

DEFLECTION OF VERTICAL EFFECT ON DIRECT GEOREFERENCING IN AERIAL MOBILE MAPPING SYSTEMS: A CASE STUDY IN SWEDEN

MOHAMMAD BAGHERBANDI*  (mohammad.bagherbandi@hig.se)

*Faculty of Engineering and Sustainable Development, University of Gävle, Gävle, Sweden
Division of Geodesy and Satellite Positioning, Royal Institute of Technology (KTH),
Stockholm, Sweden*

ARASH JOUYBARI  (arash.jouybari@hig.se)

Faculty of Engineering and Sustainable Development, University of Gävle, Gävle, Sweden

FARAMARZ NILFOUROUSHAN  (faramarz.nilfouroushan@hig.se)

JONAS ÅGREN (jonas.agren@hig.se)

*Faculty of Engineering and Sustainable Development, University of Gävle, Gävle, Sweden
Department of Geodetic Infrastructure, Geodata Division, Lantmäteriet, Gävle, Sweden*

*Corresponding author

Abstract

GNSS/INS applications are being developed, especially for direct georeferencing in airborne photogrammetry. Achieving accurately georeferenced products from the integration of GNSS and INS requires removing systematic errors in the mobile mapping systems. The INS sensor's uncertainty is decreasing; therefore, the influence of the deflection of verticals (DOV, the angle between the plumb line and normal to the ellipsoid) should be considered in the direct georeferencing. Otherwise, an error is imposed for calculating the exterior orientation parameters of the aerial images and aerial laser scanning. This study determines the DOV using the EGM2008 model and gravity data in Sweden. The impact of the DOVs on horizontal and vertical coordinates, considering different flight altitudes and camera field of view, is assessed. The results confirm that the calculated DOV components using the EGM2008 model are sufficiently accurate for aerial mapping system purposes except for mountainous areas because the topographic signal is not modelled correctly.

KEYWORDS: aerial mobile mapping systems, deflection of verticals, direct georeferencing, EGM2008, geoid, photogrammetry

INTRODUCTION

AIRBORNE MOBILE MAPPING IS ONE of the most important data acquisition methods for producing topographical maps and extracting terrain features from aerial images. The interest in 3D geospatial data is expanding, and technology is growing at an unprecedented speed with new digital camera mapping systems. Different sensors are used for data acquisition in modern airborne photogrammetry, such as Global Navigation Satellite Systems (GNSS), Inertial Navigation Systems (INS) and digital cameras. The INS comprises an Inertial Measurement Unit (IMU) and a computer unit. The IMU consists of a gyroscope, accelerometer and optional magnetometer with the orthogonal installation of sensors along the principal axis, which can measure rotational and transient motions along the three principal axes of the body frame. GNSS and INS provide the position (X , Y and Z) and attitudes (roll, pitch and heading angles) of the camera's perspective centre on the digital mobile mapping platform. The collected aerial images should be transferred to the earth fixed coordinate system by utilising a georeferencing method. Traditional georeferencing and direct georeferencing are two methods that are frequently used for this purpose. Traditional georeferencing uses ground control points (GCPs) and direct georeferencing uses integrated GNSS/INS observables (Cramer et al., 2000; Cramer, 2001; Hutton and Mostafa, 2005). Direct georeferencing is an efficient method in aerial digital photogrammetry and automated 3D mapping that requires accurate attitude and position of each image during the exposure time (Bäumker and Heimes, 2001). Besides, direct georeferencing has faster data processing and a simpler workflow and is more cost-effective with the same accuracy with respect to traditional aerial triangulation (Rizaldy and Firdaus, 2012).

Image direct georeferencing is one of the most influential subjects currently considered in the aerial mobile mapping industry. Ultimately, the aerial triangulation step can be eliminated when using direct measurements (for instance, GNSS/INS) for the exterior orientation parameters (EOPs) of every single aerial image at the camera exposure time. Direct georeferencing, therefore, enables a variety of mapping products to be generated from airborne navigation and imagery data with minimal ground control, mainly used for quality assessments (Skaloud et al., 1996; Abdullah, 2000). In this regard, Mostafa et al. (2001) have done an error analysis between two cases: (1) a standard stereomodel where the aerial triangulation is bypassed when using the direct exterior orientation information, measured by the POS/AV system, and (2) single photos are processed together with the available digital elevation models (DEMs) to produce orthorectified quads/images. They emphasise that the boresight misalignment and camera calibration can significantly influence the integrated system's final accuracy. Karjalainen et al. (2006) employed a procedure to determine the EOPs of images using existing digital vector maps with no necessity for signalised GCPs. Finally, the final EOPs are determined using an automatic method that is reliable and rapid and uses a local line scanning technique that attempts to locate the linear features from the image.

Three different error sources affect the direct georeferencing. These are errors in interior orientation parameters, EOPs and image point coordinates. The errors caused by the camera's focal length, which is directly related to the temperature and atmospheric pressure, cannot be neglected in the process of direct georeferencing (Meier, 1975; Heipke et al., 2001; Jacobsen and Wegmann, 2002). The errors caused by the principal point location also significantly influence direct georeferencing (Meier, 1975). The errors of EOPs consist of errors of linear and angular parameters in direct georeferencing supported by integrated sensors (GNSS, IMU and camera). The GNSS errors, time synchronisation, lever

arm, interpolation of GNSS stations and transformation of coordinate systems form the errors in linear parameters. The errors in angular parameters comprise IMU attitude measurement errors and boresight misalignment (Cramer and Stallmann, 2002; Jacobsen and Wegmann, 2002). Lens distortion, refraction error of the atmosphere, hypsography and earth curvature are the systematic errors that can affect image point coordinates (Yuan and Zhang, 2008). In addition, the deflection of verticals (DOV) can significantly influence the direct georeferencing, which is elaborated on in the following sections.

Combining GNSS, INS and camera observations entail reconciling several different reference frames in direct georeferencing (compare Jekeli, 2012). Transformations between different frames are defined by the aviation standard ARINC 705 (Airlines Electronic Engineering Committee, 1982). The collected inertial data (roll, pitch and heading) refers to the equipotential surfaces of the gravity field and thus approximately refers to the geoid (see Fig. 1). However, the orientation of the aerial images (ω , φ and κ) should be determined based on the earth's reference ellipsoid (Goulden and Hopkinson, 2010). Therefore, a rotation matrix should be applied to consider the slope of the geoid (or more precisely, the equipotential surfaces) with respect to the reference ellipsoid at each point. In other words, it means a rotation matrix is considered due to the DOV (Heiskanen and Moritz, 1967). The direct georeferencing equation was initially developed by Vaughn et al. (1996) and emphasised that if high precision in georeferencing is required, the DOV may need to be considered if an inertial gyroscope is used for local attitude determination. Nowadays, the DOV rotation matrix should be considered in direct georeferencing of airborne photogrammetry because precise INS sensors are available. Equation (1) shows the reconciliation of GNSS, INS and digital camera frames in direct georeferencing presented by Vaughn et al. (1996) and used by other scholars (for example, Goulden and Hopkinson, 2010; Pepe et al., 2015):

$$\mathbf{r}_{Ground} = \mathbf{r}_{GNSS} + \mathbf{R}_{DOV}\mathbf{R}_{INS}(\mathbf{r}_{lever\ arm} + s\mathbf{R}_{Boresight}\mathbf{r}_{image}) \quad (1)$$

where \mathbf{r}_{Ground} is the transformed image coordinates in an earth fixed coordinate system, \mathbf{r}_{GNSS} is the absolute position of the mobile mapping system derived by GNSS, \mathbf{R}_{DOV} is the rotation matrix due to the DOV (transformation from local level frame to ellipsoidal frame), \mathbf{R}_{INS} is the rotation matrix from the IMU body frame to the local level frame, $\mathbf{r}_{lever\ arm}$ shows the offset between the phase centre of GNSS and camera in the IMU body frame, s is the scale factor, $\mathbf{R}_{Boresight}$ is the rotation matrix using misalignments of the IMU with respect to the camera frame that is often referred to as the IMU boresight angles (Hutton and Mostafa, 2005) and \mathbf{r}_{image} denotes the image coordinates (in the camera frame). Equation (1) differs from the traditional transformation formula by adding the additional \mathbf{R}_{DOV} matrix to account for the additional rotation generated when the gravitational field plays a key role. In other words, it is necessary to take these additional rotations into account if high accuracies need to be achieved. However, it is worth mentioning that equation (1) is a classical formula defined for georeferencing the collected aerial data. The DOV is still one of the main error sources restricting navigation accuracy, specifically for strap-down INS. In other words, the measurements of the high-quality optical gyroscopes (measuring changes in orientations) are not influenced by DOV. In aerial mobile mapping systems, the estimated EOPs besides velocity are influenced by DOV in direct georeferencing. Therefore, the DOV effect should be compensated by using at least an Earth Gravitational Model (EGM) (Hao et al., 2020). However, the impact of DOV is somehow mitigated or absorbed in assisted aerial triangulation. In other words, integrated GNSS/INS

