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Multi-angle Imaging SpectroRadiometer (MISR) time-lapse imagery of tsunami waves from the 26 December 2004 Sumatra–Andaman earthquake

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Abstract

On 26 December 2004, a few hours after a massive earthquake occurred off the western coast of Sumatra in the Indian Ocean generating a major tsunami, the Multi-angle Imaging SpectroRadiometer (MISR) instrument on NASA's Terra satellite captured unique, time-lapse evidence of extremely large waves occurring along the eastern coast of India. The MISR imagery provides information on the location and characteristics of tsunami waves in near-shore waters, along with estimates of the wave speed.

Keywords: Multi-angle remote sensing; Terra; MISR; Asian tsunami; Sumatra–Andaman earthquake

1. Introduction

At 00:58:53 UTC on 26 December 2004, the largest earthquake in over 40 years occurred in the Indian Ocean with its epicenter to the west of the Indonesian island of Sumatra. Details of the earthquake and the rupture process can be found in Lay et al. (2005), Ammon et al. (2005), and Bilham et al. (2005). The earthquake caused a sudden uplift of the ocean floor, triggering a major tsunami that resulted in catastrophic devastation and loss of life in the surrounding coastal regions.

In this paper we present unique observations made by the Multi-angle Imaging SpectroRadiometer (MISR) instrument on NASA's Terra-EOS satellite on the day of the earthquake, a few hours after the initial tsunami waves impacted the eastern Indian coast. Besides providing a new perspective on the tsunami event, the MISR observations allow estimates of the speed of the tsunami wave fronts in the near shore environment.

In the next section we will describe the MISR instrument and how tsunami information was obtained from the MISR imagery. After this, we present examples of tsunami wave speeds determined in two different regions along the eastern coast of India where features associated with large, breaking waves were observed. Finally, the MISR observations are compared with coincident tide gauge measurements of the tsunami waves.

2. Observations

MISR is one of five instruments onboard NASA's Terra Earth Observing System (EOS) satellite, launched in December 1999 into a near-polar orbit that crosses the equator at approximately 10:30 local time, on its descending portion. A detailed description of the MISR instrument is given by Diner et al. (1998), so only a brief summary is provided here. MISR makes measurements in four spectral bands, 446 nm (blue), 558 nm (green), 672 nm (red), and 866 nm (near infrared), using an array of nine cameras. The cameras are oriented along the direction of the satellite motion in pairs at angles of ±70.5°, ±60.0°, ±45.6°, ±26.1°, with the remaining camera pointing in the nadir (0°) direction. MISR "global mode" data are processed so that the red band has a ground resolution of 275 m × 275 m in all nine cameras. To reduce data volume, all but the nadir camera blue, green, and near infrared spectral bands are resampled to a resolution of 1.1 km × 1.1 km. MISR's image swath is approximately 400 km wide, acquiring data over the

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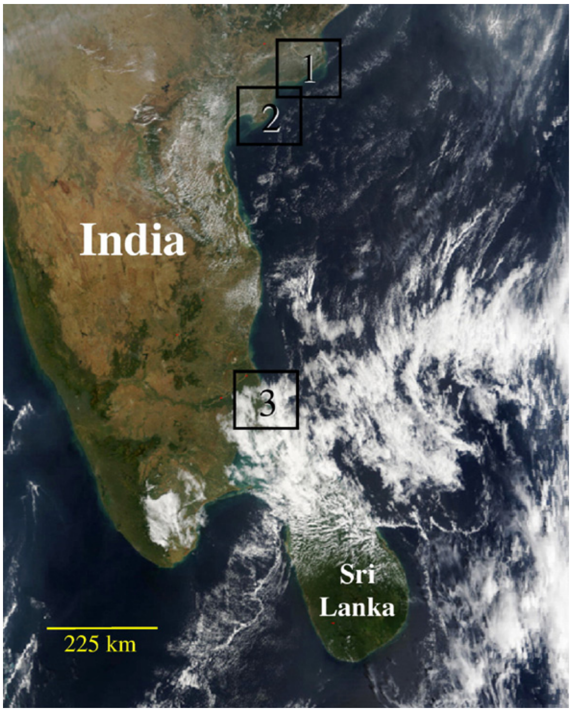

