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Airborne Gravimetry for Geoid Determination with Lacoste Romberg and Chekan Gravimeters

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Abstract—Airborne gravimetry for geodetic purposes such as geoid determination and global geopotential models requires good bias stability, as well as good performance in turbulence for large-scale national projects. DTU-Space has since many years carried out large area airborne surveys over polar, tropical and temperate regions. Recently we have started flying two gravimeters (L&R and Chekan-AM) side by side for increased reliability and redundancy in several surveys. In the paper we will give some examples of recent survey results, confirming accuracies in the 1 mGal range for a well-controlled Danish flight test, and around 3 mGal for intercomparisons of Chekan and L&R results in Nepal, one of the most challenging field survey regions on the Earth. We also indicate the good agreement between airborne gravity and GOCE data in Nepal, and outline the use for improved geoid determination.

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INTRODUCTION

Airborne gravity measurements have since the early 1990's developed into a reliable production system to accurately measure the gravity field of the Earth from aircraft. The development of airborne gravimetry has mainly been driven in the commercial domain by the need for accurate and high-resolution gravity anomaly mapping for oil, gas and mineral exploration, and accuracies below 1 mGal are now reported for state-of-the-art systems [3, 15]. In the government and academic domain, long-range GPS-based aerogravity for regional geophysics was pioneered by both US and Russian researchers [2], and later implemented in smaller aircraft by several groups [1, 9]. The dedicated applications for coastal geoid determination were developed in the late 1990's, as part of both US Arctic Ocean projects [4], as well as in the European Union project AGMASCO (Airborne Geoid Mapping System for Coastal Oceanography), see [5]. The system setup and experience developed in the AGMASCO project have since been used extensively for small aircraft, long range surveys in many different regions of the world [7, 8, 11].

The majority of the above projects have been based on the Lacoste and Romberg S-type gravimeter, an air damped beam type instrument described in details in [14]. In this paper we present the first side-by-side testing of the L&R gravimeter and a new Russian gravimeter – Chekan-AM – manufactured by Elektropribor, St. Petersburg (Fig. 1). The Chekan gravimeter principle is based on a dual quartz flexible pendulum element system with fluid damping, with movements of the two quartz sensing elements recorded by a sensitive CCD detector system, for details see [10]. The Chekan gravimeter sensor is mounted on a GPS-controlled stabilized inertial platform, more modern than the L&R relatively simple two-dimensional platform levelling gyro feed-back system. With platform level errors being a major systematic error source in airborne gravimetry, the Chekan system should therefore be superior to L&R in terms of such errors.

In the sequel we will describe joint flight tests of L&R and Chekan-AM in Denmark and Nepal, the first case being a benign low-dynamic experiment, the second case a highly dynamic case, with turbulence,

Fig. 1. Chekan AM-gravimeter.

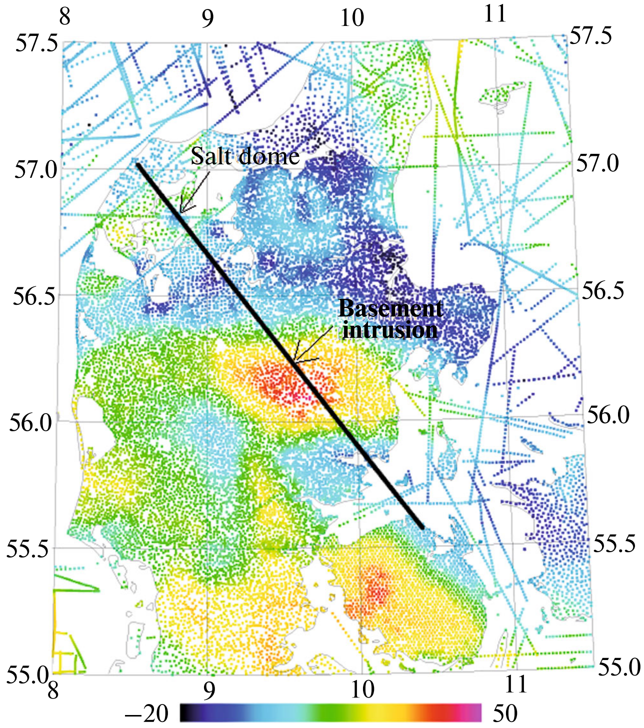

Fig. 2. Flight line of the Danish L&R and Chekan-AM flight test, with surface gravity free-air anomalies (mGal).

