A New Reference Frame for Oman, Derived by Precise Processing of the CORS Network

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SUMMARY

National Survey Authority (NSA) of Oman established a GNSS network of 46 CORS sites (OMANCORSNET) in 2016. The collected data up to the end of 2022 were used to realize a new reference frame for the Sultanate of Oman. Oman National Geodetic Datum 2023 (ONGD23), derived from OMANCORSNET, is the first reference frame of the country that is based on long-term data.

More than 6 years of 30-seconds data of 46 OMANCORSNET and 28 IGS stations were precisely processed. Positions, time series and velocities were obtained in ITRF20. Positions were calculated for epoch 2023.0. The new reference frame ONGD23 is realized, with positions and sub- to few-millimeter per year velocities of the stations of Oman block., as such, surveyors do not need to care about variations of positions in time intervals of a few years.

Precise positioning in ONGD23, similar to in every regional frame, is the proper method to study regional deformations. Rigid motion of Oman block is absorbed in the reference frame, while residual velocity field presents the internal deformation field.

ONGD23 reveals slow-rate deformations along the northern coast line, as well as central Oman. The former is likely a consequence of Arabia - Eurasia collision, while the latter effect is expected to be the result of oil and gas field operations. Densification of this network in central Oman will enable us to study the effect of oil and gas exploitation. Results of this project can be applied in multiple scientific investigations, in particular in studying kinematics of the Arabia plate.

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1. INTRODUCTION

Networks of Continuously Operating Reference Stations (CORS) are extraordinary tools for precisely investigating observation errors, temporal correlations, and error propagation in precise positioning. They allow for accurate correction of observations and results, enabling the removal of outliers and the determination of the best possible positions, velocities, and time series. These results provide valuable information that can be applied in various fields of geosciences. CORS not only facilitate surface motion monitoring but also establish high-precision regional reference frames, enabling quick and precise positioning and navigation operations. This independence from remote global reference stations empowers local surveyors and simplifies their access to precise positions, eliminating the need for sophisticated software and lengthy observation times.

Oman experiences relatively low seismic activity and lacks significant natural mechanisms of fast or large episodic deformation. This inherent stability makes it an ideal candidate for establishing a reliable and consistent reference frame. Moreover, this stable reference frame can also be extended for monitoring deformations in neighboring regions. For instance, it can be particularly valuable in assessing the tectonic and seismic activities in southern Iran, an area known for its active tectonics and seismicity.

Although Oman currently possesses its own reference frames, a new frame is needed for several compelling reasons:

- Implementation of a continuously operating network of 46 countrywide stations (OMAN- CORSNET), NSA is able to establish a more precise frame.
- In April 2022, the international GNSS community introduced the new reference frame ITRF20. This development has implications for various applications relying on precise positioning and navigation. As part of this transition, the International GNSS Service (IGS) has started delivering its products, such as satellite orbits, in the ITRF20 reference frame.
- The non-linear behavior of Earth's surface motions necessitates regular updates of the reference frame every few years.
- With the accumulation of a significant amount of precise data since the last realization of a reference frame in 2017, there is an opportunity to enhance the existing frames.

A few of the practical profits of a new reference frame based on long-term precisely processed CORS data can be summarized as:

- A more precise reference netwrok is achieved for various navigation systems and tasks across the country.
- The positions of urban data sets such as map and satellite images, that may have been affected by local or regional deformation mechanisms, are updated.
- Irregular behaviors of the CORS sites are corrected, for example relocation of a site or other types of discontinuities.

Being situated on the easternmost part of the Arabian Peninsula, Oman is surrounded by various types of plate boundaries. The diversity of the boundaries offers Oman a natural laboratory for studying the kinematics of tectonic plates.

Oman occupies a region of the Arabian tectonic plate with the characteristics of an oceanic plate. This presents scientists with a unique opportunity to study the kinematics of subduction using observation sites on the oceanic plate.

