S3-UR9: Development of Real-Time Algorithms for the Detection of Tsunami Signals on Sea-Level Records: Testing and Application to PMEL/NOAA (USA) and analysis of ISPRA (ITALY) Data

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THE TEDA ALGORITHM

The goal of the Tsunami Early Detection Algorithm (TEDA) is to discriminate the first tsunami wave from the background waves that form the ordinary sea-level oscillations. Hence a first task consists in characterising the background signal, which differs significantly depending on whether the instrument is installed offshore or along the coast (typically inside a harbour). A basic assumption of TEDA is that the incoming tsunami affects only the instantaneous signal, not the background. Coherently, the idea is that of characterising the instantaneous signal over a short time interval t_{IS} (6-12 min) and the background signal over a longer time interval t_{BS} (about 1 hour).

At each time step, the signal is characterised through specific indicators **IS**, **BS** and **CF**:

IS is the mean slope of the signal over t_{IS}, adequately corrected for the tidal slope

BS is computed over t_{BS}, in three different ways:

BS - range of **IS**

BS - standard deviation of **IS**

BS - maximum absolute value of **IS**,

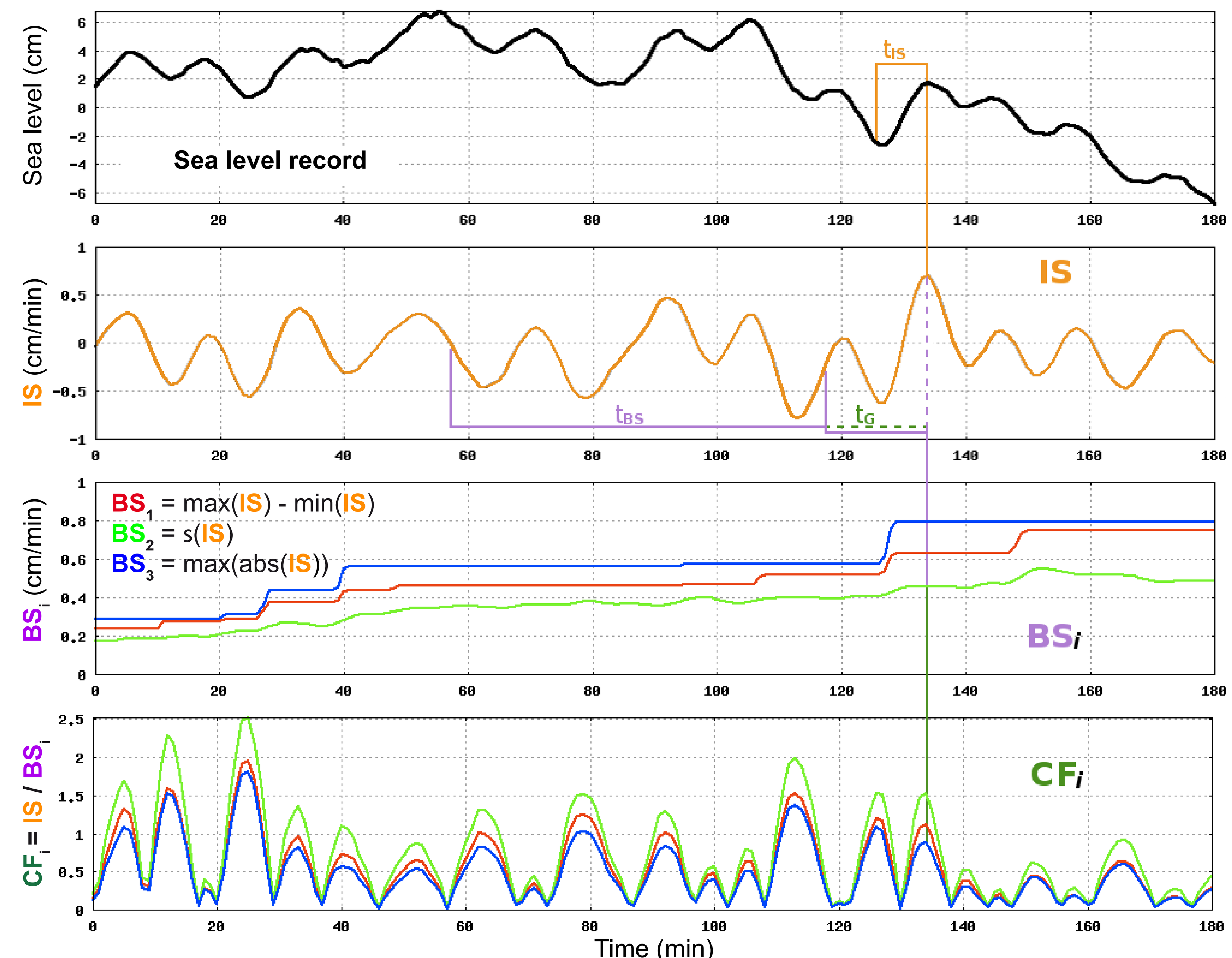
where t_{BS} spans the interval $[t_0 - t_{BS} - t_G , t_0 - t_G]$, where t_0 is the sampling time and t_G is a gap interval with the role of imposing a clear independence beween the indicators **IS** and **BS**. At the end of the development phase of TEDA one of three methods will be selected.

