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A Review of Current Development of Altimetry Technique for Tidal and Water Level Measurement Practices and Its Relevance to Energy Industry Applications

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Abstract. With massive geospatial coverage and adequate time series of sea surface height, spatio-temporal multi-mission satellite altimetry tidal modelling emerges as a profound potential solution for increasing accuracy and minimising variation across multiple offshore applications. Therefore, this article attempts to review the current implementation of satellite altimetry in the applicable area of studies relevant to conventional oil and gas applications toward sustainable energy applications. The implication of current spatio-temporal enhancement of tidal measurement by satellite altimetry at the coastal area and the offshore zone is discussed mainly to elaborate on current achievement as well as to gauge potential future optimisation for offshore applications in the energy industry. Spatio-temporal enhancement in conventional oil and gas field applications improves the integration of various offshore construction applications. The impact of this application is more significant as engineering construction adopts stringent and higher vertical data accuracy acceptance criteria. More comprehensive spatial information coverage of tidal regime, co-tidal range, the offshore co-tidal pattern should be more accessible by more intensive spatio-temporal enhancement attempts in various studies and implementations. This leads to higher reliability and integrity of offshore vertical references derivation.

1. Introduction

Various onshore and offshore services in diverse types of operations for energy provision rely on sea level measurement as standard practice to provide vertical reference levels. These activities are generally classified into upstream and downstream cycles in the conventional oil and gas industry. The upstream cycle mainly consists of the exploration, development, and production stage. Vertical reference by sea level measurement has always been a critical element for presenting the various type of survey data. The importance contributes to many aspects. It covers but is not limited to exploration data integrity, the safety aspect of navigation and operation, structural engineering integration of offshore facilities, production asset subsidence and integrity monitoring, hydrocarbon reservoir depletion monitoring. At a national level, sea level measurement has been an important component in defining national height systems [2]. The spatio-temporal enhancement of the sea level measurement will optimise vertical reference accuracy and integrity for various survey activities.

In the attempts to increase the density of estimating sea level, especially at deeper offshore areas, apart from coastal regions, various observation techniques have been developed to meet the standard accuracy requirement. Sea level measurement by tide gauges have been commonly carried out along the coastline. Meanwhile either bottom pressure recorder (BPR) or tide gauges has been commonly used to measure water level inland. As consequence, the understanding of global deep-sea surface and tides characteristic remained largely unrevealed. The emergence of satellite altimetry has been a breakthrough toward the global deep-sea surface and tides observation simplification. Furthermore, it has been a significant achievement leap in term of its massive spatio-temporal coverage advantage along with its impressive accuracy improvement over time. The spatio-temporal advantage refers to the extensive global ocean area coverage and the large time series coverage of global ocean surface observation sampling. Upgrade, enhancement and improvement in orbit determination precision, propagation media, gravity and other force modelling, geophysical corrections are fundamental enhancements that increase the accuracy of satellite altimetry measurement since experimental era to modern era [17]. Despite its limitation, the previous study concludes that in-situ sea level observation through tide gauges remain the best approach for long-term coastal sea level study, while for contemporary and regional scale's objective, satellite altimetry is more suitable. A comprehensive integration of sea level observation system at offshore deep ocean and coastal areas requires densification of tide gauges or other in-situ systems distribution at sparsely covered regions [2]. Various operational constraints of in-situ system deployment have strategically positioned satellite altimetry, and other remote sensing approaches as a profound solution to fulfil the gaps. However, assessing the accuracy and reliability of the satellite altimetry approach still requires further elaboration, especially in the offshore deep-water area.

1.1. Sea Surface Height Measurement by Satellite Altimetry

Tide gauges records as the primary data sources for tidal modelling before the launch of satellite altimetry had been commonly established in the coastal region for navigation and safety purposes. Due to its limitation on spareness and the locations which are mainly along the coast, tide gauge measurement provides limited knowledge on the open sea or offshore spatial characteristics of tides [17]. Compared to tide gauges, satellite altimetry measures sea surface height for monitoring global sea level variation and ocean tides in general. However, it has an approximate weekly (or longer) temporal sampling rate at specific fixed locations on the Earth due to the orbital design of the so-called Exact Repeat Orbits for satellite altimetry. Satellite altimetry advantage and difference compared to traditional tide gauges lies in its spatial and temporal characteristics. By satellite altimetry, sea level measurements are acquired globally.

By the emergence of satellite altimetry, the capability to observe water level changes of the sea, river, and lake has significantly improved with acceptable accuracy [14]. In principle, the measurement of the sea surface is calculated through the travel time taken by the radar signal that returns to the satellite receiver. Based on that, the water level is then derived relative to a fixed reference frame along with the satellite's altitude [17]. Markert et al. [14] conclude that although altimetry was intended primarily for ocean and ice characteristic investigation, it has been effectively deployed to monitor inland water bodies as well. Studies have shown how sea surface periodical elevation variations can be extensively monitored by the results derived from satellite altimetry. This provides indispensable information in the regions with sparse data. Various spatio-temporal enhancement of water level measurements, especially the ones by satellite altimetry approach, triggers attention on potential best practice adoptions in the relevant implementation in the energy industry.

1.2. Satellite Altimetry Estimated Accuracy and Data Verification

Sea level measurement accuracy is one of the essential elements to be reviewed and assessed prior to adoption and implementation to various areas of operation. In the beginning, when satellite altimetry was launched in 1993, TOPEX/Poseidon altimetry mission achieved a new level of accuracy in the absolute sea-level measurement of global oceans with an enhanced temporal resolution of several days to roughly a month. The ability to compute accurate orbits of the satellite altimetry, the confidence level of terrestrial reference frame as well as the knowledge of altimetry instrument biases are essential to quantify the accuracy of sea-level measurements. Since its initial presence, satellite altimetry has been evolving as a fundamental solution to various actual problems in marine geodesy, oceanography, and global climate change studies. Many outcomes are also relevant to solving various engineering objectives in energy supply activities. To date, many advancements have been developed through an abundance of satellite altimetry missions that make solutions to various complex problems feasible [15].

Table 1. Estimated accuracy of absolute sea level measurements in its experimental era (Geos-3, Seasat and Geosat) in the 1970s and 1980s up until the early decade of its modern era (ERS-1, TOPEX/Poseidon) in 1990s (adapted from [15]).