Fig. 1. MODIS Terra satellite visible image of India and Sri Lanka from 26 December 2004. The MISR swath extends down the center of this MODIS image. Numbers indicate regions where tsunami-related observations were made by MISR. Region 1 is the Godavari River Delta. Region 2 is the Krishna River Delta. Region 3 is the Nagapattinam District in the Indian state of Tamil Nadu.

entire globe in a period of nine days, with a repeat cycle of 16 days. Although MISR's nine cameras instantaneously image different points along the satellite ground track, the cameras are registered to a common reference after processing so that each point is viewed from nine different directions during an interval of approximately 7 min. The data used in this analysis are projected to the World Geodetic System 1984 (WGS84) ellipsoid (Diner et al., 1998). Stationary features lying essentially at sea level will be found at the same location in all nine camera images. The speed and direction of moving features near the surface can be measured due to the known time interval between successive camera views.

On 26 December 2004, at approximately 03:35 UTC, tide gauge records indicate that the eastern coast of India was struck by the initial wave of the tsunami generated by the Sumatra–Andaman earthquake (Bilham et al., 2005; Fine et al., 2005; Hirata et al., 2006; Nagarajan et al., 2006). The Terra satellite passed over the eastern coast of India and the western coast of Sri Lanka slightly more than 90 min later, allowing MISR to obtain images of some of the regions affected by the tsunami between approximately 05:10 and 05:18 UTC.

Animations were constructed from the sequence of red band (275 m, highest resolution) images of the area. These animations revealed unique, time-lapse sequences of what appear to be the fronts of breaking tsunami waves moving toward the Indian coast. Due to its coarse resolution relative to the small scale of the wave breaking phenomenon, MISR does not typically observe breaking ocean waves, implying that the waves observed on 26 December 2004 were of an exceptionally large and unusual character.

While the animations provided important qualitative information about apparent tsunami wave features, quantitative information was obtained through careful analysis of the images from individual cameras. Because the georectification of MISR