OMANCORNET was processed with the objective of creating a new reference frame for Oman. The network was established in 2016 with 46 stations. The extensive coverage of the network across the entire country, coupled with the extended time span of data collection, provides an ideal foundation for accurately calculating positions, velocities, and time series for each site. The primary aim of this endeavor is to establish a robust reference frame for the Sultanate of Oman, thereby replacing the existing frames that were established using short-term observations.

2. OMANCORSNET Precise Data Processing

Daily observation files with 30-second time interval were processed for the period of April 2016 to the end of 2022.

2.1 Daily Processing

OMANCORSNET (Figure 1) was processed using data from 28 global IGS stations distributed around Oman.

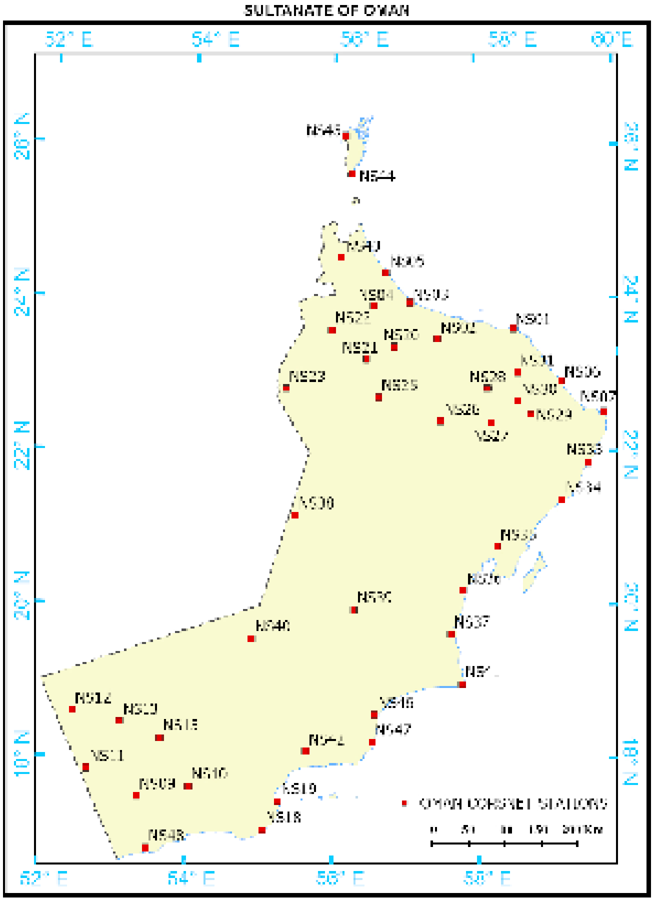


Figure 1: NSA CORS network (OMANCORSNET)

The MIT GNSS precise processing package GAMIT (Herring et al., 2018) was applied to process 30-second data in a loosely constrained solution, i.e. each daily solution is internally accurate, while different days are not explicitly connected.

The selected IGS sites were utilized within the ITRF20 reference frame. During the processing, the orbital parameters were held fixed, and the estimation of new orbits based on the regional network was deliberately avoided.

2.2 IGS Sites

Following a thorough investigation of IGS sites around Oman and considering the available data gaps, 28 sites (table 1) were carefully chosen.

The a-priori positions of the IGS sites were applied in ITRF20, while the a-priori positions of the NSA sites were extracted from RINEX files with their initial velocities set to zero in the initial iteration of the solution.

Site	Country	Site	Country	Site	Country
ABPO	Madagascar	IISC	India	Ramo	Palestine
ADIS	Ethiopia	ISBA	Iraq	SEYG	Seychelles
ANKR	Turkey	JDPR	India	SGOC	Sri Lanka
BHR4	Bahrain	KITG	Uzbekistan	SHLG	India
BUCU	Romania	LCK4	India	SOFI	Bulgaria
DJI0	Djibouti	MAL2	Kenya	TASH	Uzbekistan
DGAR	UK	MBAR	Uganda	TEHN	Iran
HAMD	Iran	MERS	Turkey	TUBI	Turkey
HYDE	India	NICO	Cyprus	YIBL	Oman
				ZAMB	India

Table 1: Selected IGS sites

2.3 OMANCORSNET Time Span

The first OMANCORSNET station began data collection on April 5, 2016, the next stations followed within a short period. The data were processed from the establishment day of each station to 31.12.2022.

