additional 20 to 30 m/s. As a result, the HWM wind climatology can underestimate the magnitude and direction of the stratospheric wind jets by as much as 50 m/s over large spatial regions for extended periods of time. These errors are large enough to result in erroneous predictions of stratospheric ducting and can lead to significant errors in calculated travel times and azimuth deviations. The situation for the accurate representation of tropospheric ducting phenomena is even worse [5].

Additional biases of 20 to 60 m/s and RMSE (root mean square error) variances of 40 to 60 m/s in the 80 to 120 km region of the HWM model also exist. Other published scientific evaluations of the MSIS model indicate the existence of occasional biases and unresolved variances in the 80 to 120 km region. Fortunately, however, atmospheric temperature profiles have significantly less climatological variance as compared to the wind vectors. The unrepresented

variability in both models has negative implications for the calculation of the propagation characteristics of thermospheric arrivals. Work by the infrasound research community to understand and access the impact of these problems is proceeding on a number of fronts.

As we shall see, the observed variability and climatological model biases of the lower atmosphere (0-55 km) can be eliminated by combining the HWM/MSIS models with Numerical Weather Prediction (NWP) data. In order to correct the current biases and improve RMSE errors in the lower thermospheric portion of the HWM/MSIS models the data used to characterize the biases will need to be assimilated into the models. Work on this will continue at NRL over the next few years. Related research by the atmospheric science community is also continuing to develop and apply techniques to routinely measure and model the 60 m/s RMS variances, or synoptic meteorology, of the 80 to 120 km region.

In summary, climatologies are based on historical data and by their nature are subject to biases and systematic observational errors. They will always depart from reality for specific events or conditions. The extent to which this occurs is latitudinally and seasonally dependent. Even though the HWM/MSIS models provides a decent frame of reference and are convenient to use, they are less than ideal for performing accurate source location calculations at certain locations and times of the year.

### **Global Scale Numerical Weather Prediction Analyses**

Lower atmospheric Numerical Weather Prediction (NWP) is an important national and international activity. A number of organizations and agencies such as the World Meteorological Organization (WMO), (US) National Oceanographic and Atmospheric Administration (NOAA), and various Defense Departments build and maintain networks of ground-based weather stations and meteorology satellites. Operational

measurements are continuously assimilated into complex numerical models using the combination of rigorous statistics and geophysical fluid dynamics. There are several well known operational atmospheric modeling centers; the European Center for Medium Range Weather Forecasting (ECMWF) [6], NOAA National Centers for Environmental Prediction (NCEP) [7], and the US Navy's Fleet Numerical Meteorology and Oceanographic Center (FNMOC) [8]. These centers produce both weather forecasts and observational summaries called analyses. The spatial resolution of these global analysis products and forecasts is typically  $1^\circ \times 1^\circ$  or better (about 4500 km<sup>2</sup> at mid-latitudes). To achieve kilometer scale resolutions nested mesoscale models like the Navy's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS<sup>a</sup>) are available [9]. These mesoscale systems include highly detailed oceanic, topographical, and nonhydrostatic effects.

Unfortunately, none of the operational centers regularly measure, specify, and produce forecasts much beyond the upper stratosphere (50 to 55 km), with several only providing output for general consumption below 35 km. This is in part due to the fact that civil and military demand for specifications above 35 km is minimal, but also because it is more difficult and costly to make measurements above this altitude. Presently monitoring of stratospheric temperatures and inferred winds fields are obtained by only one or two space-based operational sensors. Operational NWP centers and climate researchers have, however, identified the importance of extending the upper boundary of the data assimilation and prediction models, if only for the reason that it has been shown to improve their forecast skill in the lower atmosphere. As a result, the upper boundaries of forecast and data assimilation systems are gradually being extended into the mesosphere and beyond. Consequently, reliable operational observations are needed in these regions to drive and constrain the models. Thus in the near term, current climatologies are the infrasound community's only readily available

source of environmental information above 55 km.

Eventually new scientific instruments to measure and infer the temperatures and wind fields from the stratosphere on upwards will become a reality. For example, a new temperature sounder was launched last year onboard the DMSP F-16 satellite. Once the instrument is calibrated and validated it promises to provide improved upper stratospheric temperatures for use by operational numerical weather prediction centers. The development of space-based instruments capable of making direct wind measurements throughout the middle and upper atmosphere are also being researched and tested, though it may be some time before dedicated operational sensors are flown. Revolutionary prototypes have already provided vast amounts of high quality, quasi-global wind measurements that will be used to improve the HWM wind climatology.

