A new empirical tidal model for the Great Barrier Reef, Australia

Fardin Seifi[1], Xiaoli Deng[1] and Ole Baltazar Andersen[2]

[1] School of Engineering, Faculty of Engineering and Built Environment, the University of Newcastle, Australia, [2] DTU Space, Technical University of Denmark

E-mail: *Fardin.Seifi@uon.edu.au, Xiaoli.Deng@newcastle.edu.au and oa@space.dtu.dk*

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1. OUTLINE

The Great Barrier Reef (GBR) is the world's greatest reef system. Stretching more than 2 km along Queensland's north-east coasts, it is one of the most biologically diverse systems on earth. Resonant and near-resonant responses of the tidal waves and the non-linearity in dynamic equations promote the complexity of tidal analysis over coastal zones[1]. In comparison to the non-reef zones, reefs can exert a noticeable effect on the tides and other large-scale flows in certain parts of GBR which leads tidal behaviour in the region to be even more complicated [2].

In a Remove and Restore procedure the most recent FES model, FES2014, is used to detide satellite altimetry observations, including Topex, Jason1, Jason2, ERS2 and Envisat, over GBR. Analysing the residuals to extract tidal corrections for major constituents, extracting more influential constants in this area and expanding tidal constants using a depth dependant least squares collocations (LSC) method over a regular grid contributes to better performance of the new model in comparison to the base model, FES2014.

The new 2'*2' model covers the Australian north-eastern waters including the Great Barrier Reef, bounded by latitudes from -10° to -26° and longitudes from 142° to 156°.

2. DATA

Modelling

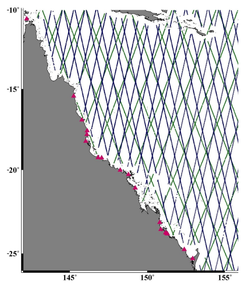

Fig. 1

Table 1
Tide-gauges* and satellite altimetry along track locations used in this study to extract tidal constants for modelling procedure (Fig. 1)

Symbol	▲	▲	▲	▲
Instrument	Tide gauge	T/P, J1 and J2	Envisat	ERS2
Time Span	1993 - 2015	1992 - 2016	2002 - 2010	1995 - 2010

* For tide gauges harmonic analysis is used to extract tidal constants

Table 2
Sentinel 3A along track locations used to assess model performance at tidal height prediction in validation part (Fig. 2)

Symbol	▲
Instrument	Sentinel 3A
Time Span	2016 - 2018

Validation

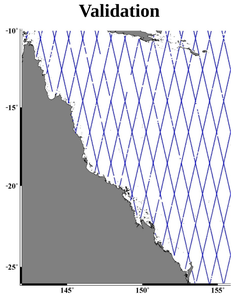

Fig. 2

- FES2014 is used as the base model for the Remove and Restore procedure.
- This model includes 34 tidal constituents, namely 2N2,EPS2,J1,K1,K2,L2,La2,M2,M3,M4, M6,M8,Mf,MKS2,Mm,MN4,MS4,MSf,MSqm,Mtm,Mu2,N2,N4,Nu2,O1,P1,Q1,R2,S1,S2,S4,Sa,Ssa,T2.
- FES2014 has a spatial resolution of 3.75' * 3.75'.
- According to analysis of the coastal tide gauges using harmonic method it was found that there are three more influential tidal constituents not included in FES2014 (e.g. OO1, SO1 and MK3).

3. GRIDDING

- There are considerable fluctuations in bottom topography over GBR. Due to the coral reefs and small islands, there are sudden changes in bathymetry from 100m to 1m.
- The tidal wavelength is related to bathymetry through [3]:

$$\Lambda = (gd)^{1/2}T \qquad (1)$$

Where Λ is tidal constituent wavelength, g is gravity acceleration, d is depth and T is tidal constituent period.

- The gridding method has to account for the variations in bathymetry over this area.
- Depth dependent least squares collocation approach is used to address this issue in spreading tidal constants on a regular grid.
- In LSC approach the covariance function which is dependent on both distance and tidal wavelength is formulated as [4]:

$$c(r,\Lambda) = C_0\left(1+\frac{r}{\alpha(\Lambda)}\right)e^{\left(-r/\alpha(\Lambda)\right)} \qquad (2)$$

Where r is the spatial distance, C_0 is the error variance and α is the correlation length where 50% correlation is obtained.

4. METHOD

Remove and Restore

Step 1

Tidal constants for 34 constituents implemented in FES2014 are interpolated over satellite along track locations shown in Fig.1.

Step 2

Time-series of sea level anomalies (that include ocean tides) observed by satellites, Table1 and Fig.1 , are detided using tidal height predicted by FES2014 and time-series of sea level anomaly residuals (SLARs) are calculated.

Step 3

Time-series of SLARs are analyzed using Response Method to extract tidal corrections of 8 major constituents (e.g. K1, O1, P1, Q1, M2, S2, N2 and K2). These corrections are applied to corresponding constituents of step 1.

Step 4

Time-series of SLARs are analyzed to extract tidal constants of OO1, SO1 and MK3 using harmonic analysis.

Step 5

Tidal constants of 37 constituents are spread over a regular grid of 2'*2' using LSC method.

