IMPORTANCE OF PRECISE GRAVITY FIELD MODELING IN DIRECT GEOREFERENCING AND AERIAL PHOTOGRAMMETRY: A CASE STUDY FOR SWEDEN

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ABSTRACT: Direct georeferencing of airborne mobile mapping systems is developing with unprecedented speed using GNSS/INS integration. Removal of systematic errors is required for achieving a high accurate georeferenced product in mobile mapping platforms with integrated GNSS/INS sensors. It is crucial to consider the deflection of verticals (DOV) in direct georeferencing due to the recently improved INS sensor accuracy. This study determines the DOV using Sweden's EGM2008 model and gravity data. The influence of the DOVs on horizontal and vertical coordinates and considering different flight heights is assessed. The results confirm that the calculated DOV components using the EGM2008 model are sufficiently accurate for aerial photogrammetry purposes except for the mountainous areas because the topographic signal is not modeled correctly.

1. INTRODUCTION

Aerial photogrammetry is one of the most important geospatial data acquisition techniques nowadays. It has been used for producing topographical maps and extracting terrain features from aerial images for many years. In addition, the applications of 3D geospatial data are expanding, and technology is growing at an unprecedented speed with new mapping systems. Different sensors are used for data acquisition in modern airborne photogrammetries such as GNSS-INS (Inertial Navigation Systems) sensors and digital cameras. GNSS/INS applications are developing, especially for direct georeferencing in airborne photogrammetry. To accurately obtain georeferenced products from the integration of GNSS and INS, one must remove existing systematic errors/biases in the mobile mapping systems due to different reference systems, i.e., separation of the geoid and the Earth's reference ellipsoid. The collected data should refer to the same reference system; otherwise, it can impose a systematic shift in the results. In this study, we quantify the impact of different reference systems on the obtained horizontal and vertical coordinates in Sweden.

Direct georeferencing is an efficient method in aerial digital photogrammetry and automated 3D mapping that requires accurate attitude and position of each image during exposure time (Bäumker and Heimes 2001). The collected inertial data (roll, pitch, and heading) refer to the equipotential surfaces of the gravity field and thus approximately refer to the geoid (Figure 1).

However, the orientation of the aerial images (ω, φ, and κ) should be determined in relation to the Earth's reference ellipsoid ((Goulden and Hopkinson, 2010)). Therefore, a rotation matrix needs to be applied to consider the slope of the geoid (or more precisely, the equipotential surfaces) with respect to the reference ellipsoid in each point. In other words, a rotation matrix has to be considered due to the deflection of verticals (DOV) ((Heiskanen and Moritz 1967)).

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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 (e.g. (Goulden and Hopkinson 2010), and (Pepe et al. 2015)):

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

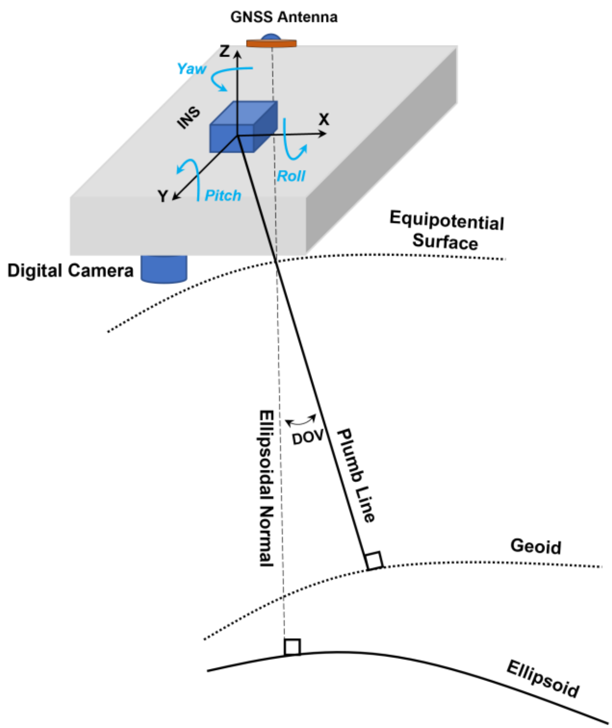

Figure 1. A schematic presentation of different aerial photogrammetry sensors and their relationship with geodetic reference systems.

