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IONOSPHERIC TSUNAMI POWER INDEX (ITPI) TESTING FOR TSUNAMI DETECTION

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ABSTRACT

Ionospheric Tsunami Power Index (ITPI) has been proposed for tsunami detection. The index is derived from Total Electron Content (TEC) Global Navigation Satellite System (GNSS) data. The ITPI method already used for tsunami detection is limited to two earthquake cases. Therefore, the method needs to be tested before implementing the ITPI method operationally. ITPI testing was conducted for nine tsunami events in Indonesia. The test shows that ITPI can detect tsunami effects on the ionosphere. There are four of nine tsunami events that can be detected with ITPI consistently. The five ITPI tsunami events could not be detected. It is caused by the TEC data being too far from the tsunami epicentre and local tsunamis caused by landslides.

Keywords: *Ionospheric Tsunami Power Index (ITPI), Total Electron Content (TEC), GNSS*

1. INTRODUCTION

A *tsunami* is an earthquake originating from a shallow seabed or coastal subduction zone that causes a tsunami that comes quickly and unexpectedly (Manta et al. 2020). For example, the Sumatra M 7.6 earthquake in 1907, which caused a tsunami on the coast of Simeulue, Nias, and Batu islands, was named the tsunami earthquake by (Kanamori et al. 2020). Likewise, the Mentawai earthquake on October 25, 2010 (Mw7.8) is also known as the tsunami earthquake described by (Lay et al. 2011). (Kanamori et al. 2020) first proposed that the earthquake has the same characteristics. Furthermore, several methods of tsunami detection with TEC GNSS are discussed from the beginning to ITPI. There are several methods before the presence of the ITPI method. The tsunami detection method using the ionosphere has been used by Artru, namely with a high pass filter with a cut-off of 30 minutes (Artru et al. 2005) to eliminate diurnal variations and GNSS receiver bias (Artru et al. 2005). Galvan et al. use another method, namely polynomial and bandpass filtering, whose explanation is as follows:

a. Polynomial Function
   The polynomial functions can eliminate TEC variations with more extended periods, such as diurnal variations and changes in satellite elevation angles.
b. Band Pass Filtering
   Band Pass Filtering applied is 0.5-5 MHz (corresponding to the wave period of 33.3 to 3.3 minutes, with a typical range of tsunami periods). The filter extracts the Mesoscale Traveling Ionospheric Disturbance (MSTID) period caused by the tsunami.

Another way of detecting the effect of a tsunami on the ionosphere is to limit the TEC error to 0.03 TECU. It means that the accuracy of measuring the phase of the GPS carrier wave is less than 1 mm. According to the law of error propagation, the TEC measurement error is about 0.01 TECU. Thus, the TEC measurement error dominates these errors. Under near-quiet conditions, the lowered TEC value will typically fall within three sigmas of around 0.03 TECU. Furthermore, If the TEC value is above 0.03 TECU, can detect the anomaly.

This study focuses on ITPI testing related to the entire spectrum of AGW energy (Manta, et al. 2020). This ITPI indication of the tsunami effect on the ionosphere is not affected by pass-band filtering or polynomial fitting. It means that the ITPI value in the Mentawai case is 14. The disturbance is 14% greater than the average spectrum value of the previous six days in TEC observations (Manta, et al. 2020). The existence of unique characteristics of AGW compared to the mean background level (MBL) was revealed by Manta et al. from TEC data a few days before the earthquake until the time of the earthquake. The ratio between the TEC spectrum on the tsunami day and the average TEC spectrum six days before the tsunami can calculate ITPI. Manta et al. mention that the value can eliminate the influence of ionospheric dynamics. It has been successfully tested in two earthquake cases (Manta, et al. 2020). The paper discusses the results of the ITPI testing for tsunami detection that has occurred in Indonesia. The aim is to know the ITPI used operationally to strengthen the tsunami early warning system in Indonesia.Data and Methodology

1.1 Data

The data are nine earthquakes with the potential for a tsunami, and observed tsunami. The data was downloaded from ngdc.noaa.gov, by filtering 1996-2021 in Indonesia.