2.4 Corrections

The ionosphere-free linear combination observables were exploited, incorporating ambiguity parameters derived from pseudo-ranges. This approach is appropriate for modern receivers that employ P code for L1 and L2 frequencies, as outlined by Herring et al. (2015). The following corrections were applied in order to maximize the reliability of the solution:

- The zenith delay was corrected by estimating a single value for each station and every 12 hours.
- Both phase center variations (PCV) of the satellite and the receiver antenna were applied using a tabular form.
- The observations were corrected for earth tides. Various models were applied to account for corrections of earth-, pole-, ocean- and atmosphere-tides.
- Non-tidal atmospheric loading was corrected.

2.5 Daily Results

The daily processing indicates loosely constrained results for each day, i.e. each day's solution is internally consistent. We apply „Generalized Constraints“ method to constrain the solutions and achieve consistent results. „Generalized Constraints“ implements rotations and translations of the daily frames to combine the results.

2.6 Combination of Daily Results

Daily results of positions and velocities were combined in a „Generalized Constraints“ process with high weights for IGS sites to conlcude consistent results.

The resulting positions and velocities were used in a second iteration as the a-priori values. The iterated solution is expected to converge faster and produce a robust solution that is less sensitive to the a-priori conditions. If necessary, this procedure is iterated until a rapid convergence is achieved.

Positions are assumed to be piecewise continuous. The solution provides coordinates for each site at a specific epoch, along with a constant velocity. This allows for the calculation of the position of each site at any time by Equation 1:

$$\boldsymbol{X}_{t_1} = \boldsymbol{X}_{t_0} + \boldsymbol{V}(t_1 - t_0) \tag{1}$$

where $\boldsymbol{X}_{t_1}$ and $\boldsymbol{X}_{t_0}$ are position vectors at epochs t_1 and t_0, while $\boldsymbol{V}$ is the estimated constant velocity vector.

The robust solution of positions and velocities was applied as initial conditions to generate time series. The study focused then on discontinuities. Subsequently, the temporal correlations in the time series were examined, and noise parameters were estimated. This analysis led to a more realistic estimate of uncertainties.

2.7 Time Series

The robust positions and velocities serve as a-priori values to calculate time series, where one position is estimated for each station per day. The daily positions are stabilized (i.e. brought into a reference frame) by the robust positions of the IGS sites.

Discontinuities were detected at the stations:

- HAMD, due to the Iran – Iraq order earthquake of 12.11.2017.
- NS35, due to the relocation of the station for renovation of the supporting building.
- NS16
- NS12.

Moreover, Outliers were removed after a χ^2-test. Daily results that changed the χ^2 value by larger than 15 were regarded as outliers. This process cleans the time series. An exampe of a time series before and after cleaning is presented in Fgiure 2.

