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Tidal Datum Transfer in Shallow Waters: A Comparison of Classical and Parametric Methods in the Northern Persian Gulf

Hamed Esmaeil Nazari[1], Abbas Abedini[1*], Bahman Tajfirooz[2]

[1] School of Surveying and Geospatial Engineering, College of Engineering, University of Tehran, Tehran, Iran;* hamednazari.1379@ut.ac.ir, aabedeni@ut.ac.ir

[2]Darya Tarsim Consulting Engineer Co., Tehran, Iran; bahman.tajfirooz@gmail.com

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ABSTRACT

Accurate tidal datum transfer is crucial in hydrographic surveying and coastal engineering, particularly in regions characterized by complex tidal regimes. This study evaluates the performance of tidal datum transfer methods in a mixed semi-diurnal environment using simultaneous water level observations from a reference and a secondary station situated in the Persian Gulf and Strait of Hormuz. This specific area was selected due to its unique hydrodynamic conditions, shallow bathymetry, and significant non-linear tidal interactions that complicate conventional datum establishment. The classical Range-Ratio approach is systematically compared against Grant's parametric least-squares method, which mathematically estimates a scale factor, a time shift, and a datum shift by fitting the continuous tidal curve. To assess the robustness, accuracy, and sensitivity of these methods to observation lengths, a moving-window analysis was implemented over record lengths of 0.5, 1, 3, 7, and 15 days using 10-minute shift steps. Initial harmonic analysis of the observed data yielded form factor values of 0.38 and 0.43, confirming a mixed, predominantly semi-diurnal regime that theoretically satisfies the prerequisites for applying the Range-Ratio method. However, evaluation based on the Root Mean Square Error (RMSE) across all tested windows demonstrated that the parametric least-squares method is significantly more stable and reliable. By utilizing the entire continuous record rather than discrete data points, Grant's method mitigates the inherent limitations of the classical approach, which relies solely on a limited number of high and low water extrema and remains highly sensitive to short-term meteorological noise and shallow-water effects. Ultimately, the findings strongly advocate adopting continuous curve-fitting techniques combined with moving-window analyses for precise hydrographic datum transfers in complex coastal basins.

1. Introduction

Tidal datums form the foundation of hydrographic and coastal engineering activities. They serve as reference surfaces from which depths are measured and coastal boundaries are delineated [1]. These vertical reference planes, defined by tidal stages such as high water, low water, or mean sea level, provide the essential framework for safe navigation, coastal zone management, and maritime boundary delimitation [2]. The accurate determination of tidal datums carries significant legal implications, particularly in regions where the boundary between state and private ownership is defined by tidal water levels [3]. As Marmer [4] noted in his seminal work, the relationship between these reference surfaces and adjacent coastal land affects both navigation safety and coastal property rights.

From a practical perspective, the reliable realization of these reference planes requires long-term observations spanning a full nineteen-year National Tidal Datum Epoch to account for all astronomical periodicities affecting tidal variations [5]. However, such extended observation periods are rarely feasible for hydrographic surveys or coastal engineering projects. This practical consideration has motivated the development of various techniques collectively known as tidal datum transfers, which enable the estimation of datum elevations at a secondary site using short- to medium-term observations in conjunction with data from a reference station where the datum is already established [6]. Among these, the Range-Ratio method has emerged as the most widely adopted approach in hydrographic practice worldwide [7]. This method assumes that the ratio of vertical distances from respective datum planes to mean water level at the secondary and reference sites equals the ratio of their tidal ranges, offering conceptual simplicity and ease of implementation.

However, the performance of datum transfer methods varies considerably depending on the tidal characteristics of a region. Areas with mixed tides, pronounced diurnal inequalities, or significant spatial variations in tidal ranges present particular challenges for conventional approaches. The Range-Ratio method, which primarily relies on extremal tidal values, utilizes only a fraction of the available observational data and may inadequately capture the full complexity of the tidal signal [8]. This limitation becomes particularly evident in locations where the ratio between diurnal and semi-diurnal constituents varies spatially or where rapid changes in tidal range occur over short distances.

