Analysis of Swarm Electric Field Data in View of Tsunami Events and related Earthquakes

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It is proven that different events on the Earth and in its atmosphere have their own impact on Earth electric field, and the earthquakes are amongst these phenomena. Many strong earthquakes (EQ) induce tsunamis, which are also suspected as contributing to the gravity waves having an impact on the ionospheric TEC.

The sensitivity of Swarm LP and POD GNSS data to EQs and tsunamis is analyzed in this study at around 500 km high orbit. Three Swarm satellites are equipped with Langmuir Probes (LP) measuring in-situ electron density of Earth electric field and POD GNSS receivers determining topside Total Electron Content (TEC) in the topside ionosphere. The integrity of both data sources is also analyzed.
The investigation of Swarm data in view of Tsunamis and earthquakes is difficult due to the several factors. The major drawbacks are:

- only three satellites (with respect to GNSS systems), the two of which fly almost together, which gives in fact only two survey tracks

- lower orbits in relation to GNSS

- orbital repetition is far from exact, which seriously limits the number of comparable observations in terms of the location and time of the day

- number of large earthquakes and tsunami events in time of Swarm science mission is limited, and many Earthquakes do not coincide sufficiently with Swarm passes in time and space
Swarm LP data is analyzed just after the earthquakes, as well as several days before and after the earthquakes and resulting tsunami events. The GNSS POD topside TEC from Swarm is analyzed together with LP data, in order to validate LP and assess integrity of both data sources. In-situ electron density disturbances are compared to selected/available STEC measurements between LEO and GNSS satellites.

Some preliminary calculations of GNSS phase differences from selected nearby ground stations are also compared. These initial comparisons are made in order to look for possible correlations between Swarm POD TEC and ground GNSS data, and to prepare for further work.
Spectral look on LP and TEC data close to EQ/tsunami events

• Analyzed are Swarm LP data (EFIxLP, L1B) and TEC (Level2daily) data

• Signal and its disturbances are composed of various frequencies – corresponding to various phenomena. Different frequencies can originate from normal solar activity, and different from wide range of phenomena in the electric field - therefore FFT is used for spectral analysis

• Swarm speed is fast and its interaction with TIDs can be extremely short – therefore we should analyze the signal carefully and find TIDs wavelengths precisely (other reason of frequency domain application)

• LP Ne data have calculated ROD and RODI and ROD (or subsequently residual ROD') is used in spectra short-term FFT (STFFT) analysis

• TEC data have calculated ROT and ROTI and ROT (or subsequently residual ROT') is used in STFFT analysis
Spectral look on LP and TEC: the closest large tsunami events during Swarm mission

3 EQ/tsunami events with closest passes are investigated:

<table>
<thead>
<tr>
<th>WAVE</th>
<th>HEIGHT</th>
<th>EQM</th>
<th>LAT</th>
<th>LON</th>
<th>DATE</th>
<th>TIME</th>
<th>DEPTH</th>
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</tr>
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</table>

Alaska Kamchatka Solomon Islands New Zealand Papua Chile
Spectral look on LP and TEC:

- Frequencies - (sampling) from 1s. to 256 s. (2 points to 512 points) for LP (2 Hz) and from 1s. to 256 s. (1 point to 256 points) for TEC (1 Hz)

- Spectrograms: Large overlapping of windows (small time step) - overlap = (256 – 10) s.

- Scale in Hz and also in seconds of Swarm track (wavelengths must be later recalculated to km)

- Spectrogram window: In first iteration: Tukey Window 512 points (256 seconds from 2Hz data) for LP, and 256 points for 1Hz POD TEC

- Signal decomposition by FFT for selected bands, primarily we divided signal into 3 bands: (max. – 180 s., 107 - 41 s., 57 - 12 s., kindly suggested by MHP (UPC) ;-)), so the frequencies above 12 s. were removed

- Selected are 3 close passes from different days: \( \Delta \varphi < 2^\circ, \Delta \lambda < 5^\circ, \Delta UTC < 0.4 \text{ h} \) from central pass in day of EQ, just after EQ

FFT parameters
Spectral look on LP and TEC: selection of the most similar passes

CHILE

% Chile, Pacific  467  8.3
  -31.5700  -71.6540
  20150916  225433  24.9

NEW ZEALAND

% New Zealand,  231  7.8
  -42.7570  173.0770
  20161113  110256  23.0

PAPUA NEW-GUINEA

% Papua, Pacific  19  7.9
  -4.5090  153.4500
  20161217  105112  103.0
Spectral look on LP and TEC: selection of the most similar passes

