NOAA Tsunami Forecasting System
SIFT Overview

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Concepts and algorithms used in SIFT

SIFT (Short-term Inundation Forecasting for Tsunamis) is a tsunami forecasting system that combines real-time tsunami event data with numerical models to produce forecasts of tsunami wave arrival times and amplitudes.

SIFT is comprised of various algorithms that calculate the following tsunami forecasts:

- Propagation (Composite) Forecast of offshore wave amplitudes
- Travel times
- Coastal and DART™ Station Forecasts of travel times and first wave amplitudes
- Time Series of the tsunami wave train at Warning Points, DART™ buoys, coastal water-level stations

Offshore wave amplitudes and arrival times are based on a combination of pre-computed tsunami propagation solutions using the Method of Splitting Tsunamis (MOST) model. Each solution is based on a single unit source with a 7.5 moment magnitude (M_w) and a 1-meter slip. These solutions are scaled and linearly combined based on the magnitude and location of the earthquake event. Titov *et al.* (1999) and Gica *et al.* (2007) describe the methodology behind the pre-computed tsunami propagation solutions.

Unit Source Selection and Slip Distribution

Unit Sources

Unit sources are aligned to fit the geometries of known subduction zones and tsunamigenic faults. Refer to Kirby *et al.* (2006) for more details on defining unit sources. Each unit source has the following parameters:

- Length: 100 kilometers
- Width: 50 kilometers
- Slip angle: 90 degrees
- Depth: 5 kilometers on the offshore side

Slip

Dip and strike describe the orientation of the fault, we also have to describe the direction of motion across the fault. That is, which way did one side of the fault move with respect to the other. The parameter that describes this motion is called the slip. The *slip* has two components, a "magnitude" which tells us how far the rocks moved, and a direction (it's a vector). We usually specify the magnitude and direction separately.

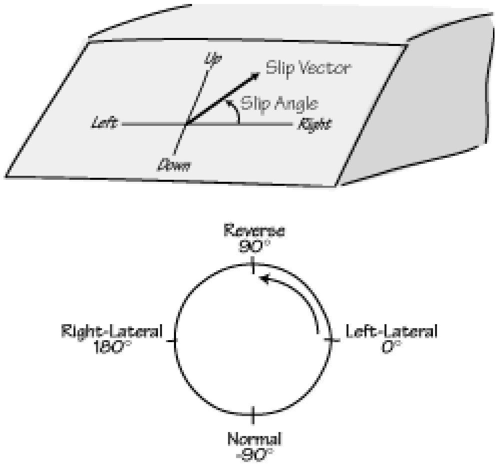

Figure 1.1 Slip angle.

The magnitude of slip is simply how far the two sides of the fault moved relative to one another; it's a distance usually a few centimeters for small earthquakes and meters for large events. The direction of slip is measured on the fault surface, and like the strike and dip, it is specified as an angle. Specifically the slip direction is the direction that the hanging wall moved relative to the footwall. If the hanging wall moves to the right, the slip direction is 0°; if it moves up, the slip angle is 90°, if it moves to the left, the slip angle is 180°, and if it moves down, the slip angle is 270° or -90°. (Reference: http://eqseis.geosc.psu.edu/~cammon/HTML/Classes/IntroQuakes/Notes/faults.html)

Algorithms for unit source selection and slip distribution

Unit sources are selected and the slip distribution is determined in one of two ways:

1. Automatic selection based on Seismic Monitor Client or TestEvent input of the earthquake epicenter location and moment magnitude (M_w).
2. Manual selection through the SIFTView *Source Editor*

Unit sources are selected automatically by first determining the total number of unit sources and the width needed based on the moment magnitude (Table 3.1). Then the appropriate number of unit sources that are closest to the epicenter location are selected. A list of unit sources is created ordered by increasing distance from the epicenter to the center of the unit source. The closest unit source is chosen first, the second unit source is the closest to the epicenter if it has the same grid, zone, and position number and the width count has not been exceeded. The third unit source will be the closest to the epicenter that has the same zone as the first unit source as long as the width count has not been exceeded. The fourth will be the closest to the epicenter if it has the same grid, zone, and position number as the third as long as the width count has not been exceeded. If no unit source is found or the width count has been exceeded, the next closest is chosen that has the same zone as the first unit source and is adjacent to an already selected unit source. This pair-wise selection continues until all unit sources have been found.

