Tide-Generated Internal Solitary Waves generated on a large sill of the Mascarene Plateau excite Coastal Seiches in Agalega and Rodrigues Islands

After the ISWs crossed 528 and 833 kilometers of the Indian Ocean in 2 and 3 days, respectively

By

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Abstract

Large amplitude (~100 m) and fast (3 m/s) mode-1 internal solitary wave packets generated by the interaction of strong tidal currents with a central sill (12.61°S, 60.84°E) in the Mascarene Plateau during perigean-spring tides (28-SEP-2015; 14-NOV-2016), propagated northwestward and southeastward hundred of kilometers before impinged on Agalega (2 days later) and Rodrigues islands (3 days later), respectively. The arrival of the ISWs packets coincided with a simultaneous increase in coastal seiche activity at both islands.

Introduction

The first scientific evidence of coastal seiche excitation by tide-generated internal solitary waves (ISWs) was found after the analysis of 13 years of tide gauge records from Magueyes Island, located in Puerto Rico (Giese et al., 1982; Giese et al., 1990). The ISWs generated at Aves Ridge during spring-perigean tides travel 540 km across the Caribbean Sea in 3.6-5.1 days to impinge in the upper slopes off the edge of the 10 km wide insular shelf, exciting 50-minute coastal seiches (Alfonso-Sosa, 2012). Later, it was found that the coastal seiches recorded in Puerto Princesa, Palawan Island, were excited too by tide-generated internal solitary waves that cross the Sulu Sea in 2.3-2.5 days (Giese and Hollander, 1987; Giese et. al., 1998). A successful theoretical model to explain the generation of surface coastal seiches by deep-sea internal solitary waves was developed (Chapman and Giese, 1990). The internal soliton impinges on the submarine slopes near the shelf break generating a horizontal current impulse. The current impulse at the shelf break excites a natural period standing oscillation in the shelf waters, with maximum amplitude near the coast. About 30 years later, more evidence of coastal seiche excitation by internal waves was found at Trincomalee Bay, Sri Lanka (Wijeratne et. al., 2010). Wijeratne proposed the hypothesis that internal waves generated at the Andaman Sea during spring tides travel 1200 km across the Bay of Bengal in 6-8 days to reach Trincomalee Bay. But the authors did not provide any evidence of the internal waves by means of direct ship measurements or satellite imagery. Four years later, satellite images detected packets of ISWs crossing the Bay of Bengal (Alfonso-Sosa, 2014). These packets moved West (270°) and crossed 1270 km in about 5.4 days to reach the entrance of Trincomalee Bay, Sri Lanka. The average inter-packet distance was 122 km, suggesting that the packets were phase locked with the internal tide. Offshore of Trincomalee Bay entrance a nonlinear internal wave field was observed. In 2016, we discovered that ISWs packets generated at the Nicobar Islands passages during perigean-spring tides can propagate a great distance (2420 km) across the Indian Ocean in 10.5 days before exciting seiches in the waters of the Addu Atoll, Maldives Island (Alfonso-Sosa, 2016). On the same year, we discovered that the 2.3-minutes coastal oscillations in Flying Fish Cove in Christmas Island are coastal seiches excited by ISWs coming from the Sumba Strait. These ISWs cross a distance of 1503 km in about 8 days. These previous works sustain the hypothesis that the coastal oscillations recorded in North Agalega Island and in Rodrigues Island are coastal seiches excited by distant generated ISWs. Inside and outside Port Mathurin in Rodrigues Island there were recorded seiche periods of 25 minutes (Lowry et al., 2008). The authors proposed in their article that Port Mathurin seiches could be excited by large amplitude internal waves generated around the Mascarene Plateau in the Indian Ocean but they **did not** provide direct evidence such as satellite images showing the internal waves impinging on the island during the seiche events. This paper will provide the satellite imagery evidence necessary to prove the connection between the tide-generated ISWs and the seiches at Port Mathurin

In the last nine years, 250-m resolution MODIS images acquired by the Earth Observing System Terra and Aqua Satellites during sunglint conditions allowed us to survey high-frequency nonlinear internal solitary wave occurrences on a near-global scale (Christopher Jackson, 2007). It is possible to detect internal solitary wave packets leaving the generation area during fortuitous conditions: minimum cloud cover, near-specular reflectance pattern of sunlight off the ocean surface (sunglint) and strong oceanic stratification. The origin and speed of Aves Ridge's ISWs in the Caribbean Sea and Ceará ISWs in the Atlantic Ocean had been determined by analysis of MODIS images (Alfonso-Sosa, 2012; Alfonso-Sosa, 2013). Using MODIS/Aqua/Terra and SUOMI/NPP/VIIRS images it is possible to track ISWs crossing vast ocean distances from the generation area up to arrival to the island where they excite coastal seiches (Alfonso-Sosa, 2017; 2016).

Analysis of a comprehensive dataset of Synthetic Aperture Radar (SAR) images acquired over the sea area around the Mascarene Plateau in the western Indian Ocean revealed that first-mode and second-mode internal solitary waves (ISWs) radiate both west and east from a central sill located (12.5°S, 61°E) between the Saya de Malha and Nazareth Banks (da Silva et al., 2011). The surface manifestation of ISWs were mainly detected during and near spring tide conditions. The authors found that on the west side of the ridge, ISWs travel towards about 300° T and on the east side towards about 120° T. Also they calculated an average propagation speed of 2.38 m/s for the eastward traveling leader ISW (mode-1) and 2.99 m/s for the westward traveling leader ISW (mode-1). Years later combining SAR imagery with a MITgcm fully nonlinear and nonhydrostatic simulation (da Silva et al., 2015), the authors discovered that large-scale primary mode-1 ISWs at the eastern (upstream) side of the sill evolve " from the disintegration of a multimodal baroclinic structure that appears on the upstream side of the sill" and not from the traditional lee-wave generation mechanism. The multimodal baroclinic structure evolves into a large density front that later steeps into a deep density-waveform of depression that finally evolves into a mode-1 ISW train owing to the effects of nonlinearity and dispersion. The mode-1 ISWs travelling east can be interpreted as formed by an "internal tide release" mechanism similar to that described in Buijsman et al. (2010).

The focus of this paper is to provide direct evidence that internal solitary waves generated during perigean-spring tides at the Mascarene Plateau are responsible for exciting seiches in the Agalega Islands and in Rodrigues Island.

Methods

Records of one-minute and three-minute water levels were obtained from the Sea Level Station Monitoring Facility at Port Mathurin, Rodrigues Island and at St. James, North Agalega Island. Outliers and spikes were removed from the record. The station is maintained by the Mauritius Meteorological Services (Mauritius). http://www.ioc-sealevelmonitoring.org/station.php?code=agal, http://www.ioc-sealevelmonitoring.org/station.php?code=rodr

MODIS/Aqua/Terra and SUOMI/VIIRS images were browsed and downloaded using NASA/Worldview. This tool from NASA's EOSDIS provides the capability to interactively browse global, full-resolution satellite imagery and then download the underlying data. Images were selected around the dates of the closest perigee-syzygy (shown in Table 1) in years 2015 and 2016. Table 1 shows the dates of the closest Moon's perigee occurring less than 3 hours from syzygy, for the years 2015 and 2016. If the perigee coincides with syzygy, equinox and the longitude of the lunar node, **N** equals 180 degrees (Minimizing Lunar Declination) all these factors will maximize the semidiurnal form of the tides. N crossed 180° (i.e., lunar declination reached minima) on October 2015. During the whole year 2015 and 2016, the position in the 18.6 Nodal Cycle was favorable for the generation of strong semidiurnal tides and ISWs. The closest perigee of 2015 was on September 28th and the closest perigee of 2016 was on November 14th with a value of 356511 km. All these factors contributed to an exceptional generation of semidiurnal internal tides and ISWs. The last time a full moon was this close occurred 69 years ago, on January 26 1948 with a distance of 356462 km. The next one will occur on November 25 2034 with a perigee of 356447 km.

Table 1 - Times of Perigee

MM dd YYYY	hh:mm	Perigee	Phase -/+	
Sep 28 2015	1:47	356876 km	++ F-	1h
Nov 14 2016	11:24	356511 km	++ F-	2h

Results

A MODIS/Aqua image captured on October 1st 2015 overlaid on Google Map shows packets of mode-1 internal solitary waves (ISWs) propagating in deep water away from a sill located (12.61°S, 60.84°E) between Saya de Malha and Nazareth Banks, part of the Mascarene Plateau (Figure 1). The packets move straight to Agalega Islands (yellow arrow). A red line traces the propagation path and it is perpendicular to the sill. On the opposite side of the sill, another ISWs packet propagates southeast. Figure 2 clearly shows four mode-1 ISWs packets propagating northwest, the first (1) and farthest one was generated at the sill on September 28th. The inter-packet distance between the leading wavefronts of the third and fourth ISWs packets (orange arrows) is about 132 km. Assuming a M2 semidiurnal generation period (12.42 h) then the leading ISW speed is 2.95 m/s, resulting in a 2.1 days travel from the sill to Agalega Is. We were fortunate to get a second cloud-free sunglint image for the same day captured by the MODIS/Terra sensor. This allowed us to compare both images and measure the displacement of the two selected wavefronts (Figure 3) in the third packet (3). Knowing the time interval between the two images (170 minutes) we calculated speeds of 2.65 m/s and 2.35 m/s for the first (orange arrow) and second wavefront (blue arrow), respectively. These values correspond to 2.3 days and 2.6 days of travel to cross the 528 km distance from the Mascarene sill to Agalega Is. The island long-axis is perpendicular to the wavefronts and the ISWs propagate parallel to the coast (Figure 4) but some of the waves are reflected after impinging on the island. The St. James sea-level record at North Agalega Island starts looking noisier at October 1st. Increased activity continues for the next five days (Figure 5). Figures 6 to 9 show that during those five days persisted a 2-hour coastal oscillation with heights of about 0.1 meters. The crests are signaled with blue arrows and are hardly visible in the tidal record.

Figure 1 shows that Rodrigues island is located 833 km south-southeast of the sill. We did not found cloud-free and sunglint images for the days following October 1st 2015, making impossible to detect the southeastward propagating packets, but Figure 10 and 11 shows that soon after the 1800 hour of October 2nd (4 days after perigee) started an increase in the seiche activity in Port Mathurin, Rodrigues Is. The 25-minute seiche activity increased and persisted in the subsequent four days (see Figures 12-14).

We succeed in finding two images showing the south-southeast propagation of the ISWs approaching Rodrigues Island (Figure 15) on the 17th November 2016 (3 days after the perigean full moon). Comparing these two images (Figure 16) we found that the leading wavefront displacement was 33 km in a time interval of 168 minutes, for a resultant speed of 3.27 m/s. For the third wavefront – in the same packet - the speed was 2.88 m/s. These speeds represent travel times from the sill to Rodrigues Island of 2.9 days and 3.4 days, respectively. Figure 17 and Figure 18 show the internal waves impinging on Rodrigues Island and crossing its western waters on the 19th and 20th of November 2016. Figures 19-22 show an increase in seiche activity on the 19th and 20th of November 2016. The concurrent seiches and internal waves is a definite proof of their direct relationship.

During the same period ISWs are impinging in Agalega Is. (Figures 23-26). But the Agalega seiches increased activity on November 18th, one day earlier than in Rodrigues because the first one is at a closer distance from the sill.

