Application Note
General Aspects of Gravimetry Survey using iCORUS

Company Confidential ☐
Commercial-in-Confidence ☒

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DOCUMENT CHANGE RECORD

I = Issued; C = Checked
AI = Approved (iMAR)
AC = Approved (Customer)

Rev.	Paragraph	Comments		Date	Name	Function
1.00	All	Document created	I	26.07.17	DaBe EvH	DE CEO
1.01	all	Update	I C/AI	06.04.23	EvH AlLö	CEO PJM

DOCUMENT CHECK & APPROVAL REQUIREMENTS

CHECK required	APPROVAL by iMAR required	APPROVAL by Customer required
No	No	No

Acronyms of Functions

Industrial/MIL Projects / Industrie- & MIL-Projekte

CEO	Chief Executive Officer (Geschäftsführer)
CUST	Customer (Kunde)
DE	Design Engineer / Development Engineer (Entwicklungsingenieur)
HD	Head of Development (Entwicklungsleiter)
PGM	Program Manager (Projektmanager)
PJM	Project Manager (Projektleiter)
PM	Production Manager (Fertigungsleiter)
QA	Quality Assurance (Qualitätssicherung)
QM	Quality Manager (Qualitätsmanagementbeauftragter)

Aviation & Space Projects / Luft- und Raumfahrtprojekte

AM	Accountable Manager
CUST	Customer (Kunde)
DE	Design Engineer / Development Engineer (Entwicklungsingenieur)
HD	Head of Design (Entwicklungsleiter)
HoA	Head of Office of Airworthiness (Leiter Musterprüfleitstelle)
HoD	Head of Design Organisation
PGM	Program Manager (Projektmanager)
PJM	Project Manager (Projektleiter)
PM	Production Manager (Fertigungsleiter)
CVE	Compliance Verification Engineer (Musterprüfingenieur)
QA	Quality Assurance (Qualitätssicherung)
QM	Quality Manager (Qualitätsmanagementbeauftragter)

TABLE OF CONTENTS

LIST OF FIGURES

1 INTRODUCTION

This application note answers general questions regarding the operation and data analysis of iMAR's strapdown gravimeter iCORUS.

Figure 1: iCORUS-02 Strapdown Airborne Gravimeter

2 FREQUENTLY ASKED QUESTIONS (FAQ)

- **WHAT IS THE ADVANTAGE OF THE STRAPDOWN GRAVIMETER iCORUS AGAINST GIMBALLED GRAVIMETERS, LIKE MICRO-G-LACOSTE?**

  iCORUS is a full strapdown airborne gravimeter, containing dedicated high accurate and robust accelerometers, gyroscopes and a special internal signal processing by digitization and synchronization hardware and software. In contradiction to this, other systems on the market are fully gimballed and have a high sensitivity against mechanical errors, and thus not easy to operate and requiring a significant amount of maintenance.

  On the other hand, iMAR also manufactures 2-axes and 3-axes gimbals for companies manufacturing dedicated gravimeter cores - like cold atom gravimeters - which require an accurate levelling, because they have only one single measuring axis. These gimbals are being manufactured by iMAR based on customized specifications, for seaborne and airborne applications. A picture of such gimbal is presented in the following:

Figure 2: 3-axes Gimbal for Cold Atom Gravimeter Stabilization (example)

Note: Such gimballed setups are more than 10 x heavier than our strapdown gravimeter iCORUS.

The iCORUS itself contains all required gravimeter sensors (like ultra-high-performance servo accelerometers and digitization) and is temperature stabilized.

- **CAN AN AIRBORNE CAMPAIGN BE OPERATED BY ONLY 1 PERSON?**

  Nobody is required on board to operate the iCORUS strapdown gravimeter, the system is self-sustaining. At the beginning of the mission, an alignment at standstill is required, the same also at the end of the mission. At the location of these alignments the absolute gravity has to be known. Consequently, in the scientific world, the signal processing is called “gravimetry disturbance determination” and not “absolute gravimetry”.

