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14. ABSTRACT

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InfraMAP integrates advanced infrasound propagation models (ray-tracing, parabolic equation, normal mode) and environmental representations. It also incorporates algorithms for assessing propagation variability and for localizing infrasound sources based on both observations and model calculations. New InfraMAP modules enable integration of propagation models with two near-real-time atmospheric characterizations. Output from the NRLG2S (Naval Research Laboratory Ground to Space) specification can be imported and used to characterize the entire propagation environment. Naval Research Laboratory's NRL-G2S is a semi-empirical spectral model that fuses climatological models with output from operational numerical weather prediction models.

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INTEGRATION OF INFRASOUND PROPAGATION MODELS AND NEAR-REAL-TIME ATMOSPHERIC CHARACTERIZATIONS

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BBN Technologies

Sponsored by Air Force Research Laboratory

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Numerical modeling of infrasound propagation directly supports infrasound source location and phase identification. Predicting the details of infrasound propagation relies on characterization of the propagation medium, namely the global atmosphere from the ground to altitudes above 100 km, and the accuracy of propagation modeling depends on the fidelity of the atmospheric characterization. The analysis tool kit InfraMAP (*Infra*sound *M*odeling of *A*tmospheric *P*ropagation) has been upgraded to offer new options for specifying the propagation environment. Near-real-time atmospheric updates, such as the output from numerical weather prediction models, supplement the baseline climatological characterization of temperature, wind and air composition.

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Validation efforts are essential to build confidence in the modeling procedures and are used to assess the value of potential improvements to the atmospheric specification. Observed infrasound events with known ground truth represent valuable sources of opportunity for use in validating propagation modeling techniques. InfraMAP has been used to model long-range propagation of infrasound originating from the space shuttle, bolides, and other sources. Model predictions of infrasound arrival times and azimuths resulting from use of various environmental characterizations are compared with observed data.

OBJECTIVES

The primary objective of this research effort is development of a software tool kit with capabilities for higher-fidelity infrasound propagation modeling by the incorporation of near-real-time atmospheric characterizations. This effort is intended to support improved event localization, and phase identification. A validation effort has also been undertaken, using a diverse set of observations and ground truth, in order to improve confidence in the modeling techniques and provide calibration in support of operational needs. Anticipated uses of the software include: in-depth analysis of events and scenarios of particular monitoring interest, sensitivity analyses, and detailed infrasound localization and detection studies.

RESEARCH ACCOMPLISHED

Near-Real-Time Environmental Updates to InfraMAP

The InfraMAP software tool kit is composed of research-grade infrasound propagation models (3-D ray tracing, parabolic equation and normal modes) and upper-atmospheric characterizations, integrated to allow for user-friendly model execution and data visualization. InfraMAP was developed to enable the efficient application of advanced computational models, in support of the nuclear explosion monitoring research and development community. InfraMAP can be applied to predict travel times, bearings, and amplitudes from potential event locations worldwide. Such predictions can be used to identify infrasound phases and to define travel-time and bearing corrections, which can improve localization performance (Gibson and Norris, 2002a). Recent enhancements to the InfraMAP suite of computational tools enable analysis of propagation variability due to environmental effects, calculation of source location using measurements and model predictions, and prediction of network localization performance (Norris and Gibson, 2002).

Global characterizations of temperature, wind, and air composition are incorporated into the propagation models to account for temporal and spatial variability of the atmosphere. Modeling of spatial variability enables range-dependent propagation modeling to be performed. The baseline atmospheric characterizations in InfraMAP are two empirical models: the horizontal wind model, HWM-93 (Hedin *et al.*, 1996), and the mass spectrometer-incoherent scatter radar extended model, NRLMSISE-00 [Picone *et al.*, 2002]), which provides temperature and air composition. (Note: NRLMSISE-00 is a recent upgrade from the earlier baseline temperature model, MSISE-90 (Picone *et al.*, 1997)). Using these characterizations, wind, temperature, and molecular densities are modeled from the surface into the thermosphere and include spatial, diurnal, and seasonal effects. The models are climatological in that they predict the mean environmental state based on assimilation of multiple years of data.