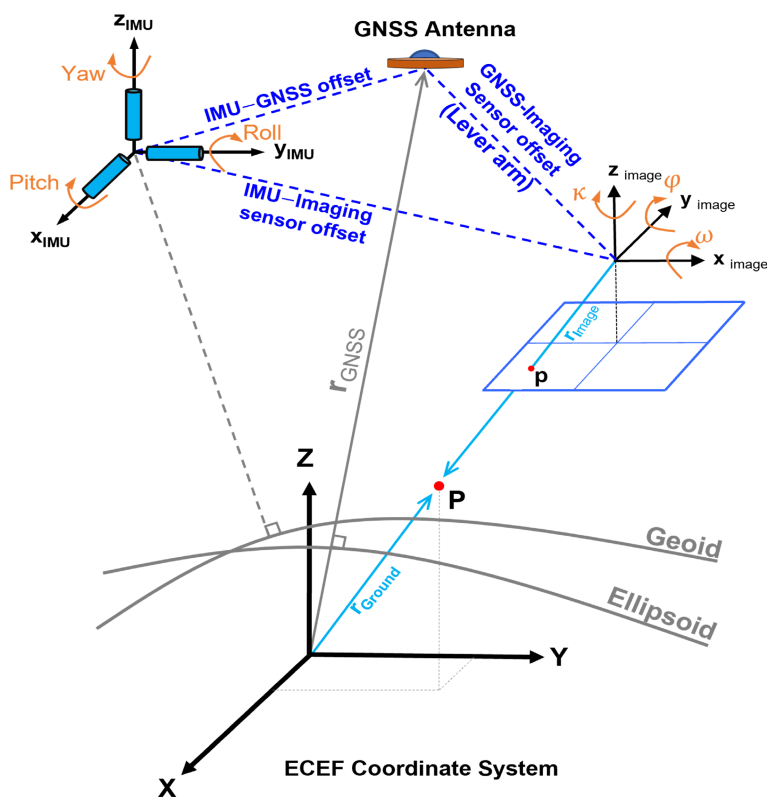


FIG. 1. A schematic diagram (not to scale) of an aerial mobile mapping system showing different angular frames in aerial mapping systems.

and aerial triangulation (AT) are complementary, and by combining these, the assisted AT is obtained. In addition, aerial laser scanning (ALS) is directly influenced by DOV due to direct georeferencing, especially in a long single ALS flight line (Goulden and Hopkinson, 2010). However, the professional software(s) (like Applanix POSPac MMS and Inertial Explorer) use at least information about the geoid to remove the influence of the DOV from the orientation parameters from aerial images.

Vaughn et al. (1996) ignored the DOV effect because the gyroscope accuracy was not accurate in the 1990s (~180"). With the advance in technology, the gyroscope accuracy has been significantly improved. For example, the published gyroscope accuracy by the Applanix company for the POS AV 610 model is about 9" for roll and pitch and 18" for heading (yaw). These higher accuracies indicate that the DOV effect should be considered for georeferencing. The DOV effect is usually not considered in commercial georeferencing software. This results in a systematic error that is significant at high flight altitudes to compensate the INS data for the gravity field effects, for instance, DOV (cf. Jekeli, 1999).

Some scholars investigated the effect of the DOV on airborne images and lidar observations. For example, Goulden and Hopkinson (2010) studied whether ignoring the DOV will cause errors in the derived coordinates in lidar systems. To answer this question,

they compared the DOV effect with respect to the accuracy of commercial lidar systems (for example, Optech ALTM 3100 EA sensor). Their study shows that the impact of DOV is more significant than the positional error of the Optech ALTM 3100 EA lidar system, and the DOV will cause a predictable error in the derived coordinates for the study area in Canada. Also, the impact of the DOV on direct georeferencing has been globally analysed and simulated by Pepe et al. (2015). They showed that the DOV effect could strongly affect direct georeferencing. Therefore, studying the DOV effect using the local geoid model is proposed. In another study, Barzaghi et al. (2016) studied the impact of the DOVs using the EGM2008 model (Pavlis et al., 2012) and DOV estimated from the gravity data used for the ITALGEO05 geoid model. They concluded that the DOV values calculated based on the EGM2008 model can be used to improve the position and attitude of the sensors above 3000 m flight height in airborne photogrammetry and remote sensing applications in Italy.

This paper aims to study and quantify the induced error/bias due to the DOV when integrating different sensors, focusing on GNSS and INS for 3D mapping in airborne mapping systems in Sweden. This problem is studied by evaluating the DOVs obtained from the EGM2008 model and computed based on the official Swedish quasigeoid model SWEN17_RH2000 (Ågren et al., 2018). The high accuracy of the geoid model in Sweden, at the cm–dm level (Ågren et al., 2018), provides a great opportunity to examine the effect of DOV in direct georeferencing in different regions of Sweden. However, other parameters also affect the results, for example, the camera field of view impact, flight direction and flight altitude, which are also investigated in this paper.

Data and Study Area

In this study, the EGM2008 and SWEN17_RH2000 quasigeoid models (Ågren et al., 2018; see Fig. S1 in the supplementary materials) were used to assess the horizontal and vertical errors due to ignoring the DOV components. The standard uncertainty of SWEN17_RH2000 has been estimated to be 8 to 10 mm except for a few areas where the uncertainty is larger, mainly in Lake Vättern, at sea and in the highest mountains to the north-west (with an uncertainty of about 2 to 4 cm). In addition, the Swedish national elevation model is also used in this study. This model is available online via the Lantmäteriet (Swedish Mapping, Cadastral and Land Registration Authority) website. The elevation data for the version used here is stored in a 50 m grid format (Lantmäteriet, 2020). This elevation model was produced from 2009 to 2017 using airborne laser scanning. For this study, the SWEN17_RH2000 height anomalies and elevation data are stored from north to south between 54.5° N to 69.5° N and 10.5° E to 24.5° E with the resolution of 0.01° and 0.02° in latitude and longitude directions, respectively. The study area and three subareas, highlighted with purple-coloured rectangles, are shown in Fig. 2.

METHODS

Determination of the Deflection of Verticals

The DOV is the angular difference (see Fig. 3) between the plumb line and the normal to the reference ellipsoid, for example, GRS80 (Heiskanen and Moritz, 1967; Moritz, 2000). It is important to mention that the DOV can refer both to the earth's surface (or any other point above the surface) and to the geoid (see Fig. 3). For example, the DOV (at the geoid surface) is related to the infinitesimal change of the geoid height dN versus an infinitesimal distance ds (Sjöberg and Bagherbandi, 2017) as:



FIG. 2. The geographical location of the study area (Sweden) with the selected regional areas for evaluating the impact of azimuth angle variations (highlighted by purple rectangles). From low to high latitudes, the regions are Jönköping, Dalarna and Norrbotten, respectively. Source of the map: *Encyclopaedia Britannica* (<https://www.britannica.com/place/Sweden>).

$$\Phi = -\frac{dN}{ds} \quad (2)$$

where Φ is the DOV in the direction of ds . Thus, the DOV can be obtained by differentiating the geoid height with respect to the distance in different directions. The minus sign in equation (2) is a convention to obtain the DOV components using formulas of Vening Meinesz with the correct sign corresponding to the definition of DOV components in equation (3a) (see Heiskanen and Moritz, 1967, pp. 112 and 114). The DOV

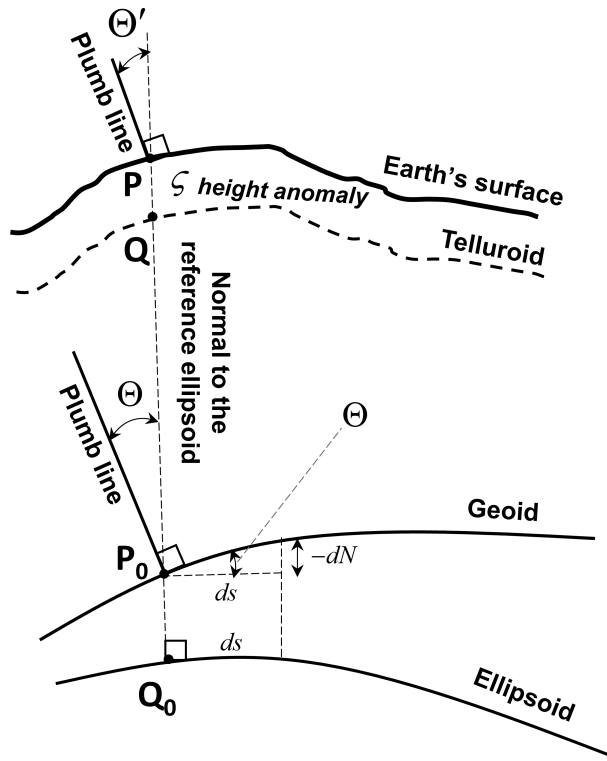


FIG. 3. The deflection of verticals definition at the earth's surface (Φ') and geoid (Φ).

