Advances in Airborne Gravity Gradiometry at Gedex

Gedex Systems Inc.
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Extreme Challenge of AGG Development

• Developing a low-noise, high resolution airborne gravity gradiometer requires:
  – Near perfect gradiometer: balance, rigidity, etc
  – Accurate measurement of exceedingly small displacements of the gradiometer masses
  – Near perfect thermal stability, electronics, shielding from EMI
  – Frictionless rotational stabilization

• Significantly improving data quality puts developers at the bleeding edge of many technologies

Gedex has end-to-end control of virtually all aspects of development, manufacture and implementation
Advances in Gravity Gradiometry

Past: Early systems possessed poor SNR for most applications.

Current: Upgraded processing and systems have significantly reduced noise levels.

Future: New developments are significantly advanced:
- HD-AGG (Gedex),
- VK1 (Rio Tinto),
- FTG-Plus (Lockheed Martin)

Simulation of the improvement in AGG performance over time using the SEAM II Foothills Model.

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Gravity Gradiometry 101

In concept, gravity gradiometers determine the change in the gravitational field by taking the difference in displacement between two proof masses.

![Diagram of a gravity gradiometer with two proof masses and a spring connecting them. The signal is given by \( \text{Signal} = \frac{(L_1 - L_2)}{d} \).]

1 Eotvos is \( 10^{-4} \) mGal/m

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The “proof-masses” in the Gedex instruments are attached through a rigid balance beam centered on a spring. Accurately balanced beam is insensitive to translational accelerations. Balance about pivot to 1 nm. Sub-surface density causes rotation of beam.
Gedex HD-AGG™ Instrument

Rotation of aircraft can create erroneous gravity gradiometer response

Implementing a second beam allows rotations in a common direction to be rejected
Instrument “in theory” does not have a first order response to rotational or translational motions

However, instrument scissors in response to a gravity gradient
Configuration of 2-Axis Instrument

Gxx, Gyy and Gzz can be calculated by simple arithmetic combination of these two components, resulting in a 37% lower noise level.

Actual balance beam machined from solid Niobium measures about 10 cm across.

$\frac{1}{2}(G_{zz}G_{yy})$

$\frac{1}{2}(G_{zz}G_{xx})$

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Key Enabling Technologies

HARDWARE
(HD-AGG™ System - Proprietary to Gedex)

Gravity Gradiometer Instrument
Flight Cryostat
GeoMIM Isolation Mount

Dash-8 Survey Aircraft

SOFTWARE
(Specialized Programs Proprietary to Gedex)

Post-Processing Software
Geophysical Processing & Imaging Software
Geological Analysis Software

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Flight Cryostat

Superconducting quantum interference devices (SQUIDS) precisely measure the rotation of the balance beam sensors. Accommodating a liquid helium cryostat in an aircraft has been a key engineering accomplishment.

- Interior temperature 4 Degrees above absolute zero
- Temperature kept constant to within a millionth of a degree
- Pressure kept constant to within 10 millionths of an atmosphere

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Isolation Mount

As gradiometer sensors pairs cannot be balanced perfectly, motion isolation is required. This is accomplished with a 6-degree of freedom isolation mount with frictionless rotational air-bearings.
Gedex HD-AGG™ System

Two-axis Instrument
The sensor unit in the lower half of the image is 20cm across

Motion Isolation System
Mounted inside a Cessna Caravan test aircraft

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System Performance Validation

• Lab tests
  – Confirm quiescent noise levels (noise floor)
  – Confirm calibration with signal test
  – Simulated flight testing

• Flight tests
  – High-level surveys
    • First-pass confirmation of noise
  – Low-level surveys
    • Confirmation of noise and resolution
    • Test surveys over known deposits/geology
Lab Testing: Quiescent Noise Level

- No stabilization during test
- Excellent long-period performance
- Mainly residual electronic noise

Gzz Noise: 1.5E RMS @ 1Hz

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Lab Testing: Signal Validation

Move known mass past Instrument to confirm signal is being measured as expected
Lab Testing: Flight Simulation

- Repeatable...can rapidly quantify impact of any upgrades
- Can playback actual flights...but cannot duplicate all disturbances experienced in the aircraft
Lab Testing: Flight Simulation

- Compensation of kinematics and other affects: no additional filtering
- No correction for movement relative to the local gravitational field
- Excellent long-period stability

Gzz Noise: 4.3E RMS @ 1Hz

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Low-Level Validation Survey

• Two common ways to establish noise level of an airborne gravity gradiometer system
  1. Independently measure signal as accurately as possible with high resolution ground gravity and Lidar data (e.g. R.J. Smith test range, Australia). Subtract from measured data to determine noise.
  2. Repeat AGG survey and compute difference to determine noise. Assumes noise is random and is similar for the two surveys.

• With high quality Lidar data the resolution of the system can also be established.
Low-level Validation Survey

Survey Parameters:
100m line spacing, flown at constant altitude 100m above highest peak

Lidar Inset:
1m sampling interval
5 cm vertical accuracy

SRTM surrounding area:
30m sampling interval

Investigate resolution of system with high accuracy Lidar data
Low-level Repeat Surveys

Data processing involves compensation for residual kinematic effects, line leveling and final noise reduction utilizing equivalent source processing.

The similar noise levels and character between the two surveys suggest a good noise estimate will result from the repeat survey analysis.

Survey 1 (Std-dev 20.5E)

Survey 2 (Std-dev 21.1E)
Low-level Repeat Surveys

• Sources of residual noise
  1. Primarily system noise
  2. Self-gravity effect due to motion of sensors relative to isolation mount and aircraft
  3. Spatial differences in flight lines for the two surveys. Noise due to XY variation is negligible and noise due to Z variation is approximately 0.5E

Plot shows an example of the measured vertical gravity gradient (colours) compared with terrain response (10E contours) computed from Lidar/SRTM data. Very close correspondence is seen between the two datasets even for small and relatively weak anomalies.
Road Ahead

- **Current Flight Tests**
  - Low level test surveys – Currently validating noise level and resolution for drape surveying
  - Flight over known deposits planned

- **Further Improvements**
  - Further upgrades to reduce system noise
  - Install and test in Dash 8
  - Targeting < 5 E Hz^{-1/2}

- **Additional modifications will be implemented to move towards 1 E at 60m resolution**

- **End-to-end development allows Gedex to identify and rapidly implement improvements**
• Excellent progress with validation program
  – Flight results confirm sub-10E Hz^{-1/2} noise level consistently achieved in the Caravan test aircraft at commercially viable production levels
  – Very good correspondence between measured gravity gradient and modelled signal
  – Lab simulations invaluable but no substitute for airborne testing
  – Noise level and operational window are being regularly improved...well on our way to achieving a low-noise, high resolution system