分散性を考慮した津波波線追跡と初期海面変動の推定：2015年スミスカルデラ地震への適用
Ray tracing for dispersive tsunamis and estimation of initial sea-surface displacement: Application to the 2015 Smith Caldera earthquake

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Ray tracing method based on the optics theory has been applied to tsunamis in order to calculate travel times and refractions due to bathymetry variations. Previous methods are applicable to linear long-waves [e.g. *Satake*, 1988, PAGEOPH; *Woods and Okal*, 1987, GRL]. However, real tsunamis are dispersive, that is, have frequency-dependent propagation speeds so that the method needs to be extended to dispersive tsunamis.

The method is also used for estimation of the initial sea-surface displacement in combination of Green's law, that is based on the conservation law of the potential energy of linear long-waves [e.g. *Abe*, 1973, PEPI; *Satake*, 1988, PAGEOPH]. By using the law, previous studies estimated the height of the initial sea-surface displacement assuming that the peak amplitudes of the initial displacement and outgoing waves from a source region are the same. However, this assumption might lead to an underestimation of the initial wave height, because tsunami waves behave differently inside the source region.

In this study, we first propose a new ray-tracing method extended to dispersive tsunamis. We create frequency-dependent velocity maps from 2-D bathymetry data by solving iteratively the formula of dispersion relation of the linear gravity wave by a recursive algorithm. Then ray paths at different fixed frequencies are traced on the frequency-dependent velocity fields by integrating ray equations for seismic surface waves [e.g. *Yomogida and Aki*, 1985, JGR].

For more precise modeling of the initial sea-surface displacement, we investigate tsunami behaviors near the source region by waveform simulations to confirm that outgoing waves from the source region have a wave height less than a half of the height for various initial sea-surface displacement models. We propose an alternative way to estimate the initial sea-surface displacement. First, the source region is estimated by means of the back-projection using arrival times of tsunami signals at stations. Secondly, the wave height of outgoing waves from the source region is derived from an observed height by using Green's law. Finally, we obtain the height of the initial sea-surface displacement by using the ratio of the peak amplitudes of the initial static displacement models and simulated outgoing waves from the source region.

These two methods are applied to a real tsunami event that was caused by an abnormal volcanic earthquake near Smith Caldera with a diameter of about 7 km on the Izu-Bonin arc. The earthquake had a CLVD-type focal mechanism and generated larger tsunami waves compared to its magnitude (M5.7), and therefore the earthquake may be regarded as a "volcanic tsunami earthquake." Dispersive tsunamis were recorded by a dense array of ocean bottom pressure (OBP) gauges, 100 km to the NNE from the epicenter

[*Fukao et al.*, 2016, JpGU]. It is notable that the measured slowness direction of wavefront deviates from the great circle path and varies as a function of frequency.

Our new ray tracing for dispersive tsunamis shows that ray paths are significantly dependent on its frequency, particularly at deep oceans. Simulated slowness direction and arrival time at the array change as a function of frequency, which is consistent with the observations by *Fukao et al.* [2016, JpGU]. By minimizing the misfit between observation and ray tracing, the peak point of the tsunami source can be constrained within Smith Caldera. In addition, we model the initial sea-surface displacement using our new method with the tsunami data at the OBP array. The boundary of the source region is located close to the inner-wall of Smith Caldera. By assuming a column-shaped displacement with the size of Smith Caldera, we obtain the initial wave height of at least 30 cm. Although some uncertainties remain, these results imply that these methods are very powerful to preliminarily estimate the initial sea-surface displacement.

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