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Accuracy Analysis of Terrestrial Data Transformation from Bessel Datum for Precision Well-Head Mapping

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Abstract

The use of local Bessel 1841 datum in historical terrestrial datasets within the oil and gas sector presents challenges for integration with the modern WGS84/SRGI2013 reference system. This study aims to evaluate the positional accuracy of terrestrial data based on Bessel 1841 Datum in representing well-head locations in Sukowati Field after transformation to WGS84/SRGI2013 using 2D Helmert Transformation. The dataset consisted of 41 well-head points grouped into two clusters, namely SP.A and SP.B, with GNSS survey data collected in 2023 used as the references. Transformation parameters were estimated using the Least Squares method with a centroid approach to improve numerical stability. The results revealed a systematic shift between the two datums of approximately +105 m in the Easting direction and −41 m in the Northing direction. Accuracy assessment showed total RMSE values of 0.273 m for Cluster SP.A and 0.328 m for Cluster SP.B. These results indicate that the transformed coordinates achieve decimeter-level accuracy and remain below the 0.5 m tolerance threshold. Therefore, historical datasets based on Bessel 1841 Datum can still be reliably utilized after transformation to WGS84/SRGI2013 to support mapping activities and asset management in the oil and gas industry requiring high positional accuracy.
Keywords: *datum bessel 1841, helmert 2d, coordinate transformation, srgi2013, well-head*

Abstrak

Penggunaan datum lokal Bessel 1841 pada data terestris historis di sektor migas menimbulkan tantangan dalam integrasi dengan sistem referensi modern WGS84/SRGI2013. Penelitian ini bertujuan menganalisis tingkat akurasi data terestris berbasis Datum Bessel 1841 dalam menggambarkan posisi well-head di Sukowati Field setelah ditransformasikan ke WGS84/SRGI2013 menggunakan Transformasi Helmert 2D. Data yang digunakan terdiri atas 41 titik well-head yang terbagi dalam dua cluster, yaitu SP.A dan SP.B, dengan data GNSS tahun 2023 sebagai acuan. Parameter transformasi dihitung menggunakan metode Least Squares dengan pendekatan centroid untuk meningkatkan stabilitas numerik. Hasil penelitian menunjukkan adanya pergeseran sistematis antara kedua datum sebesar sekitar +105 m pada arah Easting dan −41 m pada arah Northing. Evaluasi ketelitian menunjukkan nilai RMSE total sebesar 0,273 m pada Cluster SP.A dan 0,328 m pada Cluster SP.B. Nilai tersebut menunjukkan bahwa hasil transformasi memiliki ketelitian pada tingkat desimeter dan berada di bawah batas toleransi 0,5 m. Dengan demikian, data historis berbasis Datum Bessel 1841 masih dapat dimanfaatkan secara andal setelah ditransformasikan ke WGS84/SRGI2013 untuk mendukung kegiatan pemetaan dan pengelolaan aset migas yang memerlukan ketelitian posisi tinggi.
Kata Kunci: *datum bessel 1841, helmert 2d, transformasi koordinat, srgi2013, well-head*

1. Introduction

Precision mapping activities in the oil and gas sector require high positional accuracy to ensure that all production facilities can be monitored and managed efficiently. The accuracy of mapping and surveying data is a fundamental factor in ensuring operational safety, the precision of technical designs, and the reliability of infrastructure and asset management in the oil and gas industry. It is also essential for producing reliable geospatial information. The quality of the data used has a significant influence on the accuracy of analytical results and spatial decision-making processes [1, 2]. One of the most critical aspects is the use of an appropriate coordinate system and geodetic datum to guarantee positional consistency among observation points. A datum is a set of parameters that defines a coordinate system and specifies its position relative to the Earth's surface [3]. Datums are generally classified into local and global datums. As a complement to these reference systems, the geoid model is essential for all nations as the primary vertical datum, serving as a reference datum to accurately estimate the elevation of a point. One of the local datums still used in Indonesia is Genuk Datum. Genuk Datum is a mapping reference system inherited from Dutch colonial era and is based on Bessel 1841 ellipsoid. It was established through triangulation surveys conducted between 1862 and 1880 to determine the position of Java Island [4]. This datum has a semi-major axis of a = 6.377.397.155 m and a flattening factor of f = 1/299.1528153. It is a local datum with its origin located in Genuk, Java, and was optimized based on terrestrial measurements carried out during the nineteenth century [5]. Despite being more than a century old, several oil and gas companies, including those operating in Sukowati Field, still utilize spatial data referenced to this local datum as a positional framework for reservoir-related activities.

