ISSN 8755-6839

SCIENCE OF TSUNAMI HAZARDS

Journal of Tsunami Society International

Volume 31 Number 2 2012

SEA LEVEL SIGNALS CORRECTION FOR THE 2011 TOHOKU TSUNAMI

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ABSTRACT

The paper analyses the signals measured during the M9.0 Tohoku Tsunami in order to identify the effect of the subsidence on the measurements and to determine correction factors to be applied to the measurements. The objective is to have a coherent set of measurements that can allow the correct estimation of the source term for this event through inversion techniques. In fact the inversion techniques tend to minimize the difference between the measured signals and the calculated value; which means that in the initial period and also for the peak, the solution found without considering this correction tends to get higher values of the source (the peak in some cases is almost 1.4 m higher on a maximum of 4-5 m, thus is not negligible).

The amount of the correction has been determined using the long-term displacement shown in the measurements; the subsidence estimates are also compared with the values obtained using GPS instruments. The analysis shows that the subsidence has a notable influence on the measurements where the deformation is large and that taking into account the deformation in the signals may improve the quality of the estimation of the initial deformation.

Key Words: *Tsunami, Sea Level Measurements, GPS, Tsunami Source, Earth Deformation*

1. INTRODUCTION

A large earthquake occurred off shore the Pacific coast of Tohoku, Japan (38.1035◦N, 142.861◦E, M 9.0 at 5:46:18 UTC on March 11, 2011, that generated a large Tsunami and caused more than 15000 fatalities and more than 4500 missing in the east coast of Japan (Fujii et al, 2011). USGS identified the fault mechanism as dipping trust with strike parallel to the close Japan Trench. The fault movement caused large movements of the earth crust; the continuous measurements of GPS indicated a subsidence of about 1.2 m, close to Central Myagi (Geospatial Information Authority of Japan (GSI)).

The sea level measured during the event is extremely important in order to assess the impact of the Tsunami that has been generated[1]. It is important "during" the event in order to give the Tsunami Warning System operator the information needed to raise or delete an alert of an ongoing event but is also of paramount importance "after" an event in order to estimate the original source of the Tsunami through comparison with focal mechanisms estimations or via inversion methods that use the sea level to find the better combination of source parameters that can explain the observations.

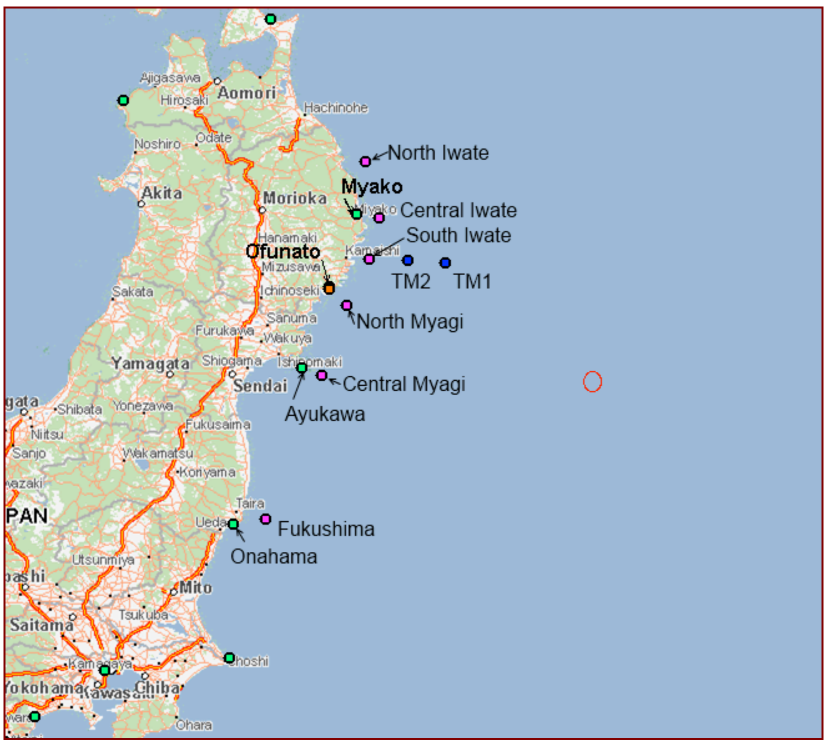

Figure 1 – Identification of several sea level measurements in Japan mentioned in the article

The Japan event is a very important for its dramatic consequences in terms of human lives as well as from the scientific point of view due to the wealth of information available from the large amount of instrumentation present in Japan (e.g. sea level monitoring stations, GPS stations, broadband stations

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[1] The sea level datum considered here is the level measured with respect to the mean sea level (MSL) and in general it approximates the Lowest Astronomical Tide.

etc, Figure 1). This instrumentation is able to give the whole picture of the event. This report is aimed at analyzing the response of the Sea Level Instrumentation and to determine if it is necessary to correct some of the measures. In particular the effect of the important subsidence on the measured sea level is not negligible: if on the coast the sea level arrived up to 30-40 m and therefore 1.2 m of subsidence may be negligible, for off shore measurements or tide gauge measurements that shows deviation from their zero in the order of 3-6 m the subsidence plays an important role and may influence the evaluation of the source terms done with the inversion technique. The inversion technique consists in performing a large number of calculations with a fixed fault plane (ex. 50x50 km) and with unitary slip. The comparison with the measured data allows, via least square non-negative solutions (nnls) methods to estimate the contribution of each segment.

