String Magnetic Gradiometer System

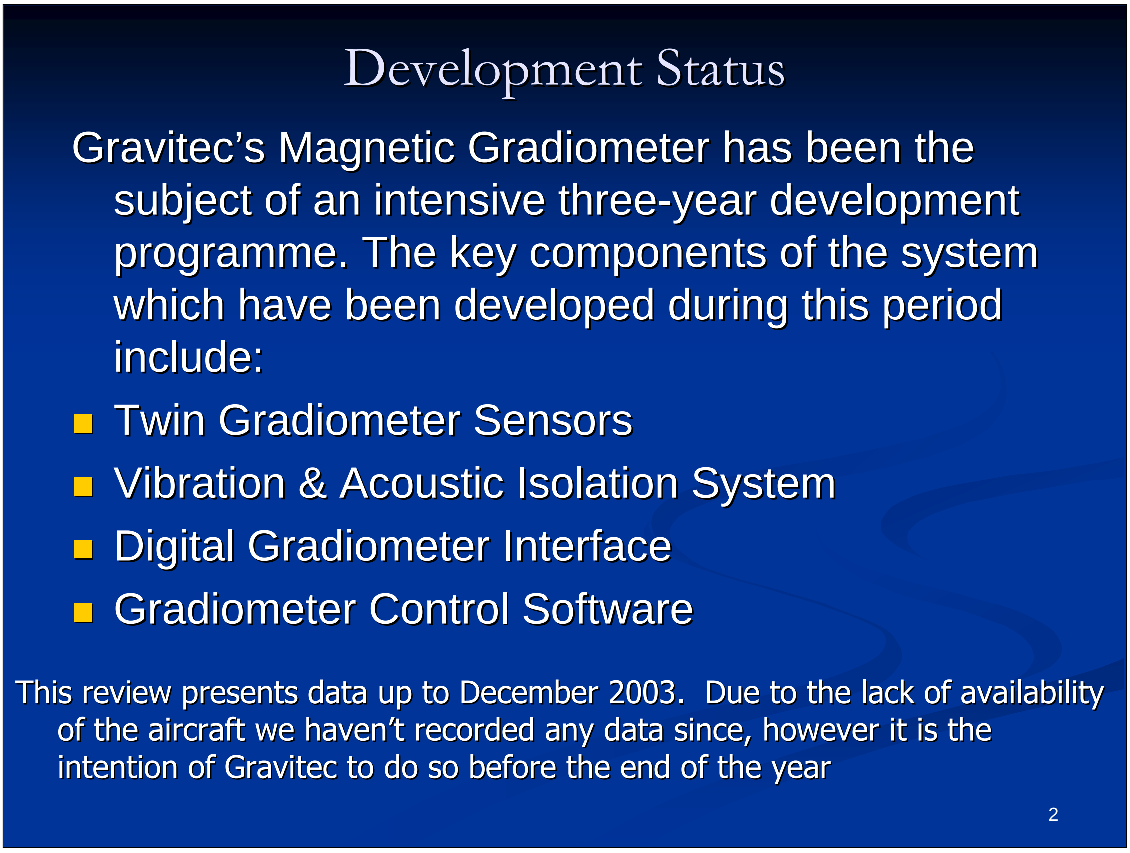
Recent Airborne Trials

October 14th, 2004

Magnetic Gradiometry

Gravitec Instruments Ltd has been working for the last few years on perfecting the commercial version of a string magnetic gradiometer system.

Airborne trials over the last 3 years have shown some problems associated with the environment of a typical surveying aircraft and we’ve been actively working with the Industrial Research Limited in New Zealand and the University of Western Australia, Perth on solutions to these problems.