Discussion

Mode-1 ISWs approaching Port Mathurin from the northwest excite seiches on the platform waters along a length of 4.3 km and a depth of 8 m, applying Merian's Formula for a quarter-wave oscillator results in a seiche period of 25.6 minutes. These oscillations increased when the internal waves impinged on the Island. The relationship between coastal seiches and tide-generated internal solitary waves have been proved before in other locations such as Puerto Rico (Giese et al. 1982), Palawan Island (Giese and Hollander, 1987), Sri Lanka (Wijeratne et. al., 2010), Maldives (Alfonso-Sosa, 2016), Christmas Island (AU) (Alfonso-Sosa, 2017). The seiche activity increases - sometimes dramatically - between five to ten days after perigee-spring tides. The lag is due to the travel time of the ISWs packets from the source generation area to the destination island. The speed of the ISWs is different for each particular location and oceanic conditions. If the leading ISW has a larger negative amplitude then it moves faster. The speed calculated for the Mascarene Ridge ISWs propagating southeastward reached around 3 m/s suggesting that they have large amplitudes. This result corroborates the previous ship observation in the east side of the sill of a sequence of huge internal soliton-like waves with up to 90 m amplitudes (in the upper thermocline) and phase speed of 3 m/s (Konyaev et al., 1995). The large and fast ISWs cross the 833 km between the sill and Rodrigues Island in just 3 days. A numerical model show mode-1 ISWs at 129 km of the sill with a maximum 200 m amplitude at 255 m depth, and with a speed of 2.77 m/s (da Silva et al., 2015). Our results and previous ones confirm that during perigean spring tides the strong tidal currents in the sill are capable of generating large-amplitude and fast mode-1 internal solitary waves packets about 100 km from the sill.

The St. James sea-level station is located about 21 km north from the southernmost point in the Agalega Islands platform. If we assume a water body with a length of 21 km with a uniform depth of 13 meters, applying Merian's Formula for a quarter-wave oscillator results in a seiche period of 124 minutes (2.07 hours). It is possible that ISWs impinging in the southern slopes of Agalega's platform are responsible for exciting the 2-hour seiches recorded in St. James. The Mode-1 ISWs arrived in just 2.3 days after their generation and simultaneously coastal seiches showed increased activity. These ISWs generated during perigean-spring tides are fast, implying that their amplitudes must be large.

Conclusion

Large amplitude and fast mode-1 internal solitary wave packets generated by the interaction of strong tidal currents with a central sill in the Mascarene Plateau during perigean-spring tides, and propagated northwestward and southeastward hundred of kilometers before impinged on Agalega and Rodrigues islands, respectively. The arrival of the ISWs packets coincided with a simultaneous increase in coastal seiche activity at both islands.

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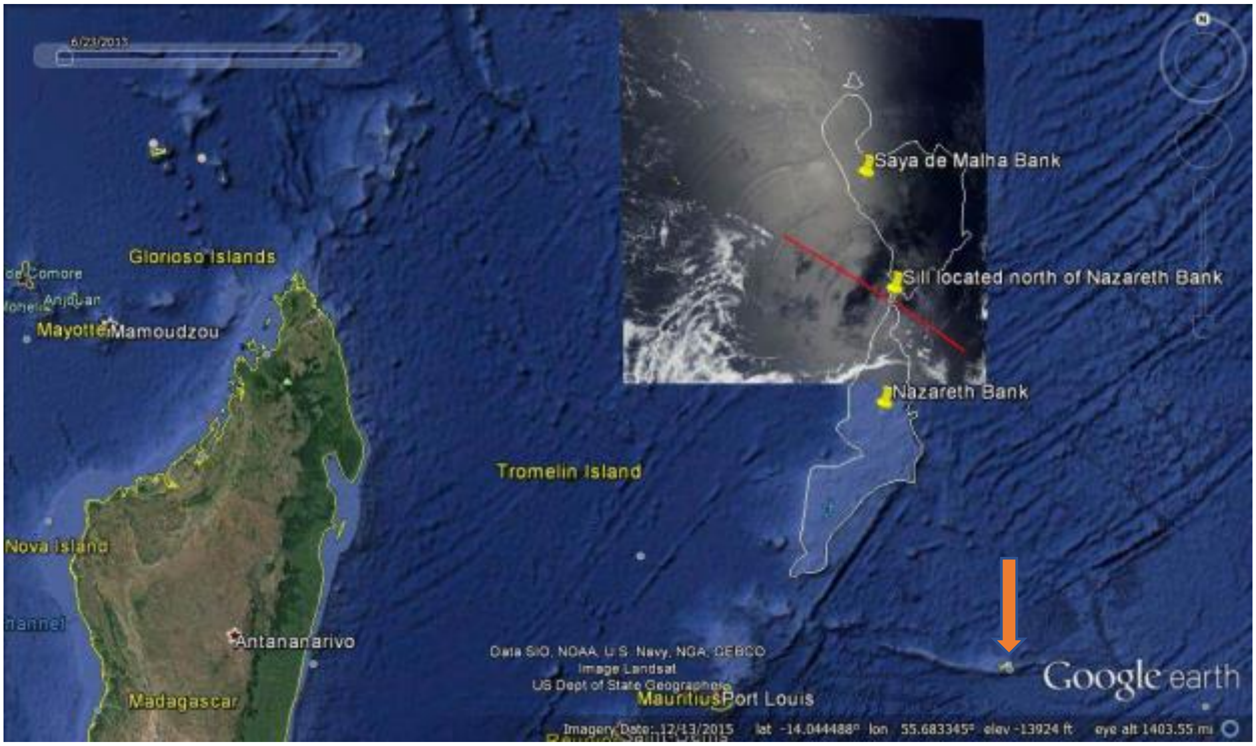
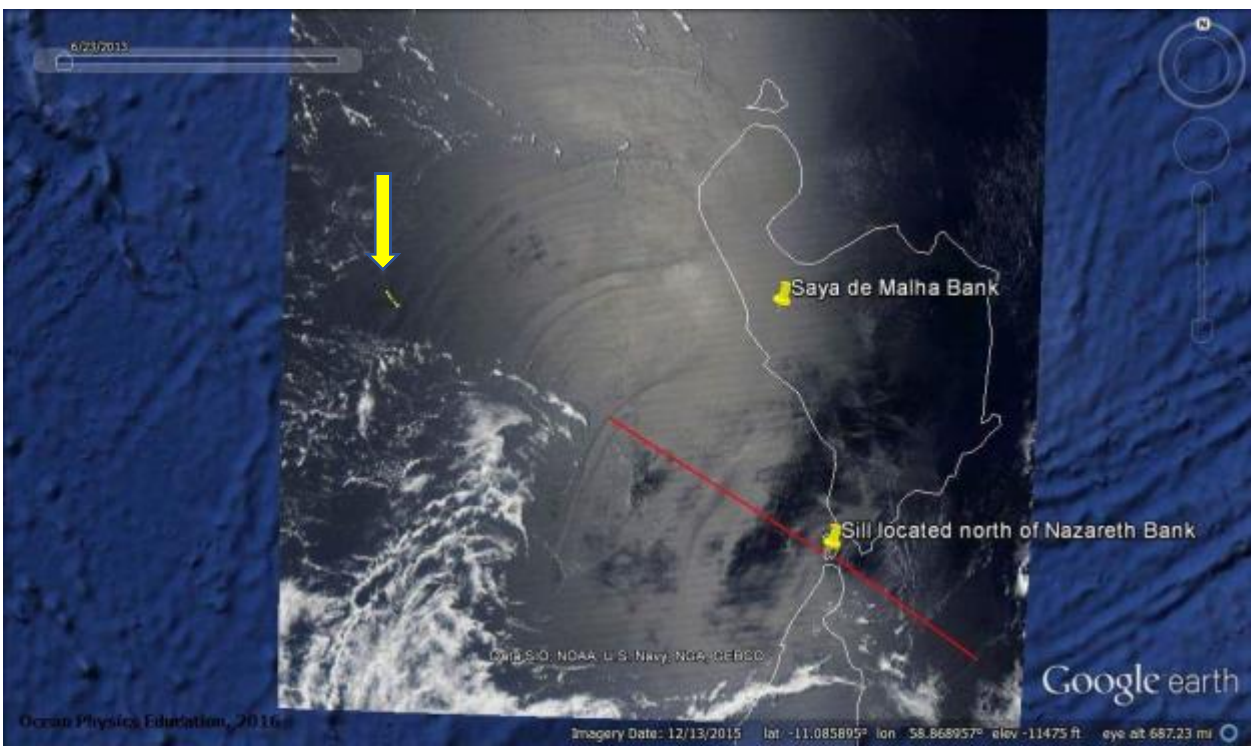


Figure 1. Location of the Mascarene Plateau and the sill (center yellow pin). The orange arrow points to Rodrigues Island. The MODIS/Aqua image overlay show the propagation path (red line) of the ISWs



packets at both sides of the sill. Agalega Island (yellow arrow) receives a direct impact of the ISWs train.