The HWM and MSISE models were chosen for use in InfraMAP due to their high fidelity over a wide range of altitudes and temporal scales, their global domain, and the relative ease of software integration. However, global climatological models such as HWM and MSISE that are based solely on historical data do not capture fine-scale atmospheric structure that evolves over time. This research addresses the use of appropriate near-real-time sources of atmospheric information to improve the estimate of the infrasound propagation environment.

During this effort, new InfraMAP modules have been developed to incorporate output from physics-based synoptic models that assimilate observations from a number of sources. Range-dependent propagation modeling is now possible using these updated global atmospheric characterizations. Previously, updated atmospheric profiles could be used, but only in range-independent propagation modeling scenarios. In addition, a number of other enhancements have been introduced in InfraMAP to improve the fidelity of the environmental characterization. They include:

- Integration of an archive of solar flux and geomagnetic disturbance parameters (F10.7, F10.7A, and A_P) from the National Geophysical Data Center;
- Incorporation of variable molecular weight in sound velocity calculations;
- Incorporation of variable specific heat ratio in sound velocity calculations.

These new features are primarily intended to improve fidelity of the modeling of thermospheric infrasound at little or no computational cost, as discussed previously (Gibson and Norris, 2003).

The near-real-time global atmospheric characterizations that have been integrated with infrasound models are:

- The Naval Research Laboratory Ground to Space (NRL-G2S) specification; and
- The Navy Operational Global Atmospheric Prediction System (NOGAPS).

Output from the NRL-G2S specification (Drob, 2003) can be used to characterize the entire propagation environment. NRL-G2S is a semi-empirical spectral model that fuses climatological models with output from operational numerical weather prediction models from the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), and other sources. The G2S atmospheric characterizations from the surface to approximately 55 km utilize the output of multiple numerical weather prediction systems and other relevant global data sets. Above this region, upper atmospheric characterizations are based on the NRLMSISE-00 and HWM-93 climatologies. NRL-G2S employs spherical and vector spherical harmonics in the data assimilation process to produce a set of model coefficients for each day and time of interest. Coefficient sets can then be used to reconstruct fields of each atmospheric state variable as well as spatial derivatives.

An InfraMAP user can access NRL-G2S coefficient sets from a data repository, import the coefficients, and utilize the resulting specifications within InfraMAP to define a propagation environment. InfraMAP incorporates "client-side" routines (Drob, 2003) that perform inverse transforms necessary to determine vertical atmospheric profiles over the entire globe using the NRL-G2S coefficients. The NRL-G2S system is configured to produce coefficient sets autonomously every six hours, and also for special events of interest.

NOGAPS provides near-real-time global grids of temperature and wind, several times per day, over three spatial dimensions (Bayler and Lewit, 1992). NOGAPS, originated by the Navy's Fleet Numerical Meteorology and Oceanography Center (FNMOC), is a numerical weather prediction system that utilizes not only profiles measured by radiosondes, but also an extensive data set of ship-based, land-based, and satellite measurements. Output data from NOGAPS are readily available from the ground up to the 10 mb pressure surface (approx. 30-35 km). As shown previously, there is considerably more fine-scale structure in the NOGAPS characterization than in the climatology at altitudes below 35 km (Gibson and Norris, 2003). However, because infrasound propagation modeling requires atmospheric information above the NOGAPS domain, climatological models remain an essential tool for estimating the environment, particularly at high altitudes.

Techniques have been developed within InfraMAP to merge NOGAPS grids at lower altitudes with climatological models at higher altitudes. InfraMAP modules import and decode NOGAPS grid files. A user then selects a subset of the global grid (i.e., a range of latitude and longitude cells) for use in a propagation scenario of interest. Within the region of interest, NOGAPS output is used in conjunction with the HWM and MSISE characterizations to define the propagation environment. A user specifies the thickness of the transition layer above NOGAPS. A cubic interpolation algorithm that matches the values and their derivatives at the boundaries is employed to join NOGAPS temperatures, zonal winds, and meridional winds with the climatologies.