### Selected Comparable Times of Passes (the most close that possible in time of the day, Lat and Lon), first point of selected track compared and approximately repeated

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Chanel</th>
<th>DFI</th>
<th>DLA</th>
<th>PSI</th>
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<tbody>
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<td>Chile</td>
<td>0.197</td>
<td>-3.61</td>
<td>-88.9</td>
</tr>
<tr>
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<td>14:37</td>
<td>New Zealand</td>
<td>1.984</td>
<td>-0.88</td>
<td>2.165</td>
</tr>
<tr>
<td>2016-11-10</td>
<td>14:38</td>
<td>Papua</td>
<td>1.989</td>
<td>-0.94</td>
<td>2.194</td>
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<td>2016-11-10</td>
<td>14:37</td>
<td>New Zealand</td>
<td>1.989</td>
<td>-0.94</td>
<td>2.194</td>
</tr>
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</table>

### Spectral Look on LP and TEC

Chile

<table>
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<tr>
<th>Date</th>
<th>Time</th>
<th>Chanel</th>
<th>DFI</th>
<th>DLA</th>
<th>PSI</th>
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<tr>
<td>2015-09-16</td>
<td>23:30</td>
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<tr>
<td>2016-11-10</td>
<td>14:37</td>
<td>New Zealand</td>
<td>1.989</td>
<td>-0.94</td>
<td>2.194</td>
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</tbody>
</table>

New Zealand

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Chanel</th>
<th>DFI</th>
<th>DLA</th>
<th>PSI</th>
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</thead>
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<tr>
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<td>11:24</td>
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<td>0.92</td>
<td>2.178</td>
</tr>
<tr>
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<td>11:25</td>
<td>Papua</td>
<td>1.986</td>
<td>0.92</td>
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<td>2016-11-27</td>
<td>11:25</td>
<td>New Zealand</td>
<td>1.986</td>
<td>0.92</td>
<td>2.178</td>
</tr>
</tbody>
</table>

### Notes

- \(\Delta \phi < 2^\circ, \Delta \lambda < 5^\circ, \Delta UTC < 0.4\) h
- \(\Delta \phi > 2^\circ, \Delta \lambda > 5^\circ, \Delta UTC > 0.4\) h
In the vicinity of Chile-Illapel EQ, Swarm crosses edges of equatorial anomaly, which is a dominating signal in spectral sense. On the other hand, Swarm B is higher than A/C. Separation and removal of long-wavelength patterns must be done.
The equatorial anomaly signal occupies LP signal at wide band of frequencies and it is hard to separate the same frequencies along the whole Swarm track. Different frequencies occur in different places.
POD TEC, SFFT SPECTROGRAMS
CHILE 2015
EQ > 2015.09.16  22:54:33

6 DAYS BEFORE

JUST AFTER

6 DAYS AFTER

Tukey Window, Size 256 s.,

POD TEC shows similar behavior. TEC models can be helpful in the further research for detrending. However, some separated signal parts can be noted also from these SFFT samplings. Resampling after efficient detrending must be made.
LP, SFFT SPECTROGRAMS
NEW ZEALAND 2016 (first pass)

EQ > 2016.11.13 11:02:56

ROD, Swarm A
Tukey Window, Size 256 s.,

3 DAYS BEFORE

3 DAYS AFTER

JUST AFTER

Noisy signal, occupying many frequencies, 3 days before the EQ and quite far to the South from NZ

Some signal before middle point is separated, not mixed with high freq. noise, as before
3 DAYS BEFORE

The largest amount of high freq. noise, as well as in LP signal

JUST AFTER

Less noise, more low frequencies, and are better separated

3 DAYS AFTER

Long wavelegth dominates
LP, SFFT SPECTROGRAMS
PAPUA NEW-GUINEA 2016
EQ > 2016.12.17 10:51:12

Tukey Window, Size 256 s.,

3 DAYS BEFORE
This signal at 30 s. is not present 3 days before or after EQ

3 DAYS AFTER
Long wavelegth (worth removal) dominates 3 days before

JUST AFTER
Long wavelegth dominates 3 days after
LP, FFT DECOMPOSITION
PAPUA NEW-GUINEA 2016
EQ > 2016.12.17 10:51:12

ROD, Swarm A

FFT decomposition into freq.: 12-57 s., 41-107 s., 108-max. s.

