The development of the Geodetic Reference Frame of Palestine (PAL-GRF2023)

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***Abstract*— Accurate spatial data, including precise mapping, effective land management, and robust Geographic Information Systems (GIS), is fundamental for national development. Recognizing this, the Palestinian Land Authority (PLA) initiated a crucial project to establish a modern geodetic framework. Palestine's existing geodetic networks are remnants of the British Mandate era, severely outdated and inadequate for current spatial data demands. This deficiency hinders the production of accurate cadastral and topographic maps and impedes the seamless integration of spatial information into vital land information systems. The "Development of the Palestinian National Geodetic Framework (PAL-GRF)" project involved establishing 10 new local stations across the West Bank, each fitted with forced centering steel pillars. These stations were integrated with fiducial stations from the International GNSS Service (IGS) and ITRF2020 networks to ensure global consistency. Palestinian Land Authority engineers conducted extensive GNSS observations, with each station observed simultaneously for at least 8 hours. All data was rigorously processed using the Bernese GNSS Software (BSW52) and products from the CODE analysis center. The project successfully determined precise final coordinates for all PAL-GRF2023 network stations within the ITRF2020 system at epoch 2023.50. This includes detailed Cartesian and ellipsoidal coordinates and velocity components for each station. Furthermore, the project derived essential datum transformation parameters to enable seamless conversion between the new PAL-GRF, the historical PAL1923, and the current CORS-Network coordinate systems. This new framework provides a reliable and accurate foundation for all future geospatial activities in Palestine.**

I. Introduction

The accurate and reliable positioning of spatial data constitutes a fundamental pillar of modern national development and governance. A robust geodetic framework is the invisible yet essential backbone that underpins virtually all geospatial activities, from the precise demarcation of land parcels to the sophisticated modeling of climate change impacts. It ensures consistency, precision, and interoperability across myriad spatial datasets. It defines the fundamental coordinate system that allows diverse geographical information to be referenced, integrated, and analyzed seamlessly within a common framework. In an era increasingly reliant on precise location-based services, advanced Geographic Information Systems (GIS), and comprehensive national spatial data infrastructures, the imperative for an up-to-date, highly accurate, and internationally compatible geodetic infrastructure cannot be overstated. Such a framework is not merely a technical prerequisite but a critical enabler for socio-economic growth, efficient resource management, and effective disaster preparedness and response [1].

Historically, geodetic systems evolved from local astronomical observations and triangulation networks, providing regional references with varying degrees of accuracy. However, the advent of satellite-based positioning technologies, particularly Global Navigation Satellite Systems (GNSS) such as GPS, GLONASS, Galileo, and BeiDou, revolutionized geodesy. These systems provide unprecedented global coverage and precision, necessitating a shift from local to global geodetic reference frames [2]. International Terrestrial Reference Frames (ITRF), maintained by the International Earth Rotation and Reference Systems Service (IERS), provide the global standard for expressing positions on the Earth's surface and their time evolution. These global standards ensure that national geodetic data can be seamlessly integrated with international scientific research, global navigation systems, and cross-border applications [4]. For any nation aiming for sustainable development and effective participation in the global spatial data economy, establishing a modern, GNSS-compatible geodetic infrastructure, anchored to an ITRF, is an indispensable strategic imperative [5].

The State of Palestine has operated with a geodetic infrastructure primarily inherited from the British Mandate era for an extended period. While foundational in its historical context, this legacy network was designed using technologies and methodologies that are fundamentally incompatible with modern GNSS-based surveying techniques and the accuracy requirements of contemporary spatial data applications. These

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older networks typically relied on terrestrial triangulation and traverse measurements, often establishing localized datums not rigorously connected to a global reference frame. Consequently, their accuracy is limited to a few decimeters at best, and their coverage is frequently sparse, leading to significant inconsistencies and considerable difficulties in integrating newer, more precise data collected with modern GNSS receivers.