- **DOES iCORUS USE THE EARTH MAGNETIC FIELD?**

  The signal processing of iCORUS performs highly precise inertial measurements and GNSS measurements followed by a dedicated data fusion; furthermore, it uses the knowledge of the absolute gravity at the starting point and the end point of the mission. No further measurement data are required or used in the data processing (i.e. no earth magnetic field, no barometric or true airspeed measurements or similar data).

- **WHAT IS THE OUTPUT OF iCORUS?**

  iCORUS very precisely determines the inertial acceleration vector, the inertial rotation rate vector, GNSS raw data, the time (down to sub-microseconds) and temperatures. Furthermore, the knowledge of the absolute gravity at the starting point and at the end point of the mission is required. No further measurement data are used in the data processing. In geodesy / geophysics terms, the output of the data analysis is called "Gravity Disturbance" or deviation from the normal gravity. Together with the knowledge of the absolute gravity at the starting point and at the end point of the trajectory, also absolute gravity can be calculated, derived from the gravity disturbances. Please note, that iCORUS does not and cannot determine the absolute gravity values at the starting point / end point of the trajectory – these need to be determined independently by the operator (typically once, e.g. at the airport on a marked alignment position).

- **WHAT IS THE RESOLUTION AND RANGE OF iCORUS?**

  iCORUS provides a resolution of < 0.5 mGal (0.5 µg). The measurement range is more than ±5 g (5'000'000 mGal) and here the strapdown airborne gravimeter also shows significant advantages against traditional airborne gravimeters. This resolution typically leads, depending of system version, to gravimetrical performance of approx. 1 mGal after linewise bias removal. For details see our product datasheets.

  The required range of measurements is about 9.77 … 9.83 g for global operation and thus, iCORUS is covering this range perfectly and even significant more. Furthermore, iCORUS also keeps on track during flying curves while traditional gravimeters require a significant time to recover. Hence, iCORUS allows a much more time efficient execution of the whole mission.

  While traditional gravimeters are very restricted regarding "drape flying" (i.e. changing flight altitude during the mission), the iCORUS strapdown system shows no significant limitations even under strong gravity gradients.

- **CAN iCORUS ACCOMMODATE FLIGHTS WITH VARYING ALTITUDE, LIKE DRAPE FLYING AT CONSTANT HEIGHT ABOVE THE TOPOGRAPHY?**

  Yes, drape flying is possible, and we have multiple customers operating in this mode regularly. It is not easy to quantitatively specify the limits of such drape-flying (i.e. how harsh the (vertical) maneuvering should be done). Attached are two diagrams, taken from a survey test flight. This test flight was carried out with an iCORUS-02, with a resulting accuracy of 1 mGal(*). The pilot has reported a "medium to high" turbulence level for this flight, so the conditions were actually challenging. You can approximately infer from the shown altitude profile and also the climb rate [in m/s] how the drape flying was implemented for this flight.

  (*) The accuracy of 1.0 mGal was determined as the total RMS of 6 repetitions of the same test survey line, at 50 seconds resolution.