The global temperature and wind profiles from both the NRL-G2S and the NOGAPS characterizations can be viewed using InfraMAP's environmental menu. Furthermore, either near-real-time characterization can be used in range-dependent infrasound propagation modeling using ray-tracing or parabolic equation techniques or, alternatively, in range-independent propagation modeling using ray-tracing, parabolic equation, or normal modes. This flexibility allows the direct comparison of the results of calculations using climatology or user-defined profiles with predictions using the near-real-time enhancements. It also allows the user to choose between computationally fast range-independent modeling and slower, higher-fidelity range-dependent modeling. Supplementing the baseline climatological models with available near-real-time updates is anticipated to yield improved infrasound predictions, particularly for propagation paths that dwell primarily in the lower and middle atmosphere, where updated data are more readily available.

A beta version of the software, including graphical user interfaces, was provided to selected users, and feedback received from the testers was used to prioritize research and development activities. Recent development efforts have focused on improving calculation speed and efficiency of range-dependent propagation modeling. The near-real-time update capabilities and other environmental enhancements have been integrated into the InfraMAP software tool kit, and an updated user manual has been developed. The most recent software release, InfraMAP 4.0, produced during this effort, provides the near-real-time atmospheric functionality described herein.

Examples of Infrasound Modeling using Near-Real-Time Characterizations

This section provides an example of the use of climatology, NRL-G2S and NOGAPS in a range-dependent propagation modeling study for an event of interest.

A bolide was observed over the state of Washington on 3 June 2004. A video camera in Vancouver Island, Canada observed the fireball at 09:40:12 UTC, according to a news bulletin report from the Dutch Meteor Society (http://www.xs4all.nl/~dmsweb/fireballs/20040603_US_fireball.html). The Pacific Northwest Seismograph Network localized the event at 47.9717N, 121.9782W, with an estimated altitude of 43.45 km, according to a press release (http://www.pnsn.org/NEWS/PRESS_RELEASES/June3_2004_meteor.html) and accompanying analysis (http://www.pnsn.org/WEBICORDER/INTERESTING/bolide040603.gif).

The event was observed infrasonically by the I56US array at Newport, Washington, and the I57US array at Pinon Flat, California. Preliminary analyses of the infrasound observations were reported by Stephen Arrowsmith and Michael Hedlin of UCSD (http://mabu.ucsd.edu/~arrowsmith/bolide.htm). At I56US, detections (Progressive Multichannel Cross-Correlations {PMCC]) were reported from 09:59:05 to 10:07:35 UTC, with an apparent main arrival at approximately 10:05 UTC. At I57US, detections (using PMCC) were reported from 11:11:55 to 11:19:25 UTC.

In this study, propagation modeling was conducted with InfraMAP using the seismically determined latitude, longitude and altitude and the visually determined origin time. The resulting range to I56US is 363 km (with a back azimuth of 266.7 degrees) and to I57US is 1661 km (with a back azimuth of 345.5 degrees). Modeling with the HWM and MSISE climatology used atmospheric profiles that were range-dependent as well as time-evolving (i.e., stepping forward from the event origin time as calculations progressed). Modeling with NRL-G2S used a coefficient set calculated for 10:00 UTC. Modeling with NOGAPS used a grid calculated for 12:00 UTC.

Using the ray-tracing model, with the bolide modeled as an omnidirectional point source, eigenrays were identified if they came within 5 km of the I56US array or within 10 km of the I57US array. (This rather loose eigenray constraint is intended to identify elevated rays as well as those that reach the ground at the receiver range. Energy from elevated rays may reach the ground through diffraction.)