The direct implications of this outdated system are pervasive and pose substantial challenges to the Palestinian Land Authority (PLA) and other national agencies responsible for land surveying, mapping, urban planning, and the development of spatial information systems. The most immediate and critical impact is on producing accurate cadastral maps. These maps legally define land ownership and boundaries, and any imprecision in their underlying geodetic reference can lead to ambiguities, protracted land disputes, and significant inefficiencies in land registration processes. This directly affects property rights, economic transactions, and the rule of law. Similarly, the lack of a precise and consistent geodetic datum severely hinders the creation of high-quality topographic maps, essential for various engineering projects, natural resource management, and national strategic planning [6]. Infrastructure development, for instance, requires highly accurate height and horizontal positioning for roads, utilities, and buildings to ensure their structural integrity and optimal functionality [7].

Furthermore, integrating diverse spatial information—from demographic data and public services to environmental monitoring and geological surveys—into a cohesive and unified Land Information System (LIS) becomes exceptionally formidable when the underlying geodetic reference is inconsistent or imprecise. Data collected using different local datums or with varying levels of accuracy cannot be easily combined or analyzed, leading to data silos, redundancy, and unreliable outputs. Without a standard, accurate geodetic datum, efforts to build a comprehensive National Spatial Data Infrastructure (NSDI)—a framework designed to efficiently share, manage, and use spatial data across various governmental, private, and academic organizations—are fundamentally undermined. The absence of such a robust and unified framework restricts the nation's capacity for efficient land governance, impedes sustainable development initiatives, and ultimately limits effective decision-making processes that rely on reliable and integrated geographical information. The economic costs associated with inaccurate data, duplicated efforts, and legal challenges stemming from imprecise spatial definitions are substantial and underscore the urgent need for a modernized geodetic system.

Recognizing these critical deficiencies and fully appreciating the paramount importance of a modern geodetic foundation for national sovereignty and progress, the Palestinian Land Authority (PLA) embarked on a truly strategic national project: the Development of the Palestinian National Geodetic Framework (PAL-GRF). This ambitious initiative is not merely an incremental upgrade. However, it represents a fundamental re-establishment of the national geodetic backbone, meticulously designed to rectify the historical networks' shortcomings and support future spatial data requirements for many decades to come. The project embodies a commitment to adopting international best practices in geodesy and spatial data management, positioning Palestine to leverage the full potential of modern geospatial technologies.

The overarching objective of the PAL-GRF2023 project is to define a new, precise national coordinate system entirely consistent with international geodetic standards, particularly the latest realization of the International Terrestrial Reference Frame (ITRF), specifically ITRF2020. This consistency is crucial; it ensures that all spatial data collected within Palestine can be accurately integrated with global datasets, fostering seamless international collaboration on scientific and developmental fronts, and facilitating the widespread adoption of advanced geospatial technologies and applications. By providing a unified, accurate, and internationally recognized reference, PAL-GRF2023 will be the authoritative datum for all surveying, mapping, GIS, and navigation activities across the West Bank. This singular, reliable reference point will lay the groundwork for a truly integrated, efficient, and resilient spatial data ecosystem, eliminating the confusion and inconsistencies associated with multiple, disparate local datums. Furthermore, the establishment of PAL-GRF2023 is a crucial step towards the eventual development of a Continuously Operating Reference Station (CORS) network across Palestine, which would provide real-time GNSS correction data and further enhance positioning accuracy for a wide range of applications [7][8].

II. Project Design and Methodology

The first step of the new coordinate system design is the selection of reference parameters that define the shape of the Earth and the proper method of map projection. In PAL-GRF2023, the GRS80 ellipsoid and Transverse Mercator projection, in Table I, were selected due to their relation to ITRF systems and suitability to the longitudinal shape of the country [3]. Table I illustrates the PAL_GRF2023 parameters.