CF (Control Function) is the ratio between the instantaneous and the backgorund indicators (**IS**/**BS**)

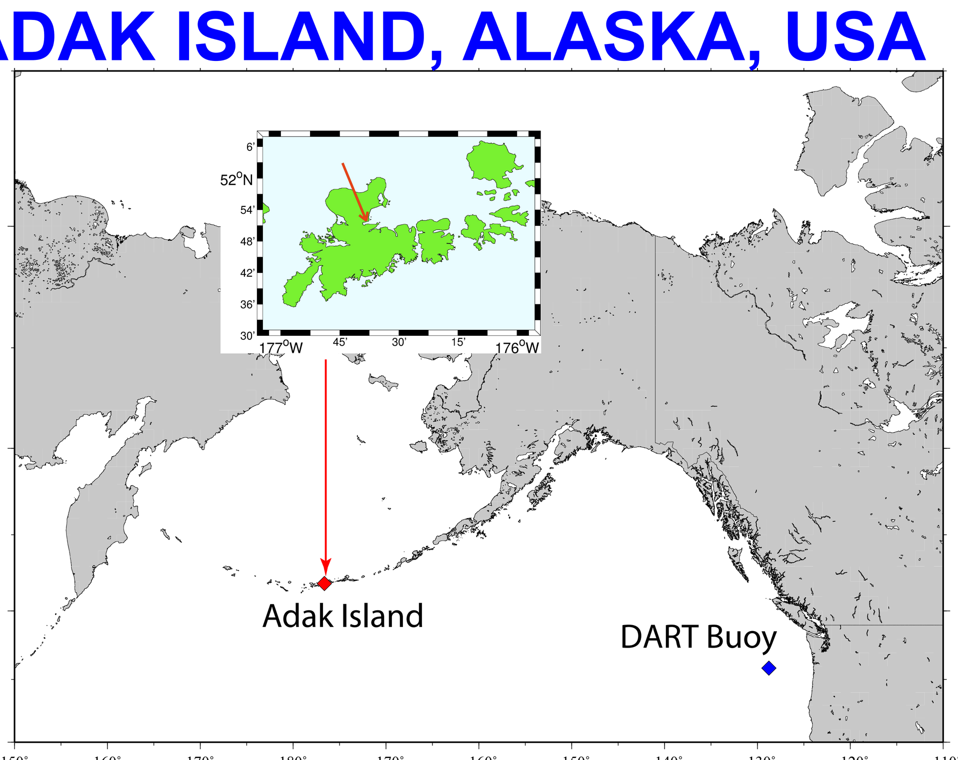
TEDA produces a "tsunami alert state" when **IS** and **CF** exceed each a given threshold. The "tsunami alert state" is terminated, and the detection restarted, when **BS** decreases to the value it attained at the instant when the tsunami was detected. TEDA is meant to be applicable to any site condition, implying that t_{IS}, t_{BS} and t_G, and hence **IS**, **BS** and **CF** must be defined site by site.