Table 1. Data on the 10 largest earthquakes in Indonesia

No.	Year	Month	Day	Hour	Minute	Quake Magn. (SR)	Location Name	Latitude	Long.	Max. Water Height (m)
1	1996	2	17	5	59	8.2	Irian Jaya	-0.891°	136.952°	7.7
2	2000	5	4	4	21	7.6	Sulawesi	-1.105°	123.573°	6
3	2002	10	10	10	50	7.6	Irian Jaya	-1.757°	134.297°	5
4	2004	12	26	0	58	9.1	Offshore West Coastal Sumatra	3.316°	95.854°	50.9
5	2005	3	28	16	9	8.6	Indonesia	2.085°	97.108°	4.2
6	2006	7	17	8	19	7.7	South of Java	-9.254°	107.411°	20.9
7	2007	9	12	11	10	8.4	Sumatra	-4.438°	101.367°	5
8	2010	10	25	14	42	7.8	Sumatra	-3.487°	100.082°	16.9
9	2018	9	28	10	2	7.5	Sulawesi	-0.178°	119.840°	10.73
10	2018	12	22	13	55	n/a	Krakatau	-6.102°	105.423°	85

1.2 Ionospheric Tsunami Power Index (ITPI)

The computation of TEC uses a method similar to (Calais and Minster 1995), namely the carrier wave phase (L1 & L2), not using an inaccurate apparent distance measurement (P1 & P2). TEC of the phase data is computed using Equation (1) (Manta et al. 2020):

$$TEC = \frac{(L1 - L2)}{40.3} \frac{f_1^2 f_2^2}{f_1^2 - f_2^2} \qquad (1)$$

Where f1 and f2 correspond to high and low GPS frequencies and TEC is the Total Electron Content measured in TEC units (1 TECU = 1016 el/m2). A consequence of the integrated nature of TEC is the presence of ionospheric disturbances. The observed ionospheric disturbances are generated in the range from the height of the satellite to the

receiver. However, the combination of TEC variation comes from around the maximum height of ionospheric ionization (F2 layer).
The ITPI index can be made from the TEC data to identify ionospheric disturbances caused by the tsunami using Equation (2) (Manta et al. 2020).

$$ITPI = \left(\frac{PSD_{MAX}}{MBL} - 1\right) \cdot 100. \qquad (2)$$

The ITPI is proportional to i with the ratio between the TEC spectrum on the day of the tsunami the average spectrum for the previous six days. The intended ratio is the ratio between the Maximum Power Spectral Density (PSDMax) levels of TEC during the event. Mean Background Level (MBL) is defined as the average PSD observed six days before the earthquake. The use of background averaging over several days before an earthquake is intended to remove outliers and smooth out parts of the noise associated with other disturbances in the ionosphere. These parameters are for the automatic identification of tsunamigenic potential (Manta et al. 2020).

Figure 1 below shows the methodology flow. The explanation of each stage in Figure 1 is presented below:

Compute the TEC from observation data of dual-frequency GNSS signal using Equation (1).

1. The TEC calculation is obtained from the observation data of the dual-frequency GNSS signal using Equation (1).
2. Compute the IPP (GNSS signal trajectory in the ionosphere) six days in advance of today's events of earthquake days.
3. Compute the latitude and longitude IPP using Equation (3) to (5) (Pooja et al. 2018).
   latitude_IPP = $\phi + \cos(A)$
   longitude_IPP = $\lambda + z \sin A \cos(latitude\_IPP)$
   With $z = cos-1 rere+h \cos E - E$
   Where, re: radius from earth = 6378137.0, h: height = 350, ϕ: latitude, λ: longitude, E: elevation angle, A: azimuth angle, latitude_IPP: latitude from IPP, longitude_IPP: longitude from IPP.
4. Filter the data using polynomials to eliminate the influence of satellite motion and other biases on TEC data.
5. Analyze the spectrum for each TEC for every one hour of moving observations in 30 seconds.
6. Determine the average PSD for six days before the tsunami computation.
7. Determine the power spectrum distribution on the day with the average power spectrum six days before the tsunami.
8. Compute the ITPI using Equation (2).
9. Analyze the correlation between ITPI and earthquake magnitude.
10. Determine the ITPI correlation with tsunami height.
11. Determine the empirical modelling of the relationship between the ITPI index and tsunami height.
12. Determine the empirical modelling of ITPI's relationship with earthquake magnitude.

