Project SIFT (Short-term Inundation Forecasting for Tsunamis)

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Abstract. PMEL's Project SIFT conducts research and development to provide the Pacific Disaster Center (PDC) and NOAA's Tsunami Warning Centers with forecast guidance tools during an actual tsumami event. The Method Of Splitting Tsunami (MOST) model is being used to create a forecast database of pre-computed generation/propagation and inundation scenarios, which will be combined with real-time data to optimize the final, site-specific forecast. The current effort concentrates on forecasting the inundation of Hilo and Kahului, Hawaii by tsunamis generated by earthquakes in the Alaska Aleutian Seismic Zone. The initial real-time data stream to be assimilated consists of seismic information and tsunami measurements acquired by Deep-ocean Assessment and Reporting of Tsunamis (DART) systems. First, offshore wave parameters will be estimated by exploiting the linearity of tsunami generation/propagation scenarios to construct a composite solution that best matches the available seismic and DART data (Titov and González, 1999). These offshore estimates are then combined with the site-specific inundation scenarios to construct an inundation forecast for that particular location. An overview of the implementation and testing of this methodology for the Hawaii sites will be presented. Future plans include the assimilation of coastal tide gage data and an extension of coverage to West Coast, Alaska, Hawaii, and other Pacific island communities at risk.

1. The Need for SIFT

Emergency managers and other officials are in urgent need of operational tools that will provide short-term inundation forecasting for tsunamis (SIFT) as guidance for rapid, critical decisions in which lives and property are at stake. These decision-makers must issue warnings, direct vessels to put to sea, order the evacuation of coastal communities, send search-and-rescue teams into the disaster area, and sound an "all clear" that officially declares to citizens and vessel operators that it is safe to return to homes, businesses, coastal ports, and harbors. Because such decisions must be made throughout the life of the emergency, forecasts must be constantly updated to assess the current hazard and provide continual guidance during the entire duration of the event.

2. Exploitation of Measurement and Modeling Technologies

Recent advances in tsunami measurement and numerical modeling technology can be exploited, combined, and integrated to create an optimal tsunami forecasting system. Neither technology can do the job alone. Observational

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networks will never be sufficiently dense; the ocean is vast, and establishing and maintaining monitoring stations is costly and difficult, especially in deep water. Numerical model accuracy is inherently limited by errors in bathymetry and topography and uncertainties in the generating mechanism, especially in the near field; furthermore, case studies that compare model results with observations generally demonstrate that model accuracy degrades with successive tsunami waves.

Weather forecasting is an obvious example in which models and real-time data are combined to improve predictions by using data assimilation techniques to optimize agreement between model simulations and observations. Essentially, the model functions as a sophisticated space-time interpolator between measurement stations.

3. Time as a Fundamental Constraint

Even a perfect SIFT capability requires a finite period of time to acquire seismic and tsunami data and execute a forecast algorithm. And it can be expected that the more time available to prepare a forecast, the more effective the forecast—more observational data can be incorporated into the forecast and more time is available for evacuation or other appropriate community responses. Thus, in emergency management terms, SIFT will be more effective in the case of a “distant tsunami” than the case of a “local tsunami.” This can also be stated in simple mathematical terms. If t_M is the tsunami travel time to a measurement station, t_C is the arrival time at a coastal community, and T is the (effective) period of the first tsunami wave, then the time available to acquire adequate tsunami data and provide a forecast before the tsunami strikes is approximately

$$t_F = t_C - \left(t_M + \frac{T}{4} \right).$$

Here, it is assumed that the forecast algorithm execution time is negligible, that the magnitude of the first tsunami extremum is essential input to the algorithm, and $T/4$ is the time delay for arrival of the first extremum at the measurement station. This can be written

$$t_F = (t_C - t_M) - \frac{T}{4} = t_{CM} - \frac{T}{4}$$

where t_{CM} is the time difference between arrival of the first wave at the coastal community and the measurement station. Thus, the greater the inequality $t_{CM} > T/4$, the more effective we can expect the forecast to be.

