Preliminary Investigation of Applications of KINEMATIC KSA-GRF in Saudi Arabia

Iurii GOLUBINKA, Muhammad ALQARNI, Othman ALRUBAYYI, Oleksandr LOMPAS, Abdulwasiu SALAWU, Tariq ALQRNI, Sultan ALSHAHRANI and Rossen GREBENITCHARSKY
General Authority for Survey and Geospatial Information, Kingdom of Saudi Arabia

Key words: Temporal Geodetic Reference System, Kinematic Geodetic Reference Frame (KGRF), Crustal Motion, SANSRS, Geodynamics Monitoring

1. SUMMARY

The General Authority for Survey and Geospatial Information (GEOSA) of Saudi Arabia has formulated a conceptual framework for a Temporal Saudi Arabia National Spatial Reference System (T-SANSRS). The implementation of this system is necessitated by the increasing demand for high-precision four-dimensional (4D) geodetic data that accurately accounts for the Earth's stochastic and systematic dynamic processes.

The T-SANSRS architecture comprises three primary components: a Kinematic Geodetic Reference System (KGRS), a Time-varying Vertical Reference System (TVRS), and a Dynamic Geoid (DGEOID). This paper delineates the preliminary research findings regarding the establishment and implementation of the KGRS within the Kingdom. The primary objective of this system is to provide highly accurate spatial positioning while monitoring temporal variations resulting from regional and local geodynamic activities, as well as various anthropogenic influences.

Preliminary Investigation of Applications of KINEMATIC KSA-GRF in Saudi Arabia

Iurii GOLUBINKA, Muhammad ALQARNI, Othman ALRUBAYYI, Oleksandr LOMPAS, Abdulwasiu SALAWU, Tariq ALQRNI, Sultan ALSHAHRANI and Rossen GREBENITCHARSKY, Kingdom of Saudi Arabia

2. INTRODUCTION

The Earth's surface is inherently dynamic, undergoing continuous deformation driven by tectonic, seismic, and anthropogenic factors. Consequently, geodetic science has transitioned toward a four-dimensional approach to account for these temporal variations. In response to these requirements, the General Authority for Survey and Geospatial Information (GEOSA) of the Kingdom Saudi Arabia has initiated the National Temporal Geodetic Infrastructure (NTGI). This initiative aims to provide a sustainable, high-precision reference system and its subsequent realizations. Central to this infrastructure is the Temporal Saudi Arabia National Spatial Reference System (TSANSRS), a conceptual framework that integrates three primary components: a Kinematic Geodetic Reference System (KGRS); a Time-varying Vertical Reference System (TVRS); a Dynamic Geoid (DGEOID).

The KGRF serves as the practical realization of this system. As reported by (Alshahrani, et al, 2025), it leverages the robust KSA-CORS (Continuously Operating Reference Stations) network alongside planned Core Collocated Stations, which should integrate advanced geodetic techniques including VLBI, SLR, DORIS, and GNSS with absolute, superconducting, or quantum gravimetry. The primary objective of the KGRF is to provide precise 3D positioning which accounts for the kinematic processes of the Earth's crust resulting from geodynamic and anthropogenic activities across global, regional, and local scales

3. INTERNATIONAL DEVELOPMENTS

The global geodetic community increasingly acknowledges that static reference systems are no longer sufficient for high-precision applications, given the inherently dynamic nature of the Earth's surface. The ITRF2020 currently represents the most sophisticated global terrestrial reference frame, explicitly modeling tectonic plate motion and post-seismic deformations (Altamimi et al., 2023a). Consequently, several nations have pioneered the transition from static to semi-kinematic or fully kinematic reference frames, tailored to their specific geodynamic environments, to sustain geodetic accuracy over time.

- New Zealand (NZGD2000): This semi-dynamic datum is fixed to a specific epoch but incorporates a National Deformation Model which accounts for secular plate motion and episodic events, such as seismic activity, thereby ensuring stability while maintaining high-precision alignment with global frames (Mercury Project Solution, 2018).

- Malaysia (MGRF2020/GDM2020): To address a tectonic drift of approximately 3 cm/year, Malaysia uses the MGRF2020/GDM2020 system, which provides coordinates based on velocity fields and post-seismic deformation models, enabling grid-based corrections for GIS and cadastral systems (Azhari et al., 2020).
- United States (NSRS Modernization): The National Geodetic Survey is moving toward plate-fixed semi-dynamic frames (e.g., NATRF2022) that utilize intra-frame velocity models to account for residual motions. Under this modernized system, coordinates will be time-tagged and derived primarily from GNSS observations (NGS, 2017).
- Chile (REDGEOMIN): the static reference frames have incurred meter-level misclosures in seismic regions characterized by significant co-seismic displacements and inter-seismic rates. To mitigate these errors, the fully dynamic REDGEOMIN@2022.00 frame was developed which integrates inter-seismic, co-seismic, and post-seismic deformations to achieve millimeter-to-centimeter precision with real-time coordinates (Tarrío et al., 2024).

4. RESEARCH METHODOLOGY AND PRELIMINARY INVESTIGATION

The research uses GNSS data, processed using Bernese software (Dach et al., 2015), from 209 stations of the KSA-CORS network (see Figure 1) spanning a interval of over seven years.

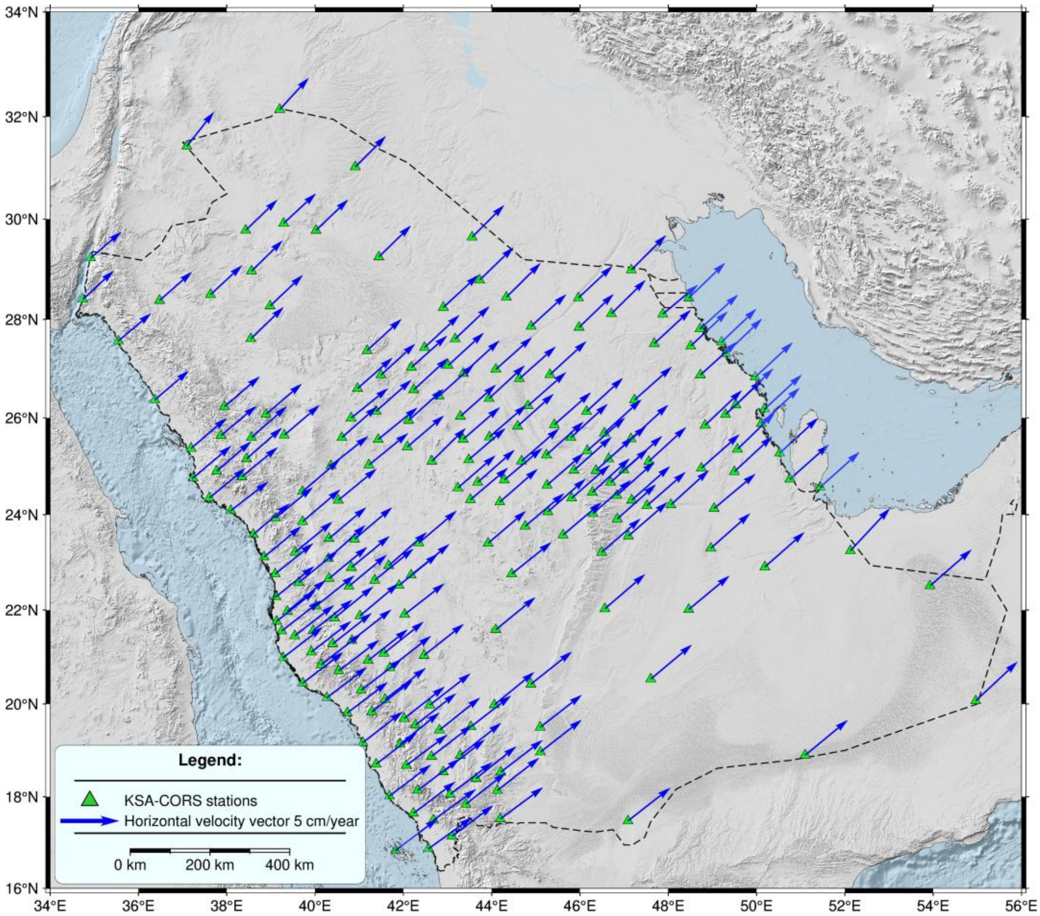


Figure 1. Distribution of KSA-CORS stations and their velocities

This research focused on the differentiation of crustal kinematics by identifying and isolating periodic signals (annual and semi-annual cycles), episodic seismic impacts (co-seismic and post-seismic deformations), and secular tectonic motions. Furthermore, the study examined intraplate variations resulting from local geodynamic processes or anthropogenic influences.

