INTEGRATION OF NEAR-REAL-TIME ATMOSPHERIC MODELS WITH INFRAMAP AND APPLICATIONS TO MODELING INFRASOUND FROM ROCKETS

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ABSTRACT

The accuracy of infrasound propagation modeling depends on the fidelity of the environmental characterization. The analysis tool kit InfraMAP (*Infra*sound *M*odeling of *A*tmospheric *P*ropagation) utilizes the empirical environmental models MSISE and HWM to model temperature and wind, respectively. Opportunities for improved specification of the propagation environment are discussed. Of particular interest is the incorporation of near-real-time atmospheric updates, such as numerical weather prediction models or *in situ* radiosonde measurements, to supplement climatological characterization of the environment.

Approaches to integrating the output of meteorological synoptic models with infrasound propagation modeling codes are under development. Prognostic models such as the Navy Operational Global Atmospheric Prediction System (NOGAPS) provide near-real-time, global grids of temperature and wind over three spatial dimensions. To propagate three-dimensional rays through gridded data, wind and temperature values and their spatial derivatives must be estimated at each point along a ray path. Because ray models are highly sensitive to sharp changes in sound speed, the estimation approach must avoid introducing gradient variability that is not inherent in the original data grid. A natural cubic spline algorithm is being developed to interpolate data for use with ray modeling.

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. Infrasound signals have been observed at several infrasound arrays in North America following launches of the space shuttle and of other large rockets. InfraMAP has been used to model propagation of infrasound originating from shuttle launches. The moving vehicle is modeled as a series of discrete infrasound sources separated in space and time. Launch ascent trajectory models are used to estimate source locations of the orbiter and solid rocket boosters during flight. Predictions of infrasound arrival times and azimuths resulting from three-dimensional ray tracing through empirical environmental characterizations are compared with observed data.

OBJECTIVES

The primary objective of this research effort is development of an enhanced InfraMAP software tool kit that enables higher fidelity infrasound propagation modeling by making use of linkages to near-real-time atmospheric characterizations. This effort is intended to support improved event localization and phase identification. An extensive validation effort is also being 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 propagation models (3-D ray tracing, normal modes and parabolic equation) and upper-atmospheric characterizations, integrated to allow for user-friendly model execution and data visualization. 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, 1999).

Temporal and spatial variability of the atmosphere is addressed by modeling range-dependent temperature and winds and incorporating them into the propagation models. The baseline atmospheric characterizations in InfraMAP are two empirical models: the horizontal wind model, HWM-93 (Hedin *et al.*, 1996), and the extended mass spectrometer-incoherent scatter radar temperature model, MSISE-90 (Picone *et al.*, 1997). Wind, temperature, and 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 profiles 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. Validation studies conducted to date using InfraMAP with the HWM-93 and MSISE-90 characterizations indicate generally good agreement between modeled propagation paths and infrasound measurements. However, there exist cases in which measured infrasound phases are not adequately predicted using the baseline InfraMAP.

Global climatological models such as HWM and MSISE that are based solely on historical data do not capture local temporal and spatial atmospheric structure. The ability to add near-real-time sources of information will significantly improve the estimate of the infrasound propagation environment. Classes of near-real-time atmospheric updates include:

- *in situ* observations, such as measured profiles from radiosondes, and
- physics-based synoptic models that assimilate observations from a number of sources.

Models generally produce gridded output, whereas observed profiles (e.g., radiosondes) are not gridded; i.e., the observations are not uniformly sampled geographically or in altitude. However, none of the updated sources of data provide the complete set of temperature and wind speed profile information needed for infrasound modeling. In particular, most available data pertain to altitudes less than approximately 35 km, whereas propagation modeling requires information well into the thermosphere (approx. 120 km).

Therefore, empirical atmospheric models remain an essential tool for estimating the environment, particularly at high altitudes. Supplementing the climatological models with available near-real-time updates is likely 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. The incorporation of updated atmospheric information, in the form of synoptic models or *in situ* measurements, will allow estimates of the propagation environment to be improved over the baseline climatology. Furthermore, it is desired to increase the capability of the InfraMAP software by offering greater flexibility in the range of data sources that can be accommodated.