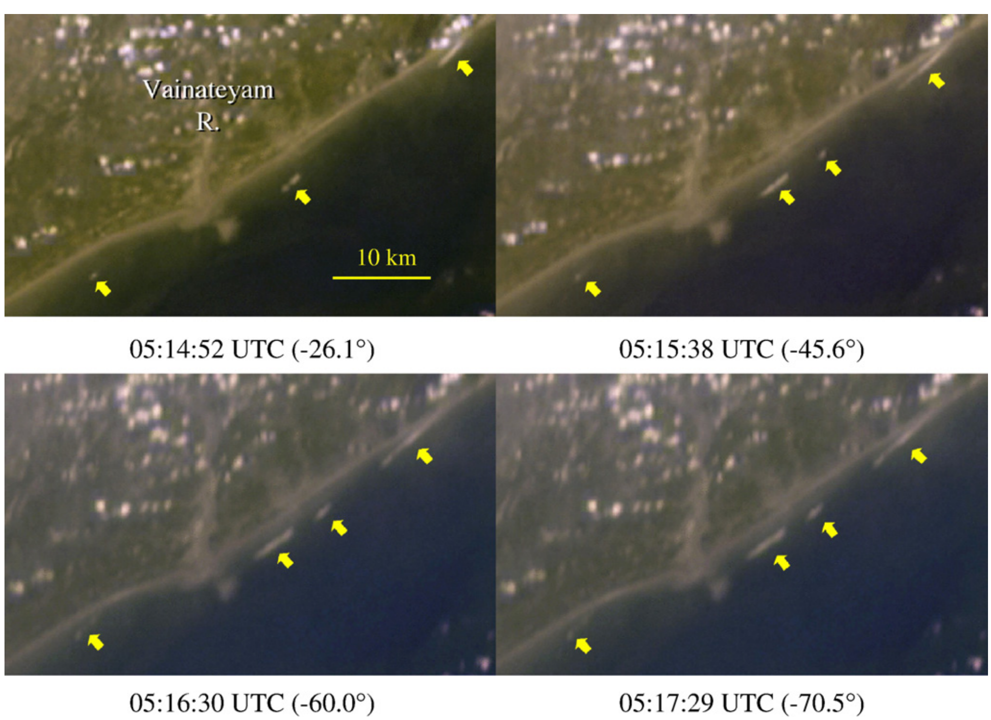

Fig. 2. MISR image sequence of tsunami wave features along the Godavari River Delta. Times and MISR viewing camera zenith angles are indicated below each panel. Arrows indicate positions of tsunami features along the coast.

imagery is accurate to approximately 50 m (Jovanovic et al., 2002), pixel-by-pixel comparisons of consecutive images allow the determination of the direction of motion and distance covered by clearly identifiable features. When coupled with accurate temporal information available from the satellite, it is further possible to calculate with high accuracy the speed at which these features move. Temporal information is also critical in order to relate features seen in MISR imagery to observations of the tsunami made by other instruments, such as tide gauges (e.g., Nagarajan et al., 2006).

Fig. 1 shows a portion of the Moderate Resolution Imaging Spectroradiometer (MODIS) image from the Terra satellite as it passed over the Indian Ocean region on 26 December 2004. MODIS accompanies MISR on the Terra platform, but has a 2330 km image swath compared to the narrower 400 km swath of MISR. Although MISR data are only available along the center of the MODIS swath, MODIS acquires data from a single viewing direction at a single time and, therefore, MODIS data are not used in this analysis. The three regions indicated in the figure are locations where significant tsunami-related events were observed in the MISR imagery. Region 1 is the Godavari Delta, region 2 is the Krishna Delta, and region 3 is the Nagapattinam District in the Indian state of Tamil Nadu. Below we describe the imagery in greater detail.

2.1. The Godavari delta

The Godavari Delta, in the Indian state of Andhra Pradesh, drains the second longest river in India and covers an area of approximately 5100 km^2 (Malini & Rao, 2004). Fig. 2 shows views of the southeastern portion of the delta, just to the south of the port of Kakinada, from four MISR cameras. The MISR

Fig. 3. MISR image sequence of tsunami wave features along the Krishna River Delta. Times and MISR viewing camera zenith angles are indicated below each panel. Arrows indicate position of various features.

imagery is projected using the Space Oblique Mercator (SOM) reference grid, with north toward the top of the image (Diner et al., 1998). The Vainateyam River runs from north to south near the image center. These “true color” red–green–blue (RGB) images were produced at 275 m resolution by projecting the information from MISR’s green and blue bands at 1.1 km resolution onto the 275 m resolution red band, then this derived, higher-resolution data was used to construct the image. Clouds appear bright white, the vegetated land is greenish, and the ocean has a bluish color. Sediment deposited by the rivers into the Bay of Bengal can be seen as stationary, light colored areas in the darker water. The increase in atmospheric optical path-length with increasing camera angle accounts for the haziness that appears in the last few images in the sequence.

A number of long, linear features, indicated by the arrows, can be seen just off the southeastern coast of the Godavari Delta in all the images. The longest feature begins just south of the mouth of the Guatami River, which is off the image to the upper right, and extends to the southwest, making a slight angle relative to the coast. Animations constructed by combining all nine MISR images of this region span an interval of approximately 7 min and clearly show the features moving toward the coast. MISR images from the same region obtained on different days, both months and years earlier, do not contain any such features. The features are unlikely to be clouds due to their extremely narrow, linear character, along with the fact that they are present only in the near-shore water, but absent over the land. Furthermore, the features are significantly darker than the cumulus clouds that are prevalent elsewhere in the image; and they move northwestward, toward the coast, whereas the clouds have apparent northward motion, primarily as a result of geometric parallax due to their elevation above the WGS84 ellipsoid (Moroney et al., 2002). Based on this chain of reasoning, these features are almost certainly associated with tsunami wave