4.1 Periodic Motions

The majority of GNSS stations exhibit non-linear periodic fluctuations of an annual and semi-annual nature. These variations are characterized as residual signals resulting from the inherent limitations in the accuracy of existing models for tidal and non-tidal loading effects. The Bernese facilitates the extraction of these periodic components through the analysis of long-term positional time series (Dach et al., 2015). The spatial distribution and amplitudes of the annual and semi-annual signals across the KSA-CORS network are illustrated in Figure 2 and Figure 3, respectively.

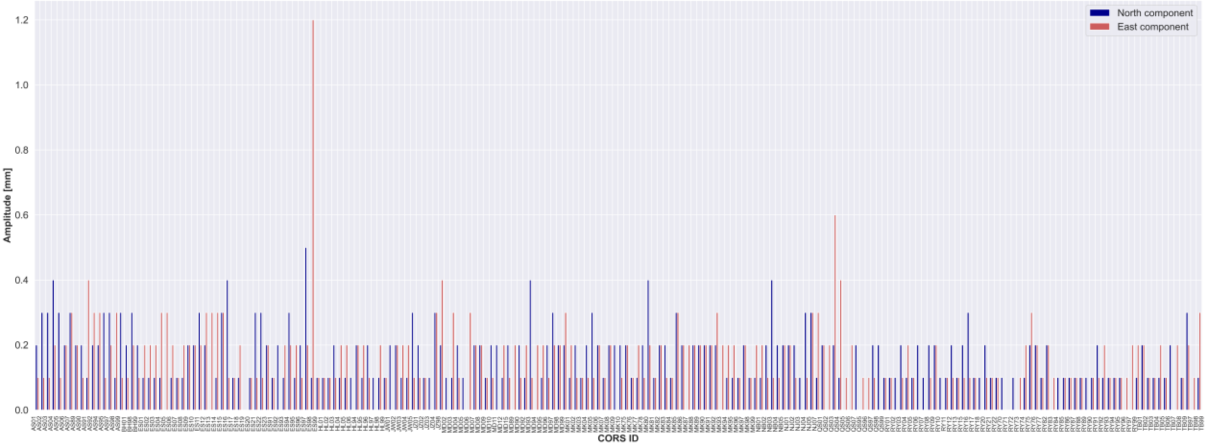


Figure 2. Amplitudes of annual periodic signals in KSA-CORS time series

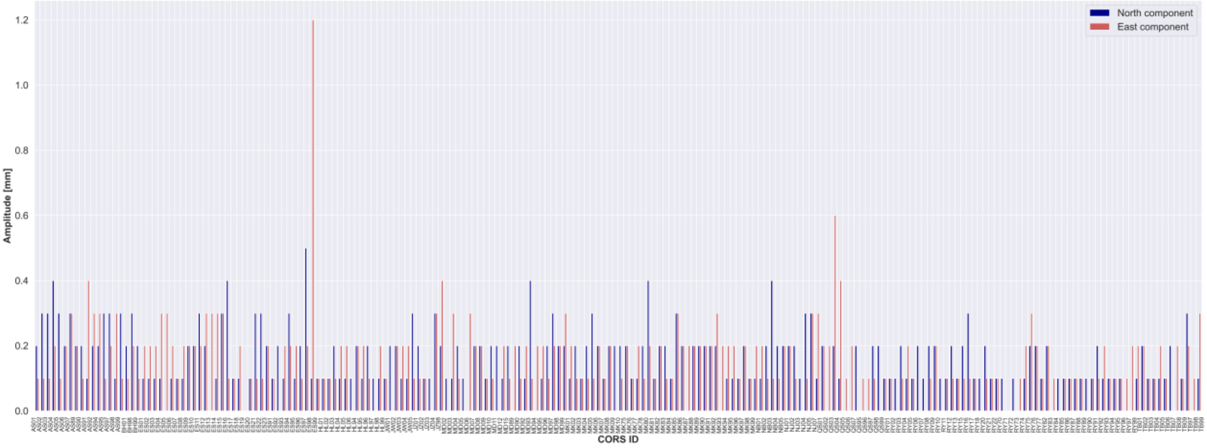


Figure 3. Amplitudes of semi-annual periodic signals in KSA-CORS time series

An analysis of the KSA-CORS dataset revealed that the maximum horizontal amplitudes for annual signals for North and East components reached 2.2 mm and 4.2 mm. Semi-annual signals exhibited lower magnitudes, with maximum amplitudes of up to 1.2 mm observed in the East component.

4.2 Seismic motions

The stability of a geodetic reference frame is significantly influenced by high-magnitude seismic events. The extent of this impact is contingent upon the earthquake magnitude and the station's proximity to the epicenter, manifesting as abrupt, episodic displacements of geodetic points, such as those in a CORS network. These co-seismic displacements are quantified through the rigorous analysis of discontinuities within long-term positional time series. The Bernese software provides a tools for such analyses (Dach et al., 2015), enabling the detection and recovery of co-seismic effects from two seismic events: the 12 November 2017 earthquake (M_{ω}=7.3) and the 6 February 2023 earthquake (M_{ω}=7.8). These events caused measurable shifts across several stations within the KSA-CORS network (see **Fejl! Henvisningskilde ikke fundet.**). The statistical characteristics of these co-seismic displacements are summarized in Table 1.