In 2011, the Indonesian government introduced One Map Policy, which requires all geospatial information activities to adopt WGS84 as a unified reference system [6]. This policy is aligned with the implementation of the Indonesian Geospatial Reference System 2013 (SRGI 2013) as regulated through the Regulation of the Geospatial Information Agency (BIG) No. 15 of 2013 (BIG, 2013). The World Geodetic System 1984 (WGS84) is a global geocentric datum developed by the United States Department of Defense with parameters of a = 6,378,137.000 m and f = 1/298.2572236, and it has become the standard reference system for Global Positioning System (GPS) applications worldwide [7].

The geometric differences between Bessel 1841 and WGS84 ellipsoids are substantial, as reflected in their respective semi-major axis lengths, flattening values, eccentricities, and reference origins. While Bessel 1841 is a locally fitted datum referenced to Genuk, Java, WGS84 is geocentric and referenced to the Earth's center of mass. Consequently, spatial data referenced to Bessel Datum cannot be directly integrated with Global Navigation Satellite System (GNSS)-based data without a coordinate transformation process [8]. These differences may lead to significant coordinate discrepancies within a working area, potentially reaching hundreds of meters depending on geographic location [9, 10].

One commonly applied approach for datum conversion is two-dimensional Helmert Transformation (Four-Parameter Transformation), a conformal similarity transformation that preserves geometric shape through four parameters consisting of two translations, one rotation angle, and one scale factor [11]. To improve numerical stability, coordinate centralization using a centroid is employed before parameter estimation, considering that large-magnitude UTM coordinates may cause ill-conditioning in the Least Squares normal matrix. The quality of the transformation results is subsequently evaluated using Root Mean Square Error (RMSE), which is compared with the positional accuracy tolerance specified in SNI 8202:2020 [12].

Numerous studies on datum transformation in Indonesia have focused on developing mathematical transformation models and evaluating transformation parameters. [13] analyzed the transformation from Indonesian Datum 1974 (ID74) to National Geodetic Datum 1995 (DGN95) using both ten-parameter transformation model and Bursa-Wolf model. Their findings indicated that ten-parameter model provided better coordinate accuracy. Similarly, [3] investigated the transformation of coordinates from ID74 to WGS84 for the Indonesian National Marine Environmental Map, emphasizing the selection of optimal transformation methods and the quality of observation data within a global reference framework.

Although these studies have contributed significantly to the field, several research gaps remain. Previous investigations generally relied on GNSS observations or regional-scale mapping data and therefore did not specifically evaluate the accuracy of historical terrestrial data referenced to local datums such as Bessel (Genuk). Furthermore, existing studies have mainly focused on comparing transformation parameters and coordinate errors without assessing their practical implications for objects requiring very high positional precision. The investigated objects were also generally associated with broad-scale applications such as boundary mapping rather than specialized industrial operations. In operational areas such as Sukowati Field, where geological conditions are highly complex, positional accuracy becomes particularly critical because even centimeter-level errors may significantly affect operational safety and the management of subsurface infrastructure [14]. Therefore, this study aims to evaluate the positional accuracy of terrestrial survey data referenced to Bessel Datum in representing well-head locations in Sukowati Field after transformation to WGS84 reference system using GNSS survey data as the reference standard. Through this analysis, a better understanding of the reliability of local coordinate systems and the necessary correction measures is expected to be obtained, ensuring that spatial data remain accurate and compliant with national geospatial standards.

2. Material and Methods

This study adopted a quantitative research design using a comparative analytical approach to assess the positional accuracy of transformed terrestrial survey data relative to GNSS-derived coordinates [15]. In this study, the approach was used to compare the transformation results of terrestrial survey data referenced to Bessel Datum with coordinate data obtained from GNSS observations referenced to WGS84/SRGI2013 coordinate system.