A summary of ray-tracing model results for I56US using the three atmospheric representations is shown in Table 1. In each case, two thermospheric eigenrays were identified, one with an upward launch elevation angle and one with a downward launch elevation angle. Travel times vary by 1% or less across the three model scenarios. Azimuth deviation results vary by 0.5 degrees or less across the three scenarios. The predicted arrival times (approximately 10:04 and 10:06 UTC) are within 1 minute of the apparent main arrival in the observed data. Arrivals as early as 09:59 UTC were not predicted using any of the atmospheric characterizations.

Table 1. Ray-tracing parameters for eigenrays identified to I56US using three atmospheric characterizations

	Elev. Ang.	Az. Dev.	Time	Arr. Time	Arr. Vel.
HWM/MSISE	23.9	0.1	1427	10:03:59	0.254
	-33.8	0.5	1541	10:05:53	0.235
NRL-G2S	27.7	0.3	1415	10:03:47	0.256
	-36.0	1.0	1550	10:06:02	0.234
NOGAPS	21.4	0.1	1410	10:03:42	0.257
	-33.0	0.6	1542	10:05:54	0.235

Amplitude fields calculated using the parabolic equation model for the path to I56US are shown in Figure 1 for both the NRL-G2S and the NOGAPS atmospheric characterizations. The modeled frequency is 0.1 Hz. The two plots show generally similar predictions of energy distribution, although the prediction using NOGAPS shows a somewhat higher concentration of energy in the stratospheric duct.

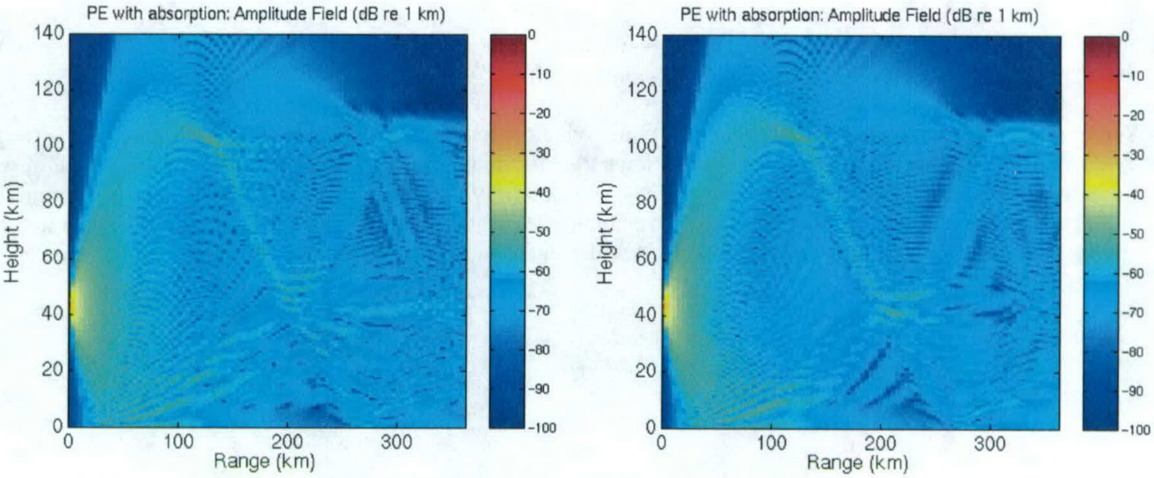

Figure 1. Amplitude fields at 0.1 Hz calculated using parabolic equation modeling to I56US for NRL-G2S atmospheric characterization (left) and NOGAPS characterization (right).

A summary of ray-tracing model results for I57US using the three atmospheric representations is shown in Table 2. The rays shown are limited to those with launch elevation angles of up to 35 degrees from the horizontal. In each case, six or seven thermospheric eigenrays were identified. Using the HWM and MSISE climatology, two stratospheric rays were also identified. Considering only the thermospheric rays, the travel time of the earliest arrival varies by up to 1.5% across the three model scenarios. The stratospheric rays identified using HWM and MSISE are predicted to arrive approximately 7 to 8 minutes earlier than the earliest thermospheric rays. Azimuth deviation results vary by less than 1 degree across the three scenarios.