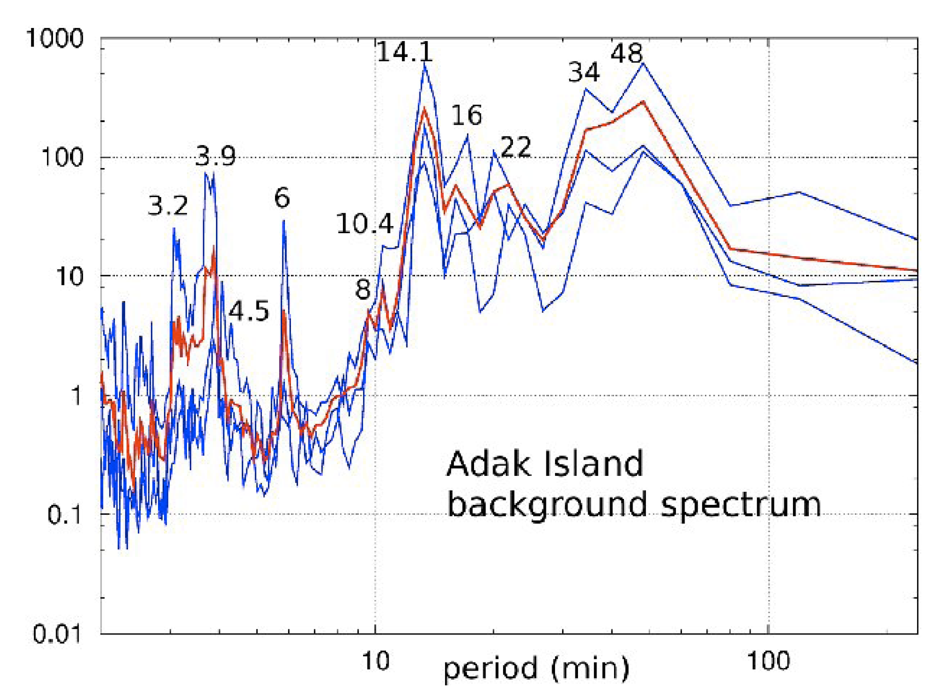
The criteria followed to define the time intervals and the thresholds are:

- minimisation of false detections
- minimisation of missed detections
- fast detection



