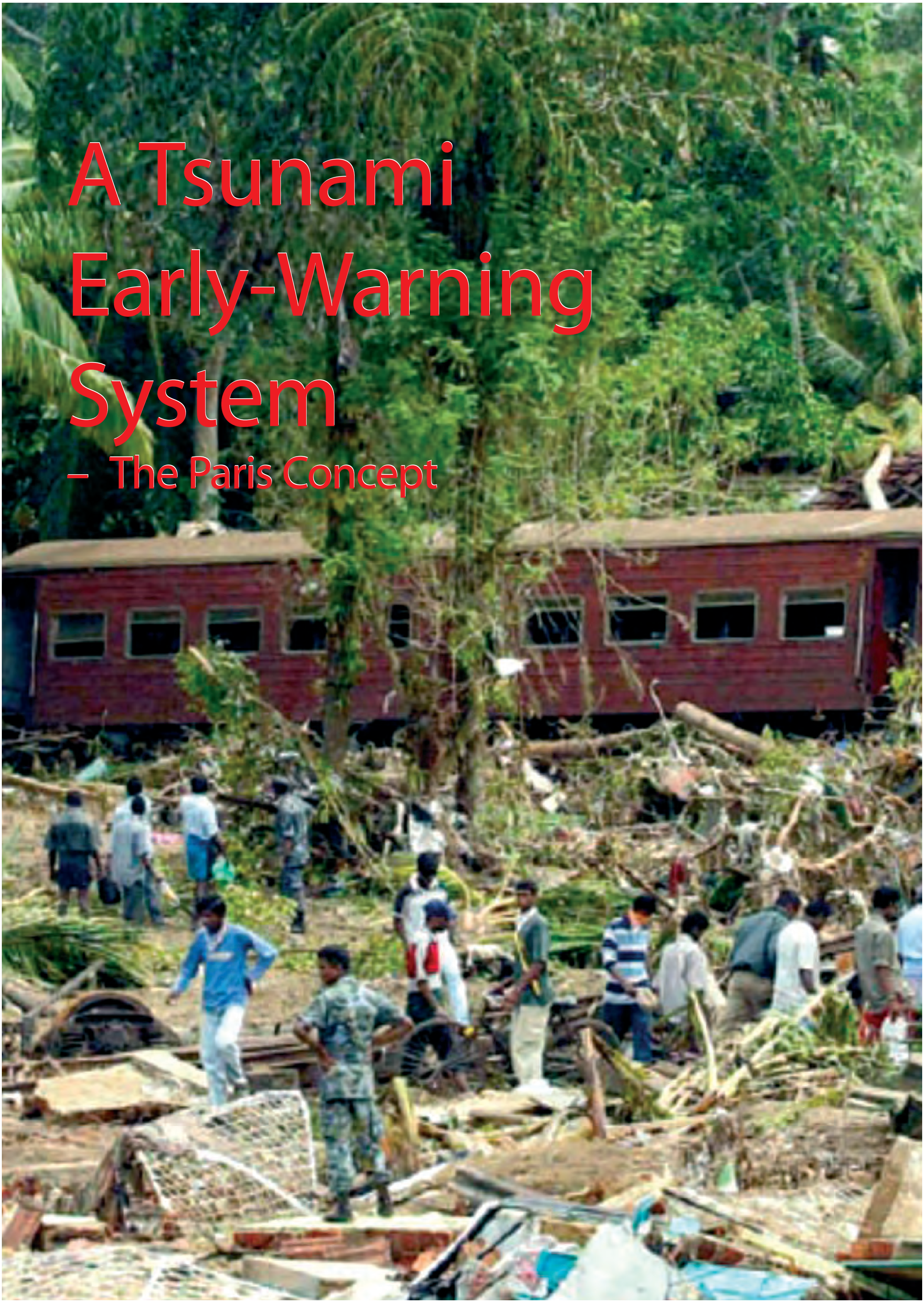

A Tsunami Early-Warning System

– The Paris Concept

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Last December a tsunami generated by an earthquake, with its epicentre in the Indian Ocean to the west of Indonesia, resulted in a devastating human catastrophe throughout the region. Several proposals for establishing a network of sensors for tsunami detection have since been put forward, including the concept proposed here. The Passive Reflectometry and Interferometry System (PARIS) makes use of Global Navigation Satellite System (GNSS) signals reflected from the ocean's surface to perform mesoscale ocean-altimetry measurements, but it can equally well be applied to the task of rapid tsunami detection.

"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."