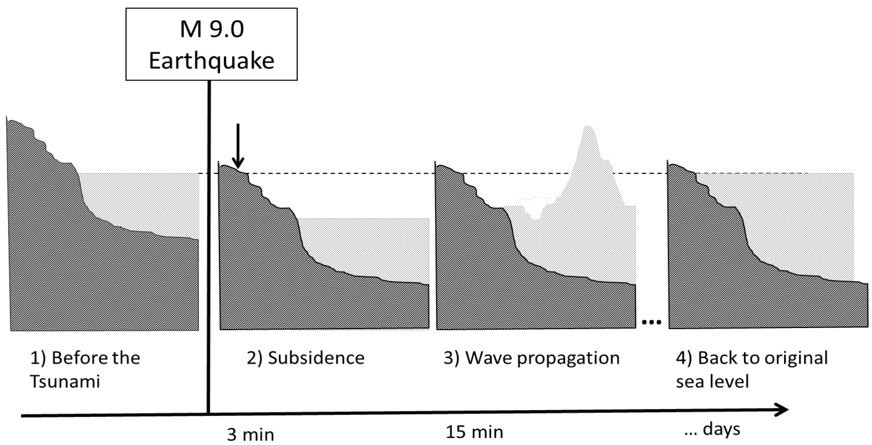

Figure 2 – Sea level response due to the subsidence

2. SEA LEVEL RESPONSE DUE TO THE SUBSIDENCE

Figure 2 shows the sequence of events in case of subsidence. Before the Tsunami (1) the sea level is at a certain elevation dictated by the local tide conditions. At the end of the deformation (estimated in about 3 min for Tohoku Earthquake, USGS), the crust moves downward (2); let's assume the maximum measurement, 1.2 m. As the bottom of the sea also moves, the sea level follows the movement of the crust and thus does not change close to the coastal areas. Far from the coast the deformation may be larger and thus the sea level can be lower than close to the coast. The third phase is characterized by the large wave propagation (3) and is the one that produces damages to the coastal areas. After several hours or days the sea level returns to its original elevation, which does not, depends by the Tsunami and is function of the local tide conditions (4). However since in the meantime the earth crust lowered, there will be parts that were out of the water that now are under the water.

3. SEA LEVEL RESPONSES OF THE VARIOUS INSTRUMENTATION TYPES

The response of the instrumentation to the situation shown above depends strongly on the type of instruments and the measurement method. Three sensors will be considered: the tidal gauges, the floating GPS and the pressure cables or DARTs.

Figure 1 shows the location of the sea level measurements relevant for the Tohoku Earthquake and mentioned in this article. The color indicates the type of device: green or orange dots are tidal gauges, pink dots shows GPS buoys while the blue dots are the bottom pressure cable. It should be noted that the amount and the quality of the instrumentation in Japan has no equivalent on other countries worldwide and allow to analyze in great detail what happened during the 11 March 2011 event.

3.1 Tidal Gauges

The Tidal Gauges are located close to the shore, generally in port areas and consist in a fixed sensor located above the water, connected mechanically with the fixed earth. The sensor (generally microwave) measures the distance between the sensor itself and the water; other types of tidal gauges measure the pressure within a tube connected to the earth and converts it in level. In both cases however the sensor is strictly connected with the earth: any movement of the earth is transmitted to the sensor that thus follows the subsidence.
This means that during the subsidence the measured level may oscillate but after the subsidence it will be very close to the initial one (Figure 3). During the wave propagation or during the return to the original sea level, the sensor may be flooded and can stop working, as occurred in Ofunato (Figure 4). It can be seen by the same figure that the level oscillates after the earthquake but there is not a sharp decrease as it will be evident in the case of the GPS sea level data. After several hours the sea level returns to the original level of tide but the measurement sensor is either destroyed or in any case will show a level greater than the initial level. If the case is the second one the long term level difference between the measured level and the expected tide is a measure of the deformation due to the earthquake.