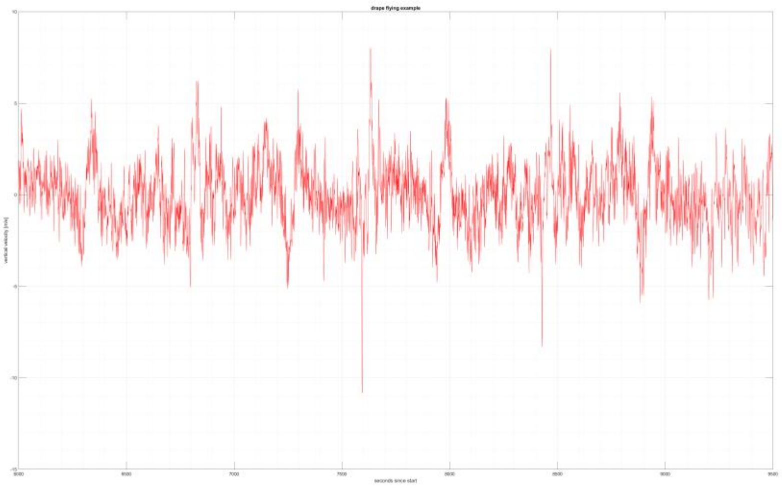

Figure 3: Drape flight example - climb rate

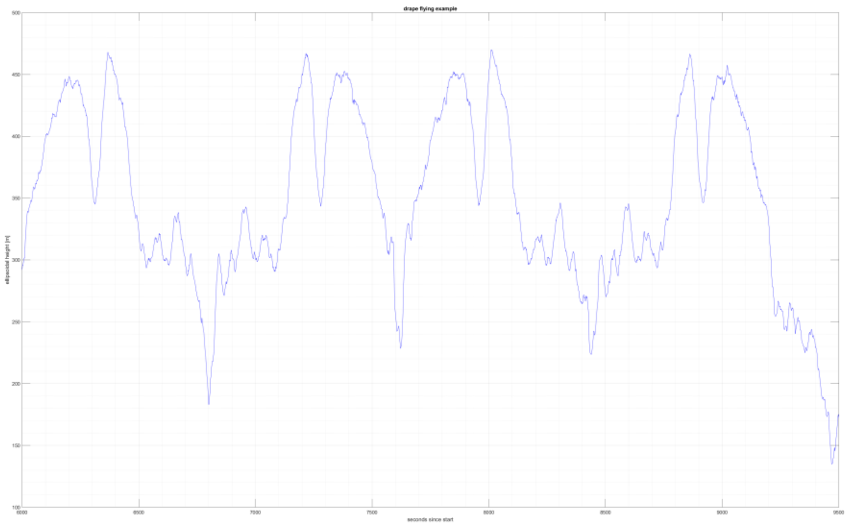

Figure 4: Drape flight example - altitude

- **IS THERE ANY DRIFT ON THE GRAVITY OUTPUT OF iCORUS?**

  The measurements of iCORUS are referenced at the beginning and at the end of the mission with the absolute gravity, i.e. with a ground reference value (independently measured by the operator with an accuracy of < 0.1 mGal, typically at the apron of the airport), which is connected to a known Absolute Gravity Point (so-called gravity tie). Therefore, there is no day-to-day drift of the processed measurements of iCORUS. Of course, the internal measured specific forces show a certain drift, but this drift is quite small, due to the high precise inertial sensors, the superb temperature stabilization and time synchronization.

General comment: Today, airborne gravimetry is always a relative measurement, related to a well surveyed ground reference point with absolute gravity at the apron of the airport. Not to forget, LaCoste Micro-g and other providers measure relative gravity in the air (and no absolute gravity) as well, and relate these measurements afterwards to an absolute ground reference point.

- **IS iCORUS USEABLE IN SEABORNE APPLICATIONS?**

  iCORUS is qualified for airborne applications, where the time between starting point and end point of the mission is no longer than several hours. Nevertheless, tests over more than 60 hours showed a superb long-term sensor stability which is mandatory for seaborne applications. iCORUS is also successfully in use in such environment, requesting a very long time performance without the availability of periodic reference points, but the data are up to today under confidential agreement by the operators, because the current clients are using the data for defence applications.

- **WHAT'S THE MAXIMUM TURBULENCE (IN TERMS OF ACCELERATION) THAT THE iCORUS CAN ACCOMMODATE TO KEEP THE GRAVITY DISTURBANCE ACCURACY BELOW 1 MGAL?**

  It is difficult to quantify a maximum turbulence level for a survey flight: The sensor is specified to operate up to 20g of acceleration. Singular turbulence events are in general less problematic. Continuous strong turbulence (over entire segments of a survey line, over minutes or more) may however in general lead to a degradation of the gravity accuracy. However, to our knowledge, no customer had ever to repeat a survey flight with our instruments because of bad gravity estimates due to strong turbulence, meaning that any typical flight condition (including more turbulent ones) should produce useful gravity results at the specified gravity levels.

  Note again the "medium to large" turbulence level of the drape flying example (see Figure 3, Figure 4) still ending up with 1.0 mGal accuracy.

