Tsunami Detection Using the PARIS Concept

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Abstract

On 26 December 2004 a tsunami generated by an earthquake with its epicentre in the Indian Ocean West of Indonesia caused a real human and material catastrophe in the region. After the event some proposals to establish a network of sensors for tsunami detection were put forward.

This paper presents an alternative concept that can be applied from satellite, aircraft or from the coast, and which can complement such a network of sensors for fast tsunami detection. The concept makes use of GNSS signals reflected from the ocean's surface to perform mesoscale ocean altimetry. The technique, designated PARIS (Passive Reflectometry and Interferometry System), aims at capturing fast topographic events happening on the ocean surface such as eddies and fronts.

The paper includes details of some aircraft experiments whereby a PARIS altimeter was used to map a topographic signature with amplitude and wavelength similar to a tsunami in open ocean.

Introduction

"Our mastery of major technology projects must lead us to reflect on how we can place our expertise and technology at the service of all the world's citizens, in particular those who are suffering today or who may one day suffer from the various scourges that afflict our Earth. There are of course limits to what we can do but we must do whatever we can....

...this plan will concern both the reconstruction phase in South-East Asia and a further phase devoted to the detection and prevention of such events."

J.J. Dordain, ESA DG, "Letter to all staff", 15 of January 2005.

Need for a Global Tsunami Detection System

On Boxing Day 2004, the entire world was shocked to hear of the sub-oceanic earthquake off the coast of Sumatra and the subsequent tsunamis which devastated shoreline communities from Indonesia to Thailand and from Sri Lanka to Somalia. Since then, worldwide, governments and policymakers have looked to seismologists and oceanographers for at least the means to provide a substantiated warning in the event of any such occurrence happening again in the future. In fact, the principle for such a global warning system already exists. It requires only that it be fully developed and exploited for the benefit of all coastal regions around the globe.

The PARIS Concept

Since 1993 ESA and later European industry have been working on an idea to make use of GNSS signals reflected from the ocean's surface in order to perform altimetry [1]. The technique, designated PARIS (Passive Reflectometry and Interferometry System), has been proven first through experiments over a pond at ESTEC, then from the Zeeland bridge (NL) and most recently from an aircraft flying over the Mediterranean near Barcelona. In all these experiments, the results have been convincing suggesting that a spaceborne PARIS instrument would be capable of detecting sea surface height with a precision in the order of some centimetres.

PARIS is a very wide swath altimeter, capable of reaching 1000 km swath or even more, depending on orbital altitude, as it picks up ocean-reflected (and direct) signals from several GNSS satellites (typically 6 GPS and 6 Galileo when available). This wide swath means that a constellation of 10 PARIS satellites with an orbital inclination of 45° could cover the most populated central part of the Earth (from 45°S to 45°N in latitude) with a revisit time of less than an hour. A 30-60 cm 100 km wavelength tsunami wave in this region would be observable as the typical resolution of PARIS is 5-10 cm in height and 20-50 km in spatial resolution.

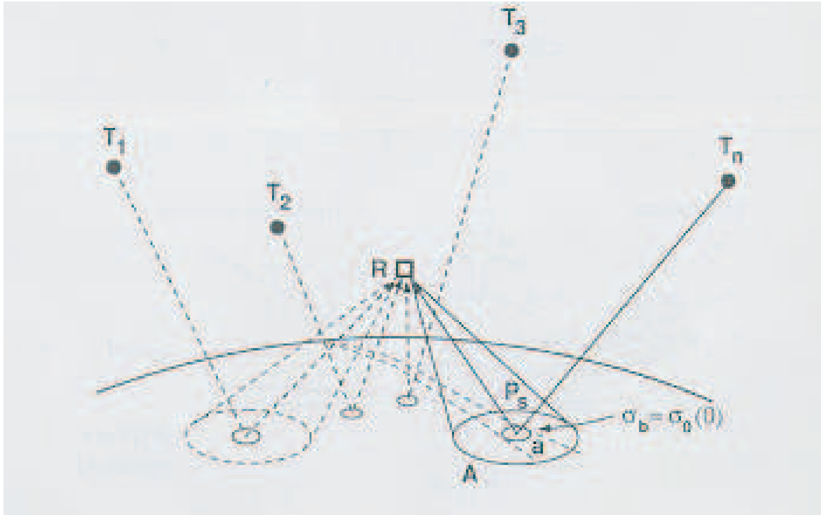

Figure 1: The PARIS Concept

Global and Long Term Coverage

The beauty of PARIS for tsunami detection is that it is passive resulting in a relatively low cost instrument and, unlike conventional altimeters, it can measure and monitor the sea surface height at a large number of locations simultaneously depending on the availability of GNSS signals within the antenna's field of view. Current ideas for a space-based PARIS sensor envisage the antenna having 12 independently tracking beams. This means that coverage of the world's oceans is already improved by a factor of 12, compared to a conventional altimeter, for a single instrument.

