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Analysis of tsunami signals from tide gauges and ocean-bottom pressure gauges through Iterative Filtering

Angeli C.(*), Armigliato A., Zanetti M., Zaniboni F.

Dipartimento di Fisica e Astronomia (DIFA), Alma Mater Studiorum - Università di Bologna, Italy – (*)cesare.angeli2@unibo.it

Lorito S., Romano F.

Istituto Nazionale di Geofisica e Vulcanologia (INGV) – Rome, Italy

1. TSUNAMI TIME SERIES

A well known problem in tsunami science regards the analysis of sea level time series to extract the signal relative to tsunami occurrences. In the time series recorded by coastal tide gauges (TGs), offshore buoys or ocean bottom pressure gauges (OBPG), the tsunami signal is “hidden” and superimposed on other signals of different amplitudes and frequencies, including tides, coastal/harbour normal mode oscillations, waves excited by meteorological effects, ocean bottom deformations.

We present a technique developed in other research fields and adapted here to tsunami signals, capable of dealing with non-linearities and superpositions of phenomena of different time scales.

2. (FAST) ITERATIVE FILTERING

The **Iterative Filtering** (IF) technique was introduced by Lin et al. (2009), as a variant of iterative data-driven signal analysis techniques, such as the EMD. These iterative methods decompose a signal into oscillatory components I_k, called Intrinsic Mode Functions (IMFs) that

- have zero local average;
- have a number of local extrema and zero crossings that differ at most by one.

Given a function f, the technique produces an additive decomposition such that

$$f(t) = \sum_{i=1}^{N} I_k(t) + r(t) \qquad (1)$$

Consider an operator L that computes the local average of f and define $Sf = f - Lf$. Then, IMFs are computed iteratively as

$$I_k = \lim_{n\to\infty} S^n(f - I_1 - I_2 - \cdots - I_{k-1}) \qquad (2)$$

Different techniques define L in different ways. In the case of IF, it is computed as the convolution $Lf = w * f$. The mask w is taken as the convolution with itself of a symmetric, non-negative, smooth, bounded function with compact support of length $2l$. A different mask length l_k is chosen to compute each IMF, according to the density of local extrema.

Properties of IF:

- no need for a choice of basis functions, completely data-driven;
- suitable for non-linear and non-stationary signals;
- preserves the position of relative maxima (as opposed to causal filters);
- robust w.r.t. to noise (Cicone et al., 2016);
- the choice of w guarantees convergence (Cicone et al., 2016);
- no mode mixing (Cicone et al., 2021);
- easily adjustable mode splitting;
- no unwanted oscillations (L_1 energy conservation, Cicone et al.. 2022);
- can be implemented using FFT, lowering computational time (FIF, Cicone & Zhou, 2021).

3. THE IMFOGRAM FOR TFR

The IMFogram algorithm (Cicone et al., 2022) is a time-frequency representation (TFR) developed specifically to analyse signals decomposed into IMFs. It is based on the assumption that each IMF presents only *interwave* modulation.

It is based on practical definitions for local frequency and amplitude:

- at each zero crossing we assign a frequency as the reciprocal of half the distance from the next zero crossing. The **instantaneous frequency** at each point is obtained interpolating the obtained values.
- at each point we compute the interpolation of the absolute value of relative extrema. The **instantaneous amplitude** is taken as the maximum value between the obtained interpolation and the absolute value of the IMF.

Local frequencies and **amplitudes** are obtained as moving average of instantaneous values over an arbitrary window length. Values are organized in a matrix with the entry A_{ij} being the sum of the amplitude at time j and frequency i for each IMF.

These simple definitions are justified a posteriori by noting that the IMFogram matrix converges to the usual spectrogram.

4. CRETE 2020-05-02 TSUNAMI – IERAPETRA TG RECORD

A $M_W = 6.6$ earthquake occurred on the 2^{nd} May 2020 at 12:51:06 UTC, 80 km offshore of the island of Crete.

The earthquake caused no damage and the resulting tsunami was recorded by a couple of TGs (Ierapetra and Kasos) and observed by eye-witnesses (Papadopoulos et al., 2020).