The research was conducted in Sukowati Field, one of Indonesia's oil and gas production areas. The study utilized data from 41 wellhead observation points distributed across two well clusters: Cluster SP.A, consisting of 14 wells (S-A01 to S-A14), and Cluster SP.B, consisting of 27 wells (S-B01 to S-B27). These wellhead locations served as common points for evaluating the positional accuracy of the transformed terrestrial coordinates against the GNSS-derived coordinates.

Figure 1. The location of the research

Two primary datasets were utilized in this study. The first dataset consisted of terrestrial survey data referenced to the local Bessel Datum, with UTM coordinates obtained from the well location as-built drawings available in AutoCAD format. The second dataset comprised GNSS data referenced to the WGS84/SRGI2013 coordinate system, with UTM coordinates derived from geodetic GPS observations conducted in 2023, which served as the ground truth reference. In this study, the coordinate transformation was performed using the two-dimensional Helmert Transformation with centroid centralization (Helmert 2D Centroid). This method was selected to improve numerical stability and minimize the effects of large coordinate values during parameter estimation. The transformation process was carried out according to the following computational procedure. The transformation model from the original coordinates ((x, y)) to the transformed coordinates ((X, Y)) is expressed as follows:

$$X = T_x + ax - by$$
$$Y = T_y + bx + ay \qquad (1)$$

with:

$$a = s\cos\ \theta$$
$$b = s\sin\ \theta$$

The transformation parameters to be estimated are:

$$T_x,\ T_y,\ a,\ b$$

Calculation of the centroid of the original coordinate system:: $\bar{x} = \frac{\Sigma x}{n}$

$$\bar{y} = \frac{\Sigma y}{n} \qquad (2)$$

Target Coordinate Centroid: $\bar{X} = \frac{\Sigma X}{n}$

(3)

$$\bar{Y} = \frac{\sum Y}{n}$$

$$\bar{Y} = \frac{\sum Y}{n}$$

Computation of Centroid-Reduced Coordinates$x_i' = x_i - \bar{x}$

$$y_i' = y_i - \bar{y}$$
$$X_i' = X_i - \bar{X}$$
$$Y_i' = Y_i - \bar{Y}$$

Least Squares Adjustment Model Following Centroid Reduction$X_i' = ax_i' - by_i'$

$$Y_i' = bx_i' + ay_i'$$

The matrix formulation for each individual point can be expressed as: $\begin{bmatrix} X_i' \\ Y_i' \end{bmatrix} = \begin{bmatrix} x_i' & -y_i' \\ y_i' & x_i' \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix}$

the initial unknown parameters computed in this phase is $\hat{x} = \begin{bmatrix} a \\ b \end{bmatrix}$

In constructing the design matrix Aeach geodetic control point yields two independent observation equations, formulated as two consecutive rows corresponding to the Easting X' and Northing Y'components.

$$A = \begin{bmatrix} x_A' & -y_A' \\ y_A' & x_A' \\ x_B' & -y_B' \\ y_B' & x_B' \\ x_C' & -y_C' \\ y_C' & x_C' \\ x_D' & -y_D' \\ y_D' & x_D' \end{bmatrix} \quad (5)$$

The observation matrix L comprises the target coordinates that have been reduced relative to their respective centroid:

$$L = \begin{bmatrix} X_A' \\ Y_A' \\ X_B' \\ Y_B' \\ X_C' \\ Y_C' \\ X_D' \\ Y_D' \end{bmatrix} \quad (6)$$

Least Squares Normal Equations : $\hat{x} = (A^T A)^{-1} A^T L$

with: $N = A^T A$; $U = A^T L$

then: $\hat{x} = \begin{bmatrix} a \\ b \end{bmatrix} = N^{-1} U$ (7)