The development of GNSS systems in the future also guarantees the "transmitter segment" for decades -an important feature for tsunami detection-with assured continuous improvement in capabilities (transmitted power, bandwidth and frequencies).

PARIS Airborne Demonstrations

On 25 September 2001, within the PARIS-Alpha contract with ESA, the Institute of Space Studies of Catalonia (IEEC), Spain, carried out a flight of a PARIS altimeter off the Costa Brava [2]. In this region of the Mediterranean Sea, a trench in the sea floor (Palamos Canyon) disturbs the water current and produces a 30 cm dip about 100km long in the mean sea level. The amplitude and wavelength of such a topographic feature are similar to those of a tsunami in open ocean.

The aircraft over-flew a Topex track which provided the reference sea level profile. Several GPS-buoys were deployed to provide some ground truth points. GPS stations were installed at several places along the coast as well, and kinematic differential GPS was used to retrieve the plane's trajectory. The C/A code was processed by IEEC, whereas the encrypted P-code (Y-code) processing was done by JPL-NASA for IEEC.

Valid data was recorded for the full path when flying north, but only during part of it when returning south. The results of the C/A and P-code processing are shown on the left of Figure 2: besides some offset which appears depending on the flight direction (north or south) for the C/A code solution, the Palamos Canyon 30cm dip is observed in both C/A and P-code derived profiles. The topographic profile due to the continental platform is also recovered. The closeness of the P-code solution to the Topex profile is remarkable.

The same flight was repeated one year later, on 27 September 2002, using the same PARIS altimeter over an extended track [3]. This time, it was within the PARIS-Gamma ESA contract with Starlab (Barcelona, Spain) and thus, using a fully independent data processor. Only the C/A code was processed and the results are shown on the right of Figure 2. The retrieved profile looks very similar to the one obtained in PARIS-alpha showing the robustness of the PARIS technique. The Palamos Canyon dip is again observable, as are the gentle surface slopes above the continental shell. The deviation between the PARIS and Jason-derived sea surface heights is below 10 cm rms.

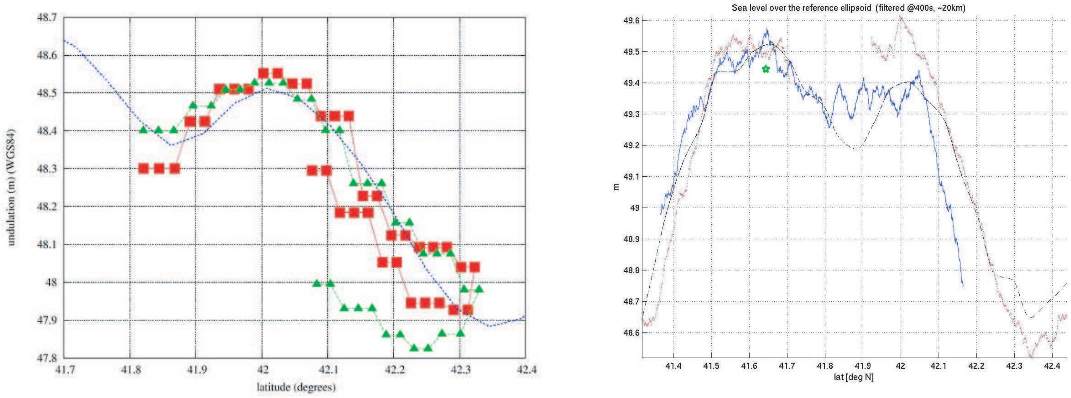

Figure 2: Left: PARIS-Alpha aircraft test – retrieved sea surface height from 1000 m altitude over the Palamos Canyon using the GPS C/A code (triangles) and the P-code (squares) *-courtesy of IEEC and JPL-* Right: PARIS-Gamma aircraft test – same result but over an extended track and using only the GPS C/A code: dashed-black is Jason sea surface height, blue and red are the ascending and decending track PARIS-derived topography and green is a buoy tie-point.

UK-DMC: towards a Satellite Demonstration

In September 2003 the UK-DMC (Disaster and Monitoring Constellation) satellite was launched into a 685km sun-synchronous orbit to provide imaging in quick response to disaster situations such as the earthquake and tsunami that devastated Southeast Asia. The satellite included a pioneering experiment of PARIS, realized by Surrey Satellite Technology Limited with support from the British National Space Centre: a downward looking medium gain antenna (12dBic), a link to an onboard data recorder and enhanced delay-Doppler mapping processing. Even at this high altitude and with a modest gain antenna the results to date have been very promising with ocean-scattered signals found in every ata collection under a wide range of ocean conditions. Figure 3 shows two signals detected under very different ocean conditions [4]: on the left is a strong sea reflected signal (PRN 28, 12-3-2004) when the wind speed was 2.5m/s (derived indirectly from wind models), whereas the much weaker signal on the right (PRN 29, 24-5-2004) corresponds to a QuickSCAT measured wind speed of 11 m/s. The signals will be processed for altimetric applications and by extension, for Tsumani detection.