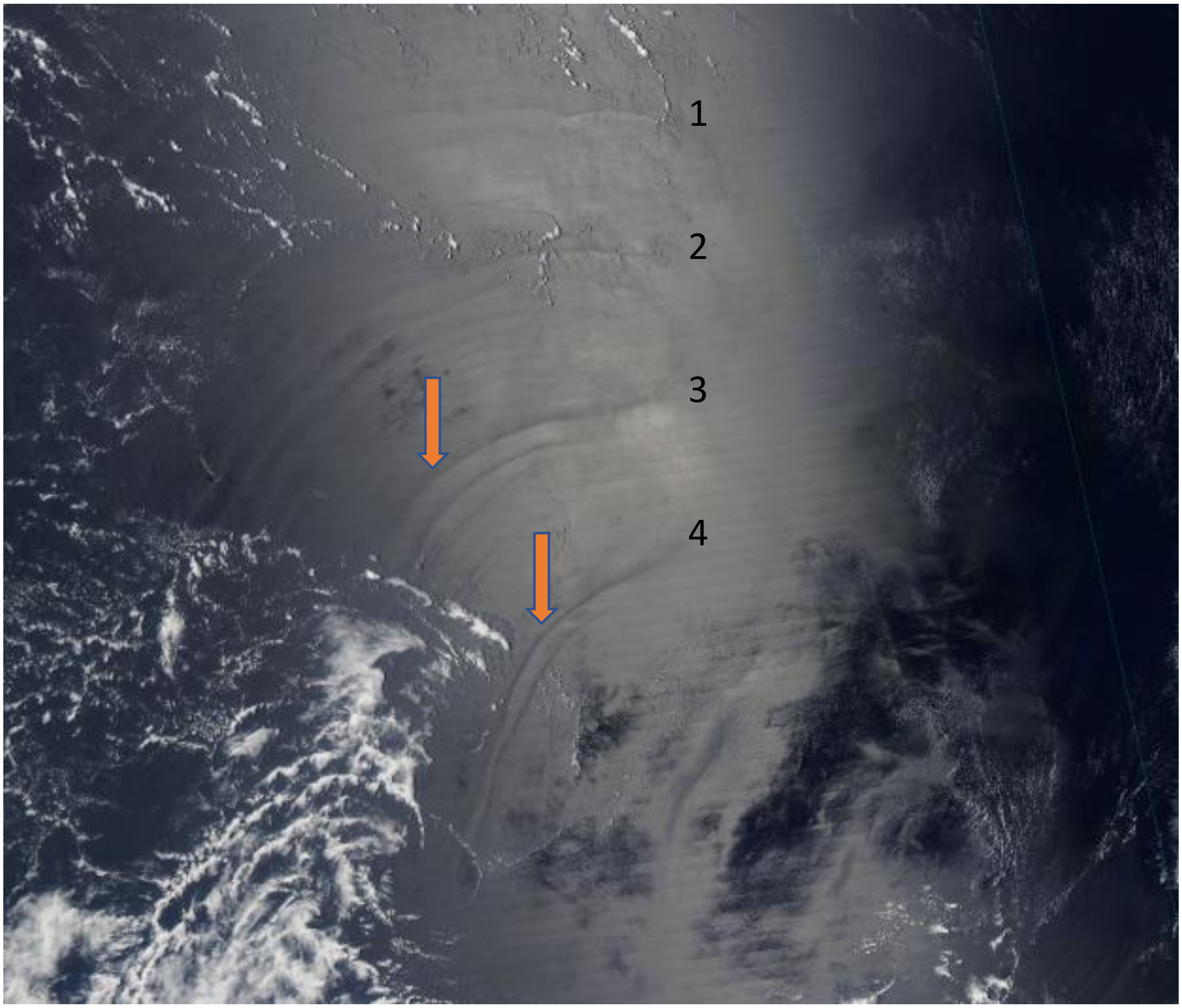
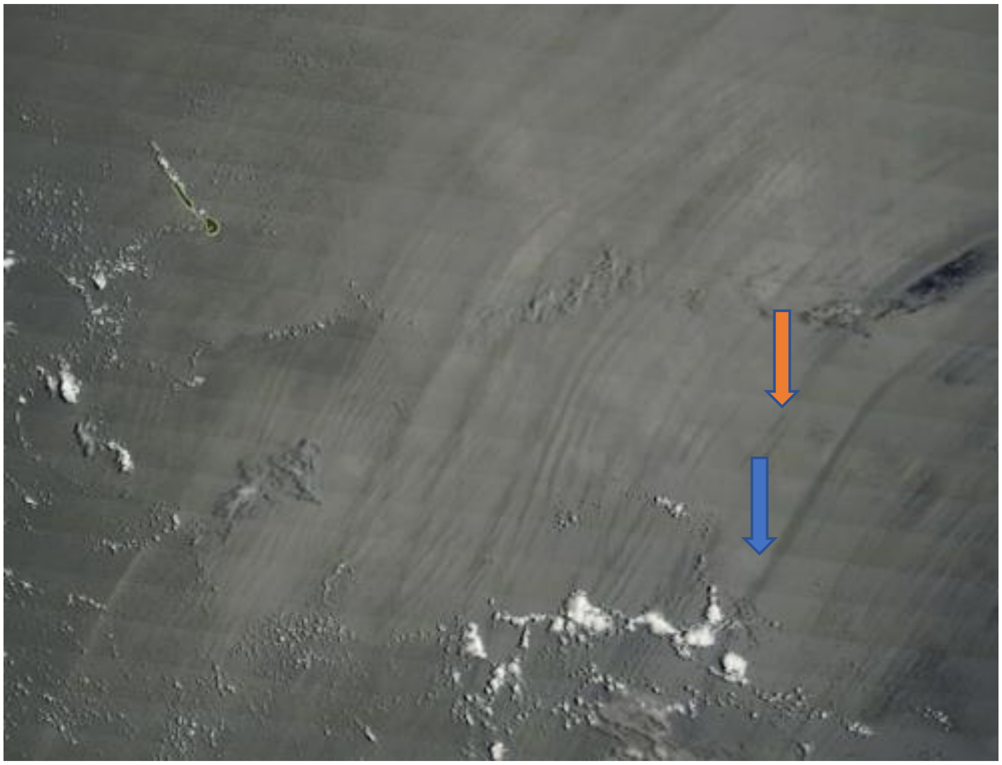


Figure 2. 1-OCT-2015 0934. Aqua/MODIS. Between the lead wavefronts (two orange arrows) there is a separation distance of 132 km. Assuming a M2 semidiurnal generation period (12.42 h) then the lead wavefront speed is 2.95 m/s, a 2.1 days travel to Agalega Is.



1-OCT-2015 0643 Terra/MODIS.

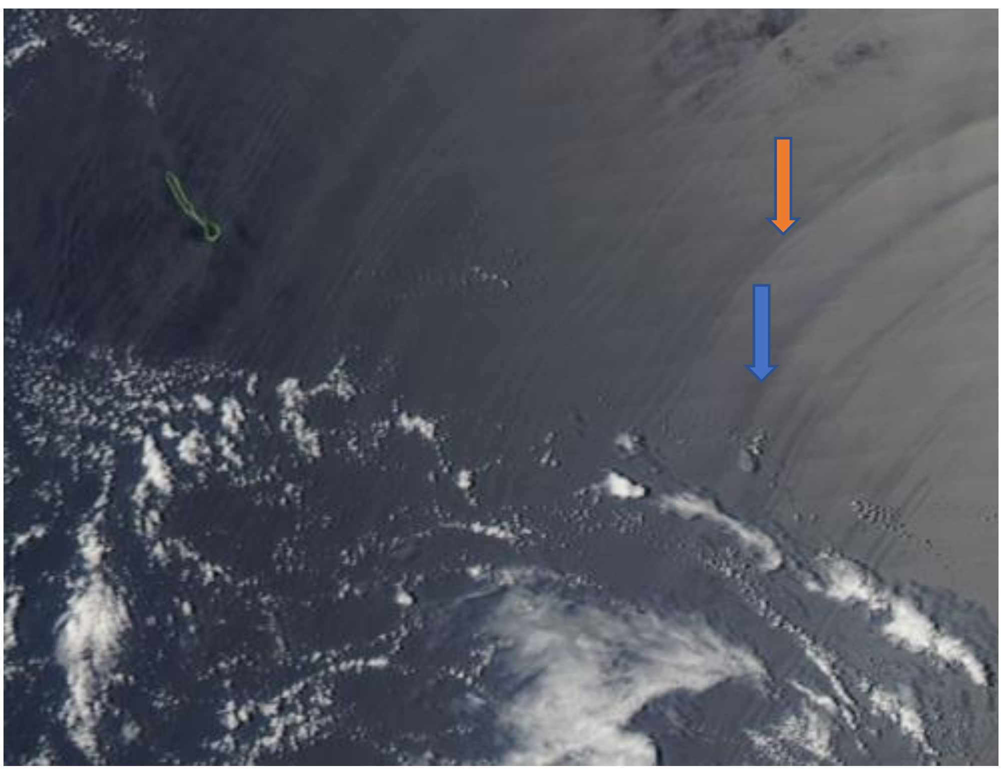
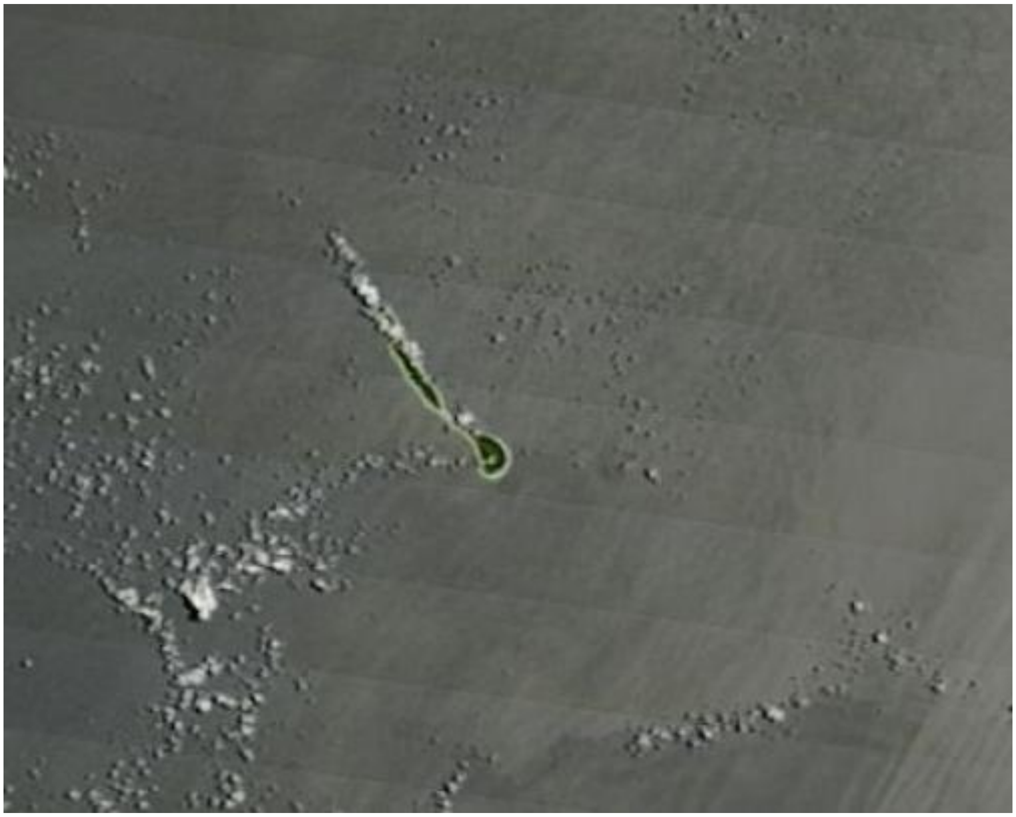


Figure 3. 1-OCT-2015 0934. Aqua/MODIS. The blue arrow signals the same wavefront in each image, from its displacement and time interval we calculated a propagation speed of 2.35 m/s, a 2.6 days travel to Agalega Is. The orange arrow signals another wavefront with a speed of 2.65 m/s, a 2.3 days travel to Agalega Is.



1-OCT-2015 0643 Terra/MODIS.

Figure 4. ISWs wavefronts and Agalega Islands. 1-OCT-2015 0934. Aqua/MODIS.

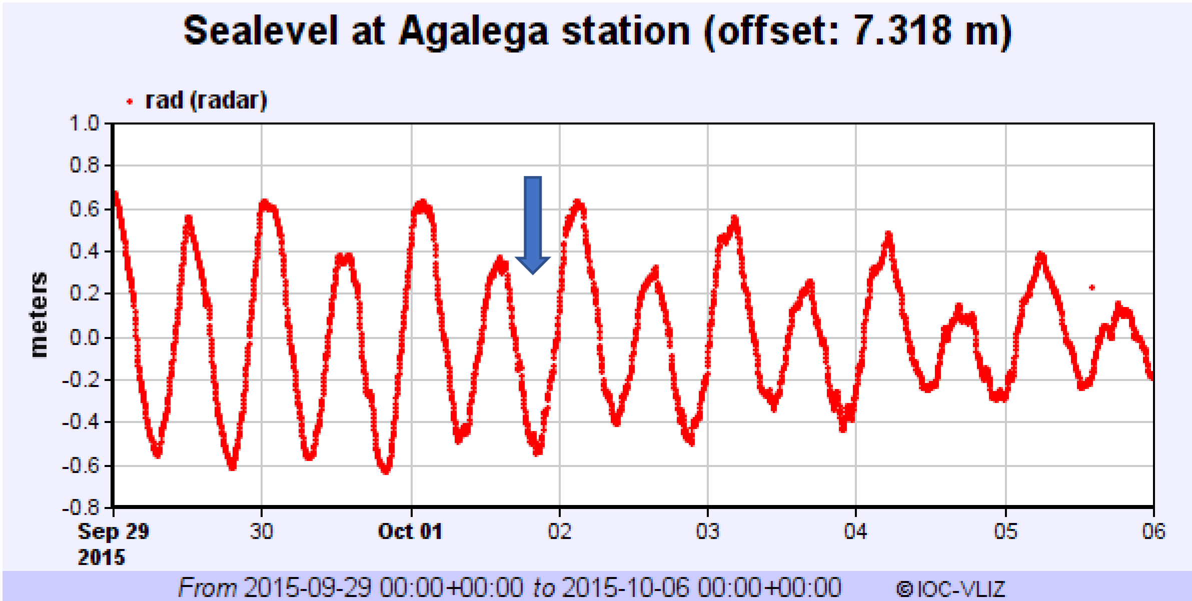


Figure 5. Sea-level record at Agalega Is. Blue arrow signals the start day of the increased seiche activity. Figure 6 below zooms in that particular section of the record. Figures 6 to 9 zoom in each day of the record.

