Airborne Gravity Survey of Uganda 2020

Acquisition and processing report

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Background

This report describe the data acquisition and results of the airborne gravity survey of Uganda, carried out by DTU Space in Jan-Feb 2020, in cooperation with the Uganda Ministry of Lands, Housing and Urban Development (MLHUD) and COWI A/S (aircraft provider). The data acquisition was funded by the US National Geospatial-Intelligence Agency (NGA), in support of global gravity field model development (EGM2020 and successors). The airborne gravity data will be used for an improved geoid model of Uganda, as part of the national survey infrastructure modernization of MLHUD; the geoid computation will be described in a separate report.

Left picture: King Air B90 aircraft at Entebbe (on left: pilot B. Nelson; right: H. Teitson, DTU Space). Right picture: MLHUD partners (F Azisua, senior surveyor, left; W. Ogaro, Surveyor General; right).

Logistics and permissions

The airborne gravity survey was carried out using a Beechcraft King Air 90 aircraft, with instruments for the survey installed in Roskilde Airport, Denmark on DEC 15-16, 2019. The aircraft started transit to Entebbe, Uganda, on JAN 6, 2020, arriving Entebbe late the following day. Customs clearance was smooth, thanks to MLHUD preparations. Delays in permissions from the Ugandan Air Force and aviation authorities meant airborne operations could first be initiated on JAN 19. The intermediate waiting period was used for equipment checks, gravity base readings, and local reference gravity ties, as well as several meetings with MLHUD, the Department of Surveys and Mapping, the aviation authorities, and the Danish Embassy.

The delayed survey flights took place in the period JAN 19-FEB 4, under a mix of reasonable and challenging weather conditions. The survey flights were flown in a line-by-line constant altitude mode, with flight elevations ranging from 2500 to 6200 m, as needed to clear terrain, and avoid clouds and associated turbulence (most flight days had varying degrees of cloud cover). A nominal flight speed around 180 kts was used throughout the campaign. Airspace clearances for line turns were in place with South Sudan, whereas flights into other countries were not permitted, meaning some loss of data along the borders (separate border flights were added to mitigate this).

All flights flown are shown below in Figure 1. All survey flights were operated in/out of Entebbe International Airport. Flight spacing of lines was 10 nm, as required by NGA for the EGM development; denser fill-in lines were flown over the Kampala/Entebbe on request of MLHUD, in order to get data for improved geoid accuracy around the capital region.

