CRC-P-57322 High-resolution Real-time Airborne Gravimetry

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SUMMARY

Airborne gravimetry relies on removing inertial aircraft accelerations from total accelerations measured by an on-board gravimeter.

NASA developed a Navigation Doppler Lidar (“NDL”) for the US Space Program. The NDL measures velocities at the 1 mm/sec level in the laboratory, so such devices should be able to determine aircraft inertial accelerations much more accurately than is possible with GNSS data alone.

A prototype NASA NDL was integrated with both stabilised platform and strapdown airborne gravimeters to acquire data in three airborne campaigns.

We demonstrated that it is possible to consistently produce gravity data with lower noise over repeat lines by including NDL data with GNSS and gravimeter data in a Kalman filter, compared to using GNSS and gravimeter data alone.

We also produced gravity data at sub-mGal noise levels using the NDL and gravimeter data without including GNSS data in the Kalman filter. This makes it feasible to undertake extra-terrestrial gravity surveys using the same instruments that are used for spacecraft navigation.

Key words: Airborne gravimetry, Doppler Lidar, strapdown gravimeter.

INTRODUCTION

The major limitation of airborne gravimetry stems from Einstein’s “equivalence principle”, which prescribes that no inertial sensor can distinguish between spatial variations in the gravity field (the signal) and variations in the acceleration of the aircraft (undesired noise). Global Navigation Satellite System (GNSS) data are currently used to determine the aircraft inertial accelerations, which are then subtracted from the total accelerations as measured by a gravimeter to determine the spatial variations in the gravity field along survey lines (e.g. Gumert, 1998; Bell et al., 1999; Forsberg and Olesen, 2010).

The required accuracy is achieved by applying filters of the order of 100 seconds to the GNSS data (e.g. Childers et al., 1999), resulting in a spatial resolution of a few kilometres depending on the speed of the aircraft. Advances in GNSS technology alone are unlikely to improve its resolution greatly (van Kann, 2004), particularly in the vertical because of the geometry of the constellations and atmospheric refraction. We therefore investigated alternatives to determine aircraft accelerations more accurately.

Scientists from NASA Langley Research Center developed a Navigation Doppler Lidar (“NDL”) for the US Space Program as part of a spacecraft Autonomous Landing and Hazard Avoidance Technology (“ALHAT”) system (e.g. Amzajerdian and Pierrottet, 2012 and Amzajerdian et al., 2012). This NDL measures velocity with a precision of 1 mm/sec level determined from bench tests in the laboratory, so such devices may be able to measure the inertial accelerations of an aircraft much more accurately than is possible with GNSS alone. If so, determination of spatial gravity variations at significantly lower noise levels, or with improved spatial resolution, or both, might be possible (Gabell, A. R., 2018).

While important for existing airborne gravimetry systems, it is potentially even more significant once more sensitive mobile gravimeters, such as cold atom gravimeters (e.g. Bidel et al 2013, Hardman et al, 2016) are capable of measurement at the 0.1 mGal level or better.

Our project investigated integration of this technology with existing airborne gravity acquisition systems. One of NASA's prototype NDLs was made available to our CRC-P project team and integrated with two different state-of-the-art airborne gravimeter systems to acquire data in three airborne campaigns firstly in Utah, and then twice in South Australia.

METHOD AND RESULTS

The test flights reported here all comprise repeat lines because this approach provides a good indication of instrument performance without requiring prior knowledge of the gravity signature of the test area or the additional consideration of upward or downward continuation (cf, Elieff and Ferguson, 2008).

Two types of gravimeter were tested with the NASA NDL. These were stabilised platform gravimeters (the GT-2A and GTz) (Berzhitzky et al, 2002, Gabell et al, 2004,) and a strapdown INS (Inertial Navigation System) gravimeter (the iMAR iNAT-RQH-4002 iCORUS).

The NDL data were integrated with the proprietary processing software used with the stabilised platform gravimeters (Golovan and Vavilova, 2007; Bolotin and Golovan, 2013) by substituting the NDL velocities in place of the GNSS velocities. This was done in an ASCII file which forms one of the standard inputs to the Kalman filter program that we use to generate the free air gravity anomaly.

In the case of the strapdown INS we modified a Kalman filter program, developed specifically for the iMAR INS for determination of the gravitational response (cf. Becker, 2016), to accommodate the NDL data as an additional state variable in the Kalman filter. We could then choose to process the data in multiple permutations and combinations with all available velocity data , or without the GNSS or NDL data.

The First Series of Test Flights

The first series of flights were undertaken over a 4 day period in September 2017 from the airport in Provo, Utah, USA. The repeat line was located over the Great Salt Lake Desert. This area has high reflectance at the operating wavelength of the lidar (1.558μm), and is very flat, which reduced the variables that needed to be considered for the first test flights.