TABLE I. PAL-GRF2023 MAP PROJECTION & ELLIPSOIDAL PARAMETERS

Parameter	Value
Ellipsoid	GRS80
Semi-major axis (a)	6378137.00
Inverse flattening (f -1)	298.257 222 100 882
Semi-minor axis (b)	6356752.31414
Projection Method	Transverse Mercator (TM)
Scale	1,000,003
False Easting	220,000.00
False Northing	500,000.00

Parameter	Value
Central Meridian	35.2350000000 35d 14m 06.000s
Latitude of Origin	31,777777777 31d 46m 40,000s

The design and implementation of the PAL-GRF2023 network were meticulously planned and executed to ensure optimal coverage, long-term stability, and the highest achievable accuracy. The first critical step involved the strategic selection of the primary geodetic stations. Following extensive reconnaissance field visits across the West Bank and comprehensive consultations with leading geodetic scientists and local experts, 10 primary local stations were carefully chosen. The selection criteria were rigorous, focusing on several key factors: geological stability of the site to minimize localized ground movements, good sky visibility to ensure optimal GNSS satellite reception and minimize multipath effects, accessibility for monument construction and routine maintenance, and strategic geographical distribution to provide comprehensive and homogeneous coverage across the West Bank [8]. Each selected site was then equipped with a forced centering steel pillar. These monuments are not merely simple markers; they are precisely engineered structures designed to ensure GNSS receivers' exact and repeatable placement. The robust design and deep foundation of these pillars are crucial for guaranteeing the long-term stability and reliability of the network points, thereby preserving the integrity of the geodetic reference over time. More illustrations can be found in Fig.1.

A pivotal aspect of defining coordinates within a global reference system like ITRF2020 is the rigorous integration of fiducial stations. These are internationally recognized, highly stable GNSS stations whose coordinates are precisely known in the global reference frame. Given the relatively sparse distribution of International GNSS Service (IGS) stations in the immediate African and Middle Eastern regions, the PAL-GRF2023 project strategically incorporated three additional, well-established fiducial stations directly from the IGS and ITRF2020 networks [9]. These stations provide the necessary robust links to the global reference frame, enabling the accurate and unbiased transformation of locally observed data into the ITRF2020 system. This strategic inclusion of external, globally referenced stations is vital for achieving geodetic datum consistency, ensuring global compatibility, and minimizing potential systematic errors in the network adjustment.

The GNSS observation campaigns were meticulously planned and rigorously conducted by highly trained engineers from the Palestinian Land Authority, adhering to international standards for high-precision geodetic surveys. To ensure the highest level of precision and accuracy for the network points, each station within the PAL-GRF2023 network was observed for a minimum continuous duration of 8 hours during each campaign. Crucially, these observations were conducted simultaneously across multiple stations within the network and with the selected fiducial IGS/ITRF2020 stations. Simultaneous observation is a key principle in GNSS network processing, as it allows for the effective cancellation or mitigation of various common-mode error sources, including atmospheric delays (tropospheric and ionospheric effects), satellite orbit errors, and satellite clock errors [10]. The raw GNSS observation data collected from these campaigns, typically in RINEX format, formed the indispensable input for the subsequent sophisticated processing and coordinate determination phases. Data logging equipment included high-quality geodetic-grade dual-frequency GNSS receivers and calibrated antennas, further ensuring the integrity and quality of the collected data.

Figure 1. *The new PAL-GRF2023 major stations in the Westbank.*

Data processing was performed using the industry-standard Bernese GNSS Software (BSW52), a sophisticated, widely recognized, and highly regarded geodetic software package developed by the Astronomical Institute of the University of Bern. BSW52 is renowned for its advanced algorithms and capabilities in processing large GNSS networks with high precision [12]. To ensure the highest level of accuracy and consistency with global geodetic standards, the processing workflow meticulously relied on precise ephemerides, satellite clock corrections, and other essential products provided by the International GNSS Service (IGS) Analysis Centers, specifically utilizing the CODE (Center for Orbit Determination in Europe) products [13]. This meticulous approach to data processing, combining robust, scientifically validated software with high-quality external IGS products, is absolutely fundamental to achieving the sub-centimeter level accuracy required for a national geodetic framework [14]. The detailed processing methodology involved several critical steps: pre-processing of raw GNSS data (e.g., cycle slip detection and repair, data screening), rigorous ambiguity resolution (determining the integer number of carrier phase cycles), accurate modeling of atmospheric delays (tropospheric and ionospheric), precise satellite orbit determination, and ultimately, the rigorous least-squares network adjustment of the entire GNSS observation set to derive the most accurate and reliable coordinates for all the PAL-GRF2023 network stations [15]. The final coordinates are expressed in the ITRF2020 system, referenced to the precise epoch of 2023.50, which signifies the specific point in time to which the coordinates refer [14][16].