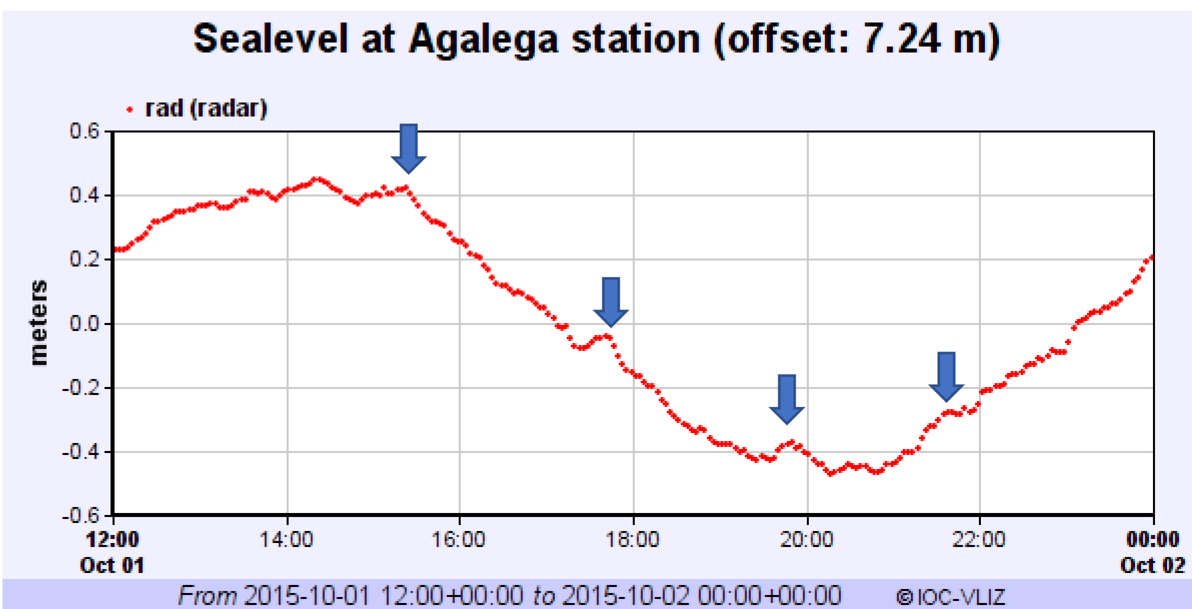


Figure 6. Zoom in during the start of seiche activity. Blue arrows shows the crest of each oscillation separated by about 2 hours.

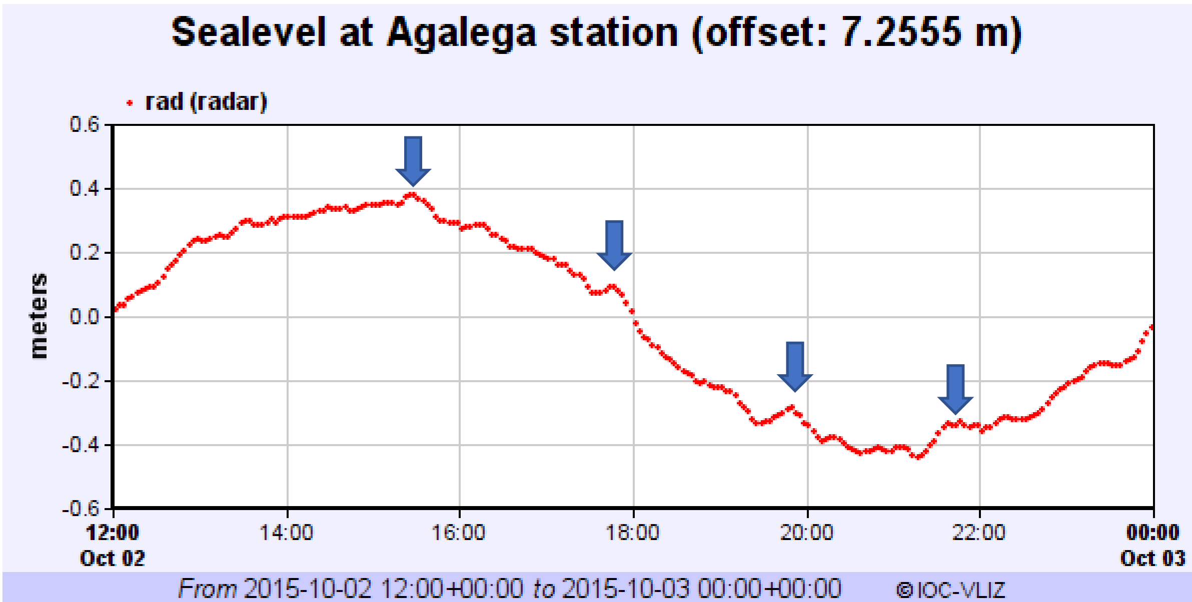


Figure 7. Zoom in during seiche activity. Blue arrows shows the crest of each oscillation separated by about 2 hours.

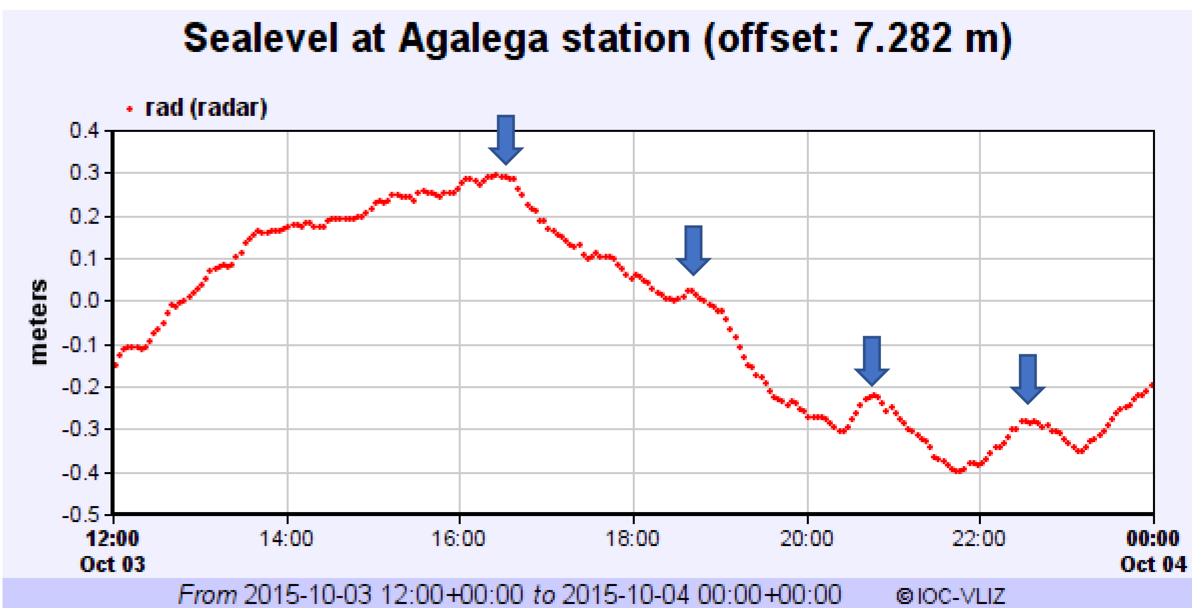


Figure 8. Zoom in during seiche activity. Blue arrows shows the crest of each oscillation separated by about 2 hours.

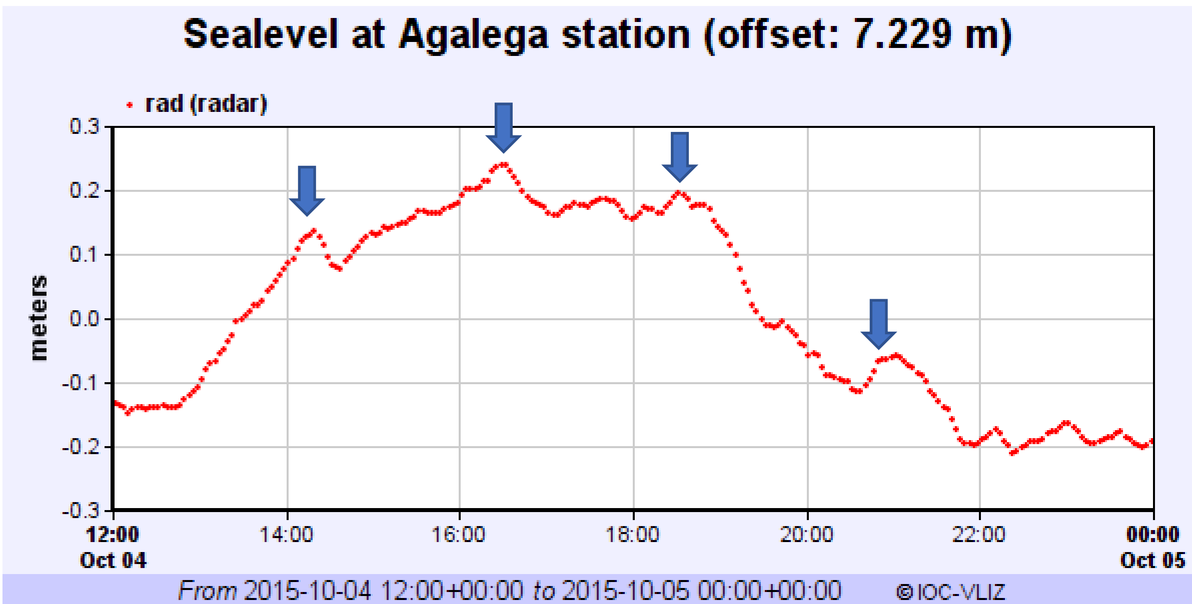


Figure 9. Zoom in during seiche activity. Blue arrows shows the crest of each oscillation separated by about 2 hours.

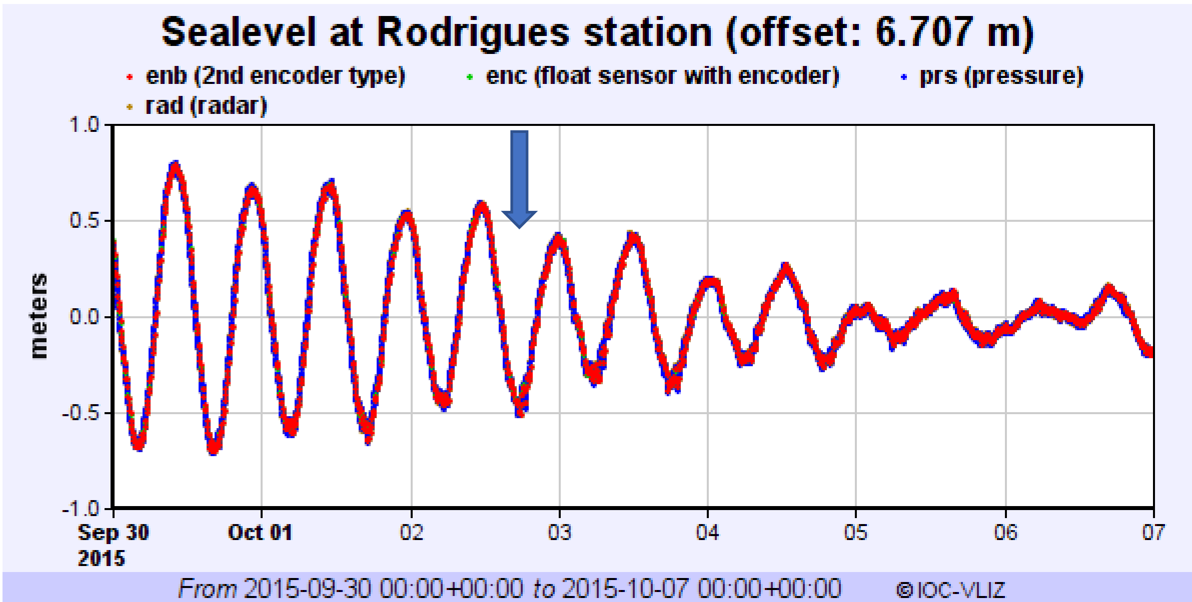


Figure 10. Sea-level record at Port Mathurin, Rodrigues Island. Blue arrow signals the start day of the increased seiche activity. Figure 11 below zooms in that particular section of the record.