M_W values	Number of Unit sources	Width of sources	Number for inversion	Width for inversion
$M_W <= 7.9$	1	1	6	2
$7.9 < M_W <= 8.05$	2	1	8	2
$8.05 < M_W <= 8.3$	4	2	12	3
$8.3 < M_W <= 8.6$	6	2	15	3
$8.6 < M_W <= 8.8$	8	2	18	3
$8.8 < M_W <= 8.95$	15	3	28	4
$8.95 < M_W <= 9.09$	18	3	32	4
$9.09 < M_W <= 9.20$	21	3	36	4
$9.2 < M_W$	44	4	65	5

Table 1.1 Selection of unit sources is based on the magnitude and location.

Next, the total slip is distributed evenly across the selected unit sources. First, the seismic moment (M_0) is determined from the moment magnitude (M_w) by the empirical equation,

$$M_0 = 10^{1.5(M_W + 10.7)}$$

Then, the slip (u_0) is determined by the equation,

$$u_0 = \frac{M_0}{\mu A}$$

where μ is rock rigidity (4×10^{1} dyne/cm^2), and A is the total area for all unit sources. The total area is defined by

$$A = \sum_{i=1}^{S} L_i W_i$$

where S is the number of selected unit sources, and L_i and W_i are the length and width, respectively, of the i^{th} unit source.

The slip is then evenly distributed across all selected unit sources by the equation,

$$u_i = u_0$$

where u_i is the slip of a single selected unit source.

Offshore Wave Amplitude Forecasts

Offshore wave amplitudes are calculated to produce a *Propagation Forecast*. The Propagation Forecast is calculated using the selected unit source distribution based upon Table 3.1. Pre-computed model results are multiplied by the slip distribution for each unit source,

$$\eta_i = \alpha_i \eta_0$$

where η_0 is the pre-calculated amplitude at every n^{th} grid point where n is based on striding (default: $n = 5$), α_i is the component coefficient and η_i is the resultant amplitude of the selected unit source.

The resulting grids for each selected unit source are then summed,

$$\eta = \sum_{i=1}^{S} \eta_i$$

where S is the number of selected unit sources, and η is the composite amplitude. The maximum amplitude over the entire time series is determined for every n^{th} grid point, and the result is displayed in SIFTView. SIFT initially samples the grid at a course resolution to provide an immediate display of wave amplitudes and then progressively refines the forecast by subsampling the grid at higher resolutions (lower “skip” values). By default, SIFT produces a propagation forecast at spatial resolutions of 32,16, 8 and 4 grid points. The progressive refinement of the propagation forecast is defined using SIFT properties (see Appendix A in the SIFT System Manual).

Coastal Wave Amplitude Forecasts

The coastal forecast of wave amplitude is determined by scaling a pre-selected offshore grid point linearly to the coast by Green’s Law,

$$\eta_c(x_c, y_c) = \eta(x_g, y_g)\left[\frac{h(x_g, y_g)}{h_c(x_c, y_c)}\right]^{1/4}$$

where η_c and h_c are the coastal wave amplitude and depth, respectively, at the coastal location (x_c, y_c), and η and h are the scaled maximum wave amplitude and depth, respectively, of the offshore grid point (x_g, y_g). For this approximation, the coastal point is assumed to reside just off the coast at a depth of 1 centimeter,

$$h_c(x_c, y_c) = 1$$

Offshore grid points are selected as the nearest offshore value to the warning point that is outside of harbor or estuarine areas. Since the offshore grid points are not collocated at the warning point site and are at a different depth, it is necessary to adjust the wave travel time.