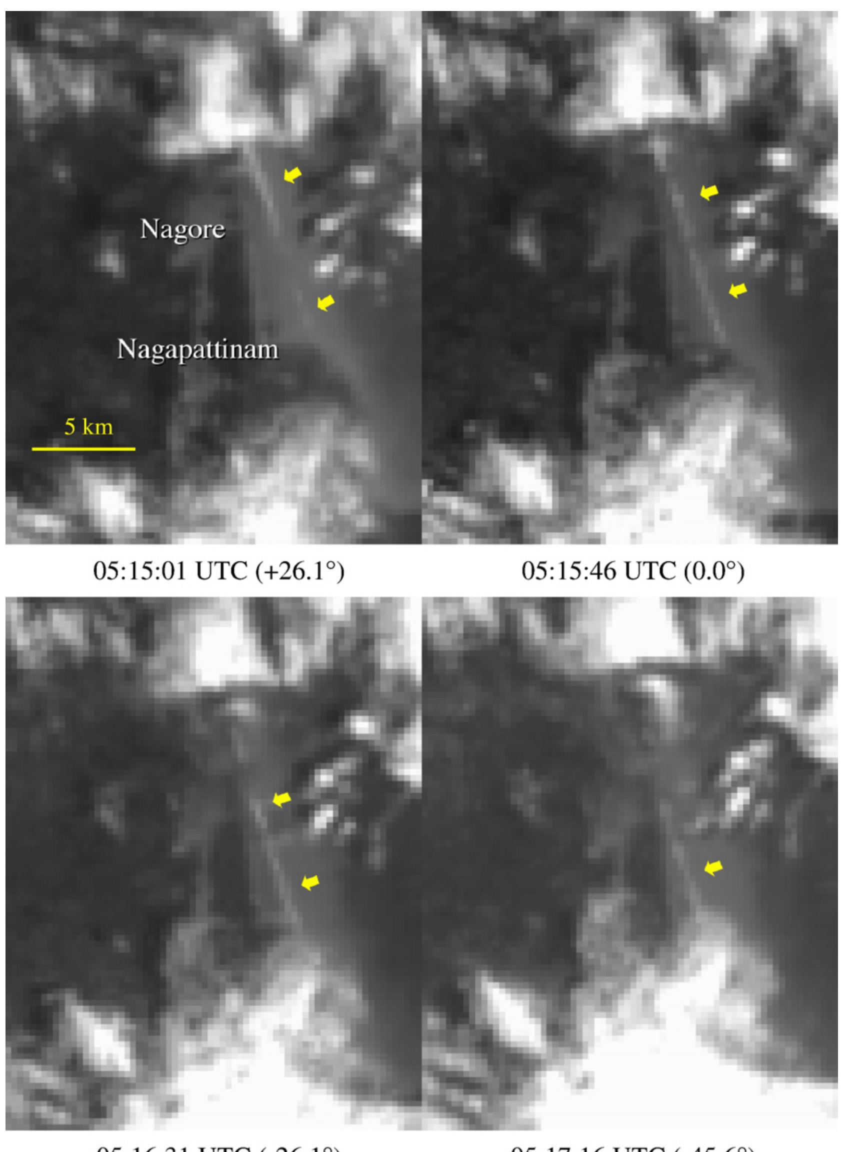

Fig. 4. MISR image sequence of a tsunami wave feature along the Nagapattinam District coast. Times and MISR viewing camera zenith angles are indicated below each panel. Arrow indicates position of tsunami wave feature.

fronts. Without corroborating information, such as eyewitness accounts, it is impossible to tell if they are the breaking tsunami waves themselves or the whitewater caused by a turbulent leading bore (Peregrine, 1983). The size of these waves is significant based on the fact that the features can be seen at the 275 m pixel resolution of the MISR instrument. Typical breaking waves, such as those that occur along the coasts of the Hawaiian Islands, are not visible as moving features in MISR imagery. The identification of the features with tsunami waves is supported by an examination of the tide gauge records from the nearby port of Visakhapatnam which indicated that waves of significant height continued to impact the eastern Indian coast many hours after the arrival of the initial wave around 03:35 UTC (Fine et al., 2005; Nagarajan et al., 2006).