Investigations have begun into the improvements attainable in propagation modeling by incorporating near-real-time atmospheric updates. The first steps are to develop links to near-real-time atmospheric observations or grids and to import the files for use in InfraMAP in conjunction with the HWM and MSISE empirical characterizations.

Based on the early success of empirical models at defining the propagation environment in the baseline InfraMAP software, automated integration of *in situ* data sources with propagation models has so far been determined not to be a high priority. However, the software provides a capability to incorporate updated atmospheric profiles, for purposes of evaluating potential improvements in propagation modeling. InfraMAP currently provides an option for user-defined atmospheric profiles for range-independent propagation modeling. Thus, updated wind and temperature data, such as from radiosonde observations, can be incorporated with the propagation models. Radiosonde observations are currently available twice a day from over a thousand weather stations worldwide. However, many regions of the world, particularly in the southern hemisphere, do not have dense radiosonde coverage. Available measurements consist of temperature, wind speed and direction from the ground up to approximately 35-km altitude (10-mb atmospheric pressure). Examples of observed temperatures from several radiosondes in the southwestern US on 23 April 2001, corresponding to observation of the Pacific bolide, are presented along with corresponding MSISE-90 characterizations in Figure 1. Observed zonal and meridional winds for the same radiosondes are shown along with corresponding HWM-93 characterizations in Figure 2.

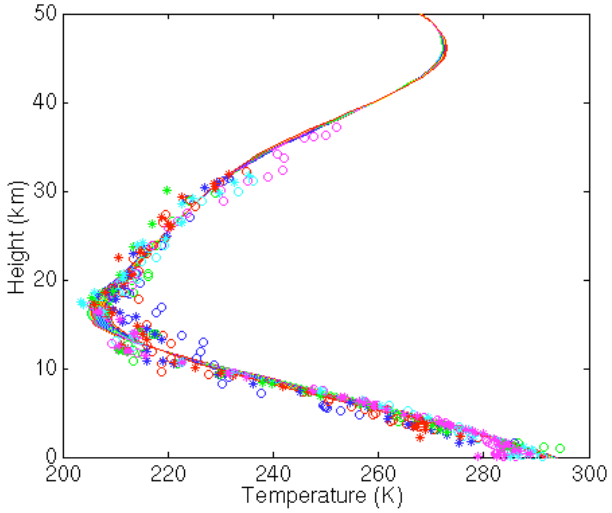

Figure 1. Radiosonde observations of temperature in the southwestern US on 23 April 2001 (shown as symbols) and corresponding MSISE-90 characterizations (shown as lines).