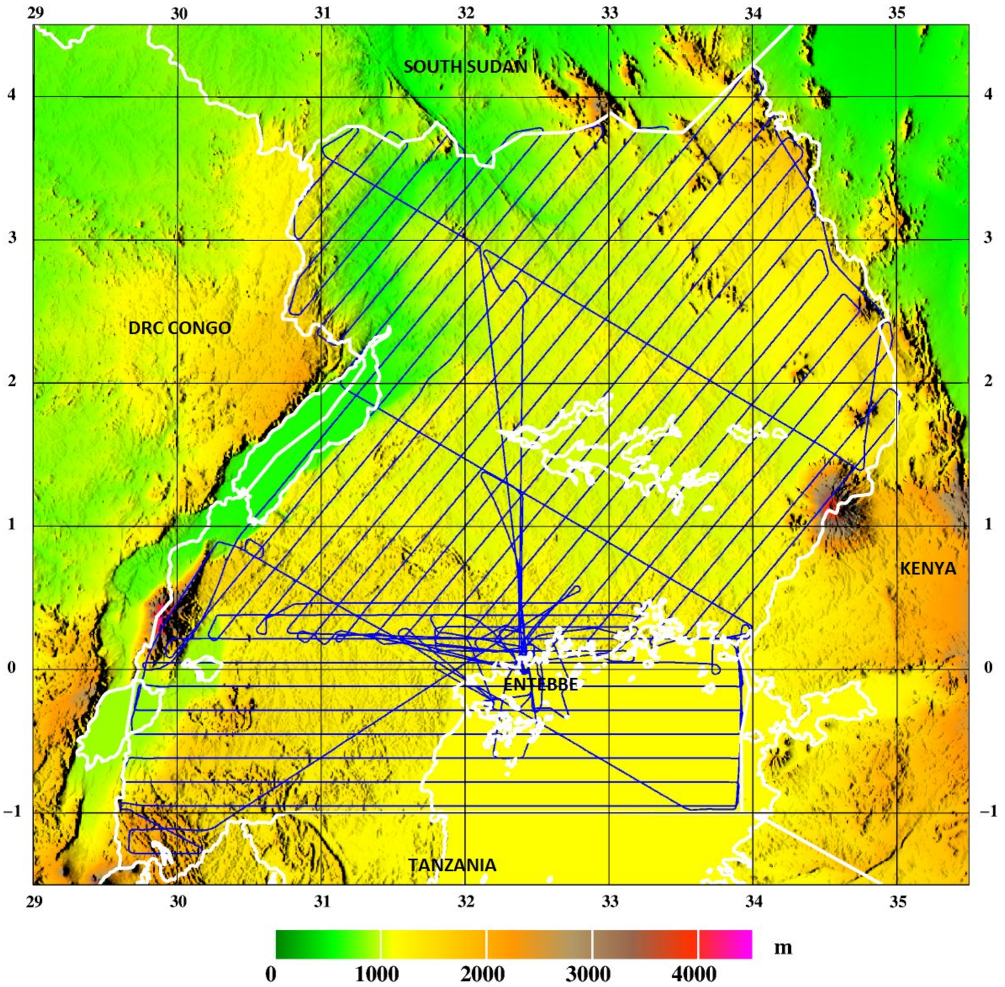

Fig. 1. Uganda gravity survey flights. Highest mountain is Mt. Stanley, Rwenzori Mts. (5109 m, in SW)

Instrument setup

The following instruments were installed in the COWI aircraft, registration OY-JJT; it was first time this specific aircraft was used for aerogravity by DTU Space(chosen due to the long 5.5 hr+ endurance):

- *LaCoste & Romberg Air/Sea gravimeter S-38*
- *iMAR RQH-4001 strapdown inertial survey unit, with build-in GPS rcvr*
- *Javad Delta GPS receivers, sharing aircraft antenna via beam splitter*
- *DTU-developed power rack with DC/AC inverters, UPS etc*
- *Data logging PC's with real-time GPS display for the pilot*

The setup is identical to earlier DTU Space airborne gravity campaigns. The L&R gravimeter S-38 is the primary instrument, providing the long-wavelength accuracy, while the iMAR IMU, with the higher dynamic range, provide the short-wavelength details, and allow flights under more turbulent conditions. Fig. 2 shows installation details. The gravimeter and iMAR systems were kept powered continuously throughout the survey for sensor thermal stability.