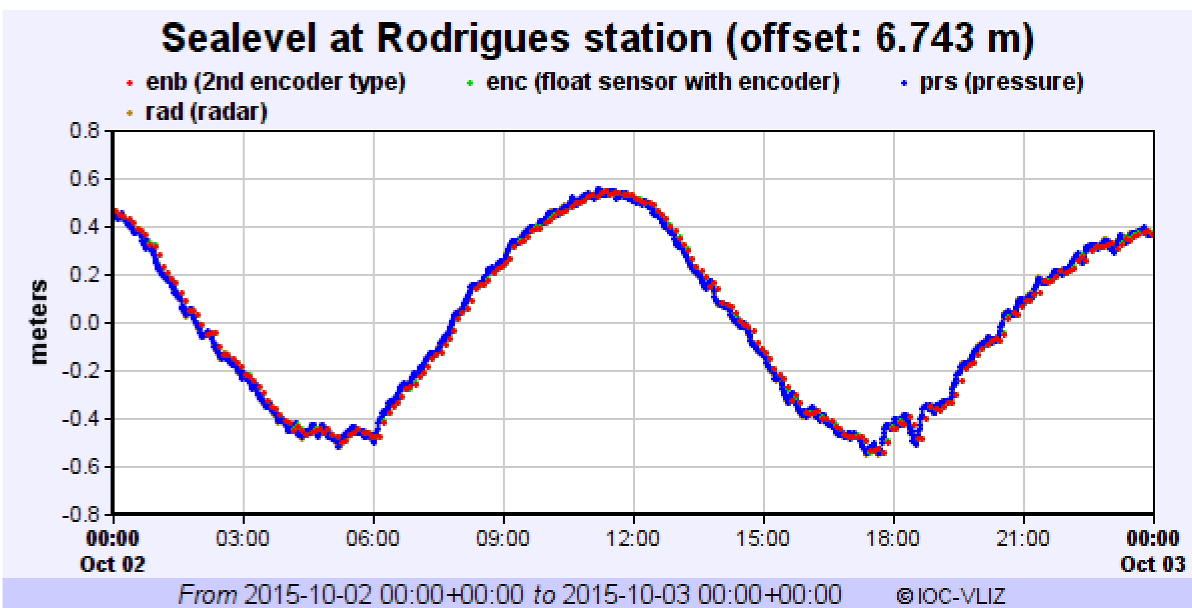


Figure 11. A relatively large amplitude coastal oscillation was observed around the 1800.

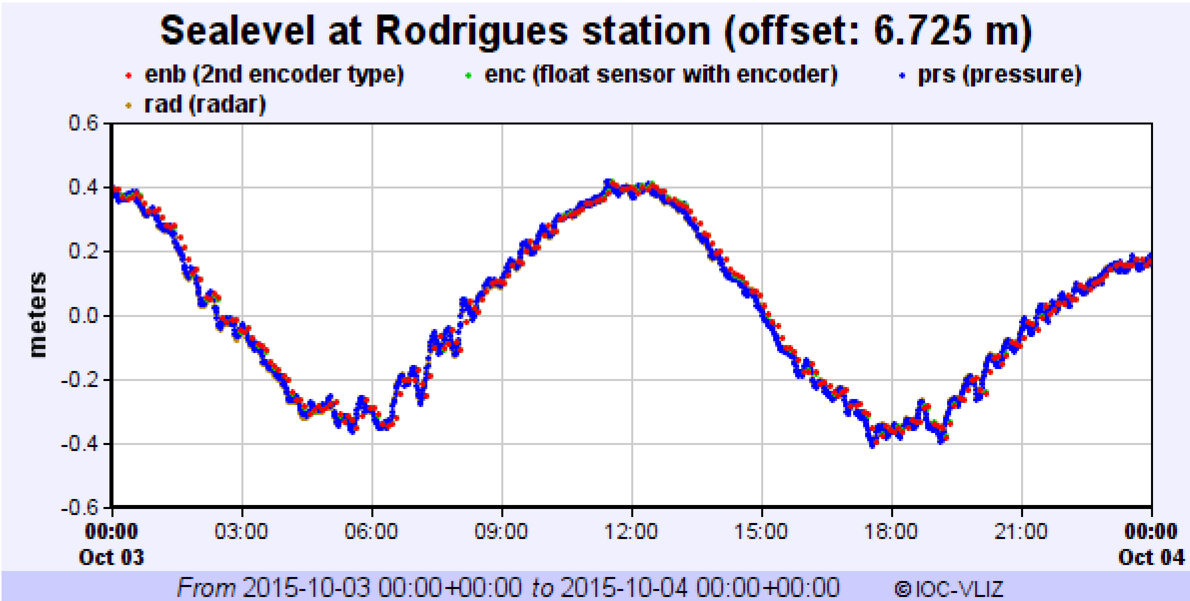


Figure 12. Sea-level record at Port Mathurin, Rodrigues Island during large seiche activity.

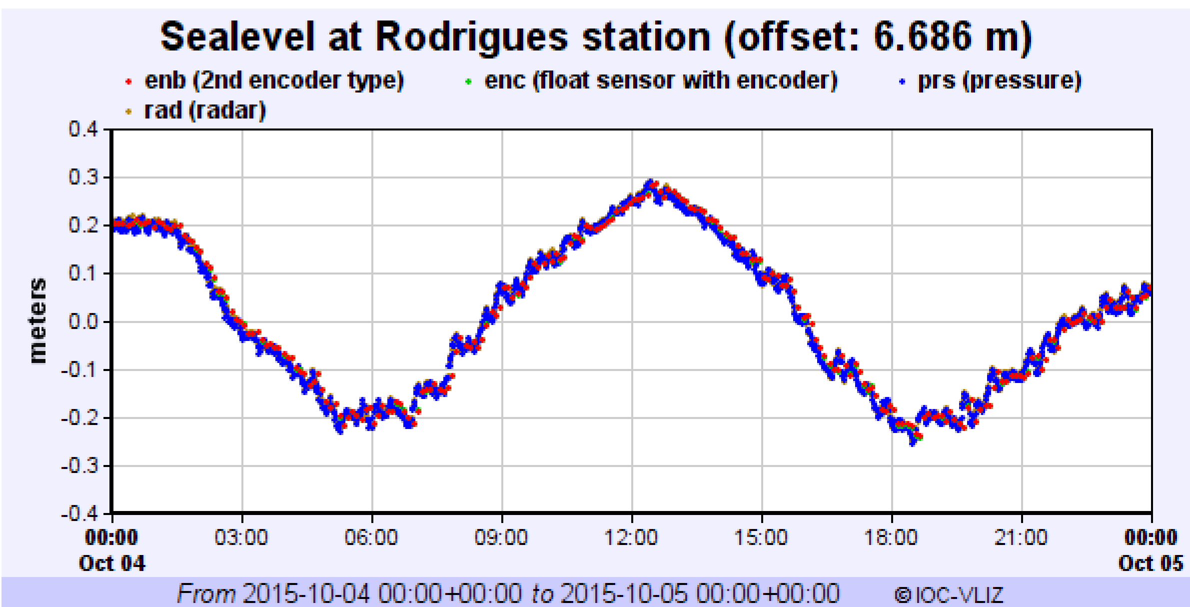


Figure 13. Sea-level record at Port Mathurin, Rodrigues Island during large seiche activity.

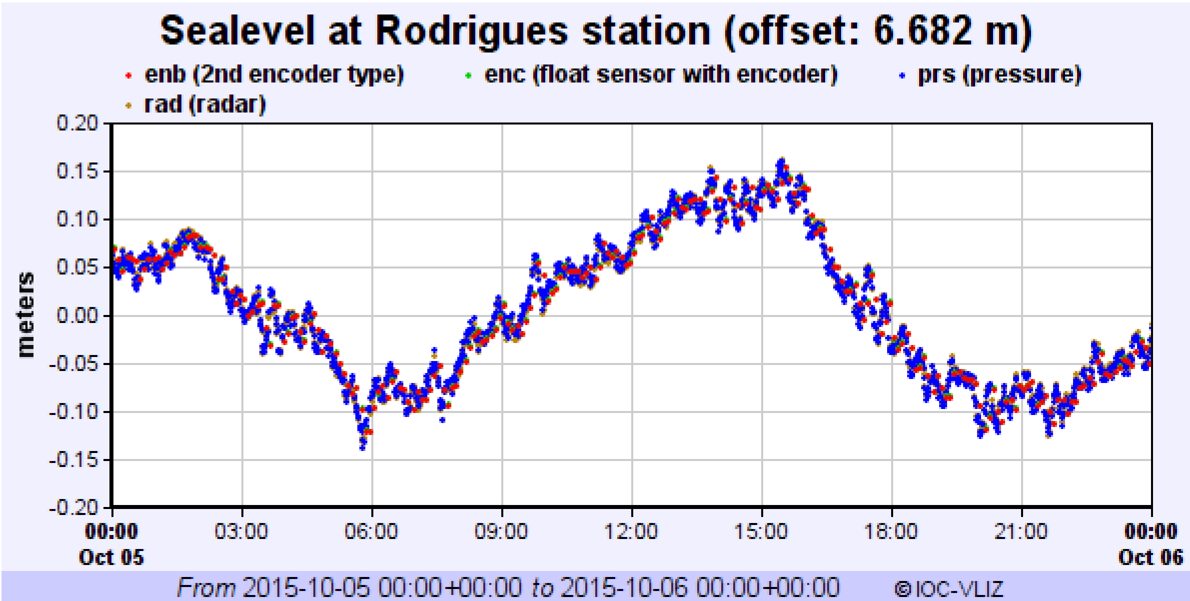


Figure 14. Sea-level record at Port Mathurin, Rodrigues Island during large seiche activity.