	Geos-3	Seasat	Geosat	ERS-1	TOPEX/ Poseidon
Altimeter					
Instrument Noise	50cm	10cm	5cm	3cm	<2cm
Bias Uncertainty	-	7cm	5cm	3-5cm	3cm
Time Bias	-	5ms	3-5ms	1-2ms	<1ms
EM Bias	10cm	5cm	2cm	2cm	<2cm
Skewness	2cm	1cm	1cm	1cm	1cm
Dry Troposphere	2cm	2cm	1cm	1cm	1cm
Wet Troposphere	15cm	3cm	4cm	1.2cm	1.2cm
Ionosphere	2-3cm	2-3cm	2-3cm	2-3cm	1.3cm (2cm)
Orbit	30-50cm	30cm	20cm	18cm	3.5cm
Root-sum-squared error	67cm	33cm	22cm	19cm	<5cm

Table 1 summarised several satellite altimetry missions estimated accuracies of absolute sea-level measurements in the early decade of its experimental and modern era. The sea level measurements here are referred to as a reference ellipsoid, where the orbits are computed and defined in the absolute terrestrial reference system. From the table, Shum et al. [15] concluded that the uncertainty of the satellite's instantaneous radial position with respect to the centre of earth mass is a predominant error of source. Progressively the system has been improving, reaching the operational life span of 28 years in 2021. Five yearly, periodical international symposium has been the forum where the community commemorate the advancement of radar altimetry. It extends the yearly Ocean Surface Topography Science Team meetings. These meetings bring together international scientists to understand Earth's oceans and their interaction with the climate system using ocean altimetry satellite observations. The 15th and 20th years of progress meetings were held in Venice, Italy, in the years 2006 and 2012. Lastly, the 25 Years of Progress in Radar Altimetry Symposium was held in Ponta Delgada, Azores, Portugal, in 2018.

Figure 1 demonstrates (1) experimental era, (2) modern era, and (3) future era of satellite altimetry development. The figure describes the timeline overview of the altimeter satellite missions, orbit repetition period and the origin country of the satellite missions [31].

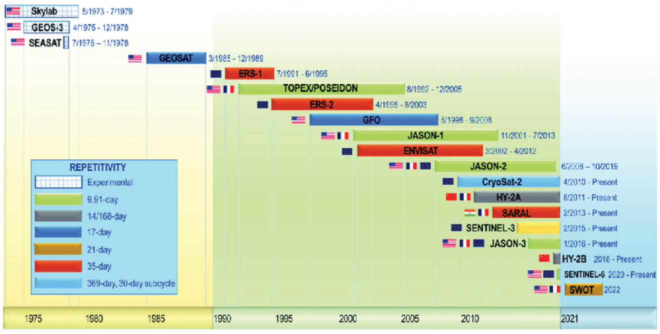

Figure 1. Satellite altimetry mission timeline (experimental era (yellow), modern era (green), and future altimetry era (blue)), orbit repetition and its country of origin [31].

Figure 2 demonstrate tremendous satellite altimetry error improvement from Geos-3 (Geodynamics and Earth Ocean Satellite), which was launched in 1975 (experimental era), up to Sentinel-6 was launched in 2020 (modern era).

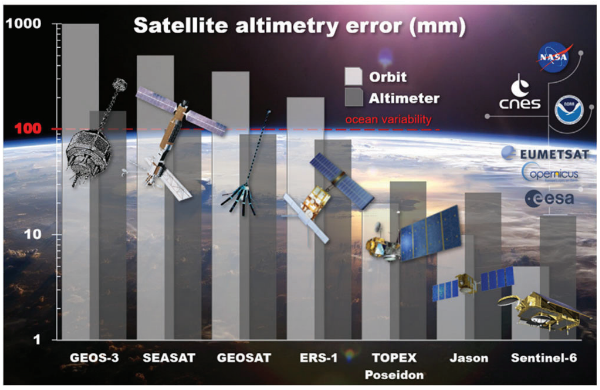

Figure 2. The improvement of satellite altimetry error (altimeter and orbit) in mm [6].

About sea surface observation accuracy assessment, Hamid et al. [20], examined sea level anomaly correlation between multi-mission of satellite altimetry over 1993–2015 with Malaysian coastal tide gauges. Radar Altimetry Database System (RADS) comprises 8 satellite altimetry missions are utilised to determine sea level anomalies (SLA). Tidal measurements from eight tide gauge stations around the west and east Malaysia are utilised for altimetry SLA assessment. The correlation coefficient indicator is using R^2 and Root Mean Square Error (RMSE). As shown in Figure 3, a strong correlation and similar pattern between SLAs from altimetry and tide gauge at the same time interval are observed. R^2 indicates value > 0.9 and RMSE value range from 3.12 cm to 4.76 cm, which is relatively very small and indicates good agreement [20]. RMSE at that value reflects adequate precision and feasibility for oil and gas construction engineering applications.

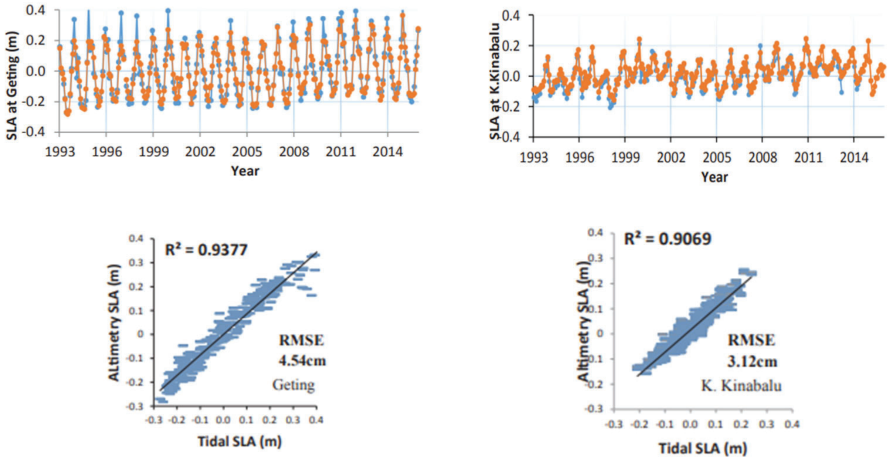

Figure 3. Sample of SLA time series comparison between satellite altimetry data and tide gauge station at Getting and Kota Kinabalu [20]

2. Estimating Water Level

Estimating water level offshore, coastal or inland water bodies is commonly practised to determine water depth, water volume information, safe navigation aid, and many other applications. Various applications require vertical measurement data as a primary deliverable as well as to serve and support engineering project objectives that utilise vertical measurement data as critical data input. The water level is handled and computed with a reliable methodology to obtain a consistent vertical reference or vertical datum. Despite the various varieties of the methodology and approach, the vertical reference should be consistent as a common reference for measured vertical data. The selected approach should be adopted by awareness of the expected accuracy to suit specific project objectives and technical criteria.