is usually projected into two components, the north–south (ξ) and east–west (η) components. Traditionally, the DOV components could be determined astronomically by subtracting the astronomic (Φ, Λ) and geodetic latitudes and longitudes (φ, λ):

$$\xi = \Phi - \varphi, \eta = (\Lambda - \lambda)\cos \varphi \quad (3a)$$

and the total DOV, for instance, Φ , is then given by:

$$\Phi = \sqrt{\xi^2 + \eta^2}. \quad (3b)$$

According to equation (2), the north–south and east–west components are given by:

$$\begin{aligned} \xi(r, \theta, \lambda) &= -\frac{1}{r} \frac{\partial N}{\partial \theta} = -\frac{1}{r\gamma} \frac{\partial T}{\partial \theta} \\ \eta(r, \theta, \lambda) &= -\frac{1}{r \sin \theta} \frac{\partial N}{\partial \lambda} = -\frac{1}{r\gamma \sin \theta} \frac{\partial T}{\partial \lambda} \end{aligned} \quad (4)$$

where (r, θ, λ) are the geocentric distance, co-latitude and longitude, respectively (Sjöberg and Bagherbandi, 2017, p. 36), N is the geoid height and γ is normal gravity strictly at the

point (Q_0) with the same normal potential ($U(Q_0)$) as the real potential ($W(P_0)$), that is, $W(P_0) = U(Q_0)$.

The disturbing potential T can be determined using, for instance, a gravitational earth model such as EGM2008 or regional gravity data and geoid modelling methods such as the KTH method or remove–compute–restore (RCR) technique (see Schwarz et al., 1990; Sjöberg, 2003; Sansò and Sideris, 2013; Sjöberg and Bagherbandi, 2017).

Using normalised spherical harmonic coefficients, the disturbing potential is given by:

$$T(r, \theta, \lambda) = \frac{GM}{a} \sum_{n=2}^{n_{\max}} \sum_{m=0}^n \left(\frac{a}{r}\right)^{n+1} (\Delta\bar{c}_{nm} \cos m\lambda + \bar{s}_{nm} \sin m\lambda) \bar{P}_{nm}(\cos \theta) \quad (5)$$

where GM is the product of the gravitational constant and earth's mass, a is the semi-major axis of the reference ellipsoid, $\Delta\bar{c}_{nm}$ are the differences between the normalised geopotential coefficients and the harmonic coefficient generated by the normal gravity field, \bar{s}_{nm} are the normalised geopotential coefficients and \bar{P}_{nm} are the fully normalised Legendre polynomial of degree n and order m . High-resolution spherical harmonic models (like EGM2008), whose main application is to compute accurate global geoid models, can also be used to calculate other physical quantities like the DOVs. Jekeli (1999) is a comprehensive study that analyses the influence of high-frequency gravitational information (for instance, obtained from a geopotential model) and the amplification of errors for computing the DOVs.

Using equations (4) and (5), the DOV components can be computed as (Heiskanen and Moritz, 1967; Reed, 1973):

$$\xi(r, \theta, \lambda) = \frac{GM}{a\gamma} \sum_{n=2}^{n_{\max}} \sum_{m=0}^n \left(\frac{a}{r}\right)^{n+1} (\Delta\bar{c}_{nm} \cos m\lambda + \bar{s}_{nm} \sin m\lambda) (\bar{P}_{nm+1}(\cos \theta) - m \tan \varphi \bar{P}_{nm}(\cos \theta)) \quad (6a)$$

and

$$\eta(r, \theta, \lambda) = \frac{GM}{a\gamma r \sin \theta} \sum_{n=2}^{n_{\max}} \sum_{m=0}^n \left(\frac{a}{r}\right)^{n+1} m (\Delta\bar{c}_{nm} \sin m\lambda - \bar{s}_{nm} \cos m\lambda) \bar{P}_{nm}(\cos \theta). \quad (6b)$$

The normal gravity γ can be computed at any point on the reference ellipsoid (for example, GRS80) using Somigliana's formula (Moritz, 2000) and can then be upward continued using equations (2–124) in Heiskanen and Moritz (1967).

The DOV components (ξ, η) can be also determined using the formulas of Veining Meinez (Heiskanen and Moritz, 1967, pp. 114 and 312) and regional gravity and elevation data. Since the SWEN17_RH2000 model is strictly a quasigeoid (ζ) model (it models the height anomaly), the DOV at the earth's surface needs to be computed by Heiskanen and Moritz (1967, Sect. 8–9):

$$\xi = -\frac{1}{R} \frac{\partial \zeta}{\partial \theta} - \frac{\Delta g}{\gamma} \frac{1}{R} \frac{\partial H}{\partial \theta} \quad (7a)$$

$$\eta = -\frac{1}{R \sin \theta} \frac{\partial \zeta}{\partial \lambda} - \frac{\Delta g}{\gamma} \frac{1}{R \sin \theta} \frac{\partial H}{\partial \lambda} \quad (7b)$$

where Δg is the gravity anomaly, R is the earth's mean radius and H denotes the height of the topography. The partial derivatives are obtained by numerical integration.

The DOVs obtained from SWEN17_RH2000 using equations (7a) and (7b) refer to the earth's surface (top of topography). For this study, these surface DOVs should then be upward continued (up to the flight altitude) using Poisson's integral (Heiskanen and Moritz, 1967, p. 35) or Taylor expansion techniques. The Poisson integral has some limitations, and it is valid only for harmonic functions, and some approximations have to be assumed for numerical integration. The DOV components were calculated using in-house programs, and the GRAVSoft software package (Forsberg and Tscherning, 2014) was used only for the upward continuation and calculation of the DOVs above the earth's surface (at the flight altitude z) in this paper. The GEOFOUR program (from the GRAVSOFT package) has been applied for upward continuation of ξ and η . The DOV components can be upward continued on a per gradient basis (separately) by applying Cartesian approximation. Considering this assumption, it can be assumed that the DOVs are harmonic functions outside the masses (Andersen, 2013). The calculated DOV components can be determined above the earth's surface (for example, at flight altitude) using the fast Fourier transform (FFT) which is given by:

$$F\left([\xi \ \eta]_{(k,z)}\right) = F\left([\xi \ \eta]_{(k,0)}\right) \exp(-2\pi k z) \quad (8)$$

where $F()$ represents the two-dimensional discrete FFT of the grid of ξ and η values, x , y and z are the assumed local Cartesian coordinate system. k_x and k_y are the wavenumbers equal to one over half the wavelength in the x and y direction, therefore $k = \sqrt{k_x^2 + k_y^2}$ (compare Andersen, 2013).

Alternatively, equation (8) can be simplified by Taylor expansion. Assuming that V is an arbitrary function on the assumed reference surface (sphere or flat earth approximation), it can be upward continued to the flight altitude (z) using the Taylor series as follows:

$$V(\theta, \lambda, z) = V(\theta, \lambda, H) + \frac{\partial V}{\partial r}(z - H) + \dots \quad (9a)$$

where $\partial V / \partial r$ is then computed assuming a spherical shape using equation (9b), which gives errors to second order (Heiskanen and Moritz, 1967, Sec. 1 – 18):

$$\frac{\partial V}{\partial r} = -\frac{V(\theta, \lambda)}{R} + \frac{R^2}{2\pi} \int_{\lambda'=0}^{2\pi} \int_{\theta'=0}^{\pi} \frac{V(\theta', \lambda') - V(\theta, \lambda)}{l_0^3} \sin \theta' d\theta' d\lambda' \quad (9b)$$

where $l_0 = 2R \sin(\psi/2)$ and ψ is the geocentric angle between computation (θ, λ) and running (θ', λ') points.