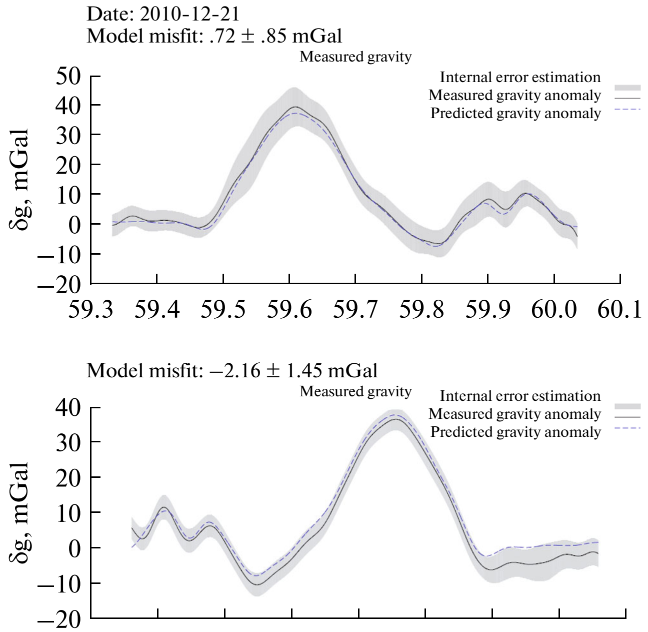

Fig. 3. Results of the SE-NW and NW-SE flights, compared to upward continued ground gravity.

mountain waves and some of the must rugged gravity field on the planet. The tests outlined in sequel are based on software for L&R data processing originally described in [12], and new DTU-developed software for analysis of Chekan data, taking into account both quartz element measurement sensors and the known hardware filtering of the Chekan system.

FLIGHT TEST OF CHEKAN-AM IN DENMARK

A flight test of Chekan-AM was carried out in December 21, 2010 using a Beech King Air 200 aircraft, belonging to COWI company, Denmark. The flight test was repeated forward and backward at two different low levels along a SE-NW oriented line across Denmark, with dense ground control gravity data from the Danish national gravity data base (Fig. 2). The profile crossed two major anomalies: the “Silkeborg high”, a large anomaly due to assumed basement intrusions below thick sediment sequences, and the narrow “Mors low” anomaly, due to a major shallow salt dome. The profile results compared to the upward continued ground truth are shown in Fig. 3.

The comparison of the two flights show a difference between the airborne free-air anomalies and the upward continued surface gravimetry data of 0.72 ± 0.85 mGal for the outbound (northward) flight, and −2.16 ± 1.45 mGal for the return flight, a highly satisfactory result, giving the unavoidable errors in the upward continuation FFT process, especially leakage from the less covered marine areas. The relatively high King Air flight speed also plays a role in the comparison noise. The test therefore demonstrates that the Chekan-AM instrument is capable of generating results at the 1 mGal accuracy level under good flight conditions.

JOINT AIRBORNE GRAVITY SURVEY OF NEPAL WITH CHEKAN-AM AND L&R GRAVIMETERS

The Nepal aerogravity flight campaign was carried out for nationwide geoid mapping of Nepal, as part of a cooperation with the Nepal Survey Department, supported by the US National Geospatial Agency. The campaign was carried out in the period December 4–17, 2010, using the same aircraft as in the Danish test. Figure 4 shows the Chekan-AM and the L&R gravimeters as installed in the COWI Beech King Air aircraft. This aircraft, equipped with a pressurized cabin, was flown to Nepal from Denmark, as no local suitable aircraft was available for the challenging flights over the highest mountains on the earth.

