Sizing a tsunami

“With GDGPS data, we can reliably estimate a tsunami’s destructive potential within minutes, well before it reaches coastal areas.”

Tony Song
NASA Jet Propulsion Laboratory

by Laura Naranjo

Few people are likely to forget the 2004 Sumatra Earthquake, which produced a devastating tsunami that killed more than 230,000 people across Southeast Asia. When an undersea earthquake strikes near a coastal area or a remote seafloor, the resulting large ocean waves can cause more damage than the earthquake. Although warning systems are in place along many coastal areas, current methods of predicting tsunamis are sometimes inadequate. In the case of the Sumatra Earthquake, there was no warning system at all for the entire Indian Ocean.

Researcher Tony Song at the NASA Jet Propulsion Laboratory (JPL) has been leading a team to develop a way to quickly measure and forecast tsunami size and direction using models coupled with a worldwide network of Global Navigation Satellite System (GNSS) satellites and ground receivers. GNSS can capture a variety of measurements, including land movement resulting from coastal or undersea earthquakes. These data could provide a more direct measurement of strength of the energy unleashed. If researchers can score the magnitude of an earthquake and the intensity of a hurricane, why not create a warning scale for tsunamis?

A tsunami strikes northeast Japan after the 2011 Tohoku Earthquake, generating waves up to 133 feet high along some areas of the coast. Although the Japan Meteorological Agency issued a warning, the tsunami was responsible for more deaths and more damage than the earthquake itself. (Courtesy S. Tomizawa)

When Earth moves water

Traditionally, scientists have looked at the earthquake itself—using location, magnitude, and depth—to estimate the size and direction of the tsunami. As an oceanographer, Song knew that historic records had proven this method did not always work well. “The scale of the tsunami can be different from the earthquake scale,” he said. “Sometimes it’s the smaller earthquakes that can generate powerful tsunamis.”

The key to understanding tsunami risk was not in the earthquake itself, but in the energy it releases into the ocean. On land, that energy dissipates once the shaking has stopped. But under water, the energy transfers through the ocean, producing waves that ripple across the seas for hundreds or even thousands of miles. Out on the open ocean, these waves may not be noticeable, but once they encounter land, they pile up, creating the devastating walls of water that crash inland.

Scientists suspected that measuring this transfer of energy might help improve tsunami prediction. Song and his colleagues theorized that if they could measure the ground displacement caused by a coastal or undersea earthquake, they could more accurately determine when a tsunami is likely, and where those waves might go. They also thought that GNSS could provide those missing measurements.

As part of the GNSS network, highly accurate Global Positioning System (GPS) receivers located all over the planet record movement in Earth’s crust by triangulating signals with a constellation of satellites. Geodetic GNSS stations are much more precise than the GPS in phones and car navigation systems. For example, a consumer GPS device might be accurate to a few meters; geodetic GNSS can be accurate to a few centimeters, and in near-real time.

The hard part often involves collecting and processing that data in a timely manner, sometimes manually. For monitoring natural hazards, Song and his colleagues needed more timely data. So they developed a system to calculate the tsunami energy or scales directly from remotely retrieved real-time GNSS data in the Global Differential Global Positioning System (GDGPS), managed by JPL. GDGPS has more than 100 receivers worldwide, making it one of the largest real-time GPS systems in the world. “With GDGPS data, we can reliably estimate a tsunami’s destructive potential within minutes, well before it reaches coastal areas,” Song said.