Computation of the Scale Factor and Rotation Angle: $s = \sqrt{a^2 + b^2}$

Rotation: $\theta = tan^{-1}\left(\frac{b}{a}\right)$

Since the adjustment model utilizes centroid-reduced coordinates, the translation parameters $T_x$dan T_y are computed only after the parameters a and b have been resolved. The formulas are given by: $T_x = \bar{X} - a\bar{x} + b\bar{y}$

$$T_y = \bar{Y} - b\bar{x} - a\bar{y}$$

Computation of the Transformed Coordinates:

$$\hat{X}_i = T_x + ax_i - by_i$$

$$\hat{Y}_i = T_y + bx_i + ay_i \quad (8)$$

Accuracy Assessment using RMSE

RMSEX = $\sqrt{\frac{V_X^2}{n}}$

RMSEY = $\sqrt{\frac{V_Y^2}{n}}$

RMSE Total = $\sqrt{\frac{\mathrm{RSME}_X^2 + \mathrm{RSME}_Y^2}{2n}}$

3. Results and Discussion

A direct comparison of the 41 coordinate points between Local Bessel 1841 and WGS84 datums reveals a highly consistent shift pattern. Within SKW PAD A Cluster, the Easting differences (dE) range from 104.59 m to 105.04 m, while the Northing differences (dN) vary between -40.93 m and -41.19 m. This consistency strongly indicates a systematic datum shift rather than random observational errors. A summary of these coordinate discrepancies is presented in Table 1.

A notable anomaly was identified at point S-B01, which exhibited a Northing shift (dN) of +59.77 m—deviating significantly from the general trend observed in Cluster B (where the average dN is approximately -40 m). Consequently, this point was flagged as a potential gross error (blunder) and was explicitly excluded from the selection of common control points. Furthermore, the elevation differences (dElev) of 1.96 m to 2.29 m observed across the majority of the points reflect the inherent variations between the geoid models underlying Bessel 1841 and WGS84 reference systems.

Table 1. Summary of Coordinate Discrepancies between Local Bessel 1841 Datum and WGS84 (Representative Sample)

Point	dE (m)	dN (m)	dPos (m)	Cluster
S-A01	104.70	-41.09	104.78	SP.A
S-A02	104.66	-41.05	104.87	SP.A
S-A03	104.79	-40.94	104.92	SP.A
S-A07	104.59	-41.01	104.70	SP.A
S-A08	105.04	-40.93	105.06	SP.A
S-B01	99.45	59.77	116.12	SP.B*
S-B02	104.15	-40.10	110.70	SP.B
S-B12	104.44	-40.27	111.94	SP.B
S-B17	104.27	-40.06	111.72	SP.B
S-B22	104.36	-40.35	111.95	SP.B
S-B26	104.82	-40.34	112.32	SP.B

** S-B01 indicates an anomaly; excluded from the common points configuration.*

Following the summary of coordinate discrepancies between Bessel and WGS84 datums, the next phase involves the Common Point Selection. Common points are selected based on the consistency of their coordinate differences and an even spatial distribution. For each cluster, four common points were chosen, as presented in **Table 2**.

Table 2. Selected Common Points

No	Field	Selected Common Points	Description
1	SKW A	S-A01, S-A02	Cluster A
2		S-A12, S-A13	
3	SKW B	SB-07, SB-12	Cluster B
4		SB-18, SB-226	

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Subsequent to the selection of the common points, the computation of the Centroid and Coordinate Reduction is performed. The coordinate centroid is calculated as the arithmetic mean of the Easting and Northing values of all common points. The results of the centroid estimation and the reduced coordinates are presented in **Table 3** until **Table 6**. Coordinate reduction yields values with a magnitude of tens of meters, which are significantly smaller than the original UTM coordinates, thereby ensuring the numerical stability of the normal matrix during the Least Squares adjustment process.