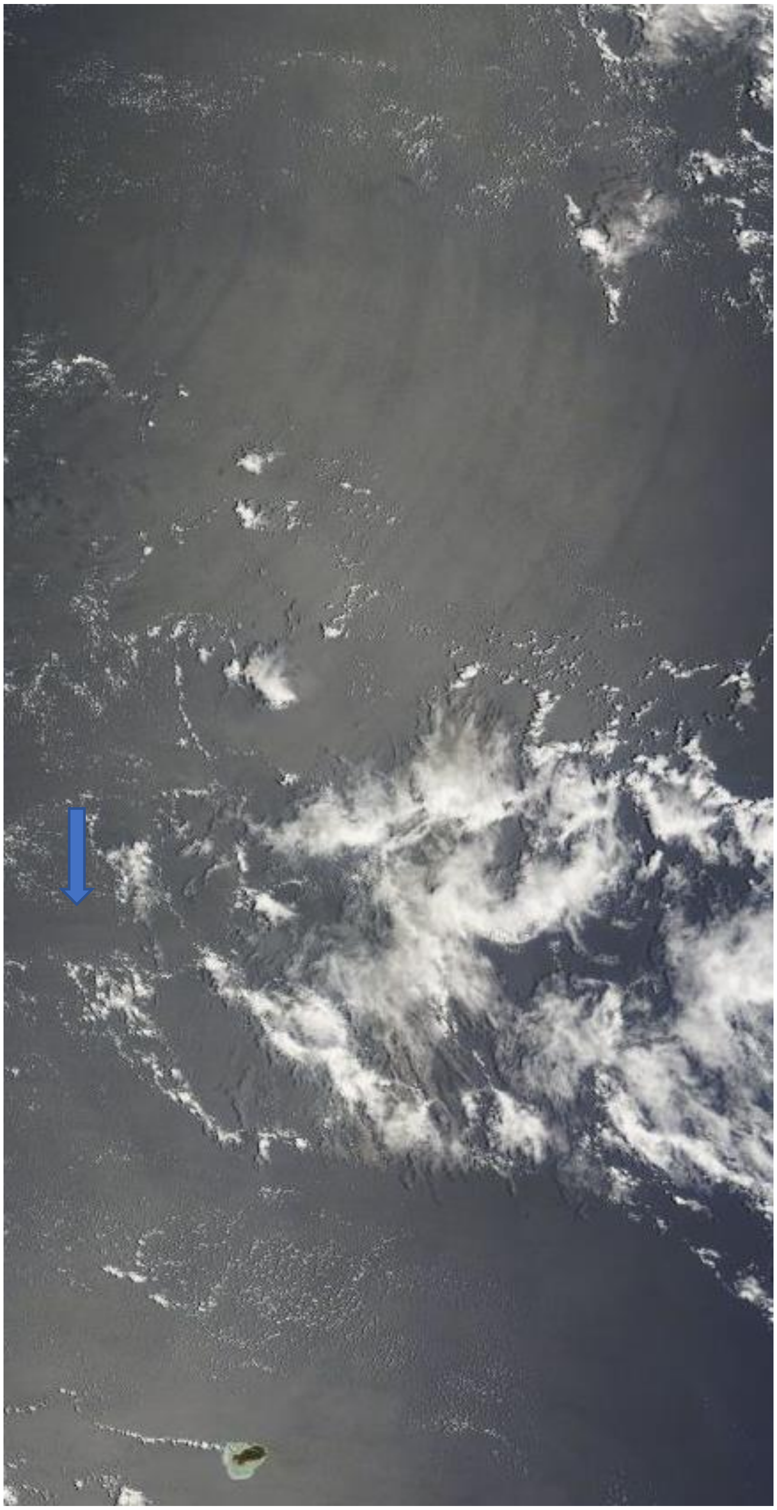
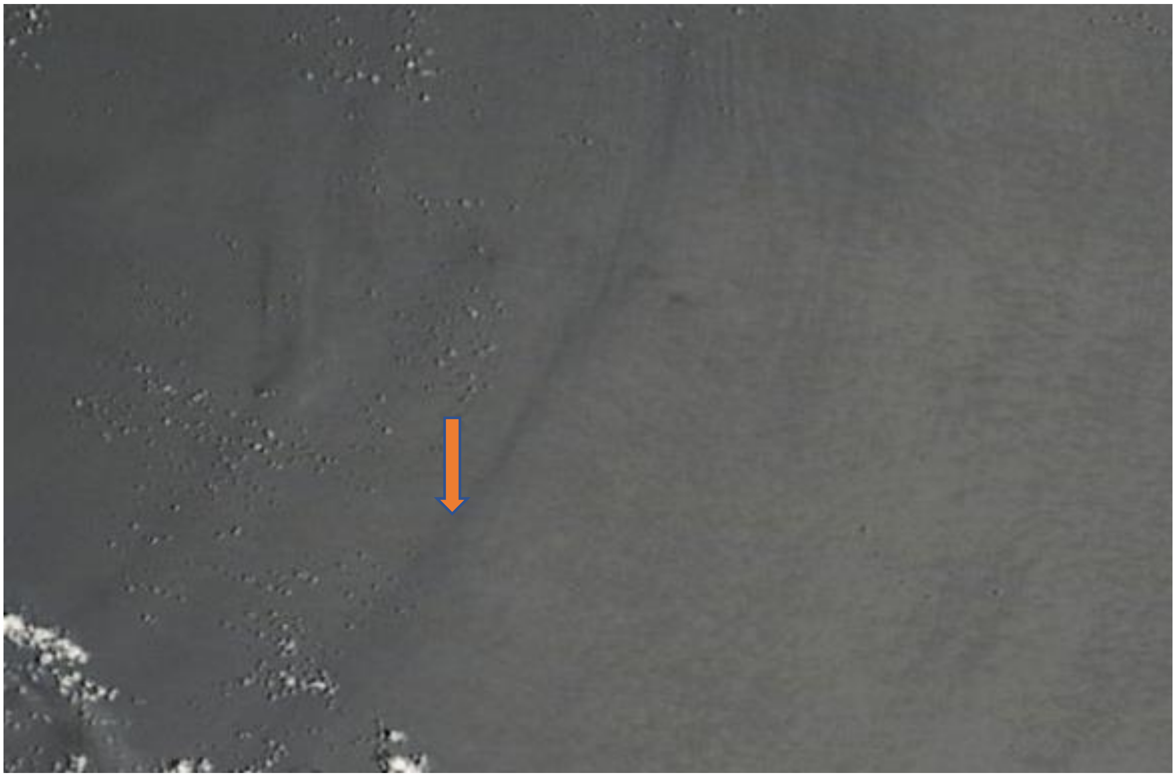


Figure 15. Large ISWs wavefronts propagating southeast. 17-NOV-2016 0614 Terra/MODIS. The blue arrow points to a wavefront moving toward Rodrigues Island, located at the bottom of the image.



17-NOV-2016 0614 Terra/MODIS

Figure 16. 17-NOV-2016 0901 Aqua/MODIS. Between the two arrows there is a separation of 33 km. The images were captured 168 minutes apart, for a speed of 3.27 m/s. The 3rd wavefront was 2.88 m/s.

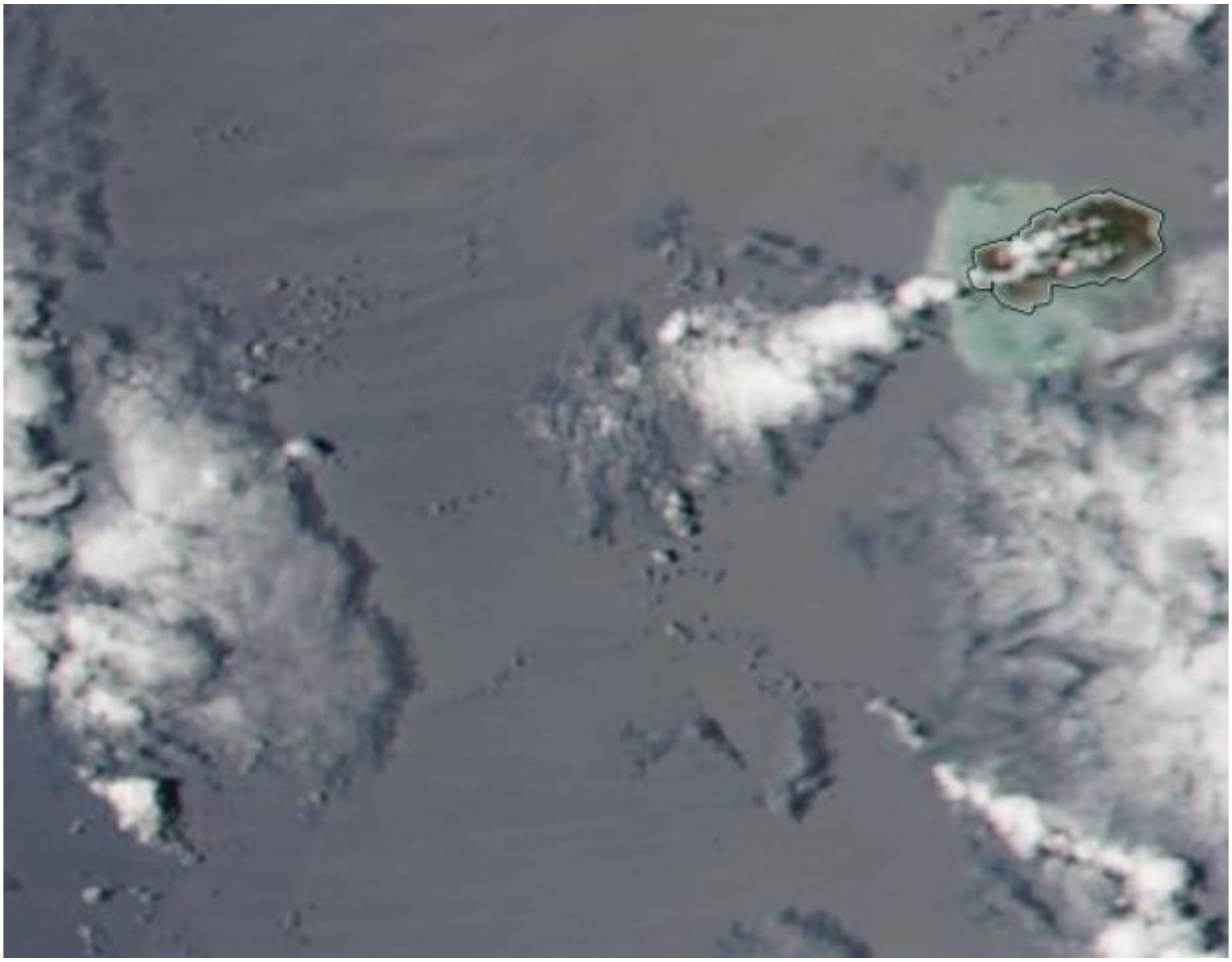


Figure 17. Internal waves impinging on Rodrigues Island and crossing its western waters. 19-NOV-2016 0905 SUOMI/NPP