Figure 1 depicts the equipment installed in the aircraft. The NDL telescope assembly was mounted directly to the airframe. As the gravimeter acceleration data are collected from a stabilised platform, the resulting data is in the navigation frame. One of the main challenges anticipated was transformation of the NDL velocities from the reference frame "along line-of-sight" of each telescope to the navigational reference frame (E, N and Up). We decided to initially use angle sensor data from the gravimeter to undertake this frame transformation.

Figure 1a (left). The GT-2A gravimeter system with the NASA NDL electronics mounted to its rear.
Figure 1b (right). The view looking up from the ground to the NDL telescope with 2" optics which was mounted in the aircraft's camera hole located forward of the GT-2A.

Free air gravity anomaly data from one of these first flights is shown in Figure 2 below.

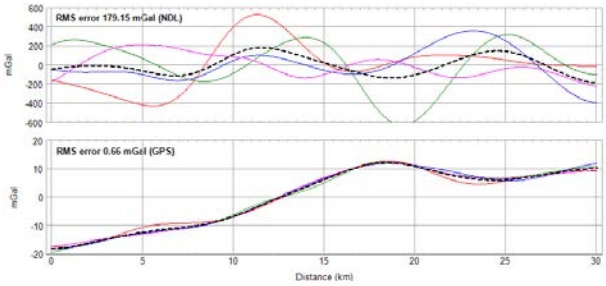

Figure 2a (top). The free air gravity anomaly calculated using NDL velocities to correct for the aircraft's inertial accelerations gives an rms error of 179.15 mGal. The range is 1,200 mGal.
Figure 2b (bottom). The free air gravity anomaly calculated using GNSS velocities to correct for inertial accelerations gives an rms error of 0.66 mGal. The range is 40 mGal. The dashed black line represents the average of all lines in each plot.

It is clear that at this early stage we were a long way from having a useable new method for airborne gravimetry. Another observation from these flights was that the NDL did not provide any useable data over water, or snow accumulations on the ground.

After more detailed analysis of the Utah test flight data, we concluded that the angle sensor data from the gravimeter platform was an order of magnitude less sensitive than required for an accurate frame transformation. For subsequent flight tests we securely fixed an IMU to the NDL optics to improve this accuracy.

Figure 3. The NASA NDL 1" optics and IMU bolted to a rigid aluminium frame, allowing frame transformations accurate to approximately 0.01°.

The Second Series of Test Flights

The second series of test flights was initially conducted in May and June 2018 out of Parafield Airport in Adelaide, but was moved further north to Leigh Creek due to an extended period of inclement weather. Technical problems restricted us to collecting reasonable data from eight flights.

As the NDL was designed to provide velocity data for navigation in real-time, the storage of NDL data to internal memory was implemented as a secondary feature. We experienced some difficulty in downloading data files in their entirety, which then required a certain amount of "reconstruction" of the raw data, sometimes resulting in problematic time-synchronisation of the different data sets.

Nevertheless, we were able to recover reasonable gravity data from two of the eight flights where we had relatively complete data from all of the main instruments.

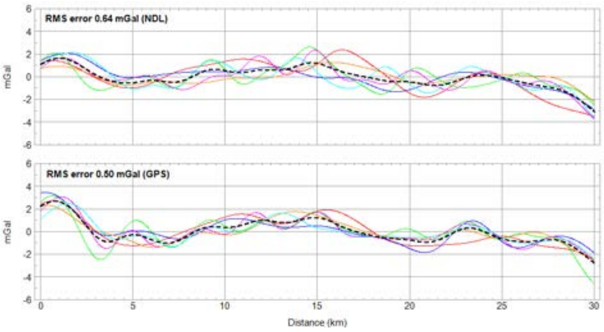

Figure 4a (top). The free air gravity anomaly where the aircraft inertial accelerations were calculated using NDL velocities, resulting in an overall rms error of 0.64 mGal. Figure 4b (bottom). The free air gravity anomaly processed using GNSS velocities to correct for inertial accelerations, resulting in an rms error of 0.50 mGal. Both plots have the same range of 12 mGal. Figure 4a represents the first known determination of reasonable quality gravity data using Doppler Lidar data and no GNSS data to determine aircraft inertial accelerations.

The Third Series of Test Flights

Prior to a third series of test flights in Adelaide in February 2019 we developed a custom interface to the NDL using a Raspberry Pi computer. This took an RS422 feed from the NDL, buffered the data, time-stamped and checked it before recording to an SD card. This also doubled as a GUI (Graphical User Interface) for the pilot to be able to start and stop data recording, turn the laser on and off, and monitor key environmental parameters such as internal temperature of the NDL electronics package. This proved to be a very effective data recording method as we experienced zero lost records in this final series of flights.