An alternative parametric approach based on least-squares estimation was proposed by Grant and O'Reilly [9] to address these limitations. Their method simultaneously determines three critical parameters: a vertical scale factor, a horizontal time shift, and a vertical datum shift. This approach effectively slides the reference station tidal curve along the time axis, translates it vertically, and stretches it to achieve optimal superposition with secondary station observations. By utilizing all available observational data rather than just extremal values, the method provides statistical indicators of parameter accuracy. The mathematical foundation rests upon the least-squares adjustment theory articulated by Vaníček and Krakiwsky [10], while practical implementation requires interpolation techniques such as cubic splines to handle discrete tidal observations [11]. This parametric framework can be interpreted as a generalized extension of the conventional Range-Ratio concept, offering enhanced flexibility for application in spatially variable tidal regimes.

The Persian Gulf provides a suitable case study for evaluating datum transfer methods under challenging tidal conditions. This semi-enclosed marginal sea, connected to the Gulf of Oman through the narrow Strait of Hormuz, exhibits dynamically diverse tidal characteristics shaped by interactions between astronomical forcing, basin geometry, and bathymetric features [12]. Pous et al. [13] demonstrated that tidal impacts on volume and salt transport through the Strait of Hormuz play a crucial role in determining circulation patterns throughout the Gulf. The tidal characteristics of this region show considerable spatial heterogeneity, with semi-diurnal constituents displaying strong variations across the Strait, while diurnal constituents exhibit sensitivity to seasonal oceanographic conditions [13]. The relative contributions of these constituents determine the overall tidal regime classification for any particular location.

Within this broader regional context, the Hormuz Strait represents one of the most hydrodynamically active areas of the Persian Gulf. Located between Qeshm Island and the Iranian mainland, this waterway is characterized by extensive mangrove forests designated as a protected area since 1972 [14]. The region hosts several major ports including Bandar Shahid Rajaee, which serves as one of Iran's primary commercial gateways. Previous modeling studies in this area have demonstrated tidal ranges of approximately three meters along the northern coast of Qeshm Island, reaching up to four and a half meters in adjacent areas, classifying the region as mesotidal to macrotidal [15]. The heterogeneous bathymetry of the channel influences tidal phase and amplitude propagation, generating current patterns that may affect the performance of datum transfer methods.

The geographical location of the study area and the positions of the two tide gauge stations are illustrated in Figure 1.

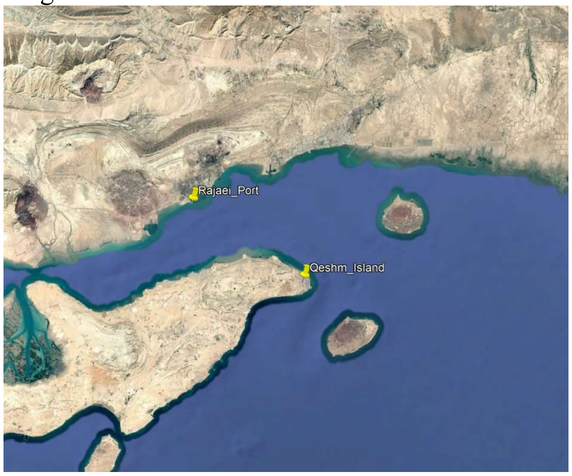

Figure 1. Location of the study area in the northern Persian Gulf, showing Bandar Shahid Rajaee and the Qeshm Island tide gauge station.

Previous investigations have well-established the baseline tidal characteristics of the region. Comprehensive tide and circulation studies, notably by Pous et al. [13], have identified the major tidal constituents and their spatial distribution throughout the Persian Gulf. These analyses confirm the predominance of semi-diurnal constituents across the region while noting significant local variations. Collectively, these investigations indicate that the tidal regime in the vicinity of the Strait of Hormuz exhibits mixed, mainly semi-diurnal characteristics, with the relative influence of diurnal and semi-diurnal constituents varying spatially depending on the exact bathymetry and location [13].

However, little comparative work has been done on datum transfer methods under northern Persian Gulf tidal conditions [16]. While the theoretical advantages of parametric least-squares approaches have been demonstrated in other regions, their practical efficacy in the spatially heterogeneous tidal environment of the Strait of Hormuz remains largely unexplored. Furthermore, the availability of three months of high-temporal-resolution radar tide gauge observations from Bandar Shahid Rajaee and a nearby station on Qeshm Island, together with complete harmonic analysis and independently established ground truth datum information, allows a systematic comparison of the methods.