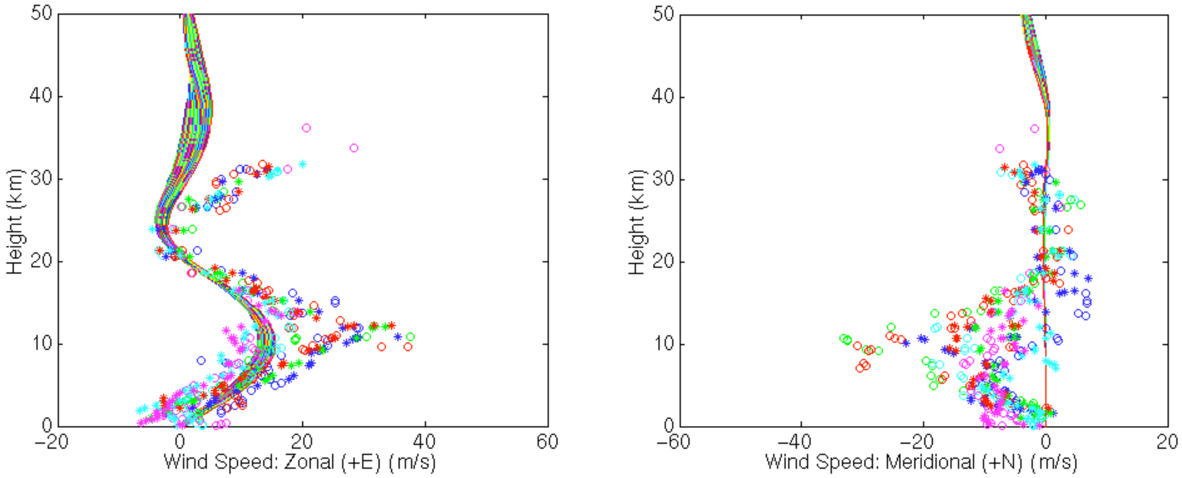

Figure 2. Radiosonde observations of zonal wind (left) and meridional wind (right) in the southwestern US on 23 April 2001 (shown as symbols) and corresponding HWM-93 characterizations (shown as lines).

In this instance, observed temperatures are well represented by the climatological model. The model of mean wind does not capture all of the features of the radiosonde wind observations, particularly the magnitude of the jet stream at approximately 10 km.

Prognostic models such as the Navy Operational Global Atmospheric Prediction System (NOGAPS) provide near-real-time, global grids of temperature and wind over three spatial dimensions. NOGAPS, originated by the Navy's Fleet Numerical Meteorology and Oceanography Center (FNMOC), is a numerical weather prediction model that utilizes not only profiles measured by radiosondes, but also an extensive data set of ship-based, land-based and satellite measurements to provide gridded temperature and wind speed at a range of altitudes. NOGAPS is a promising environmental model for use with infrasound propagation models due to its global domain and relatively high altitude coverage. The NOGAPS integration domain is from the ground to the 1-mb pressure surface (approximately 50 km), and output data are readily available up to the 10-mb pressure surface (approx. 30-35 km). Output products from NOGAPS have been obtained and decoded for purposes of integration and testing.

An example of a subset of gridded zonal wind profiles from NOGAPS is shown in Figure 3. The profiles are for a fixed time and date at the grid points defined in a 7.7 degree by 6.5 degree region over the southwestern US. These are compared to HWM-93 model output, over the same region, date and time. Mean zonal winds in the region are well predicted by the climatological model, but greater variability is shown in the NOGAPS model output.

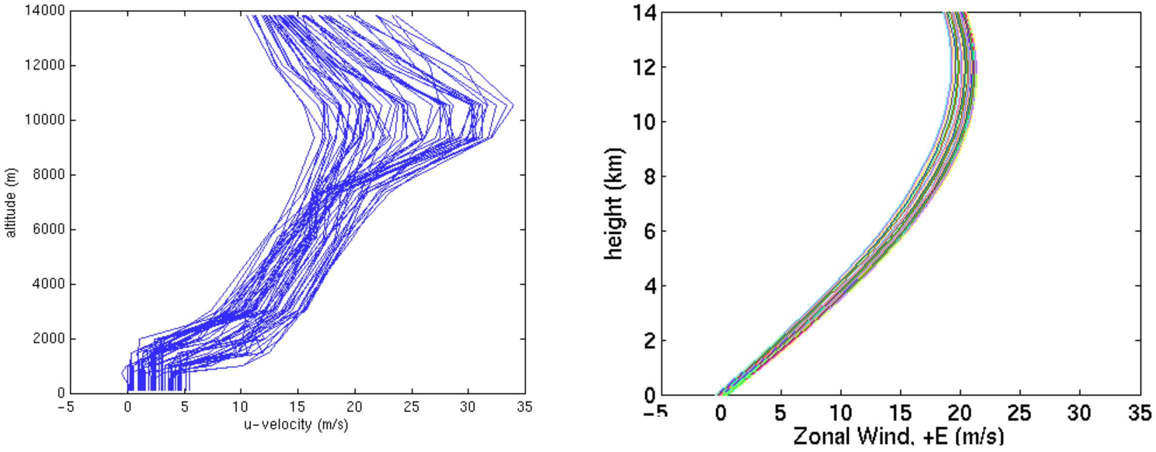

Figure 3. Predictions of zonal wind over a region in the southwestern US using NOGAPS (left) and HWM-93 (right).