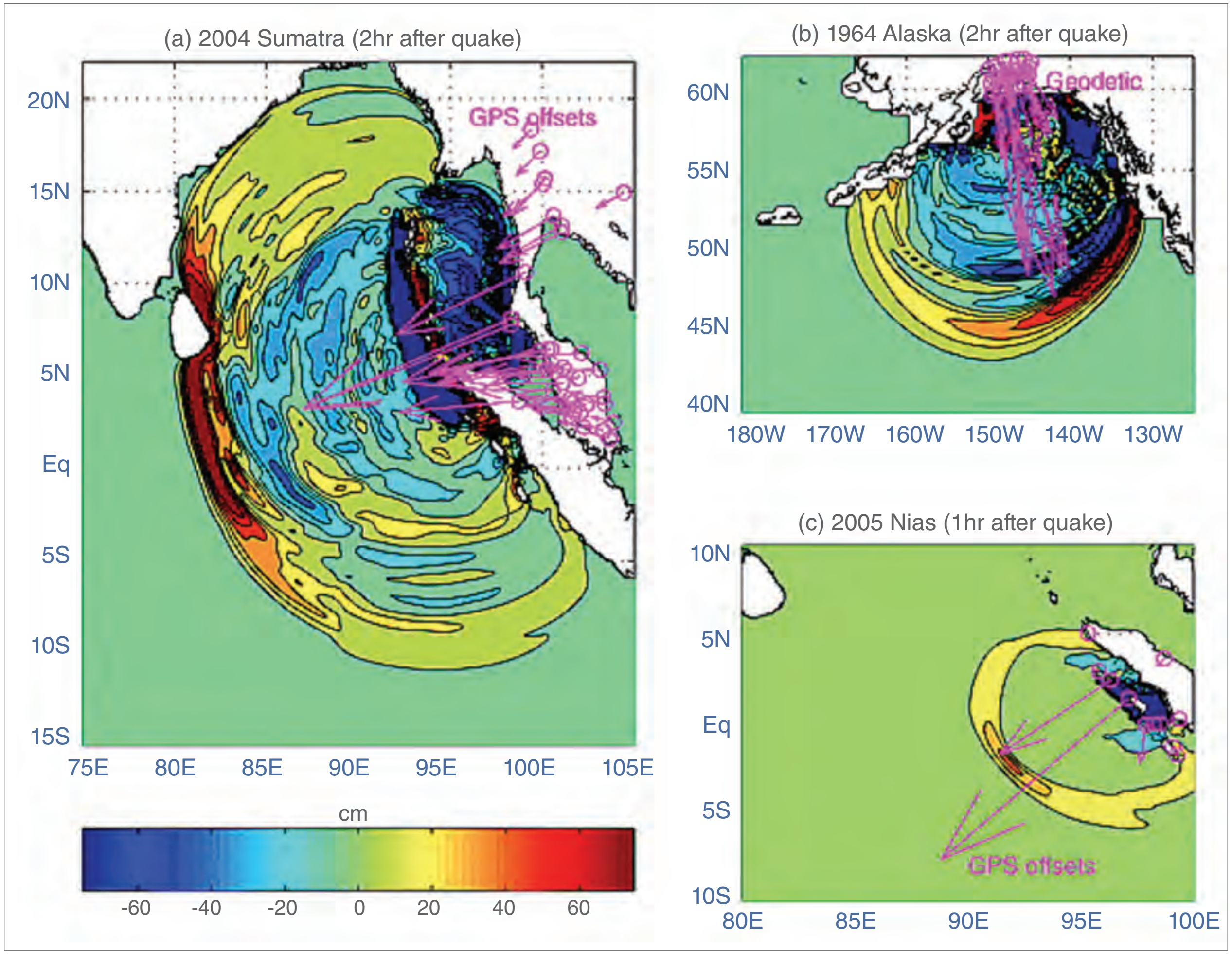
Looking back to look ahead

Even if there were no receivers near an undersea earthquake, Song and his colleagues could still detect motion from afar and assess the tsunami likelihood. Although GNSS can only detect ground motion in the receiver’s immediate vicinity, earthquakes generate such large-scale movement in Earth’s crust that the displacement can be derived from distant receivers.

To test his theory, Song looked back at three historic events: the 2005 Nias Earthquake, the 2004 Sumatra Earthquake, and the 1964 Alaska Earthquake, all major earthquakes of magnitude 8.7 or higher. “Tsunamis typically originate at undersea boundaries of tectonic plates near the edges of continents,” he said. Previously, scientists thought the culprit behind tsunamis was the upward thrust caused when one tectonic plate collided with another during an earthquake, or the vertical displacement. But Song and his colleagues found that horizontal displacement, which caused more lateral movement along faults, also influenced waves. He said, “Our team found horizontal forces are responsible for two-thirds of the tsunami’s height, and they generated five times more energy than the earthquake’s vertical displacements.” They also noted that horizontal forces best explained how the devastating 2004 tsunami spread across the Indian Ocean.


The 2010 Chile Earthquake triggered a tsunami that washed this house in Pelluhue off its foundation and into the street. (Courtesy Caritas Chile)

Song then compared their GNSS analyses to tsunami records from each of the three earthquakes. In each case, he found a match: the ground slip directions at the earthquake epicenter determined the direction of the waves. He also looked at seafloor displacement to calculate how strong the resulting tsunami might be. He said, “Based upon GPS displacement data and local topography data, we generated a new tsunami scale measurement from one to ten, much like



Scientist Tony Song used GPS to detect tsunami severity and direction after an earthquake. He tested his theory against three historic earthquakes and predicted the resulting tsunamis: (a) the 2004 Indian Ocean tsunami two hours after the quake, (b) the 1964 Alaska tsunami two hours after the quake, and (c) the 2005 Nias tsunami one hour after the quake. Pink arrows are the GPS displacement measurements (not scaled). (Courtesy T. Song, 2007, *Geophysical Research Letters*)

the Richter Scale used for earthquakes.” Any tsunami measuring more than a five on this scale would merit a basin-wide warning. For instance, Song classified the tsunami generated by the 2004 Sumatra Earthquake as a 5.8, which would have sent warnings throughout the entire Indian Ocean.