where $\mathbf{r}_{Ground}$ is the transformed image coordinates in an Earth-fixed coordinate system, $\mathbf{r}_{GNSS}$ is the absolute position of mobile mapping system derived by GNSS, $\mathbf{R}_{DOV}$ is rotation matrix due to the DOV (transformation from local level frame to ellipsoidal frame), and $\mathbf{R}_{INS}$ is rotation matrix from the IMU body frame to the local level frame, $\mathbf{r}_{lever\ arm}$ shows the offset between the phase center of GNSS and camera in the IMU body frame, s is the scale factor, $\mathbf{R}_{Boresight}$ is 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)), $\mathbf{r}_{image}$ denotes on images coordinates (in camera frame).

In this study, the induced error/bias due to the DOV when integrating different sensors, focusing on GNSS and INS for 3D mapping in airborne photogrammetry, is studied in Sweden. We assess the horizontal and vertical errors (see Figure 2) due to ignoring the DOV components using the DOVs obtained from the EGM2008 model and computed based on the official Swedish quasigeoid model SWEN17_RH2000 ((Ågren et al. 2018)). However, other parameters also affect the results, e.g., the camera field of view impact, flight direction, and flight altitude. Similar studies presented by (Goulden and Hopkinson 2010), (Pepe et al. 2015), and (Barzaghi et al. 2016) show that the impact of the DOV is significant on direct georeferencing of airborne images. Hence, we quantify and present the effect of the DOV and other related parameters such as FOV, azimuth, and flight height in this paper (as a case study in Sweden).

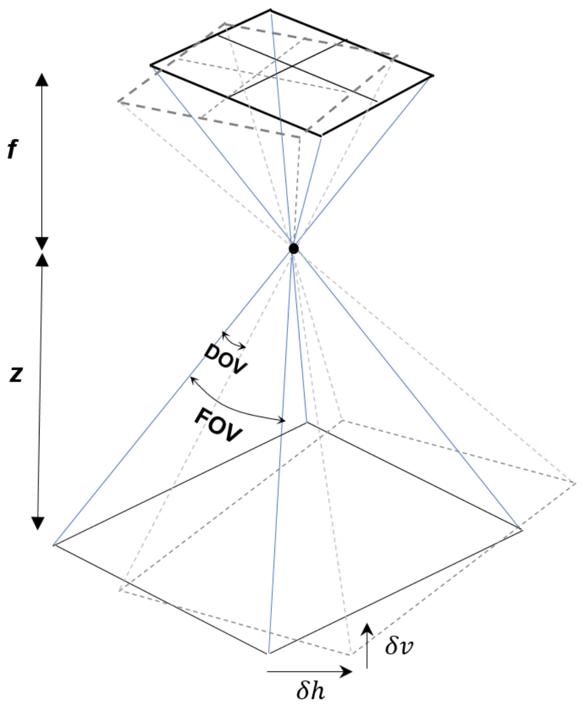

Figure 2. DOV effect on horizontal and vertical coordinates.

Note: FOV is the field of view of the imaging camera. δh and δv are the horizontal and vertical coordinates error due to the DOV. f is the focal length of the camera. z is the flight altitude. the DOV and other related parameters such as FOV, azimuth, and flight height in this paper (as a case study in Sweden).

2. MAIN BODY

2.1 Data and study area

In this study, EGM2008 and the SWEN17_RH2000 quasigeoid model ((Ågren et al. 2018)) are used to assess the horizontal and vertical errors due to ignoring the DOV components. 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. This elevation model was produced during 2009-2017 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.