2.2. The Krishna delta

To the south of the Godavari Delta lies the Krishna Delta, formed by the outflow of the Krishna River and its distributary rivers. Fig. 3 shows a sequence of five MISR “true color” RGB images of the Krishna Delta obtained on 26 December 2004. These images were produced in the same manner as those in Fig. 2. The town of Machilipatnam is located just to the north of the images. Near the top of the images runs the Hamsaladevi River, one of the major distributaries of the Krishna River, which meets the Bay of Bengal near Divi Point. The Krishna River itself flows south to two more distributary rivers, the Gollamattapaya to the east and the Nadimeru to the west, and finally empties into the Bay of Bengal near False Divi Point. The southern area of the Krishna Delta is primarily mangrove swamp, as described by Selvam (2003). The Gollamattapaya and Nadimeru rivers can be seen at the bottom of the images.

Features associated with tsunami waves, similar to those observed along the coast of the Godavari Delta, are indicated by the arrows in Fig. 3. The most prominent example is the thick, bright linear feature approaching the coast very near the mouth of the Nadimeru River. By the last image in the sequence, it has just reached the coastline. Additional features are apparent as thin, bright lines lying along the coast between the Hamsaladevi and Gollamattapaya rivers (top two arrows).

2.3. The Nagapattinam District

The Nagapattinam District, a coastal area within the Indian state of Tamil Nadu containing the town of Nagapattinam, was one of the regions of India most significantly affected by the tsunami (Chadha et al., 2005; Narayan et al., 2005). Fig. 4 shows a sequence of four MISR red band images from along the coast. Nagapattinam can just be seen in the break in the clouds. A potential tsunami wave feature, indicated by the arrow, is

Fig. 5. IKONOS 1 m color image of Nagapattinam, India obtained on 29 December 2004, 3 days after the tsunami. In the northern part of the image, damage to buildings is evident along the coast. The scale in the lower right shows 750 m, which was the estimated distance inland the tsunami waves penetrated along a transect just to the north of the cooking oil tanks that can be seen as the group of white circles on the beach in the north-central part of the image (Ramanamurthy et al., 2005). The southern portion of the image shows the Vedaranyam Canal. The tsunami waves penetrated more than 2 km inland along this waterway and much of the adjacent land appears to be covered in silt. Plumes of smoke in the lower center of the image are most likely from burning debris. Image courtesy of Space Imaging.

clearly visible in these scenes as a thin white line moving almost due west toward the shore. It is notable that the direction from which the feature approaches the shore in this region is different from the orientation of the features seen along the Godavari and Krishna deltas. Because the brightness of the location of Nagapattinam is similar to that of the nearby ocean rather than the surrounding land, it is likely that the town was already flooded at the time of the MISR observation. In fact, the first few images obtained by MISR (not shown) suggest an earlier wave moving up the Vedaranyam Canal just to the south of the town. Reports from the region corroborate these inferences. Nagapattinam was inundated by the tsunami waves on 26 December and, according to one survey, seawater penetrated inland approximately 3 km near Nagapattinam beach and 1 km at the town's port (Narayan et al., 2005). Another survey found wave run-up of 5.2 m and lateral inundation in Nagapattinam of 800 m (Chadha et al., 2005). A third survey found a maximum run-up of 3.9 m and lateral inundation of 750 m near the town lighthouse, while the nearby Vedaranyam Canal allowed the wave to penetrate up to 2.2 km inland (Ramanamurthy et al., 2005). Fig. 5 shows a 1 m image of Nagapattinam from Space Imaging's IKONOS satellite obtained on 29 December 2004, 3 days after the tsunami. The lower portion of the image shows the area near the Vedaranyam Canal. There is clear evidence of flooding in this portion of the image, as indicated by the grayish color of the land adjacent to the canal. The damage to Nagapattinam was likely exacerbated due to the relatively shallow slope of the surrounding terrain, which allowed the tsunami to penetrate farther inland as compared to other areas, as discussed by Ramanamurthy et al. (2005).