Despite some limitations, there are a number of significant advantages to utilizing operational NWP specifications in infrasound calculations. Several NWP databases developed for climate and atmospheric research exist and are publicly accessible [11]. In the 0 to 35 km region they extend back to 1960, and in the 0 to 55 km region they extend back to the early 1990s. These specifications are based on observations such as NOAA/DMSP temperature sounders, GOES radiances and cloud drift measurements, weather radars, and world wide radiosonde observations. Compared to the direct use of single observations for infrasound propagation calculations there are established infrastructures to validate, appropriately filter, and assimilate the host of measurements into reliable global and regional atmospheric specifications. The infrasound research community can accept these NWP analyses as *data*, instead of as *theoretical* models, as does much of the atmospheric science research community.

As with anything, there are also challenges associated with using the NWP data in infrasound calculations. As already mentioned, the majority of the operational measurements and specifications are focused on the 0 to 35 km region

of the atmosphere. Above this altitude the specifications are typically not included as part of the standard NWP center operational products and are based on a limited number of observational sensors. Without additional information, NWP analyses are only useful for modeling infrasound propagation that is limited to tropospheric and stratospheric ducting. Other technical hurdles include the fact that these specifications are usually provided in pressure or sigma coordinates and may contain a large number of extraneous fields. Additionally these analyses are only available at discrete time intervals (e.g. 6- to 12-hours) and are specified on discrete Cartesian grid points that are over dense and problematic near the poles. The conversion from pressure to altitude coordinate is also nontrivial, especially when considering orography. Sophisticated interpolation schemes are required for profile extraction and range dependent propagation modeling. At  $1^\circ \times 1^\circ$  resolution typical NWP analysis file sizes can exceed 20 megabyte every six hours and can be written in any number of quasi-standardized data formats and naming conventions. Compared to the solid earth and hydroacoustic models the data management and storage are significant.

### Hybrid or Composite Specifications

By intelligently combining the NWP specifications with the HWM/MSIS empirical models it is possible to side-step many of the disadvantages of the different data types while maintain some of the advantages of each. The heart of this problem lies in merging the various pieces of information into a single coherent specification which can be readily applied to an arbitrary time, location, and altitude. The first approaches to constructing composite models for infrasound calculations was to combine the data and climatologies in physical space with some sort of single or multi-dimensional cubic splining. For example, a number of researchers have appended radiosonde and NWP specifications with HWM/MSIS to investigate aspects of

infrasound propagation [11, 12]. Whenever the NWP specifications depart dramatically from climatological specifications at the information interface, however, it is easy to introduce spurious artifacts when combining the two data sets.

To avoid this problem, and solve a few others, it is possible to fuse the NWP analysis, climatologies, and any available direct observations together in a vertical pressure coordinate system in the spectral domain via vector spherical harmonic transforms. A unique atmospheric specification system was developed at the Naval Research Laboratory (NRL) to do just this. The NRL-Ground to Space semi-empirical spectral model (NRL-G2S) combines all available atmospheric data into a highly resolved, self-consistent, global and/or regional specification, ranging from 0 to 170 km. This system provides a very efficient way to synthesize, store, transmit, and reconstruct large global volumes of environmental information for infrasound event analysis. It eliminates the difficulty or need to work with NWP data in its various esoteric formats and resolutions. It also solves the pole problem and significantly compresses the data. All the information needed to perform range dependent infrasound propagation calculations anywhere in the world can be provided in a single G2S coefficient file corresponding to a specific time interval. It is further possible to account for time dependence by the interpolation of several temporally adjacent spectral coefficients sets. A mathematical discussion outlining the NRL-G2S system can be found in [5].

The operational prototype of the G2S system running at NRL system obtains and archives the operational numerical weather analyses from the NOAA, FNMOC, and other sources and then fuses them together with the HWM/MSIS empirical models to produce coefficient sets at 6-hour intervals with a time delay of a few hours. Using several historical NWP databases, G2S specifications are also produced on a case-by-case basis for infrasound ground-truth event analysis. The G2S specification are typically provided to clients in two triangularly truncated spectral

resolutions, T-72 ( $\sim 2.5^\circ$ ) for near-real-time and long-term database distribution, and T-121 ( $\sim 1.25^\circ$ ) for event driven investigations. A suite of platform independent client software tools for writing MATLAB and FORTRAN software applications to construct environmental profiles anywhere on the globe from the G2S coefficient sets are available. The MATLAB client software is simple enough to use at the command prompt, yet powerful enough to integrate directly into existing applications. Through the Tau-9 [13] and InfraMap Toolkit [14] the NRL-G2S atmospheric specifications are slowly becoming available to the infrasound community. A climatological database of G2S coefficients for 2003 to current now exists and will continue to expand. This database will soon become available to the infrasound research community.