Assuming the slope between the offshore grid point and the warning point location is linear the time correction, Δt, is

$$\Delta t = \frac{2L}{\sqrt{gh_c} + \sqrt{gh_g}},$$

where L, and g are the distance between the warning point location and the offshore grid point and the acceleration due to gravity, respectively. The coastal forecast is shifted by the above time correction.

Modeled Time Series Forecasts

Time series are stored with each pre-computed propagation solution. *Maximum wave arrival time and travel time* are calculated from the time series of the scaled solution.

Maximum wave arrival time is the arrival time of the maximum wave crest over the entire time series. This is calculated from the time series of the nearest grid point to a specified point location for each warning point.

Travel time is the arrival time of the estimated front of the first significant wave.

Travel Time Calculation

Travel time, t, is defined to be when $\left|h(t)\right| \geq T^{\pm}$, where $h(t)$ is the wave amplitude (cm) time series and $T^{\pm}$ is the threshold. The threshold is made up of several components, the first two are based on the maximum amplitude, h_{max},

$$T_{h_{\max}} = 0.05 h_{\max}$$

and on the quatiziation, q, used in the time series compression (typically 0.001 cm),

$$T_{quant} = 2q \sum_{i} \left|a_i\right|$$

where a_i is the i^{th} unit source amplitude.

Using the maximum of $T_{h_{\max}}$ and T_{quant} works for most of the model domain, however, there are regions where this simple method of determining travel time, while technically correct, produces results that do not meet expectations.

Deformation Correction

One of the regions where the simple method of determining travel time produces results that do not meet expectations is in the immediate vicinity of the earthquake, where the deformation is large. The local deformation, which will cause an immediate raising or lowering of the sea surface, can be larger than h_{max} or h_{min} of the tsunami. Since the deformation causes an immediate change in the sea surface, the travel time for the tsunami near the earthquake is zero

(Figure 1.2 left panel). This effect can be accounted for by including the deformation threshold, T_D, in the calculation of the threshold $T^{\pm}$.

The deformation tends to dominate when $|D/D_{\max}| > 0.02$, where D is the local deformation and D_{max} is the maximum deformation. The initial deformation correction is $T_D = \varepsilon|D/D_{\max}|$. However, this correction can become very large and needs to be limited. The final correction is

$$T_D = \begin{cases} \varepsilon|D| & \text{if } |D/D_{max}| < 0.02 \\ \min(\varepsilon|D|, \beta^{-1} h_{max}) & \text{otherwise} \end{cases},$$

where ε and β are deformation threshold scaling constants with values of 3.0 and 7.0, respectively.

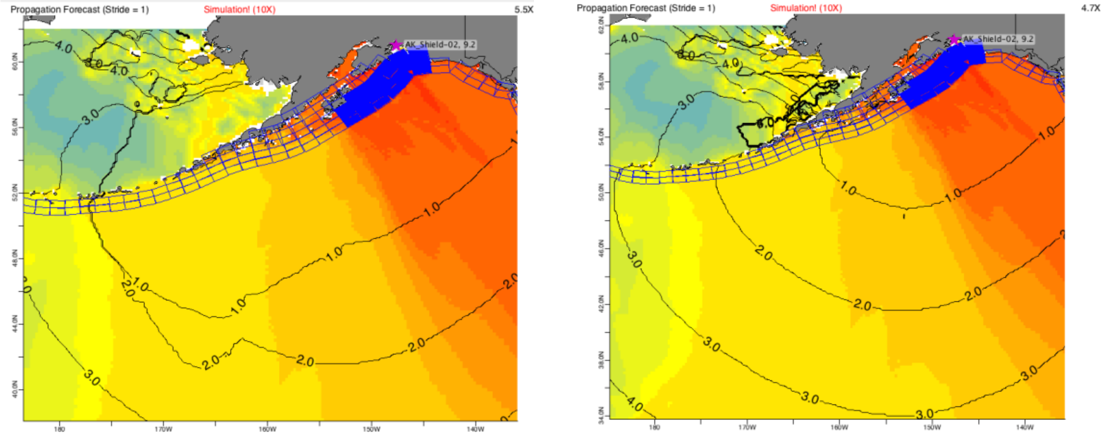

Figure 1.2: Travel time contours before (left) and after (right) the deformation correction.