All coordinate reference systems are built upon a datum. Vertical and engineering datums are most relevant to discussing the vertical references used for subsurface data in the oil and gas industry [16]. In geodesy, the vertical datum is often chosen as Mean Sea Level (MSL) at one or more points and the reference surface extended across the continents from this datum point. Mean Sea Level as vertical datum is computed from tide measurements. Two common vertical coordinate reference systems are MSL height (height above Mean Sea Level), defined in a unit of measure with a positive up direction and MSL depth (depth below Mean Sea Level), defined in a unit of measure with a positive down direction.

2.1. Monitoring Water Level and Discharges using Satellite Altimetry in Inland area

Initially designed for sea surface topography accurate measurements, satellite altimetry is also commonly utilized to continuously observe inland water levels. This capability nurtures the opportunity to solve the actual onshore oil and gas facility maintenance issues, which requires a comprehensive understanding of accurate water body behaviour. Oil and gas onshore facilities such as pipeline assets, oil and gas processing terminal, onshore receiving facility, and refinery may experience suffering due to their prone location to the occurrence of flood. In the situational scenario, flood modelling can be generated to understand water network and streamflow behaviour for accurate mitigation planning and development. The mitigation is essential to anticipate structural and geotechnical issues of the facilities due to flooding. Flood modelling requires accurate monitoring of inland water bodies such as dams, lakes and interconnected river networks in the vicinity of the facilities.

Referring to a previous study by Bogning et al. [3], satellite altimetry is commonly employed for monitoring water levels in large river basins. The study took place in Gabon, Central Africa, utilizing data from seven altimetry missions since 1995 to 2017, which consist of ERS-2, ENVISAT, Jason-2 and Jason-3, Cryosat-2, SARAL, Sentinel-3A [3]. Water level and discharges were examined through comparison with inland water level gauge station records. The performance of all missions exhibits good agreement with gauge results. More accurate annual discharge was observed by the increase of data sampling in river basin indicated by 0.03 % difference between altimetry-based approach and the in-situ average yearly discharge calculation result [3].

Currently, there are thirteen satellite altimetry missions that consist of ERS-1/2, Geosat, GFO, Cryosat-2, TOPEX/Poseidon, HY-2A, Saral/Altika, Envisat, and Sentinel-3 A and B, and Jason 1/2/3, [19]. Satellite altimetry missions are continually progressing by the launch of Jason-CS A in 2020 and scheduled to be followed by Jason-CS B in 2026. Sentinel 3 C and D was scheduled for 2021 and post-2021. Surface Water and Ocean Topography using the low incidence of Synthetic Aperture Radar (SAR) interferometry techniques is aimed to be the initial mission to obtain elevation maps beyond 2022. Besides that, there is the Global Ecosystem Dynamics Investigation (GEDI) Light Detection and Ranging (LiDAR) altimetry mission, which was launched in December 2018. GEDI LiDAR altimetry is the recent satellite laser altimeter which came with a small footprint and highly densified sampling to measure and monitor small inland water bodies. Loomis et al. [18] assessed the accuracy of the GEDI LiDAR altimetry estimation of lake water levels. By taking instrumental and environmental factors into account, the study found the increased accuracy (RMSE) of GEDI estimated to be 8.4 cm for all assessed lakes. When the errors for each lake was modelled individually, the computed accuracy is ranged between 5.6 cm and 10 cm (with no apparent bias)[19].

2.2. Estimating sea level rise

Estimated sea level rise is used as the basis for oil and gas field facility both offshore and nearshore operability analysis. By reliable methodology, the previous research found that the Global Mean Sea Level rose at a relatively minimum magnitude, especially if it was relatively compared with oil and gas application acceptance criteria. Tide gauge observations indicate that the global mean sea level rose at an average rate of ~1.7 mm/yr since 1950 [38] [39] [40]. Satellite altimetry reports faster global mean sea level rise since 1993, of 3.3+/−0.4 mm/yr [41][42][43]. However, particularly at western tropical Pacific region, sea level rose at a rate up to 3–4 times larger than the global average from the year of 1993 up to 2010 [45][42]. A recent study by Hamid et al [20] concluded that Malaysia sea level rise trends range from 3.27 ± 0.12 mm/yr off eastern Malaysia to 4.95 ± 0.15 mm/yr west of Malaysia (see Figure 4). Over the period of the year 1993 up to 2015, the average of Malaysian sea level rise is 4.22 ± 0.12mm/yr. The cumulative sea level rise is 0.05 m over the same period [20].

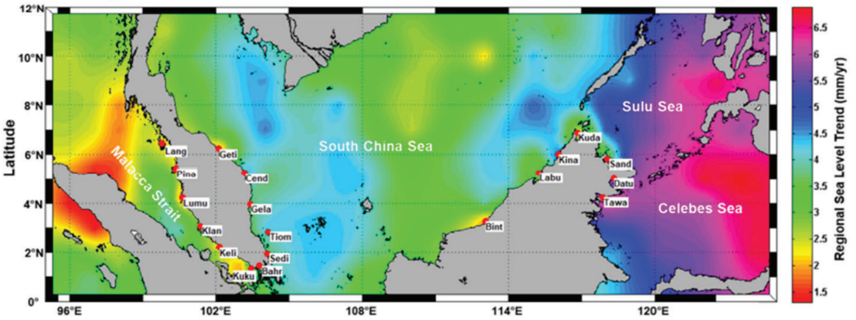

Figure 4. Map of regional sea level trend over the Malaysian seas from multi-SALT and absolute coastal T.G.s. The trend is calculated over 19 years of data from 1993 to 2011. The red dots are T.G. stations and the unit are in mm/yr [4].

The energy industry, specifically the oil and gas sector, manages both onshore and offshore operational facilities and assets across the region. The operational oil and gas field requires continuous observation of the established facilities to ensure the operability and sustainability of the assets for achieving the oil and gas lifting target during its estimated life span. It is fundamental to understand the sea level behaviour and the ocean where most of the assets are located, specifically anticipating and mitigating potential operational safety and structural integrity issues due to sea level rise.