Plumb Line Curvature

A correction due to the curvature of the plumb line should be considered for the obtained DOV. This is because the DOVs obtained from SWEN17/EGM2008 at the earth's surface (or higher up) refer to the normal plumb line. The correction here converts them to the ellipsoidal normal. However, the correction should be only considered for the north–south component of the DOV (for instance, ξ). As the normal gravity field does not change in the east–west direction, the plumb line curvature does not affect the east–west component

of the DOV (η). More details can also be seen in Heiskanen and Moritz (1967, pp. 196 and 316). The correction can be obtained by assuming a local astronomical coordinate system at point P (Fig. 4), for instance, in the (x, z) plane (Vanicek and Krakiwsky, 1986, p. 506):

$$\delta\xi = - \int_{H_P}^{H_Q} k_x dH \approx 0.17'' \sin 2\varphi \Delta H \quad (10a)$$

where ΔH is the height difference between the geopotential surfaces through P and Q in km and k_x is the curvature of the projection of the plumb line, which is given by:

$$k_x = \frac{1}{g} \frac{\partial g}{\partial x} \Big|_P \approx \frac{1}{\gamma} \frac{\partial \gamma}{\partial x} = \frac{1}{r} \frac{\partial \gamma}{\partial \varphi} = \frac{\gamma_e}{r} f \sin 2\varphi \quad (10b)$$

and the normal gravity field

$$\gamma(\varphi, h) = \gamma_0(\varphi) + \frac{\partial \gamma}{\partial h} h \cong \gamma_e(1 + f \sin 2\varphi) + \frac{\partial \gamma}{\partial h} h \quad (10c)$$

where $\gamma_0(\varphi)$ is obtained using Somigliana's formula, γ_e is the normal gravity at the equator ($9.780\,326\,7715 \text{ m/s}^2$, GRS80), f is the reference ellipsoid flattening and h is the ellipsoidal height (the height along the normal to the ellipsoid).

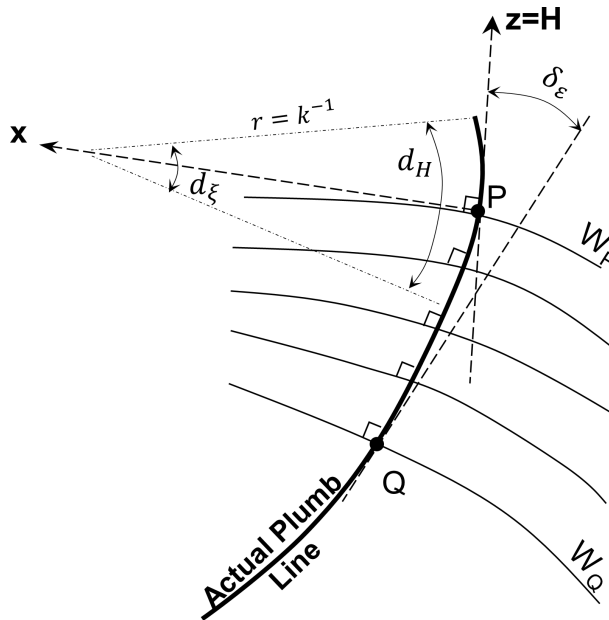


FIG. 4. The curvature of the plumb line (modified after Vanicek and Krakiwsky (1986)). $\delta\xi$ is the projection of $\delta\epsilon$ onto the meridian and prime vertical planes.

The plumb line curvature effect on the north–south component (ξ) and at 4 km flight altitude can be seen in Fig. S2 (see supplementary materials).

DOV Effect on Horizontal and Vertical Components

According to Fig. S3 (supplementary materials), the horizontal (δh) and vertical (δv) errors due to the DOV can be obtained using the following equations, respectively (compare Pepe et al., 2015). The errors depend on the flight altitude (z), the direction of flight (azimuth, α) and the camera's field of view (FOV):

$$\delta h = z \sin(DOV_\alpha) \quad (11)$$

$$\delta v = z \tan\left(\frac{FOV}{2}\right) \sin(DOV_\alpha) \quad (12)$$

where

$$DOV_\alpha = \xi \cos \alpha + \eta \sin \alpha \quad (13)$$

where DOV_α is the deflection of vertical in the azimuth α .

RESULTS AND DISCUSSIONS

Deflection of the Vertical Components Using the EGM2008 and SWEN17 Models

This section presents the comparison between the DOVs derived by the EGM2008 and SWEN17_RH2000 models in Sweden. The DOVs at the earth's surface calculated using the SWEN17_RH2000 quasigeoid model and then upward continued to flight altitude is also called SWEN17 to follow the same name as the latest quasigeoid model of Sweden. The DOVs were determined at 1, 2, 3, 4, 5 and 6 km flight altitudes in this study. The calculated DOV components using the EGM2008 geopotential model have been determined up to degree and order 2190. Fig. 5 shows the DOVs at 1 and 6 km flight altitudes (lowest and highest flight altitude scenarios in this paper) using the EGM2008 and SWEN17 models. The results show that the DOVs from both models are approximately similar, and the differences are small. This will be discussed in more detail in the next section. Generally, large values for the north–south (ξ) component can be seen in Lappland (north-west of Sweden), Västerbotten (north-east of Sweden) and Småland (south of Sweden). Similarly, significant magnitudes of the east–west (η) component are observed in Lappland (north-west of Sweden) and Västerbotten (north-east of Sweden) regions. As expected, the calculated DOV values are smoother when the flight altitude is increased from 1 to 6 km. In other words, the DOV changes with elevation and decreases while the mobile mapping sensor moves away from the earth's surface (see also Table S1 in the supplementary materials).

Since most of the photogrammetry projects designed by the Swedish Mapping, Cadastral and Land Registration Authority were flown at about 4 km flight altitude, the DOV statistics for this flight altitude are presented in Table I. The mean value of the DOV differences, obtained by the EGM2008 and SWEN17 models, shows that there is not any significant systematic bias between the two datasets. The mean values are zero for both $\Delta\xi$ and $\Delta\eta$ with a standard deviation of 0.19 and 0.22 arc-seconds, respectively.

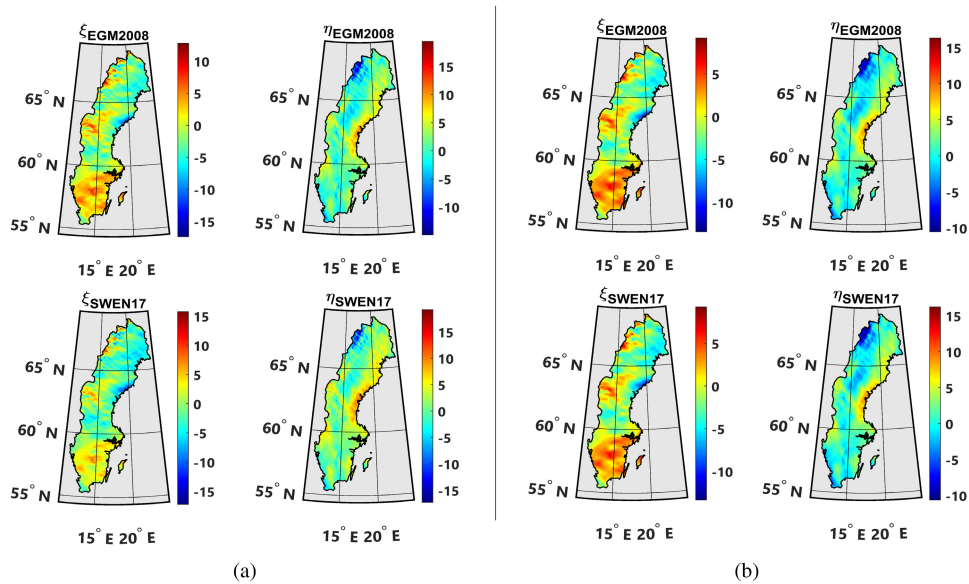


FIG. 5. The DOV components (ξ, η) obtained using the EGM2008 and SWEN17 models at different flight altitudes: (a) $z = 1$ km and (b) $z = 6$ km. Unit: arc-second.

TABLE I. Statistics of DOV components using the SWEN17 and EGM2008 models and their differences (denoted by Δ) for 4 km flight altitude in Sweden. Unit: arc-second.

	Max	Mean	Min	STD
ξ_{EGM2008}	9.88	0.66	-14.76	3.13
η_{EGM2008}	17.42	0.69	-11.94	3.51
ξ_{SWEN17}	10.04	0.67	-14.64	3.14
η_{SWEN17}	17.30	0.69	-12.27	3.53
$\Delta\xi$	1.34	0.00	-1.49	0.19
$\Delta\eta$	1.63	0.00	-1.68	0.22

To scrutinise the influence of the DOVs on the coordinates, the obtained ξ and η can be compared against the GNSS/INS system that the Swedish Mapping, Cadastral and Land Registration Authority uses. They use the Applanix POS AV 510 – GNSS/INS sensor. The published roll and pitch uncertainty is 0.005° (equal to 18”), and the uncertainty of yaw is 0.008° (corresponding to 28.8”). The obtained DOV components are almost at the same magnitude as the ones in the utilised sensor. Thus, their importance cannot be avoided.