Accordingly, the present study is structured around the following objectives: first, characterization of the tidal regime at both stations through form factor determination and harmonic analysis; second, implementation of both the conventional Range-Ratio method and the least-squares parametric approach using identical observational data; third, quantitative comparison of method performance against ground truth datum elevations; and fourth, assessment of method sensitivity to prevailing tidal conditions. The findings may help guide datum realization strategies in mesotidal mixed regimes and provide guidance for hydrographers operating in the Persian Gulf.

2. Theory of Problem

The accurate transfer of a tidal datum from a well-established reference station to a temporary secondary station relies on mathematical models that capture the relationship between the tidal dynamics at both locations. In this study, two distinct methodologies are evaluated: the conventional Range-Ratio method and a parametric least-squares approach.

2.1. Conventional Range-Ratio Method

The conventional Range-Ratio method is a well-established empirical technique used to transfer a vertical datum from a reference (primary) station to a newly established secondary station. The fundamental assumption of this method is that the ratio of the vertical distance between the datum and the mean water level at the secondary station to the corresponding distance at the reference station is equal to the ratio of their respective tidal ranges.

Mathematically, this relationship is expressed by the following principal equation:

$$d = m' - M'(\frac{r}{R}) \qquad (۱)$$

where:

d represents the unknown datum offset (relative to the mean water level) at the secondary station.

m' is the mean water level calculated at the secondary station over the simultaneous observation period.

M' is the mean water level at the primary reference station over the same period.

r is the mean tidal range at the secondary station.

R is the mean tidal range at the primary reference station.

To implement this method, the high and low water extrema must be explicitly extracted from the tidal records of both stations. The mean values of these specific extrema are then used to calculate the tidal ranges (r and R) and the mean water levels (m' and M'). While computationally straightforward, this approach relies exclusively on discrete peak and trough values, making the final datum calculation (d) highly sensitive to any high-frequency noise or meteorological disturbances occurring exactly at the times of high or low water.

2.2. Parametric Least-Squares Method (Grant's Method)

To overcome the limitations of the discrete extrema-based approach, Grant and O'Reilly [9] proposed a continuous parametric model. This method utilizes the entire simultaneous time-series dataset from both stations. The fundamental concept is to geometrically transform the reference station's tidal curve by scaling it vertically, shifting it in time, and translating it vertically to optimally align it with the secondary station's tidal curve.

The mathematical model expressing the secondary tidal height, $H(t)$, as a function of the reference tidal height, $G(t)$, at any given time t is formulated as:

$$H(t) = a.G(t+b) + c \qquad (۲)$$

In this formulation:

a represents the vertical scale factor (analogous to the range ratio).

b is the horizontal time shift, representing the phase difference between the stations.

c is the vertical datum shift.

To determine the optimal parameters (a, b, and c), the method employs the principle of least-squares estimation [10]. The objective is to minimize the sum of the squared residuals between the observed secondary water levels and the transformed reference curve. The residual function $v(t)$ is defined as:

$$v(t) = H(t) - [a.G(t+b) + c] \qquad (۳)$$

The objective function to be minimized over N simultaneous observations is:

$$J(a,b,c) = \sum_{i=1}^{N} (H(t_i) - [a.G(t_i+b)+c])^2 \qquad (۴)$$

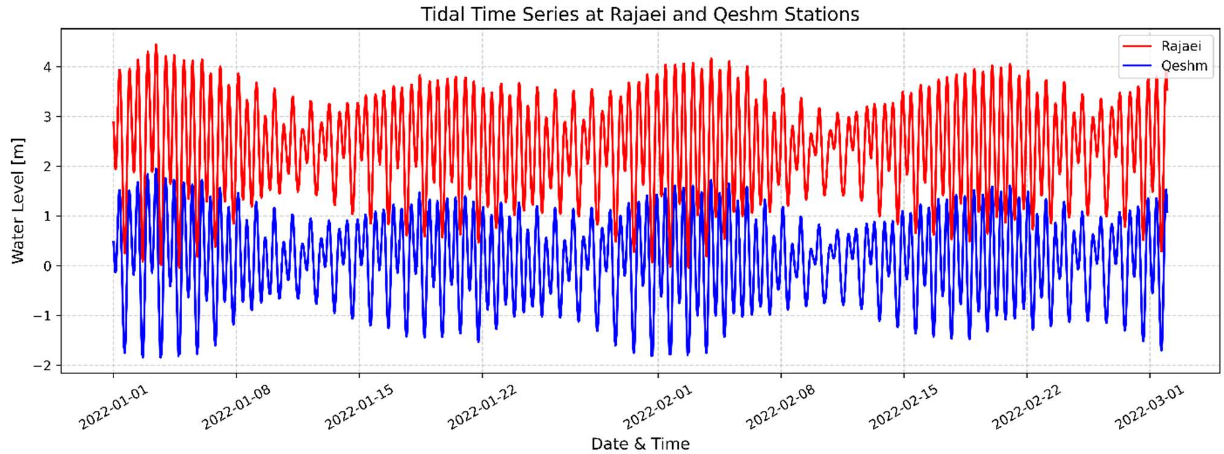

Figure 2. Raw tidal records from the Shahid Rajaei (reference) and Qeshm (secondary) radar tide-gauge stations.

Because the time shift parameter b is continuous whereas the recorded tidal observations $G(t_i)$ are discrete, $G(t_i + b)$ cannot be directly extracted from the raw data. To resolve this, cubic spline interpolation is applied to the reference station data, providing a smooth and continuous mathematical representation of the reference tidal curve [9, 11].

since the function $G(t_i + b)$ is generally non-linear with respect to the time shift parameter b, the least-squares optimization is a non-linear problem. It requires linearization using Taylor series expansion and is solved iteratively. The iterative process typically commences with initial approximations of $a_0 = 1$, $b_0 = 0$, and $c_0 = 0$, converging towards the optimal parameter set that defines the datum shift c [9].

2.3. Influence of Tidal Regimes and Form Factor

The reliability and accuracy of datum transfer methods are strongly influenced by the characteristics of the local tidal regime. Tidal types are quantitatively classified using the Form Factor (F), defined as the ratio of the sum of the amplitudes of the primary diurnal harmonic constituents ($K1$ and $O1$) to the sum of the primary semi-diurnal constituents ($M2$ and $S2$):

$$F = \frac{O1 + K1}{M2 + S2} \tag{۵}$$

Based on the value of F, tidal regimes are categorized into four groups: semi-diurnal ($F < 0.25$), mixed predominantly semi-diurnal ($0.25 \leq F \leq 0.5$), mixed predominantly diurnal ($1.5 < F \leq 3$), and diurnal ($F > 3$).

The standard equations for the conventional Range-Ratio method, as described in Section 2.1, are fundamentally predicated on the occurrence of two regular and distinct high and low waters per tidal day. Therefore, these specific formulations are mathematically valid and practically applicable primarily in semi-diurnal and mixed predominantly semi-diurnal regimes ($F \leq 1.5$). In mixed predominantly diurnal or fully diurnal regimes ($F > 3$), pronounced diurnal inequalities occur. Secondary extrema can become masked or completely vanish due to shallow-water effects or specific astronomical alignments (e.g., neap tides). When these essential extrema are missing or ambiguous, the fundamental assumptions of the standard Range-Ratio method break down, rendering it mathematically unstable or inapplicable without complex modifications.

Conversely, because the parametric least-squares approach (Grant's method) utilizes the continuous water level curve rather than relying on discrete extrema, it is not bounded by the requirement of a specific tidal form factor. It remains mathematically robust and operationally viable across all types of tidal regimes, making it particularly advantageous in complex coastal environments.

3. Experimental Investigations

3.1. Study Area and Data Acquisition

To evaluate the performance and temporal stability of the datum transfer methods, continuous water level datasets from coastal stations located in the northern coast of the Persian Gulf were utilized. For the purpose of this analysis, Shahid Rajaei was designated as the primary (reference) station, while Qeshm Island served as the secondary (subordinate) station. The geographical distribution and relative positions of these stations are illustrated in Figure 1.

The water level observations span a period of two month, from 1/1/2022 to 3/1/2022, with a sampling interval of 10 minutes. The data were provided by Darya Tarsim Company. The comprehensive metadata for each station, including geographical coordinates, mean sea level relative to the local benchmark, and basic data specifications, are summarized in Table 1.

3.2. Tidal Characteristics and Form Factor Validation

As discussed in Section 2.3, the validity of the standard Range-Ratio method depends on the presence of a semi-diurnal or mixed predominantly semi-diurnal tidal regime. To validate this prerequisite for our chosen datasets, the eight primary harmonic constituents were extracted for each station.

Table 1. Station metadata and water level data specifications.