III. RESULTS AND ANALYSIS

The completion and implementation of the Palestinian National Geodetic Framework (PAL-GRF) project marks a significant milestone for Palestine's geospatial capabilities and national development aspirations. The primary and most direct outcome is establishing an exact and internationally compatible national geodetic framework. This framework provides the definitive, authoritative reference for all future surveying, mapping, and geoinformation activities within Palestine. The final coordinates for all network stations, determined in ITRF2020 at the epoch 2023.50, represent the most accurate spatial positioning information available for the country [15]. The fundamental three-dimensional outputs of the geodetic processing, crucial for scientific validation and practical application, are presented in Table II.

TABLE II. PAL-GRF2023 MAP PROJECTION & ELLIPSOIDAL PARAMETERS

STA	X (m)	sX (m)	Y (m)	sY (m)	Z (m)	sZ (m)
PL01	4396745.2369	0.0031	3104035.0189	0.0023	3411392.0666	0.0025
PL02	4389857.6104	0.0030	3129365.0367	0.0023	3396842.9549	0.0025
PL03	4428189.0284	0.0032	3095965.9625	0.0023	3377985.4341	0.0025
PL04	4415160.9898	0.0029	3146759.9405	0.0022	3347577.0491	0.0023
PL05	4436529.0924	0.0031	3115451.9894	0.0023	3349868.0962	0.0025
PL06	4415220.8422	0.0032	3124136.4718	0.0024	3370214.0992	0.0026
PL07	4441009.5692	0.0027	3128091.1964	0.0020	3333092.7445	0.0021
PL08	4450068.6336	0.0030	3143156.3151	0.0023	3306307.9263	0.0024
PL09	4469260.2971	0.0027	3119442.1118	0.0021	3303001.0263	0.0022
PL10	4454113.3760	0.0029	3129394.8574	0.0021	3314533.5676	0.0023

Beyond the fundamental Cartesian coordinates, the project also provides ellipsoidal coordinates (latitude, longitude, and ellipsoidal height). These are often more practical and intuitively understood for mapping, navigation, and everyday geospatial applications [18]. These coordinates, essential for commonly used geodetic formats, are shown in Table III.

TABLE III. PAL-GRF2023 MAP PROJECTION & ELLIPSOIDAL PARAMETERS

STA.	Latitude			Std.dev	Longitude			Std.dev	Elip. H	Std.dev
	d	*m*	*s*	*m*	*d*	*m*	*s*	*m*	*m*	*m*
PL01	32	32	33.73654	0.0011	35	13	17.42874	0.0013	140.8009	0.0032
PL02	32	23	17.74073	0.0011	35	29	1.13067	0.0013	-43.0897	0.0031
PL03	32	11	11.21786	0.0011	34	57	33.48289	0.0013	72.0734	0.0032
PL04	31	51	53.14465	0.0010	35	28	41.21388	0.0013	-242.0254	0.0030
PL05	31	53	7.23937	0.0011	35	4	39.28594	0.0013	426.3733	0.0032
PL06	32	6	0.89644	0.0011	35	16	57.31225	0.0014	678.5779	0.0033
PL07	31	42	17.32799	0.0009	35	9	34.27758	0.0012	882.5043	0.0027
PL08	31	25	23.06869	0.0011	35	14	3.07276	0.0013	568.3492	0.0031
PL09	31	23	16.25514	0.0009	34	54	50.99479	0.0012	620.0848	0.0028
PL10	31	30	29.10888	0.0010	35	5	28.73693	0.0013	922.5812	0.0030