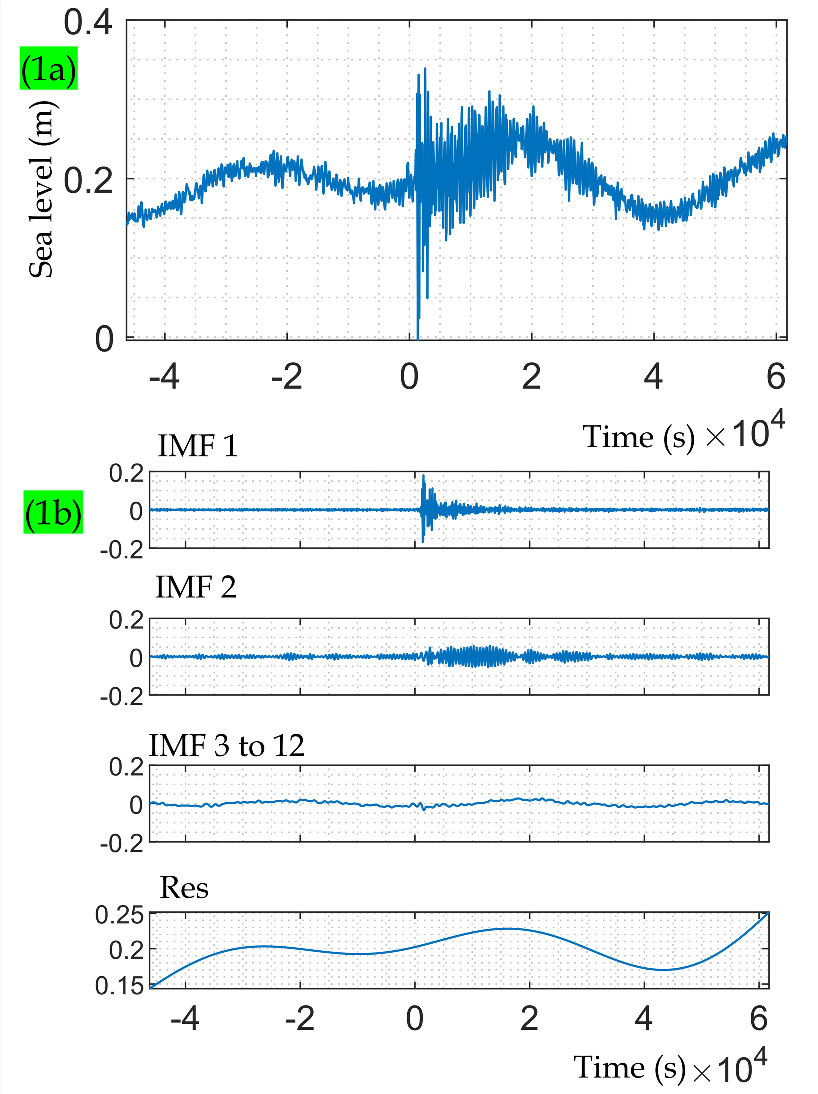


Fig. 1a: TG record at Ierapetra

Fig. 1b: IMF obtained by FIF decomposition

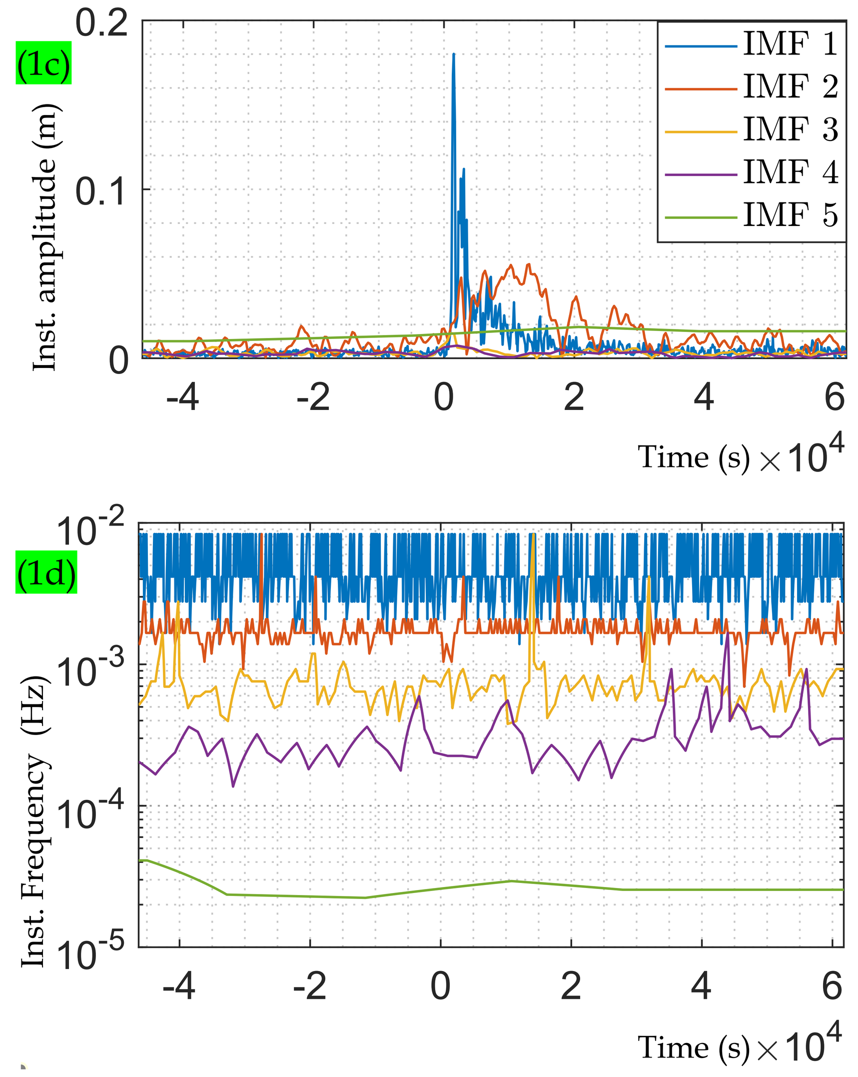


Fig. 1c: Local amplitude for IMFs in Fig. 1b

Fig. 1d: Local frequencies for IMFs in Fig. 1b

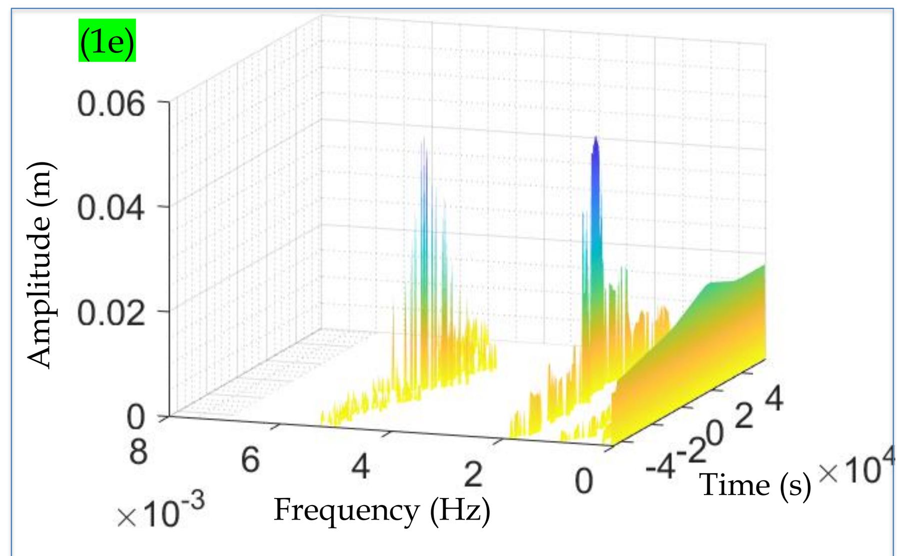


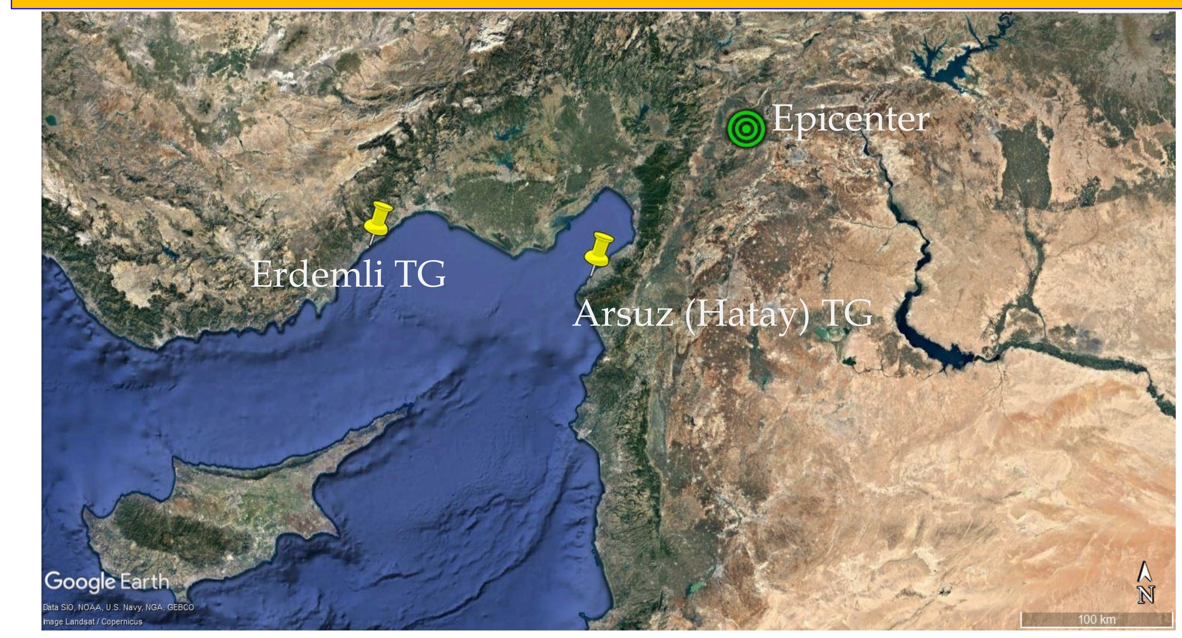
Fig. 1e: IMFogram diagram for signal in Fig. 1a

Some consideration:

- IMF 1: arrival of the tsunami (17 min after origin time), period ~3.5 min and max amplitude 18 cm.
- IMF 2: oscillations around ~10 min, lasting several hours, probably due to oscillations of the harbour.
- IMF 3 to 6 have max amplitude < 2 cm.
- IMF 7 to 12 have max amplitude < 2 mm.
- The residual represents the tidal component.

It may be concluded that IMF 1 + IMF 2 can be assumed to represent the de-tided tsunami signal.

5. TURKEY-SYRIA 2023-02-06 EARTHQUAKE



An important seismic sequence has recently hit the area between the Turkey-Syria border, with two $M_W > 7.0$ earthquakes. At least 57000 victims have been confirmed. The first event in the sequence (01:17:34 UTC, $M_W = 7.8$) also triggered a small but well observed tsunami.