Din et al. [4] estimated more than 19 years sea level trends based on a combination of multiple sensor techniques in Malaysian regions. Satellite altimetry and tide gauges distributed along Malaysian coastal line were used to derive sea level changes relative to vertical land motion. Absolute sea levels were derived from satellite altimetry. The rate of relative sea levels was derived from tide gauge stations along the coast of Malaysia corrected with the vertical land motion value of the position where the tide gauges are located. The result exhibited regional sea level trends stretch from 2.65±0.86mm/yr to 6.03 ± 0.79 mm/yr for selected areas with an overall mean increase of 4.47±0.71mm/yr [4]. The study also concluded that in any circumstance the GNSS station is not available to indicate vertical land motion, then the magnitude of monthly differences in satellite altimetry result and tide gauge data could be sufficient and reliable enough to gain some comprehension of vertical land motion characteristic at particular areas [4]. It reflects the consistent accuracy of both satellite altimetry and in-situ tide gauge so that the difference can be used to understand the vertical land motion element. The study conclusion is valuable as an input parameter of front-end engineering and geohazard assessment of offshore oil and gas fields to anticipate and estimate potential environmental issues.

3. Altimetry in offshore oil and gas field exploration phase

Exploration works such as towed marine seismic, ocean bottom seismic, geochemical survey, gravity magnetic survey are examples of offshore application that relatively has more lenient requirements of expected positioning accuracy allowance compared to offshore engineering construction work in the development phase. Vertical reference surfaces such as MSL are used in the exploration project prospect area. The variation of the instantaneous sea surface relative to MSL is often neglected, given that it is insignificant in relation to other much larger uncertainties in the seismic process [16]. Vertical positioning data from the towed marine seismic operation is reduced to vertical datum derived from the nearest tide gauge harmonic constant or opted from on-site GNSS tide derivation. The use of sea surface observation carries more contribution in gravity magnetic survey. The geoid that is derived from Mean Sea Level calculation from sea surface observation is then used as a fundamental component to compute and measure field gravity. Marine gravity anomalies play essential role in offshore explorations for understanding subsurface such as understanding crustal structures and tectonics study [7].

3.1. Satellite altimetry-derived marine gravity anomaly mapping for exploration

Nguyen et al. [7] presented a gravity anomalies estimation approach from high-resolution grid of Saral/AltiKa and Cryosat-2 satellite altimetry data. The study took place and focused on the Gulf of Tonkin, Vietnam. This study utilized 6842 sea surface height (SSH) grid points from Cryosat-2, 8823 SSH grid points from Saral/AltiKa, GPS/levelling data, 31 tide gauge station records. The validation result indicates good accuracy as the calculated standard deviation between the 56,978 marine gravity checked points measured by boat and satellite altimetry-derived gravity anomalies show the value of ± 3.36mGal. The accuracy of satellite altimetry-derived marine gravity anomaly was then also further improved to ± 2.63mGal by incorporating the ship-measured gravity anomalies in the derivation calculation. The conclusion of this research gives confidence on further implementation in various geoscience, geodetic, geophysical application especially in the coastal zone.

Nguyen et al. [7] used the remove-restore technique and crossover adjustment algorithm to remove mean dynamic topography, long-wavelength geoid height and time-varying sea surface topography. Then only by the least-squares collocation method, the residual geoid heights were used to obtain the residual gravity anomalies. Earth geopotential model was used to restore the long-wavelength gravity anomalies. The selection of the earth geopotential model (EIGEN6C4 model) and mean dynamic topography model (DTU15MDT model) were based on assessment results to GPS/levelling and 31 tidal station records [7].

In hydrocarbon exploration, gravity anomaly is an essential component of exploration methodology that is known as gravity and magnetic survey. Grandis et al. [8], in the gravity and magnetic for hydrocarbon and geothermal exploration article, stated even though seismic remains the primary method for exploring hydrocarbon prospects, the use of gravity and magnetic methods remains essential to comprehend understanding geophysical attributes and basin delineation at a regional scale of hydrocarbon exploration prospect area prior seismic detailing [8]. Gravity and magnetic methodology, as a relatively inexpensive approach, is rationally executed to detail out seismic exploration program and to support the study of existing seismic data. At the very broad regional scale, the gravity data derived either from satellite altimetry or earth gravity model is available from repositories such as Bureau Gravimétrique International or BGI (http://bgi.omp.obsmip.fr) and others [8].

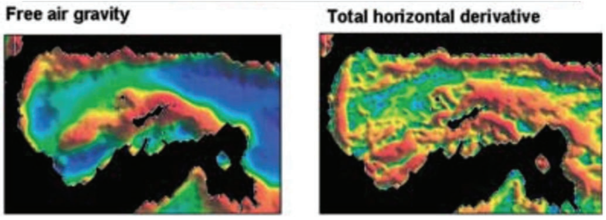

Figure 5. Nearshore improved gravity data from satellite altimetry [30]

3.2. Marine geoid assessment by satellite altimetry

For the geodesist, the marine geoid is part of the global geoid. The usual procedure of using tide gauge values as a condition in the levelling adjustment rests on the proposition of regarding the local water levels as parts of the so-called "mean sea level," which is roughly equated with an equipotential surface, specifically the geoid, as the zero references of the continental vertical datum. This proposition is acceptable under crude accuracy standards [32].

As marine geoid is an essential component of non-conventional gravity survey in oil and gas exploration, the study by Wang et al. [27] about marine geoid assessment by satellite altimetry becomes relevant to generate an understanding of how a feasible altimetry approach can be potentially adopted in common oil and gas exploration process flow. Wang et al. [28] processed satellite altimetry data to infer vertical deflection and gravity anomaly. The satellite altimetry processing result, together with the Gravity field and steady-state Ocean Circulation Explorer (GOCE) and gravity potential model (GGPM), are used to evaluate Chinese coastal marine geoids (CMG). The results indicate that CMG from molodensky method by using vertical deflection data has the highest precision. Satellite altimetry result indicates good consistency with CMG and GGPM. The study concludes that the processing result from satellite altimetry levelling is feasible as a new method for assessing marine geoid as the standard deviation between marine geoids result obtained through altimetry levelling and through different methods (the Molodensky method, least-squares collocation, Stokes formula, two-dimensional spherical fast Fourier transformation) range of 0.163 m - 0.307 m [27].