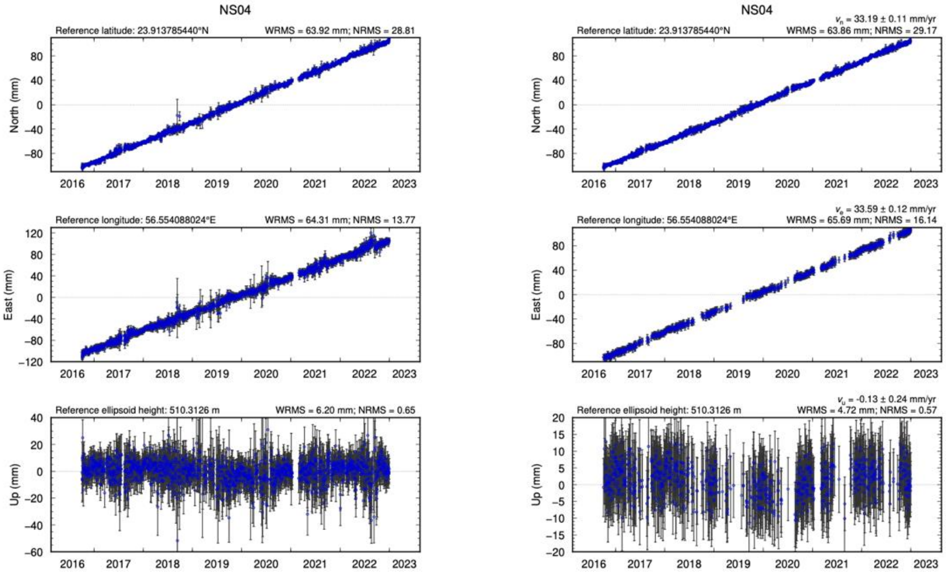


Figure 2: Time series oft he station NS04 before and after cleaning

2.8 Final Positions and Velocities in ITRF20

The above-mentioned discontinuities were modeled in the next round of calculating positions and velocities before and after each discontinuity to avoid single solutions across the relocations. Figure 3 presents the results.

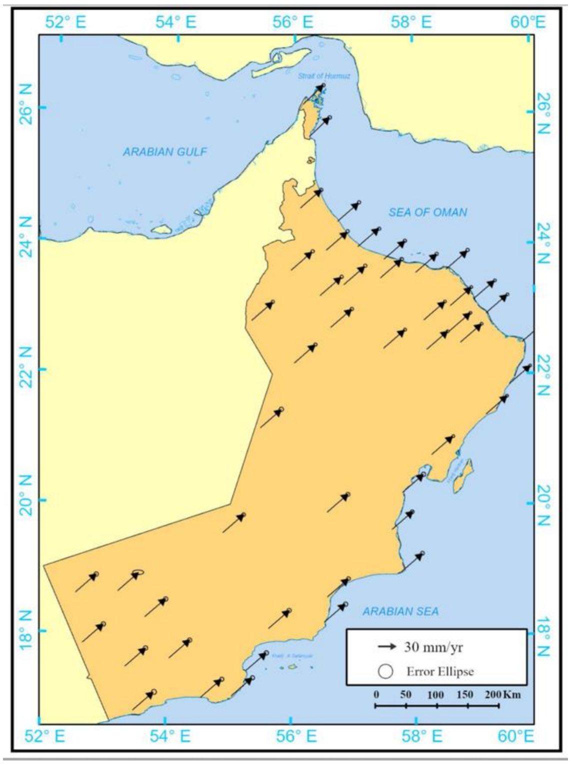


Figure 3: Final horizontal velocity field of OMANCORSNET in ITRF20

3. Realization of the New Reference Frame ONGD23

The final positions and velocities were implemented to realize the new reference frame as follows:

- The velocity field was recalculated with the well-behaved sites, 15 IGS (Figure 4) and 39 OMANCORSNET (Figure 5) stabilization stations.
- An Oman block was defined by the following OMANCORSNET sites: NS01, NS02, NS03, NS04, NS05, NS06, NS07, NS09, NS10, NS11, NS12, NS15, NS18, NS19, NS20, NS21, NS22, NS23, NS25, NS26, NS27, NS28, NS29, NS30, NS31, NS33, NS36, NS37, NS40, NS41, NS42, NS43, NS44, NS45, NS46, NS47, NS48, named the Oman block stabilization sites (Figure 6). The sites exhibit no irregularities, such as discontinuities or significant data gaps.
- The epoch of each site is determined by the time interval of the observation data. The positions at the epoch 2023.0 were calculated using Equation 1 following theassumption that temporal variations of position are piecewise linear.