Jean-Jacques Dordain,
Director General, ESA
15 January 2005

Need for a Global Tsunami Detection System

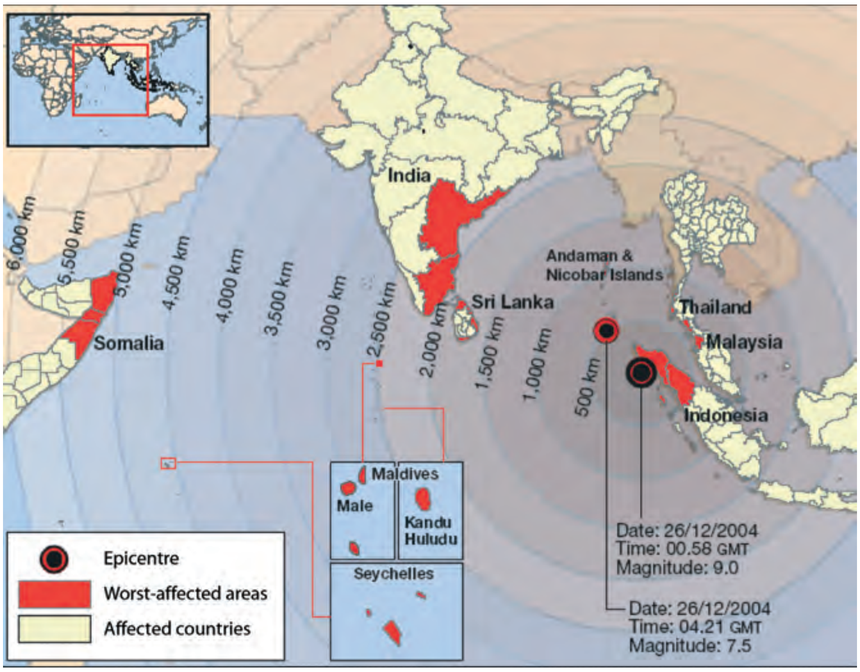
On Boxing Day 2004, the entire World was shocked to learn of the sub-oceanic earthquake off the coast of Sumatra and the subsequent tsunamis that devastated shoreline communities from Indonesia to Thailand and from Sri Lanka to Somalia.

Since then, governments and policy makers around the World 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.

The PARIS Concept

ESA and European industry have been working since 1993 on the idea of using navigation-satellite (GNSS) signals reflected from the ocean's surface to perform altimetry measurements. The validity of this technique, dubbed 'PARIS', was first established via experiments over a large pond on the ESTEC site, then from the Zeeland bridge in the southern part of The Netherlands, and most recently from an aircraft flying over the Mediterranean Sea near Barcelona. All of these experiments have produced convincing, suggesting that a spaceborne PARIS instrument would be capable of detecting sea-surface height with a precision of the order of a few centimetres.

PARIS serves as a very-wide swath altimeter, capable of achieving swaths of 1000 km or more, depending on orbital altitude, as it picks up ocean-reflected (and direct) signals from several GNSS satellites (typically six GPS and six Galileo satellites when available). This wide swath means that a constellation of ten PARIS satellites with an orbital inclination of 45 degrees 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. As PARIS has a typical height resolution of 5-10 cm and a spatial resolution of 20-50 cm, a 30-60 cm high, 100 km-wavelength tsunami wave occurring in this region would be easily observable.



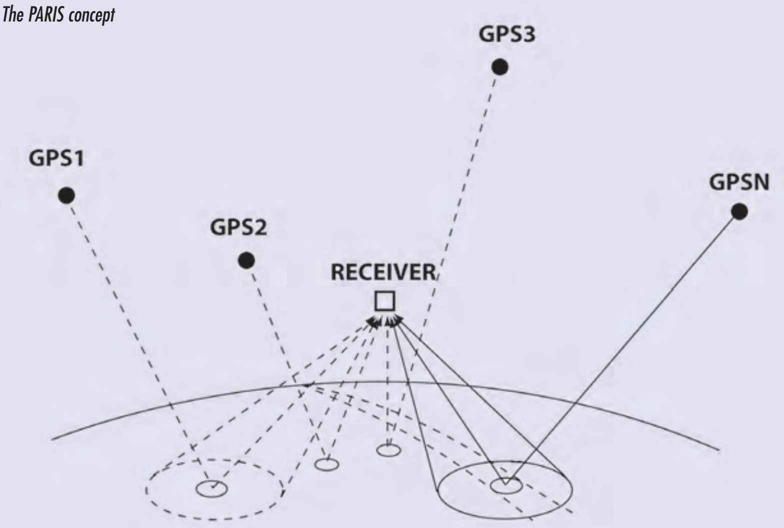
The region affected by the tsunami (source Nature)

Global and Long-Term Coverage

The beauty of using PARIS for tsunami detection is that it is passive technique, requiring only 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 number 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 with a single instrument, coverage of the World's oceans would already be improved by a factor of 12, compared to a conventional altimeter.