The computation of steps 1 to use the GOPI software are as shown in Figure 1.

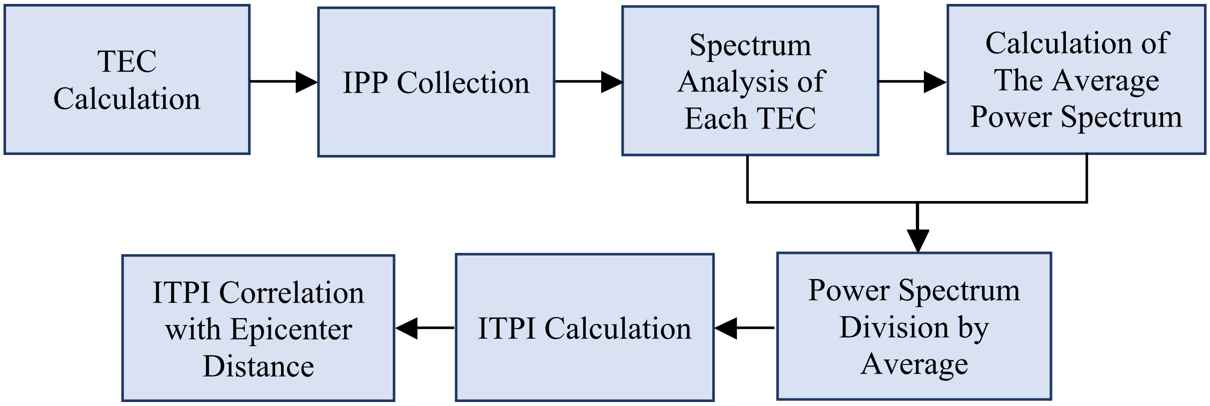

Figure 1. Methodology flow

2. RESULTS AND DISCUSSION

Figure 2 shows the average PSD TEC from satellite number 23 before the Aceh earthquake from December 20 to 25. It means that the maximum spectrum value is around t10 at 5 UT with a frequency of 0.3 MHz Figure 2 shows the PSD on December 26, 2004, in the Aceh tsunami.