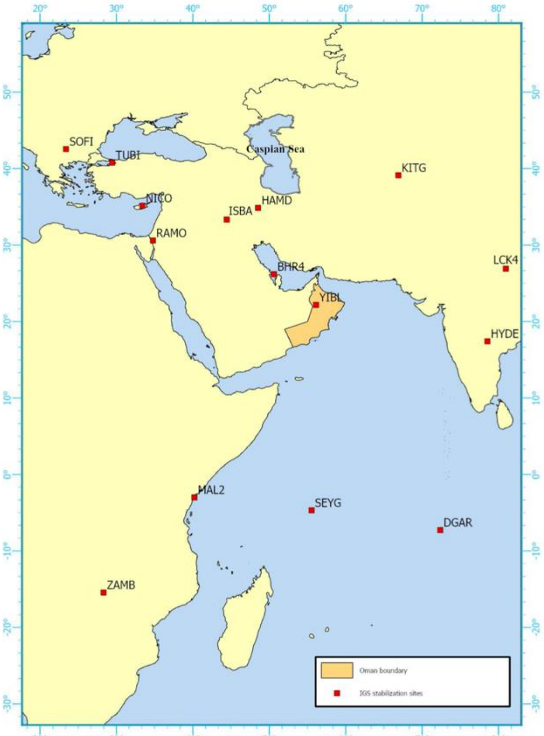


Figure 4: IGS stabilization sites

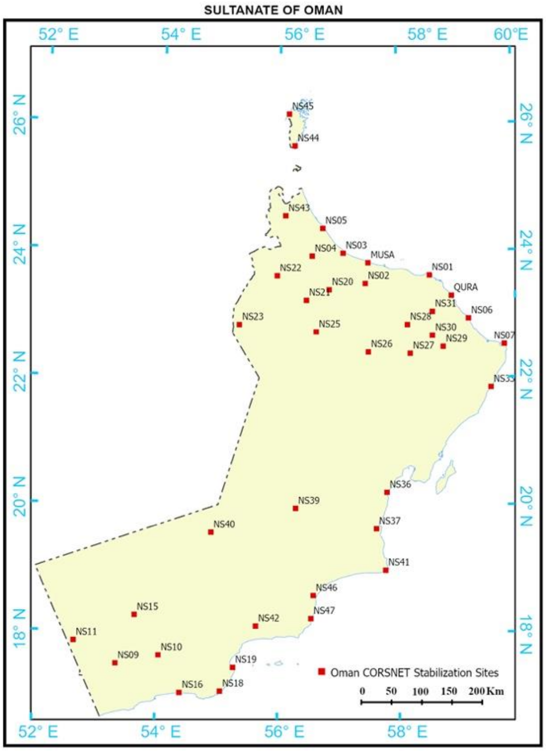


Figure 5: OMANCORSTNET stabilization sites

- Block rotation rate was calculated so that when applied to the velocity field, the residual velocities of the Oman block sites were minimized. This procedure decomposes the total observed motion to a rigid body motion, explained by rotation V_{rigid} of the Oman block, and the residuals V_{def}, that is internal deformation in the Oman block (Equation 2). The residual velocity field is expected to be minimal.

$$\boldsymbol{V} = \boldsymbol{V}_{def} + \boldsymbol{V}_{rigid} \tag{2}$$

- ONGD23 was realized by Oman block sites' positions and velocities. Positions are identical with their ITRF20 positions at epoch 2023.0, while velocities are equal to the concluded velocities for the Oman block, meaning the residual velocities V_{def} of equation 2. Figure 7 illustrates the velocity field in ONGD23, that is in fact horizontal deformation field of internal Oman.