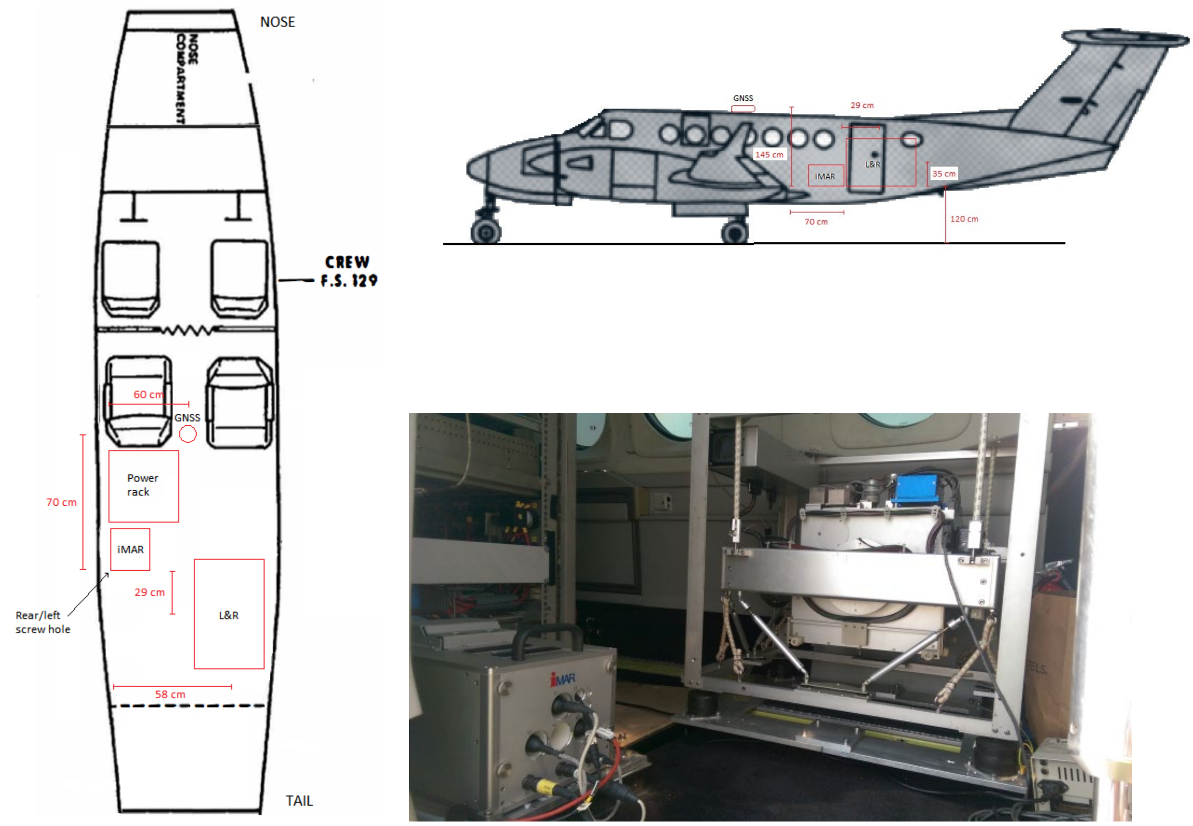

Fig. 2. Aircraft installation of instruments. Picture shows the L&R and iMAR instruments in OY-JJT.

GPS processing

Kinematic GPS processing has been based both on temporary GNSS reference stations, set up in the airport, as well as by ppp-processing, using "Waypoint" inertial explorer GNSS/IMU software from Novatel. The references for the differential solutions have been based on ITRF2014 coordinates from the AUSPOS service (http://www.ga.gov.au/bin/gps.pl), yielding absolute accuracies at the 1-2 cm level. The aircraft trajectory GPS solutions were computed using precise ephemerides from the International GNSS Service (http://igscb.jpl.nasa.gov/). Several combinations of rover and base receiver were computed for each flight, and the best performing solution chosen for the final iteration of the gravity processing.

GPS reference receiver at Entebbe airport; airport security an issue at times

Airborne Gravity processing

Free-air gravity anomalies at aircraft level from the L&R instrument are obtained by the equation

$$\Delta g = f_z - f_{z0} - h'' + \delta g_{eotvos} + \delta g_{tilt} + g_0 - \gamma_0 - \left(\frac{\partial \gamma}{\partial h}(h-N) + \frac{\partial^2 \gamma}{\partial h^2}(h-N)^2\right)$$

where f_z is the gravimeter observation, f_{z0} the apron base reading, h'' the GPS vertical acceleration, δg_{eotvos} the Eötvös correction, δg_{tilt} the platform tilt correction, g_0 the apron gravity value, γ_0 normal gravity n GRS80, h the GPS ellipsoidal height and N the geoid undulation. The above formula must be filtered along-track, typically using a zero-phase second order Butterworth filter, as shown in Fig. 3. For Uganda a half-wavelength filter of 3x170 sec was used, corresponding to a resolution around 8 km at an airspeed of 180 kts. The implementation of the L&R processing is done in the AG software, originally developed by Arne V Olesen at DTU Space (now at Westagard Geo Solutions).