3. Analysis

The MISR imagery and animation sequences described in the previous section provide a qualitative look at the unique observations related to the tsunami waves made on 26 December 2004. However, careful analysis of the imagery yielded additional quantitative information about the tsunami waves. In this section we discuss the observable characteristics of the waves along the eastern Indian coast.

3.1. Breaking waves along the Godavari and Krishna river deltas

The features associated with tsunami waves along the Godavari and Krishna river deltas are very different from that of the wave observed moving toward the coast of the Nagapattinam District. Therefore, we begin by focusing on the characteristics of the most prominent wave that appears just off the Krishna River Delta, near the mouth of the Nadimeru River, corresponding to the bottom arrow in Fig. 3. This feature was chosen because it provides the clearest example of a wave approaching the shore.

Rotating the MISR images 35° clockwise orients them such that the features propagate from the bottom to the top of the images (+y-direction) as the MISR cameras are viewed in the appropriate temporal sequence. This increases the size of the 275 m full resolution MISR pixels to 336 m when measured along the rotated axes. Using camera-by-camera analysis of the MISR imagery it is possible to determine the location of the wave feature to within ±1 (rotated) pixel, or 336 m. The MISR block center times for each camera, obtained from the MISR image file, were used to determine the relative elapsed time between successive images. The temporal error introduced into the calculation of the speed of the moving wave is on the order of the 40.8 ms line repeat time of the MISR cameras (Diner et al., 1998). The wave feature off the Krishna Delta was observed in a total of six MISR cameras, starting with the +26.1° camera and running through the aft-most −70.6° camera. The apparent motion and speed were calculated independently for each successive camera pair. The results from three of the camera pairs (+26.1° to 0°, 0° to −26.1°, and −26.1° to −45.6°) were averaged to obtain a mean speed for the

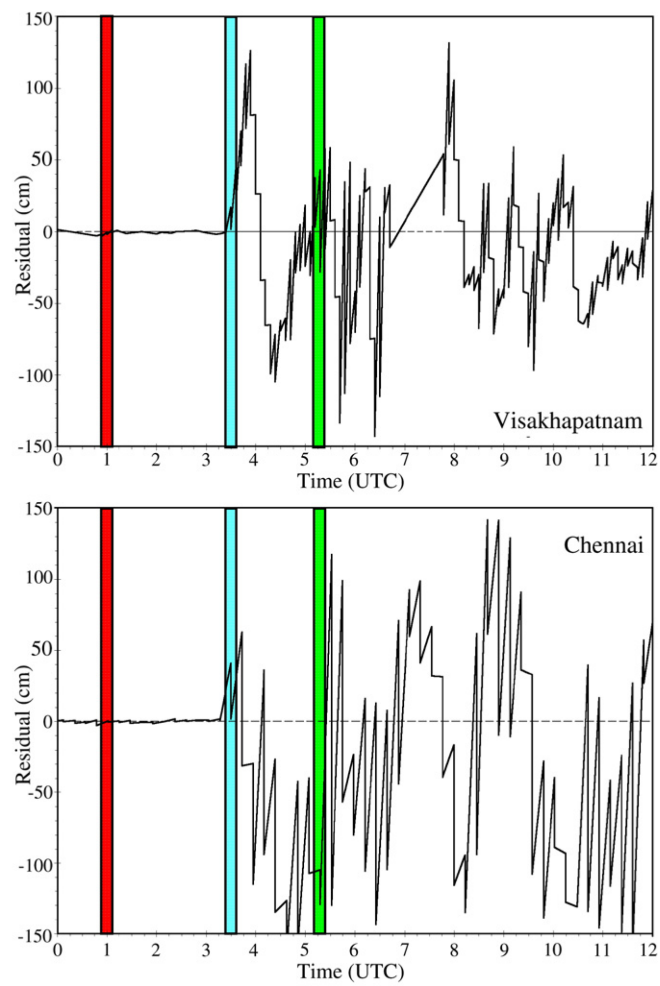

Fig. 6. Top panel, Visakhapatnam Port tide gauge residuals from 26 December 2004, 00:00 to 12:00 UTC. Bottom panel, Chennai tide gauge residuals. The first, red line indicates the time of earthquake. The second, blue line is the time of arrival for the first tsunami wave and the green line corresponds to the time of the MISR overpass. Residuals were calculated relative to semidiurnal tide modeled empirically from data from 24 h prior to 26 December. Tide gauge data was obtained from the National Institute of Oceanography, India (http://www.nio.org/jsp/tsunami.jsp). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