Specification	Reference Station	Secondary Station
Station Name	Bandar Shahid Rajaee	Qeshm Island
Coordinates	۲۷°۰۵′ N, 56°03′ E	26°57′ N, 56°16′ E
Observation Period	2 Months (Simultaneous)	
Sampling Interval	10 Minutes	
Ground Truth (Chart Datum)	−1.84 m (below MSL)	--

The amplitudes of these constituents and the resulting Form Factor (F) for each station are presented in Table 2.

As shown in Table 2, the calculated Form Factors for all stations are well below the 1.5 threshold ($F \leq 1.5$). This confirms that the tidal regimes are indeed mixed predominantly semi-diurnal, meaning distinct, regular high and low waters occur. Consequently, the fundamental conditions for applying the classical Range-Ratio method are satisfied, establishing a valid and fair baseline for comparing its performance against Grant's parametric approach.

3.3. The Moving Window Methodology

A rigorous evaluation of a datum transfer method requires assessing its sensitivity to the chosen observation period and its robustness against short-term environmental noise. To quantify the temporal stability of the estimated datums, a "moving window" algorithm was implemented.

The moving window technique operates by extracting a continuous subset of data (the window) of length W from the total available time series of length T_{total}. The chosen datum transfer algorithm is applied to this specific window to calculate a single datum difference estimate. Subsequently, the window is shifted forward in time by a constant step size, Δt, and the calculation is repeated. This iterative process continues until the moving window reaches the end of the available dataset.

The total number of independent datum estimates, k, generated for a given window length is determined by:

$$k = \left\lfloor \frac{T_{total} - W}{\Delta t} \right\rfloor + 1 \qquad (۸)$$

where $\lfloor \cdot \rfloor$ denotes the floor function. For the conventional Range-Ratio method, the window length must be sufficient to capture at least seven consecutive tidal extrema. In contrast, Grant's method can process the entire continuous curve regardless of extrema, allowing for the evaluation of various window lengths $W =$ 0.5, 1, 3, 7 or 15 days. In this study, the shift step was set to $\Delta t = 10\ min$ to provide a high-resolution temporal profile.

Table 2. Amplitudes of primary tidal constituents and the calculated Form Factor (F) for the study stations.

Constituent	Bandar Shahid Rajaee		Qeshm Island		Difference
	Amplitude (cm)	Phase (°)	Amplitude (cm)	Phase (°)	Phase (°)
M2	110.34	300.33	93.47	294.86	-5.47
S2	42.55	338.92	35.57	332.35	-6.57
K1	35.51	67.96	33.93	65.33	-2.63
O1	22.97	56.54	21.86	54.97	-1.57
N2	26.47	279.38	22.63	274.86	-4.52
K2	12.12	332.26	9.85	327.69	-4.57
P1	11.21	64.6	10.69	59.2	-5.4
Q1	5.03	51.04	4.83	50.67	-0.37
Form Factor and Tidal Regime Classification					
K_1+O_1	58.48		55.79		
M_2+S_2	152.89		129.04		
Form Factor	0.38		0.43		
Regime Type	Mixed, mainly semi-diurnal		Mixed, mainly semi-diurnal		

4. Results and Discussion

4.1. Visual Implementation of the Transfer Models

To illustrate the operational differences between the two methods, we examine their specific interaction with the water level datasets. For the conventional Range-Ratio method, the computational algorithm dictates the precise identification of high and low