The continued development of GNSS

The PARIS concept

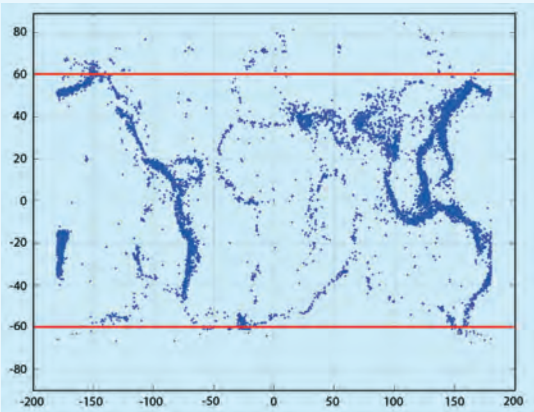


The Tsunami Phenomenon

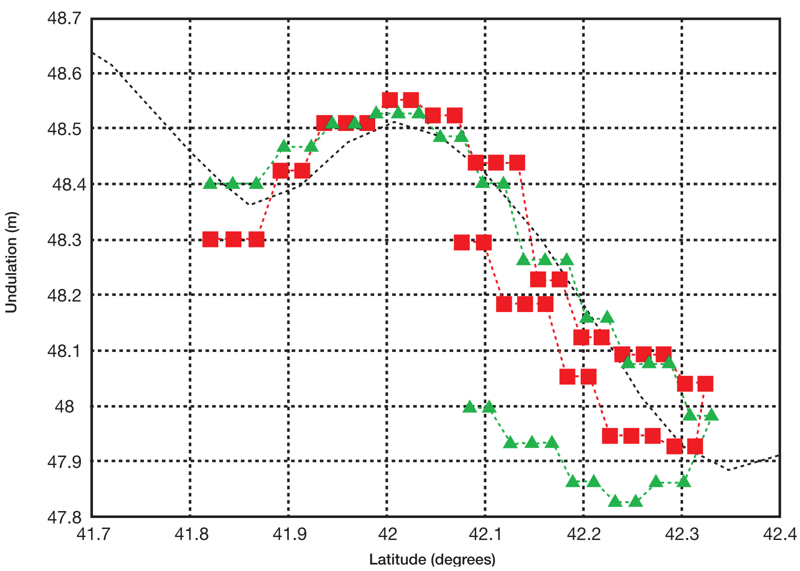
A tsunami is a wave train generated in a body of water by an impulsive disturbance such as an earthquake, which vertically displaces a column of water. Tsunamis have historically been referred to as tidal waves, because as they approach land they take on the characteristics of a violent onrushing tide. 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's waves is determined by the degree of deformation of the sea floor. The greater the vertical displacement, the larger the waves will be. As the tsunami crosses the deep ocean, its wavelength may be a hundred kilometres or more and its amplitude will typically be in the order of 30-60 cm. Because a tsunami has an extremely long wavelength (> 100 km), it behaves like a shallow-water wave even in deep ocean waters (5000 m), and its speed v depends only on the Earth's gravitational pull and the water depth *D* via the relation:

$$V = (g \text{ x } D)^{1/2}$$

Consequently, a tsunami travels relatively slowly in very shallow water (about 50 km/h) but very quickly in deep water (more than 500 km/h).



Around 18,000 earthquakes of magnitude 6 or greater occurred from 1 January 1900 to 31 December 1995 (from "Seismicity Catalogue" of the National Geophysical Data Centre)



Retrieved sea-surface height from the PARIS aircraft flight at 1000 m altitude over the Palamós Canyon
Green triangles = C/A code; Red squares = P-code

systems in the future also guarantees the availability of the 'transmitter segment' for decades – an important feature for tsunami detection – with continuous improvements in transmitted power, bandwidth and frequencies also assured.