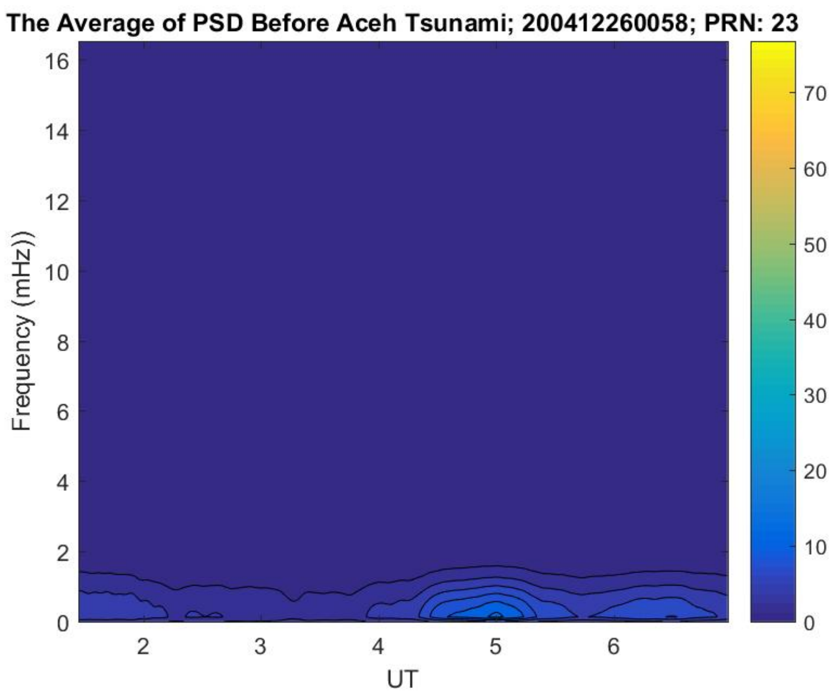

Figure 2. Average PSD before the Aceh earthquake on satellite number 23

The maximum value of the spectrum was above 70 at around 5 UT, with a frequency value of about 0.3 MHz (55.6 minutes period). The increase in spectrum value starts at 3.9 UT. At that time, the ionosphere is at coordinates 13.24° South Latitude, 96.66° East Longitude, and altitude 350 km. Also, from the epicentre of the earthquake at 3.316° South Latitude and 95.854° East Longitude, ionospheric anomalies occurred at a distance of 16.556° latitude and 0.806° longitude. The horizontal distance is 16.575° (1839.89 km).