Propagation models in InfraMAP interface with environmental characterizations in three ways:

- Range dependent, using the empirical atmospheric model functions to determine the environment at each step;
- Range independent, using average profiles determined from the empirical models evaluated along the propagation path;
- Range independent, using user-defined profiles.

In order to accommodate an environment defined by a gridded database such as NOGAPS, modifications must be made to InfraMAP's interface between propagation and environmental software modules, particularly in order to allow range dependence. There are a number of technical issues to be addressed, including: interpolation and extrapolation techniques; formation of consistent, repeatable representations; and evaluation of prediction sensitivity to interpolation methods. To propagate three-dimensional rays through gridded data, wind and temperature values and their spatial derivatives must be estimated at each point along a ray path. Because ray models are highly sensitive to sharp changes in sound speed, the estimation approach must avoid introducing gradient variability that is not inherent in the original data grid. A natural cubic spline algorithm is being developed to interpolate data for use with ray modeling. Cubic spline interpolation provides a smooth first derivative and continuous second derivative, ensuring compatibility with the ray model. Algorithms are currently being tested for integration into InfraMAP.

The enhanced InfraMAP capabilities that are being developed in this effort are shown schematically in Figure 4. The baseline InfraMAP functionality is shown in light gray, the capabilities that are currently being developed in a separate effort (Norris and Gibson, 2002) are shown in dark gray, and the new components under development in this effort are shown in blue.