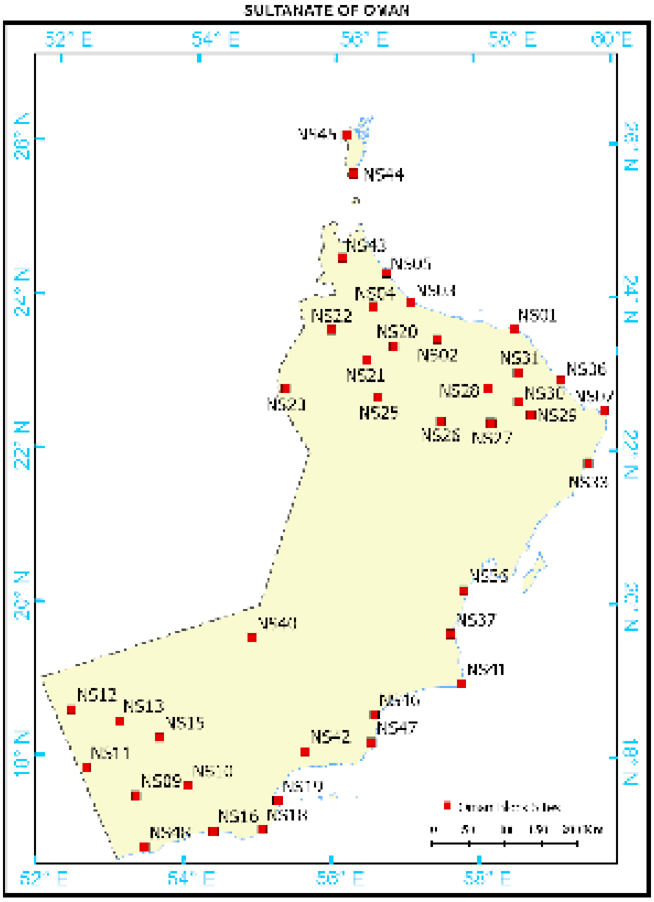


Figure 6: Oman block sites

4. Final Position and Velocity Solution

Positions and velocities were recalculated after cleaning the time series. This represents the final solution that was subsequently implemented to establish the new reference frame ONGD23. Figure 7 presents horizontal velocities of ONGD23.

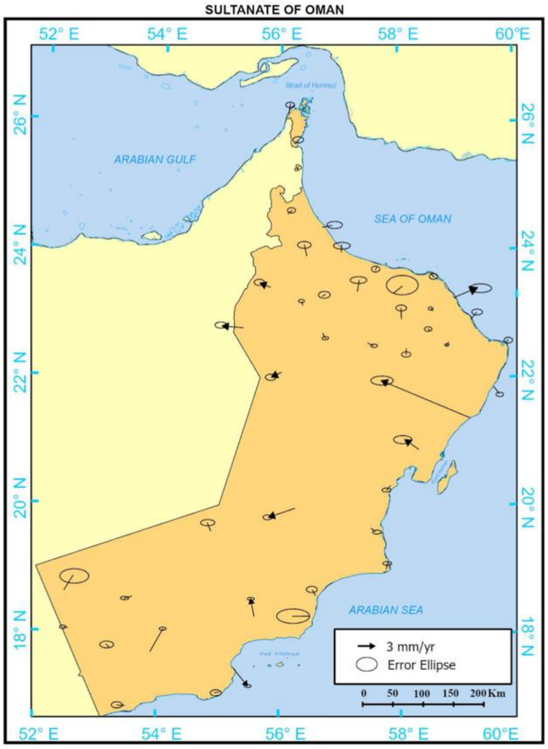


FIGURE 7: Velocity field of ONGD23

With the exception of only 1 site, the velocities are small enough to neglected in many positioning and mapping activities. The relatively large velocity at the exceptional station NS16 is to be examined, the site is likely affected by local effects.

5. Transformation Parameters

The Bursa - Wolf model was applied to evaluate transformation parameters. The model is based on small angle approximation, which assumes that sine of a small angle is equal to the angle in Radians, while cosine of a small angle is approximately equal to 1.

ONGD23 is equivalent to ITRF20 at epoch 2023.0. ITRF20 is based on the ellipsoid GRS80. The transformation parameters have been calculated between ONGD23 and ONGD17, the previous reference frame implemented by NSA.