### **Conclusions/Recommendations**

Insight into the relationship between infrasonic observables, propagation models, atmospheric specifications, and source characteristics has been gained by studying ground-truth infrasound events in combination with different atmospheric specifications, propagation models, and assumptions. Compared to the travel time errors achievable by the seismic monitoring community and the number of ground truth events and detectors at their disposal, the infrasound community must use every resource available. Ground-truth studies and model validation efforts will continue to be helped along by the efficient integration of near-real-time environmental updates, propagation model improvements, and the availability of large environmental databases. The issue of whether detailed atmospheric specifications can improve infrasound source location calculations is still an open question, as a number of independent theoretical and observational investigations into this matter have produced conflicting result, though most favor the need for better atmospheric specifications [5, 15, 16, 17].

For these investigations, it is important to remember that during certain seasons and locations the instantaneous atmospheric conditions in the lower atmosphere may not deviate much from the climatological average. Because the G2S model and the HWM/MSIS models are essentially the same above 55 km there will effectively be no difference between the models and any resulting calculations. On the other hand, at other times and locations conditions can be quite different from the monthly average climatology (e.g. winter mid- and high-latitudes). Furthermore, when investigating this issue it is very important to consider the extent to which information is lost by any assumptions and approximations in the propagation models.

Currently there is hesitation to abandon and/or adapt existing seismic source location infrastructures to address inherent atmospheric time dependence. This is because of; 1) the moderate increase in computational and data storage capacity required, 2) the lack of easily accessible codes to efficiently for incorporate this information, 3) limited resources and manpower to modify existing codes to exploit this information, 4) skepticism that this information will improve the existing monitoring systems.

Unless the number of available IMS and research arrays is dramatically increased, it is unlikely that it is possible to engineer around the problem of having to know the details of the atmosphere. A continuing challenge to the infrasound community is therefore to improve our ability to perform propagation and source location calculations utilizing the wealth of atmospheric information that is available.

Given the advanced state of today atmospheric specifications and available computational resources, there is no reason why source location travel time tables and other information needed for operational event detection and location can not be calculated in near-real-time. A number of possibilities from hourly, daily, to weekly environmental and travel time table updates are available. If implemented correctly this would almost certainly reduce false associations caused by the presence of the highly variable and sporadic

tropospheric and stratospheric ducts which have propagation characteristics very different from the climatologically predicated conditions. Beyond improvements to automated infrasound detection and source location, human interactive event analysis and screening should be performed with high resolution atmospheric specifications, and eventually exploit resources like the COAMPS mesoscale analysis system in conjunction with hybrid models. The quality of the meteorological information from NWP centers, and available thought the near-real-time G2S specification and other resources, are more than adequate for both these purposes.

Independent of what a particular infrasound application calls for, future updates of the HWM/MSIS empirical models in the mesosphere and lower thermosphere will also be very beneficial to the infrasound community. Finally, though not discussed in this article, continuing investigations into the mathematics of geophysical inverse problems with infrasound, both for atmospheric remote sensing and source location, provides a very powerful way to understand and quantify the relationship between infrasonic observables and the atmospheric specification problem. With all of these advances, unknowns, and new techniques it is truly an exciting time to be involved in infrasonic research.

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## Advanced Tools for Infrasonic Modeling

David Norris and Robert Gibson

*Infrasound stations around the world record a wealth of man-made and natural infrasonic signals for study. To sort out the various signals, the analyst needs the capability to model the dynamics that affect the received signals. This modeling can be used to predict signal characteristics, localize source regions, and infer properties of the source itself.*

*To effectively model infrasound, one must be able to account for the source mechanism, state of the atmosphere, and propagation. While a large variety of models and characterizations exists in each of these areas, it is the integration of these tools that enables successful modeling of infrasonic signals. This article describes a software tool kit, InfraMAP, that provides these integrated capabilities. It is not the goal to review every feature of the tool kit, but to provide a sample of its capabilities and recent applications in the study of infrasonic propagation.*

## InfraMAP

InfraMAP is an acronym for Infrasonic Modeling of Atmospheric Propagation. It is a software tool kit that has been developed for use by researchers and analysts active in the study of infrasonic propagation and monitoring. InfraMAP integrates state-of-the-art sound propagation models and atmospheric characterizations into a user-friendly, menu-driven interface. The integrated models enable sophisticated analysis of infrasound propagation corresponding to event locations worldwide. Users can readily compare complex measured data to results of predictive models. InfraMAP enables the evaluation and display of atmospheric characteristics that affect the performance of infrasound network monitoring. In addition, localization performance over a network of infrasound stations can be evaluated by defining measurement errors and evaluating propagation variability.

