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Rose Pearson
Technological University Dublin, C17330076@mytudublin.ie

Eugen Niculae
Technological University Dublin, eugen.niculae@tudublin.ie

Analysis of the Vertical Movement Of Active GNSS Stations As A Result Of Semidiurnal Tides

Rose PEARSON [1] rosepearson14@hotmail.com/ C17330076@mytudublin.ie, Eugen NICULAE.[1], eugen.niculae@TUDublin.ie

[1] Technological University Dublin, Bolton Street, Dublin 1, Ireland

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ABSTRACT

Ireland is subject to the constant effects and influence of semidiurnal tides. Western coastal regions are exposed to tidal ranges up to and exceeding five metres, consequentially introducing varied water volumes with temporal intervals. In addition, the Earth is elastic in composition, resulting in morphing and warping at the hands of celestial and oceanic forces.

This study looked at Online Precise Point Positioning (PPP) service to accurately monitor the vertical movement of coastal lands. In addition, GNSS Static Post-processing was conducted to discern which method of the global navigation satellite system (GNSS) processing is best for detecting VLM (vertical land motion). The study took place throughout 2020, focusing on the tidal peaks and troughs of the 21st of each month. Six-hour time windows were created around tidal peaks and troughs using data from the Marine Institute. GNSS data files replicating these time windows were processed using both PPP and manual network adjustment methods. MATLAB Online analysis aided in concluding the study.

Results were inconclusive in determining which method of GNSS processing were best for identifying VLM. Based on the evidence provided by this study, the influence of semidiurnal tidal peaks and troughs cannot be deemed significant in magnitude to require mitigation. Western Irish coastal zones are therefore not subjected to large scale VLM. Similar studies of coastal zones that experience tidal ranges exceeding five metres would be recommended. An extended study period would also be recommended to better understand semidiurnal tidal influences in Ireland.

1. INTRODUCTION

This project looked at the Earth dynamics effects on heights of coastal active GNSS stations as a consequence of semidiurnal tides. The authors aimed to:

- Determine whether semidiurnal tides have an influence over coastal vertical positions.
- Determine the magnitude of the semidiurnal tidal influences.
- Determine whether trends are present in semidiurnal tidal influences with respect to tidal maximum and minimum levels or periods of the year.

2. METHODOLOGY AND DATA PROCESSING

2.1 Tide Gauge Location and Data Acquisition

Tidal predictions were utilised for this study due to the availability of the data. Tidal predictions are approximated values to the water level, derived "from harmonic analysis of data measured at the tide gauges around the Irish coast" (Marine Institute, 2020), which form the Irish National Tide Gauge Network. Tidal predictions are available for download from the Marine Institute website (http://www.marine.ie/Home/site-area/data-services/marine-forecasts/tidal-predictions link accessed 20 October 2020).

Fenit tide gauge was selected to provide coverage over the susceptible southwest of Ireland (Quine, 2015). In addition, Sligo tide gauge and Galway Port tide gauge were added to the study to facilitate site dispersion and full western coverage.

2.2 Active GNSS Station Location and Data Acquisition

Active GNSS stations, part of the Irish Network of Continuously Operating Reference Stations (CORS), were utilised to monitor the vertical displacement resulting from semidiurnal tidal due to such data's inherent accuracy and reputation. Brown and Ogundare (2020) similarly used permanent GNSS stations to analyse the effects of Post Glacial Rebound (PGR), further affirming this data acquisition method.

Ordnance Survey Ireland (OSI), Ireland's national mapping agency, is responsible for maintaining a network of real-time kinematic GNSS stations. This network consists of a number of CORS stations that actively receive multi constellational GNSS transmissions. CORS stations facilitate the "collection of high precision positional data" (Quine, 2015), which is freely available for download to the public (https://www.osi.ie/services/geodetic-services/active-gnss-data/ link accessed 5 October 2020). In addition, the whole 24-hour period of the 21st day was downloaded in RINEX (Receiver Independent Exchange Format) to ensure tidal data correlation.

To correspond with the tide gauges selected above, Sligo (SLGO), Galway (GLW1) and Tralee (TRL2) CORS stations were selected for study (Figure 1). In addition, Portlaoise (PRT2) was also selected under the assumption this midland location would be unaffected by tidal influences. Therefore, PRT2 would act as the control station for the network adjustment.

2.3 Tide Gauge - CORS Relationship

Tide gauges and CORS stations are not coincident in this study. The tide gauges are located directly on the coast, while active GNSS receivers are installed inland on prominent buildings in the vicinity.