Although GNSS data proved a strong indicator of tsunami wave size and direction, Song also merged his findings with other data to produce a model of the ocean environment through which the waves would be traveling. Song’s colleague, oceanographer C. K. Shum, said, “Tony’s method is innovative because it also includes the general ocean circulation models in addition to tsunami modeling, leading to more accurate tsunami prediction.” By feeding these data into JPL’s supercomputers, Song was able to generate results that validated his GNSS findings, and in less than twenty minutes.

A new wave of data

Song’s research had proven that GNSS-based tsunami detection is far more accurate than trying to predict a tsunami solely from the size and location of an earthquake. And when a magnitude 8.8 earthquake struck the coast of central Chile in February 2010, Song was also able to test his system’s timeliness. Unlike hurricanes, which scientists can track for days before they strike land, tsunamis can strike within hours after an earthquake. Immediately following the 2010 earthquake, Song received data from a GDGPS station in Santiago, Chile. Although this was a large earthquake, the undersea fault transferred only a small amount of energy into the ocean, so Song and his colleagues calculated the tsunami scale at 4.8. This meant that the Chilean coast nearest the epicenter would bear the worst of the tsunami, while nations along the Pacific Rim would likely be safe. Song’s scale proved accurate: unfortunately, Chile did experience destructive tsunami waves, while Japan and Hawaii suffered little damage.

“We were fortunate to have a station sufficiently close to the epicenter,” said Yoaz Bar-Sever, JPL manager of the GDGPS system, who participated the 2010 Chile test. Bar-Sever said that more receivers around the world are needed to provide better coverage.

The 2011 Japanese tsunami gave them another chance to test their system—in retrospect. Song’s team retrieved data from the Geospatial Information Authority of Japan, the largest GPS monitoring array in the world, and demonstrated that the existing Japanese GPS network could have determined the tsunami energy or scale more accurately for early warnings, instead of using of the earthquake's magnitude. Had the GPS system been used in an operational way, more lives could have been saved.

Developing the tsunami scale is just the first step in the process. "NASA is not developing the tsunami warning system," Song said, "but rather a tsunami detection system." Now Song is working on the next step: how to quickly relay the GNSS-derived tsunami scales to the agencies that do issue those warnings. He and his colleagues are collaborating with the Pacific Tsunami Warning Center (PTWC) in Hawaii, and the Pacific Marine Environmental Laboratory (PMEL) in Seattle. PTWC monitors earthquakes across most of the Pacific and Indian Oceans, and determines when to issue tsunami warnings, while PMEL focuses on tsunami observations and research development. Shum said, "Tony's wave energy detection system can be a useful tool, along with the available buoy data, to help a tsunami disaster center decide whether a tsunami threat is imminent or not."

Song, Shum, Bar-Sever, and their colleagues are still developing a way to integrate Song's tsunami scales into the PMEL and the PTWC systems. They hope that offering more accurate tsunami warnings to all Pacific Rim nations will reduce the number of false alarms, as well as save lives.

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About the data used

Satellite	Global Navigation Satellite System (GNSS)
Sensor	GNSS Receivers
Data set	GNSS Data Archive
Resolution	30 second or more frequent
Parameter	Latitude and longitude
Data center	NASA Crustal Dynamics Data Information System (CDDIS)

About the scientists

Yoaz Bar-Sever is a principal engineer at the NASA Jet Propulsion Laboratory, where he is the program manager of the Global Differential GPS System. He has been involved in GPS technology development and its scientific applications. His key contributions cover the areas of GPS orbit and signal modeling for precision terrestrial and spaceborne GPS navigation. NASA supported his research. Read more at http://www.gdgps.net/about/index.html. (Photograph courtesy Y. Bar-Sever)

C. K. Shum is a professor and distinguished university scholar at the Division of Geodetic Science, School of Earth Sciences, Ohio State University (OSU). He studies satellite geodesy, sea level changes, satellite oceanography and hydrology, and geodynamics and ice mass balance. NASA and NSF supported his research. Read more at http://www.geology.ohio-state.edu/faculty_bios.php?id=83. (Photograph courtesy C. K. Shum, Ohio State University)

Tony Song is an oceanographer at the NASA Jet Propulsion Laboratory. He studies using GPS to detect tsunami scales and genesis, as well as researching ocean circulation, ocean modeling, and crustal oceanography. NASA supported his research. Read more at https://science.jpl.nasa.gov/people/Song. (Photograph courtesy T. Song, JPL)

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For more information

NASA Crustal Dynamics Data Information System (CDDIS)
http://cddis.nasa.gov

NASA Global Differential GPS System (GDGPS)
http://www.gdgps.net