The best results achieved during this third series of flights came from the experimental set-up depicted in Figures 5 and 6 using a wing pod on the aircraft used for testing.

The total weight of the equipment in the wing pod was approximately 27 kg. Data from a total of 7 flights are presented in Figures 7a to 7c.

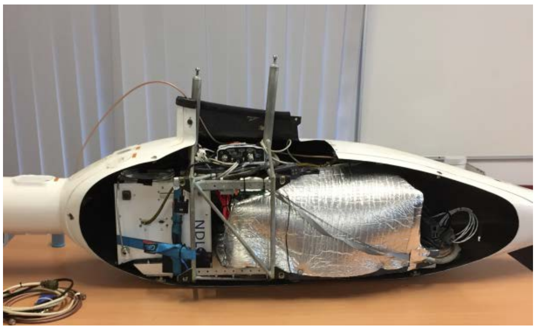

Figure 5. The wing pod from the test aircraft with gravimetry equipment installed. The NDL electronics module is forward. Inside the silver thermal housing is the NDL optics/IMU, with the iMAR iNAT-RQH-4002 iCORUS INS gravimeter, Raspberry Pi control computer and a dual frequency GNSS receiver. Basic thermal control was provided by a digital thermostat coupled to a fan.

Figure 6. The wing pod mounted on the test aircraft. A GNSS antenna is mounted above the pod on the leading edge of the wing.

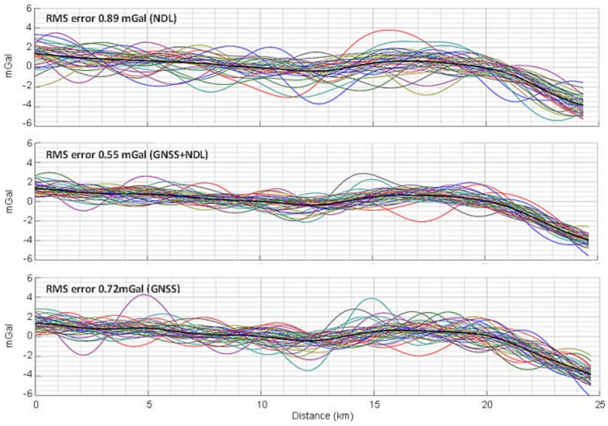

Figure 7a (top). Gravity data calculated using only NDL velocities to correct for the aircraft's inertial accelerations, with an overall rms error of 0.90 mGal.
Figure 7b (middle). Gravity data using both GNSS and NDL velocities as inputs to the Kalman filter to correct for inertial accelerations, with an rms error of 0.55 mGal.
Figure 7c (bottom). Gravity data using only GNSS data to correct for inertial accelerations, with an rms error of 0.72 mGal. The distribution around the mean (dashed lines on all plots) is noticeably tightest in Figure 7b (middle).

The iMAR iNAT-RQH-4002 iCORUS was used as a strapdown gravimeter for all of these flights which were undertaken at the height of summer in conditions ranging from quite calm to very turbulent.

As shown in Figure 7b, all 7 flights with this configuration produced data with reduced noise levels when the NDL data were included in the processing stream. These data showed from 14 to 29% less noise, with an average 23% improvement compared to processing using GNSS data alone to determine the inertial aircraft accelerations.

Subsequent data analysis included simulations using the airborne data collected to estimate the significance of key parameters. One outcome of this study was that the optimum results should be obtained when the orientation of the telescope is measured to 0.001°. We believe that we only measured the telescope orientation to 0.01°, which suggests that there is significant potential for further improvement.

Our simulations also suggest that a 0.1 mGal gravity meter could produce close to 0.1 mGal gravity by using an NDL in the best case scenario. If using GNSS data alone to determine aircraft inertial accelerations, the resulting data would still be limited to ~0.5 mGal.

CONCLUSIONS

We added a Navigation Doppler Lidar (NDL) to the “usual configuration” for airborne gravimetry of a gravimeter and GNSS receiver. A prototype NASA NDL was integrated with both stabilised platform and strap-down airborne gravimeters to acquire data in three separate airborne campaigns. We demonstrated that it is possible to consistently produce gravity data with lower noise over repeat lines by including NDL data with GNSS and gravimeter data in a Kalman filter, compared to using GNSS and gravimeter data alone. We also produced gravity data at sub-mGal noise levels using the NDL and gravimeter data without including any GNSS data in the Kalman filter. This makes it feasible to undertake extra-terrestrial gravity surveys using the same instruments that are used for spacecraft navigation.

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