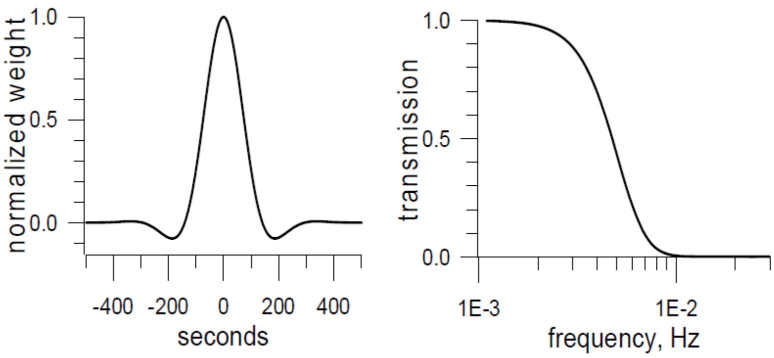

Fig. 3. Typical Butterworth filter for DTU Space airborne gravity

The L&R processing is aided by Waypoint Kalman filtering processing. The vertical accelerometer bias state is used as a proxy for short-wavelength gravity changed, and merged with the L&R estimate through a line-by-line trend fitting, yielding a composite iMAR/L&R solution. The used iMAR IMU seemed to have some long-wavelength variations in δg_z bias in Uganda, and iMAR results were therefore slightly less accurate than in earlier DTU Space campaigns (the cause of these variations are currently unknown, could likely be issues with the temperature stabilization of the iMAR unit during the hot climate).

For the final gravity free-air anomalies, the PGM2017 geoid model was used for conversion of gravity disturbance δg to geodetic free-air anomaly Δg, and an atmospheric correction (at altitude) applied as well. Absolute gravity value were subsequently computed from Δg and the derived orthometric heights by PGM2017. Fig. 4 shows the final free-air anomaly results.