2.2 Method

2.2.1 Determination of the deflection of verticals:

The DOV components (ξ , η) can be determined using the formulas of Veining Meinez ((Heiskanen and Moritz 1967), p. 114 and 312) and regional gravity and elevation data. Since the SWEN17_RH2000 model is strictly a quasigeoid (ς) 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):

$$\xi = -\frac{1}{R}\frac{\partial \varsigma}{\partial \theta} - \frac{\Delta g}{\gamma}\frac{1}{R}\frac{\partial H}{\partial \theta} \tag{1a}$$

$$\eta = -\frac{1}{R\sin\theta}\frac{\partial \varsigma}{\partial \lambda} - \frac{\Delta g}{\gamma}\frac{1}{R\sin\theta}\frac{\partial H}{\partial \lambda} \tag{1b}$$

where Δg is 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 calculated DOV components can be approximately determined above the earth's surface (e.g. at flight altitude) using upward continuation techniques (cf. (Sjöberg and Bagherbandi 2017)) e.g. a Fast Fourier Transform (FFT) technique that is based on:

$$F\left(\begin{bmatrix}\xi & \eta\end{bmatrix}_{(k,z)}\right) = F\left(\begin{bmatrix}\xi & \eta\end{bmatrix}_{(k,0)}\right)\exp^{(-2\pi kz)} \tag{2}$$

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 wave-numbers equal to one over half the wavelength in the x and y direction, therefore $k = \sqrt{k_x^2 + k_y^2}$ (cf. (Andersen 2013)).

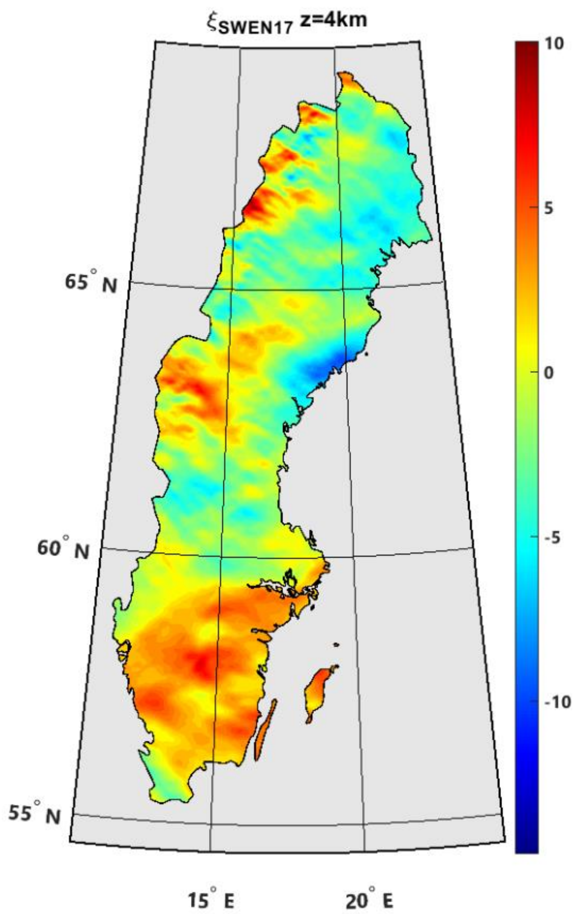

Figure 3. North-south DOV component (ξ) using SWEN17 for 4 km flight altitudes in Sweden. Unit: arc second.