Development Status

Gravitec’s Magnetic Gradiometer has been the subject of an intensive three-year development programme. The key components of the system which have been developed during this period include:

- Twin Gradiometer Sensors
- Vibration & Acoustic Isolation System
- Digital Gradiometer Interface
- Gradiometer Control Software

This review presents data up to December 2003. Due to the lack of availability of the aircraft we haven’t recorded any data since, however it is the intention of Gravitec to do so before the end of the year

The key developments are from the last 3 years are:

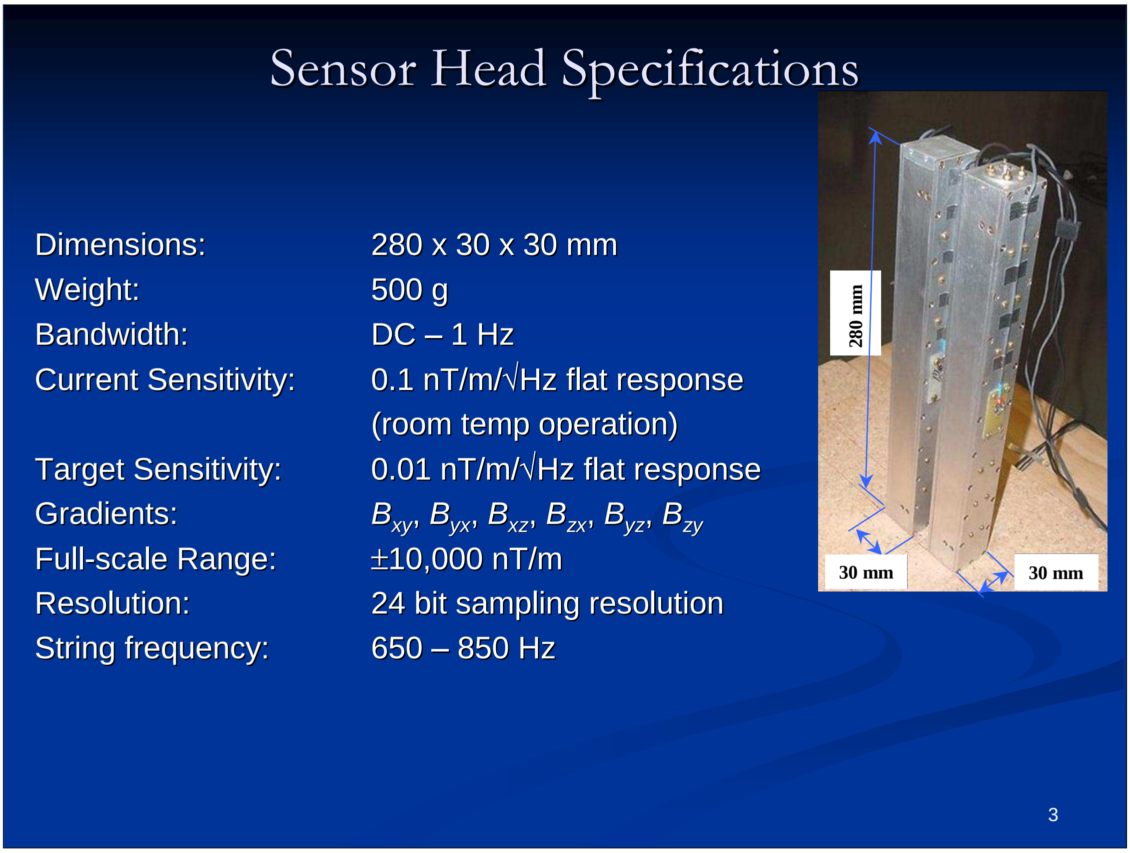
The completion and successful testing of a twin sensor magnetic gradiometer system

The development of a vibration and acoustic isolator for airborne deployment

A digital DSP system capable of running a sensor head processing, including tracking changes in the operating characteristics and processing the output signal from the sensor head

Design of testing of software to run the DSP unit and interface a Laptop PC

The results in the presentation cover data recorded up to December 2003. Due to lack of availability of the aircraft, we’ve been unable to record any further field data. We expect to do this before the end of the year.



Sensor Head Specifications

Dimensions:	280 x 30 x 30 mm
Weight:	500 g
Bandwidth:	DC – 1 Hz
Current Sensitivity:	0.1 nT/m/√Hz flat response (room temp operation)
Target Sensitivity:	0.01 nT/m/√Hz flat response
Gradients:	B_{xy}, B_{yx}, B_{xz}, B_{zx}, B_{yz}, B_{zy}
Full-scale Range:	±10,000 nT/m
Resolution:	24 bit sampling resolution
String frequency:	650 – 850 Hz

The sensor head is self-contained in a small package, convenient for deployment in a range of applications.