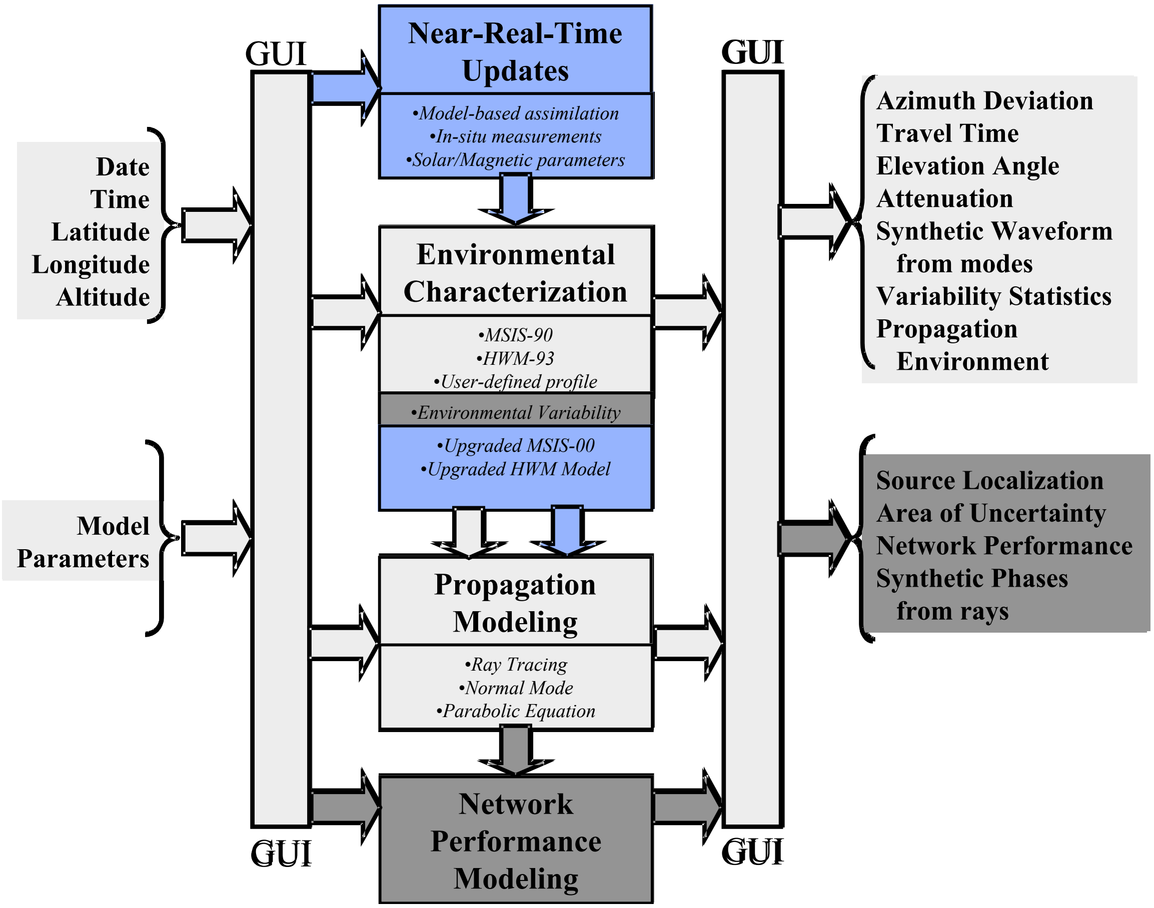

Figure 4. Schematic representation of InfraMAP functionality, with capabilities being developed in this effort shown in blue.

Model validation using infrasound from rocket launches

Validation efforts are essential to build confidence in the modeling procedures and to identify areas where further refinements are required. Where ground truth is available, validation results support event localization, phase identification and calibration efforts.

Rocket launches may serve as useful ground truth data for infrasound (McLaughlin *et al*., 2000) and also represent an excellent source of opportunity for model validation. Space shuttle launches from Cape Kennedy, Florida, have recently been observed at infrasound arrays at Los Alamos, New Mexico, (DLIAR prototype array) and at Lac du Bonnet, Canada (IS10 array). Rocket and missile launches from the eastern US were observed extensively in the 1960’s and 1970’s by infrasound arrays at Palisades, New York, and elsewhere, and Balachandran and Donn (1971) and other scientists at Lamont-Doherty Geological Observatory and the US Army Electronics Command issued a series of reports. A number of important findings resulted from this early work, including identification of two distinct source regions, one near the launch site and one near the re-entry location of the first stage.

Trajectories for specific shuttle missions have been modeled using actual launch parameters. Trajectories for the shuttle’s solid rocket boosters, which are released from the orbiter approximately two minutes into the ascent, have also been estimated. Modeled trajectories for two observed shuttle missions, STS-96 (27 May 1999) and STS-93 (23 July 1999) are shown in Figure 5. Launch ascent trajectories for a typical mission of shuttle orbiter and solid rocket boosters (SRB) are shown in Figure 6.

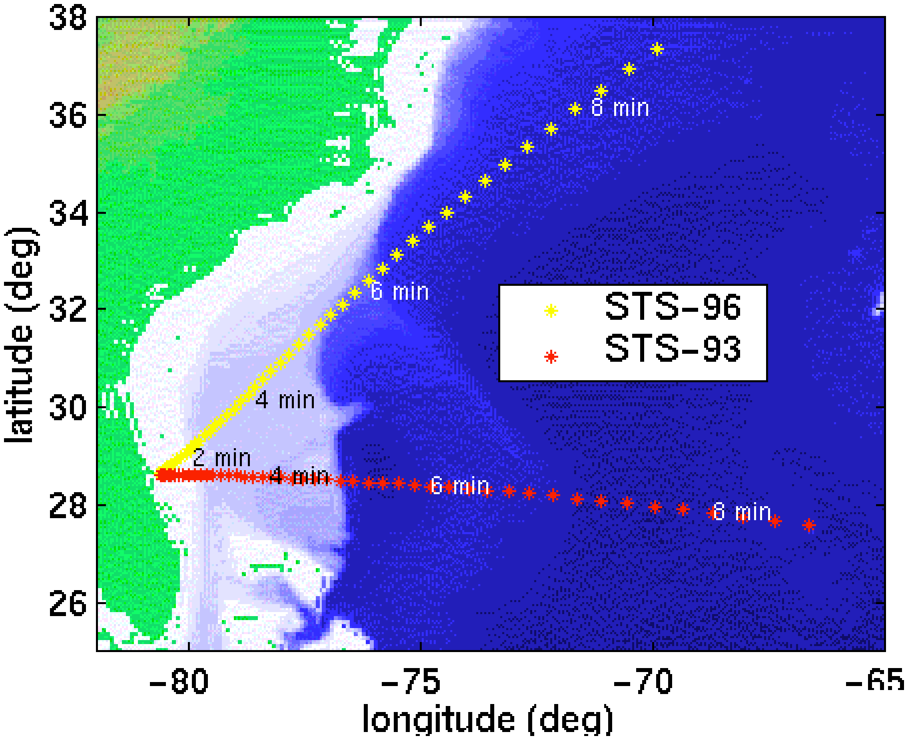

Figure 5: Space shuttle trajectories for two missions.