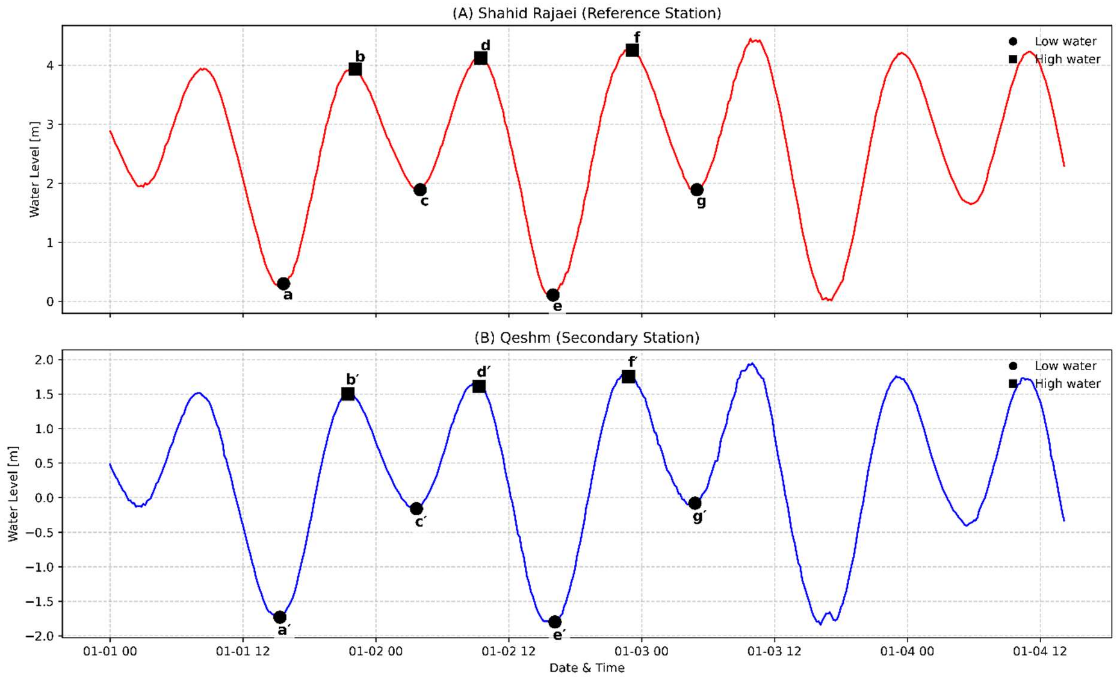

Figure 3. Identification of high and low water extrema required for the classical Range-Ratio method at both primary and secondary stations.

water extrema. Figure 3 demonstrates this process for a sample period. Only these discrete points (marked on the curves) are utilized in calculating the mean ranges and the range ratio. This visual representation highlights the method's inherent vulnerability: any localized disturbance or measurement noise occurring exactly at these extrema points will directly distort the final datum calculation.

In contrast, Figure 4 illustrates the application of Grant's parametric least-squares method over the same sample period. The upper panel shows the data points alongside the continuous fitted mathematical

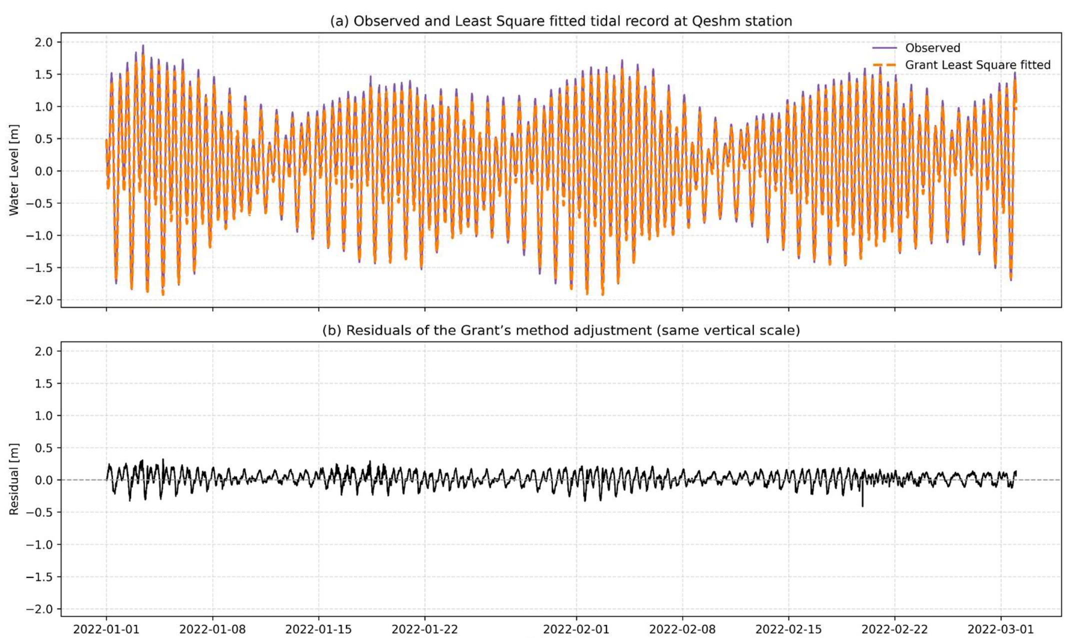

Figure 4. Application of Grant's method. Top panel: Data points and the fitted continuous curve. Bottom panel: Residuals demonstrating the goodness-of-fit.

model
$H(t) = a.G(t + b) + c$. Instead of isolating extrema, the method utilizes all available data points within the window, effectively acting as a curve-fitting filter. The lower panel displays the residuals (the difference between the raw data and the fitted curve). The random distribution and small magnitude of these residuals confirm a good fit and the model's ability to successfully separate the dominant tidal signal from high-frequency environmental noise.