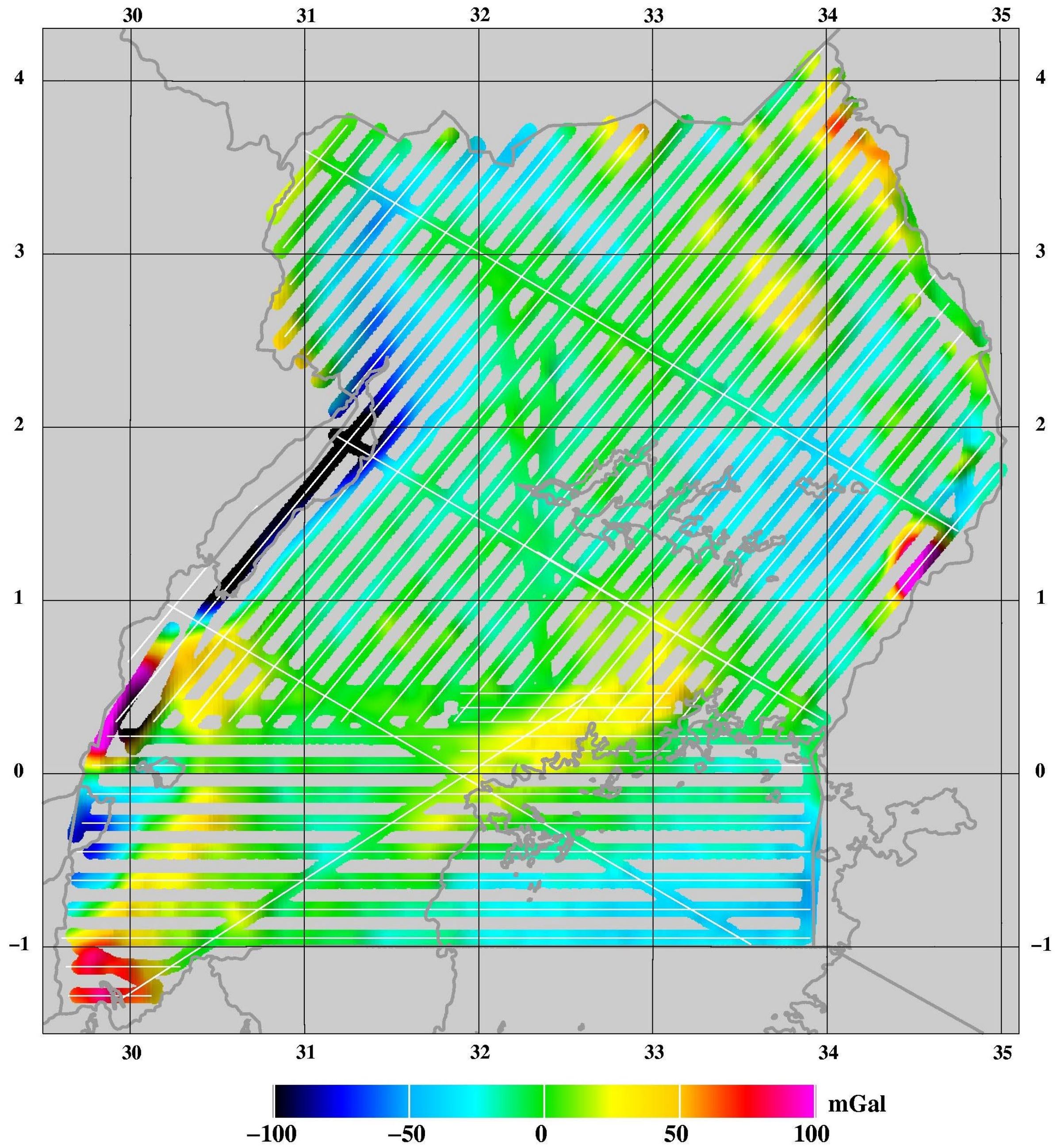

Fig. 4. Free-air anomalies for Uganda 2020 aerogravity survey. The data has a good coherence across tracks, and show large anomalies associated with Mt Elgon (at Kenya border to the right), and with the East Africa rift valley spur to the left). The large positive anomaly in SW is due to Rwenzori Mts.

Validation of the processed gravity data

The airborne free-air anomalies refer to the flight elevation. The primary validation method is the *cross-over* analysis between lines. These are shown in Fig. 5. The cross-over analysis indicate an r.m.s. cross-over of 2.67 mGal for 132 x-over points, indicating an accuracy of the airborne survey of 1.89 mGal, a good result giving the challenging flight conditions, and the difference in flight heights (not taken into account; real accuracy therefore less).

It should be pointed out that the error estimate is *without* any adjustment of cross-overs, which is normal practice in geophysical aerogravity (but not useful for EGM or geoid use, due to risk of leakage from short-wavelength errors to longer wavelengths).