No tidal delay coefficient was applied as distances between tide gauges, and GNSS stations were less than 15 kilometres (Table 1).

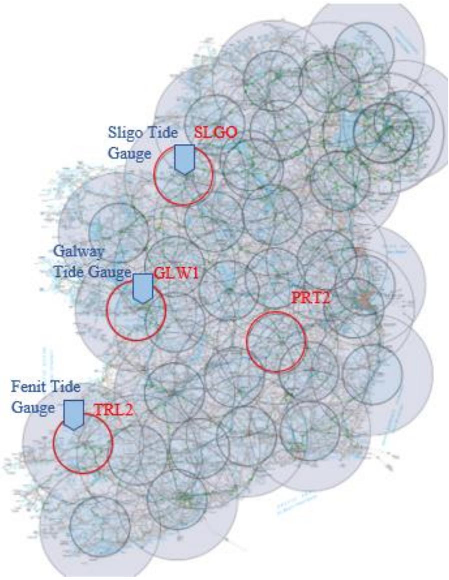

Figure 1. OSI CORS Network with stations and tide gauges (OSI, n.d. with author edits)

CORS Station	Tide Gauge	Distance (km)
Sligo (SLGO)	Sligo	8.70
Galway (GLW1)	Galway Port	1.55
Tralee (TRL2)	Fenit	13.12

Table 1. Straight-line distance between CORS stations and tide gauge

2.4 Selection of Study Day

For consistency of data collection, the 21st of each month was chosen. As tidal influence was the main concern, collecting data during a period of celestial prominence was imperative. Upon analysis of moon phases (https://www.timeanddate.com/moon/phases/@3230615?year=2020 link accessed 18 March 2021) for Sligo, Galway and Tralee – a substantial range of dates for the occurrence of New Moon and Full Moons were noted. Full moon occurrences fell within the range of the 1st to the 30th. The New moon had a shorter span of the 14th to the 24th day of the month. Thus, the 21st provided a tidal average.

2.5 Pre-Processing

Tidal data was segmented into six-hour windows, corresponding to 3 hours on either side of the tidal peak and trough on the 21st. If this occurrence took place within the first thirty minutes of the hour, the hour itself was taken. Any time after this was considered to be the following hour.

WinTEQC Editor desktop application provided the software solution behind time windowing GNSS data to create a single RINEX file containing six-hours of GNSS data for submission with the Canadian Spatial Reference System-Precise Point Positioning Service (CSRS-PPP).

This process was conducted for SLGO, GLW1 and TRL2 CORS stations for tidal peaks and troughs, ending with a total of 72 RINEX files.

2.6 PPP GNSS Processing and Post-Processing

CSRS-PPP online service was used for GNSS data. Users can immediately access the free, reliable services (Alkan et al., 2020) of the CSRS-PPP online service following email registration with Natural Resources Canada (NRCan). Compressed folders of results were returned via email within twenty-four hours of submittal. As GNSS data was obtained from a CORS station, 'Static' mode was selected for processing. Through selecting static, "one corrected averaged single point" (NRCan, 2020 B) was computed for each submitted RINEX file. The option of inserting an ocean tide loading file was withheld to prevent the effects of semidiurnal tides being dampened or cancelled out.

The International Terrestrial Reference Frame (ITRF) was selected as the data output spatial reference system. ITRF could be considered the "official scientific global spatial reference frame", according to Natural Resources Canada (2020 B). The version of ITRF utilised by CSRS-PPP has been "realised by the International GNSS Service (IGS) at the epoch for which the precise GNSS orbit ephemerides were computed" (NRCan, 2020 B). Through opting for ITRF, coordinates could be easily converted into the national spatial reference system of Ireland.

Single point averaged figures were sourced within the compressed files and stated in ITRF. ITRF ellipsoidal heights were transformed to ITM using the Grid InQuest II desktop application. The application provides seamless three-dimensional coordinate transformations between global and national coordinate systems across Great Britain and Ireland (OSI, 2018). Only vertical components were of interest to this study. ITRF input values were extracted from CSRS-PPP summary reports, compiled into Comma-Separated Value (.csv) file formats and transformed into Irish Transverse Mercator.

2.7 Static GNSS Network Adjustment

A network adjustment within Trimble Business Centre (TBC) was carried out to compute adjusted GNSS elevations tied to a fixed static point. Processed vectors are run through a least-squares adjustment to estimate and proportionally distribute any random errors present within the data, thus minimising their effects, to deliver a single adjusted solution. The network adjustment was computed iteratively on an automatic basis. A fixed point (PRT2), constrained in both two dimensions and elevation, is used to shift all other coordinates around by assigning control quality.