Shielded Area Correction

An additional correction is required when a tsunami is shielded by one or more islands to the open ocean. The ocean beyond the islands then can have a very small tsunami, but still have a significant wave from the initial deformation. This can complicate finding the leading edge of the tsunami. To address this problem, an adjustment was made in the application of the quantization threshold, wherein a slightly different value of T_{quant} is used depending on the sign of the wave amplitude.

$T^{+}_{quant} = 0.75T_{quant}$, for $h > 0$ and $T^{-}_{quant} = 1.25T_{quant}$, for $h < 0$. The results of the shielded area correction are illustrated in Figure 1.3.

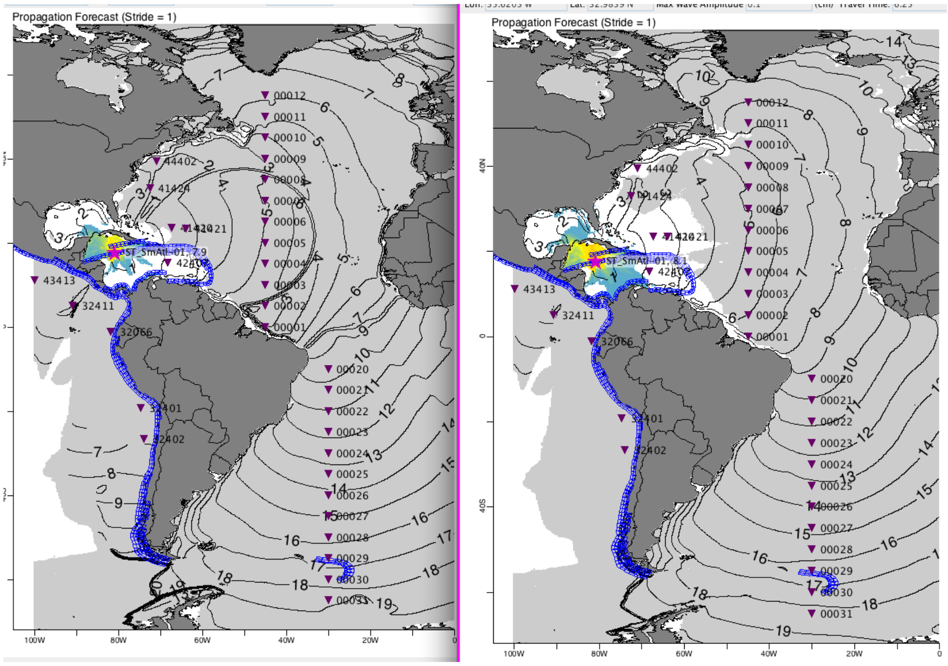

Figure 1.3: Travel time contours before (left) and after (right) applying the shielded area correction.

Corrected Travel Time Algorithm

Finally, it is useful to limit the magnitude of the threshold. The threshold limit, T_{max}, is presently set at 30 cm. Putting this altogether, the threshold, $T^{\pm}$ is defined to be

$$T^{\pm} = \min(T_{\max}, \max(T_D, T_{h_{\max}}, T^{\pm}_{quant})).$$

The *travel time* is calculated from the time series of the nearest offshore grid point to a specified point location for each warning point. These values are displayed as the arrival times in the *Coastal/Station Forecast* table. The *travel time* and *maximum wave arrival time* are, optionally, delineated on modeled time series in the *DART Forecast Series* plots.

DART Station Forecasts (DART Forecast)

The Station Forecast is a point forecast for a selection of water-level stations and their corresponding unit sources. Offshore grid points are selected from the propagation forecast as the nearest offshore value to the water-level station. These points are NOT scaled like the coastal forecast. *Maximum wave arrival time and travel time* are calculated from the time series of the solution in the same manner as the Modeled time series forecasts.