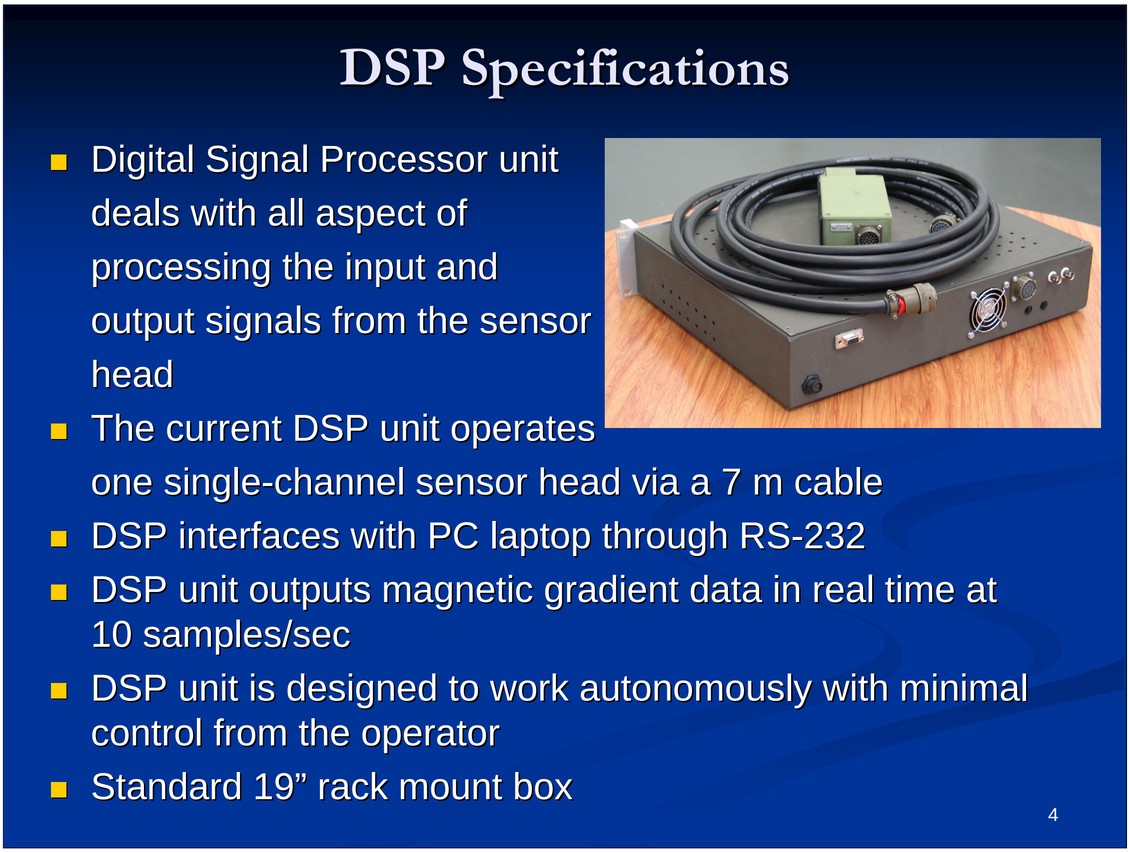
It is 280 mm long and weighs 500 g. The output bandwidth of the sensor is DC–1 Hz after digitisation and processing of the signal.

Operating at room temperature and after allowing sufficient time to reach equilibrium, the sensor has a flat noise profile limiting its current sensitivity to 0.1 nT/m. This noise floor can be further decreased to at least 0.01 nT/m.

The sensor is deployable both horizontally and vertically, allowing it to measure all 6 off diagonal magnetic gradient tensor components. It is theoretically possible to deploy a multiple sensor system to measure the full magnetic gradient tensor field in a single package.

The current system outputs 10 samples/s from a single sensor with a full-scale range of ±10,000 nT/m at 24-bit resolution.

And the sensor operates between 650 and 850 Hz, well away from 1/*f* noise and the low frequency noise of an aircraft.