InfraMAP is developed and maintained by BBN Technologies in Arlington, Virginia, USA. Over the last seven years, InfraMAP has been supported by various agencies within the U.S. government. The original version was released in October 1999, and the work leading to this release is summarized in a technical report [Gibson and Norris 2002]. Since

that time, many additional features, models, and capabilities have been added, and new software versions have been created [e.g. Norris and Gibson, 2003]. In fact, InfraMAP development is ongoing, with new atmospheric characterizations and propagation models being developed and integrated for future software releases.

We begin our review with an overview of the InfraMAP system and user interface, followed by a summary of the atmospheric characterizations and propagation models. The article concludes with an example application of the tool kit.

## System and User Interface

InfraMAP is executable on both Sun workstations running Unix and PCs running Linux. The software is started in MATLAB, where all the Graphical User Interface (GUI) menus and figures are generated. Numerically intensive environmental and propagation models are run as batched executables on the operating system. The geo-display window along with the expanded user windows is shown in Figure 1.

The geo-display enables quick selection of areas of interest in the world and access to all tool menus. Various menus can be brought up relating to

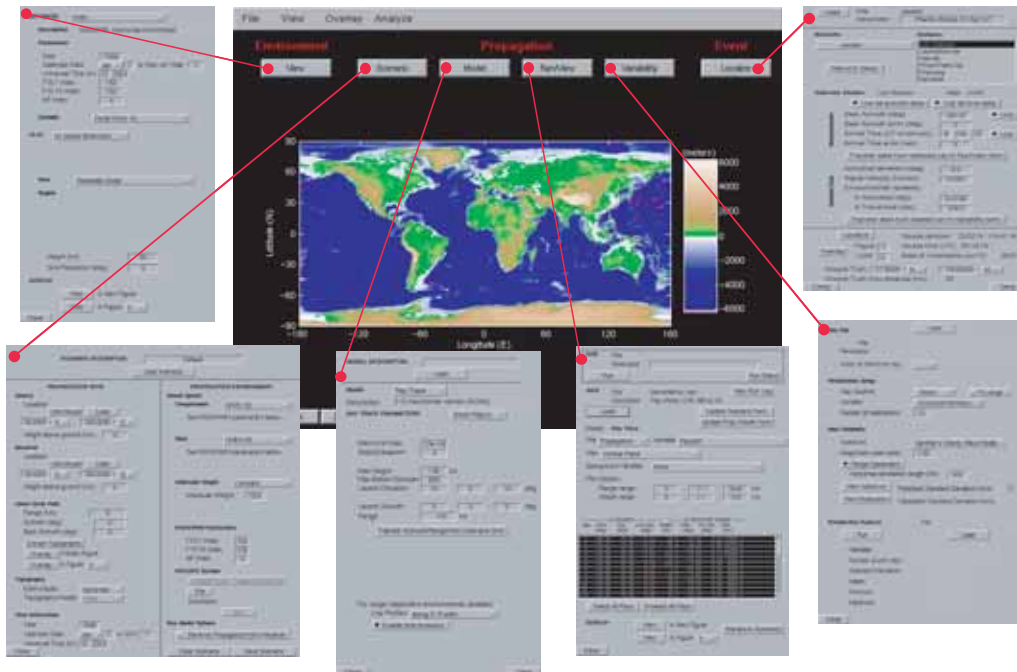


Figure 1. InfraMAP Geo-display shown with expanded user menus.

environment, propagation, variability, and localization. The menu access and cross-reference to the geo display allows the user to quickly and efficiently set up an infrasound scenario of interest, assess the environment, and model the propagation.

### Atmospheric Characterizations

Sound propagating in the atmosphere is primarily affected by wind and temperature, and secondarily by average molecular weight, specific heat ratio, and air composition. Temperature establishes the static sound speed. Wind can be added to the static sound speed in a given direction to define an effective sound speed. The presence of wind also creates a moving medium through which the sound propagates. Molecular weight and specific heat ratio, like temperature, affect the static sound speed, although to a smaller degree. Air composition, including the presence of water (humidity), determines in part the sound absorption levels.