In this study, the effect of the curvature of the plumb line is considered to calculate the impact of DOV on horizontal (δh) and vertical (δv) coordinates. For instance, the curvature of the plumb line varies between 0.64 and 0.46 arc-seconds with a mean value of 0.56 arc-seconds and a standard deviation of 0.05 arc-seconds assuming 4 km flight altitude (see Fig. S2 in the supplementary materials).

The Effect of ξ and η on Horizontal and Vertical Coordinates

The impact of DOVs that induces horizontal (δh) and vertical (δv) errors is obtained using equations (11) and (12). Figs. 6a and b show the DOV effect on horizontal and vertical coordinates using the SWEN17 model, respectively, by assuming flight direction toward the north ($\alpha = 0^\circ$) and 4 km flight altitude. Generally, the DOV effect varies from a few centimetres to a decimetre (for instance, the absolute error without any form of georeferencing). To determine the significance of the DOVs on the coordinates, the obtained results in Fig. 6 can also be compared with the Applanix POS AV 510 – GNSS/INS equipment's position accuracy (see Applanix, 2012). The published horizontal and vertical accuracies of the Applanix POS AV 510 are 5 and 10 cm, respectively (for the smart-based post-processing mode). Therefore, the effect of the DOVs in GNSS INS applications cannot be avoided because the magnitude δh and δv errors are more significant than the employed GNSS INS position errors. Hence, a high accuracy DOV model is needed to remove the effect of the DOVs, and its influence should be reported in quality assurance reports (compare Goulden and Hopkinson, 2010). It should be mentioned that the Applanix company suggests considering the DOV components if high accuracy is required.

The statistics of the DOV effect assuming flight direction toward the north ($\alpha = 0^\circ$) and different flight altitudes are presented in Table II. Both 46.1° (along-track) and 67°

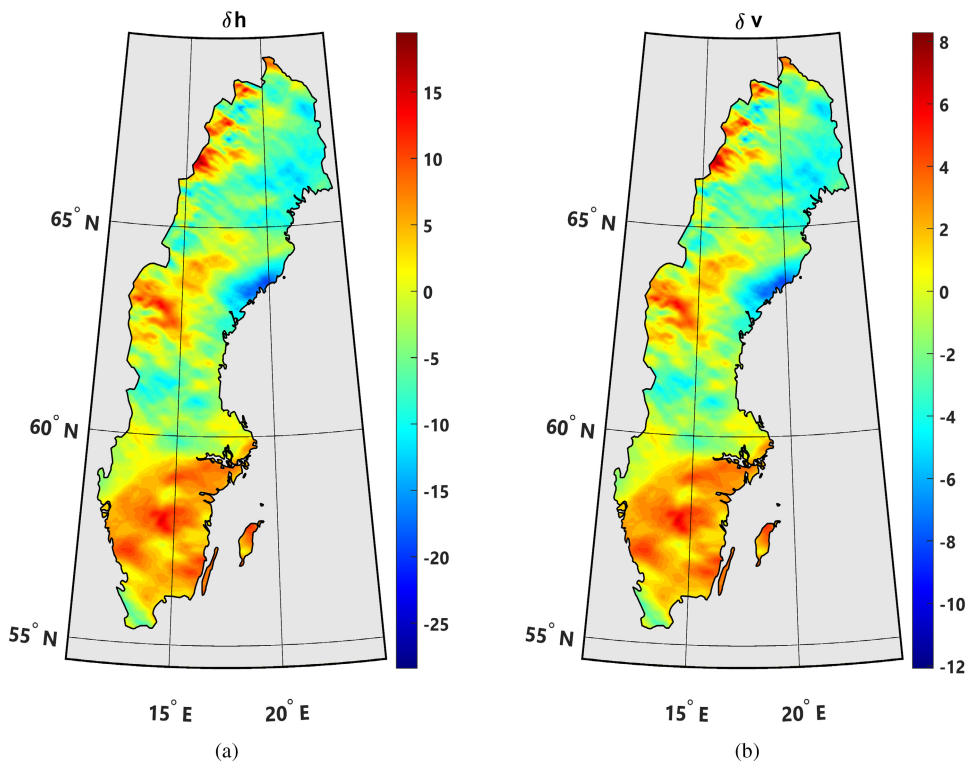


FIG. 6. Effect of DOV on (a) horizontal (δh) and (b) vertical (δv) components using the SWEN17 model and assuming azimuth $\alpha = 0^\circ$ and FOV = 46.1° at 4 km flight altitudes. Unit: cm.

TABLE II. Statistics of the DOV effect on horizontal and vertical components using the SWEN17 model in Sweden. Unit: cm.

		Flight altitudes (km)					
		$z = 1$	$z = 2$	$z = 3$	$z = 4$	$z = 5$	$z = 6$
δh (Az = 0°) cm	Max	7.64	11.98	15.55	19.47	23.36	26.97
	Mean	0.33	0.66	0.98	1.29	1.60	1.91
	Min	-8.36	-15.76	-22.39	-28.39	-33.84	-38.82
	STD	1.70	3.26	4.71	6.09	7.41	8.68
δv (Az = 0°) Cm	FOV = 46.1°	Max	3.25	5.10	6.62	8.29	9.94
		Mean	0.14	0.28	0.42	0.55	0.68
		Min	-3.56	-6.71	-9.53	-12.08	-14.40
		STD	0.72	1.39	2.01	2.59	3.15
	FOV = 67°	Max	5.06	7.93	10.29	12.89	15.46
		Mean	0.22	0.44	0.65	0.86	1.06
		Min	-5.53	-10.43	-14.82	-18.79	-22.40
		STD	1.13	2.15	3.12	4.03	4.91

(across-track) camera FOVs have been considered in this study, according to the specification of the Ultracam Eagle MARK 3 digital photogrammetric aerial camera. Presently, this camera is used by the Swedish Mapping, Cadastral and Land Registration Authority for photogrammetry projects. The analysis shows that the error, due to the DOV effect, on horizontal and vertical coordinates will increase by changing the flight altitude from 1 to 6 km. This systematic error will be more significant at very high altitudes (compare Jekeli, 1999; Barzaghi et al., 2016). The minimum horizontal error varies between -8.3 and -33.8 cm when the flight altitude changes from 1 to 6 km, respectively. Moreover, Fig. S4 (see supplementary materials) visualises the presented statistics in Table II and compares the statistics of horizontal (δh) and vertical (δv) errors at different flight altitudes and FOVs using the SWEN17 model.

However, the main question left is whether the discrepancies between the obtained DOVs from EGM2008 and SWEN17 are significant in Sweden or not. Similar to equations (11) and (12), the discrepancy can be investigated of the horizontal and vertical errors obtained by subtracting the errors by the DOVs from the EGM2008 and SWEN17 models, which are given by:

$$\begin{aligned}\Delta\delta h &= z [\sin(DOV_{\alpha}^{\text{EGM2008}}) - \sin(DOV_{\alpha}^{\text{SWEN17}})], \\ \Delta\delta v &= z \tan\left(\frac{FOV}{2}\right) [\sin(DOV_{\alpha}^{\text{EGM2008}}) - \sin(DOV_{\alpha}^{\text{SWEN17}})]\end{aligned}\quad (14a)$$

where

$$DOV_{\alpha}^{\text{EGM2008}} = \xi_{\text{EGM2008}} \cos \alpha + \eta_{\text{EGM2008}} \sin \alpha \quad (14b)$$

and

$$DOV_{\alpha}^{\text{SWEN17}} = \xi_{\text{SWEN17}} \cos \alpha + \eta_{\text{SWEN17}} \sin \alpha. \quad (14c)$$

Fig. 7 shows the horizontal ($\Delta\delta h$) and vertical ($\Delta\delta v$) coordinate errors calculated by the discrepancy of the DOVs ($\Delta\xi, \Delta\eta$) for 4 km flight altitude. Table S2 (see supplementary materials) also presents the statistics of $\Delta\xi$ and $\Delta\eta$ effects on the horizontal and vertical coordinates using different flight altitudes and FOVs. The results show that the discrepancy