Table 2. Ray-tracing parameters for eigenrays identified to I57US using three atmospheric characterizations

	Elev. Ang.	Az. Dev.	Time	Arr. Time	Arr. Vel.
HWM/MSISE	2.0	-0.8	5568	11:13:00	0.298
	-1.9	-0.8	5588	11:13:20	0.297
	7.8	-2.1	6031	11:20:43	0.275
	-11.2	-1.7	6117	11:22:09	0.272
	21.0	-1.5	6349	11:26:01	0.262
	-24.0	-1.3	6492	11:28:24	0.256
	29.3	-1.2	6784	11:33:15	0.245
	-33.0	-1.0	6947	11:35:59	0.239
NRL-G2S	11.6	-2.9	6091	11:21:43	0.273
	-15.1	-2.3	6185	11:23:16	0.269
	26.0	-1.9	6404	11:26:56	0.259
	23.0	-2.1	6420	11:27:12	0.259
	-28.0	-1.7	6558	11:29:30	0.253
	32.9	-1.6	6815	11:33:47	0.244
	-35.2	-1.4	6980	11:36:32	0.238
NOGAPS	5.5	-2.2	6004	11:20:16	0.277
	-7.9	-1.8	6105	11:21:57	0.272
	16.2	-1.8	6342	11:25:54	0.262
	17.0	-1.9	6343	11:25:55	0.262
	-22.5	-1.5	6468	11:28:00	0.257
	28.4	-1.4	6730	11:32:22	0.247
	-32.0	-1.2	6893	11:35:05	0.241

The predicted thermospheric arrival times (approximately 10:20 UTC and later) are somewhat late compared to the arrivals detected in the observed data. The predicted stratospheric arrival times are consistent with the beginning of the main coherent cluster detected in the observed data.

Synthetic waveform envelopes, determined by convolving the train of arrival times with a Gaussian that is weighted by the calculated absorption along the propagation path, are shown in Figure 2 for the modeled ray-tracing results using the three atmospheric characterizations. The spread in travel times can be seen. The source strength in the model was chosen arbitrarily, so only the relative amplitudes are of interest. The differences in relative amplitudes among the three modeled cases is primarily due to differences in the predicted upper turning height of the rays.

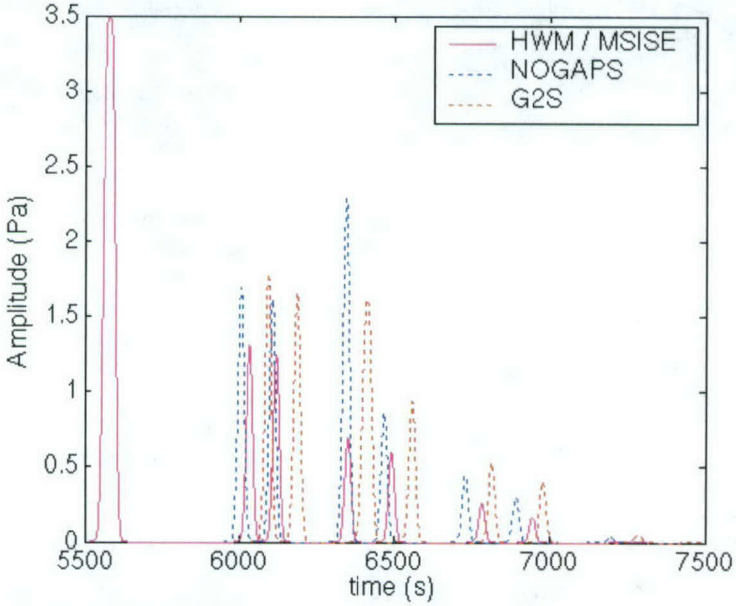

Figure 2. Synthetic waveform envelope determined from calculations using ray-tracing modeling to I57US for three atmospheric characterizations. Since source strength is unknown, the absolute signal amplitudes are not calibrated in the model results.