All of the above atmospheric properties, with the exception of humidity, can be characterized within InfraMAP. The baseline atmospheric models are MSISE-90 (Picone et al., 1997) and HWM-93 (Hedin, 1996). These are global, empirical models originally developed at NASA and currently maintained at NRL. They are based on multiple years of climatological measurements and capture dominant seasonal and diurnal atmospheric variability. MSISE (Extended Mass Spectrometer -

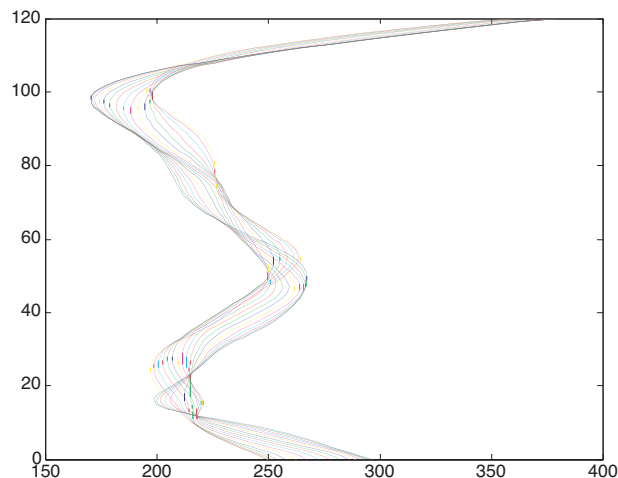


Figure 2. Profiles of MSIS-90 temperature along a profile from the equator to the North Pole.

Incoherent Scatter Radar) provides temperature and air composition from the ground into the thermosphere and beyond. HWM (Horizontal Wind Model) provides zonal and meridional winds over the same height range.

InfraMAP provides the interface to enable rapid visualization and evaluation of atmospheric properties. For example, in Figure 2, profiles of MSIS-90 temperature are given along a great-circle path. Figure 3 shows the HWM-93 horizontal winds displayed globally in both magnitude (color mapping) and as vectors. Output can also be generated as a function of model parameters, as shown in Figure 4. Here the HWM-93 zonal winds at a location in the continental U.S. are given as a function of time of year. The seasonal dependence of stratospheric wind direction is quite evident.

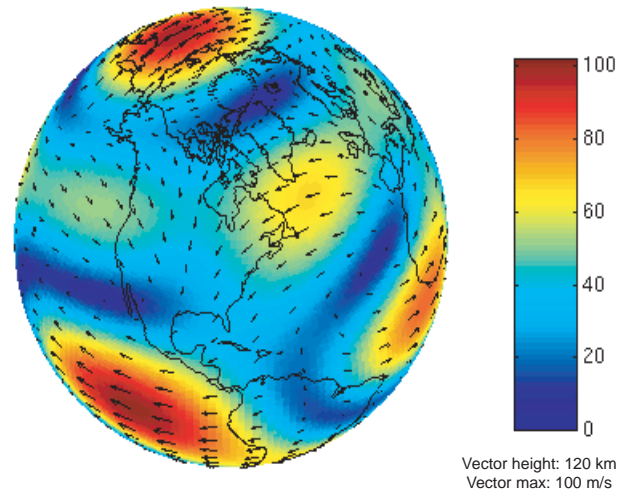


Figure 3. Global visualization of HWM-93 winds at 120 km height.

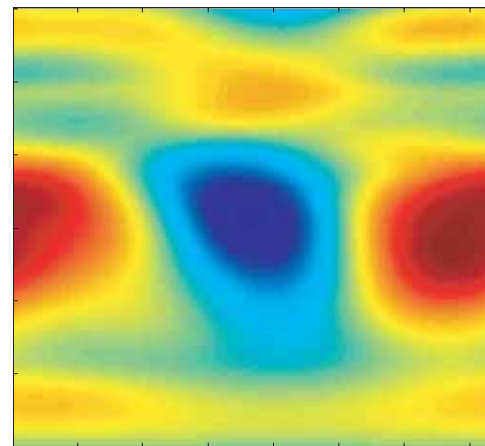


Figure 4. Variation in zonal wind with time of year over continental U.S.

Other atmospheric user-options and more sophisticated models exist or are being integrated into InfraMAP, as summarized below (the interested reader is directed to the associated references):

- User-defined profiles, range-dependent, and range-independent options [Norris and Gibson, 2003].
- Gravity wave spectral model for smaller-scale variability in horizontal winds [Norris and Gibson, 2002].
- Near-real time atmospheric realizations, including use of the Navy's NOGAPS and NRL's G2S model output [Gibson and Norris, 2002].

### Propagation Models

Output from the atmospheric characterizations described in the previous section are integrated with propagation models to generate infrasonic predictions of phase arrival time, amplitude, azimuthal deviation, and other waveform parameters. InfraMAP provides environmental integration and execution capabilities for a baseline set of three acoustic propagation models: ray trace, normal mode, and Parabolic Equation (PE).