The forward problem is described in matrix form using the equations 3 and 4:

$$\boldsymbol{X}_2 = \boldsymbol{T}_x + (1 + \delta s)\boldsymbol{R}_{xyz}\boldsymbol{X}_1 \tag{3}$$

where $\boldsymbol{X}_1(X_1,Y_1,Z_1)$ and $\boldsymbol{X}_2(X_2,Y_2,Z_2)$ are the positions of a point in the first and the second coordinate systems, $1 + \delta s$ is the scale factor and $\boldsymbol{R}_{xyz}$ is the superposition of 3 rotations.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_2 = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_1 + \begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix} + \begin{bmatrix} \delta s & R_z & -R_y \\ -R_z & \delta s & R_x \\ R_y & -R_x & \delta s \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_1 \tag{4}$$

Equation (4) is reformulated for the inverse problem:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_2 - \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_1 = \begin{bmatrix} 1 & 0 & 0 & 0 & -Z_1 & Y_1 & X_1 \\ 0 & 1 & 0 & Z_1 & 0 & -X_1 & Y_1 \\ 0 & 0 & 1 & -Y_1 & X_1 & 0 & Z_1 \end{bmatrix} \begin{bmatrix} T_x \\ T_y \\ T_z \\ R_x \\ R_y \\ R_z \\ \delta s \end{bmatrix} \tag{5}$$

Each tie point provides a set of 3 equations, and in order to perform a 7-parameter transformation, a minimum of 3 tie points is required.

An inverse problem was solved with OMANCORSNET sites as tie points of ONGD17 and ONGD23.

$$\boxed{\begin{aligned} T_x &= 0.2171 \pm 0.1305\ m \\ T_y &= -0.2409 \pm 0.1247\ m \\ T_z &= 0.1157 \pm 0.1030\ m \\ R_x &= -0.8316 \pm 3.7495\ mas \\ R_y &= 3.2598 \pm 2.5239\ mas \\ R_z &= -20.2781 \pm 4.9861\ mas \\ \delta s &= -1.6731 \pm 11.6012\ ppb \end{aligned}} \tag{6}$$

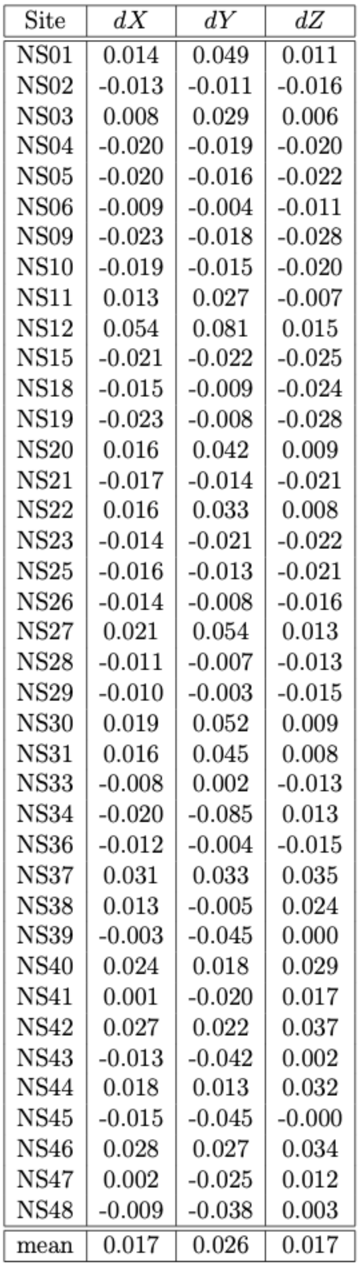
Equations (6) provide the transformation parameters. The residuals are listed in table (2), and the means of the absolute values of the residuals are provided in the last row as a quality measure.