Physically, t_{CM} is maximized if the measurement station is near the source and the threatened community is far from the source, i.e., if t_C is large and t_M is small. It is minimized when either (a) the community is very near the source, i.e., t_C is small, or (b) the station is very near the community, i.e., $t_C \sim t_M$, regardless of the source location. We also note that the wave period, T, is typically in the range 5–45 minutes, but is generally longer for large tsunamis and shorter for small tsunamis. In addition, for a given tsunami, it can be expected that dispersive effects will result in a shorter T in the near-field.

4. SIFT Measurement Strategy

The above discussion suggests that, although we have no control over t_C, we could attempt to minimize t_M by establishing measurement stations near potential sources. However, most sources produce a tsunami that is, to a greater or lesser degree, directional. This generally means that the closer a station is to one potential source, the less coverage that station provides for other potential sources in the area. Station siting strategy, therefore, must involve a careful trade-off between (a) minimizing t_M, tsunami travel time to a measurement station, and (b) maximizing the area of potential sources covered by that station.

5. SIFT Modeling Strategy

A "Holy Grail" of the tsunami modeling community is the **real-time model forecast**—i.e., the provision of site- and event-specific generation/propagation/inundation scenarios by numerical model computations that are initiated at the onset of an event and completed well before the first wave arrives at threatened sites. Technical obstacles to achieving this are many, but three primary requirements are *accuracy*, *speed*, and *robustness*.

5.1 Accuracy

Errors in two broad categories are especially important:

- *Model Physics Error.* The physics of propagation are better understood than that of generation and inundation. For example, landslide generation physics is currently a very active research topic, and comparative studies have demonstrated significant differences in the ability of inundation models to reproduce idealized test cases and/or field observations.

- *Model Input Error.* This issue is also known as the "garbage in, garbage out" problem, i.e., model accuracy can be degraded by errors in (a) the Initial Conditions set for the sea surface and water velocity, due to inadequate physics and/or observational information, and (b) the bathymetry/topography computational grid, due to inadequate areal coverage, resolution and accuracy, including the difficult issues encountered in merging data from different sources.

Generally speaking, the practical manifestation of these errors are *temporal* and *near-field degradation* of model accuracy. *Temporal degradation* refers to the fact that only the first few wave computations can be considered reliable. Thus, forecasting later tsunami waves with existing deterministic numerical models is generally not possible. However, near-site tsunami observations can be subjected to efficient, newly-developed statistical algorithms that provide estimates of the largest future tsunami wave expected during a particular event. *Near-field degradation* refers to the fact that near-field computations are generally very sensitive to spatio-temporal details of the source and computational grid. In contrast, far-field solutions are much less sensitive to spatio-temporal details of the source; for example, numerical experiments demonstrate that the far-field solution depends primarily on the magnitude and location of the epicenter and is relatively insensitive to other earthquake parameters. Furthermore, hindcast studies indicate that if existing numerical models are exercised and interpreted with care by an experienced tsunami modeler, they can produce results that adequately match measurements of the first few waves in the far-field.

5.2 Speed

We refer here to **forecast speed**, relating to the time taken to make the first forecast product available to an emergency manager for interpretation and guidance. This process involves at least two important, potentially time-consuming, steps:

- *Source Specification.* Seismic wave data are generally available first, but finite time is required to interpret these signals in terms of descriptive parameters for earthquakes, landslides, and other potential source mechanisms. Tsunami waves travel much slower and, as noted above, time on the order of $T/4$ will be needed to incorporate these data into a forecast. Seismic networks are much more dense than tsunami monitoring networks, but inversion algorithms for both must be developed that provide greater source detail, more rapidly.

- *Computation.* Currently available computational power can provide useful, far-field, real-time forecasts before the first tsunami strikes a threatened community; if the time available for forecasting, t_F, is sufficiently large, the source can be quickly specified, and an accurate computational grid is available. In fact, if powerful parallel computers and/or pre-computed model results are exploited, model execution time can be reduced almost to zero so that the minimum t_F required for an effective forecast might be very small, at least in principle.