APPLICATION TO THE COASTAL TIDE-GAUGE OF ADAK ISLAND, ALASKA, USA

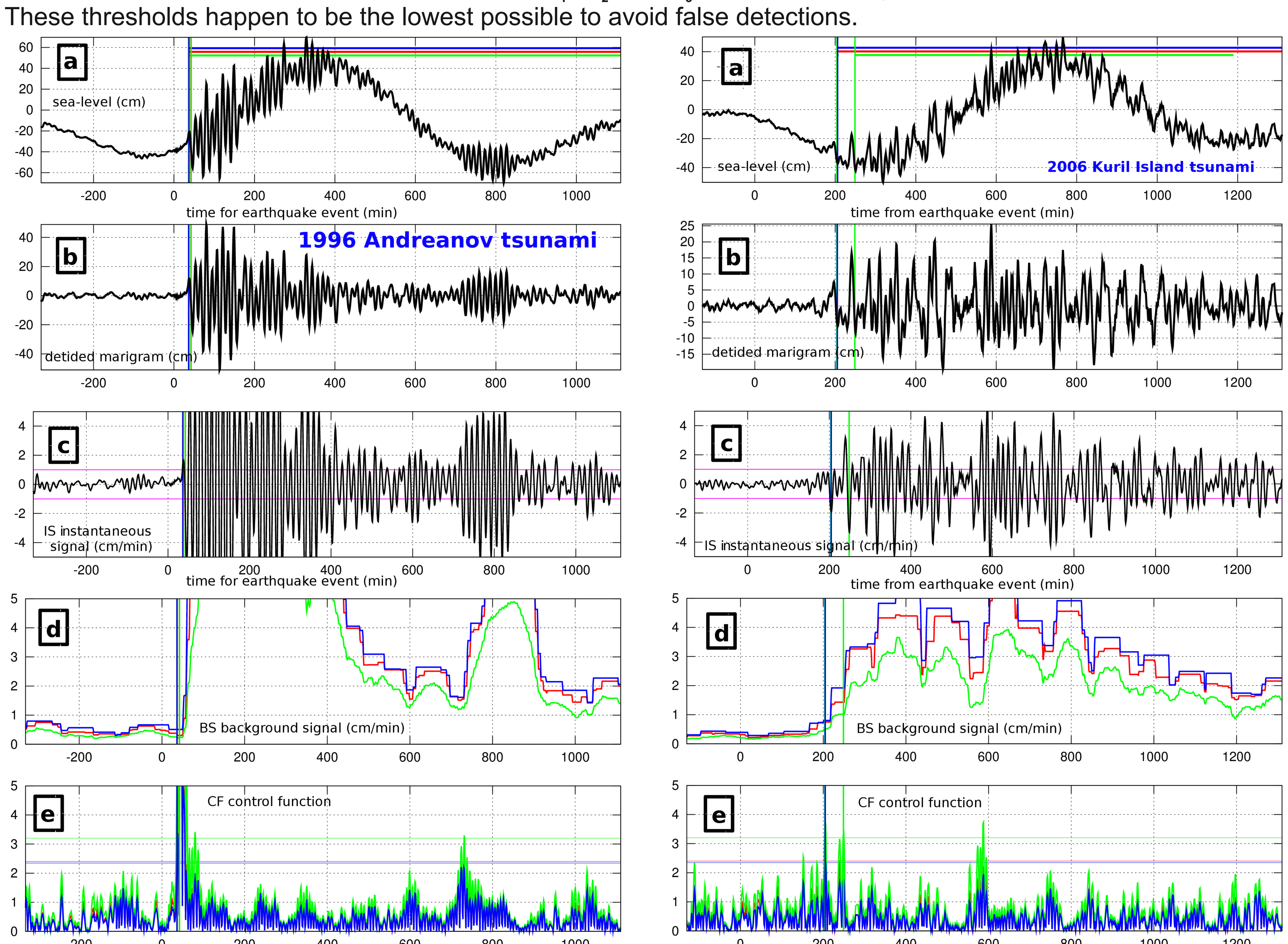




TEDA has been applied to data provided by NOAA/PMEL (USA) registered both by coastal tide-gauges and DART buoys. Here we present the results of the application of TEDA to data registered by the coastal tide-gauge installed at Adak Island, Alaska, USA, which is a station that keeps track of several historical tsunamis.

The plot here above on the left shows the background spectrum computed over 12 hours in different sea state conditions (in **blue**) and the average spectrum computed over 10 days (in **red**).

The 10 June 1996 Andreanof (M=7.9) and the 15 November 2006 Kuril Islands (M=8.3) earthquake-generated tsunamis are used here as test cases to illustrate the behavior of TEDA. A tsunami detection is set when **IS** passes the threshold of 1cm/min and at the same time CF_1, CF_2 and CF_3 pass respectively the thresholds of 2.4, 3.2 and 2.35. These thresholds happen to be the lowest possible to avoid false detections.