Time series of coordinates resulting from the processing of individual daily sessions can be analyzed and modelled in local components (North, East, and Up) or global components (X, Y, Z). The coordinate components, both local and global, for each station were analyzed separately, and the effects on station coordinates and time-dependent coordinate changes were modeled [17]. The functional model, in equation (1), including station coordinate at reference epoch, discontinuities, one or more linear velocities, and a set of periodic functions, is adapted to the data's time series according to the components' significance. Parameters that were found to be statistically insignificant were eliminated from the model. Outliers are also identified and removed from the data using a statistical test [14].

$$X(t_i) = X_0 + V_0(t_i - t_0) + \sum_{k=1}^{n_o} O_k\, H_{o,k}(t_i) + \sum_{k=1}^{n_v} V_k\,(t_i - t_k)\, H_{v,k}(t_i) + \sum_{k=1}^{n_p} (A_k \cos(w_k\,(t_i - t_0)) + B_k \cos(w_k\,(t_i - t_0)))\, H_{p,k}(t_i) \quad (1)$$

Where;

X_0 , station coordinate at an epoch t_0

V_0 , V_k , one or more station velocities

O_k , discontinuities

$H_{p,k}$, periodic functions with the predefined frequency w_k and the parameters (A_k and B_k)

Crucially, determining velocity components (Vx, Vy, Vz) for each of the PAL-GRF2023 stations is a vital output. Since Palestine is situated in a tectonically active region, the Earth's crust is continuously undergoing subtle movements [19]. Table IV shows the velocity components that account for these ongoing tectonic shifts. All PAL-GRF2023 stations' velocities are expressed in meters per year, illustrating their dynamic movement over time and enabling high-precision time-dependent positioning. These components ensure that the geodetic framework can be precisely updated to any future epoch, allowing users to accurately transform coordinates from the reference epoch to the observation epoch, maintaining high precision over time.

TABLE IV. LIST OF PAL-GRF2023 STATIONS HORIZONTAL AND VERTICAL VELOCITIES.

Station	Longitude (deg)	Latitude (deg)	h (m)	VX (m)	VY (m)	VZ (m)	Velocity vector
PL01	35.22150	32.54270	140.8	-0.022	0.012	0.017	0.030
PL02	35.48364	32.38826	-43.08	-0.021	0.014	0.017	0.030
PL03	34.95930	32.18644	72.07	-0.022	0.012	0.016	0.030
PL04	35.47811	31.86476	-242.02	-0.022	0.013	0.018	0.032
PL05	35.07757	31.88534	426.37	-0.021	0.013	0.017	0.030
PL06	35.28258	32.10024	678.57	-0.021	0.014	0.017	0.031
PL07	35.15952	31.70481	882.5	-0.020	0.014	0.018	0.030
PL08	35.23418	31.42307	568.34	-0.020	0.014	0.018	0.030
PL09	34.91416	31.38784	620.08	-0.020	0.014	0.017	0.030
PL10	35.09131	31.50808	922.58	-0.020	0.014	0.018	0.030

A particularly valuable and practical output of the PAL-GRF2023 project is the derivation of comprehensive datum transformation parameters. These parameters are rigorously calculated to enable seamless, accurate, and reliable conversion between the newly established PAL-GRF2023 datum, the historical PAL1923 datum (still present in legacy maps and records), and coordinates derived from the current CORS-Network (if existing or to be developed further) [19]. This capability ensures backward compatibility with existing legacy data and forward compatibility with modern systems and international standards. Such robust transformation models are essential for integrating historical cadastral records with new surveys, migrating existing GIS databases to the new national datum, and ensuring data interoperability across different platforms, organizations, and periods. It minimizes the risk of data inconsistencies and facilitates the coherent evolution of Palestine's spatial data infrastructure.

Using global satellite systems, measurements were made to calculate geodetic parameter conversion coefficients between PAL-GRF2023 and PAL1923. (GNSS) at 53 Old triangulation point with known coordinates in the Cassini-Soldner projection according to the PAL1923 standard. During these measurements, some PAL-GRF points were also observed and selected simultaneously. The figure below shows the distribution of common points across the country where GNSS measurements were made. These common points can be said to show a good distribution at the national level [20].