The flight tracks flown over Nepal were spaced at approximately 6 nautical miles, cf. Fig. 5. Because of the highly varying topography, the individual flights heights were varying from 4 km for the southernmost lines to 10 km for the northern lines, as required by clearance of topography. Cross-lines were all flown at high altitude. For this reason cross-over errors of survey lines can not readily be used for estimating the quality of the survey, but an integrated upward/down-

Fig. 4. Gravimeters used: Chekan-AM (left), L&R-S34 (center), both installed in King Air aircraft (right).

ward continuation process must be applied, as outlined in [7]. Especially for the northern flights, jet streams at altitude with wind speeds occasionally in excess of 100 knots provided a major operational challenge, generating major turbulence and mountain waves, strongly affecting the gravity measurements, with a few sections of the lines impossible to measure or process, leaving unavoidable gaps in data, cf. Fig. 5.

While the processed L&R data covered the entire country, except for the minor gaps seen in Fig. 5, the Chekan-AM data showed more problems, with malfunctions on a couple lines (in part due to some power problems), but especially some cases where the sensor was saturated in turbulence, and hit the hard stops of the sensor. Figure 6 shows the overall processed Chekan-AM data, and Fig. 7 examples of flight line data for L&R and the Chekan-AM data. One of these example lines shows clearly the effect of out-of-scale Chekan measurements. These effects can be detected from asymmetry (m_1–m_2) in the dual measurements of the Chekan sensor, and some recovery is possible. Overall, however, the turbulence tolerance is less for the Chekan than the L&R.

The overall comparison of the two gravimeter sensors, along the lines of overlapping data, are shown in Table 1; the data are filtered with triple Butterworth forward/backward filters, with a nominal ground resolution around 8 km. Table also shows the cross-over errors of the two airborne gravimeter data sets, after a harmonic upward/downward continuation to 6000 m elevation. This continuation was done using least-squares collocation methods, combined with use of terrain reduction; details of this method are outlined in [8].

Because the Chekan-AM and L&R data do not have the same number of cross-overs, due to the lack of some lines in the southern part of the survey with a more benign gravity field, the difference in cross-over errors between the two gravimeters is likely not significant. A combination solution has therefore been done by averaging the two gravimeters results, improving the overall continuity and completeness of the airborne survey. The combined solution corresponds to an over-

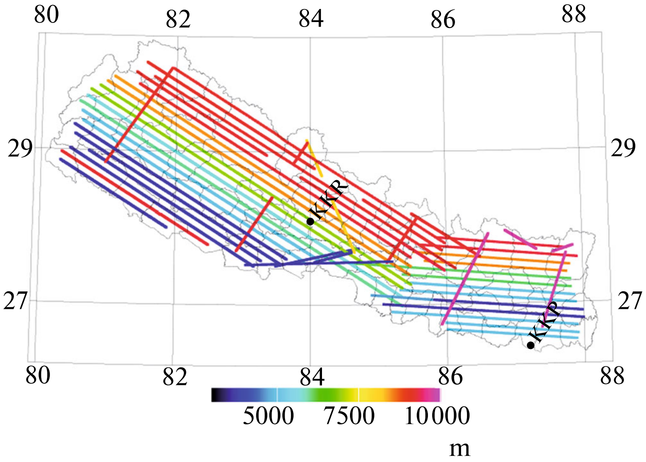

Fig. 5. Flight line elevations (m) of the Nepal airborne gravity survey, for the processed L&R data.