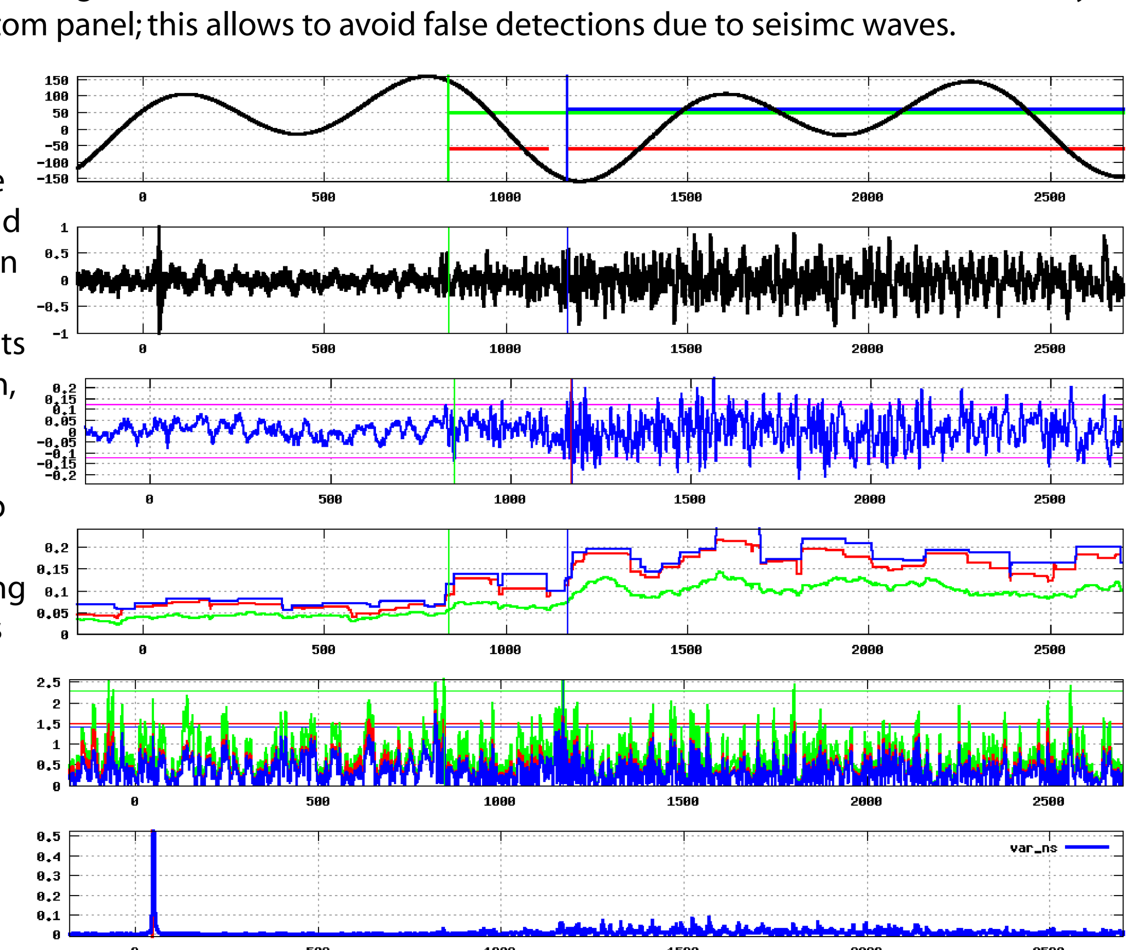
The main results obtained from the application of TEDA to the aforementioned events as well as to other events in the same site, and also to DART buoys signals indicate that:

- **tsunamis of suitable amplitude are correctly detected**
- **TEDA is able to minimise the false alarms due to moderate seiche events**
- **very small amplitude tsunamis are not detected**
- **it is extremely difficult to completely eliminate the false alarms**