wave of 7.43 m/s (26.8 km/h) with a standard deviation of ±0.04 m/s (±0.15 km/h). The total time elapsed between the +26.1° camera view of the region and the −45.6° camera view was 135.5 s. The line repeat time of 40.8 ms contributes negligibly to the estimated error, whereas a single pixel error in the camera pair with the smallest time difference (44.9 s for the +26.1° to 0° pair) translates into a minimum resolvable speed of 1.49 m/s (5.38 km/h).

Etaya et al. (2005) used a similar approach to determine tsunami wave speeds from satellite observations using the 2.707 s time difference between the acquisition of SPOT 10 m panchromatic and SPOT 20 m multispectral images of the Banda Ache region. They found a maximum wave speed of 59.9 km/h at one offshore location. The minimum detectable speed using this technique is 3.7 m/s (13.3 km/h), more than twice as large as the minimum speed that can be detected using the MISR imagery for the Krishna River Delta. In addition, SPOT only provides two views of a particular scene, leading to ambiguities in image interpretation and attribution of actual motion that are alleviated somewhat by the multiple views available from MISR.

3.2. Breaking wave along the coast of the Nagapattinam District

Because only a single wave feature was evident off the coast of the Nagapattinam District and much of the length of the coast was obscured by clouds, as shown in Fig. 4, less information could be gleaned from examination of this feature. Nevertheless, analysis was performed in much the same way as described above to estimate the wave speed.

The orientation of this wave feature relative to the coast is quite different from the orientation of the features seen along the Godavari and Krishna deltas. This is likely due to the complex interaction of wave reflection and refraction within the Indian Ocean basin and the proximity of this portion of India to the northern tip of Sri Lanka. In order to rectify the orientation of the wave along the Nagapattinam District, a clockwise rotation of 18° was applied. With this transformation, the waves propagate from right to left (negative x-direction) through the sequence of MISR images. The dimensions of the 275 m full resolution MISR pixels are increased to 289 m by the rotation.

The speed of this wave was estimated using four camera pairs (+45.6° to +26.1°,+26.1° to 0°, 0° to −26.1°, and −26.1° to −45.6°), during which a total period of 181 s elapsed. The result was a wave speed of 9.58 m/s (34.5 km/h), with a standard deviation of ±1.6 m/s (±5.9 km/h). While this speed is nearly 30% larger than the 7.43 m/s speed obtained for the wave along the Godavari and Krishna river deltas, this difference may not be significant given the error in the measurements.

4. Discussion

The preceding section focused on the characteristics of the waves that could be determined from the MISR images. In this section, we compare our observations with tide gauge measurements from along the Indian coast.

MISR's nine cameras imaged the eastern coast of India on 26 December 2004 between 05:10 and 05:18 UTC. The Sumatra–Andaman earthquake occurred at 00:58:53 UTC with the epicenter located at 3.30°N and 95.95° E, as determined by the United States Geological Survey (USGS) National Earthquake Information Center (NEIC) (http://neic.usgs.gov/neis/eq_depot/2004/eq_041226/). According to tide gauge records from the ports of Visakhapatnam and Chennai, the first waves from the tsunami generated by this massive earthquake struck the eastern coast of India at approximately 03:35 UTC (Bilham et al., 2005; Fine et al., 2005; Hirata et al., 2006; Nagarajan et al., 2006).