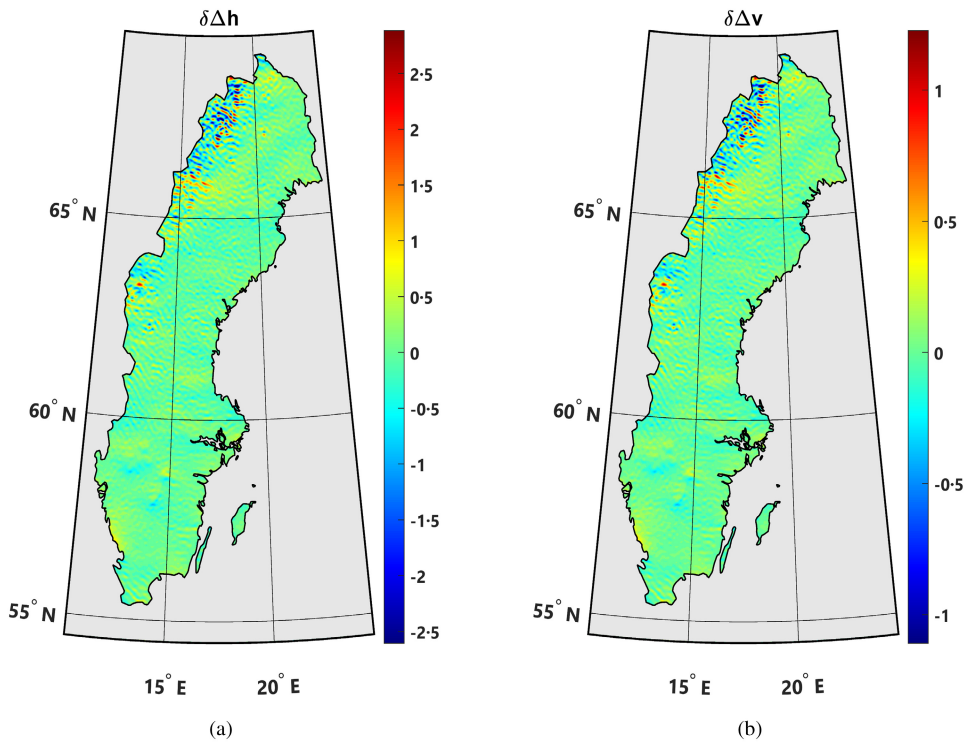


FIG. 7. The DOV anomaly ($\Delta\xi, \Delta\eta$) effects, computed using the SWEN17 and EGM2008 models, on (a) horizontal ($\delta\Delta h$) and (b) vertical ($\delta\Delta v$) coordinates by assuming azimuth $\alpha = 0^\circ$ and FOV = 46.1° at 4 km flight altitude. Unit: cm.

between SWEN17 and EGM2008 is about 2 to 3 cm (in horizontal) and 1 to 2 cm (in vertical) using across and along-track FOVs equal to 46.1° and 67° , respectively. Large discrepancies can be observed in the Jämtland and Lappland regions (the boundary between Sweden and Norway, see Fig. 2), where the topographic signal is not modelled correctly by the EGM2008 model due to the limited resolution of EGM2008 (cf. Barzaghi et al., 2016).

Effect of Azimuth Variations on Horizontal and Vertical Coordinates

One of the main parameters to estimate the impact of DOV components on the coordinates is the dependency of the errors on the azimuth/direction of the flight in airborne photogrammetry (see equation (13)). This has not been reported in the related previous studies performed by, for example, Goulden and Hopkinson (2010), Pepe et al. (2015) and Barzaghi et al. (2016) since the azimuth has a considerable impact on the coordinate errors. In this section, the effect of the azimuth variations on horizontal and vertical coordinates is investigated using Figs. 8 and 9, respectively. The figures show the impact of azimuth (varying from 0° to 360° with 10° intervals) for different flight altitudes (1 to 6 km) using

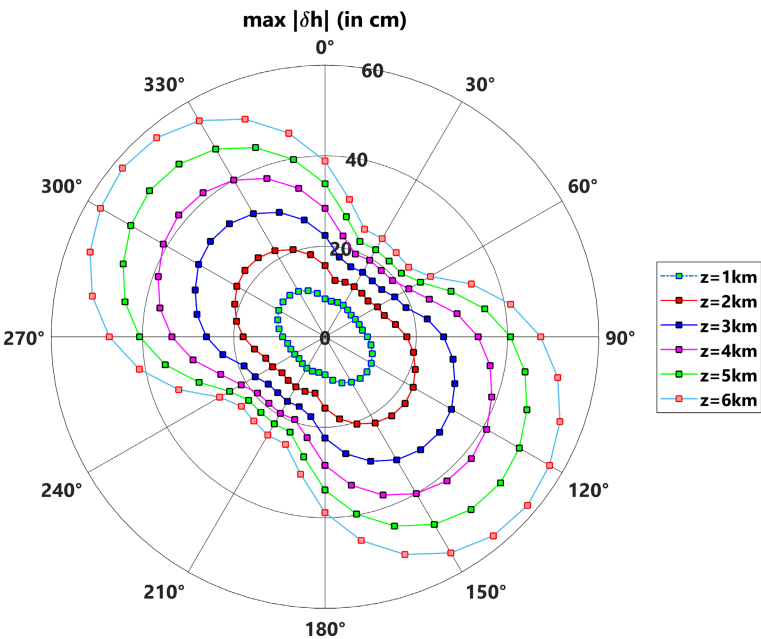


FIG. 8. Impact of azimuth angle variations on horizontal (δh) coordinates using the SWEN17 model at different flight altitudes in Sweden (the polar plots show maximum absolute value of δh). Unit: cm.

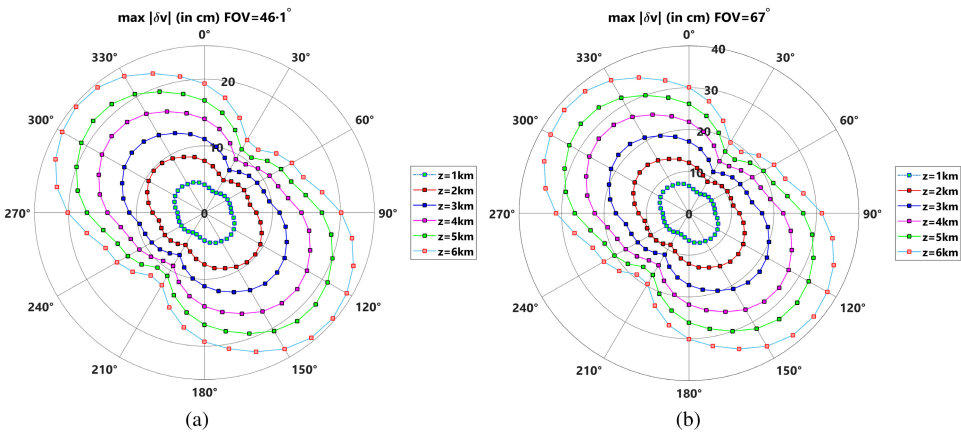


FIG. 9. Impact of azimuth angle variations on vertical coordinates using the SWEN17 model at different flight altitudes assuming (a) $FOV = 46.1^\circ$ and (b) $FOV = 67^\circ$ in Sweden (the polar plots show maximum absolute value of δv). Unit: cm.

polar plots in Sweden. The maximum absolute values of δh and δv are also plotted. In addition, the figures illustrate that the influence of the DOVs is minimised if the flight lines are designed toward azimuths between 30° and 50° .

The variations of the maximum absolute values of δh and δv presented in Figs. 8 and 9 were obtained based on the coordinate errors in Sweden (for example, the results presented in Fig. 6). However, these findings are acceptable on a national scale. The effect of azimuth can also be analysed spatially by partitioning the study area into three subregions of north, middle and south, where Norrbotten, Dalarna and Jönköping regions represent them, respectively (see Fig. 1). Table III shows the best azimuths for the selected subregions. In addition, Fig. 10 illustrates the impact of azimuth angle variations on horizontal and vertical coordinates in the south of Sweden (in Jönköping). Similar figures can be seen for Dalarna and Norrbotten in Figs. S5 and S6 (see supplementary materials). The results show that the azimuth impact is more substantial in specific directions, and it decreases when the flight directions are changed (azimuth). For example, Fig. 10 shows that the maximum error of coordinates due to the DOVs diminishes in azimuth 110° (or 290°) in the Jönköping region. However, this issue can be scrutinised further in smaller subregions when the flight strips are designed. In addition, the findings show that the azimuth has not a significant impact in the middle subregion (for instance, Dalarna, see Fig. S5) because the graphs show a homogeneous variation.

CONCLUSIONS

In this paper, the impact of the geoid slope was studied with respect to the earth's reference ellipsoid in 3D mapping using aerial photogrammetry in Sweden. This issue is

TABLE III. The best flight direction (azimuth angle) in the selected regions.