6. Conclusion

Processing of the selected network of OMANCORSNET and IGS sites concluded a very high precision, which aligns with expectations of a stable permanent network. OMANCORSNET sites demonstrated their stability. Daily results and the combined solutions yielded highly satisfactory values. Moreover, transformation from the existing reference frame ONGD17 to ONGD23 demonstrates residuals in the order of few centimeters. Considering that ONGD17 is based on only one week of data in 2017, these results demonstrate a high level of satisfaction.

Applications of the new reference frame based on the continuous OMANCORSNET are not limited to surveying and mapping. A few examples of applications where Oman can benefit from a precisely processed reference frame can be mentioned:

- Precise deformation monitoring in oil and gas reservoirs.
- GNSS meteorology
- GPS leveling
- Deformation monitoring, for example to study tectonic motion of the Arabian plate.



Site	dX	dY	dZ
NS01	0.014	0.049	0.011
NS02	-0.013	-0.011	-0.016
NS03	0.008	0.029	0.006
NS04	-0.020	-0.019	-0.020
NS05	-0.020	-0.016	-0.022
NS06	-0.009	-0.004	-0.011
NS09	-0.023	-0.018	-0.028
NS10	-0.019	-0.015	-0.020
NS11	0.013	0.027	-0.007
NS12	0.054	0.081	0.015
NS15	-0.021	-0.022	-0.025
NS18	-0.015	-0.009	-0.024
NS19	-0.023	-0.008	-0.028
NS20	0.016	0.042	0.009
NS21	-0.017	-0.014	-0.021
NS22	0.016	0.033	0.008
NS23	-0.014	-0.021	-0.022
NS25	-0.016	-0.013	-0.021
NS26	-0.014	-0.008	-0.016
NS27	0.021	0.054	0.013
NS28	-0.011	-0.007	-0.013
NS29	-0.010	-0.003	-0.015
NS30	0.019	0.052	0.009
NS31	0.016	0.045	0.008
NS33	-0.008	0.002	-0.013
NS34	-0.020	-0.085	0.013
NS36	-0.012	-0.004	-0.015
NS37	0.031	0.033	0.035
NS38	0.013	-0.005	0.024
NS39	-0.003	-0.045	0.000
NS40	0.024	0.018	0.029
NS41	0.001	-0.020	0.017
NS42	0.027	0.022	0.037
NS43	-0.013	-0.042	0.002
NS44	0.018	0.013	0.032
NS45	-0.015	-0.045	-0.000
NS46	0.028	0.027	0.034
NS47	0.002	-0.025	0.012
NS48	-0.009	-0.038	0.003
mean	0.017	0.026	0.017

Table 2: Residual (in meters) of transformation from ONGD17 to ONGD23 with the average of the absolute value of residuals

7. Further Studies

Complementary to the establishment of a stable horizontal reference frame in Oman, the following studies can improve geodetic, surveying and mapping activities in Oman, promote Geodesy internationally and deepen the regional knowledge of the earth deformations.

- The implementation of a new Geoid model as a vertical datum will hold significant value in Oman. This will be complementary to the horizontal reference frame ONGD23. A well modeled Geoid goes hand in hand with OMANCORSNET to establish GNSS leveling across the country. Precise levelling in harsh climate such as vast parts of Oman is cumbersome, expensive and impossible to carry out in several months of the year. On the other hand repeated vertical positioning is essential in regions of important vertical deformation, for example in oil and gas reservoirs and in coastal regions with strong climate impacts.
- With the advancements in satellite Geodesy, the frequent updates of international references frames and the availability of improved correction and processing models, it is recommended to periodically reprocess old data.
- Comparatively larger deformations are observed along the northern coastline, as well as around oil reservoirs with large data gaps. Densification of OMANCORSNET in these regions will give a more complete image of Oman internal deformations. InSAR (Interferometric Synthetic Aperture Radar) is another valuable tool to quickly study the vertical deformation in the center of Oman where OMANCORSNET is not dense.
- Beyond national interests, international community will benefit from a combination of OMANCORSNET with neighboring countries. By merging with the other CORS networks on the Arabian peninsula, it is possible to establish a geodetically valuable reference frame for the Arabian plate.

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