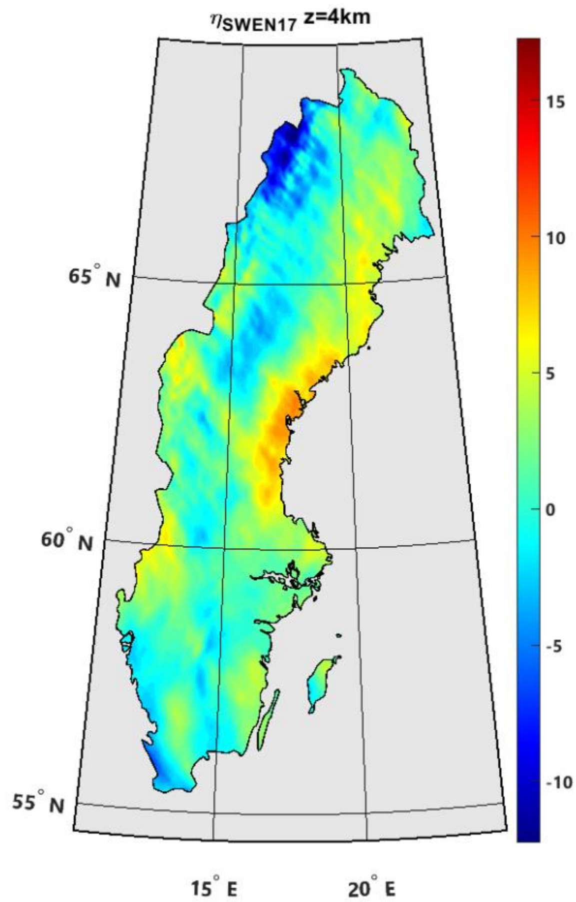

Figure 4. East-west DOV component (η) using SWEN17 for 4 km flight altitudes in Sweden. Unit: arc second.

2.2.2 DOV effect on horizontal and vertical components:

According to Figure 2, the horizontal (δh) and vertical (δv) errors due to neglecting the DOV can be obtained using the following equations, respectively (cf. (Pepe et al. 2015)). The errors depend on the flight altitude (z), direction of flight (azimuth, α), and the camera's field of view (FOV):

$$\delta h = z \sin(DOV_{\alpha}) \tag{3}$$

$$\delta v = z \tan\left(\frac{FOV}{2}\right)\sin(DOV_{\alpha}) \tag{4}$$

$$DOV_{\alpha} = \xi \cos\alpha + \eta \sin\alpha \tag{5}$$

where DOV_{α} is the deflection of vertical in the azimuth α . More details about Eq. (5) can be seen in (Vanicek and Krakiwsky 1986).

2.3 Results

This section presents the results of the DOV impact on the horizontal and vertical coordinates. The DOVs at the earth's surface calculated using the SWEN17_RH2000 quasigeoid model and then upward continued to flight altitude is called SWEN17_DOV to follow the same name as the latest quasigeoid model of Sweden. We determined the DOVs at 1, 2, 3, 4, 5, and 6 km flight altitudes in this study. Table 1 presents the DOV components for the above-mentioned flight heights in Sweden.

Figures 3 and 4 visualize the DOV components (ξ , η) using SWEN17 for 4 km flight altitudes in Sweden. The results show that the calculated DOV values are smoother when we increase the flight altitude from 1 to 6 km.

		Flight altitudes (km)					
		z = 1	**z = 2**	**z = 3**	**z = 4**	**z = 5**	**z = 6**
ξ *(arc second)*	***Max***	15.77	12.36	10.69	10.04	9.63	9.27
	Mean	0.69	0.68	0.67	0.67	0.66	0.66
	Min	-17.25	-16.25	-15.39	-14.64	-13.96	-13.35
	STD	3.51	3.36	3.24	3.14	3.06	2.98
η *(arc second*	***Max***	19.20	18.50	17.87	17.30	16.76	16.24
	Mean	0.72	0.71	0.70	0.69	0.68	0.67
	Min	-17.31	-14.99	-13.42	-12.27	-11.37	-10.62
	STD	3.89	3.74	3.62	3.53	3.44	3.36

Table 1. Statistics of the DOV components (ξ , η) were obtained using the SWEN17 model at different flight altitudes in Sweden. Unit: arc second.

Comparing the obtained DOV components with recent INS sensors specification one can see the influence of the anomalous gravity field (deflection of verticals) in GNSS/INS applications is not ignorable. 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)). Figures 5 and 6 show the improvement of the different POS AV sensors over time.

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. Figures 7 and 8 show the impact of azimuth (varying from 0° to 360° with 10° intervals) in Sweden for different flight altitudes (1-6 km) using polar plots. We plotted the maximum absolute value of δh and δv here.