Table 3. Centroid Coordinates for Common Points of Local Bessel 1841 Datum – SKW A

Point	Easting (m)	Northing (m)
S-A01	600394.632	9209168.892
S-A02	600390.308	9209171.387
S-A12	600398.063	9209188.569
S-A13	600389.356	9209193.475
Centroid $\bar{x}$, $\bar{y}$	600393.090	9209180.581

Table 4. Centroid Coordinates for Common Points of Local Bessel 1841 Datum – SKW B

Point	Easting (m)	Northing (m)
S-B07	599714.208	9208688.640
S-B12	599803.037	9208662.151
S-B18	599796.070	9208643.404
S-B22	599729.094	9208631.528
Centroid $\bar{x}$, $\bar{y}$	599760.602	9208656.431

Table 5. Centroid Coordinates for Common Points of WGS84 – SKW A

Point	Easting (m)	Northing (m)
S-A01	600499.33	9209127.806
S-A02	600494.968	9209130.335
S-A12	600502.709	9209147.381
S-A13	600493.999	9209152.299
Centroid $\bar{X}$, $\bar{Y}$	600497.752	9209139.455

Table 6. Centroid Coordinates for Common Points of WGS84 – SKW B

Point	Easting (m)	Northing (m)
S-B07	599818.465	9208648.311
S-B12	599907.475	9208621.883
S-B18	599900.598	9208603.088
S-B22	599833.457	9208591.183
Centroid $\bar{X}$, $\bar{Y}$	599864.999	9208616.116

After obtaining the centroid, all coordinates are reduced with respect to the centroid of their respective datasets. These reduced coordinates subsequently serve as input for constructing the design matrix (A) and the observation matrix (L) in the Least Squares equation. By utilizing the centroid-reduced coordinates, the design matrix only contains components related to the rotation and scale parameters (i.e., parameters a and b), while the translation parameters are eliminated from the system of linear equations and calculated subsequently using the previously known centroid values. After the centroid computation and coordinate reduction, the estimation of Transformation Parameters is carried out. The resulting 2D Helmert Least Squares parameter estimations using the centroid approach for each cluster.

Table 7. 2D Helmert Transformation Parameters from Local Bessel 1841 Datum to WGS84/ SRGI2013 in SKW A

Parameter	Value
Parameter a	0.9955293121
Parameter b	0.0010187598
Translation X (Tx)	104.449 m
Translation Y (Ty)	-40.980 m
Rotation Angle	-211.078
Scale Factor	0.995530

Table 8. 2D Helmert Transformation Parameters from Local Bessel 1841 Datum to WGS84/ SRGI2013 in SKW B

Parameter	Value
Parameter a	1.0018019406
Parameter b	0.0010774371
Translation X (Tx)	8945.411423
Translation Y (Ty)	-17279.97058
Rotation Angle	-221.838

After calculating the parameter values, the subsequent step performed is the coordinate transformation. The results of well coordinate data transformation from Local Datum (Bessel 1841) to WGS84 datum (derived from Geodetic GNSS measurements), utilizing the calculated parameters are as follows:

Tabel 9. Comparison between Transformed Coordinates and GNSS Baselines with Residual Vector Analysis (SP. A)

Points	Transformed X	Transformed Y	VX (m)	VY (m)
SK-01	600499,299	9209127,820	0,031	-0,014
SK-02	600494,992	9209130,300	-0,024	0,035
SK-03	600490,570	9209132,880	0,093	0,165
SK-04	600486,271	9209135,372	-0,056	0,134
SK-05	600481,880	9209137,918	0,042	0,199
SK-06	600477,573	9209140,414	-0,015	0,151
SK-09	600473,330	9209142,758	-0,178	0,151
SK-15	600475,614	9209245,422	0,385	0,297
SK-16	600507,049	9209144,851	0,034	0,167
SK-18	600498,360	9209149,816	0,083	0,230
SK-19	600471,271	9209247,567	0,255	0,257
SK-20	600502,694	9209147,413	0,015	-0,032
SK-21	600494,021	9209152,288	-0,022	0,011
SK-22	600466,809	9209249,824	0,298	0,563

Tabel 10. Comparison between Transformed Coordinates and GNSS Baselines with Residual Vector Analysis (SP. B)