  We can, of course, not guarantee a degradation-free gravity estimation for all types of aircraft's, flight modes, flight dynamics, turbulence, types of oscillations and vibrations - instead, we encourage customers to perform their own tests, with their own aircraft and mode of operation, with a rented iCORUS from iMAR.

- **WHAT IS THE ACCURACY OF iCORUS FOR AIRBORNE APPLICATIONS?**

  Depending on the version and environment, iCORUS shows an accuracy of < 0.5 … 2 mGal (rms). We have tested and approved this with so-called cross-over flights (typically in the area of 1 mGal (rms); no need to say that the results of course also depend on the topography and the intensity of turbulences. On the other hand, mechanical spring gravimeters (as the LaCoste & Romberg S-type gravimeter) are known to much more sensitive to strong turbulences [Becker, David: Advanced Calibration Methods for Strapdowm Airborne Gravimeters; Issue 51, Schriftenreihe der Fachrichtung Geodäsie, Technische Universität Darmstadt, Oktober 2016] – just another advantage for our iCORUS system.

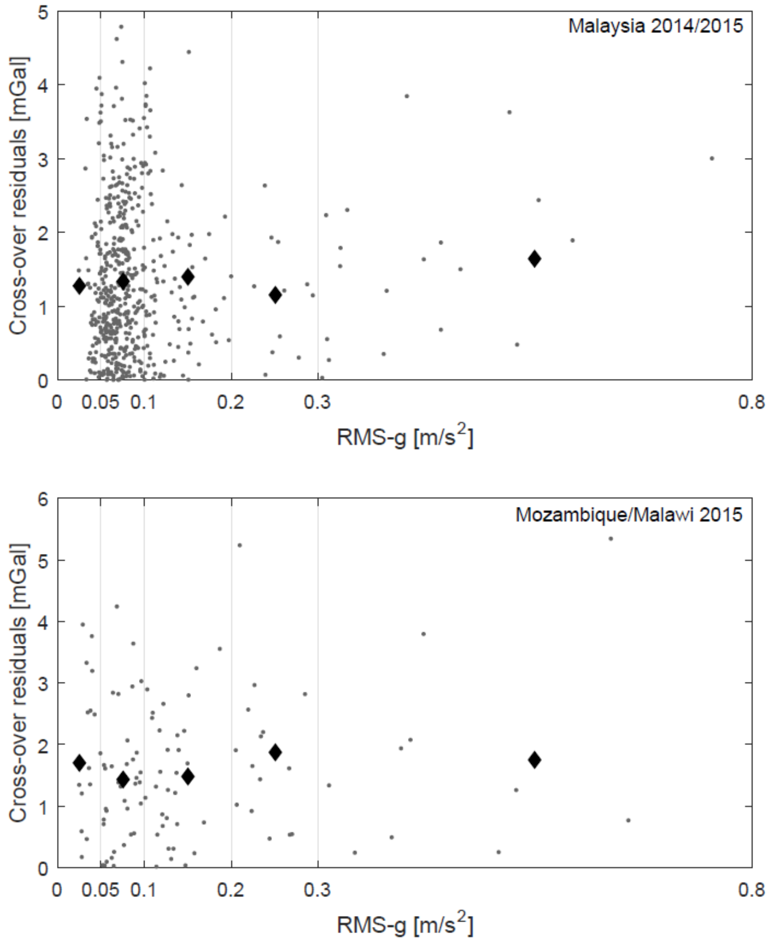

Figure 8.24: Cross-over residuals for cross over points with $\Delta h < 100\,\text{m}$, plotted against the actual RMS-g values. *Top:* Malaysia 2014/2015 (combined, 403 points). *Bottom:* Mozambique/Malawi 2015 (122 points).
The *maximum* RMS-g value of the two intersecting measurement lines is used for each point. Five bins are defined. The bin intervals are depicted by the vertical grid lines. The average cross-over residual for each bin is shown as a diamond-shaped marker.