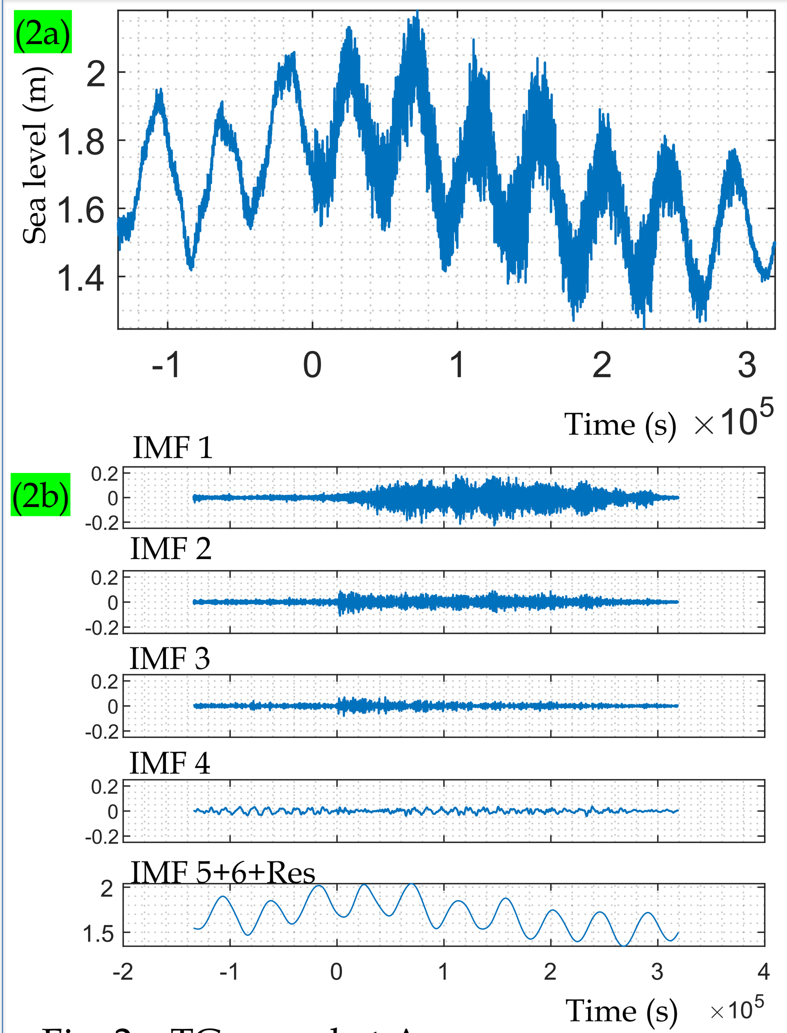


Fig. 2a: TG record at Arsuz

Fig. 2b: IMF obtained by FIF decomposition

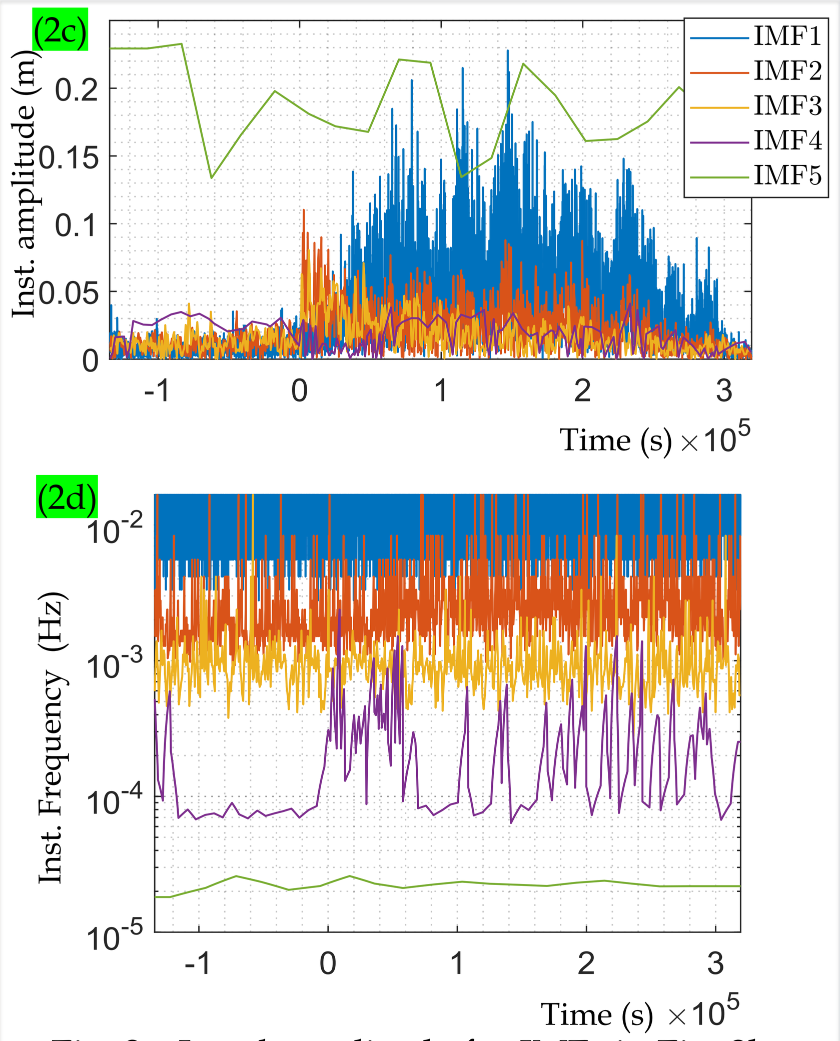


Fig. 2c: Local amplitude for IMFs in Fig. 2b

Fig. 2d: local frequencies for IMFs in Fig. 2b

The decompositions of the signals show some common characteristics:

- First IMF with period of a few times the sampling time (30 s), which can be assumed to be noise. The mean period is 1.5 and 1.9 min respectively. In the Arsuz case, the noise increases in amplitude after a few hours, with large oscillations lasting days (maxima around 20 cm, Fig. 2c).
- IMF 2 and 3 show clear signs of the tsunami wave arrival at 26 and 52 min after origin time respectively for Arsuz (Fig. 2a) and Erdemli (Fig. 3a). These components slowly decay in a few hours. The first peaks in IMF 2 and 3 for Arsuz have amplitude of 6.9 and 5.2 cm respectively at the same time, accounting for the 12 cm arrival reported by KOERI.
- Other IMFs have all mean period over an hour (Figg. 2d and 3d) and their amplitudes do not show any particular correlation with the tsunami arrival (Figg. 2c and 3c).

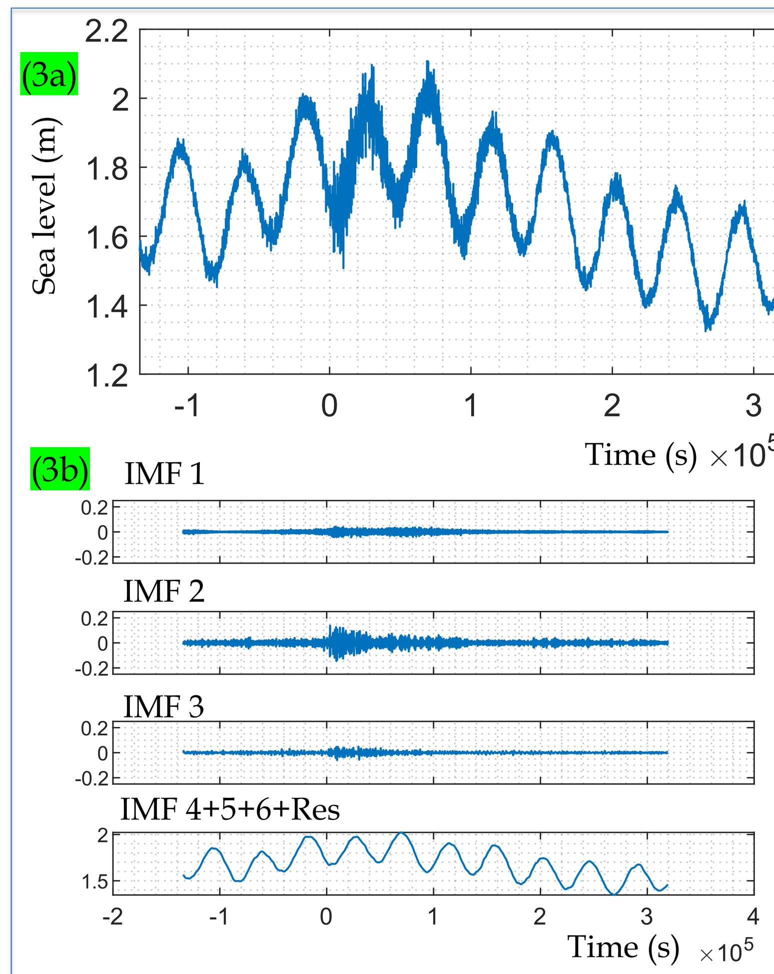


Fig. 3a: TG record at Erdemli

Fig. 3b: IMF obtained by FIF decomposition

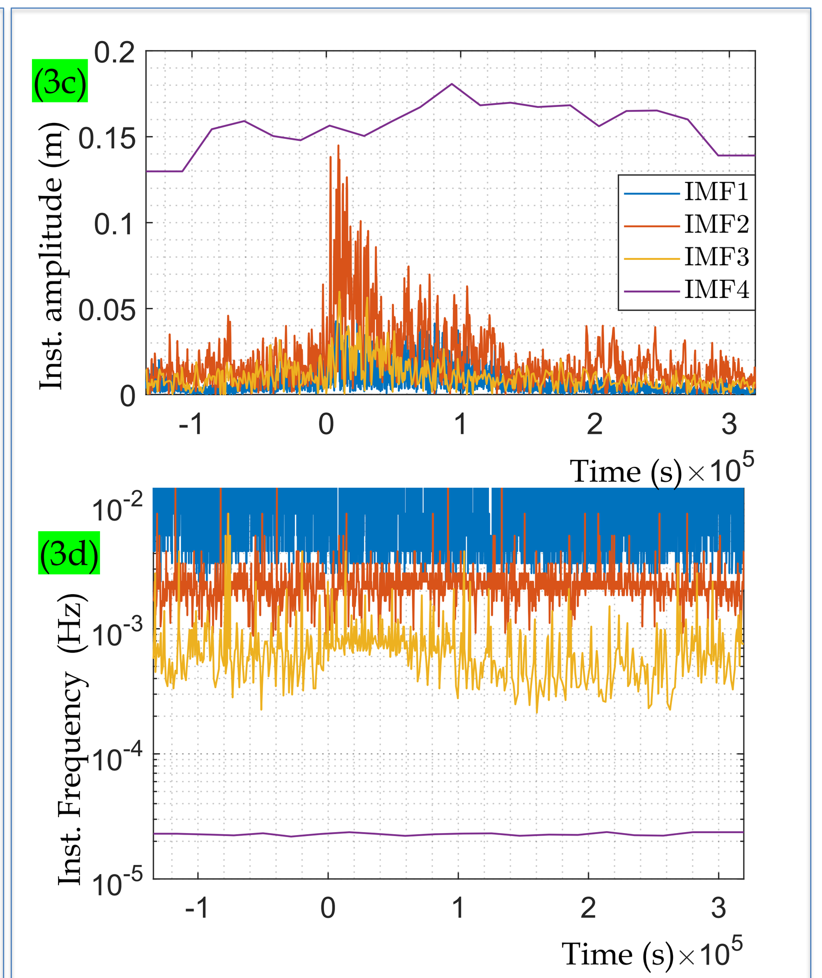


Fig. 3c: Local amplitude for IMFs in Fig. 3b

Fig. 3d: local frequencies for IMFs in Fig. 3b

6. CONCLUSIONS

- The FIF technique combined with the IMFogram algorithm is a suitable technique for the analysis of tsunami signals.
- FIF decomposition is able to separate into different IMFs components of different physical origin, efficiently dealing with non-linear and non-stationary contributions.
- FIF performs better than similar techniques (e.g. EMD and EEMD), both in terms of computational cost and stability w.r.t. noise.