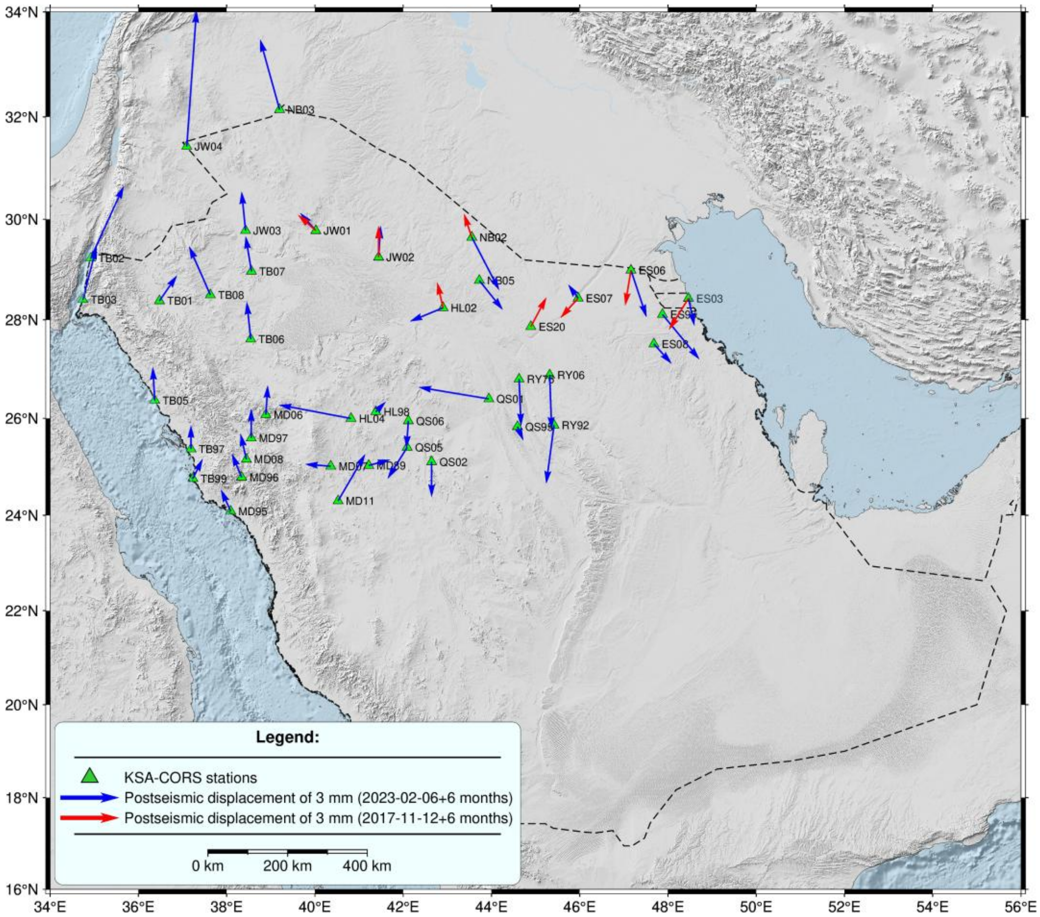


Figure 4. Co-seismic displacements of earthquakes-affected KSA-CORS

The analysis demonstrates that seismic events induce displacements in the geodetic infrastructure. For instance, for M_{ω}=7.8 earthquake, a maximum displacement of 7 mm was recorded at station JW04. This result confirms the necessity of a kinematic reference frame to account for such episodic deformations, even in regions considered geologically stable.

Table 1. Statistical characteristics of co-seismic displacements

Earthquake		d_{erq} [km]	δX_{CSD}^{North} [mm]	δX_{CSD}^{East}[mm]	δX_{CSD}[mm]
Epoch: 2017-11-12, M_{ω}=7.3	Max	797	1.6	0.8	1.9
	Min	626	-1.8	-1.0	1.2
	Mean	738	0.3	-0.4	1.5
Epoch:2023-02-06, M_{ω}=7.8	Max	1486	7.0	1.9	7.0
	Min	598	-3.0	-3.7	0.7
	Mean	1217	0.5	-0.1	2.1

Post-seismic motions are inherently non-linear and are primarily driven by stress relaxation within the mantle or the low-viscosity layers of the Earth's crust following a seismic event (Sabadini et al., 2004). The most recent realizations of the International Terrestrial Reference System (ITRS) namely ITRF2014 and ITRF2020 account for post-seismic deformation by employing logarithmic and exponential decay functions (Altamimi et al., 2023a).

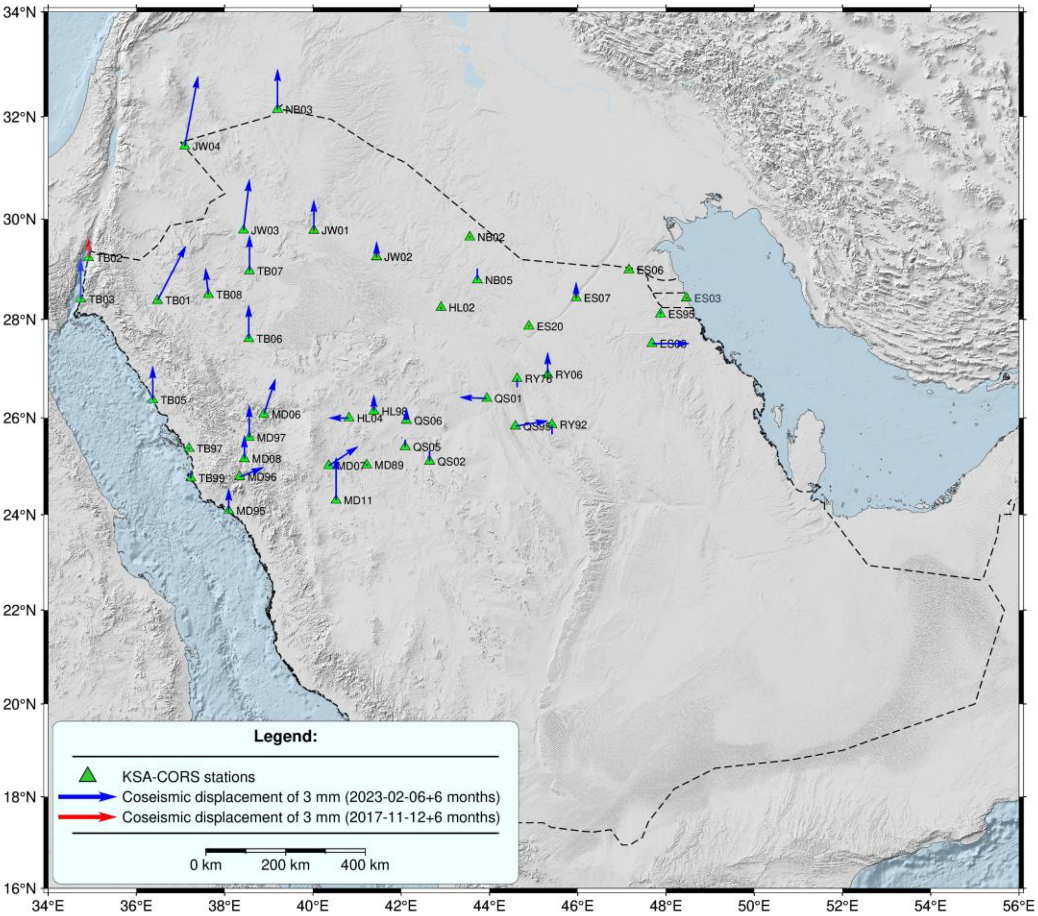


Figure 5. Post-seismic displacements of earthquakes-affected KSA-CORS

Adopting a similar methodology, we have developed post-seismic deformation models for the stations affected by the two previously mentioned earthquakes. Figure 5 illustrates the post-seismic displacements for the affected KSA-CORS stations, calculated for a temporal window of six months following the occurrence of each earthquake.

Modeling of post-seismic deformation within the KSA-CORS network indicates that the relaxation phase following the 6 February 2023 earthquake significantly impacted specific stations, resulting in displacements of up to 3 mm within a six-month epoch post-event. In contrast, the relaxation effects associated with the 12 November 2017 earthquake were found to be negligible.

4.3 Tectonic motions

The tectonic motion of the Arabian Plate can be modeled using the established geodetic approach in which the movement of a rigid plate on a spherical Earth is represented as a rotation around an Euler pole. Mathematically, this motion is defined by Euler's Fixed Point Theorem and is characterized by the spherical coordinates of the rotation pole (latitude and longitude) and the angular velocity, or alternatively, by its three Cartesian components, depending on the reference frame employed.