5. NEW MODEL VS BASE MODEL

- SLAs from Sentinel 3A, Fig. 2 and Table 2, are detided by FES2014 and the new model. The RMS of the differences are calculated. The RMS values include both tidal residuals and possible unmodelled atmospheric effects. The geographical show of these RMSs is in Fig. 3.
- The geographic range, between latitudes from -19° to -23° and longitudes from 148° to 153°, due to highly variant bathymetry and existence of the coral reefs features the challenging area where tidal models show noticeable inaccuracies.
- New model shows tangible improvement over this challenging area in comparison to FES2014.

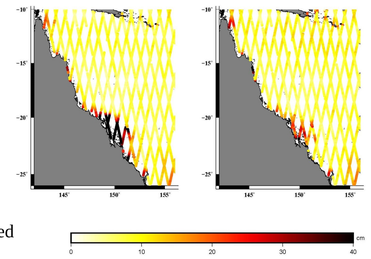

Fig. 3 The geographical view of the RMSs over Sentinel 3A along track locations for FES2014 (left) and New Model (Right)

Three different zones according to bathymetry is considered to assess the model performances numerically.

- The coastal zone with 0 m < depth < 50 m
- The shelf zone with 50 m < depth < 500 m.
- The deep ocean zone with depth > 500 m.

Table 3
The mean RMSs over different zones in cm

Model	FES2014	New Model
Coastal Zone	19.61	13.67
Shelf Zone	14.86	10.3
Ocean Zone	7.46	7.8

Fig. 4 provides a comparative idea about how the new model works with respect to the base model. The average improvement over challenging zone with highly varying bathymetry is more than 50%.

Table 4
The mean RMSs over challenging zone in cm

Model	FES2014	New Model
Challenging Zone	23.32	11.8

Over deep ocean zone the performance of the two models is fairly similar with FES2014 showing slightly better performance over a number of Sentinel 3A along track locations.

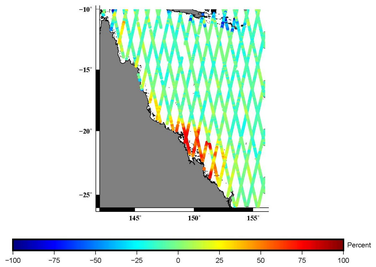

Fig. 4 Positive numbers stand for the better performance of New Model with respect to FES2014 and negative values vice versa.

6. NEW MODEL VS OTHER MODELS

- Five recent global models are taken to compare with the new model.

New Model (2') | DTU10 (7.5') | TPX08 (2') | FES2012 (3.75') | GOT 4.10(30') | EOT11a (7.5')

Table 5
The mean RMSs of SLARs over Sentinel 3A along track locations in different zones. Values are in cm.

Model	Coastal Zone	Shelf Zone	Ocean Zone	Challenging Zone
New Model	13.67	10.3	7.8	11.8
FES2012	10.6	8.00	7.75	9.07
TPX08	14.42	9.65	7.96	13.03
DTU10	13.41	9.7	7.92	12.6
GOT 4.10	14.75	12.07	7.85	16.17
EOT11a	26.5	16.62	9.84	24.5

- Together with TPX08 and DTU10 the new model stand closely behind FES2012.
- This model compares more favourable FES2014 over coastal and shelf zone in with a more spatial resolution.
- From Fig. 5, it can be said that the slightly better performance of FES2012 compared to the new model still resides over challenging zone.

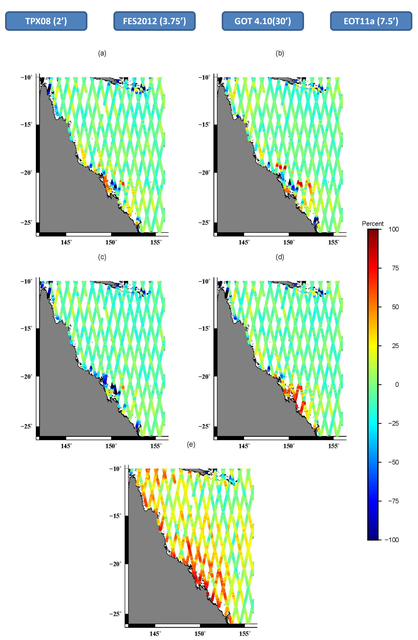

Fig. 5 Performance of the new model in tidal height prediction with respect to (a) DTU10, (b) TPX08, (c) FES2012, (d) GOT 4.10 and (e) EOT11a.

7. DISCUSSION

- To apply a Weighted Means method in order to spread tidal constants over a regular grid leads the model to perform less efficient than when a LSC approach is used. In a numerical sense the mean RMSs over Sentinel-3A along track locations when Weighted Means approach is used will be ~4 cm more than that of a LSC approach.
- Adding three more shallow water constituents, i.e. MK3, OO1 and SO1, improves the mean RMSs over coastal zone about ~ 1cm.
- Adding tidal constant corrections for the 8 major constituents improve the prediction ability of the new model more than ~ 3cm and ~1cm of mean RMS over costal and shelf zones respectively.
- Due to atmospheric effects the SLARs of Sentinel-3A observations are not merely tidal residuals therefore, obviously the performance of the models and certainly new model in tidal height prediction is even better than what has been achieved in this study.
- A massive 50% improvement of the new model compared to FES2014 over challenging zone, implies on the efficiency of the steps taken to improve FES2014.

8. REFERENCES

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