- The IMFogram algorithm allows for computation of local amplitude and frequency of IMFs with very simple definition.
- The combined use of FIF and IMFogram can be used as an alternative to filters in extracting relevant features from signals. Their stability with respect to internal parameters may allow the use for automatic feature detection, with possible applications to real-time tsunami detection.

REFERENCES

Cicone, A., Liu, J., & Zhou, H. (2016). Adaptive local iterative filtering for signal decomposition and instantaneous frequency analysis. *Applied and Computational Harmonic Analysis*, *41*(2), 384-411.

Cicone, A., Li, W. S., & Zhou, H. (2022). New theoretical insights in the decomposition and time-frequency representation of nonstationary signals: the IMFogram algorithm. *arXiv preprint arXiv:2205.15702*.

Cicone, A., & Zhou, H. (2021). Numerical analysis for iterative filtering with new efficient implementations based on FFT. *Numerische Mathematik*, *147*, 1-28.

Cicone, A., Serra-Capizzano, S., & Zhou, H. (2021). One or two frequencies? the iterative filtering answers. *arXiv preprint arXiv:2111.11741*.

Lin, L., Wang, Y., & Zhou, H. (2009). Iterative filtering as an alternative algorithm for empirical mode decomposition. *Advances in Adaptive Data Analysis*, *1*(04), 543-560.

Papadopoulos, G. A., Lekkas, E., Katsetsiadou, K. N., Rovythakis, E., & Yahav, A. (2020). Tsunami alert efficiency in the Eastern Mediterranean Sea: The 2 May 2020 earthquake (Mw 6.6) and near-field tsunami south of Crete (Greece). *GeoHazards*, *1*(1), 44-60.