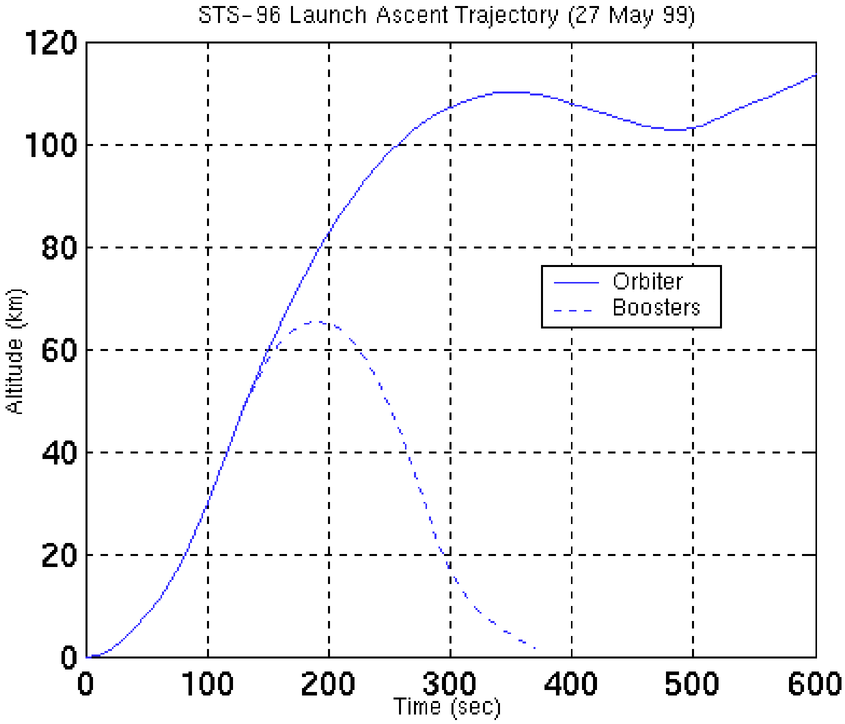

Figure 6: Space shuttle orbiter and solid rocket booster trajectories.

InfraMAP was used to determine eigenrays to DLIAR from points along the STS-96 trajectory, with HWM-93 and MSISE-90 used for environmental characterization. The continuously moving source was modeled as a series of discrete sources separated in space and time. A source was modeled every 10 seconds from the launch time out to 5 minutes after launch for the orbiter and from 200 seconds out to 6 minutes after launch for the solid rocket boosters. For each eigenray, an arrival azimuth and an arrival time (referenced to the launch time) were determined. Results are shown in Figure 7. Stratospheric rays and thermospheric rays are depicted separately for both the orbiter and the SRB. Also shown in the figure (as red asterisks) are results from the observation at DLIAR, determined by analysis using the InfraTool component of the MatSeis software package (Harris and Young, 1996).