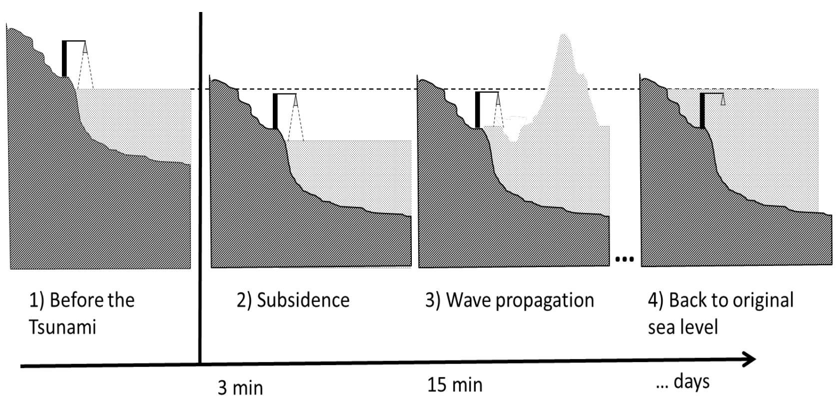

Figure 3 – Sea level response of a tidal gauge

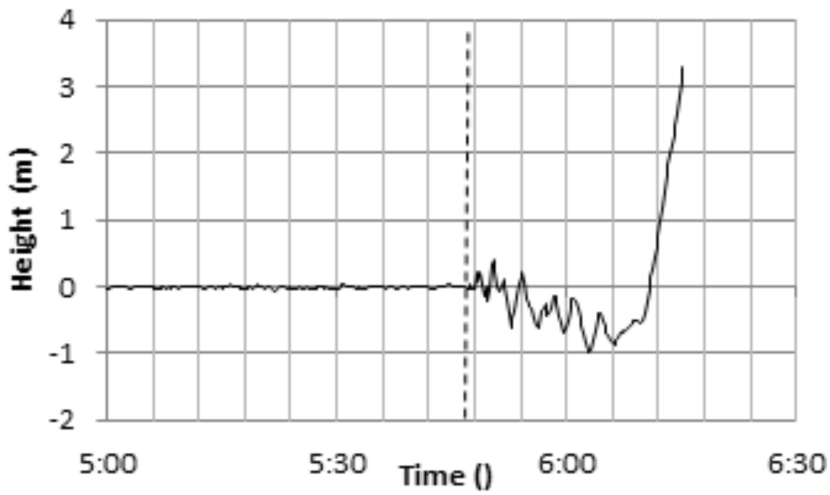

Figure 4 – Sea level measured in Ofunato with tidal gauge

3.2 Floating GPS devices

The floating GPS devices are installed on buoys located about 20 km off shore and measure the geodetic height using satellite navigation systems. However, in order to reduce the error a differential GPS is used: another station, on shore, measures the height and the system performs the difference between these two measured values. Therefore in practical terms the measurement given by the GPS is the height difference between a point on-shore (reference point) and the point where the GPS buoy is installed. The exact position of the reference point is not available for sensitivity reasons. Nevertheless it is located not far from the coast and in line with the location of the buoy[2].
Differently from the tidal gauges, in this case the earth deformation of the reference point could be different from the deformation occurring where the buoy is located because these points are 20-30 km distant each other. As in this case the buoy is closer to the source and this side of the fault is subsiding, it is reasonable to assume that the earth at the location of the buoy will deform more than at the reference point, Figure 5. If this is true the GPS signal will show a sudden decrease at the beginning (as in the case of North Myagi, Figure 6); if the deformation is the same there will be no decrease, as in the case of Fukushima, Figure 8.

In order to get the deformation at the measurement point it is therefore necessary to add 2 contributions: a) the short-term decrease contribution, due to the differential deformation given by different amount of subsidence between the location of the buoy and the location of the reference point; b) the long term offset respect to the normal tide which, as in the case of the tidal gauge, is responsible of the deformation of the reference point (Figure 7 for North Myagi and Figure 9 for Fukushima). The sea level instead has to be reduced, after time 0, only of the long-term contribution, corresponding to the deformation of the reference point.

[2] There is no need to know the precise location of the reference point. This would be useful only to compare the value found with this method with the value obtained by direct GPS measurements on-shore. Wherever is the reference point, the difference in the long term signal is the deformation of the reference point, that needs to be subtracted.