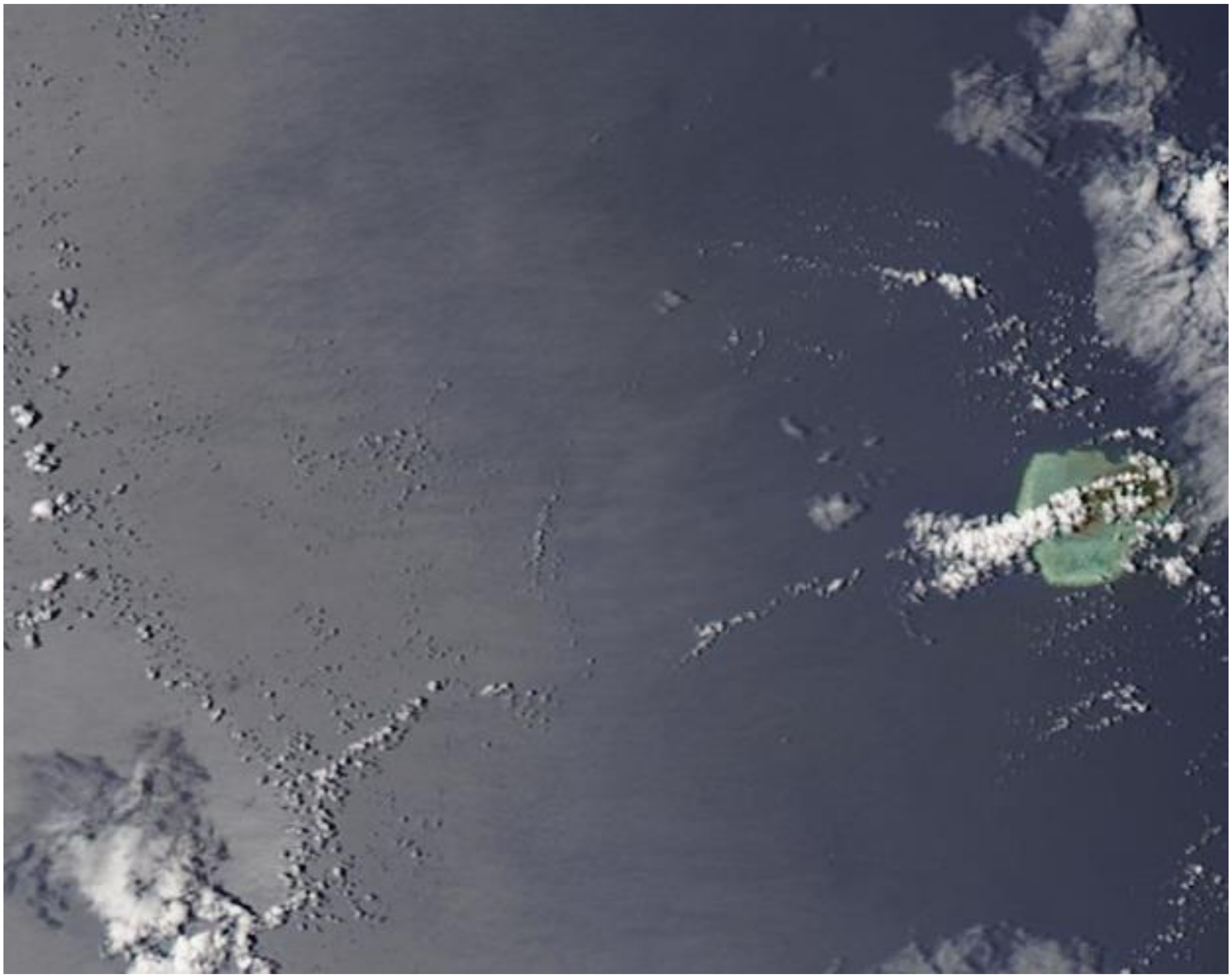


Figure 18. Internal waves impinging on Rodrigues Island and crossing its western waters. 20-NOV-2016 0930 Aqua/MODIS

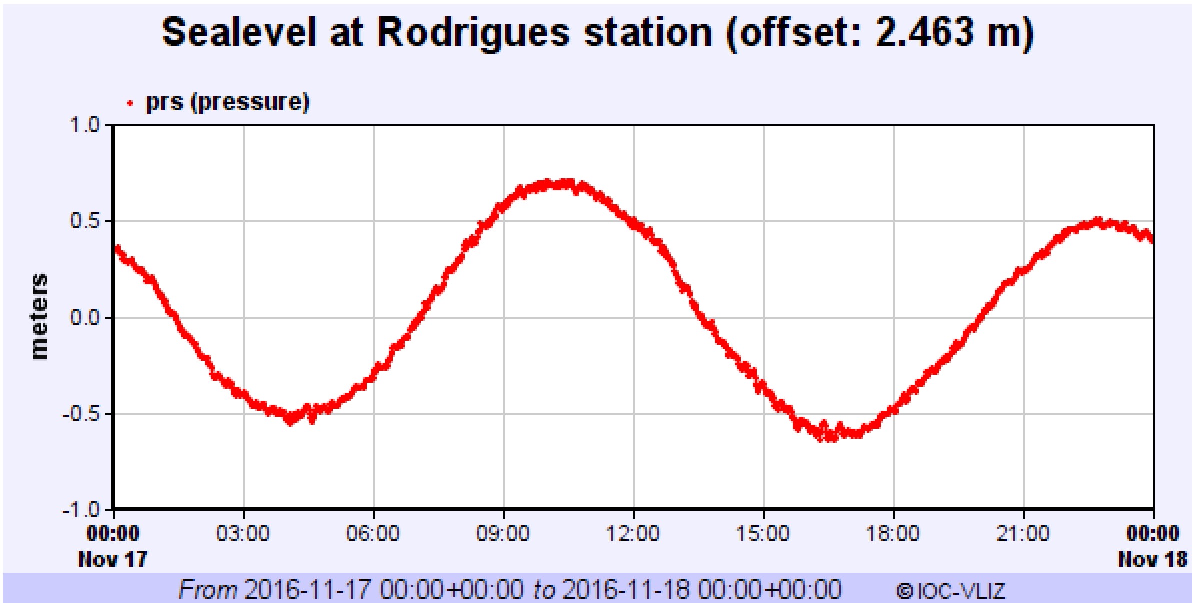


Figure 19. Sea-level record at Port Mathurin, Rodrigues Island during start of seiche activity.

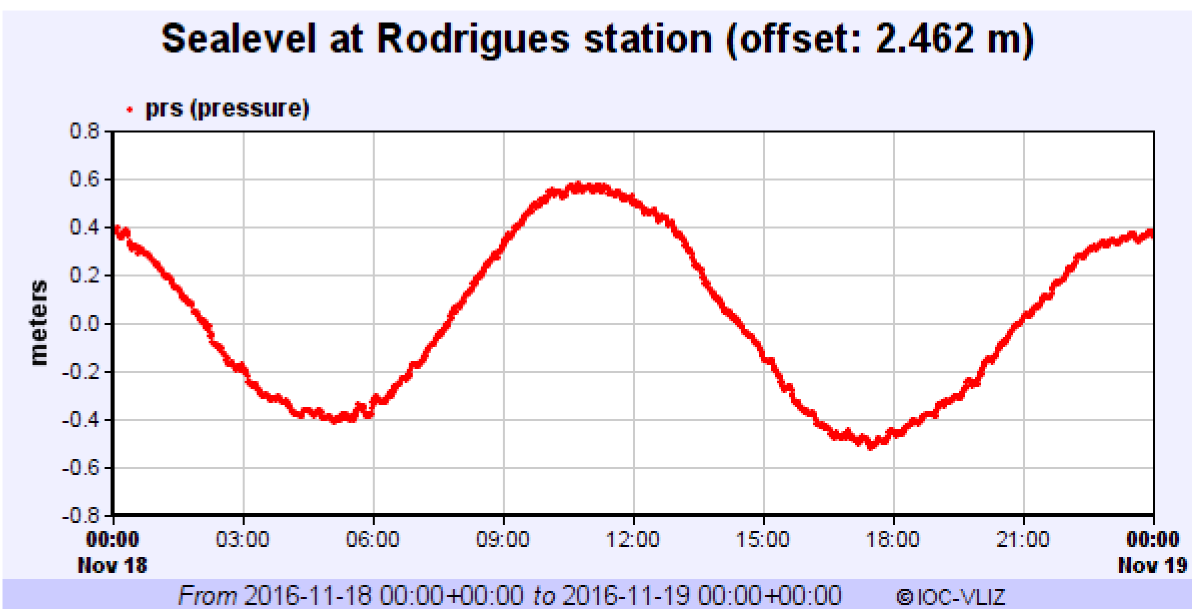


Figure 20. Sea-level record at Port Mathurin, Rodrigues Island during large seiche activity.

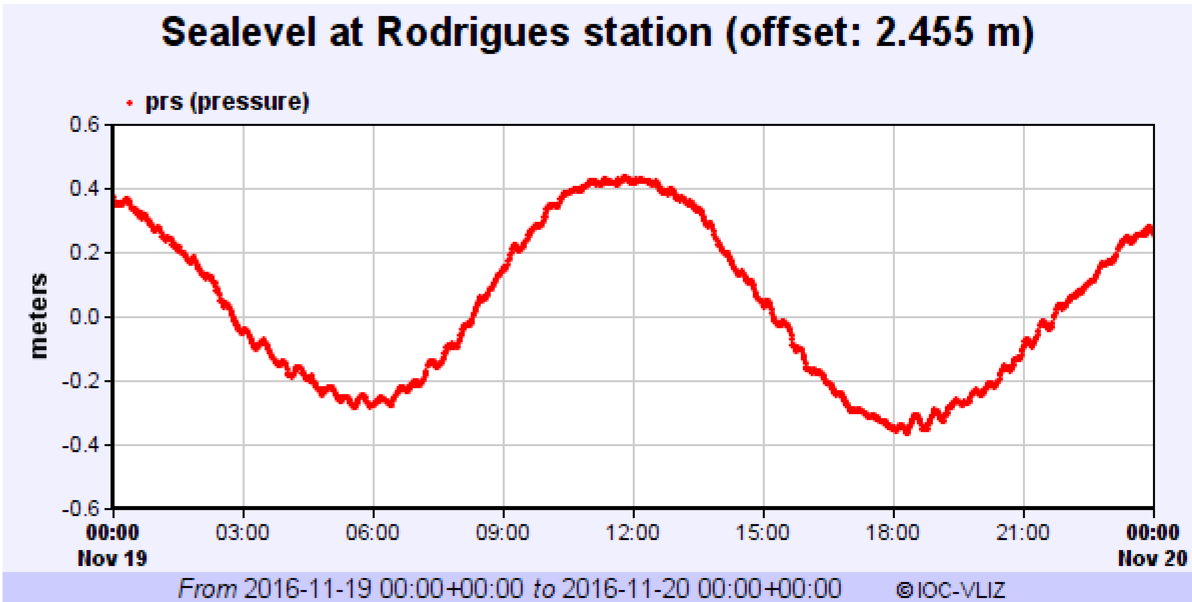


Figure 21. Sea-level record at Port Mathurin, Rodrigues Island during large seiche activity on NOV 19th.

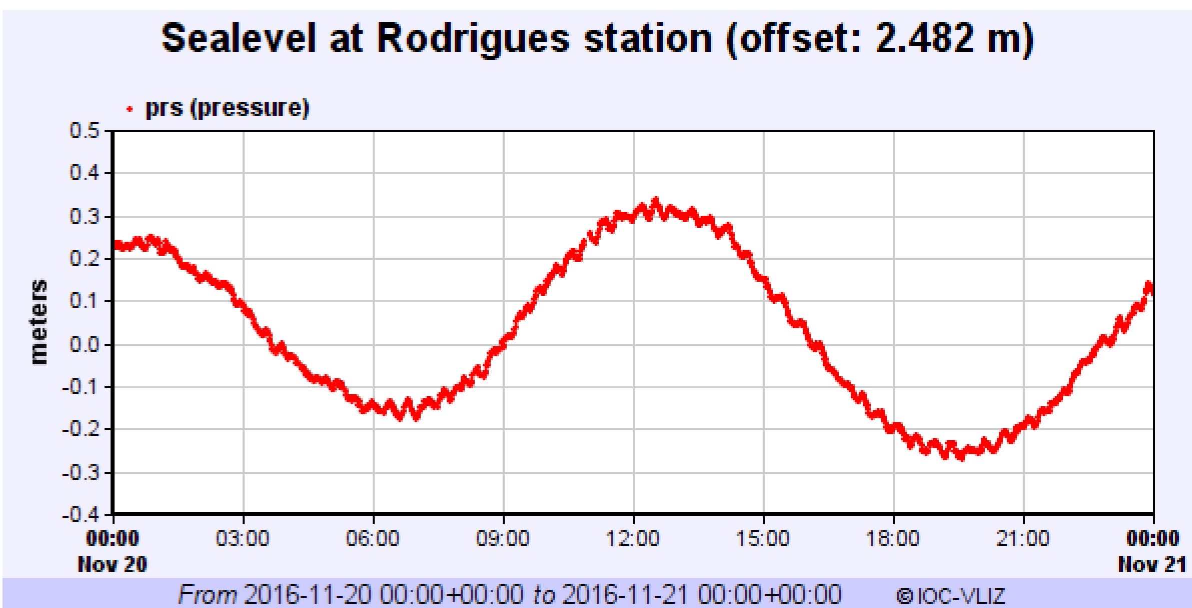


Figure 22. Sea-level record at Port Mathurin, Rodrigues Island during large seiche activity on NOV 20th.