3 DAYS BEFORE

There are large gradients at some selected frequencies.
Recalculations of units and comparison with ground data will be necessary...
POD TEC, SFFT SPECTROGRAMS
PAPUA NEW-GUINEA 2016

3 DAYS BEFORE

JUST AFTER

3 DAYS AFTER

Tukey Window, Size 256 s.,

The same observations in POD TEC. The most evident separation of the signal at 30 s. frequency.

This was also visible in LP Ne signal
RESAMPLINGS

• close tracks from 9 days taken (similar longitudes and UTC time),
  passes separated by 3 or 5 days
  \( \Delta \varphi < 2^\circ, \Delta \lambda < 6^\circ, \Delta \text{UTC} < 0.9 \text{ h} \) from central pass just after the EQ (light green)

• Long wavelength signal removal by FFT,
  from selected band 200 s. to max. long-wavelength

• Frequencies - (resampling): different spacing for lower and higher frequencies:
  from 6 s. with step 2 s. to 80 s., and from 80 s. with step 20 s. to 260 s.

• Still large overlapping of windows – (neighbouring windows moved by 10 s.)

• WINDOW: Hamming Window 64 seconds (128 points from 2Hz data for LP),
  and 64 points for 1Hz POD TEC
RESAMPLED: LP, SFFT SPECTROGRAMS
PAPUA NEW-GUINEA 2016

11 DAYS BEFORE

EQ > 2016.12.17 10:51:12

11 DAYS BEFORE

8 DAYS BEFORE

6 DAYS BEFORE

There are signatures in LP signals on Dec 6th and Dec 9th of 2016, at frequencies between 12 s. and, say 80 s.

The region is seismologically very active. Aside from 7.9 EQ/tsunami on Dec 17th, there was also 7.8 EQ/tsunami on Dec 8th.
### EQs/Tsunami events in the southern Pacific (the largest)

<table>
<thead>
<tr>
<th>Date</th>
<th>Place, Region</th>
<th>Max. peak from TG (cm)</th>
<th>Max. peak Lat</th>
<th>Max. peak Lon</th>
<th>Max. peak Time (UTC)</th>
<th>Depth (km)</th>
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<tbody>
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<td>Loyalty Islands, Pacific</td>
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<td>-71.3535</td>
<td>20150917002400</td>
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</table>

There was also previous tsunami on Dec, 8th in the region.

These 2 EQs in December of 2016 induce tsunamis and are included in tsunami database, however there were significantly more Eqs, which will be shown later...
And resampled with smaller 64 s. window, clearly separated signal at 30 s. frequency just after the EQ on Dec 17th, 2016. The closer to EQs, the stronger power spectrum and better separation of frequencies can be noticed. These frequencies occupy band somewhere between 20 s. and 60 s.
This effect can be related with normal solar activity, but please note that its wavelength is large, around 200 s. in fast Swarm track.

Here, many frequencies are occupied but the amplitudes are weaker at frequencies higher than 200 s., so the signal differs from that in left panel (although TEC is larger).
RESAMPLED: POD TEC, SFFT SPECTROGRAMS
PAPUA NEW-GUINEA 2016
EQ > 2016.12.17  10:51:12

ROT, Swarm A, PRN 32
Signals below 200 s. removed, Hamming Window, Size 64 s.,
resampling of frequencies: in points [260:-20:80,80:-2:6]

Similar signatures in POD TEC signals on Dec 6th and Dec 9th of 2016, at frequencies between 12 s. and, say 80 s.

Still remember that aside from 7.9 EQ/tsunami on Dec 17th, there was also 7.8 EQ/tsunami on Dec 8th
These signals of lower frequency and smaller amplitude can be suspected to come from the edges of equatorial anomaly: to be checked!

And again, in POD TEC, the same clearly separated signal at 30 s. frequency just after the EQ on Dec 17th, 2016.
These signals of lower frequency and smaller amplitude can be suspected to come from the edges of equatorial anomaly: to be checked!

On Dec 25th, in POD TEC, we have aside from suspected solar effects, a separated signal of unknown origin. Its frequency appears to be higher than 30 s. ! Or there are two signals!