To calculate the rotation parameters for the Arabian Plate, we utilized linear velocities derived from the KSA-CORS network (see Figure 1), determined through a rigorous combination of all available daily solutions. The resulting Euler pole parameters are presented in Table 2 alongside comparative results from previous studies.

Table 2. Rotation parameters for the Arabian tectonic plate

Solution	ω_X [mas/y]	ω_Y [mas/y]	ω_Z [mas/y]
EDG solution	1.135	-0.151	1.456
KSA-GRF17 (GEOSA, 2024)	1.199	-0.107	1.468
ITRF2014 (Altamimi Z, et al, 2017)	1.154	-0.136	1.444
ITRF2020 (Altamimi Z, et al, 2023b)	1.129	−0.146	1.438

The established model of constant tectonic motion facilitates the estimation of the internal kinematics of the Arabian Plate. This analysis was performed by deriving the residual (internal) velocities of the KSA-CORS stations, which were computed by subtracting the predicted secular tectonic motion from the observed combined velocities of the network. The resulting intraplate velocity field is illustrated in

.

As illustrated in Figure 6, the spatial distribution of the residual velocity vectors reveals distinct patterns. Specifically, several clusters of stations exhibit homogeneous velocity characteristics, which likely signify the influence of local geodynamic activity within the region. However, a definitive interpretation of these features necessitates a multi-disciplinary analysis incorporating independent geological and geophysical datasets, which remains beyond the scope of the current study.

By employing the Least Squares Collocation (LSC) technique based on the KSA-CORS intraplate velocities, we developed a regional model of intraplate motion represented as a regular grid. To construct the necessary covariance matrices, the Hirvonen analytical covariance function was utilized. The parameters for this analytical function were derived by fitting it to the empirical covariances of the observed data.

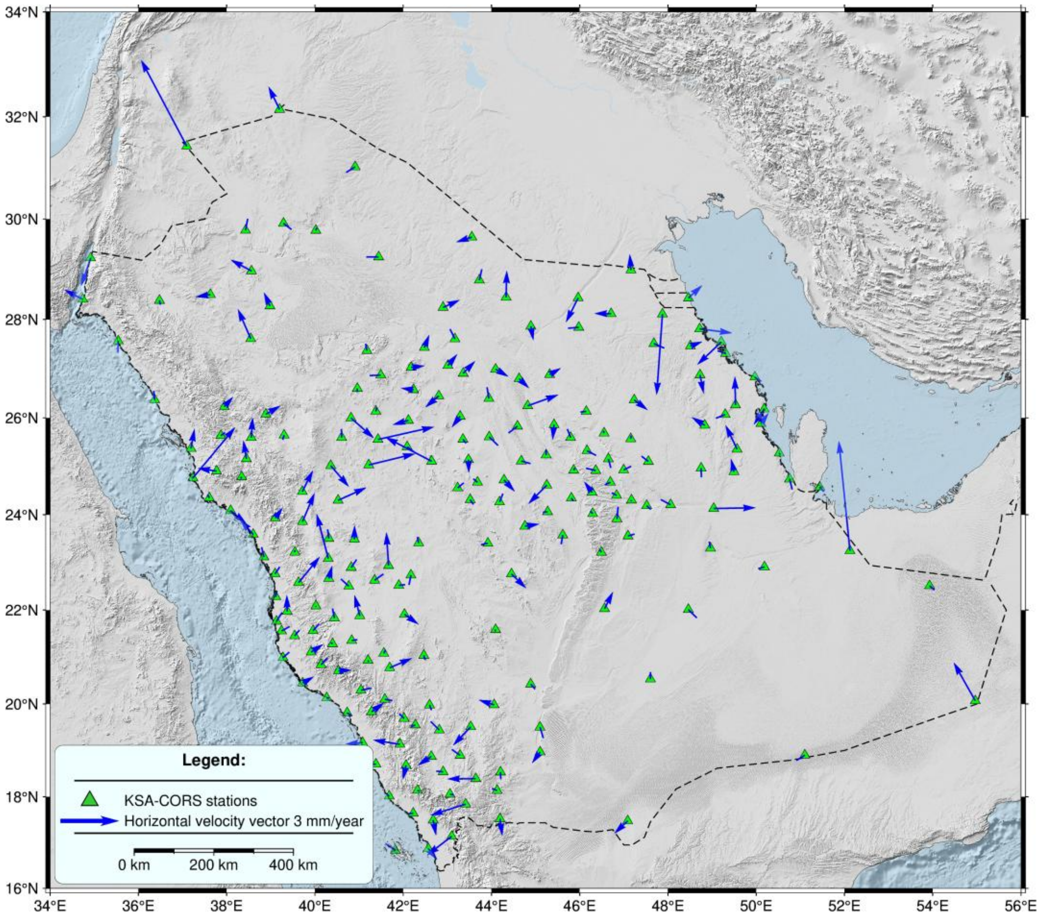


Figure 6. KSA-CORS intraplate velocities

The resulting velocity grid is depicted in Figure 7. Furthermore, the statistical evaluation of the grid quantified as the residuals between the observed and modelled velocities at the KSA-CORS station positions is summarized in Table 3.

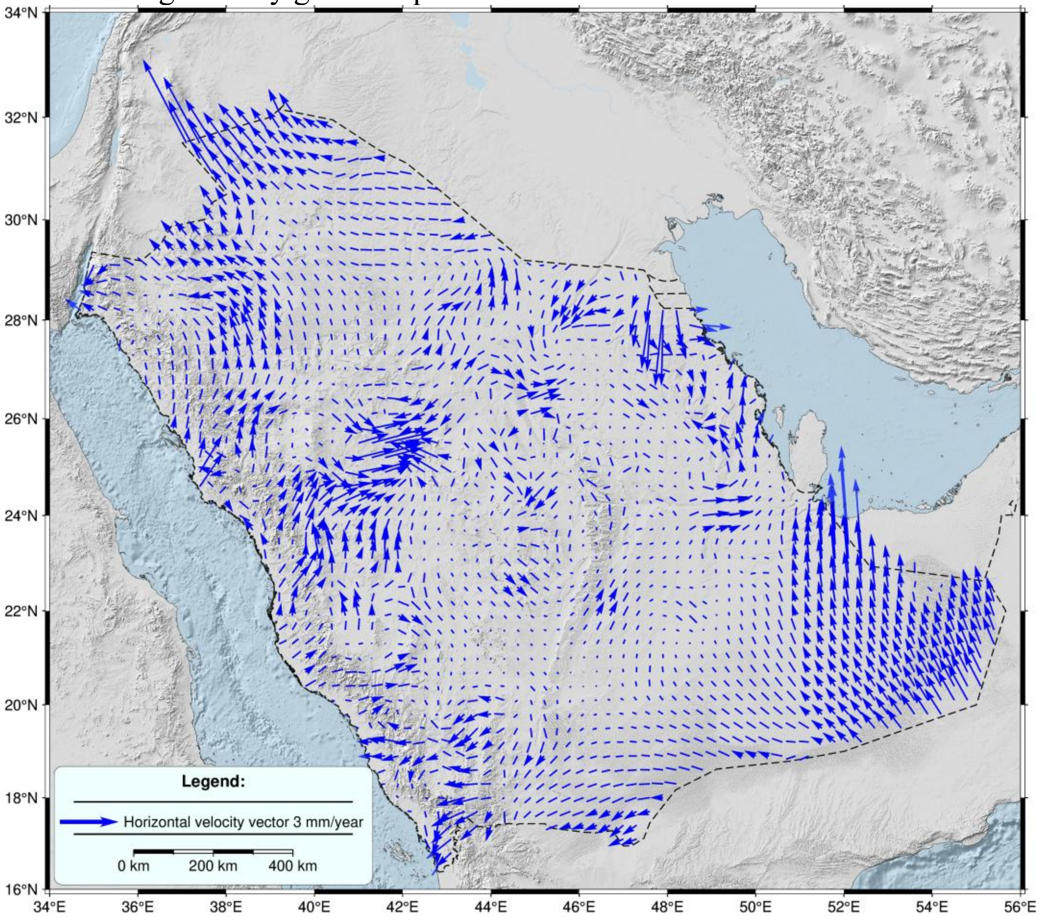


Table 3. Statistical summary of residuals between observed and modelled intraplate velocities within the KSA-CORS Network