In addition, the figures illustrate that the influence of the DOVs is minimized if one designs the flight lines toward azimuths between 30° to 50°. However, these findings are acceptable on a national scale. The effect of azimuth can also be analyzed spatially by partitioning the study area into different subregions. We investigated this in Norrbotten, Dalarna, and Jönköping regions. The results show that the best azimuths for the selected subregions are different and vary between 110° to 170° from south to north of Sweden.

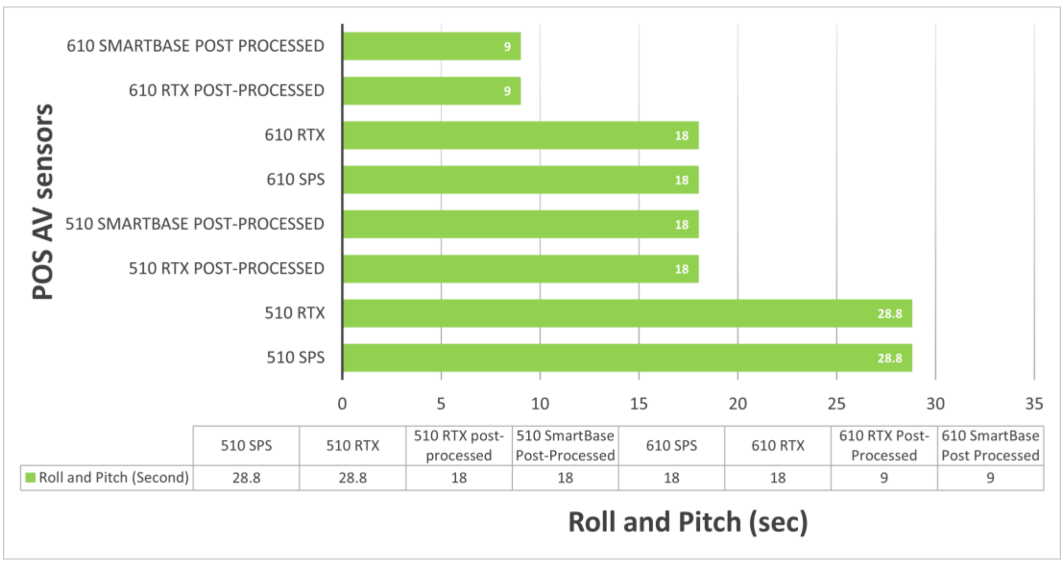

Figure 5. Accuracy of roll and pitch parameters in different POS AV INS sensors.