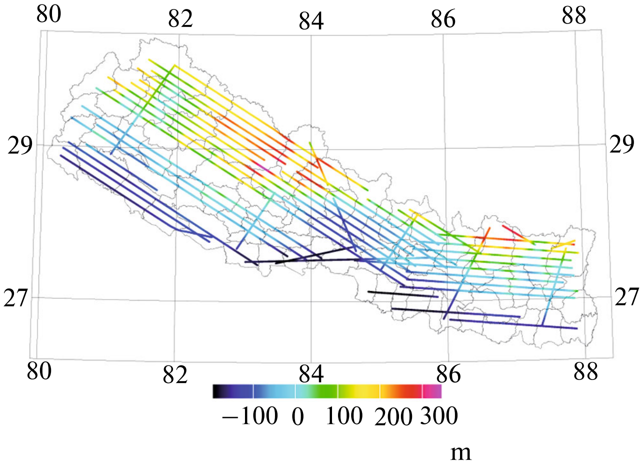

Fig. 6. Chekan-AM processed data (free-air anomaly data at altitude).

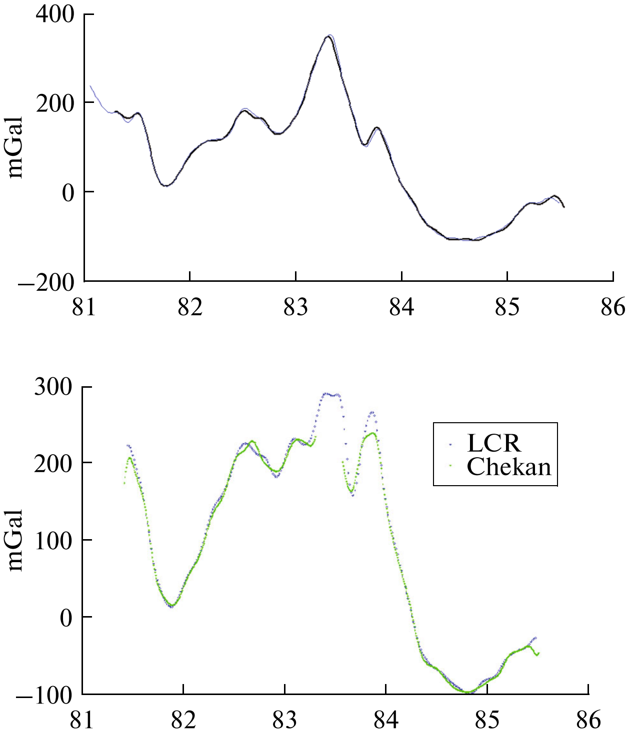

Fig. 7. Example of two lines (line 20 and line 24) in the high mountains, with L&R and Chekan-AM data processed independently, with similar filtering parameters. Line 24 shows examples of Chekan saturation.

all accuracy of the airborne gravity line data at the 3 mGal level, very satisfactory giving the flight conditions, and making a good foundation for accurate geoid estimation.

Another factor of interest for the Chekan-AM is the drift of the instrument, shown in Fig. 8. During the Nepal field campaign a relatively large Chekan drift was observed from repeated apron readings at Kathmandu airport. The drift, on the order of 50 mGal/month, is an order of magnitude larger than the L&R drift, but sufficiently linear to not play a major role in the quality of the results.

Comparisons of Chekan-AM and L&R gravity data

	R.m.s. (mGal)
Agreement between gravimeters	4.5
Cross-over error, continuation to 6000 m, L&R	4.6
Cross-over error, continuation to 6000 m, Chekan	5.1
Cross-over error, 6000 m, combined solution	3.9

IMPROVED ESTIMATION OF THE NEPAL GEOID

The merged airborne gravity data were used for an improved geoid determination of Nepal, together with new GOCE satellite data, existing surface gravimetry data, and terrain information from SRTM. The details of the geoid determination, done by remove-restore techniques, downward continuation by least-squares collocation, and spherical FFT methods, are outlined in [6, 8]. Figure 9 shows the overall distribution of airborne and surface gravimetry data, Fig. 10, the airborne data and GOCE (“direct” model, release 4) data (giving a convincing validation of GOCE), and Fig. 11, the resulting geoid.