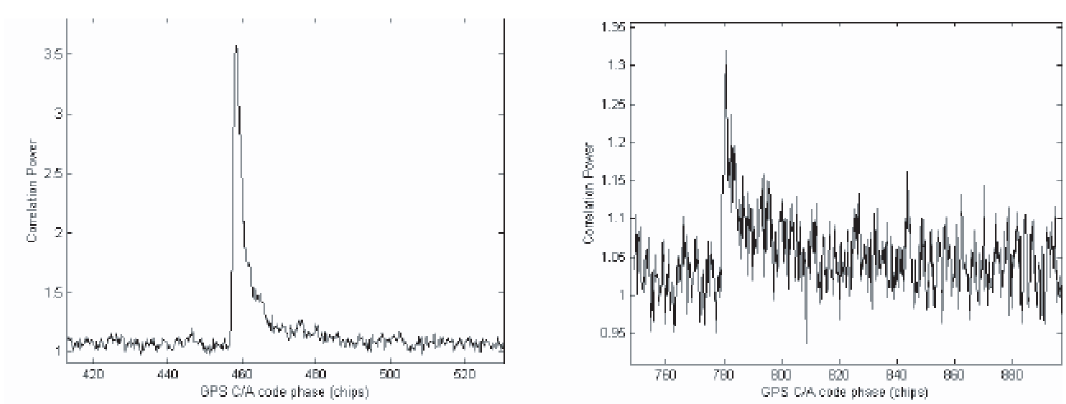

Figure 3.

Tsunami Phenomenology

A tsunami is a wave train generated in a body of water by an impulsive disturbance such as an earthquake, which vertically displaces a water column. Tsunamis were historically referred to as tidal waves because as they approach land they take on the characteristics of a violent onrushing tide. The tsunami is generated when the vertically displaced water mass moves to regain its equilibrium and radiates across the mass of water. The size of the resultant tsunami waves is determined by the quantum of the deformation of the sea floor. The larger the vertical displacement, the greater the size of the waves will be. As the tsunami crosses the deep ocean its wavelength may be a hundred kilometres or more and its amplitude will be in the order of 30-60 cm typically. Since a tsunami has an extremely large wavelength (> 100 km), tsunamis act as a shallow-water wave even in deep oceanic water (5 km) and their speed v depends only on gravity and water depth D:

$$v = \sqrt{gD}$$

So a tsunami travels slowly (tens of meters per second) in very shallow water and fast in deep water (hundreds of km per hour).

Tsunami Early Warning Satellite System

The physical characteristics of a tsunami and the capabilities of a PARIS altimeter match each other perfectly. The PARIS concept allows a synoptic view of an extremely large portion of ocean surface to be obtained. In 150 seconds an area of 1000 km×1000 km is swept by typically 12 quasi-parallel tracks (reflection points) with random spacing between them. In that amount of time a tsunami may have travelled some 30km, which is of the order of the spatial resolution of PARIS i.e. it will look almost like a static wave in the ocean during a satellite overpass. A constellation of 10 PARIS satellites should be able to detect a tsunami with a time to first alarm of less than 45min (half the orbital period). The key issue of the system is real time on-board processing and data downlink.

The strength of the concept resides in that, by providing a synoptic view of the ocean surface, the probability of false alarm of such a system will be low, i.e. the wave structure in the ocean will clearly reveal itself as a tsunami rather than an artefact due to other reasons (instrument error, ionospheric delay, etc). Low false-alarm rate in tsunami detection is important to prevent population from relaxing when an alarm is raised.

As tsunamis happen only very seldom, the proposed constellation of PARIS altimeters should serve other oceanography scientific purposes during normal operation, but the tsunami early warning function should be the real and ultimate driver of such -hopefully and expectedly- international effort.

Conclusion

From work already performed in the areas of theory, experimentation and processing it is clear that a constellation of satellites equipped with PARIS altimeters could provide a tsunami early warning system. Tsunamis and PARIS match each other quite perfectly, the former comprising high-amplitude (> 10 cm) mesoscale fast-development ocean features and the latter being an extremely wide-swath altimeter system than can provide synoptic views of the ocean surface. The probability of false alarm of such a system would be very low, a key parameter in a tsunami early warning system. Challenges ahead are the on-board real-time processing and the data downlink to ground and dissemination to the population. These areas will be covered by future ESA studies.

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