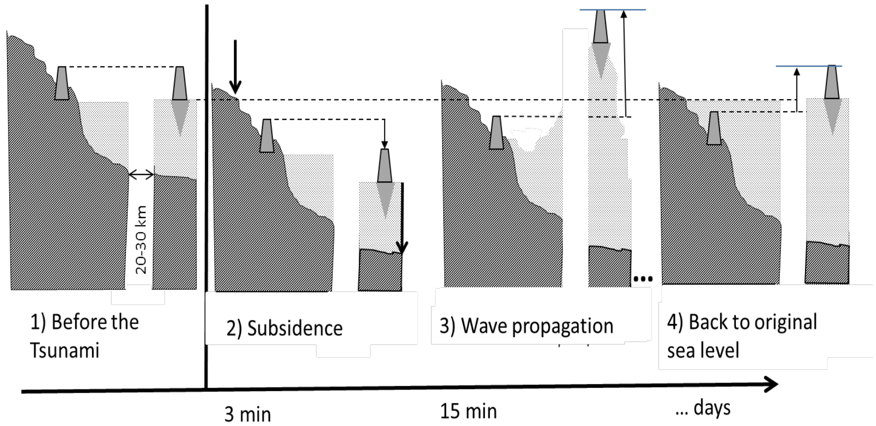

Figure 5 – Sea level response of a GPS buoy gauge

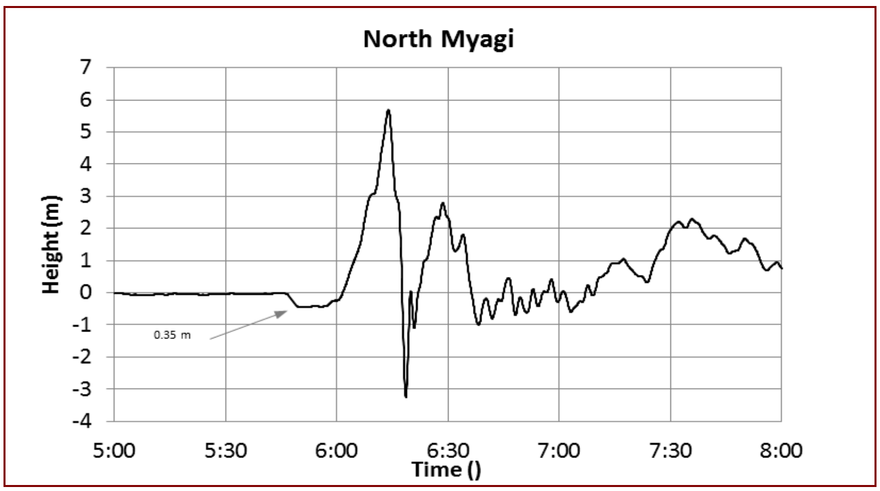

Figure 6 – Sea level measured with GPS buoy in North Myagi where a short term differential deformation of 0.35 m is present indicated with the arrow

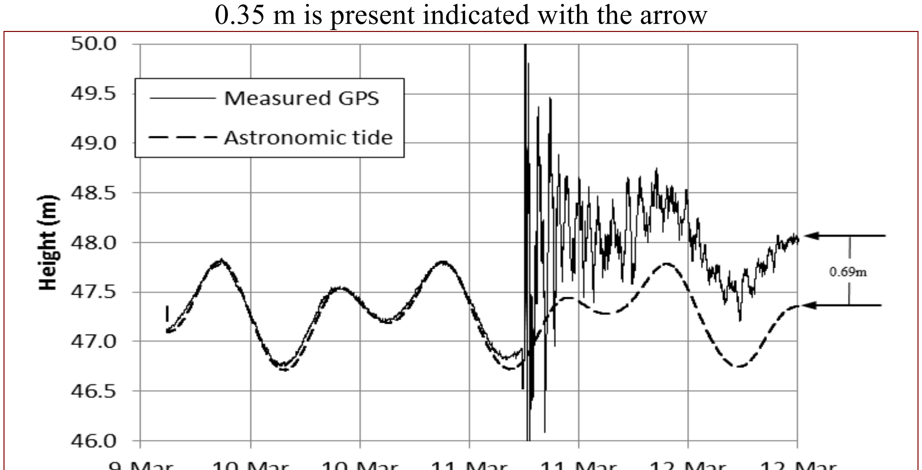

Figure 7 – North Myagi floating GPS: the dash line is the expected tidal sea level while the solid line is the measured level. The offset in the long term is the deformation of the ref. point of -0.69m.

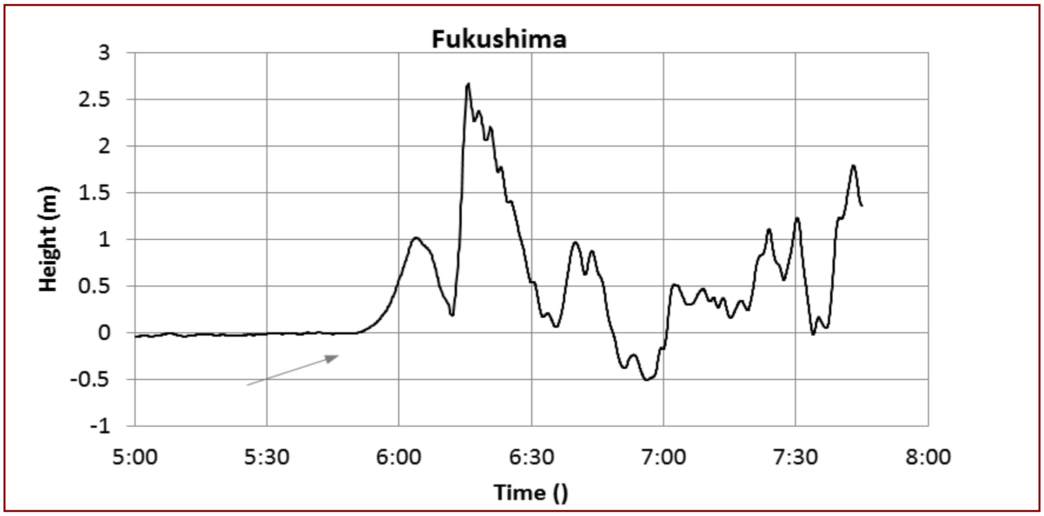

Figure 8 – Short-term sea level measured off shore Fukushima where no differential deformation is present, see the arrow.