4. Altimetry in offshore oil and gas field development phase

Conventionally, vertical reference is established by on-site tide measurement. Several different methods come with an error budget to be estimated based on project acceptance criteria. Offshore construction structural installation commonly uses 39 hours Doodson Filtering method due to the limited time window of the typical operation. The installation as part of construction activities includes but is not limited to platform, pipeline and subsea facilities. The complexity of various operational and technical element integration in oil and gas field development frequently hampers the ideal conceptual implementation aiming for reliable vertical reference provision. In offshore construction integration and installation activities, more accurate and consistent vertical data is required. As discussed earlier, short term 39 hours tides observation with the Doodson Filtering method is commonly adopted. According to Hydrographic Quality Assurance Instructions for Admiralty Survey 2004 Reference from UK Hydrographic Office, calculation of Mean Sea Level (MSL) using this 39 hours of observation is typically conducted at least in the beginning and at the end of the survey. In many cases, the observation is also conducted continuously every 39 hours during the operation. Due to daily atmospheric and weather influences, the result should be within 0.3 meters of MSL quoted in the tide tables. Users manage their expectations and confidence level by utilising this 39 hours Doodson filtering method to achieve specific project technical objectives and acceptance criteria. The Doodson filtering method is commonly adopted to compute in-situ vertical reference derivation, i.e. MSL in offshore platform installation, as shown in Figures 6 to 8. The computed vertical reference then will be used to reduce each deck's elevation as official platform as-built elevations. The study case at Bitung waters, Indonesia, found that the variation of Mean Sea Level (MSL) derived from Doodson Filter method and Monthly MSL derived from admiralty method within one year period of observation time is up to 0.3m [33]. A similar study case at Tanjung Emas Semarang, Indonesia, has shown the variation magnitude of 0.15m between the Doodson Filter and Admiralty methods [34]. The variation and expected errors are even more obvious in offshore applications that use a vertical reference from computed tidal prediction derived from harmonic constituents of nearest available tide gauges, mostly located at the coastal area and, in many cases, are too far from the intended survey location. This variation, in many cases, is not well expected and estimated in offshore structural designs.

Figure 6. Offshore platform jacket installation in oil and gas field development phase

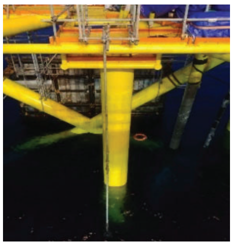

Figure 7. 39 hours Doodson Filter tide measurement method

Figure 8. Offshore topside installation in oil and gas development phase

In the oil and gas development phase, the hydrographic survey is the work scope that is normally executed independently or as an integrated part of geohazard assessment. Geohazard survey of the offshore field, which will be conducted based on finalised location layout in FEED (Front End Engineering Design), is critical as the fundamental risk assessment of the proposed field layout design. The activity will serve as geohazard analysis for construction design as well as for safety assurance of drilling rig emplacement. Drilling operation at the development phase is normally done following successful confirmation of oil and gas reserve discovery from the exploration cycle. Hydrographic survey to measure physical features under seabed is essential for detailed offshore construction planning, safe navigational aids, dredging and marine construction works. The water depth information resulting from the preliminary hydrographic survey at the area of interest is commonly adopted for further offshore structure detail design and fabrication. Therefore, seabed data and water depth data quality reduced to reliable vertical reference are essential to ensure structural installation and integration in the subsequent stage. Therefore, improving the common practice of sea surface measurement by utilising spatio-temporal advantage of satellite altimetry data is significant to increase the consistency and reliability of vertical reference derivation by accurate tidal modelling. As accurate water depth is critical information for commencing structural design and structural fabrication works, therefore the adopted concept, methodology and execution supervision during the activities in which the water depth information will be derived is essential. Those activities include but are not limited to preliminary geohazard site investigation and pre-installation survey operations.

The modernisation concept of bathymetric measurement introduced by Hamden et al. [5], known as the ellipsoidal referenced surveying technique, was practised in various hydrographic surveys serving oil and gas applications. The modernisation of bathymetry measurement is introduced by utilising GNSS on providing the value of the ellipsoidal height of the water level. Instead of referring to conventional tidal measurement, hydrography in shallow geohazard geophysical survey for oil and gas field development commonly utilises the vertical reference provided by the GNSS tide service due to its simplicity. GNSS tides service reduced the vertical data to computed 39 hours GNSS tidal data filtering (moving average) for vertical datum calculation or opted to use the geoid model (local or global) to represent mean sea level approximation. With regard to satellite altimetry, there are several altimetry-based vertical separation models generated for commercial tide service (e.g., DTU Mean Sea Surface (MSS) model, geoid model product). In some countries which successfully developed high accuracy satellite altimetry-based local geoid models, the authority may require the local geoid model to be embedded in any hydrographic survey service provided within the country. Some examples of a high accuracy separation model implemented in some countries are Australian AUSHYDROID, UKHO VROF, North Sea state BLAST, and US Vdatum [25][28]. Toward the development of the Malaysian vertical separation model, Hamden et al. [26] demonstrate the mean sea surface model of Malaysia in Figure 9.

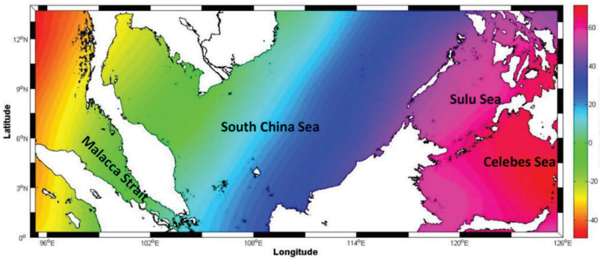

Figure 9. Mean Sea Surface Model for Malaysian Seas from 1993- 2017 [26]

As both the altimetry approach and hydrographic survey refer to GNSS ellipsoidal reference, the correlation between the two is made possible, especially to derive the level of water surface data to reliable vertical datum through altimetry tidal datum modelling [5]. This concept will achieve a higher stage of practicality if the tidal datum modelling is translated into the increased number of successful establishments of separation model to determine high accuracy geoid which is equated as Mean Sea Level. The separation model is one of the essential components in the ellipsoidal referenced survey concept for vertical datum transformation. For applications that require less stringent accuracy and less criticality for vertical data integration, the less accurate global geoid model is still preferably used in the absence of offshore on-side tide station or the absence of high accuracy local geoid model at the remote area of survey. However, by lack of awareness, the result is frequently misused and interchanged in the application area that requires high accuracy of vertical data.