Note: Since these values are determined by the nearest grid point, they may not accurately reflect actual arrival times at specified station location. Model grid spacing is ~ 0.2667 degrees on our grid. At 110km per degree that is 29,337 meters. Worst case is 1/2 of this or 14,669 meters. Tsunami speed is ~ 200m/s so worst error is estimated to around 73 seconds

Filtered Observational Time Series

Ingested observational water level data are stored in the postgreSQL database called *sift_data*. These raw data are obtained from warning center water-level databases in real-time through the WaterLevel Monitor Client and the Data Service. Raw height data are then filtered using the Kalman Filter.

Optionally the EOF filtering method described by Tolkova (2009) may be used to filter the raw height data. This method uses the previous 24 hours of data to predict and remove tides:

> Principal component or Empirical Orthogonal Function (EOF) analysis is applied to tsunameter records by treating them as two-dimensional signals, where the second dimension is created by breaking a single time series into cycles and treating the cycle number as a second dimension. Under certain conditions, principal components calculated from different records are shown to determine the same functional space. Signal decomposition into pre-calculated principal components is used to predict or extract the tidal component of a record. (Tolkova 2009)

Quality Code Filtering in Observational Time Series

As real-time water-level are ingested into SIFT they are assigned a quality code which can be used to filter the data that are plotted in water-level plots or used in inversions. SIFT currently defines the following 3 quality codes:

QC_BAD: water-level datum is either missing (NaN: Not a Number) or outside the **allowed** range defined for a water-level station.

QC_QUESTIONABLE: water level datum is not missing and within allowed range but outside the **acceptable** range defined for a water-level station.

QC_GOOD: water-level datum is not missing and is within **acceptable** range for a water-level station.

Typical values for the allowed range are ±1000 m. Typical values for the acceptable range are ±5 m. See SIFT System Manual section on defining datastreams.

Dart Inversion, alpha and Meff

The DART Inversion process estimates *Effective Tsunami Magnitude (Meff)* parameter by means of a least squares method for fitting the model tsunami time series to the observed DART tsunami data:

> The fitting procedure estimates the source parameters of each Unit Source. Realistic confidence limits on the source parameters are obtained by fitting the residual series (from the data-fitted model) to a first-order autoregressive model to account for the obvious correlation between adjacent residual values.

> Using data from more than one buoy improves the source parameter estimates, at an operational cost of some delay in time for the tsunami to reach farther stations. An appropriate fit uses the first full tsunami wave at each station with no improvement found by extending the fitted data segment further. (Percival 2009).

Alpha is computed by the DART inversion process and is shown in the *DART Inversion* results window for each Unit Source. Alpha, α, is the least squares estimator (Percival, 2009), where

$$x = \alpha \bullet g(t) + e$$

where x is the detided data, g(t) is the precomputed model and e is the residual.

Moment magnitude Mw and/or Effective Tsunami Magnitude (Meff) and location are shown across the very bottom of the *Propagation Forecast* window, and Meff is shown in the DART Inversion results window. Mw refers to the initial event submitted to SIFT and is always displayed at the bottom of the Propagation Forecast window. Meff is computed by the Dart Inversion process, and is displayed only if the Propagation Forecast being displayed was computed using the results of a DART Inversion.

For guidance in using the DART Inversion, please see Guidelines and Recommendations for the use of the DART Data Inversion Tool, available on the SIFT documentation website at http://sift-docs.pmel.noaa.gov/.

Inundation Forecast Models

Inundation Forecast Models provide real-time tsunami estimates for selected coastal locations while the tsunami is propagating through the open ocean and before the waves have reached many coastlines. The Inundation Forecast Models combine the tsunami forecast model with high-resolution topography and bathymetry that has been optimized for computation speed for selected coastal communities. Inundation Forecast Models are validated and tested for robustness and can be used in conjunction with a database of tsunami propagation in deep water to provide real-time wave height and current forecasts for a particular community during a tsunami event. See http://nctr.pmel.noaa.gov/sim.html for more information and references.