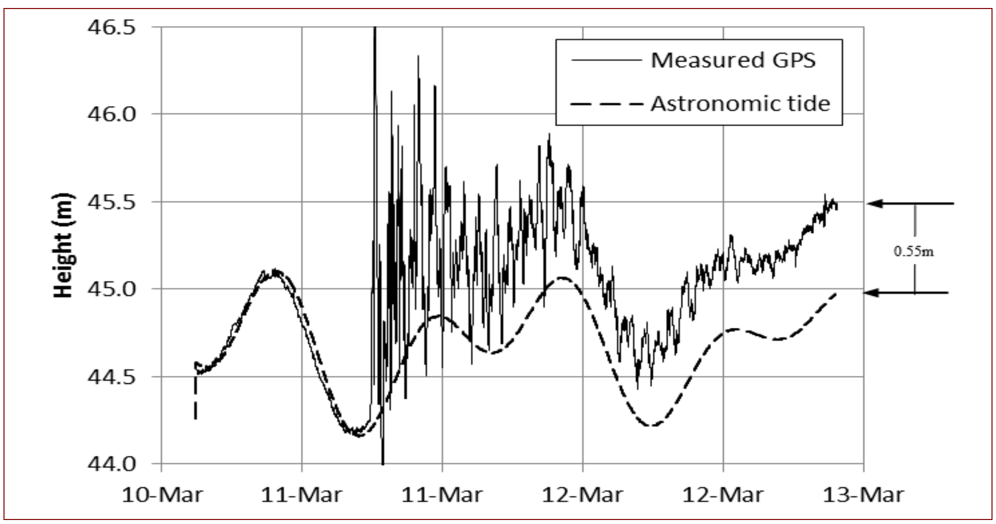

Figure 9 – Fukushima floating GPS: the dash line is the expected tidal sea level while the solid line is the measured level. The offset in the long term is the deformation of the ref. point of -0.55 m

3.3 Deep Pressure Cables or DARTs

The pressure sensors are in a condition similar to both the tidal gauges as well as the GPS sensors. The sensor is located on the bottom of the sea and from its measure it is possible to obtain the level of the water column above it. When the subsidence occurs (Figure 10) the measured level does not change because the deformation and the measurement occurs at the same place. In the long term the difference respect to the value before the Tsunami gives the subsidence level at the location of the pressure sensor. Figure 11 shows that no decrease is present but only a small oscillation after the earthquake for the cable pressure signals, Maeda et al (2011).