Figure 10 shows the conceptual model of bathymetric measurement introduced by Hamden et al. [5]. Vertical reference for vertical data (e.g., water depth) reduction represented by modelled global MSS or geoid in commercial GNSS tide service in common oil and gas operation implementation is replaced by detailed conceptual derivation of level surface consisting of the mean sea surface, mean dynamic topography and marine geoid from satellite altimetry at a specified area of interest. Tide gauge data is assimilated with satellite altimetry data.

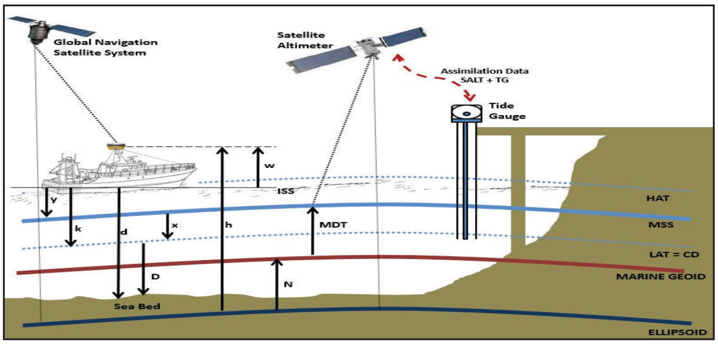

Figure 10. A Conceptual Model for Hydrographic Surveying Modernization using GNSS [5]

In order to produce bathymetry sounding depth (D) based on the chart datum (CD) reference surface to the seabed, (1) instantaneous sea surface (ISS) is to be reduced to CD, (2) distance between ISS and MSS (y) is computed by combination value of ellipsoidal height (h), water line (w), mean dynamic topography (MDT) and marine geoid (N) following the correlation shown in Figure 10, (3) distance between MSS to CD to be computed as (x), (4) distance from ISS to CD (k) can be computed by added up (y) with (x), (5) sounding depth (D) can be computed by reducing distance ISS to the seabed (d) with (k) [5].

4.1. *Satellite altimetry-based product assessments studies*

Poerbandono et al. [35] investigated the feasibility of global mean sea surface (MSS) for the potential development of a hydrographic separation model. In the assessment, the researchers took the assumption by using the MSS as the height of MSL with respect to reference ellipsoid, i.e., World Geodetic System 1984 (WGS84). MSL traditionally refers to zero-gauge. The study aimed to quantify the discrepancy of the global MSS model derived from satellite altimetry data with geodetically observed sea levels. According to the International Federation of Surveyors [36], knowing such model errors is one of the key factors in understanding the accuracy of the data. The MSS model was generated by a combination of Gravity Recovery and Climate Experiment (GRACE) Gravity Model (GGM) 02C geoid undulation (N) from the International Centre for Global Earth Models (ICGEM) extracted at 0.25 arc-degree spatial resolution. Mean Dynamic Ocean Topography (MDOT) data published by the Asia-Pacific Data Research Centre is combined with the geoid undulation. This Mean Dynamic Ocean Topography of the sea surface dataset is computed over 1992-2012 and has benefited from altimetry dataset, drifter data set, the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) improved geoid model [35]. According to the work presented here, the overall agreement between the geodetic height of sea level observed by the WA DGNSS positioning system and the MSS is 7.5 cm. RTPPP GNSS positioning system gives 39.5 cm and 36.0 cm overall agreement from away and returns tracking. The overall accuracy of a global MSS model with respect to geodetically observed sea level in this study is resolved at the end is affected by the error contribution from the selected positioning system (WA DGNSS and RTPPP GNSS).

Another study by Naumov et al. [25] aimed to assess the quality of the gridded altimetry sea level product DT18 as well as altimetry data from the Sea Level Climate Change Initiative in the Norwegian Sea. The area coverage includes the coastal area and the open sea of the Norwegian Sea. The quality assessment had been done with a tide gauge record to assess the quality in the coastal zone and surface drifting buoys to assess quality in the open sea. The conclusive analysis indicates that altimetric product D18 reproduces the sea level variability at an acceptable level at the coastal zone with an average error of 3-4 cm. The time series was also reproduced well indicated by almost 96% correlation. However, the result came with the finding that altimetry smoothened the pattern of sea level at the coastal zone and open sea, which manifests errors. At the open sea, the research concluded that internal structures of the instrumental sea level data (tide gauge stations) and altimetry data correspond well (correlation of the spectra is greater than 0.95).

Illiffe et al. [28] demonstrated the testing program result undertaken by the United Kingdom Hydrographic Office. The testing has included 245 verification on datum connections at mostly coastal points. Vertical Offshore Reference Frame (VORF) separation model corrected tidal levels were compared with tide gauge records and GNSS data. A total of 6 offshore tide gauges were deployed to support the mission. The validation result indicates VORF surfaces meet the accuracy target of 0.10m onshore and 0.15m offshore. A significant discrepancy between the test data and VORF was found in the area with high variation of tidal regime south of Portland on the southern coast of England.

5. Altimetry in offshore oil and gas field production phase

Moving forward to potential altimetry application in the oil and gas field production phase. At this phase, the construction is completed and operational. Asset integrity maintenance and monitoring become a priority to maintain the facility reaching its estimated optimal life span by design. One of the asset integrity monitoring activities is the platform air gap survey. As illustrated in Figure 11, Hamdeen et al. [26] stated that the air gap is the distance between the crest of the design wave (related to the Mean Sea Level) and the lowest point of the main cellar deck beams. The air gap must be determined at a specific location and must be sufficient for the occurrence of tides, storm surges, and waves.

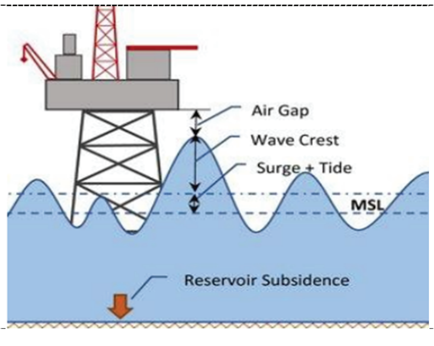

Figure 11. Offshore platform air gap survey [26]

Platform air gap survey requires at least one lunar cycle observation of 30 days of tidal measurement and use the harmonic analysis method. The harmonic tidal analysis is commonly used to determine actual vertical datum (e.g., MSL) and carry out a tidal prediction for longer tidal observation duration intended for asset integrity monitoring as well as Inspection, Repair and Maintenance (IRM) scope. The typical tides observation for structural integrity monitoring purposes is normally acquired from 30 to 60 days of tidal observation. The activity can be seen in Figures 12 to 14. The air gap figure between the water level and the cellar deck's Bottom of Steel (BOS) is also derived from this activity as an asset safety and integrity measure over time.