GNSS measurements were performed . At the PAL1923 triangulation points in 3 Groups, there was a total of 14 measurement sessions during the period from August 8 to September 6, 2023. Each point was visited twice to ensure high accuracy, and GNSS data was collected for at least 4 hours on each visit. It is also necessary to monitor at least two PAL-GRF stations . Permanently provide reference stations (fiducial stations) to define the geodetic standard. The accuracy of the measured points according to PAL-GRF2023 was about 5mm.

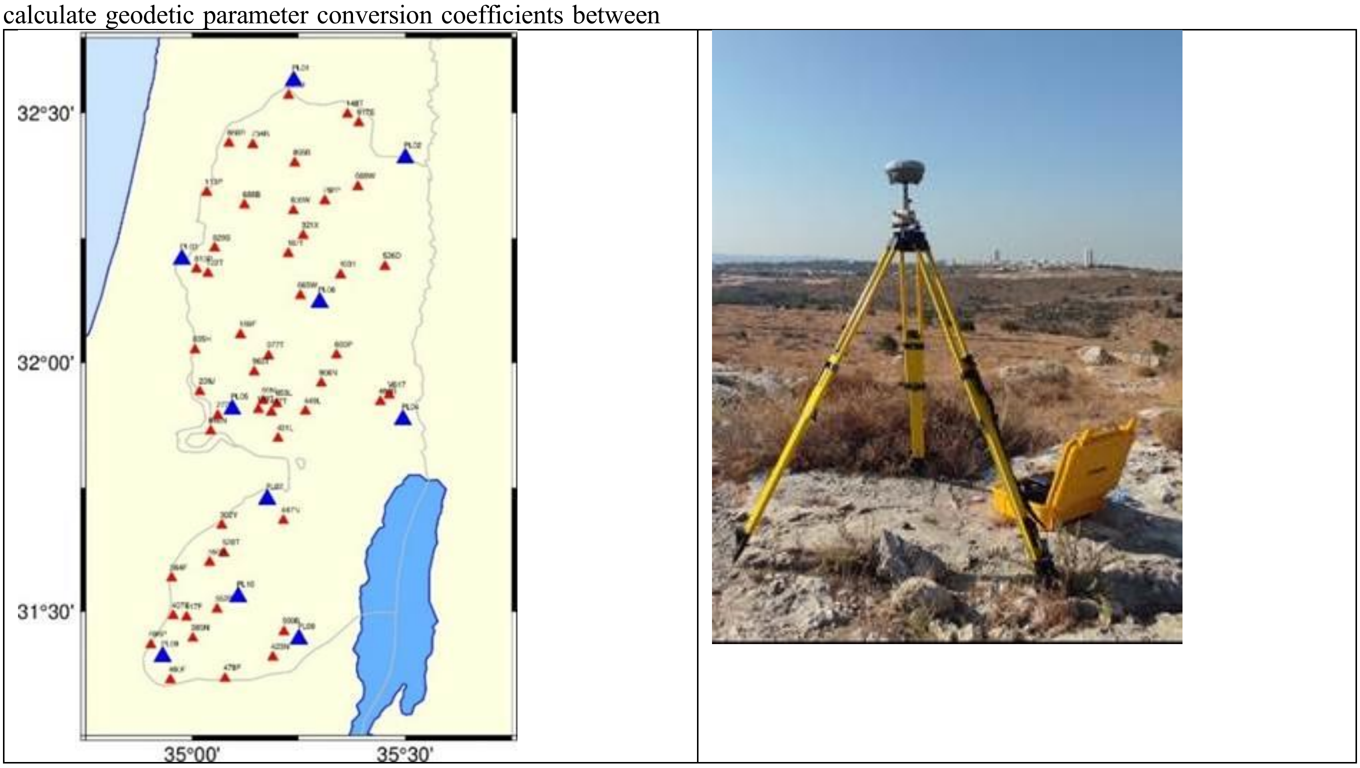

Figure 2. *Westbank. The second-order points distribution is in red, and the significant points are in blue.*

Seven parameters define the three-dimensional Helmert transformation and are called the 7-parameter transformation. This transformation reflects the relationship between Cartesian three-dimensional coordinate systems, usually geocentrically located. These seven parameters are defined below and shown in Fig.3 [18].