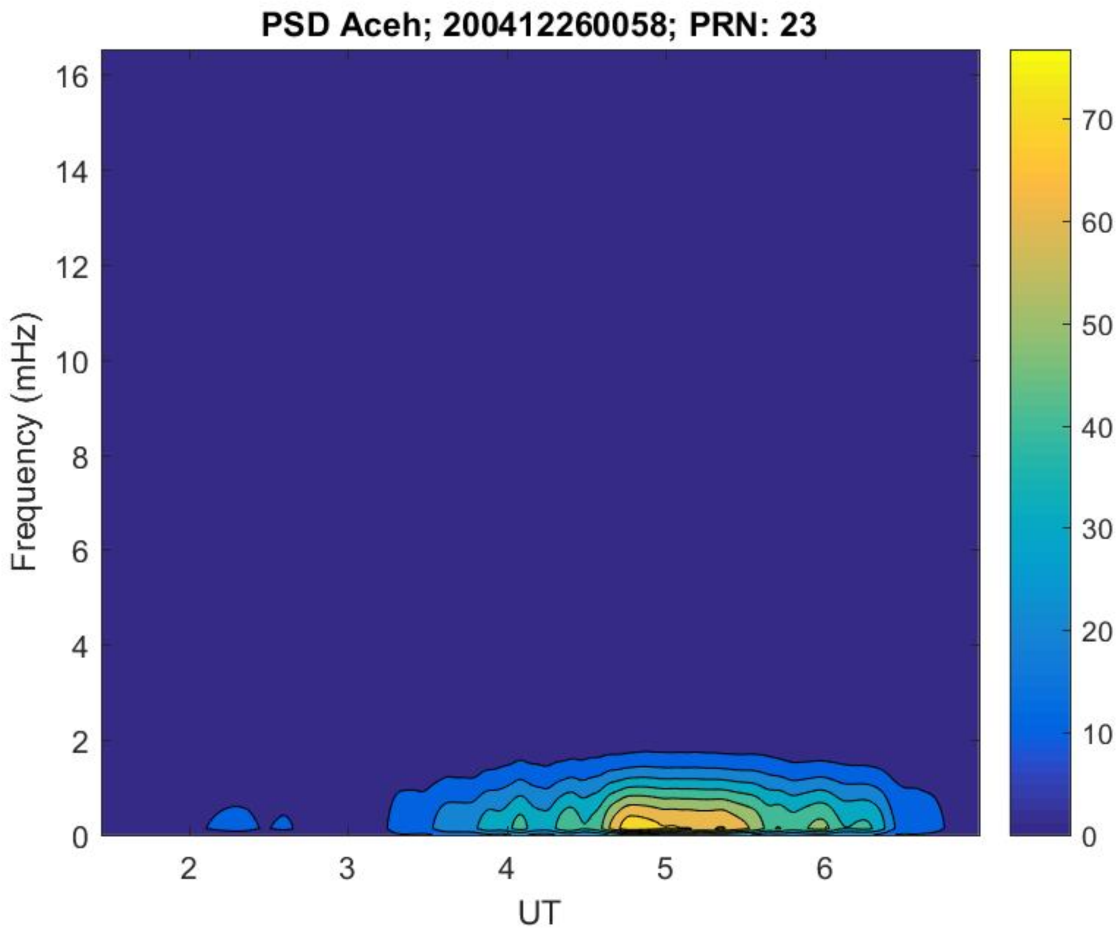

Figure 3. Aceh PSD on satellite number 23

The anomaly propagation time from the tsunami at 0.96 to 3.9 UT is 2.9 hours. Thus, the horizontal velocity is 634.44 km/hour. However, the tsunami events reference shows that the tsunami velocity is around 750 km/hour (Marghany-Maged, 2014). Therefore, the horizontal velocity observed in the ionosphere is lower than that of a typical tsunami.

Figure 3 shows ITPI Aceh during the tsunami. The apparent increase in spectrum values started at 3.5 UT at a frequency of about 1 MHz (period of internal atmospheric gravity waves 16.7 minutes).

An anomaly also appeared at 3 UT, and the frequency was around 5.8 MHz (9.7 minutes). Compared with ITPI, the ITPI method shows more anomaly detection, namely internal gravity waves and acoustic waves whose frequencies are 1MHz and 5.8 MHz, respectively. Therefore, the ITPI is more sensitive in detecting the effects of tsunamis on the ionosphere from TEC data. Based on the horizontal distance of the detected anomaly and its propagation time, the horizontal velocity of the tsunami is obtained. The propagation rates of ionospheric disturbances due to the tsunami are 707.65 km/hour (from internal gravitational waves) and 901.9 km/hour (from acoustic waves). Figure 4 shows the ITPI Aceh on satellite Number 23.