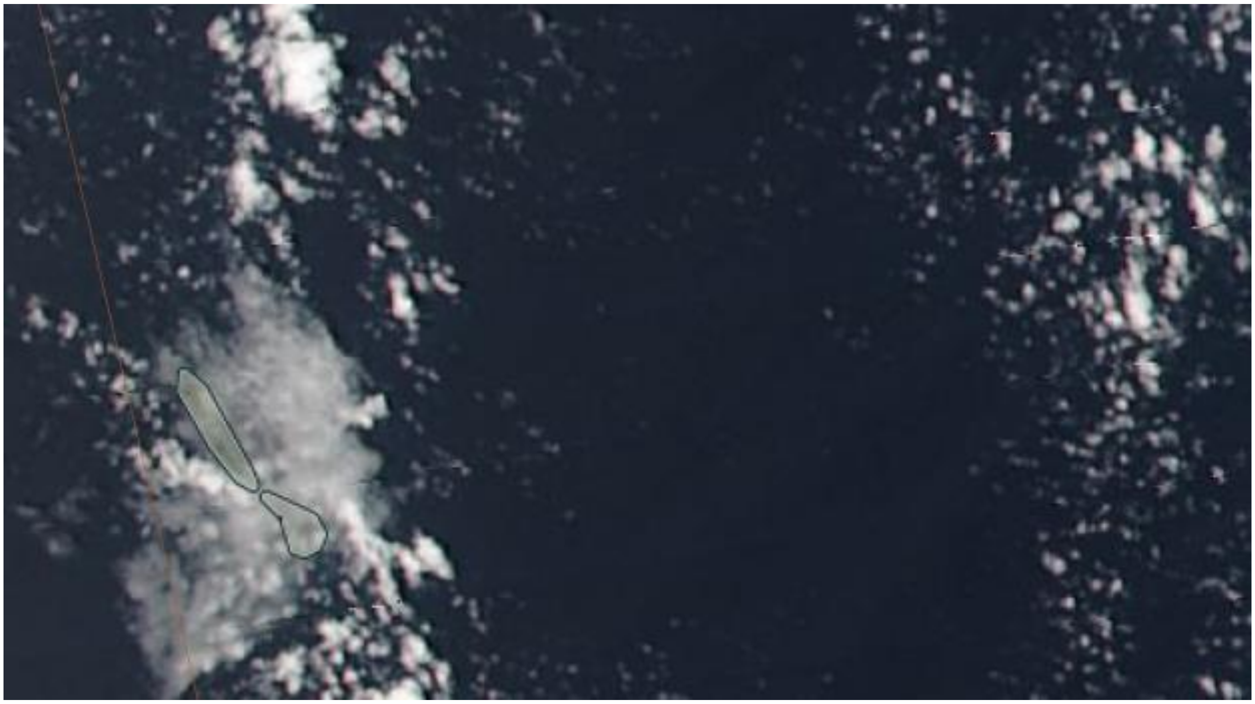


Figure 23. 17-NOV-2016 0946 ISWs arrive to Agalega Islands.

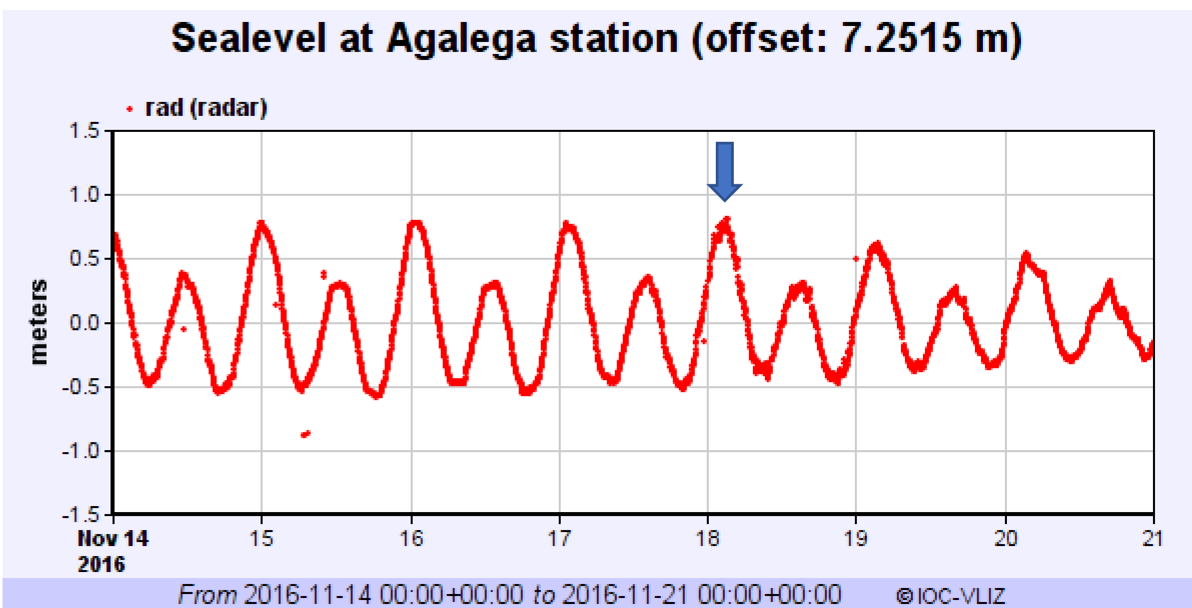


Figure 24. Sea-level record at Agalega Is. Blue arrow signals the start day of the increased seiche activity.

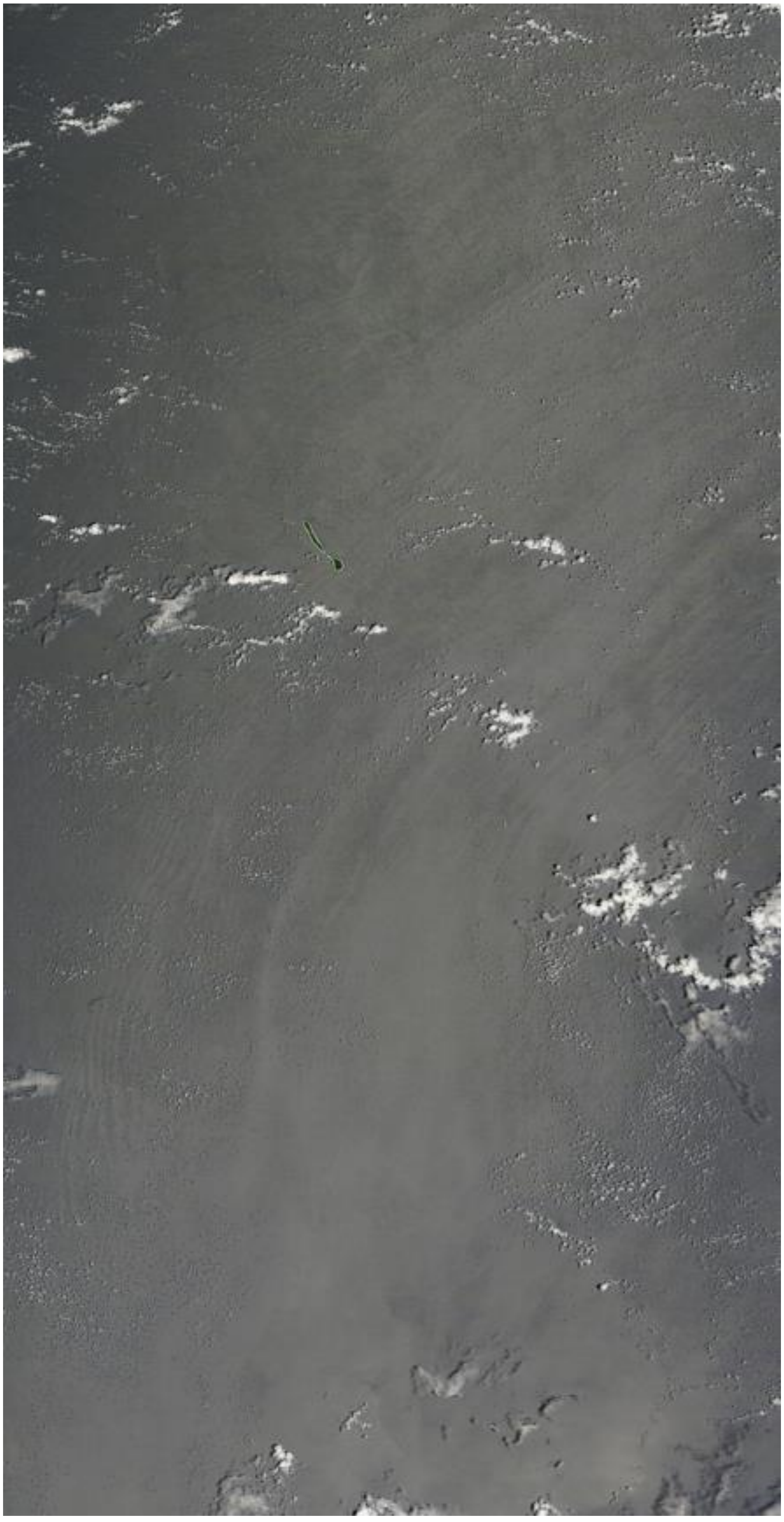


Figure 25. Large ISWs wavefronts impinging on Agalega Is. 20-NOV-2016 0643 Terra/MODIS

Figure 26. Zoom of previous image. Internal waves impinge on Agalega Islands. 20-NOV-2016 0643.

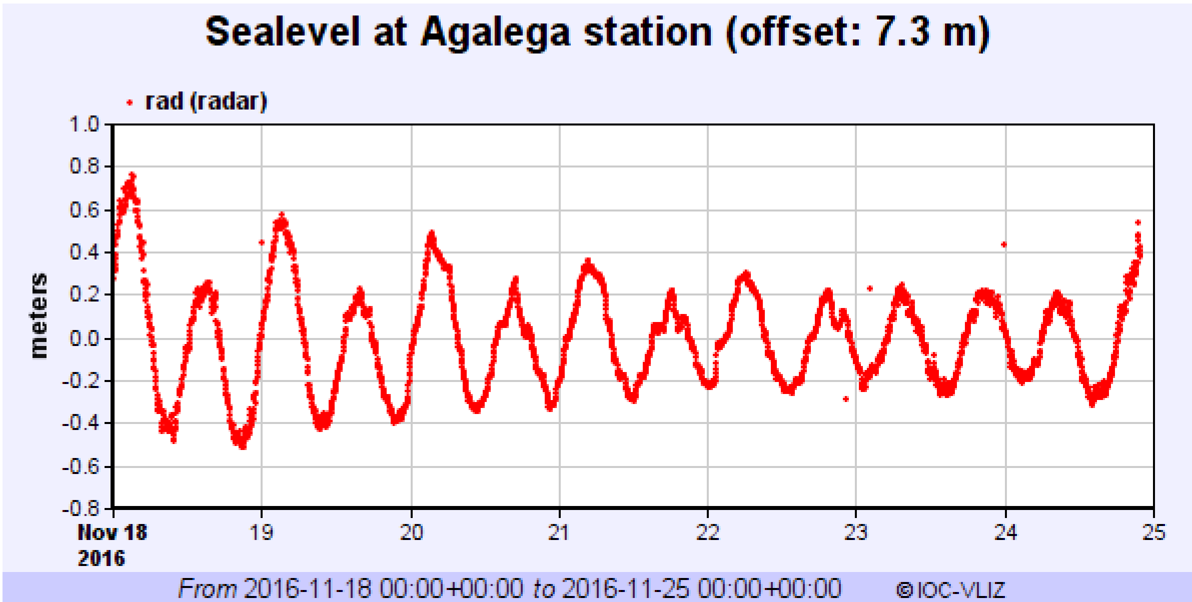


Figure 27. Sea-level record at Agalega Island during large seiche activity.