Airborne Demonstrations of PARIS

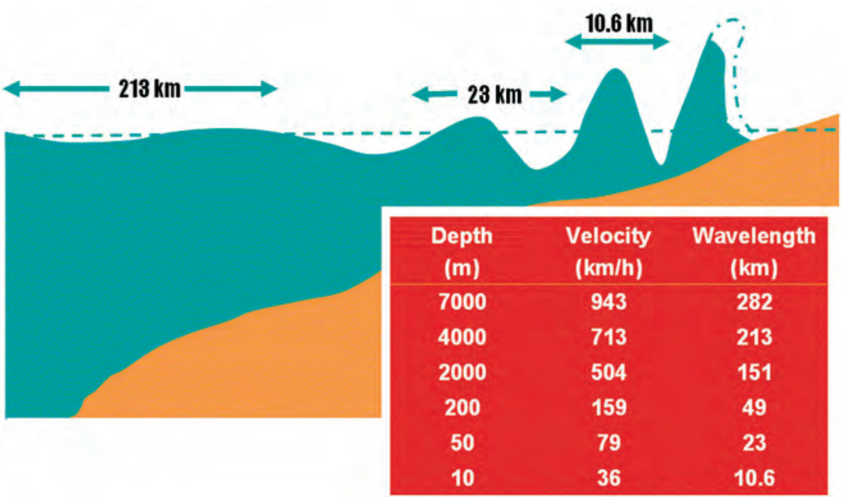
On 25 September 2001, under contract to ESA, the Institute of Space Studies of Catalonia (IEEC), Spain, flew a PARIS altimeter over the Mediterranean off the Costa Brava. In this region, a trench in the sea floor (Palamós Canyon) disturbs the water current and produces a 30 cm dip about 100 km long in the mean sea level. The amplitude and wavelength of such a topographic feature are similar to those of a tsunami in the open ocean.

The aircraft over-flew a Topex satellite ground track, which provided the reference sea-level profile, and several GPS-buoys were deployed to provide in-situ measurements. 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, and the encrypted P-code by NASA/JPL for IEEC). The Palamós Canyon 30 cm dip was observed in both the C/A and P-code derived profiles. The topographic profile due to the continental shelf was also recovered. The closeness of the P-code solution to the Topex profile was remarkable.

The same flight was repeated one year later, on 27 September 2002, using the same PARIS altimeter over an extended track, by Starlab (Barcelona, Spain), acting as a fully independent data processor. Only the C/A code was processed and the retrieved profile looked very similar to the original one, confirming the robustness of the PARIS technique. The Palamós Canyon dip was again observable, as were the gentle surface slopes above the continental shelf. The deviation between the PARIS and Jason-derived sea-surface heights was less than 10 cm rms.

Towards a Satellite Demonstration

In September 2003, the UK-DMC (UK contribution to the Disaster and Monitoring Constellation) satellite was launched into a



Depth (m)	Velocity (km/h)	Wavelength (km)
7000	943	282
4000	713	213
2000	504	151
200	159	49
50	79	23
10	36	10.6

Velocity and wavelength of a tsunami in open ocean and near the coast

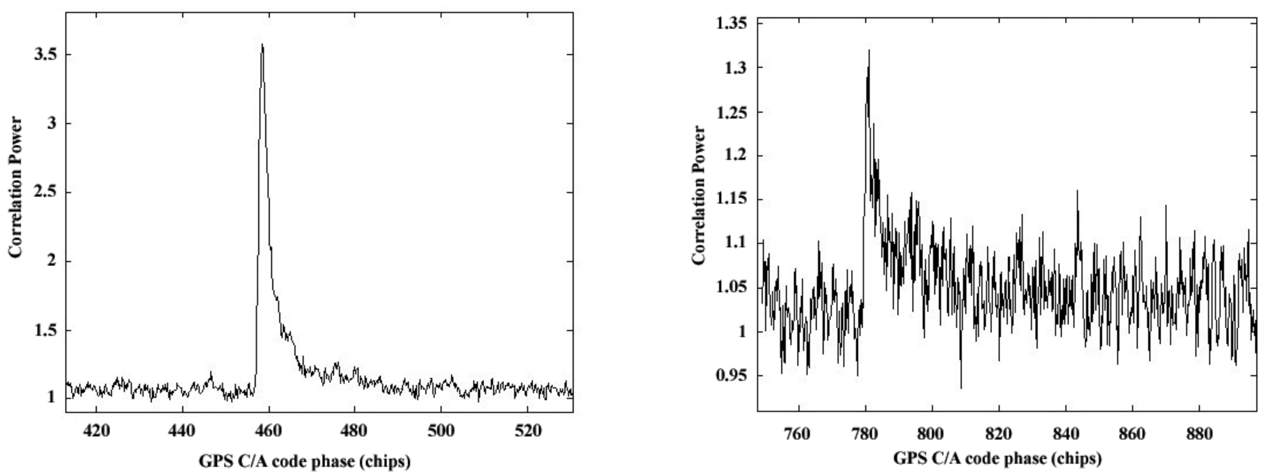
685 km, Sun-synchronous orbit to provide quick-response imaging for disaster situations such as the earthquake and tsunami that subsequently devastated Southeast Asia. It included a pioneering PARIS-based experiment, realised by Surrey Satellite Technology Ltd. with support from the British National Space Centre, in the form of a downward-looking, medium-gain antenna, a link to an onboard data recorder, and enhanced delay-Doppler mapping processing. Even at this high altitude and with modest antenna gain, the results to date have been remarkable, with ocean-scattered signals found in every data collection under a wide range of ocean conditions. The accompanying figure shows two signals detected under very different ocean conditions: on the left is a strong sea-reflected signal when the wind speed was 2.5 m/s (2 Beaufort – derived indirectly from wind models), whereas the much weaker signal on the right corresponds to a QuickSCAT measured wind speed of 11m/s (6 Beaufort).