Figure 5: Cross-over residuals of iMAR strapdown gravimeter

Among others, the following publications are available:

https://geodaesie.info/images/zfv/144-jahrgang-2019/downloads/zfv_2019_5_Johann_et-al.pdf

https://link.springer.com/chapter/10.1007/1345_2020_127

With iCORUS-02 we specify the RMS accuracy to be better than 1.2 mGal for any reasonable survey flight conditions, while test flights and feedback from our customers suggest an expectable accuracy level between 0.8 mGal and 1.0 mGal (all these figures given for 50 seconds temporal resolution).

- **HOW CAN BE ASSURED THAT THE DATA OF iCORUS ARE RELIABLE?**

  iCORUS itself performs a relative measurement, i.e. the estimated bias at the beginning of the mission and at the end of the mission can be compared and evaluated. Thus, there is a closed-loop which allows the verification of the reliability. Furthermore, the results can be adjusted to known land-based references (if any – but this must be done by skilled experts, because of different heights of the ref. points, a so-called "upward continuation" of the ground pints is required, which is indeed not a trivial task) or (as usually done) via cross-over flight analysis as mentioned above.

- **WHAT DOES THE SOFTWARE iPOSCAL-GRAV FOR iCORUS DATA COMPENSATE FOR?**

  iMAR's software iPosCAL for post-processing compensates for altitude for centripetal and Coriolis forces (also called as Eötvös correction). Scale factors are calibrated automatically, drift is compensated. Tides are not compensated so far, however, this feature could be implemented on customer request. On the other hand, in airborne gravimetry (compared to shipborne missions), the mission duration is relatively short, so that the relevance of tide compensation still needs to be proven. Remember, that the impact of tides is typically in the area of $\pm$0.1 mGal only, and hence, about 10 times less than the estimated accuracy. Other leading research groups (Forsberg etc.), nowadays do not compensate for tides either.

- **IS IT POSSIBLE TO ALSO OUTPUT RAW GRAVITY FOR POST-PROCESSING WITH CUSTOMER'S OWN PROCESSING SOFTWARE? IF YES, WHICH RAW DATA CAN BE OUTPUT/EXPORTED EXACTLY?**

  Yes - The binary log data (in iMAR's XCOM file format) contains the timestamped raw accelerometer and gyroscope readings. iMAR can provide the XCOM file format specification, so the user can implement his own data conversion and gravimetric post-processing tools, if desired. There are no further restrictions to this: The user has full open access to all of the log data. Although we suggest using our post-processing software iPosCal-GRAV, the user of course is free to use/implement his own post-processing software.

- **CAN "ANOMALIES" BE DETECTED BY iCORUS TOGETHER WITH POSITIONING DATA?**

  As iCORUS contains a full INS/GNSS strapdown navigation core, it provides also position, velocity, attitude / heading etc. in realtime. It can be used for trajectory guidance as well (see our GUI software iXCOM-CMD for details). So, a full mission plot and pilot guidance in real time is comprised, including definition of waypoints.

  The output of iCORUS are gravity disturbances, not gravity anomalies, as it relates to the altitude reference. Unfortunately, often the "disturbance" is simply called "anomaly", but in reality, these are two different effects.

- **DOES iCORUS REQUIRE A WARMING-UP PHASE AFTER POWER-ON?**

  iCORUS contains a sophisticated internal temperature stabilization. The initial thermal stabilization phase has a typical duration of less than one hour after power-on. A flag indicator within the GUI iXCOM-CMD will inform you when the stabilization phase has finished. It is possible to powercycle the system during or after the stabilization phase in case you want to switch from one power supply to another power supply (eg. to power-up the system in the hangar and then to move it to the aircraft).

3 SUPPORT

3.1 Asking for a Loan System or for Support

For new customers, iMAR can provide a loaner system to allow the customer to gather experience before purchasing systems. Please connect iMAR technical sales engineer for further information.

💻 sales@imar-navigation.de

For our support management system, we need to know the project number (Proj.No.) or alternatively P/N and S/N of the system you are speaking about.

These numbers are for example provided on the type plate (example shown in the Fig. on the right side).

Figure 6: Example of iMAR type plate

3.2 Contact

You can find general information about our products, used technologies, and about inertial navigation, and GNSS based navigation at www.imar-navigation.de.

You can reach iMAR Customer Support as follows:

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