On Dec 28th, we see again separated strong signal at 30 s. frequency
The largest EQs (>= 6.0) in Papua NG region in December 2016 (far from total numer)

<table>
<thead>
<tr>
<th>Magnitude</th>
<th>Location</th>
<th>Date/Time</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.0</td>
<td>105km SE of Taron, Papua New Gui...</td>
<td>2016-12-24 01:32:16 (UTC)</td>
<td>35.0 km</td>
</tr>
<tr>
<td>6.0</td>
<td>114km WNW of Kirakira, Solomon Isl...</td>
<td>2016-12-20 12:33:14 (UTC)</td>
<td>20.0 km</td>
</tr>
<tr>
<td>6.4</td>
<td>81km WNW of Kirakira, Solomon Isl...</td>
<td>2016-12-26 04:21:29 (UTC)</td>
<td>20.0 km</td>
</tr>
<tr>
<td>6.3</td>
<td>168km SE of Taron, Papua New Gui...</td>
<td>2016-12-17 11:27:36 (UTC)</td>
<td>8.4 km</td>
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<tr>
<td>7.9</td>
<td>54km E of Taron, Papua New Guinea</td>
<td>2016-12-17 10:51:10 (UTC)</td>
<td>94.2 km</td>
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<tr>
<td>6.0</td>
<td>132km WNW of Arawa, Papua New ...</td>
<td>2016-12-16 24:34:34 (UTC)</td>
<td>142.6 km</td>
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<tr>
<td>6.9</td>
<td>92km WSW of Kirakira, Solomon Isl...</td>
<td>2016-12-09 19:10:08 (UTC)</td>
<td>19.7 km</td>
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<tr>
<td>6.9</td>
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<tr>
<td>7.8</td>
<td>69km WSW of Kirakira, Solomon Isl...</td>
<td>2016-12-08 17:38:46 (UTC)</td>
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</tr>
<tr>
<td>5.5</td>
<td>197km SM of Vaini, Tonga</td>
<td>2016-12-03 14:11:12 (UTC)</td>
<td>155.0 km</td>
</tr>
</tbody>
</table>

The amount of smaller EQs those days was significantly larger, and continuous during whole month...
Remaining EQs (≥ 5.4) in Papua NG region in December 2016 (far from total number)

- **5.4** 52km NE of Walaga, Papua New ... 2016-12-18 14:24:24 (UTC) 262.9 km
- **5.4** 164km SSE of Taron, Papua New ... 2016-12-27 20:39:04 (UTC) 48.9 km
- **5.4** 99km WNW of Kirakira, Solomon... 2016-12-27 02:50:24 (UTC) 45.6 km
- **5.3** 92km SE of Taron, Papua New Gu... 2016-12-24 03:58:34 (UTC) 36.9 km
- **6.0** 105km SE of Taron, Papua New ... 2016-12-24 01:32:16 (UTC) 35.9 km
- **5.5** 121km SE of Honiara, Solomon Isl... 2016-12-20 20:07:32 (UTC) 16.4 km
- **6.0** 114km WNW of Kirakira, Solomon... 2016-12-20 12:33:14 (UTC) 16.9 km
- **5.6** 158km SSE of Taron, Papua New Gu... 2016-12-20 08:14:44 (UTC) 16.0 km
- **6.4** 81km WNW of Kirakira, Solomon... 2016-12-20 04:21:29 (UTC) 26.9 km
- **5.4** 92km WNW of Panguna, Papua N... 2016-12-18 19:57:55 (UTC) 32.9 km
- **5.4** 125km E of Pangai, Tonga 2016-12-18 19:17:40 (UTC) 16.0 km
- **5.5** 205km W of Ile Hunter, New Cale... 2016-12-18 12:49:20 (UTC) 31.9 km

The examples of smaller EQs at the end of this seismologically active month and region (here EQs above 5.4)
Very preliminary ground GNSS data investigation

Differences of phase observations from nearby IGS stations will be used in the validation in future research. Some examples of ROT and TEC can be shown (GPS and GLONASS satellites)
Acknowledgements

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Leader: University of Warmia and Mazury in Olsztyn, Poland

Consortium members: NOA (Athens), TUM (Munich), UPC (Barcelona)

ESA Technical Officer: Roger Haagmans

Project name:  Contribution Of Swarm data to the prompt detection of Tsunamis and Other natural hazards (COSTO)
CONCLUSIONS...

- some signal at around 0.04 frequency (around 30 s. of Swarm track) repeats in many LP and POD TEC records close to EQs and just after EQs, whereas equatorial anomaly, usually is related with frequencies lower than 100 s. (only these are available everyday)

- LP Ne and POD TEC signals show very good integrity of the signals in spectral sense

- additional detrending and resampling must be made in order to find interesting frequencies more precisely (selected frequencies taken to analyses)

- more distant places, but quiet environment (tsunami response)

- different FFT windows?

- Interpretation referring to speeds of TIDs, recalculation of frequency units, relatively to Swarm and to ground observations. Comparison with ground GNSS.