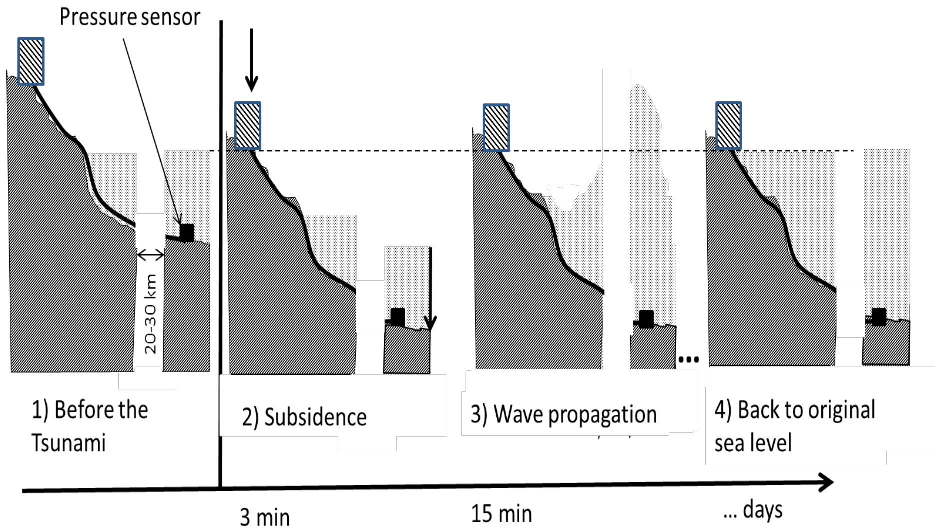

Figure 10 – Sea level response of a cable pressure

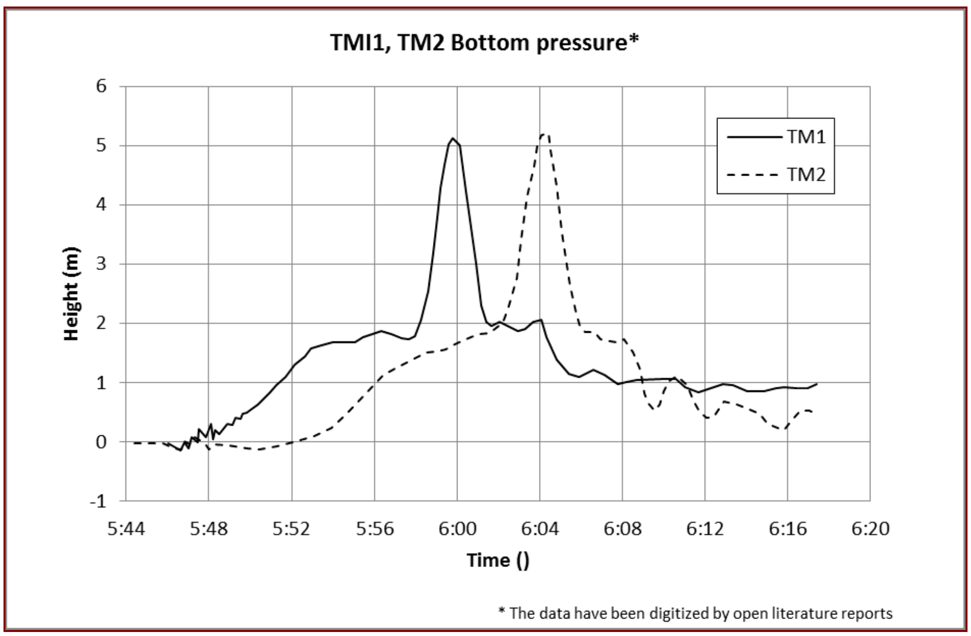

Figure 11 – Original Sea level measured by the cable pressure sensors TM1 and TM2. Long term measurements not yet available

4. SIGNALS CORRECTION FOR THE SEA LEVEL MEASUREMENTS

The analysis of the signals and their explanation indicates that it is necessary to apply a shift to all the measured curves of the devices that in order to take into account the subsidence. Table I shows the different components of the correction (differential deformation or long term offset and its sum).
The values determined are shown in the following Figure 12, which compares also with the value measured with on-shore GPS methods and the agreement is extremely good.
For the points related to TM1 and TM2 where we are not able to determine the deformation due to the absence of the long term data (data unavailable and base station destroyed after the tsunami), an estimate can be done by using the values determined by the Geospatial Information Authority (GSI) using the GPS measurements and correcting by the ratio between measured and estimated from the sea level at the South Iwate GPS buoy. The above offset correction should be applied only after time 0 of the event and within an interval of time between 3 and 5 min; in this analysis it was assumed arbitrarily as 3 min. The original and the resulting curves for 3 examples are shown in Figures 13 to 16. In some cases the correction is small or negligible but in other cases it can be very large. Therefore the comparisons between the calculated values and the measured points should include the corrections indicated above and the inversion methods for the determination of the fault mechanism will also be influenced; in fact up to now, to our knowledge, the correction is not considered and all authors try to match their estimation with the raw data with the tide removed, without any correction.
For instance our code calculations were never able to reproduce the sea level at the pressure cable while instead with this correction and the determined source the agreement is extremely good. The new estimation of the source and the code comparisons will be the subject of another paper.

Lat	Lon	Name	Type	Different. Deform(A)	Ref. Point Def. (B)	Total offset (A+B)	from GPS (GSI)
41.37	141.23	Shimokita	TIDE	0		0	-0.0054
40.12	142.07	North Iwate	GPS	0	-0.15	-0.15	-0.24
39.65	141.98	Miyako	TIDE	0		**-0.5**	-0.36
39.63	142.19	Central Iwate	GPS	0	-0.42	-0.42	-0.55
39.26	142.10	South Iwate	GPS	-0.12	-0.54	-0.66	-0.96
39.25	142.44	TM2	BP	0	n.a.	**-0.96***	-1.4
39.23	142.77	TM1	BP	0	n.a.	**-0.82***	-1.19
39.02	141.75	Ofunato	TIDE	0	-0.7511	-0.7511	-0.82
38.86	141.89	North Miyagi	GPS	-0.35	-0.69	-1.04	-1.27
38.30	141.50	Ayukawa	TIDE	0	n.a	-1.2	-1.19
38.23	141.68	Central Myagi	GPS	-0.34	-1.02	-1.36	-1.51
36.97	**141.19**	**Fukushima**	**GPS**	**0**	**-0.55**	**-0.55**	**-0.78**
36.93	140.90	Onahama	TIDE	0	-0.53	-0.53	-0.57