A Tsunami Early-Warning Satellite System

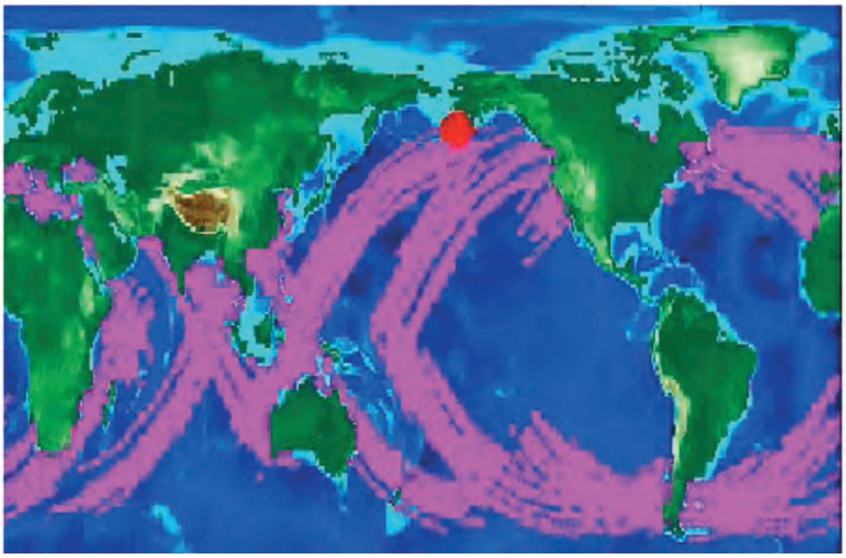
The physical characteristics of a tsunami and the capabilities of the PARIS altimeter are perfectly matched. The PARIS concept provides a synoptic view of an extremely large portion of the ocean's surface: in just 150 seconds, a 1000 km x 1000 km area is swept by typically 12 quasi-parallel tracks (reflection points) with random spacing. In that time, a tsunami may have travelled some 30 km, 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 ten PARIS satellites would be able to detect a tsunami with a time to first alarm of less than 45 minutes, with real-time onboard processing and appropriate data down-linking.

The strength of the PARIS concept lies in the fact that, by providing a synoptic view of the ocean surface, the probability of a false alarm is low. The wave structure will clearly reveal itself as a tsunami rather than an artifact due to other reasons (instrument error, ionospheric delay, etc.), and a low false-alarm rate is important to ensure that the population takes it seriously when an alarm is actually raised.

As tsunamis fortunately happen only very seldom, the constellation of PARIS altimeters can serve various other oceanographic and scientific purposes during normal operation. Also, in this way the constellation will be maintained and updated on a regular basis and, even if it is many years before the next major tsunami, will still be fully functional and capable of warning the many thousands of people at risk.



Measured reflected GPS signals, for low (left) and high wind conditions (right)



A simulated tsunami detection system, with the wave (in red) tracked by ten PARIS-carrying satellites in low Earth orbit (LEO: ground tracks in purple). The tsunami is detected in 33 minutes

Conclusion

From the work already performed, it is clear that a constellation of satellites equipped with PARIS altimeters can provide an extremely useful tsunami early-warning system. Tsunamis and PARIS are a perfect match, with the fast-developing, high-amplitude (>10 cm) mesoscale ocean features being well recognizable in the extremely wide-swath altimeter system's synoptic views of the ocean's surface. The probability of false alarms is also likely to be very low due to the very specific characteristics of a tsunami, and this is a key parameter for any early-warning system. The challenges of the onboard real-time processing and the data downlinking and dissemination to the population as risk will be addressed by future ESA studies. At first glance, a space-based system looks expensive when compared to ground-based systems, but the cost of establishing (and maintaining) a global network of buoys and pressure sensors is by no means trivial, not to mention the enormity of the task in terms of planning and execution. The PARIS-based solution would also provide a wealth of other data of immense benefit to oceanographers and other scientists.