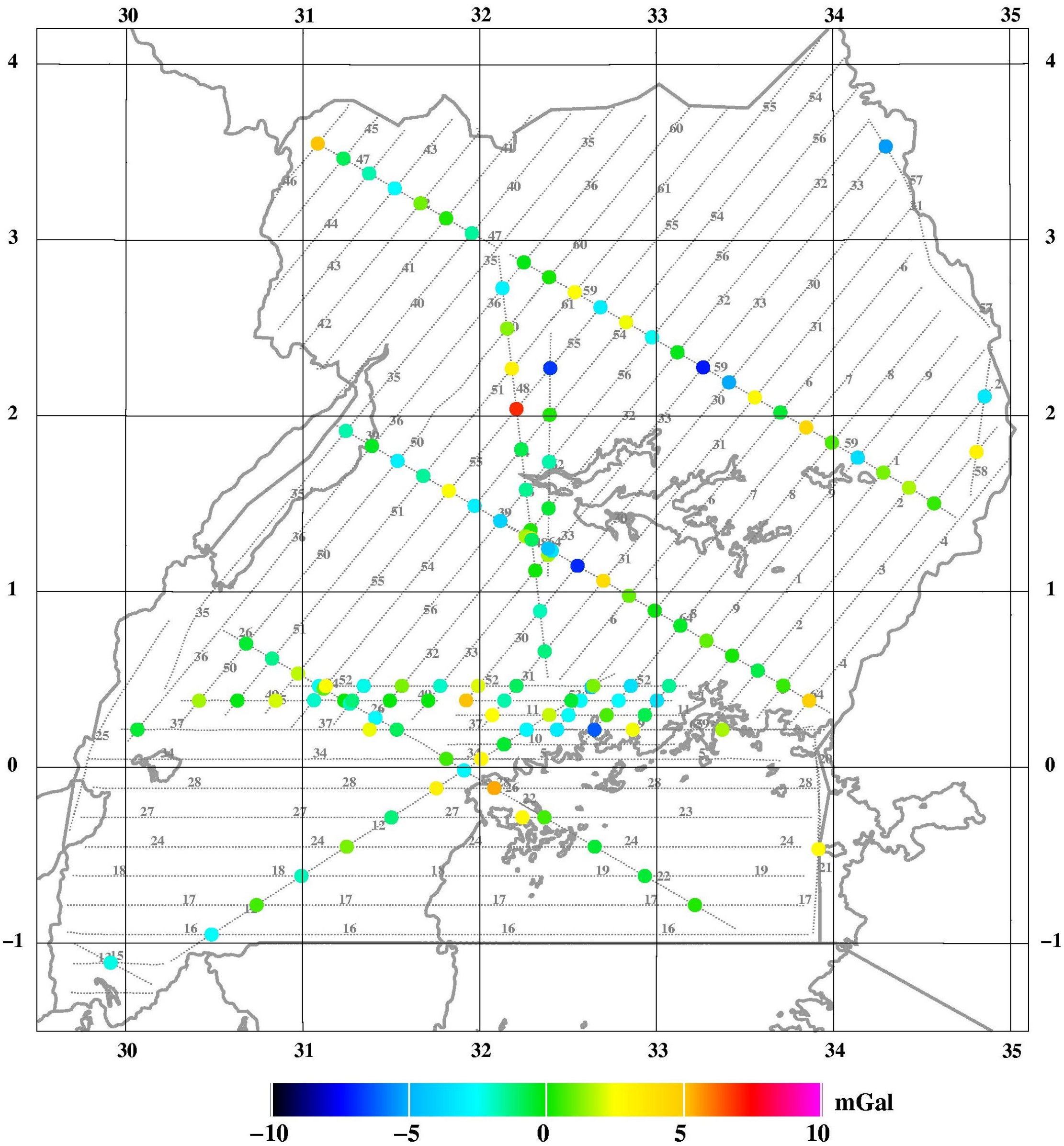

Fig. 5. Cross-over errors in the Uganda airborne survey. Numbers are internal line numbers

For validation of the *absolute level* of the airborne survey, the offset from GOCE satellite gravity are important, since the airborne data datum is determined solely from the ground reference gravity g_0 (explained in the next section). The comparison with the newest ESA

GOCE model (Release 6 “Direct”, max degree 240) gives for the entire Uganda free-air anomaly data set (16997 points) the following statistics:

Offset to GOCE R6: mean offset = <u>0.6 mGal</u>, standard deviation = 20.7 mGal

This is again a confirmation of the good quality of the airborne data set (given the noise in GOCE), as well as a confirmation of the used IGSN71 reference gravity value at the Entebbe Airport aircraft parking spot.

The final data are given in an ASCII file “*Uganda2020.faa”* with following information:

```
Id:   LineID*10000+seconds from start of line
Lat:  Latitude [degrees]
Lon:  Longitude [degrees]
H:    Orthometric height, referred to EGM2008 geoid [m]
g:    Absolute gravity value [mGal]
FAA:  Free-air anomaly [mGal] with atmospheric correction
Time: Decimal Julian day
```

First lines of file:

```
10010    0.37518   33.21173   3854.41  976853.0    9.8   19.50095
10020    0.38165   33.21707   3854.46  976852.9    9.7   19.50106
....
```

Flight line over Mt Elgon, Feb 2 (A. V. Olesen / A. Kasenda)

Gravity ties

Local gravity measurements to derive the airport reference gravity were done with the DTU Space L&R land gravimeter G-466. In addition a new reference point was requested by the Survey and Mapping Department headquarters in Entebbe, and measured at the headquarters building.

Since no absolute gravity measurement apparently existed in Uganda, the measurements were tied to IGSN71 reference stations in Uganda, with descriptions of points obtained both from NGA and Bureau Gravimetrique International (BGI) in Toulouse, France.

A search of all IGSN71 reference points (done in the 1960's era) showed that essentially all points in Entebbe or Kampala were lost, and could no longer be recovered. By chance a primary IGSN71 point (BGI 03302/ Entebbe J; NGA 3526-3) was located in the 1960's control tower building entrance area (this building was apparently saved from demolition as a memorial to the Israeli anti-terror commando action in 1976; the building is now empty, but difficult to access, since it is inside the high-security area of the presidential VIP air terminal). Given the recovery of the IGSN71 point, tie to Nairobi absolute gravity stations (planned for back-up) was not needed.