In practice, of course, there will always be situations for which $t_F < 0$, i.e., in which the source-site geometry makes it impossible to provide a warning forecast. But even a late forecast will still provide valuable assessment guidance to emergency managers responsible for critical decisions regarding response, recovery, and search-and-rescue.

5.3 Robustness

With lives and property at stake, reliability standards for a real-time forecasting system are understandably high, and the development of such a system is a difficult challenge. It is one thing for an experienced modeler to perform a hindcast study and obtain reasonable, reliable results; such exercises typically take months to complete, during which multiple runs can be made with variations in the model input and/or the computational grid that are suggested by improved observations and/or speculative experimentation, and the results examined for errors and reasonableness. It is quite another matter to design and develop a system that will provide reliable results in real time, without the oversight of an experienced modeler.

The previous discussion suggests that critical components of SIFT technology exist now that could provide rapid, usefully accurate forecasts of a limited but important category—the first few waves of a far-field, earthquake-generated tsunami. In particular, it seems feasible to develop a forecast system that combines real-time seismic and tsunami data with a forecast database of pre-computed event- and site-specific scenarios that have been thoroughly tested and scrutinized for reasonableness and sensitivity to errors. Later waves could also be usefully forecast by processing real-time tsunami data with a statistical/empirical model. Implementation of this technology requires integration of these components into a unified, robust system. This is the strategy adopted by the NOAA/PMEL SIFT Project.

6. The NOAA/PMEL SIFT Project

In the event of a Pacific Rim earthquake, the National Oceanic and Atmospheric Administration (NOAA) bears primary responsibility in the United States for real-time assessment of the tsunami hazard and, if warranted, the issuance of a warning. Similarly, the Department of Defense's Pacific Disaster Center (PDC) is responsible for providing timely and accurate information to emergency managers during a disaster. The PMEL Tsunami Program is developing a SIFT methodology for both early and later tsunami waves. Different modeling solutions are used for different stages of tsunami evolution: generation, propagation, and inundation.

6.1 Generation

The generation process of a tsunami wave may never be understood in all the details needed for short-term inundation forecasting. Many source models have been shown to produce very good agreement with observation. However, most of the data used for these source models are collected over long periods of time after the event and often include tsunami inundation observations—the very data we are trying to forecast. This problem has been long recognized in the tsunami community and real-time tsunami observations have been identified as a key for better source determination (Synolakis *et al.*, 1997).

Direct tsunami observation, however, may never be dense enough to obtain all the parameters of the tsunami source. Sensitivity studies have been performed to identify and reduce the number source parameters that are important for tsunami generation and for the short-term forecasting. Numerical experiments demonstrate that far-field solutions depend primarily on the magnitude and location of the epicenter and are relatively insensitive to other earthquake parameters. For local forecast, on the other hand, site-specific source characteristics—such as local asperities or earthquake induced landslides—are most important for tsunami forecast. In either case, only partial source characterization is needed for the tsunami forecast and limited tsunami observation can provide the data needed.

6.2 Propagation

Sensitivity studies suggest that rapid, useful forecasts of the first few waves of a far-field tsunami might be provided by a limited-size database of pre-computed scenarios that have been thoroughly tested and scrutinized for reasonableness and sensitivity to errors. Web-based user interface has been developed to exploit the database approach for the offshore forecasting. The interface allows creating a variety of offshore tsunami propagation scenarios by combining pre-computed propagation solutions. Combined with a data assimilation scheme, this approach can provide quick estimates of tsunami offshore propagation that conform to real-time buoy observations.

A data assimilation scheme is under development to combine real-time DART data of tsunami offshore amplitude with the forecast database to improve accuracy of an offshore tsunami scenario. This is a very important component of SIFT methodology, since it provides corrections for the initial imperfect “guesses” of the generation model.