Plots of effective sound speed profiles at 100 km increments along the great circle azimuth in the direction from the source location to I57US are shown in Figure 3 for the three environmental characterizations. Significant differences among the characterizations can be seen at altitudes between approximately 30 and 50 km, and these features determine the presence or absence of a stratospheric duct in this model scenario. For this event time and region, NRL-G2S predicts lower temperatures at these altitudes than MSISE, which results in the weaker stratospheric duct when using NRL-G2S, as evidenced by Figures 1 and 2. At lower altitudes, the NOGAPS profiles have more fine-scale structure than the other characterizations. The subtle differences among the sets of profiles at thermospheric altitudes result from the slightly different time of day used in the climatological representations in the three cases.

Although it is tempting to draw conclusions about the fidelity of the atmospheric characterizations based on comparisons between propagation modeling results and infrasound ground truth, it should be noted that bolides are complex sources that are challenging to model and that are not necessarily well represented by impulsive point sources. Various source mechanisms and regions may exist for a bolide event, as discussed by Brown *et al.* (2002), for example. These complexities result in modeling challenges, as shown in previous studies, e.g., Norris and Gibson (2001). Nevertheless, the sensitivity study presented here points out some of the important effects that the detailed atmospheric characterization can have on propagation model predictions. Accurate near-real-time specification of temperature and wind will ultimately improve on climatology and result in higher-fidelity infrasound predictions. Further side-by-side comparisons among the atmospheric characterizations for a larger set of observed events will be essential. It will also be important to investigate the fidelity of infrasound predictions using time-domain propagation models such as those discussed by Norris (2004), when used in conjunction with near-real-time specifications such as NRL-G2S and NOGAPS.