The Uganda aerogravity survey is therefore based on the reference gravity value of the Entebbe J point at 977709.840 mGal (quoted in IGSN71 report with an error of ±0.03 mGal). The derived Entebbe airport apron value for the Uganda Survey was determined as

$$g_0 \text{ (apron, ground level)} = 977709.325 \text{ mGal}$$

The gravity values for the new-established points, tied to Entebbe J, are shown below. The accuracy of the local ties are 0.06 mGal. Point descriptions are given in the Appendix.

Adjusted gravity values – Uganda local gravity network

No	Place	Latitude N	Longitude W	g
1	Hotel Protea Marriot	0 02.14	32 27.33	977710.35
3	IGSN71 - Entebbe J, airport	0 02.74	32 27.19	977709.84
4	Geological Museum	0 03.23	32 28.86	977707.82
6	AirServ Hangar, airport	0 02.14	32 27.33	977709.10
7	Survey and Mapping Dept	0 03.6	32 28.6	977706.51

Acknowledgements

The gravity survey of Uganda was made possible by the economic support of NGA. We thank the MLHUD Department of Surveys and Mapping colleagues, consultants and staff (W Ogaro, Fax Azisua, Mike Che, Chris Tembo, Richard Oput and others) for excellent support, and arrangements of permissions and logistics. AirServ company provided excellent hangar support. COWI pilots did a great job to accelerate the survey after the delays, especially Barry Nelson who flew most flights. The DTU team consisted of Arne Vestergaard Olesen, Adolfientje Kasenda (who did the bulk of the flights and processing), as well as Tim Jensen (installation and tests), Hergeir Teitsson, and René Forsberg.

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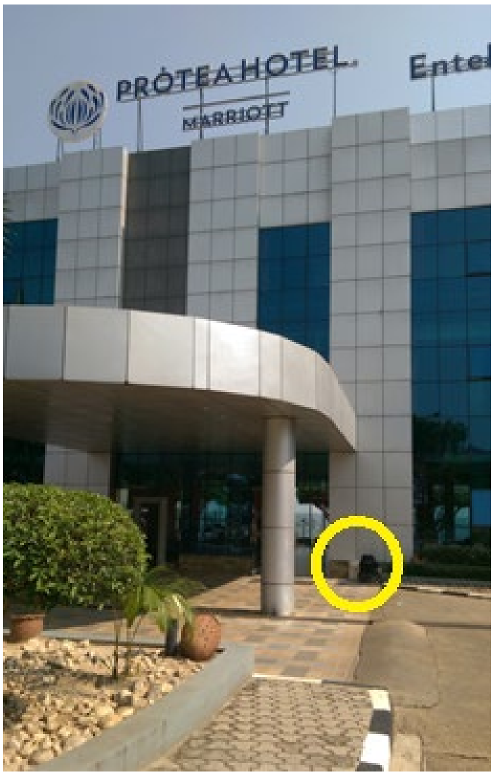
Appendix. Description of reference gravity points.

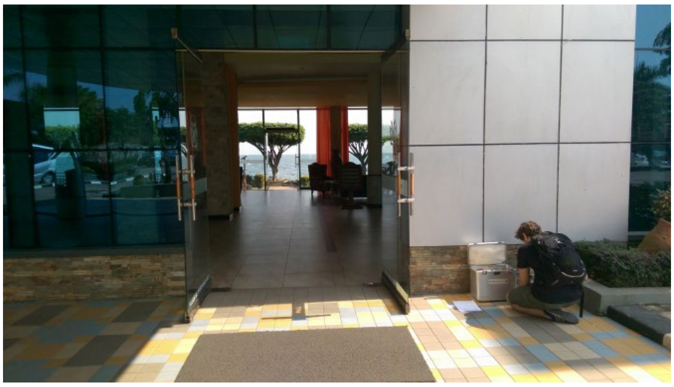


Hotel Protea / Marriot

Gravity point on tiles immediately to the right of the main entrance to Protea Hotel Marriot Hotel located shortly before airport entrance at main road to airport.