6.3 Inundation

Once the offshore scenario is obtained, the results of the propagation run are used for the site-specific inundation forecast. That is achieved in two ways. Fast preliminary estimates of inundation amplitudes can be obtained by a 1-dimensional run-up model (1 spatial dimension). The method uses results of the offshore simulation at a point offshore the target coastline as initial conditions for 1-dimensional run-up computation along selected a bathy-topo transect. The approach assumes that the wave has little long-shore dissipation. This technique was pioneered by Titov and Synolakis (1993, 1995) and has been tested to model inundation amplitudes for a number of historical events (Bourgeois *et al.*, 1999; Titov and González, 1999; Titov and Synolakis, 1993). Although the method uses simplified assumptions about tsunami inundation it can provide timely preliminary estimates of averaged tsunami run-up along a uniform portion of a coast. The advantage of having this capability is the quickness of the prediction, which can be obtained virtually at the same time as the offshore forecast. Using the 1-D run-up approach, the site-specific inundation forecast can be completed in a matter of seconds after receiving observation data. The speed and robustness of the 1-D inundation prediction can be exploited for a local tsunami forecasting, using direct input from a real-time gage measurement.

Inundation modeling in two spatial dimensions demands more computer power, time, and needs much more input data to perform an inundation forecast. At the same time, it is a more realistic simulation of the event and, therefore, can produce a more reliable forecast. Again, the input for the 2-D inundation computations are the results of the offshore forecast—tsunami parameters along the perimeter of a 2-D inundation study area. Our tests show that an inundation forecast for the first several waves at Hilo, Hawaii for a tsunami originating near Alaska can be obtained in about 20 min from the time when the offshore forecast is complete.

In summary, to forecast inundation by early tsunami waves, seismic parameter estimates and tsunami measurements are used to **sift** through a pre-computed generation/propagation forecast database and select an appropriate (linear) combination of scenarios that most closely matches the observational data. This produces estimates of tsunami characteristics in deep water which can then be used as initial conditions for a site-specific (nonlinear) inundation algorithm. A statistical methodology has been developed to forecast the maximum height of later tsunami waves that can threaten rescue and recovery operations. The results are made available through a user-friendly interface to aid hazard assessment and decision-making by emergency managers. The focus of this initial effort is on forecasting inundation at selected sites in Hawaii by tsunamis generated by earthquakes in the Alaska-Aleutian Subduction Zone (AASZ). Computations of generation/propagation scenarios for the forecast database are performed by the Method of Splitting Tsunami (MOST) model. Fast, preliminary inundation forecasts are computed by a 1-dimensional model; slower, but more detailed and accurate forecasts are provided by a 2-dimensional model. Tsunami measurements are provided by local Hawaii tide gauge stations and by real-time reporting tsunami measurement stations established near the AASZ by the PMEL Deep-ocean Assessment and Reporting of Tsunamis (DART) Project.

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7. References

Bourgeois, J., C. Petroff, H. Yeh, V. Titov, C. Synolakis, B. Benson, J. Kuroiwa, J. Lander, and E. Norabuena (1999): Geologic setting, field survey and modeling of the Chimbote, northern Peru, tsunami of 21 February 1996. *Pure Appl. Geophys., 154*(3/4), 513–540.

Synolakis, C.E., P. Liu, G. Carrier, and H. Yeh (1997): Tsunamigenic sea-floor deformations. *Science, 278*, 598–600.

Titov, V.V., and F.I. González (1999): Numerical study of the source of the July 17, 1998 PNG tsunami. *IUGG '99 Abstracts*, Birmingham, 19–30 July 1999.

Titov, V.V., and C.E. Synolakis (1995): Modeling of breaking and nonbreaking long wave evolution and runup using VTCS-2. *J. Waterway Port Coast. Ocean Eng., 121*(6), 308–316.

Titov, V.V., and C.E. Synolakis (1993): A numerical study of the 9/1/92 Nicaraguan tsunami. *Proceedings of the IUGG/IOC International Tsunami Symposium*, Wakayama, Japan, Japan Society of Civil Engineers, 585–598.