Points	Transformed X	Transformed Y	VX (m)	VY (m)
S-B01	599838.009	9208653.116	0.143	0.046
S-B02	599836.200	9208648.554	-0.164	0.189
S-B03	599834.435	9208644.335	0.210	0.610
S-B04	599832.484	9208639.216	0.372	-0.080
S-B05	599830.722	9208634.332	-0.081	-0.293
S-B06	599828.882	9208629.892	0.546	-0.055
S-B07	599827.082	9208625.083	0.119	-0.244
S-B08	599818.486	9208648.311	-0.021	-0.023
S-B09	599816.751	9208643.459	0.124	-0.293
S-B10	599814.953	9208639.137	0.332	0.204
S-B11	599813.153	9208634.480	0.261	0.201
S-B12	599907.504	9208621.883	-0.029	-0.010
S-B13	599905.765	9208616.955	-0.155	-0.240
S-B14	599823.578	9208616.115	0.296	0.061
S-B15	599904.025	9208612.453	0.126	-0.046
S-B16	599902.285	9208607.688	0.083	-0.114
S-B17	599820.060	9208606.872	-0.053	0.316
S-B18	599900.544	9208603.088	0.054	-0.016
S-B19	599821.823	9208612.031	0.414	0.787
S-B20	599898.805	9208598.359	0.222	-0.048
S-B21	599825.304	9208620.613	0.437	-0.029
S-B22	599833.461	9208591.183	-0.004	0.048
S-B23	599857.350	9208567.743	-0.522	0.198
S-B24	599891.821	9208579.820	0.286	0.335
S-B25	599893.515	9208583.862	-0.050	-0.338
S-B26	599895.238	9208588.991	0.255	0.089
S-B27	599896.970	9208593.726	0.343	-0.019

After obtaining the transformed coordinates, the next step is to evaluate the transformation accuracy by comparing the transformed coordinates with the reference coordinates obtained from Geodetic GNSS measurements in the WGS84 datum. This evaluation is performed using Root Mean Square Error (RMSE), which quantifies the positional differences between the transformed and reference coordinates. The RMSE values are calculated as follows:

Tabel 14. RSME Computation Result

Points	RMSE X (Easting)	RMSE Y (Northing)	Total
SP.A	0.160 m	0.221 m	0.273 m
SP.B	0.243 m	0.220 m	0.328 m

The analysis results indicate that the positional accuracy at both control points falls within the decimeter range. Control point SP.A has a total RMSE of 0.273 m, while SP.B has a total RMSE of 0.328 m. These values indicate that the positional differences between the transformed coordinates and the reference coordinates are relatively small and remain below 0.5 m. Along the Easting (X) axis, SP.A exhibits a smaller error (0.160 m) compared to SP.B (0.243 m). In contrast, along the Northing (Y) axis, both points show nearly identical error levels, approximately 0.22 m. This suggests that the transformation process provides relatively consistent accuracy in the north-south direction, whereas greater error variation is observed in the east-west direction. The difference in RMSE values between the two control points may be attributed to the distribution of common control points used in the transformation computation, the quality of GNSS observations, or local discrepancies between the legacy datum and the reference datum employed. Nevertheless, all RMSE values indicate that the transformation model is capable of maintaining geometric positional consistency with a satisfactory level of accuracy.

Based on the RMSE evaluation, the coordinate transformation achieved good horizontal accuracy, with total RMSE values ranging from 0.273 m to 0.328 m. Control point SP.A demonstrates higher accuracy than SP.B; however, both points exhibit relatively small positional errors. Since the RMSE values are below 0.5 m, the transformation results can be considered suitable for large-scale mapping applications and oil and gas asset management activities that require positional accuracy at the decimeter level.

4. Conclusion

This study demonstrates that terrestrial data referenced to Bessel 1841 Datum in Sukowati Field can be transformed into the WGS84/SRGI2013 reference system using the 2D Helmert Transformation with the Least Squares method. The transformation results yielded total RMSE values of 0.273 m for Cluster SP.A and 0.328 m for Cluster SP.B. These values indicate positional accuracies within the decimeter range and remain below the 0.5 m threshold. Therefore, historical data based on Bessel 1841 Datum still retain a good level of reliability after transformation and can be utilized for mapping, spatial analysis, and oil and gas asset management activities that require consistent and accurate positional information.

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6. Abbreviations

B3	Toxic hazardous materials
SKW	Sukowati
S-A	Sukowati A
S-B	Sukowati B
RSME	Root Mean Square Error

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