InfraMAP uses the 3-D ray tracing code HARPA (Hamiltonian Ray Tracing Program for Acoustic Waves in the Atmosphere) developed at NOAA. It provides ray predictions through an inhomogeneous three-dimensional representation of the atmosphere [Jones *et al.*, 1986]. Figure 5 gives an example plot of HARPA Ray Trace predictions. The model accounts for vertical and horizontal refraction as well as horizontal translation of the ray path due to the moving medium. HARPA output includes azimuth and elevation angle, travel time, and azimuthal deviation at each point along a ray path. In InfraMAP, HARPA has been integrated with an eigenray finder, so that rays can be identified that connect a source and a receiver to within a given miss distance. InfraMAP uses a version of Pierce's normal mode code [Pierce and Kinney, 1976; Pierce *et al.*, 1973; Pierce and Posey, 1970] modified by Los Alamos National Laboratory for prediction of

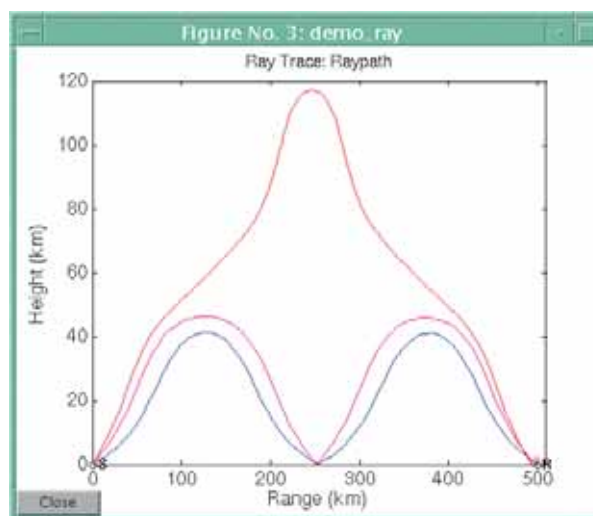


Figure 5. Vertical projection of ray paths (eigenrays).

lower-yield nuclear events [Dighe *et al.*, 1998; Hunter and Whitaker, 1997]. Figure 6 gives an example plot of a normal mode waveform prediction. The model uses the Wentzel-Kramer-Brillouin (WKB) method to calculate a dispersion curve, which in turn is used to calculate a received waveform at a given range and azimuth. The waveform is computed from the summed set of modal solutions. Only range-independent environments are supported, which can be based on source location, receiver location, or from averaged values along the entire propagation path. InfraMAP uses a continuous-wave, two-dimensional Parabolic Equation (PE) model [Jensen *et al.*, 1994; West *et al.*, 1992] based on the split-step Fourier algorithm.

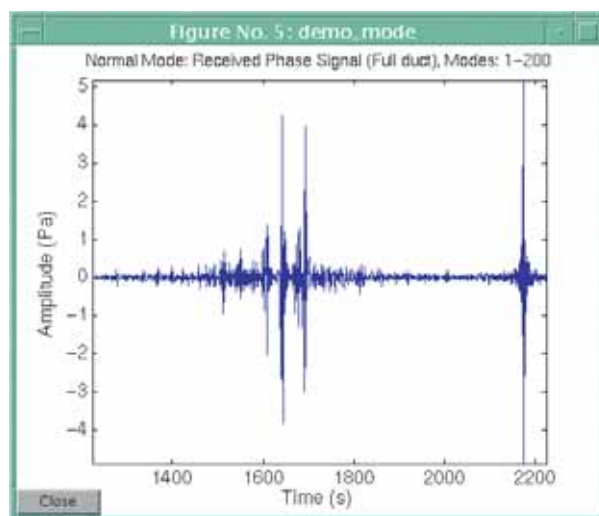


Figure 6. Waveform predicted using normal modes.

Figure 7 gives an example plot of a PE amplitude field prediction. The PE algorithm steps forward from a source, characterized by a starter field, and calculates an amplitude field in height and range at a single frequency. The atmosphere is defined at each range step and can be range-dependent.