Because of the lack of GPS-levelling data, no validation of the geoid accuracy is possible. Because no gravity data is available in China or India, the geoid will be more uncertain in the regions near the border; however, the high quality of the GOCE data diminish these effects, and overall the geoid accuracy is likely at the 10 cm level. For 8 GPS-levelling points in the Katmandu Valley, an observed 7 cm standard deviation between the GPS-levelling geoid and the airborne geoid confirms this error estimate.

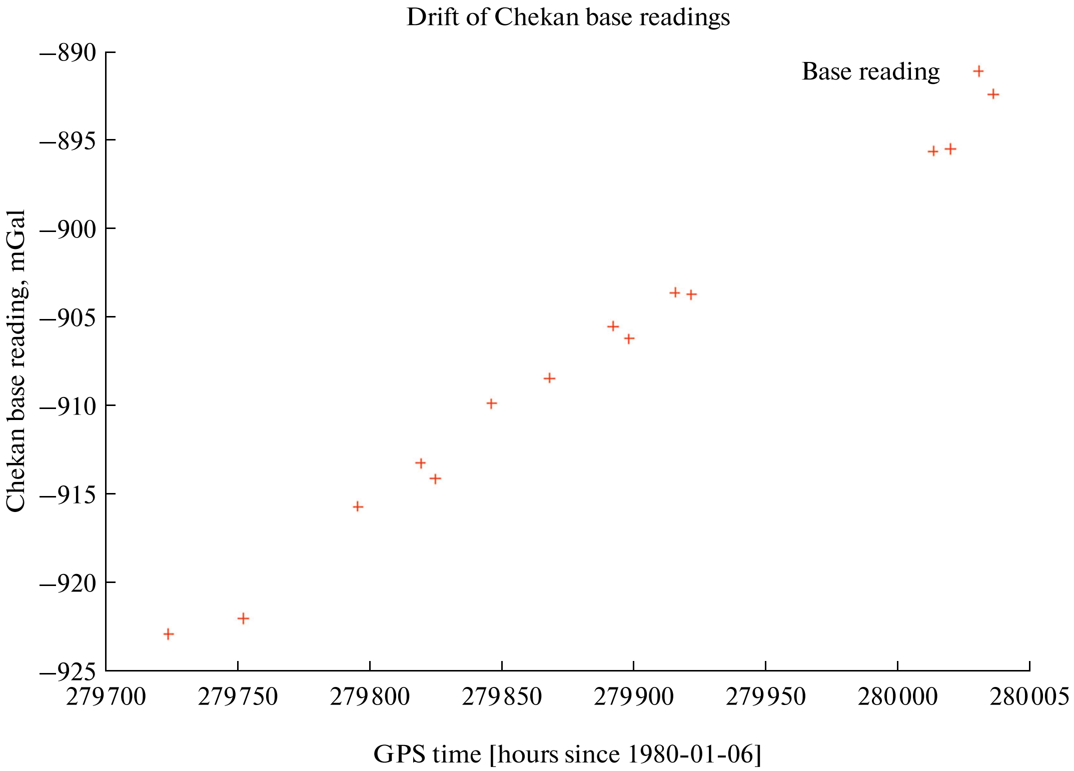

Fig. 8. Drift of the Chekan-AM gravity sensor from base readings at Kathmandu airport.

CONCLUSIONS

First results of airborne flights of the DTU-Space acquired Chekan-AM gravimeter have been reported. For a test flight in good conditions in Denmark, an accuracy around 1 mGal was demonstrated for a repeated flight line. For a large airborne survey of Nepal, with major challenges due to a rugged gravity field and turbulent flight conditions, an accuracy of around 3 mGal is estimated, comparable or slightly less than the errors of the simultaneously flown Lacoste and Romberg gravimeter S-34. For the Nepal flights, numerous problems occurred due to Chekan sensor saturation or operational errors, giving occasional loss of data. Generally the instrument fre-