Component	Max [mm/year]	Max [mm/year]	Mean [mm/year]	STD [mm/year]
North	0.25	-0.22	0.00	0.04
East	0.17	-0.17	0.00	0.04

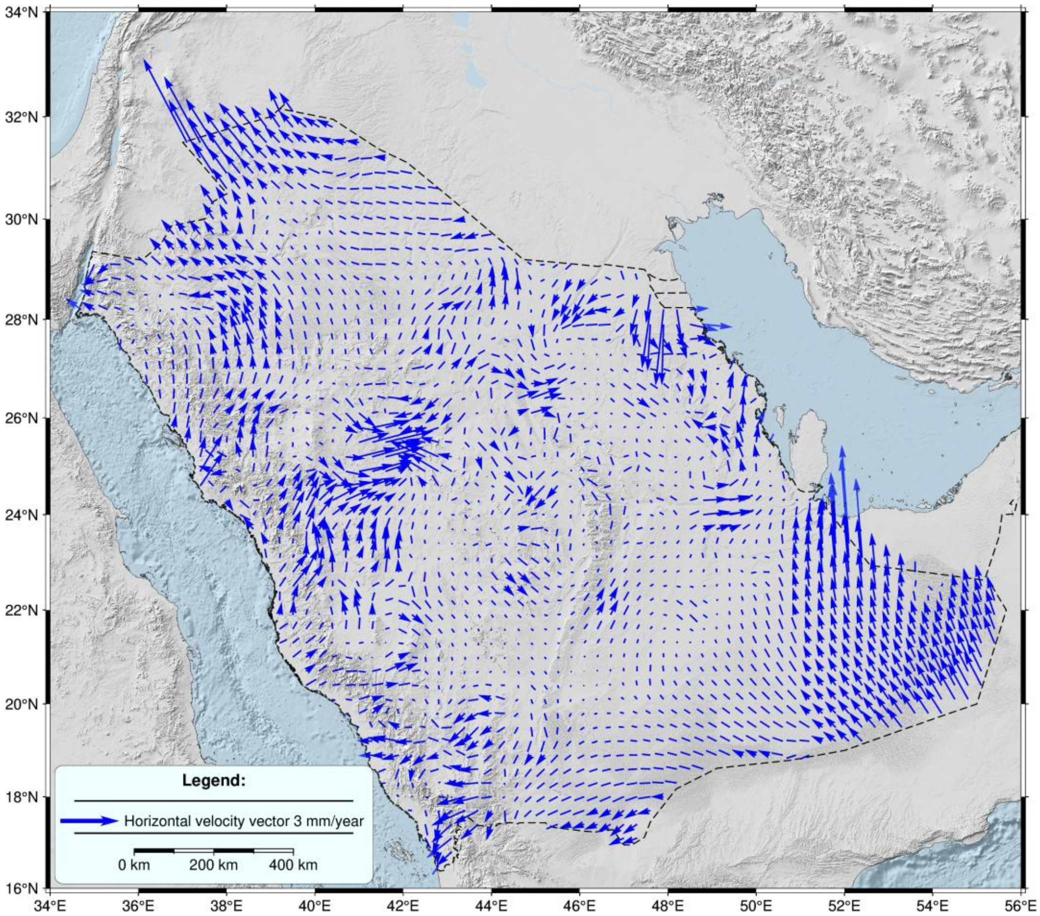


Figure 7 KSA intraplate velocities model

5. INTERPRETATION OF RESULTS

The results presented herein confirm that the kinematics of the Arabian Plate are not uniform, encompassing both homogeneous tectonic and inhomogeneous intraplate motion. These factors undoubtedly influence various geospatial applications by diminishing Positional Uncertainty (PU). However, the extent of this impact is contingent upon the accuracy requirements of the specific application.

The steady drift of the Arabian Plate in a north-easterly direction at an approximate rate of 4.2 cm/year (determined as the mean velocity for the entire plate) has immediate implications for absolute positioning technologies, such as Precise Point Positioning (PPP). Modern PPP services (e.g., Trimble RTX, SmartNet Global) achieve centimeter-level accuracy within a global reference frame at the epoch of observation. However, without the rigorous propagation of these coordinates to the national reference frame epoch, significant spatial distortions arise. Notably, the General Authority for Roads (RGA) regulations for autonomous vehicles in Saudi Arabia mandate that absolute GNSS positioning must adhere to the latest version of the Saudi Arabia National Spatial Reference System (RGA, 2023). Neglecting the

4 cm/year tectonic drift could introduce critical safety hazards, as a vehicle's perceived position would fail to align precisely with its high-definition (HD) road topology maps.
While global plate motion models, such as NNR-NUVEL-1A, provide a generalized baseline for tectonic drift, this study reveals a significant mean discrepancy of 6 mm/year when compared to the velocity model derived specifically from KSA-CORS data. The application of global models may be sufficient for some geospatial applications; however, it leads to a rapid degradation of accuracy in high-precision sectors such as geodetic and precise surveying applications.

Figure 8 illustrates the temporal intervals during which the discrepancy between global and regional tectonic plate models will attain the Positional Uncertainty (PU) of certain geospatial applications based on National geodetic specifications (GEOSA, 2025) and (Stanaway et al., 2013).

Even a marginal model error of 6 mm/year can result in a cumulative misalignment that exceeds the PU thresholds of precise surveying projects within a short temporal window (see Figure 8). This divergence underscores the necessity of adopting a robust regional kinematic model to ensure long-term consistency between the national geodetic foundation and physical real-world coordinates.