Figure 12. Oil and gas offshore production platform

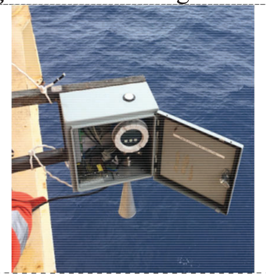

Figure 13. Non-Contact tide gauge for long-term sea-level measurement at an offshore platform

Figure 14. Non-contact tide sensor data logger

To complement and enhance common practice, Hamdeen et al. [26] suggested the conceptual approach for air gap measurement as described in Figure 15. By having a common vertical reference of the ellipsoid model with GNSS, the spatio-temporal advantage of satellite altimetry can be optimised to fulfil this project objective if a precise GNSS survey is also conducted at a selected offshore structure.

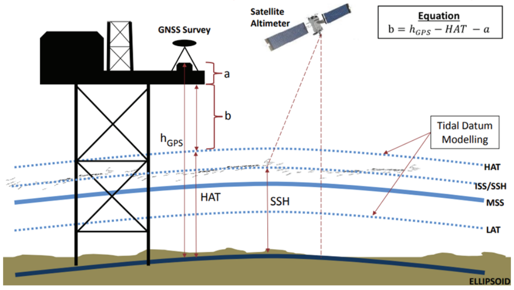

Figure 15. An air gap determination by satellite altimetry tidal modelling approach [26]

As discussed earlier, developing an accurate vertical separation model at a specific region will benefit many applications in the long term view. This also includes an offshore structure air gap monitoring survey. Initially, multi-mission satellite altimetry sea surface data at the area of interest can be processed by tidal analysis to obtain tidal datum. Once validated, the accurate vertical separation model can be developed further. This will allow the transformation between a series of models that are defined at

GNSS coincide ellipsoid model as a common base, e.g., GRS80, WGS84. The vertical separation model, which consists of HAT, LAT, MSS, MSL and common ellipsoid, will also allow the transformation of surface level between vertical reference frames. The conceptual approach in the air gap survey scope has been further extended to solve problematic integrity issues of subsided boat landing decks of production platforms. The established mean sea level used as a vertical reference for years after the platform installation indicates its disagreement with the actual sea level as observed from time to time. The boat landing decks are consistently submerged, indicating that the previous mean sea level line is no longer valid to the offshore platforms. Despite the argument of tidal modelling accuracy that was previously adopted, the subsidence factors may contribute to this occurrence over time. By its spatio-temporal advantage, multi-mission satellite altimetry data has profound potential to provide a reliable solution for obtaining a more robust tidal datum as consistent and stable reference of offshore structures in wider areas such as an oil field.

6. Altimetry for future sustainable energy development

In 2018, the International altimetry team in 5 yearly meetings, celebrated 25 years of progress in radar altimetry. On this occasion, contributions of the worldwide altimetry community from scientists, engineers and managers in the fields of global and coastal oceanography, hydrology, geodesy and cryospheric sciences were gathered to depict the state of altimetry and propose recommendations for the altimetry of the future [6]. The future of altimetry in the energy industry is even more essential toward its contribution to sustainable energy development. The following studies by Alifdini et al. [37] and Hasim et al. [1] shows current progress on how the altimetry approach venture new opportunities in the harness of future renewable energy.

6.1. Offshore tidal energy assessment in Indonesia with satellite altimetry

Tidal energy is one form of marine renewable energy as it is produced from the ocean. Alifdini et al. [37] explored the distribution of the region that have the potential of tidal energy as a source of renewable energy in Indonesia. FES2014 satellite altimetry had been utilised for that purpose. The tidal range value of each region was obtained to estimate the potential amount of energy to be generated. The government of Indonesia set a master plan on developing infrastructure to harness tidal energy in the prospective areas. As tidal barrage devices as tidal range technology have been widely used in several countries, the technology will be utilised to harness tidal energy once the prospective area is identified. The data from satellite altimetry is validated using tidal data from the in-situ measurement from 3 locations (Sunda Kelapa, Semarang and Surabaya). The validation result concludes that both tidal ranges obtained from the in-situ measurement and satellite altimetry data have very good agreement. Computed from tidal component variables, the tidal range values were 1.189m for Sunda Kelapa, 1.001m for Semarang and 3.046m for Surabaya. These results are tally with the tidal range value obtained from satellite altimetry which showed a range of 1-2m for Sunda Kelapa and Semarang, and around 3m for Surabaya. Therefore, satellite altimetry data was then utilised in this study to assess all Indonesian seas.

The research concluded that most locations in Indonesian waters have a tidal range fluctuated between 2 and 5 metres. Based on tidal range analysis, 7 locations were shortlisted as the area indicate strong tidal energy potential. Hence the areas are identified as future locations of tidal barrage system development. The selected areas consist of North Tembilahan, South tembilahan, Bagan Siapi-api (near Halang Island), Bagan Siapi-api (near Rupat Island), Gulf of Bintuni, South East of Papua (near Arafura Sea), South of Papua (near Arafura Sea). Tidal energy then was calculated using tidal barrage formulas to convert tidal to electric power. The predicted potential electrical power that can be generated ranged between 60.45 MW and 3719.13 MW. The study focused on a preliminary assessment of tidal energy potential from tidal range data. The actual development and the construction of the tidal barrage system, as illustrated in figure 16, should incorporate other factors such as basins suitability, environmental impact, community engagements for such a large-scale development project.