estimated, not measured

Table I – Correction factors for the sea level measurements

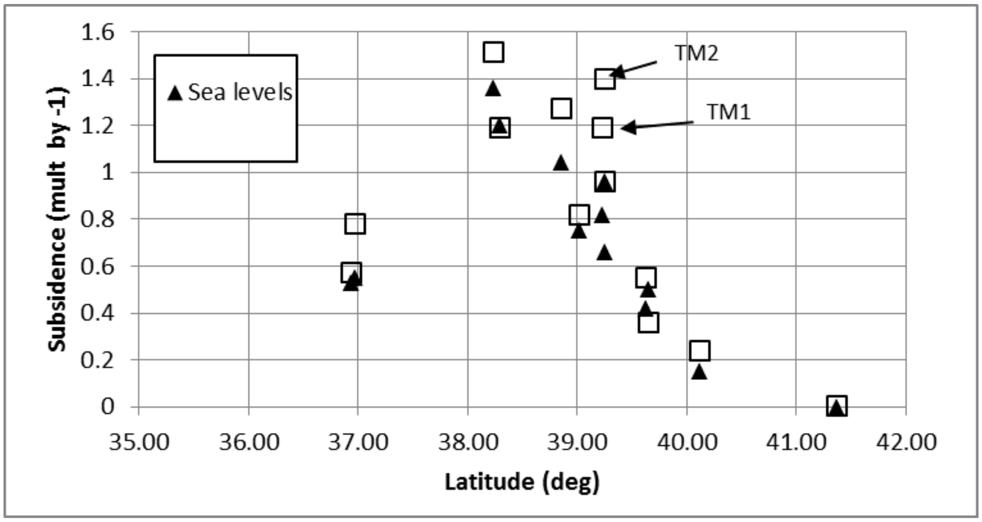

Figure 12 – Comparison of deformations obtained with sea level analysis and direct GPS measurements on land. Some of the points for the level analysis are offshore.