- 3 translations along each axis: ΔX, ΔY, ΔZ
- 3 rotations around each coordinate axis (counterclockwise): R_X, R_Y, R_Z
- A scale factor in ppm: δ

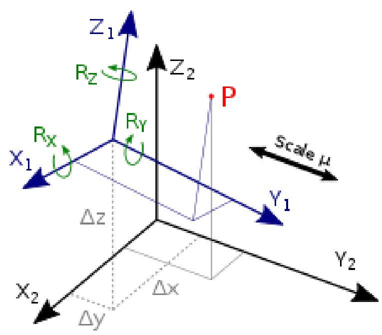

Figure 3. *Three-Dimensional Datum Transformation*

The equations are given in equations (2) and (3) in matrix form.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_2 = \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} (1+\delta) \;\; \mathrm{R} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_1 \qquad (2)$$

Where R is the rotation matrix according to:

$$R = R_Z R_Y R_X =$$

$$\begin{bmatrix} cosR_Z & sinR_Z & 0 \\ -sinR_Z & cosR_Z & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} cosR_Y & 0 & -sinR_Z \\ 0 & 1 & 0 \\ sinR_Z & 0 & cosR_Y \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & cosR_X & sinR_Z \\ 0 & -sinR_Z & cosR_X \end{bmatrix}$$

(3)

As a result of the preliminary adjustment with 53 common points, 3 points were detected as outliers and removed. The parameters calculated with the remaining 50 points are given below. The 3D Transformation Parameters (PAL-GRF2023 to PAL1923) were:

$\Delta X = \;\; 114.5200 \pm 14.8542$ m

$\Delta Y = \;\; 79.3790 \pm 9.1074$ m

$\Delta Z = -281.6324 \pm 0.5174$ m

$R_X = -10.07015 \pm 0.51744$ arcsec

$R_Y = \;\; -8.45655 \pm 0.28998$ arcsec

$R_Z = \;\; -5.37202 \pm 0.74241$ arcsec

$\delta = \;\; 15.22329 \pm 1.23256$ ppm

IV. Conclusion

Establishing the Palestinian National Geodetic Framework (PAL-GRF2023) signifies a transformative leap forward in the geospatial infrastructure of Palestine. By anchoring the national reference system to the International Terrestrial Reference Frame (ITRF2020), the project ensures international compatibility, sub-centimeter accuracy, and a robust foundation for all future surveying, mapping, and geoinformation applications. This transition from the outdated PAL1923 system to a modern GNSS-based geodetic network not only aligns Palestine with global geodetic standards but also rectifies decades of spatial inconsistencies and inefficiencies in land governance and spatial data integration.

Through meticulous station selection, precision GNSS observations, and rigorous data processing using Bernese GNSS Software (BSW52), the project achieved high-accuracy coordinate solutions, ellipsoidal parameters, and velocity components that reflect the region's tectonic dynamics. The successful modeling of station velocities and time-dependent coordinate changes ensures the long-term adaptability of the framework. Moreover, the derivation of transformation parameters enables seamless conversion between PAL-GRF2023, PAL1923, and existing or future CORS-based systems, safeguarding data interoperability and legacy system integration.

This foundational achievement paves the way for the future expansion of a Continuously Operating Reference Station (CORS) network, which will further enhance real-time positioning services and facilitate diverse applications in infrastructure development, environmental monitoring, land registration, and national security. More than a technical upgrade, PAL-GRF2023 redefines Palestine's spatial reference paradigm, empowering government agencies, researchers, and the private sector with precise, unified, and future-ready spatial data capabilities. As spatial information becomes increasingly central to development, the PAL-GRF2023 framework is a cornerstone of national resilience, strategic planning, and international geospatial cooperation.

Acknowledgment

This project was a collaborative effort, and we sincerely thank all the organizations and teams involved. We thank the World Bank Group (WBG), the Palestinian Land Authority (PLA), the research team, AXIS-GPS, and MibMap for their invaluable contributions and teamwork.

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