Raw RINEX files (time windowed as in 2.5) for GLW1, SLGO and TRL2 were imported, in addition to twenty-four hours of data gathered from PRT2. GNSS high tide and low tide data were imported separately to prevent the merging of results and consequential loss of tidal relevance.

The International GNSS Service (IGS) produce a number of orbit combination solutions, namely; ultra-rapid, rapid and final (IGS, n.d). Final orbit products corresponding to the day in question were imported into processing software. By employing final orbit products, the precision level of final GNSS coordinates could be significantly improved. Héroux & Kouba (2001) accredit the accuracy of IGS final orbits to the process by which they are captured, whereby IGS Analysis Centres (ACs) feed into the combined IGS product.

The GNSS network was adjusted using processed baselines from above. PRT2 was held to create a constrained network, allowing SLGO, GLW1 and TRL2 to shift relative to a fixed position. Network adjustment reports were reviewed. In some instances, scalars were applied to achieve the best fit. Adjusted grid coordinates were extracted from adjustment reports and compiled into an Excel spreadsheet. PPP processed results were added to facilitate direct monthly comparisons between the data. The Elevation value supplied by the OSI for Active Network Stations was appended to provide a standardised value

Average monthly GNSS elevations were obtained via PPP (2.6) and TBC network adjustments (2.7), as above. Excel charts provided the means for analysis. Deviations between PPP and TBC values were analysed.

2.8 MATLAB Online

Data analysis was carried out using MATLAB. MATLAB Online facilitates data investigation and analysis through an online platform, accessible through any web browser (Mathworks, n,d.).

A regression learner application was employed to identify models that best predict GNSS heights due to high and low tide occurrences over twelve months. The Regression Learner application enables users to "interactively train, validate, and tune regression models" (Mathworks, n.d. B). Thus, this application is ideal when the data type and subsequently the model type is unknown.

The application cycles through all possible models and trains each model to the data points supplied within the working dataset. An analysis of the root mean square error (RMSE), the model that forms the best predictor is easily identified. This exhaustive method of regression model training ensures the best predictor of the dataset was identified.

Curve fitting was conducted to identify any seasonal trends within the data, analysing high and low tides separately.
Research efforts of Brown & Ogundare (2020), were considered during the curve fitting of GNSS data influenced by the effects of tidal maximums and minimums in Ireland. Brown & Ogundare (2020) determined the effects of PGR on GNSS station "behaved like a sine wave" (Brown & Ogundare, 2020). This pattern was attributed to seasonal variation, reflected by the wavelength approximating to the length of a year.

On account of this finding, a sine wave was trialled to ascertain whether GNSS data influenced by the tide would conform to a sine wave. It was assumed GNSS stations in proximity to the coast would respond similarly to the effects of PGR through presenting movement along the vertical axis. PGR incurs rates of uplift dependent on the mass of displaced glacier. Semidiurnal tides incur pressure maximums and minimums along coastal regions due to varied water volumes. Tidal influenced uplift could therefore be expected to be cyclically represented.

Fourier model was also applied. A Fourier series contains terms of cosine and sine; thus, the possibility of a better fit was likely. R-Squared (coefficient of determination) and RMSE were compared to identify the model of best fit.

Autocorrelation Function (ACF) was applied using the '*autocorr(y)'* command. This plots the "sample autocorrelation function of the univariate, stochastic time series y with confidence bounds" (Mathworks, n.d C). 'y' corresponds to the GNSS elevation observed during high or low tide. The plots generated graphically represent the relationship between observations in a time series with observations taken at prior moments in time (Machine Learning Mastery, 2020).

Partial Autocorrelation Function (PACF) was conducted using the command' *parcorr(y)'*. PACF seeks to determine the correlation between an observation and its lag. This is at variance to the ACF, whereby a relationship between an observation and any other previously observed observation - both direct and indirect dependence is possible (Machine Learning Mastery, 2020).

The '*fitmethis'* command was used to create an interactive and numerical method of determining the best distribution fit to the GNSS elevation data. *Fitmethis* seeks out the "best-fitting distribution to data vector" and permits the selection of continuous or discrete distributions (Mathworks, n.d D). Results were analysed based on their Akaike Information Criterion (AIC). The AIC provides a method for model selection. When comparing the AIC values generated for models, Akaike's theory states that the most accurate model will have the lowest AIC (Mathworks, n.d E). Thus, the AIC determines the quality of models representing the data relative to each other. This makes the AIC an essential factor in optimal model selection.