Subregion	Latitude	Longitude	Best azimuth
Jönköping	56° to 58° N	13° to 16° E	~110° (290°)
Dalama	61° to 63° N	13° to 16° E	~150° (330°)
Norrbotten	66° to 68° N	17° to 20° E	~170° (350°)

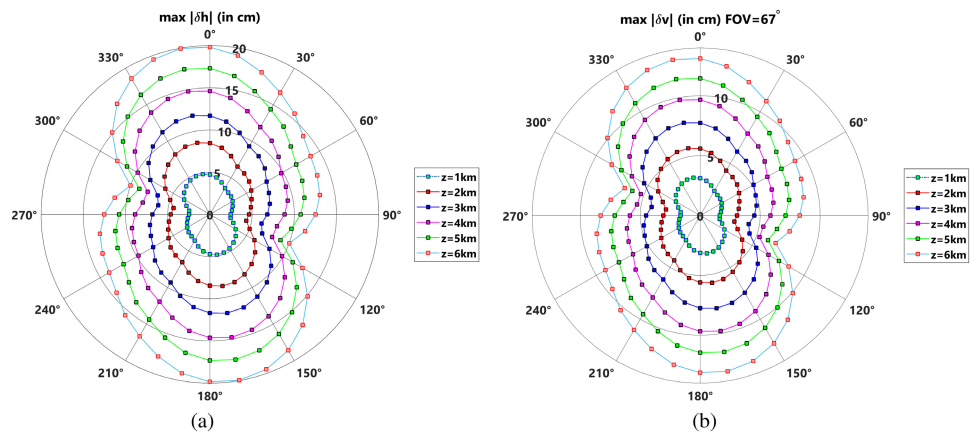


FIG. 10. Impact of azimuth angle variations on (a) horizontal (δh) and (b) vertical (δv) components using the SWEN17 model at different flight altitudes and assuming FOV = 67° in Jönköping, south of Sweden (the polar plots show maximum absolute value of δh and δv). Unit: cm.

important because one of the essential tasks in direct georeferencing of remotely sensed data (such as aerial images) is determining the EOPs and relating the recorded data to a reference coordinate system. With the integration of the GNSS and INS data, the observables of the position and orientation parameters of the aerial images, for instance, direct georeferencing, becomes feasible for automated 3D mapping. The collected data should refer to the same reference system; otherwise, it can impose a systematic shift in the obtained positions from aerial photogrammetry images. The collected inertial data (roll, pitch and heading) refers to the geoid (physical shape of the earth). However, the orientation of the aerial images should be related to the GNSS reference surface (for instance, earth's reference ellipsoid). Therefore, the difference between the plumb line and the normal to the reference ellipsoid, called the deflection of verticals (DOV), should be considered to determine the EOPs. Hence, reducing noises and biases in the airborne photogrammetry system due to integrating GNSS and INS sensors is an important task that can be performed using a precise geoid model. The uncertainty of the INS sensors is improving, for example, the latest Applanix company's INS sensor (POS AV 610 model) provides inertial data with high accuracy (about 9" for roll and pitch and 18" for heading (yaw)). This shows that the DOV effect should be considered for georeferencing because the DOV components in the north–south and east–west directions are in the order of (or larger than) the INS sensor uncertainty. Most of the existing commercial software uses a global model for the geoid, which is not accurate enough, especially in mountainous areas. The DOV was determined using the EGM2008 global geopotential model and regional gravity data (SWEN17 model) in different flight altitudes (varying from 1 to 6 km) in Sweden. By increasing the flight altitude, the maximum absolute value of the DOV components (ξ and η) decreases from 17.25 to 13.35 and 19.20 to 16.24 arc-seconds, respectively, using the SWEN17 model. The results showed that the calculated DOV using the EGM2008 model is sufficiently precise in Sweden except for the mountainous areas because the topographic signal was not corrected in the EGM2008 model. Therefore, the determined DOV obtained from regional gravity data (SWEN17 model) is proposed for the rough topography areas. The results also show that the camera FOV and the flight direction have effects on coordinate uncertainties. The influence of the DOV on horizontal and vertical coordinates (absolute value) varies between 8.3 to 38.8 cm and 5.5 to 27.7 cm (considering FOV = 67°), respectively. Finally, it was shown that the influence of the DOVs is minimised if the flight lines are designed toward a specific flight direction (azimuth) based on the location of the study area. The fewer uncertainties achieved in flight directions vary between 110° and 170° from the south to north of Sweden.

The high accuracy of the geoid model in Sweden, at the cm–dm level (Ågren et al., 2018), provided a great opportunity to examine the effect of DOV in direct georeferencing in photogrammetric computations in different regions of Sweden. However, the methodology and analysis explained in this paper can be useful and further applied to other regions or countries wherever a high accurate geoid is available.

ACKNOWLEDGEMENTS

The authors acknowledge the support of the Swedish Mapping, Cadastral and Land Registration Authority, Lantmäteriet, for providing the dataset and scientific advice in this paper. The authors would also like to show their gratitude to Anders Ekholm and Håkan Ågren for sharing their pearls of wisdom during this research.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study is available from the corresponding author upon reasonable request.

REFERENCES

- ABDULLAH, Q., 2000. Camera orientation without aerotriangulation: system performance and productivity. *International Archives of Photogrammetry and Remote Sensing*, 33: 4–11.
- ÅGREN, J., KEMPE, C. and JIVALL, L., 2018. Noggrann höjdbestämning med den nya nationella geoidmodellen SWEN17_RH2000. Presented at the Kartdagarna conference, 20–22 March 2018, Linköping, Sweden (in Swedish).
- AIRLINES ELECTRONIC ENGINEERING COMMITTEE, 1982. *ARINC Characteristic 705 – Attitude and Heading Reference System*, Aeronautical Radio, Annapolis, Maryland.
- ANDERSEN, O. B., 2013. Marine gravity and geoid from satellite altimetry. *Geoid Determination*. Springer, Heidelberg, Germany: 401–451. DOI: https://doi.org/10.1007/978-3-540-74700-0_9.
- APPLANIX, 2012. GNSS-inertial direct georeferencing with integrated flight management for airborne mapping. <https://geo-matching.com/inertial-navigation-systems-ins/postrack> [Accessed: 10th May 2022].
- BARZAGHI, R., CARRION, D., PEPE, M. and PREZIOSO, G., 2016. Computing the deflection of the vertical for improving aerial surveys: a comparison between EGM2008 and ITALGEO05 estimates. *Sensors*, 16(8): 1168. <https://doi.org/10.3390/s16081168>.
- BÄUMKER, M. and HEIMES F. J., 2001. New calibration and computing method for direct georeferencing of image and scanner data using the position and angular data of an hybrid inertial navigation system. *OEEPE Workshop, Integrated Sensor Orientation*: 1–17.
- CRAMER, M., 2001. On the use of direct georeferencing in airborne photogrammetry. Universität Stuttgart, Fakultät Bauingenieur- und Vermessungswesen, Institut für Photogrammetrie, Stuttgart, Germany.
- CRAMER, M. and STALLMANN, D., 2002. OEEPE test on “integrated sensor orientation” – IFP results and experiences. *Proceedings of the OEEPE Workshop, Integrated Sensor Orientation*, September.
- CRAMER, M., STALLMANN, D. and HAALA, N., 2000. Direct georeferencing using GPS/inertial exterior orientations for photogrammetric applications. *International Archives of Photogrammetry and Remote Sensing*, 33(B3/1; Part 3): 198–205.
- FORSBERG, R. and TSCHERNING, C. C., 2014. *An Overview Manual for the GRAVSOFT Geodetic Gravity Field Modelling Programs*. National Space Institute, (DTU-Space), Denmark: 1–59.
- GOULDEN, T. and HOPKINSON, C., 2010. Investigating the effect of the deflection of the vertical on lidar observations. *Canadian Journal of Remote Sensing*, 36(Suppl. 2): S365–75. <https://doi.org/10.5589/m10-056>.
- HAO, S., ZHANG, Z., ZHOU, Z., ZHAO, J., CHANG, Z. and XU, Z., 2020. Analysis of deflection of vertical compensation for inertial navigation system. *Mathematical Problems in Engineering*, 2020: 1–15. <https://doi.org/10.1155/2020/1975672>.
- HEIPKE, C., JACOBSEN, K. and WEGMANN, H., 2001. *The OEEPE Test on Integrated Sensor Orientation – I*. <http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.503.7404> [Accessed: 10th May 2022].
- HEISKANEN, W. A. and MORITZ, H., 1967. *Physical Geodesy (Book on Physical Geodesy Covering Potential Theory, Gravity Fields, Gravimetric and Astrogeodetic Methods, Statistical Analysis, etc.)*, Freeman, San Francisco, California.
- HUTTON, J. and MOSTAFA, M. M. R., 2005. 10 years of direct georeferencing for airborne photogrammetry. *GIS Business (GeoBit)*, 11(1): 33–41.
- JACOBSEN, K. and WEGMANN, H., 2002. Dependencies and problems of direct sensor orientation. *Integrated Sensor Orientation, OEEPE Official Publication*, 43: 73–84.
- JEKELI, C., 1999. An analysis of vertical deflections derived from high-degree spherical harmonic models. *Journal of Geodesy*, 73(1): 10–22. <https://doi.org/10.1007/s001900050213>.
- JEKELI, C., 2012. *Inertial Navigation Systems with Geodetic Applications*, Walter de Gruyter, Berlin, Germany. <https://doi.org/10.1515/9783110800234>.
- KARJALAINEN, M., HYYPÄ, J. and KUITTINEN, R., 2006. Determination of exterior orientation using linear features from vector maps. *The Photogrammetric Record*, 21(116): 329–41. <https://doi.org/10.1111/j.1477-9730.2006.00399.x>.
- LANTMÄTERIET, 2020. *Produktbeskrivning, GSD-Höjddata grid 50+ nh*. Lantmäteriet, Gävle, Sweden (in Swedish).
- MEIER, H. K., 1975. The effects of environmental conditions on distortion, calibrated focal length and focus of aerial survey camera. *Conference of Working Group on Image Geometry*, Comm. I. ISP, Ottawa, Canada.