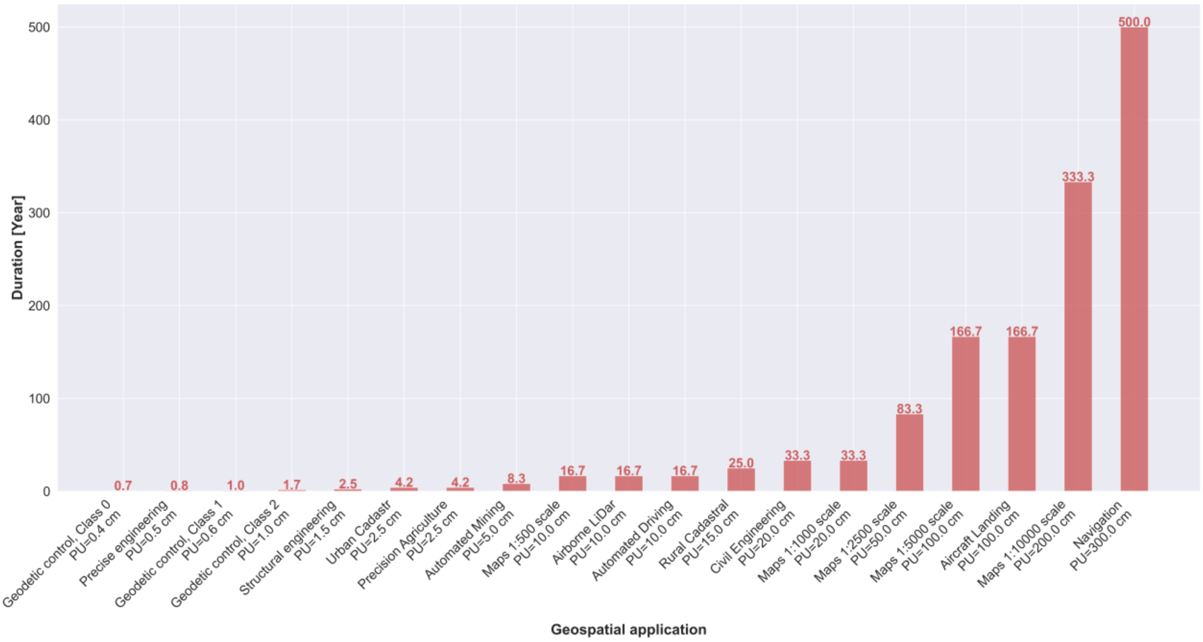
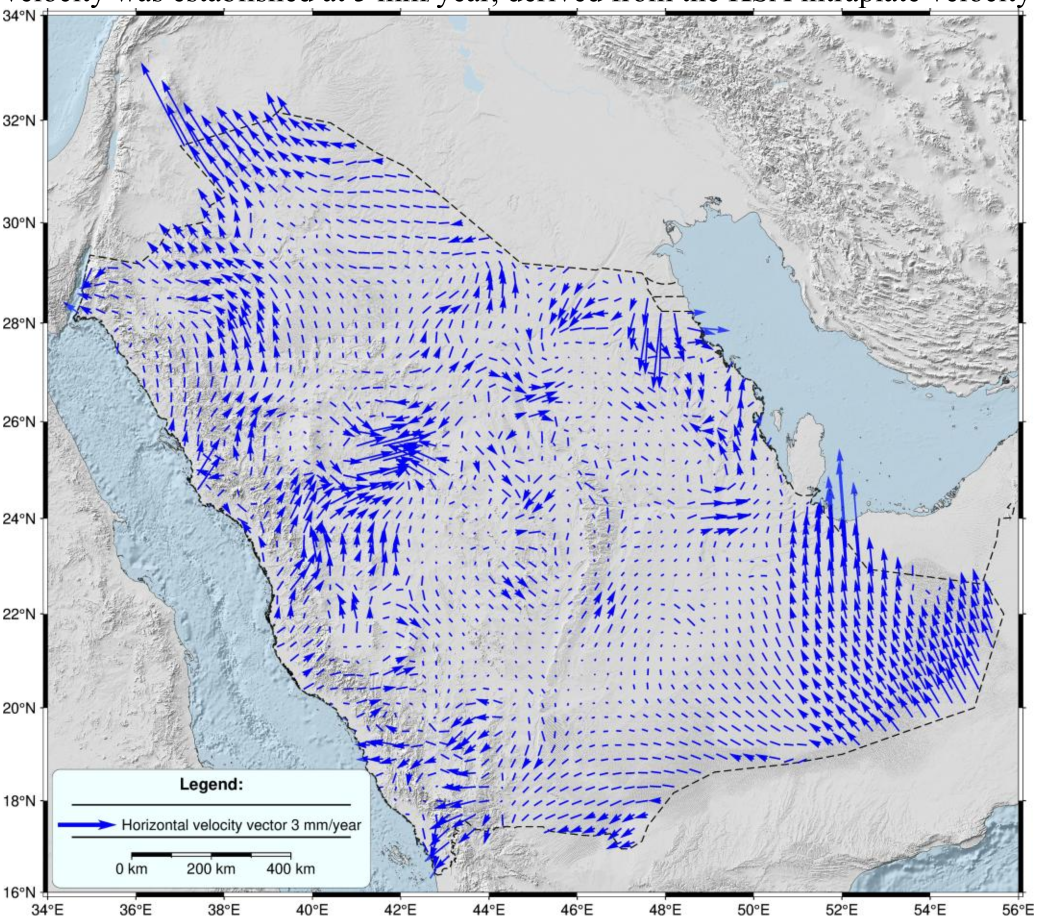


Figure 8. Impact of tectonic plate motion model discrepancies on the PU of diverse geospatial applications

To investigate the influence of regional geodynamics, the maximum magnitude of intraplate velocity was established at 5 mm/year, derived from the KSA intraplate velocity model (see Figure 7). The temporal analysis presented in Figure 9**Fejl! Henvisningskilde ikke fundet.**, illustrates the intervals at which these intraplate velocities exceed the accuracy thresholds of various geospatial applications (GEOSA, 2025), (Stanaway et al., 2013).



The results indicate that neglecting these intraplate motions leads to a significant degradation of precision. For a Class 0 geodetic network, coordinate integrity may be compromised in as little as 10 months if these velocities are not modeled. Conversely, the impact on lower-precision applications, such as general GIS, mapping, and navigation, remains negligible within standard maintenance cycles.