0° 2.14' N   32° 27.33' W

g = 977710.35 mGal

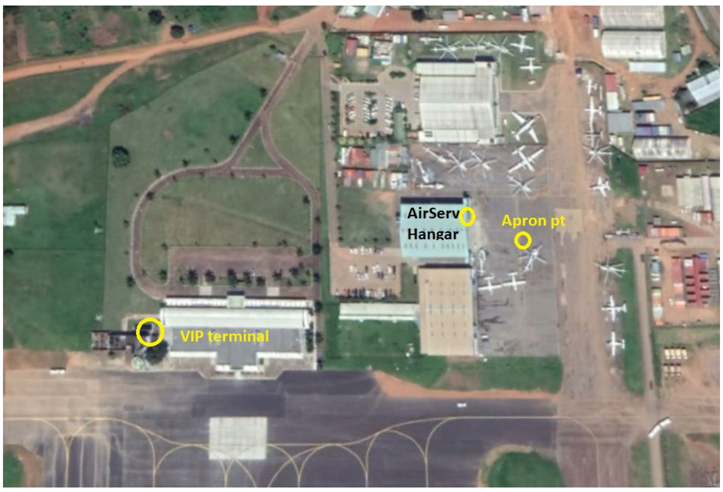


IGSN71 Entebbe J

Located to the W side of the presidential air terminal. Abandoned building with shot holes, ground level, immediately inside from entrance (memorial for 1976 Israeli commando raid). Point located between two door openings. Unmarked.

0° 02.74' N 32° 27.19' W

g = 977709.84 mGal



Geological Museum, Entebbe

Point is close to Entebbe-A IGSN station, but not identical (building changes). Museum is located to the left of the main entrance to Geological Survey of Namibia main office. Point located at top of stairs, back entrance to the West. Unmarked.

0° 03.23' N 32° 28.86' W

g = 977707.82 mGal

Department of Surveys and Mapping, Berkeley Road, Entebbe

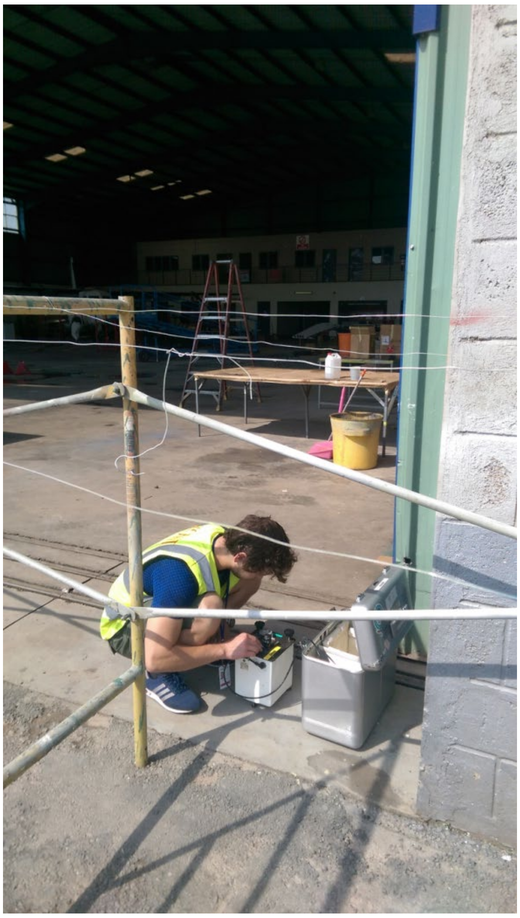
Gravity point located on top of stairs, west entrance near CORS antenna. Unmarked.

0°3.6' N 32°28.6' W

g = 977706.51 mGal

Entebbe Airport, apron reference point

COWI aircraft parked in front of AirServ hangar, general aviation side of airport. Reference point at right side of hangar door, as seen from the apron side. Unmarked, see yellow marks below. The aircraft were parked in front of hangar, at a slightly different elevation.



0° 03.6' N   32°28.6' W

g = 977709.10 mGal