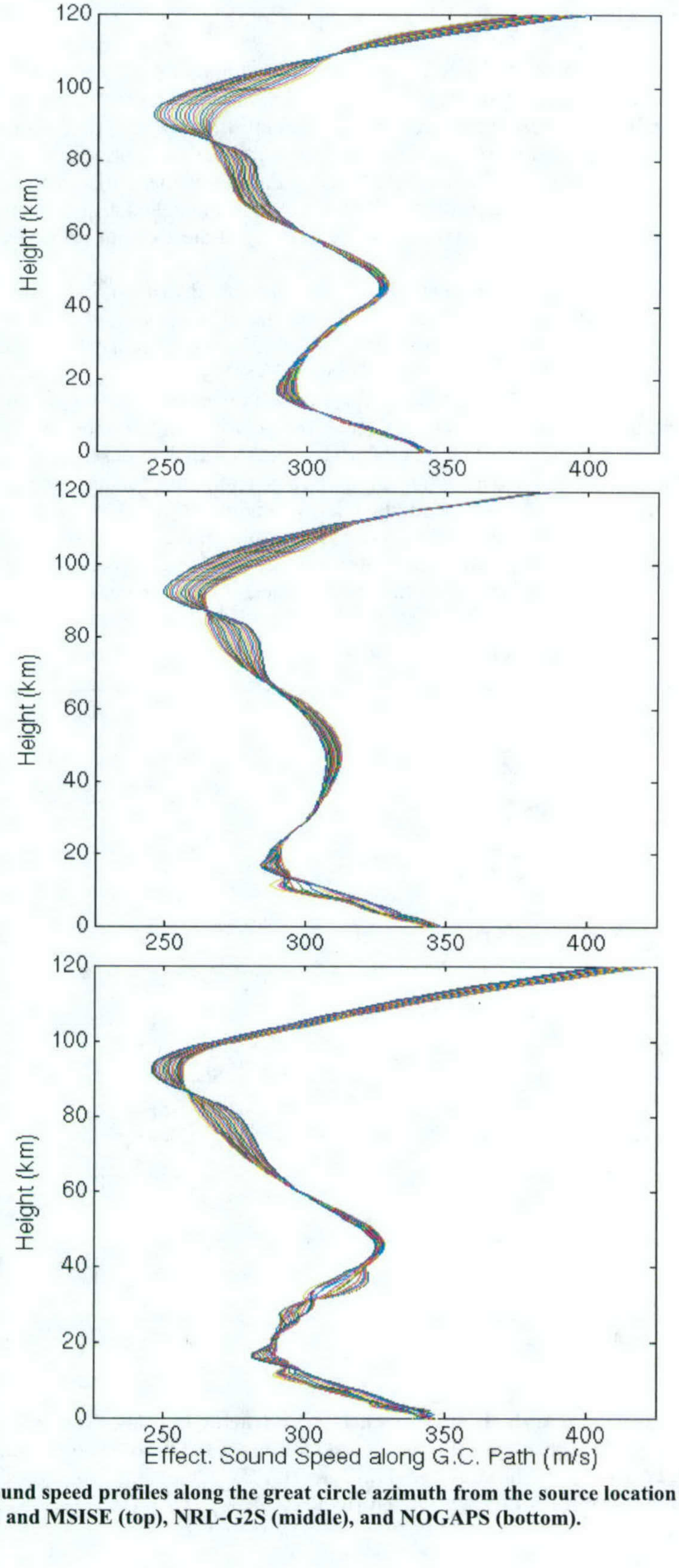

Figure 3. Effective sound speed profiles along the great circle azimuth from the source location to I57US, determined using HWM and MSISE (top), NRL-G2S (middle), and NOGAPS (bottom).

Other Model Validation Efforts

As the database of ground truth infrasound events grows and as additional NRL-G2S coefficient sets become available for both recent and historical events, further validation of modeling techniques will be enabled. Earlier validation activities conducted as part of this effort focused on infrasound from space shuttle launches, as discussed by Gibson and Norris (2002b). Components of infrasound signals have been associated with both the ascending orbiter and the descending solid rocket boosters. Reasonably good agreement in both travel time and azimuth has been obtained between ray tracing model results and observed infrasound, and analyses have been conducted of annual trends in observability, travel time and azimuth. Modeling of these events primarily used climatology.

The authors also participated in the Department of Defense Columbia Investigation Support Team Infrasound Working Group, the work of which was presented in the *Report to the Department of Defense on Infrasonic Re-Entry Signals from the Space Shuttle Columbia (STS-107)* (Bass, 2003). InfraMAP was used to model infrasound from the reentry and approach of the space shuttle Columbia (STS-107) up to the point of its untimely breakup. During this investigation, the NRL-G2S specifications were used to characterize the propagation environment. Range-independent propagation modeling was conducted from a large number of points along the reentry trajectory to the locations of those infrasound arrays in the western US and Canada that observed the event. Ray tracing model predictions of arrival time, azimuth, and elevation angle were generally in good agreement with the observations. One example is presented here to illustrate the model fidelity. Figure 4 shows a comparison of ray-tracing results with detections at I57US as computed using MatSeis and Infratool (Young, *et al.*, 2002). The analysis passband is 1-8 Hz. The observed trends in azimuth and travel time from the moving source are generally well predicted. The results can be used to determine what portion of the reentry trajectory contributed to infrasound signals received at a given time of interest.