APPLICATION TO DART BUOY SIGNALS

An example is given here of TEDA applied to DART signal. The DART buoy rcorded the 2001 Peru tsunami, generated by a M=8.4 earthquake. The position of the buoy is indicated with a bule diamond in the map here on the left. In the plot here below, the time axis is in min from the earthquake event. From top to bottom, a) elevation of sea-level; b) detided sea-level; c) IS corrected by tidal slope through TEDA; d) three possible background signal BS defined as for the Adak Island case; e) corresponding control functions **CF1 (red)**, **CF2 (green)** and **CF3 (blue)**, with thresholds set to 1.6, 2.3 and 1.5; f) unexplained variance used to identify seismic waves. Vertical lines in panels mark the detection times corresponding to the three considered methods, while in the last panel they mark the seismic signal identification. Seismic waves arrive at about t=45 min, identified by the unexplained variance in the bottom panel; this allows to avoid false detections due to seisimc waves.

The arrival time of tsunami is at about t=815 min, 13.5 h after the earthquake. TEDA detects the 2nd tsunami wave at about t=850 min for **CF1** and **CF2** parameters, while **CF3** parametrization detects the tsunami at about t=1070 min, almost 6 h after the 1st tsunami wave. The duration of the 'tsunami state' is given in the top picture with horizontal lines, which last until the corresponding BS function decreases back to its value at the detection time. Tsunami state lasts for the entire event for CF2 and CF3, while it stops after about 5h for CF1; tsunami is again detected at about time t=1070 min.



PRELIMINARY ANALYSIS OF THE ISPRA (ITALY) DATA

ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale, ex APAT), although not in relation to the S3 project, has provided RU9-UNIBO with sea-level data, that UNIBO was anyhow allowed to use for the S3 project purposes. The data are relative to the Italian sea-level network and in particular to the stations of Porto Empedocle and Lampedusa, in Sicily, and of Trieste. The data cover a time period ranging from 2007 to the first part of 2009. The sampling rate is 10 minutes for the two Sicily stations and 1 minute for Trieste.

In general, though with limitations deriving from the applied sampling rate, the eigenmodes of the basin where the station is installed can be recognised together with sea-level variations induced by meteorological factors, superimposed on the tide signal.

The time series relative to Porto Empedocle and Lampedusa are very interesting since they contain several occurrences of the so-called "marrobbio", which is a phenomenon typical of the basin delimited by Sicily and by Tunisia. The "marrobbio" consists in rapid fluctuations of the sea level: these oscillations can show amplitudes of about 1 m and sometimes they can be amplified by the harbour characteristics and by the continental platform, giving rise to amplitudes up to 2 m. The "marrobbio" phenomena are of atmospheric origin and are caused by sudden variations of the atmospheric pressure.

The analysis performed so far by UNIBO regards some parts of the 2007 signals for Porto Empedocle, of 2008 for Lampedusa and of 2009 for Trieste.

Porto Empedocle: the sampling rate of 10 minutes does not allow for a determination of the typical harbour oscillation periods. It is only possible to discriminate periods of about 33, 41, 45, 58 and 90 minutes, that are too long to be ascribed to harbour oscillations. A spectral analysis of six "marrobbio" events was performed, in particular of the events occurred in 2007 on May 3 and 26, on June 3 and on July 20.

Lampedusa: as in the previous case, it is not possible to single out the different eigen-frequencies of the harbour. When the "marrobbio" phenomenon occurs (as in March 19-20 2008) it is possible to observe an oscillation with period of about 2 hours.

Trieste: UNIBO analysed data covering the period January 1-February 19 2009. An analysis in the frequency domain was applied to data filtered out from the tide. The typical harbour oscillation periods were retrieved by studying in particular the data for January 23-25, February 2-5 and February 17-18, which exhibit the largest high-frequency sea level fluctuations. The spectra show eigenperiods corresponding to 5-6 minutes, 18 minutes, 45 minutes, 60 minutes and 2, 3 and 6 hours.