3. CONCLUSIONS

No model exists to predict GNSS height to an acceptable standard through analysing the Regression Learner data. This has been proved through training all regression models available to the user in the MATLAB suite and analysing the results of the best predictor. The best models have been found to poorly represent GNSS elevations and cannot be used as a predictor for future values. The best level of fit achieved was in Galway at low tide with an R-Squared of 0.40. This indicates a fit of less than 50%, thus deeming it weak. Visual analysis of the Response, Observed versus Predicted, and Residual plots reinforced this. The use of the Regression Learner proved that GNSS elevations for a year might only be poorly predicted using regression models.

The sum of the sine model was trialled on the data to surmise how well it fitted to the GNSS tidal influenced data instead of PGR incurred motion. Relatively low R-Square and adjusted R-Square values manifested from the sine model on the research data. The Fourier model provided higher R-Square and adjusted R-Square values, indicating a better fit. Out of all curve fitting options available to the user in MATLAB Online, the Fourier series best represented the plot of data points for each location and tidal period. It must be noted that a twelve-month period of data was all that was available for analysis. Therefore, determining a trend within the data was not possible. Curve fitting with a more extended period of time would assist in identifying the possibility of seasonality within the data.

The following table summarises the presence or absence of both autocorrelation and partial autocorrelation. Combinational lags of ACF do not influence successive month's GNSS elevation values. Partial autocorrelation has been noted in the majority of plots, except for Tralee at high tide. Specific individual lags, therefore, have an influence over successive months. Consistent peaks at position six across most graphs are of interest. Overall, it is difficult to confidently say the significance of the identified partial autocorrelation over GNSS monthly elevations as no consistency is evident within twelve-month periods.

Occurrence	Autocorrelation	Partial Autocorrelation
Galway High Tide	No	Yes
Sligo High Tide	No	Yes
Tralee High Tide	No	No
Galway Low Tide	No	Yes
Sligo Low Tide	No	Yes
Tralee Low Tide	No	Yes

Table 2. Summary of Autocorrelation and Partial Autocorrelation Plots

No significant conclusion can be drawn from the data values to confidently state whether PPP or TBC is the more reliable method of processing. PPP values tended to follow a higher rate of consistency in terms of deviation from the published value. Deviations of TBC from published values tended to fluctuate at a higher rate. With this said, TBC values agreed with published values very satisfactorily in Sligo. This fit is seemingly unknown as the distance between Sligo's tide gauge; and consequently, the coast; lies 8.7km from the active station. On a proximity basis, it would be expected that Galway would demonstrate the largest trends as distance here is only 1.55km.

The VLM hypothesis based on the relationship between coastal water volumes and varying pressures on the land remains unknown. Tabulated below is a summary of derivation behaviours. Derived values equalling to those published are classed as a disagreement to the hypothesis as a clear increase/decrease in elevation as a result of water volume cannot be identified.

Occurrence	PPP Hypothesis Status	TBC Hypothesis Status
Galway High Tide	Agree	Agree
Sligo High Tide	Disagree	Disagree
Tralee High Tide	Agree	Agree
Galway Low Tide	Disagree	Disagree
Sligo Low Tide	Agree	Disagree
Tralee Low Tide	Disagree	Disagree

Table 3. Vertical Land Motion Hypothesis

No conclusive evidence is present to determine which processing method provides the best results as deviations are evident between both datasets. Neither method drastically disagrees with published values. Consistency is the only factor which can be drawn in to make a conclusion.

As a result of running the *'fitmethis'* command, the optimal distribution type could be identified. The AIC value was enlisted to identify the best distribution type. In each case, this was the Uniform distribution model. A goodness of fit script aided in assessing the quality of this fit. Values of *'h'* and *'p'* enabled the assessment of the hypothesis status. Therefore, the null hypothesis (H_0) can be accepted meaning that the data is uniformly distributed for each location and tidal occurrence.

With respect to predefined study aims:

- Semidiurnal tides have an influence over coastal vertical positions identified through deviation from the OSI published height value.
- A definitive magnitude of semidiurnal tidal influences could not be drawn due to disparities between PPP and network adjusted results.
- Trends adhering to a Fourier model best represent semidiurnal tidal influences with respect to tidal maximum and minimum levels along the west coast.

Conclusions drawn above could be substantially improved upon with a larger data range.

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