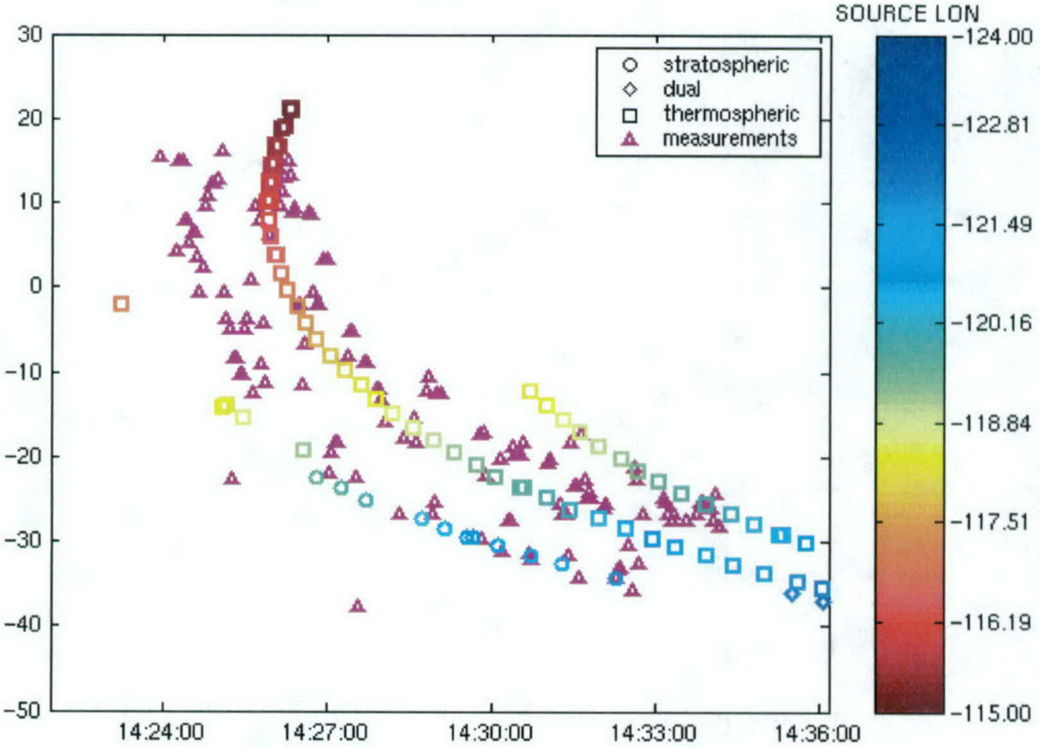

Figure 4. Predicted infrasound arrivals at I57US using ray-tracing (circles, diamonds and squares) compared to observations (triangles) from the reentry of Columbia (STS-107). Vertical axis shows azimuth (degrees) and horizontal axis shows arrival time (UTC). Color bar indicates the longitude of the orbiter at the origin time of each modeled ray arrival.

CONCLUSIONS AND RECOMMENDATIONS

The InfraMAP tool kit is used to predict the critical propagation characteristics that affect infrasound localization and detection. Adequate atmospheric characterization is necessary to correct for biases in travel time and azimuth that result from the propagation environment in order to avoid phase misidentification or large location errors.

The NRL-G2S atmospheric specifications and the output from the NOGAPS numerical weather prediction model have been integrated with range-dependent propagation models. The integrated set of models will allow for higher fidelity propagation modeling than has previously been available to the infrasound monitoring community.

Efforts should continue on the development of time-domain propagation modeling techniques, including the consideration of non-linear effects. Although ray-tracing is a powerful technique for predicting travel time and azimuth deviation, it is not always sufficient for predicting the detailed features of infrasound observations from ground-truth events. The integration of time-domain models with near-real-time atmospheric characterizations should be undertaken in order to conduct model comparison studies and to model infrasound propagation from observed events.

Other high-fidelity environmental characterizations should be considered for integration into an enhanced version of the InfraMAP software, particularly mesoscale models for use in studying short-range events of interest.

Rocket events and bolides generate infrasound signals for use in model validation studies. Further modeling of a large set of observed ground truth events, using updated atmospheric characterizations, should continue in order to quantify the improvements in travel time and azimuth predictions that are achievable. These investigations should focus on first establishing a baseline and then documenting the modeling improvements achievable with near-real-time updates as compared to climatology. The results may also be useful for identifying improvements that could be made to the atmospheric specifications.

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Doug Drob provided NRL-G2S client software, advised us on the use of the G2S specifications, and produced the G2S coefficient sets. Dean Clauter and Rod Whitaker provided useful feedback on modeling requirements and software functionality. Michael Hedlin and Stephen Arrowsmith provided analysis of the 03-June-2004 bolide via a link from the *inframatics.org* website.

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