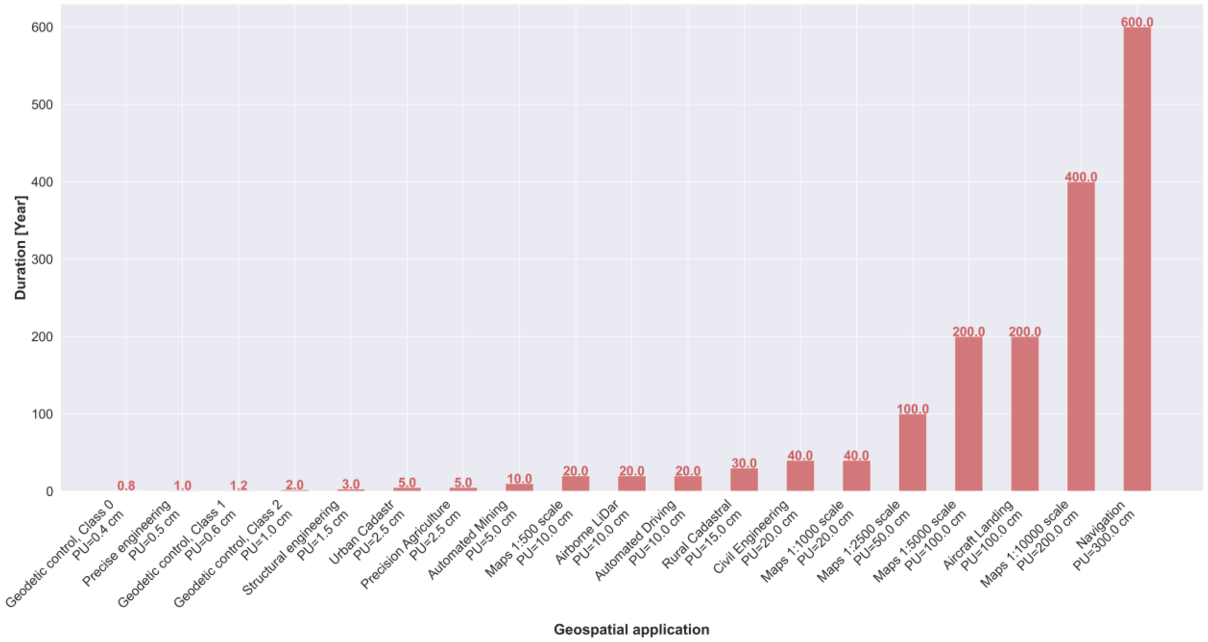
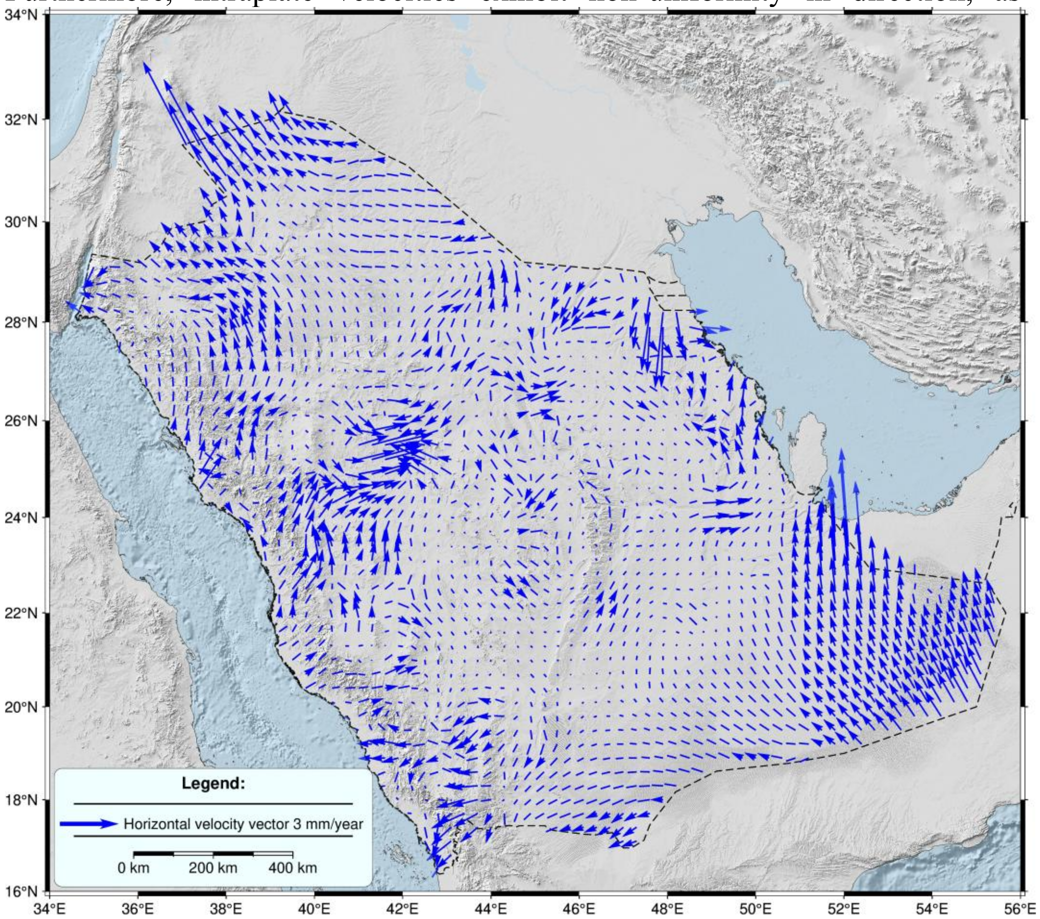


Figure 9. Temporal impact of Arabian intraplate motions on the PU of various geospatial applications

Furthermore, intraplate velocities exhibit non-uniformity in direction, as illustrated in Figure 7. This spatial inhomogeneity introduces additional deleterious effects on positional accuracy. The magnitude of this impact can be estimated by calculating the intraplate offset the change in distance between two points resulting from their relative displacement.



To quantify this effect within the Arabian Plate, the intraplate velocity grid was categorized into six distinct clusters using a K-means algorithm, accounting for both the magnitude and orientation of the velocity vectors (see Figure 10 Distribution of clusters of KSA intraplate velocities

Using the mean values from Table 4 we computed the annual mean displacements for each cluster, resolved into North and East components. To quantify the relative impact of intraplate motion, we calculated intraplate offsets by designating Cluster 0 as a reference and determining the relative displacement between it and the remaining clusters (see Table 5).

Table 5 Relative intraplate offsets between Cluster 0 and remaining clusters

Cluster #	Offset [mm]
1	3.5
2	5.5
3	3.8
4	3.7

5	4.3

Analysis of the results in Table 5 reveals that neglecting intraplate movements between Cluster 0 and Cluster 1 induces a positional distortion of 3.5 mm/year. While the offsets in Clusters 1, 3, and 4 remain below the PU thresholds established for Class 0 geodetic control (GEOSA, 2025), a contrary trend is observed in Clusters 2 and 5.

These findings indicate that intraplate motions must be rigorously accounted for in high-precision geodetic applications. This is particularly critical for long-linear engineering projects (such as pipelines and highways) and other surveying tasks where cumulative relative displacements can compromise structural integrity or geodetic consistency over time.

) The statistical characteristics of each cluster are detailed in Table 4.

Table 4 Statistics of clusters of KSA intraplate velocities

Cluster Number	**Cluster colour**	**Intraplate velocities azimuths [^{0}]**			**Intraplate velocities magnitudes [mm/year]**		
		Min	**Max**	**Mean**	**Min**	**Max**	**Mean**
0	Red	0	63	24	0.0	2.6	0.4
1	Magenta	64	151	104	0.0	2.5	0.4
2	Blue	152	219	193	0.0	3.0	0.3
3	Cyan	220	269	244	0.0	1.3	0.3
4	Green	270	320	297	0.0	2.1	0.3
5	Brown	321	360	343	0.0	4.9	0.4