Emphasis on the arrival time of the initial tsunami wave, however, tends to obscure the fact that significant waves continued to be observed in tide gauge records throughout the region hours and even days after the arrival of the first wave (Merrifield et al., 2005). Moreover, at some locations, including the three surviving tide gauge sites maintained along the eastern coast of India, the first tsunami wave was not the largest, and a number of hours passed between the arrival of the first wave and the arrival of the largest one (Merrifield et al., 2005; Nagarajan et al., 2006).

Fig. 6 shows the residual wave heights determined from tide gauge measurements within the ports of Visakhapatnam and Chennai obtained from the National Institute of Oceanography, India (http://www.nio.org/jsp/tsunami.jsp). For reference, the Godavari and Krishna deltas lie just to the south of the port of Visakhapatnam, while the town of Nagapattinam is to the south of the port of Chennai in Tamil Nadu. The mean magnitude of the semidiurnal tide at each gauge was first determined empirically using the variation of the gauges 24 h prior to the time of the earthquake. The residuals were then calculated by subtracting these mean tides from the tide gauge data obtained between 0:00 and 12:00 UTC on 26 December 2004. Superimposed on the tide gauge records are vertical bars indicating the time of the earthquake, the time of the first tsunami wave arrival, and the time of the MISR overpass, in sequence from left to right.

The tide gauge data shown in Fig. 6 are consistent with eyewitness accounts collected by Chadha et al. (2005) from along the coast in the Indian state of Andhra Pradesh, which lies just to the north of Tamil Nadu, and includes the port of Visakhapatnam. The eyewitnesses observed a total of four tsunami wave trains striking the coast, with the second set of waves being the most destructive and deadly. A 2005 report by the Indian Department of Ocean Development, Integrated Coastal and Marine Area Management, Project Directorate, Chennai entitled "Preliminary Assessment of Impact of Tsunami in Selected Coastal Areas of India" (available online at http://dod.nic.in/tsunami.pdf) provides some additional timing information for these tsunami wave trains. According to the report, the initial tsunami wave hit Chennai around 03:30 UTC, followed by waves at 05:15, 07:00, and 09:40 UTC. It should be noted that the sampling interval for the tide gauges at both Visakhapatnam and Chennai was 5 min (Nagarajan et al., 2006), so more precise timing is not possible. The tide gauge data from Chennai presented in Fig. 6 does, however, show broad wave peaks around these times. Note that the MISR observations apparently coincide with the arrival of the second and most destructive wave tsunami wave train at Chennai. It is interesting that no evidence for whitewater features such as those seen along the Godavari and Krishna river deltas and off the coast of the town of Nagapattinam was found in the MISR imagery near the two ports where the tide gauges were located. However, as discussed by Merrifield et al. (2005), float type tide gauges, such as those at Visakhapatnam and Chennai (Nagarajan et al., 2006), are typically located in stilling wells within harbors, so they do not necessarily reflect the conditions experienced along exposed coastlines, where the waves were observed by MISR. The similarity in timing between the MISR observations and the tide gauge detection of large waves along the eastern Indian coast, however, is additional evidence that MISR did indeed observe tsunami waves on 26 December 2004.

5. Conclusions

On 26 December 2004, MISR observed the eastern coast of India between 05:10 and 05:18 UTC, slightly more than 4 h after the Sumatra–Andaman earthquake initiated a destructive tsunami in the Indian Ocean. MISR imagery contains what appear to be breaking wave features along the Godavari and Krishna River Delta regions and off the coast of the Nagapattinam District in Tamil Nadu. From the imagery it was possible to estimate an apparent wave speed of 7.43 m/s (26.8 km/h) for the wave off the Krishna River Delta and a speed of 9.58 m/s (34.5 km/h) for the wave off the Nagapattinam coast. Both these values are consistent with general eyewitness estimates of tsunami wave speeds as they move onshore.

In addition to the observations of tsunami wave features presented here, interesting observations were made of other features off the southwestern coast of Sri Lanka in the MISR imagery that appear to be due to internal waves generated by the tsunami. This will be the subject of a future study.

The MISR images provide an interesting new perspective on the behavior of tsunami waves, particularly as they approach the shore. Because MISR views the same scene over time, information can also be extracted about the temporal behavior of such phenomena.

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