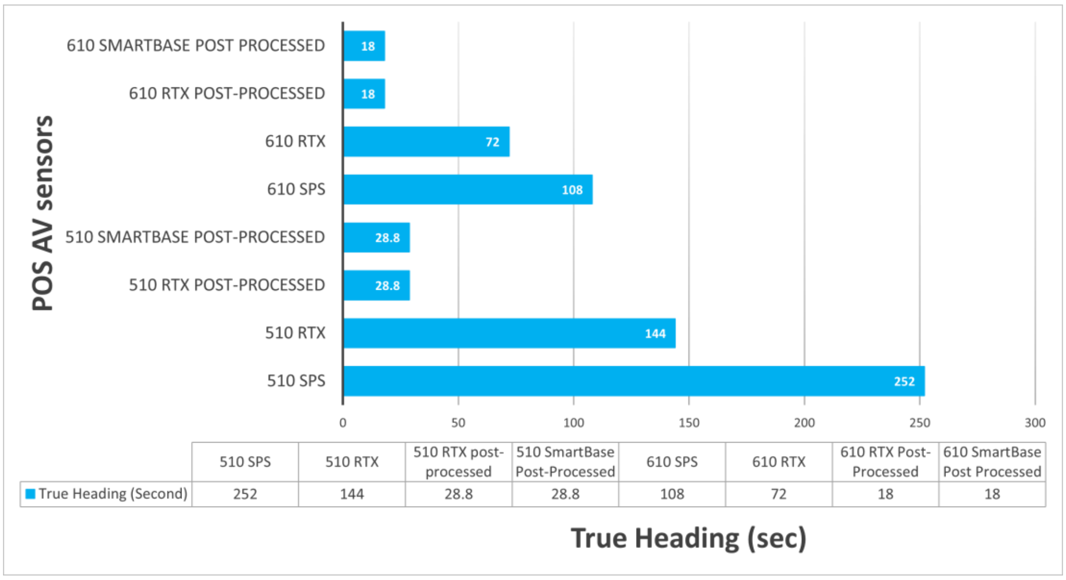

Figure 6. Accuracy of Heading parameters in different POS AV INS sensors.

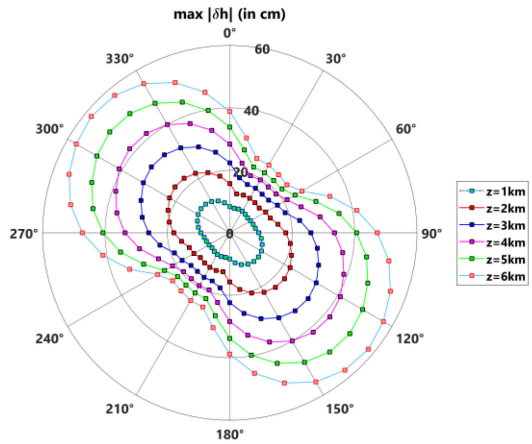

Figure 7. Impact of azimuth-angle variations on horizontal (δh) coordinates using SWEN17 model at different flight altitudes in Sweden (the polar plots show maximum absolute value of δh). Unit: cm

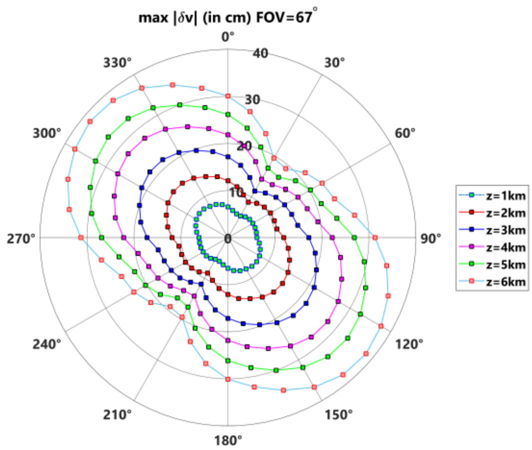

Figure 8. Impact of azimuth-angle variations on vertical coordinates (δv) using SWEN17 model at different flight altitudes assuming FOV=67˚ in Sweden (the polar plots show maximum absolute value of δv). Unit: cm

3. CONCLUSIONS

The influence of ignoring the slope of geoid with respect to the Earth’s reference ellipsoid in aerial photogrammetry was studied in Sweden in this paper. The separation of geoid and reference ellipsoid forms the deflection of verticals (DOV) i.e., the angle between the vertical to the geoid and normal to ellipsoid. The effect of DOV is important for the calculation of exterior orientation parameters in direct georeferencing. This study also compared two DOV models, i.e., the DOV derived using the national precise geoid model in Sweden, i.e., SWEN17_RH2000 and the DOV obtained using EGM2008 models. The results showed that the calculated DOV using the EGM2008 model is sufficiently precise in Sweden except for the mountainous areas because the EGM2008 model does not adequately model the high-frequency topographic signal. Therefore, the determined DOV obtained from regional gravity data (SWEN17_DOV model) is proposed for the rough topography areas. Our results also show that the camera field of view (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, we showed that the influence of the DOVs is minimized if one designs the flight lines toward a specific flight direction (azimuth) based on the location of the study area. The fewer uncertainties are achieved in-flight directions vary between 110° to 170° from south to north of Sweden.

4. ACKNOWLEDGEMENTS

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