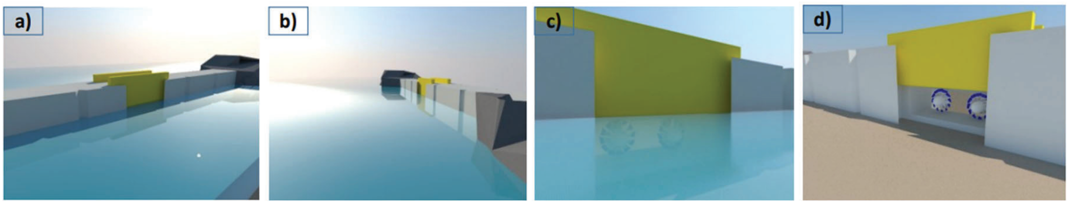

Figure 16. The illustration of tidal barrage (a) inner side of the tidal barrage (b) outer side of tidal barrage (c) turbine position (when flooded by high tides) (d) turbine positions (when tides are low) [37]

6.2. Offshore wind energy resources assessment in Malaysia with satellite altimetry

Satellite altimetry contribution is not limited to sea level measurement, but it is also significant to assess offshore wind energy potential in the region. Satellite altimetry global dataset obtains long term accurate and wide coverage of wind speed data to identify potential offshore wind energy in Malaysia [1]. The wind speed data was obtained from Radar Altimeter Database System. The study by Hashim et al. [1] used three different perspectives, i.e., theoretical, technical, and practical, to present the outcome of offshore wind energy resources assessment within Malaysia. Theoretically, the study concluded that Malaysia, particularly at Terengganu, Sabah and Sarawak, has a potential offshore wind energy density above 500kWh/m2, predominantly in Borneo waters. The study comprehends that offshore wind farm development in Malaysia may face difficulties, especially on technical and practical challenges. The technical obstacle was concluded based on consideration of the available offshore wind turbine technology in the country.

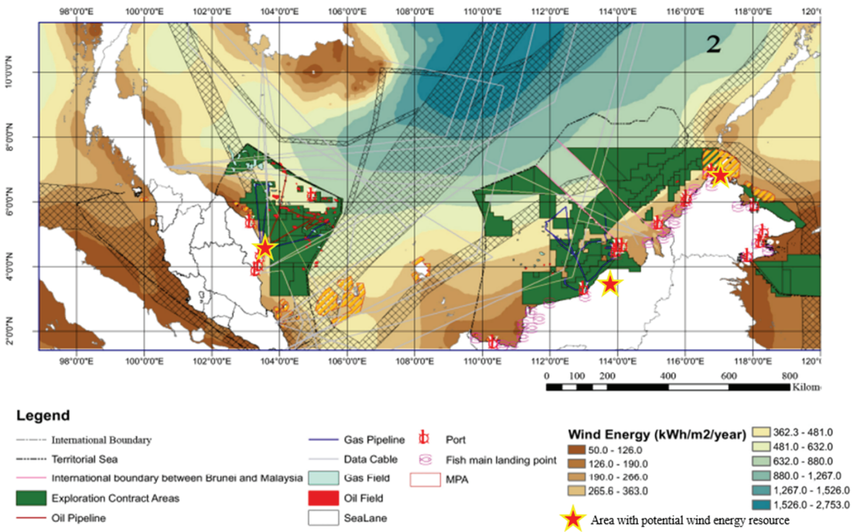

Figure 17. Map of theoretical offshore wind energy location with physical, socioeconomic and environmental constraints considered for offshore wind farm development [1]

As shown in Figure 17, the practical mapping is essential to provide a comprehensive understanding of various practical vicinity elements that correlate to the areas that have the potential for wind farm development for offshore energy harvest. Several infrastructures and area concession coverage elements such as port, shipping lane, fibre optic cable, oil and gas pipeline, oil and gas exploration and production concession blocks, fisheries facilities were considered in offshore wind energy practical map development [1]. Practicality issues are observed due to conflicting concession areas and environmental constraints at specified locations with high offshore wind energy potentials. As can be seen in the practical map shown in Figure 17, the three potential locations pointed out from the theoretical potential analysis, particularly at Terengganu and Sabah, may not be practically suitable for wind farm development. The prospective wind farm areas were located at the existing operational oil and gas exploration and production concession block. It is indicated that the existing underwater oil and gas pipeline assets in Terengganu and Sabah may obstruct the installation grid connection and offshore wind turbine support structure. As for Sarawak, the potential wind farm theoretical location is located in an area with fish main landing points, and fisheries facilities indicate active commercial fishing activities. This area practically may not be suitable for further development of wind farm infrastructure. However, the study emphasised that satellite altimetry is a reliable and accurate data source for wind energy assessment, complementing the lack of on-site measurement buoy distribution in Malaysian waters [1].

7. Artificial Intelligence and Altimetry Data

The abundance of large masses of altimetry spatial data and other correlated datasets can be further enhanced, utilised, optimised, manipulated, processed, interpreted, and presented through the field of artificial intelligence (AI) science, leveraging the value [6]. Intuitive AI may simplify the complex representation of the various model to fully accessible and optimised full spatio-temporal analysis. The simplicity and enhanced analysis through AI are potentially open extended applications of monitoring mesoscale ocean signals such as fisheries, military defence, marine safety, pollution tracking, commercial navigation, oil spills, offshore oil and gas construction, marine renewable energies. With AI, sea-state forecast, significant wave height (SWH), wind speed, and wave periods measured by altimetry are playing an essential role for various maritime activities such as offshore oil drilling operation and navigation through the provision of informative analysis and prediction to operational forecast centre [6].

8. Results and Discussion

Research about altimetry is relevant in various technical needs in conventional offshore oil and gas operation towards marine-based renewable energy potential assessment and application. Further specific study about the relevance of satellite altimetry practical implementation in marine energy projects considering the acceptance criteria and offshore technical specification is critical to be formulated in the future worklist to represent the performance figure in the exploration, development and production phase. In order to achieve a confidence level of satellite altimetry reliability in the open sea and deep-water area, offshore tide gauges data beyond 10km from the coastline should be used for data comparison and validation. The multi-mission satellite altimetry tidal model requires validation by in-situ tidal data, especially in areas with sparseness issues such as open sea or offshore areas far away from coastal regions where the conventional tide gauges are typically distributed. Densification of tide gauges and co-located GNSS networks at sparse regions covering coastal and open sea is necessary to fully integrate sea level observing systems [2].

AI and many other user-friendly technologies are worth being fully optimised for practical representation of the approach, which may lead to massive implementation penetration into the current and future energy industry. The intuitive interface will give the most beneficial practical outcome out of spatio-temporal advantage of satellite altimetry data through continuous advancement, and optimisation in various operational conditions and circumstances

9. Conclusion

Multi-mission satellite altimetry tidal modelling indicates reliability to support, enhance, complement, substitute the current tidal measurement in various offshore oil and gas applications. A comprehensive comparative study, feasibility study, optimisation and implementation strategy development are essential to further adapt and penetrate the methodology in the current industrial accepted best practices.

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