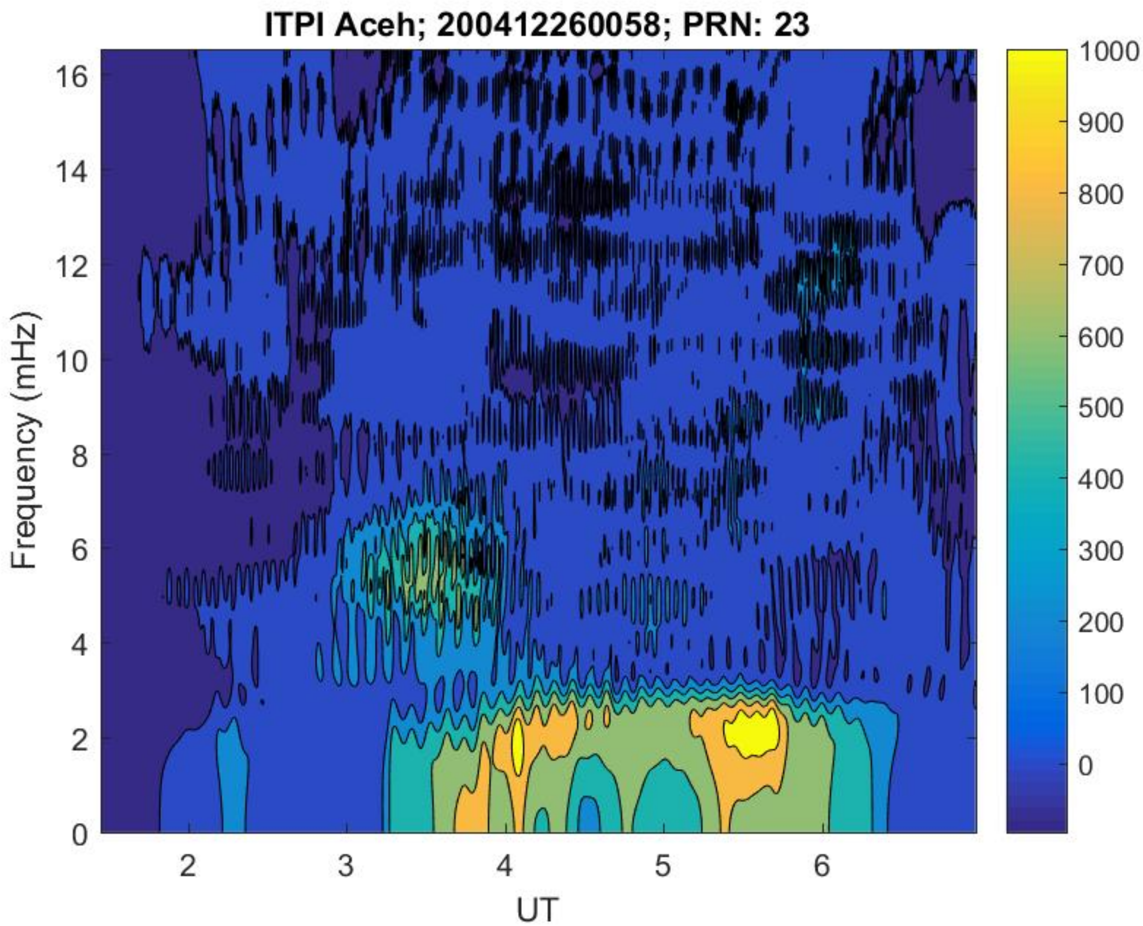

Figure 4. ITPI Aceh on satellite number 23

The other satellite observations and tsunami events in total can be seen in Table 2 below.

Table 2 List of tsunami events relation to distance and ITPI value

Location	Station	Epicenter		Date	Time	Satellite number	ITPI		Frequency (mHz)	Delay (hours)	Distance (km)	ITPI Max	Velocity (km/hr)
		Lat (°)	Long (°)				Lat (°)	Long (°)					
Aceh	COCO	3.32	95.85	26/12/2004	0:58	11	-11.98	98.42	3.0	2.8	1721.581	3500	614.850
		3.32	95.85	26/12/2004	0:58	20	-16.19	97.41	3.2	2.6	2172.044	1600	835.401
		3.32	95.85	26/12/2014	0:58	23	-13.96	96.88	2.5	2.1	1921.015	1000	914.769
		3.32	95.85	26/12/2004	0:58	23	-12.74	96.54	5.0	2.4	1783.842	550	743.267
		3.32	95.85	26/12/2004	0:58	23	-14.14	96.96	0.4	2.2	1941.501	400	882.501
		3.2	95.85	26/12/2004	0:58	31	-13.79	93.07	2.6	2.5	1923.748	3000	769.499
Krakatau	BAKO	-6.10	105.42	22/12/2018	13:55	23	-9.10	106.15	4.2	0.8	342.423	1200	428.028
		-6.10	105.42	22/12/2018	13:55	18	-2.78	109.57	6.0	1.0	589.799	140	589.799
Pangandaran	XMIS	-9.25	107.41	17/07/2006	8:19	19	-13.22	104.91	5.0	0.6	520.449	350	867.414
		-9.25	107.41	17/07/2006	8:19	20	-9.87	101.17	16.0	1.5	696.117	200	464.078
Mentawai	NTUS	-3.49	100.08	25/10/2010	14:42	22	5.18	103.40	3.1	2.8	1030.126	80	367.902
		-3.49	100.08	25/10/2010	14:42	25	1.68	106.50	10.5	3.2	914.579	600	285.806