- MORITZ, H., 2000. Geodetic reference system 1980. *Journal of Geodesy*, 74(1): 128–133.
- MOSTAFA, M. M., HUTTON, J. and LITHOPOULOS, E., 2001. Airborne direct georeferencing of frame imagery: an error budget. *Proceedings of the 3rd International Symposium on Mobile Mapping Technology (MMS2001)*, January.
- PAVLIS, N. K., HOLMES, S. A., KENYON, S. C. and FACTOR, J. K., 2012. The development and evaluation of the Earth Gravitational Model 2008 (EGM2008). *Journal of Geophysical Research: Solid Earth*, 117(B4): 1–38. <https://doi.org/10.1029/2011JB008916>.
- PEPE, M., PREZIOSO, G. and SANTAMARIA, R., 2015. Impact of vertical deflection on direct georeferencing of airborne images. *Survey Review*, 47(340): 71–76. <https://doi.org/10.1179/1752270614Y.0000000087>.
- REED, G. B., 1973. Application of kinematical geodesy for determining the short wave length components of the gravity field by satellite gradiometry. *Ohio State University Report*, 201: 164.
- RIZALDY, A. and FIRDAUS, W., 2012. Direct georeferencing: a new standard in photogrammetry for high accuracy mapping. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 39(B1): 5–9.
- SANSÒ, F. and SIDERIS, M. G., 2013. *Geoid Determination: Theory and Methods*. Springer Science & Business Media., Heidelberg, Germany. DOI: <https://doi.org/10.1007/978-3-540-74700-0>.
- SCHWARZ, K. P., SIDERIS, M. G. and FORSBERG, R., 1990. The use of FFT techniques in physical geodesy. *Geophysical Journal International*, 100(3): 485–514. <https://doi.org/10.1111/j.1365-246X.1990.tb00701.x>.
- SJÖBERG, L. E., 2003. A computational scheme to model the geoid by the modified Stokes formula without gravity reductions. *Journal of Geodesy*, 77(7): 423–432. <https://doi.org/10.1007/s00190-003-0338-1>.
- SJÖBERG, L. E. and BAGHERBANDI M., 2017. *Gravity Inversion and Integration*. Springer International Publishing AG, Basel, Switzerland.
- SKALLOUD, J., CRAMER, M. and SCHWARZ, K. P., 1996. Exterior orientation by direct measurement of camera position and attitude. *International Archives of Photogrammetry and Remote Sensing*, 31(B3): 9–19.
- VANICEK, P. and KRAKIWSKY, E. J., 1986. *Geodesy: The Concepts*. Elsevier, Amsterdam, The Netherlands.
- VAUGHN, C. R., BUTTON, J. L., KRABILL, W. B. and RABINE, D., 1996. Georeferencing of airborne laser altimeter measurements. *International Journal of Remote Sensing*, 17(11): 2185–2200. <https://doi.org/10.1080/01431169608948765>.
- YUAN, X. and ZHANG, X. P., 2008. Theoretical accuracy of direct georeferencing with position and orientation system in aerial photogrammetry. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Sciences*, XXXVII(B1): 617–622.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article.

Résumé

Les applications GNSS/INS se développent, notamment pour le géoréférencement direct en photogrammétrie aéroportée. Pour obtenir des produits géoréférencés avec précision grâce à l'intégration du GNSS et de l'INS, il faut éliminer les erreurs systématiques des systèmes de cartographie mobile. L'incertitude du capteur INS est de plus en plus faible; par conséquent, l'influence de la déviation de la verticale (DOV, l'angle entre le fil à plomb et la normale à l'ellipsoïde) doit être prise en compte dans le géoréférencement direct. Autrement, une erreur est commise dans le calcul des paramètres d'orientation externe des images aériennes et du balayage laser aérien. Cette étude détermine les DOV en utilisant le modèle EGM2008 et les données gravimétriques en Suède. L'impact des DOV sur les coordonnées horizontales et verticales est évalué en considérant différentes altitudes de vol et différents champs de vision de la caméra. Les résultats confirment que les composantes DOV calculées à l'aide du modèle EGM2008 sont suffisamment précises pour les systèmes de cartographie aérienne, sauf pour les zones montagneuses où le signal topographique n'est pas modélisé correctement.

Zusammenfassung

GNSS/INS-Anwendungen entwickeln sich, insbesondere für die direkte Georeferenzierung in der luftgestützten Photogrammetrie. Um präzise georeferenzierte Produkte aus der Integration von GNSS und INS zu erhalten, müssen systematische Fehler in den mobilen Kartierungssystemen beseitigt werden. Die Unsicherheit des INS-Sensors nimmt ab; Daher sollte der Einfluss der Abweichung von Vertikalen (DOV, der Winkel zwischen der Lotlinie und der Normalen zum Ellipsoid) bei der direkten Georeferenzierung berücksichtigt werden. Andernfalls wird ein Fehler für die Berechnung der äußeren Orientierungsparameter der Luftbilder und der Lufilaserabtastung auferlegt. Diese Studie bestimmt die DOV unter Verwendung des EGM2008-Modells und Schwerkraftdaten in Schweden. Der Einfluss der DOVs auf horizontale und vertikale Koordinaten unter Berücksichtigung verschiedener Flughöhen und Kamerasichtfelder wird bewertet. Die Ergebnisse bestätigen, dass die berechneten DOV-Komponenten unter Verwendung des EGM2008-Modells ausreichend genau für Luftkartierungssysteme sind, mit Ausnahme der Berggebiete, da das topografische Signal nicht korrekt modelliert wird.

Resumen

Se desarrollan aplicaciones GNSS/INS, especialmente para georreferenciación directa en fotogrametría aérea. Lograr productos georreferenciados con precisión a partir de la integración de GNSS e INS requiere eliminar errores sistemáticos en los sistemas de cartografía móvil. Al reducirse la incertidumbre del sensor INS, la influencia de la deflexión de la vertical (DOV, el ángulo entre la plomada y la normal al elipsoide) requiere ser considerada en la georreferenciación directa. De lo contrario, los parámetros de orientación exterior de las imágenes aéreas y/o el escaneo láser aéreo tendrán un error sistemático debido a la DOV. Este estudio determina el DOV usando el modelo EGM2008 y datos de gravedad en Suecia. Se evalúa el impacto de la DOV en las coordenadas horizontales y verticales, considerando diferentes altitudes de vuelo y campo de visión de la cámara. Los resultados confirman que los componentes del DOV calculados con el modelo EGM2008 son lo suficientemente precisos para los sistemas de cartografía aérea, excepto en zonas montañosas porque la componente topográfica no se modela correctamente.

摘要

GNSS/INS的应用正在发展中,特别是用于机载摄影测量的直接地理参考。要从GNSS和INS的整合中实现精确的地理参考产品,需要消除移动测绘系统中的系统误差。由于INS传感器的不确定性在下降,因此,在直接地理参考中应考虑垂直方向的偏差(DOV,铅垂线与椭圆体法线之间的角度)的影响。否则,在计算航空影像和航空激光扫描的外部方位参数时就会出现误差。本研究使用EGM2008模型和瑞典的重力数据来确定DOV。考虑到不同的飞行高度和相机视场,评估了DOV对水平和垂直坐标的影响。结果证实,使用EGM2008模型计算的DOV分量对于航测目的是足够准确的,但山区除外,因为地形信号没有被正确建模。