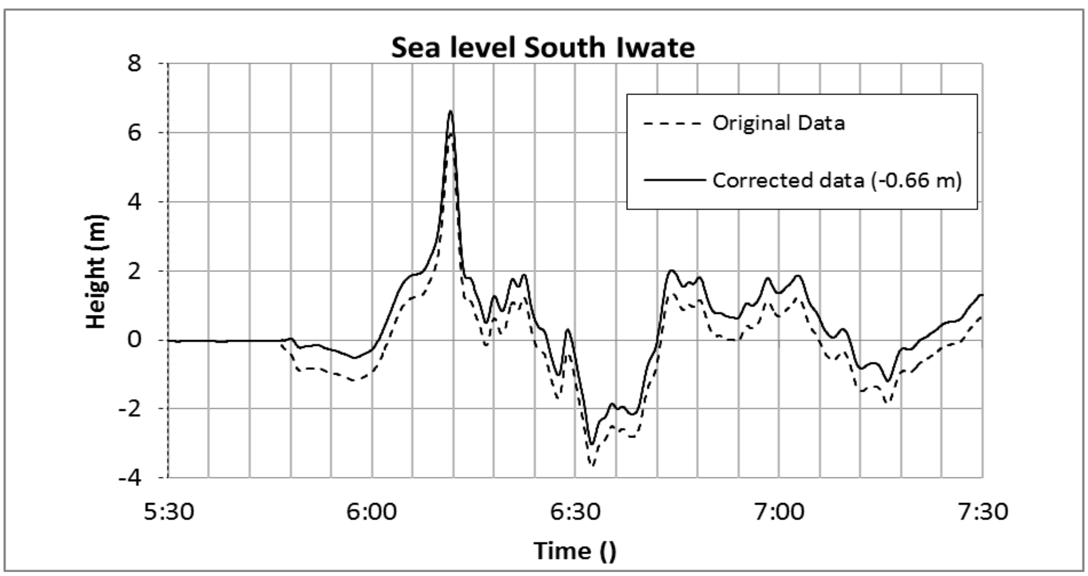

Figure 13 – Original and corrected sea level data for South Iwate

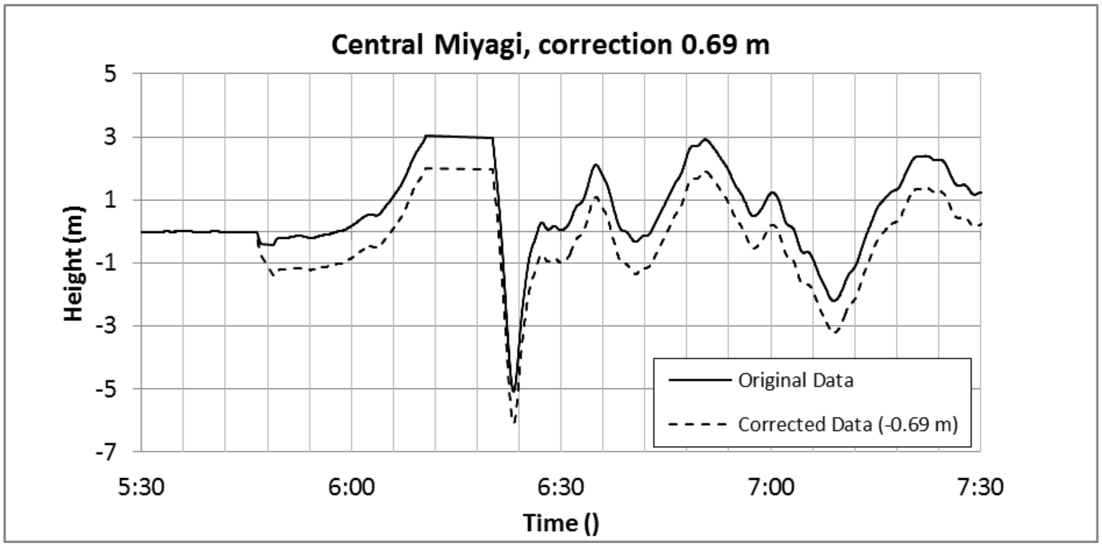

Figure 14 – Original and corrected sea level data for Central Myagi

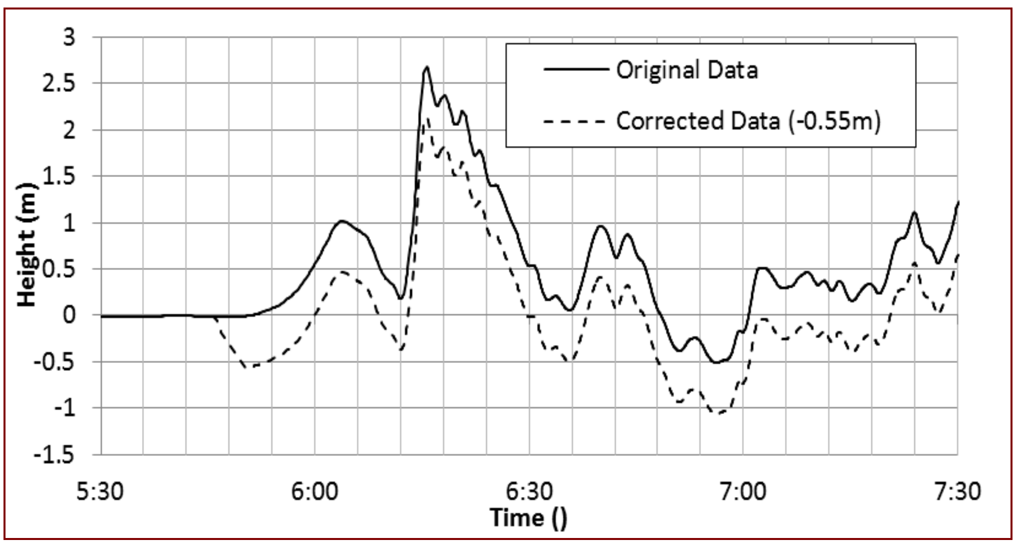

Figure 15 – Original and corrected data for Fukushima

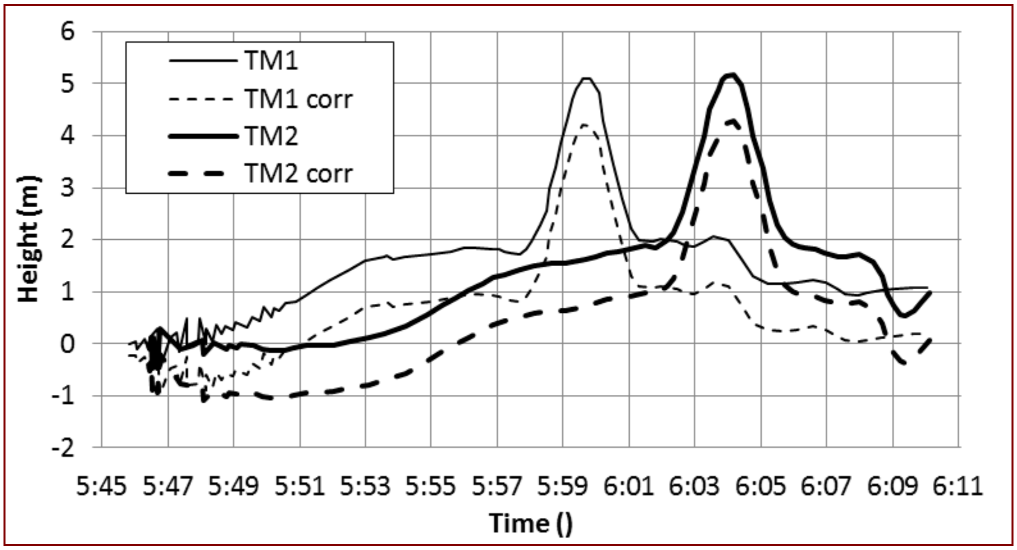

Figure 16 – Original and corrected sea level data for TM1 and TM2, (the data have been digitized by open literature reports)

5. CONCLUSIONS

The analysis of the sea level allowed to estimate the correction factors to be applied in order to take into account the large co seismic subsidence occurred during the Tohoku earthquake. The paper identified 3 different methods of correction for the 3 main types of sea level devices (tidal gauges, GPS buoys and cable pressure or DARTs). It was shown that it is necessary to determine the sea initial level drop and the final sea level offset (differential deformation and long term offset). Through these values it is possible to estimate the initial displacement due to the subsidence.
Although in Japan there is already a large number of on-shore GPS measurements, this paper identified and estimated the subsidence at the location of the GPS buoys and the cable, which are important because in the direction of the fault. It is also possible to estimate the deformation trend along a direction orthogonal to the fault and compare it with the derived source models. Future comparisons with sea level for this event should include the identified correction factors for a proper analysis.

ACKNOWLEDGEMENTS

The author would like to strongly thank the Japan Meteorological Agency and in particular Dr.Takeshi Koizumi. Ports and Harbors Bureau (PHB) under the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) and Port and Airport Research Institute (PARI) provided tide gauge, wave gauge and GPS wave gauge data. GPS deformation data have been provided by Geospatial Information Authority of Japan**.**

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