4.2. Temporal Stability and Statistical Analysis

To quantitatively evaluate the temporal stability, the moving window algorithm (Section 3.3) was applied. The performance was assessed by tracking the Root Mean Square Error (RMSE) and the statistical distribution of the datum differences.

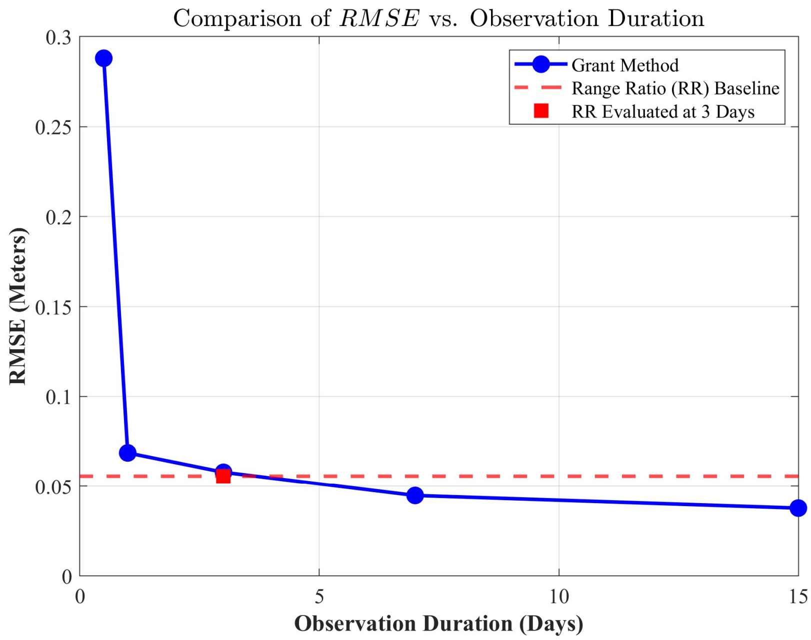

Figure 5. The trend of RMSE for Grant's method over varying window lengths, compared to the Range-Ratio baseline.

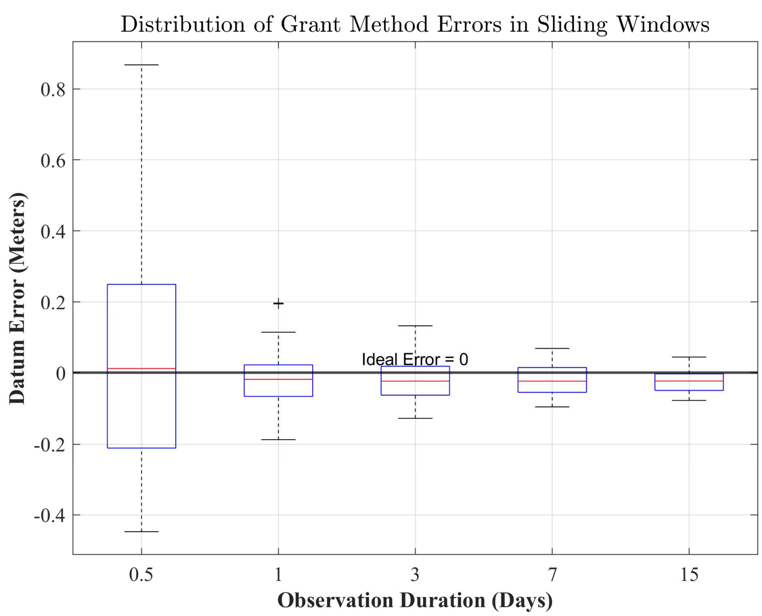

Figure 6. Boxplot illustrating the distribution and variance of datum transfer errors for the evaluated methods.

Figure 5 presents the trend of the RMSE for Grant's method as a function of the observation window length, compared against the baseline established by the 3-day Range-Ratio method.