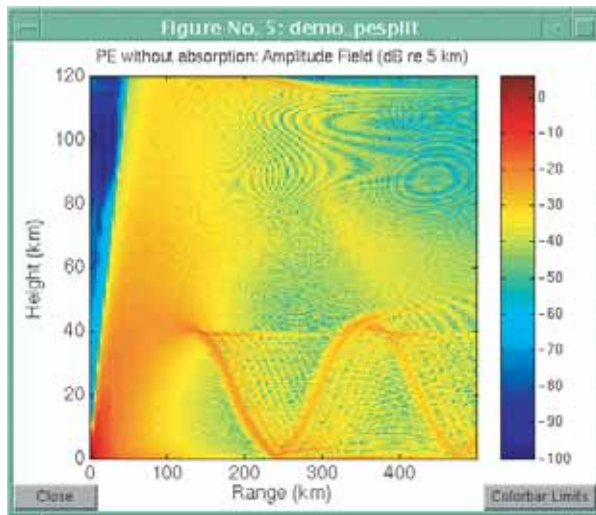


Figure 7. Amplitude field from parabolic equation (PE) model.

All three of these baseline propagation models account for spreading loss due to the expansion of the outgoing acoustic wave. Attenuation of the acoustic wave can also occur due to atmospheric absorption. An absorption model is integrated into InfraMAP based upon the work of Sutherland and Bass (1996). The Sutherland and Bass model was developed for low frequencies and high altitudes and accounts for both classical (translation and diffusion) and relaxational (rotation and vibration) losses. It uses temperature and air gas densities provided by MSIS to predict absorption coefficients (loss per range). Figure 8 shows an example absorption coefficient profile calculated at 0.5 Hz. Note that at high altitudes, the loss can be quite significant (1 dB per kilometer at 120 km).

Additional propagation models are being researched or are in various stages of integration. These include:

- A new version of the Normal Mode model
- The Time-domain Parabolic Equation (TDPE) model
- The Nonlinear Progressive wave Equation (NPE) model

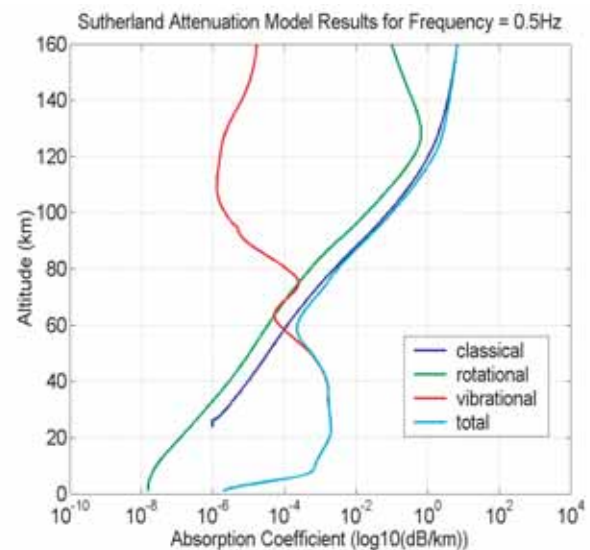


Figure 8. Absorption Coefficients at 0.5 Hz from Sutherland and Bass model and MSIS.

### Source Localization

InfraMAP provides the capability to localize a source measured across a regional network of sensors. The localization algorithm is a Maximum Likelihood Estimator (MLE) implementation (Kay, 1993) in geophysical coordinates (Perl, 1981). The algorithm inputs are a set of back azimuth and arrival time measurements and associated uncertainties from a finite number of spatially separated sensors. The uncertainties can include both measurement error and uncertainty associated with the propagation. The algorithm outputs are: source position in spherical coordinates (latitude, longitude); origin time; and Area of Uncertainty (AOU), which defines the 95% confidence bounds of the localization.

### Example Application: El Paso Bolide

On 9 Oct 1997, a large bolide traveled above Texas near El Paso. The height of the bolide, as determined from satellite observations, was 29 km. This bolide was detected at both the Los Alamos DLIAR array (range 445 km) and the Southern Methodist University TXIAR array (range 359 km). The received data at TXIAR has been studied to evaluate the ability to verify or refine the source height estimate.

To model the bolide signal, eigenrays were computed (using HARPA, MSIS-90, and HWM-93) over a range of source height from 0 to 50 km. Over the range of heights, there are 1-3 stratospheric eigenrays and 2-3 thermospheric eigenrays. Figure 9 shows the eigenray solutions at 30 km source height.

Synthetic waveforms were next computed for each source height and mapped into an image as a function of arrival time and source height (bottom of Figure 10). A Gaussian waveform of standard deviation 10 sec was used as the source function. For sources near the ground, single eigenrays can be observed, which then split into multiple eigenrays at the height increases. The split rays for a given v-shaped branch correspond to two similar paths, one propagating up at the source, the other propagating down, reflecting off the ground, and then propagating up. The eigenray image can be compared to the measured waveform (top of Figure 10), and a source height estimate can be made by correlating the measured arrival times with the predicted amplitudes. The three measured arrivals match the predictions at source heights of 33, 26, and 23 km, respectively. Although there is a spread in these heights, they are in general agreement with the satellite-determined source height of 29 km.