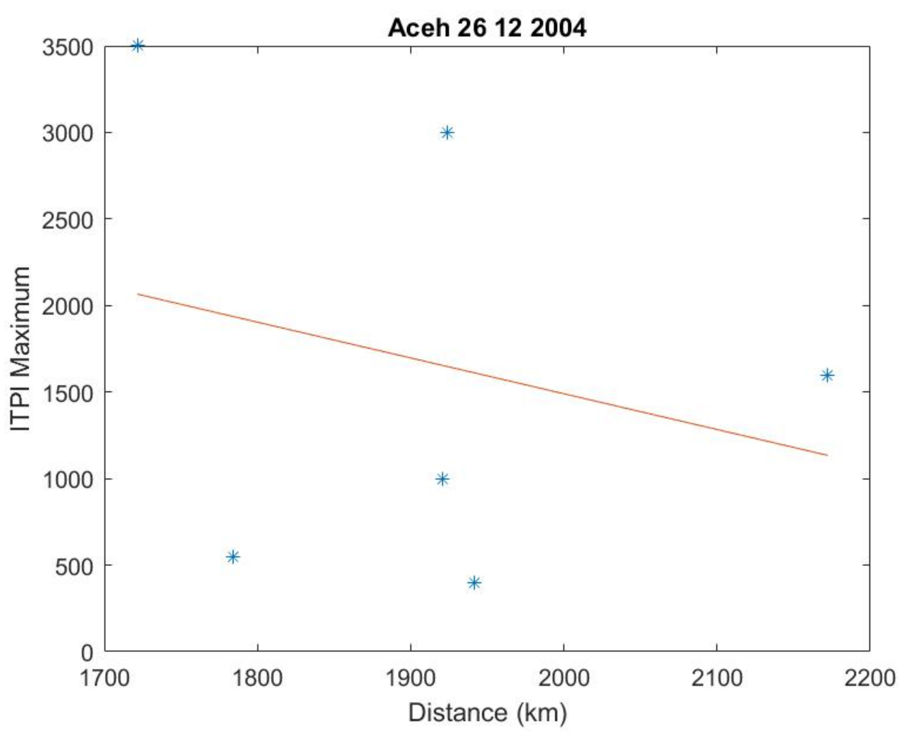

Figure 4. Linear trend of the relationship between the distance of the satellite to the epicentre of the earthquake with the maximum ITPI value

Table 2 shows that the distance and speed of a tsunami are affected by the type of tsunami present. Based on UNESCO's ITIC, there are two types of tsunamis: local and regional tsunamis. A local tsunami is a tsunami originating from a distance of about 100 km or less than 1 hour from the tsunami's travel time from the affected coastline. Meanwhile, regional tsunamis are tsunamis capable of hitting a specific geographic area, generally within 1000 km from the earthquake's epicentre. Regional tsunamis can arrive at the affected coastline within 1-3 hours of movement. Thus, their strength can distinguish the two types of earthquakes.

The Aceh Tsunami is a regional tsunami type with a strength of 9.1 Mw. The ITPI method can show the Aceh tsunami impacting the ionosphere at a distance of more than 1000 km from the epicentre.

If analyzed using a linear trend line, the maximum distance between the ionospheric disturbance and the epicentre is no more than 2200 km. Thus, it proves that the farther the ionospheric satellite observation from the epicentre, the lower the ITPI value.

2. CONCLUSIONS AND RECOMMENDATIONS

The discussion and results show that the closer the earthquake centre is to the satellite, the higher the ITPI value. On the other hand, the farther the distance between the epicentre and the satellite, the lower the ITPI value. In addition, the results are not appropriate in local tsunami events such as (Sulawesi, 28 September 2018). The result is due to several factors, the far distance from the epicentre to satellite observations. Based on ten tsunami events, Aceh uses a model of the tsunami effect on the ionosphere. ITPI results show a tsunami of 4 consistent events, namely (Aceh, Krakatau, Pangandaran, and Mentawai). The four events are global and local tsunamis.

Recommendations for further research are:

a. The study to use local GNSS observation data, which is closer to the tsunami event.
b. The study to use more precise filtering related to the type of wave (acoustic and gravity).
c. To use more GPS station data so that the spatial pattern is clearer.

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