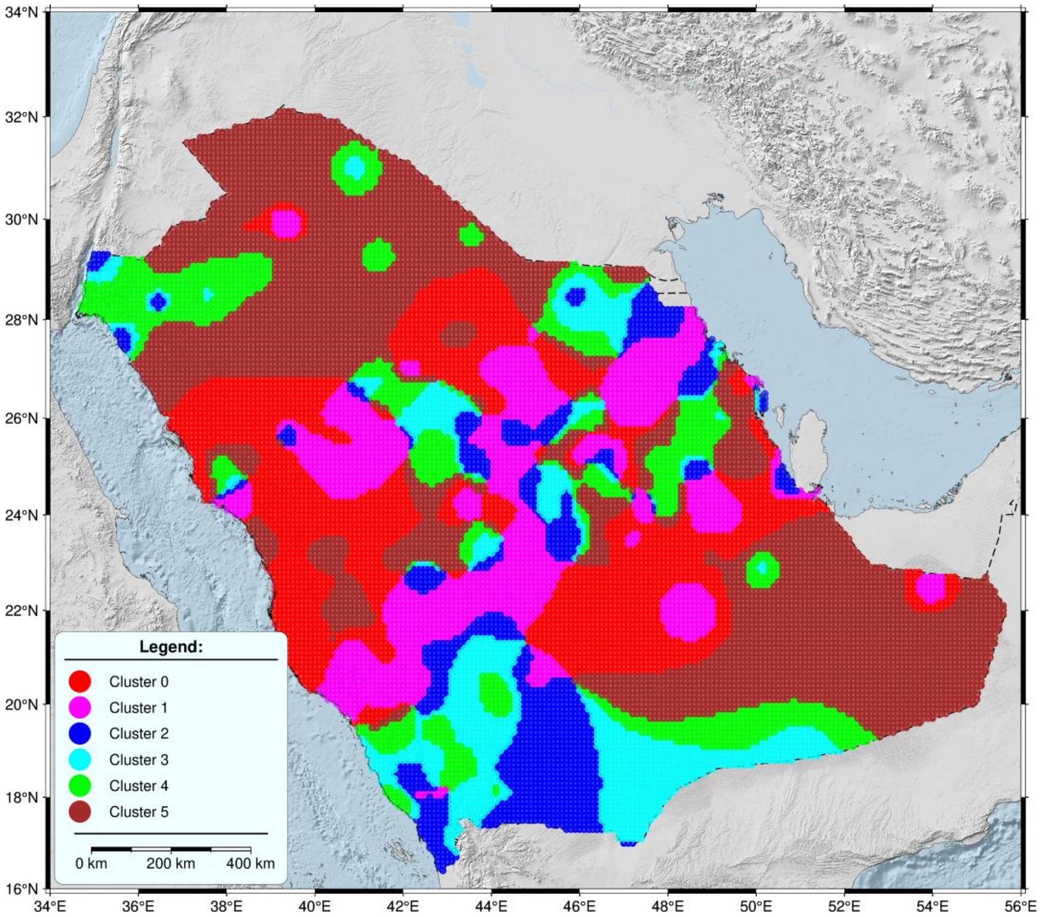


Figure 10 Distribution of clusters of KSA intraplate velocities

Using the mean values from Table 4 we computed the annual mean displacements for each cluster, resolved into North and East components. To quantify the relative impact of intraplate motion, we calculated intraplate offsets by designating Cluster 0 as a reference and determining the relative displacement between it and the remaining clusters (see Table 5).

Table 5 Relative intraplate offsets between Cluster 0 and remaining clusters

Cluster #	Offset [mm]
1	3.5
2	5.5
3	3.8
4	3.7
5	4.3

Analysis of the results in Table 5 reveals that neglecting intraplate movements between Cluster 0 and Cluster 1 induces a positional distortion of 3.5 mm/year. While the offsets in Clusters 1, 3, and 4 remain below the PU thresholds established for Class 0 geodetic control (GEOSA, 2025), a contrary trend is observed in Clusters 2 and 5.

These findings indicate that intraplate motions must be rigorously accounted for in high-precision geodetic applications. This is particularly critical for long-linear engineering projects (such as pipelines and highways) and other surveying tasks where cumulative relative displacements can compromise structural integrity or geodetic consistency over time.

6. CONCLUSION

This preliminary investigation confirms that the major case study of geospatial applications - Earth's surface undergoes dynamic changes, which must be considered in the geospatial area. This fact, combined with the growing need for positional accuracy and the rapid dissemination of geospatial information in many industries, necessitates a transformation of the traditional "static" approach to the Temporal Spatial Reference System. Also, the Arabian tectonic plate is subject to kinematic, periodic, and episodic variations that cannot be adequately characterized by a static reference frame. A kinematic approach is essential, as the cumulative effect of neglecting even minor tectonic and intraplate motions rapidly exceeds the error budget of modern high-precision industries.

Transitioning to the Kingdom of Saudi Arabia Kinematic Geodetic Reference Frame supported by a robust kinematic model will ensure that coordinates remain accurate and synchronized with the dynamic geophysical environment. This transition is not only necessary for traditional surveying and high-precision positioning but is also critical for the operational safety and functionality of autonomous navigation, precision agriculture, and large-scale civil engineering infrastructure.

REFERENCES

Alshahrani, S., Grebenitcharsky, R., Golubinka, I., Lompas, O., Salawu, A., Alrubaia, U., & Alqahtani, A. (2025). A concept for kinematic geodetic reference system for the Kingdom of Saudi Arabia. IAG Scientific Assembly 2025: Geodesy for a Changing Environment, (pp. Abstract 48, p. 36). Rimini. Retrieved from https://eventi.unibo.it/iag2025/final-program/iag_abstract-book.pdf

Altamimi Z., Métivier L., Rebischung P., Rouby H., Collilieux X. (2017). ITRF2014 plate motion mode. Geophysical Journal International, 209(3), pp. 1906–1912. doi:https://doi.org/10.1093/gji/ggx136

Altamimi, Z., Rebischung, P., Collilieux, X., Métivier, L., Chanard, K. (2023). ITRF2020: an augmented reference frame refining the modeling of nonlinear station motions. Journal of Geodesy, 97(47), pp. 1-22. doi:https://doi.org/10.1007/s00190-023-01738-w

Altamimi Z., Métivier L., Rebischung P., Collilieux X., Chanard K., Barnéoud J. (2023). ITRF2020 Plate Motion Model. Geophysical Research Letters, 50(24), p. e2023GL106373. doi:https://doi.org/10.1029/2023GL106373

Azhari M. et all. (2020). Semi-kinematic geodetic reference frame based on the ITRF2014 for Malaysia. De Gruyter, 91-109.

Dach, R., Lutz, S., Walser, P., & Fridez, P. (2015). Bernese GNSS Software Version 5.2. User manual. Bern: Astronomical Institute, University of Bern. doi:https://doi.org/10.7892/boris.72297

Dong, D., P. Fang, Y. Bock, M. K. Cheng, and S. Miyazaki. (2002). Anatomy of apparent seasonal variations from GPS-derived site position time series. J. Geophys. Res., 107(B4). doi:https://doi.org/10.1029/2001JB000573

GEOSA. (2024). Technical Summary for Saudi Arabia National Spatial Reference System (SANSRS). V3. Riydh: GEOSA.

GEOSA. (2025). Technical Guidlines for Geodesy. Retrieved from National Geospatial Platform: https://www.geoportal.sa/Geoportal/pdf/Geodesy%20Technical%20Guideline.pdf

Hagi Ronen et all. (2017). Kinematic Datum Based on the ITRF as a Precise, Accurate, and Lasting TRF for Israel. Journal of Surveying Engineering, 143(4), 04017013. doi:https://doi.org/10.1061/(ASCE)SU.1943-5428.0000228

José Antonio Tarrío et all. (2024). Geodetic innovation in Chilean mining: The evolution from static to kinematic reference frame in seismic zones. Journal of Geodetic Science.

Mercury Project Solution. (2018). Implications of a Dynamic Datum on the Cadastre: Final Report. CRCSI.

NGS. (2017). 2017 Geospatial Summit: Modernizing the National Spatial Reference System. Silver Spring, MD: NOAA Special Publication NOS NGS 12.

RGA, R. G. (2023). Saudi Higway Code (SHC). SHC 801 – Autonomous Vehicles Requirements. 1, 62. Riyadh, Kingdom of Saudi Arabia.

Sabadini, R.; Vermeersen, B.; Cambiotti, G. (2004). Global Dynamics of the Earth: Applications of Viscoelastic Relaxation Theory to Solid-Earth and Planetary Geophysics. Kluwer Academic Publishers.

Stanaway, R., Roberts, C., Blick, G. (2013). Realisation of a Geodetic Datum Using a Gridded Absolute. Earth on the Edge: Science for a Sustainable Planet, International Association of Geodesy Symposia, 139, pp. 259-256. Melbourne. doi:doi:10.1007/978-3-642-37222-3_34

United States Geological Survey (USGS). (2025). Retrieved from USGS Earthquake Hazards Program: https://www.usgs.gov/programs/earthquake-hazards

BIOGRAPHICAL NOTES

The authors are representatives of the General Authority for Survey and Geospatial Information (GEOSA) in Saudi Arabia, specializing in the development and operating of national geodetic infrastructure.

CONTACTS

Eng. Othman ALRUBAYYI
General Authority for Survey and Geospatial Information
8713 Olaya, 2638 Olaya District
Riyadh
KINGDOM OF SAUDI ARABIA
Tel. +966503299793
Email: u.alrubaia@geosa.gov.sa
Web site: www.geosa.gov.sa