**Summary**

InfraMAP is a software toolkit developed to assist researchers and analysts in the study of infrasonic events. The key to its utility is the integration of atmospheric realizations and propagation models with geo-centered menu

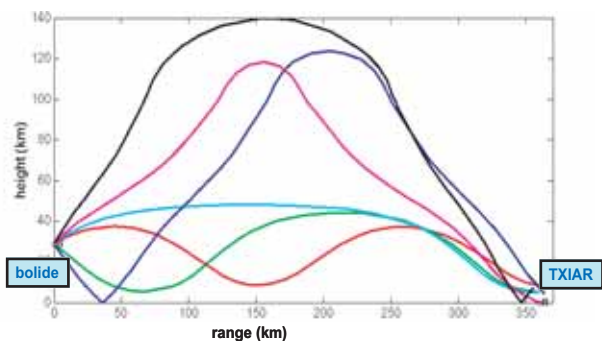


Figure 9. Eigenray solution between El Paso bolide at source height of 30 km and receiver at TXIAR.

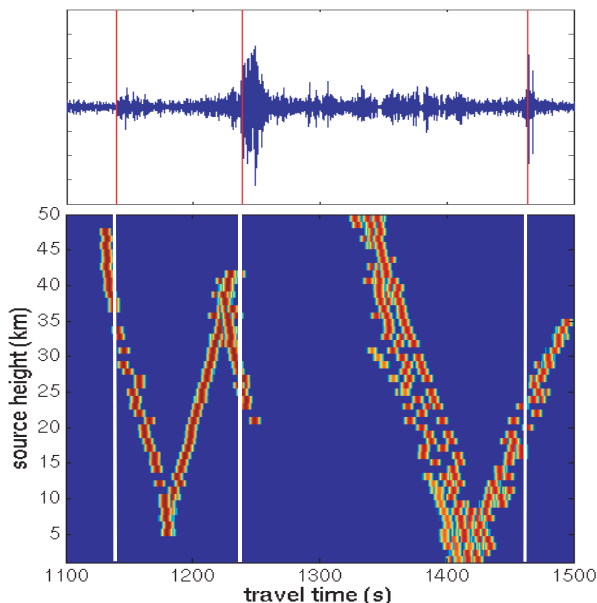


Figure 10. Comparison of measured arrival times (above) with synthetic waveform prediction from eigenrays solved over 0 to 50 km (below).

interfaces and graphics capabilities. In this article, some of the baseline features of the tool kit have been reviewed. Additional features, including near-real time atmospheric updates and time-domain propagation models, are being developed and can be reviewed at a future date. The ultimate goal is to continue to advance the state-of-the-art capabilities in infrasonic modeling and reduce the gap in agreement between predictions and observations. Through this process, increased modeling confidence and validation will support improvements in detection/classification, source characterization, and event localization.

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## Geophysical Institute Acquires Infrasound Sensor Technology

Daniel Osborne

*The University of Alaska is now in the process of completing the purchase of the assets of Chaparral Physics Consultants of NM, Inc. An agreement was signed three months ago to transfer the technology, knowledge and assets of Chaparral, along with exclusive rights to all of the company's products and name to the Geophysical Institute (GI) at the University of Alaska Fairbanks. The GI was selected as the successful candidate among many interested institutions seeking to acquire Chaparral's assets.*

Chaparral Physics is renowned for its line of high-quality infrasound sensors. These sensors have the highest sensitivity, lowest noise and lowest power requirements of any currently available commercial infrasound sensors. The GI will build on Chaparral's long and successful history in this market by preserving this unique technology and improving upon it.

Chaparral Physics is now a division of the GI and will continue to supply infrasound sensors to the scientific community. Production of these acoustic sensors is underway and the microphones will meet and surpass all of Chaparral's original specifications. To date, GI research professionals Jay Helmericks and Daniel Osborne, after a period of training with Chaparral's Ed Bullard, have

produced Chaparral Models #2, #5 and #7 both in New Mexico and in Fairbanks, Alaska, as a part of the technology transfer.

Many international researchers have preferred Chaparral infrasound sensors to advance the science of infrasound and detect weak infrasound signals, because of their excellent sensitivity and low noise. These sensors' very low power consumption helps to reduce the installation and operating cost of battery or photovoltaic powered infrasound arrays.

Chaparral products will be built to order and Models #2 and #5 are currently available. Scientific users may view model specifications online at <http://www.chaparral.gi.alaska.edu/>.

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