As shown in Figure 5, even at shorter window lengths, Grant's method exhibits a lower RMSE compared to the conventional method. In addition, as the duration of the observation window increases, the RMSE for Grant's method demonstrates a clear downward trend, indicating that longer continuous datasets significantly enhance the stability of the parametric estimation.

To further analyze the variance and the presence of outliers, a boxplot of the datum transfer errors is presented in Figure 6.

The boxplot (Figure 6) clearly shows that the Range-Ratio method possesses a much wider interquartile range and a higher number of outliers. This wide spread signifies a lack of temporal stability. Conversely, the boxes representing Grant's method are significantly more compact, confirming tighter clustering of the estimates around the true mean.

The visual findings from Figures 5 and 6 are quantitatively supported by the statistical summary in Table 3.

Table 3. Performance comparison and statistical summary of the datum transfer methods using the moving window approach.

Method	Record Length	Number of Windows	RMSE (m)
Range-Ratio	3 days	۱۰۹	0.0557
Least-Square (Grant)	12 hours	119	0.2880
Least-Square (Grant)	24 hours	118	0.0686
Least-Square (Grant)	3 days	114	0.0579
Least-Square (Grant)	7 days	106	0.0448
Least-Square (Grant)	15 days	90	0.0378

4.3. Discussion

The empirical results strongly align with the theoretical expectations. Although the selected study area possesses a Form Factor of $F \leq 1.5$ (Table 2) which theoretically validates the use of the Range-Ratio equations, the operational performance of the conventional method is severely limited by its discrete nature. Relying solely on 7 to 10 points over a 3-day period makes the Range-Ratio method highly susceptible to short-term meteorological effects and random measurement errors.

Grant's method overcomes this fundamental flaw by employing a least-squares optimization over the entire continuous dataset. By utilizing hundreds of data points within the same 3-day window, the method inherently filters out non-tidal anomalies. The continuous mathematical formulation ($H(t) = a.G(t+b)+c$) ensures that the extracted datum difference (c) is robust, stable, and less dependent on the exact timing of high or low waters. Consequently, Grant's approach appears to be a more effective alternative for vertical datum transfer, even in tidal regimes well-suited for classical methods.

5. Conclusions

Accurate vertical datum transfer is a critical component of hydrographic surveying, coastal engineering, and marine navigation. In this study, the performance of the traditional Range-Ratio method was comparatively evaluated against Grant's Least-Squares methodology for tidal datum transfer between Bandar Shahid Rajaee (reference station) and Qeshm Island (subordinate station). A continuous moving-window approach was employed to rigorously evaluate the stability, accuracy, and operational viability of these models over varying record lengths.

The harmonic analysis revealed that both stations exhibit a "Mixed, mainly semi-diurnal" tidal regime with Form Factors of F=0.38 and F=0.43. While the condition of F≤1.5 theoretically validates the application of the Range-Ratio method in this region, empirical findings demonstrated its inherent operational limitations. For a standard 3-day observation period, both methods yielded almost similar accuracies; the traditional Range-Ratio method produced a Root Mean Square Error (RMSE) of 0.0557 m, while Grant's method resulted in a comparable RMSE of 0.0579 m.

However, the fundamental advantage of Grant's method over the conventional approach lies in its mathematical structure and its capability to utilize continuous datasets. The Range-Ratio method is intrinsically limited to merely 7 high and low water extrema over a 3-day period. This reliance on isolated data points not only makes the model highly susceptible to short-term meteorological noise but also restricts its potential for achieving better accuracies.

In contrast, Grant's continuous least-squares optimization model processes hundreds of continuous data points. Because it is not restricted to extrema, Grant's method allows for the inclusion of larger datasets to improve precision. By extending the observation window, the model reduces the influence of non-tidal anomalies and random measurement errors. As demonstrated, increasing the continuous data record to 15 days using Grant's method reduced the RMSE to 0.0378 m, an accuracy level not observed in the Range-Ratio results.

Based on these comprehensive empirical results, it is concluded that Grant's least-squares approach offers a more robust and flexible alternative for vertical datum transfer. While it matches the accuracy of the conventional method over short timeframes, its advantage becomes more evident from its ability to process larger continuous datasets to yield significantly higher precision. Therefore, adopting Grant's method is may be considered for routine use for modern hydrographic applications and precise datum establishment.

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