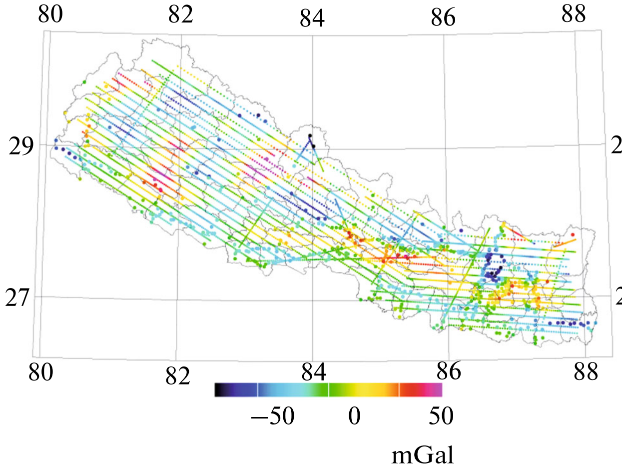

Fig. 9. Combined data set of airborne and surface gravimetry data for Nepal. The airborne data thinned to 30 sec for the geoid determination process; the strong winds at altitude, coming dominantly from the west, means the E-W flights will have a more dense ground sampling than W-E flights, clearly seen in the northern flights.

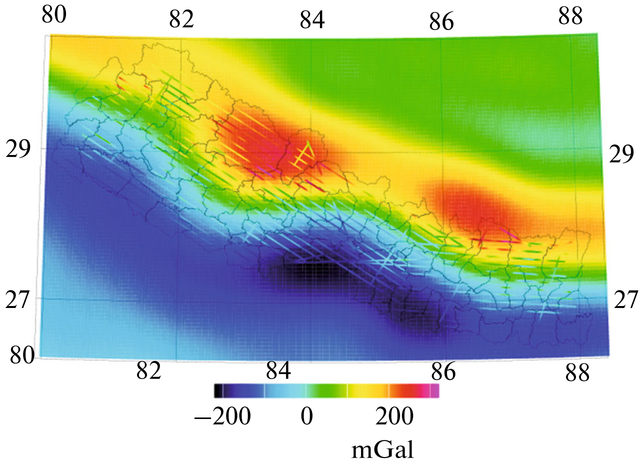

Fig. 10. Combined airborne gravity data set, overlain on the GOCE rel. 4 gravity anomalies.

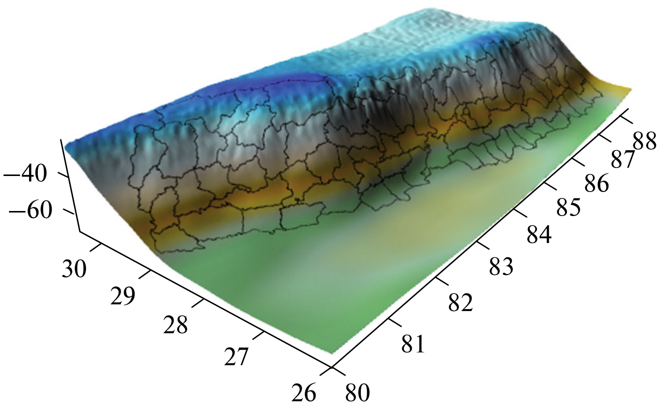

Fig. 11. Geoid model of Nepal from airborne gravity data and GOCE.

quently went out of scale in strong turbulence or mountain wave conditions; such conditions could be identified from the internal dual-sensor measurements of the Chekan-AM, therefore giving the opportunity of warnings of these phenomena also for flights with only a Chekan instrument.

The Chekan and L&R gravimeter data was for Nepal combined to a single airborne gravity solution, and subsequently used for an improved national geoid model, together with new GOCE satellite data, and terrain data from SRTM. The new geoid data are estimated to have an accuracy around 10 cm over most of the country, confirmed by a limited GPS-levelling data set in the Kathmandu Valley.

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