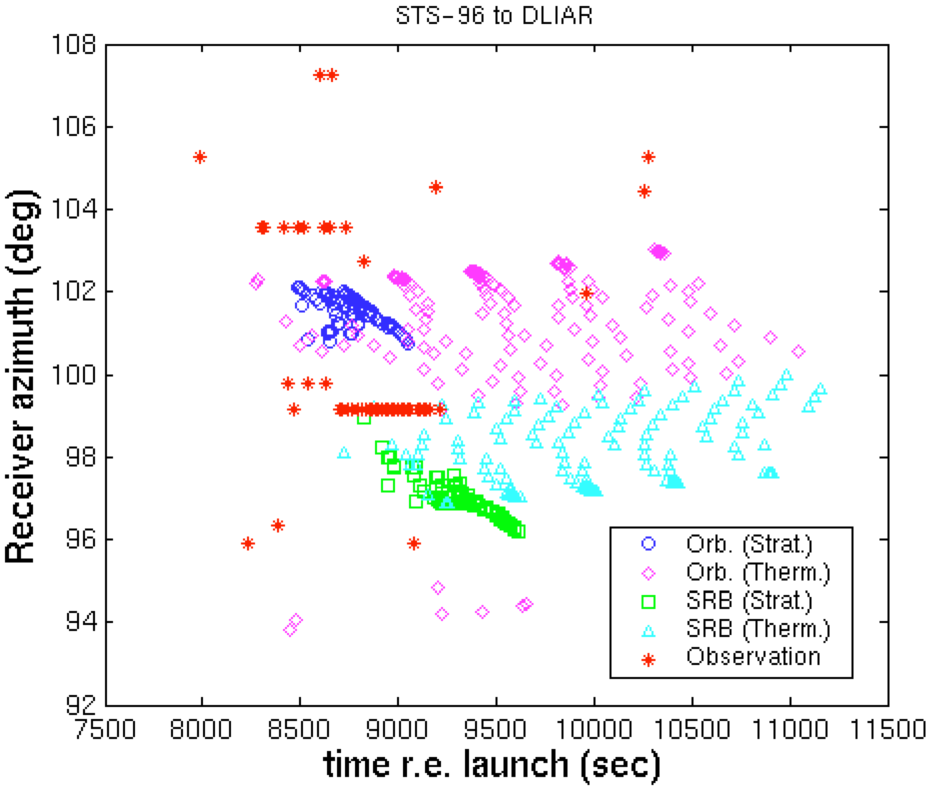

Figure 7: Predicted and observed infrasound arrivals from STS-96 to DLIAR.

The two primary observed arrivals (at approximately 103.5 and 99 degrees) are reasonably well modeled by the stratospheric rays from the orbiter (blue circles) and boosters (green squares), respectively. However, a bias in azimuth of approximately 2 degrees can be seen for both primary arrivals. Further modeling of the launch event using an updated atmospheric characterization, in order to see if travel-time and azimuth predictions could be improved, is of interest in this case.

Further investigation into this and other rocket launches, such as those of the Titan IVB, is underway. Data have been collected and trajectories modeled for several missions from 1998 to the present. Trends of observability, arrival time, and azimuth are being analyzed. Propagation model results are compared with observations and biases quantified. Several technical issues are of interest during this study, including:

- The modeling improvements achievable with near-real-time updates as compared to HWM and MSISE;
- Further understanding of the infrasound source mechanism in order to identify the regions of the trajectory (altitude, velocity, etc.) that contribute most strongly to observed signals;
- Quantifying attenuation along the ray paths to support identification of observed phases;
- The use of propagation modeling to predict observability of events.

The results of the analyses will serve to validate the environmental and propagation modeling techniques.

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 large location errors. *In situ* observations of winds and temperature can be used in InfraMAP for range-independent propagation modeling. Techniques are being developed to integrate output from the NOGAPS numerical weather prediction model with range-dependent propagation models. InfraMAP's integrated set of models will allow for higher fidelity propagation modeling than has previously been available to the infrasound monitoring community. As new high-fidelity environmental characterizations become available, they should be considered for integration into an enhanced version of the InfraMAP software.

Rocket launches generate infrasound signals for use in model validation studies. Infrasound is generated by both rocket ascent and booster descent. Launch trajectory models provide useful approximations of ground truth for use in conjunction with propagation modeling. Comparisons of measured and modeled arrival times and azimuths suggest that baseline infrasound modeling techniques are good but that higher fidelity would likely be obtained with the use of near-real-time wind and temperature characterizations. Further modeling of a large set of observed events, using updated atmospheric characterizations, is recommended in order to quantify the improvements in travel-time and azimuth predictions that are achievable.

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