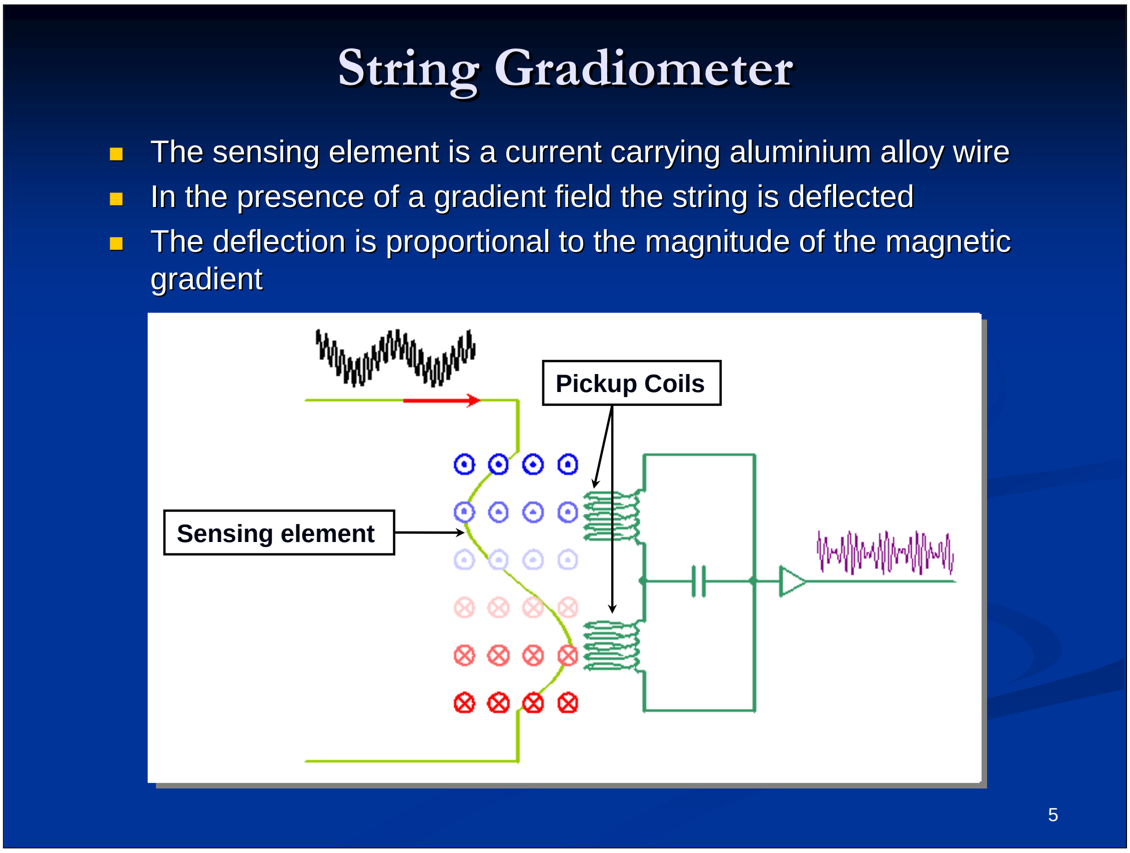
DSP Specifications

- Digital Signal Processor unit deals with all aspect of processing the input and output signals from the sensor head
- The current DSP unit operates one single-channel sensor head via a 7 m cable
- DSP interfaces with PC laptop through RS-232
- DSP unit outputs magnetic gradient data in real time at 10 samples/sec
- DSP unit is designed to work autonomously with minimal control from the operator
- Standard 19” rack mount box

The DSP unit generates the control and feedback signals to the sensor head. It monitors the output signals from the sensor, first demodulating the signal then filtering to DC–1Hz bandwidth.

The DSP is separated from the sensor head by a 7 m camera cable, which carries all signals and power lines to the preamplifier box. It interfaces to a Laptop computer via an RS232 port, supplying real time data at 10 samples per second and allowing an operator to monitor the performance of the sensor and electronics.

The DSP is designed to work autonomously after power up and auto-configuration. The entire DSP package is mounted in a standard 19” rack mount case for easy installation in an aircraft.



String Gradiometer

- The sensing element is a current carrying aluminium alloy wire
- In the presence of a gradient field the string is deflected
- The deflection is proportional to the magnitude of the magnetic gradient

The string sensor operates based on fairly simple physics. The string sensing-element is an aluminium alloy wire, stretched under tension so that its fundamental string vibration mode is between 325 and 425 Hz.

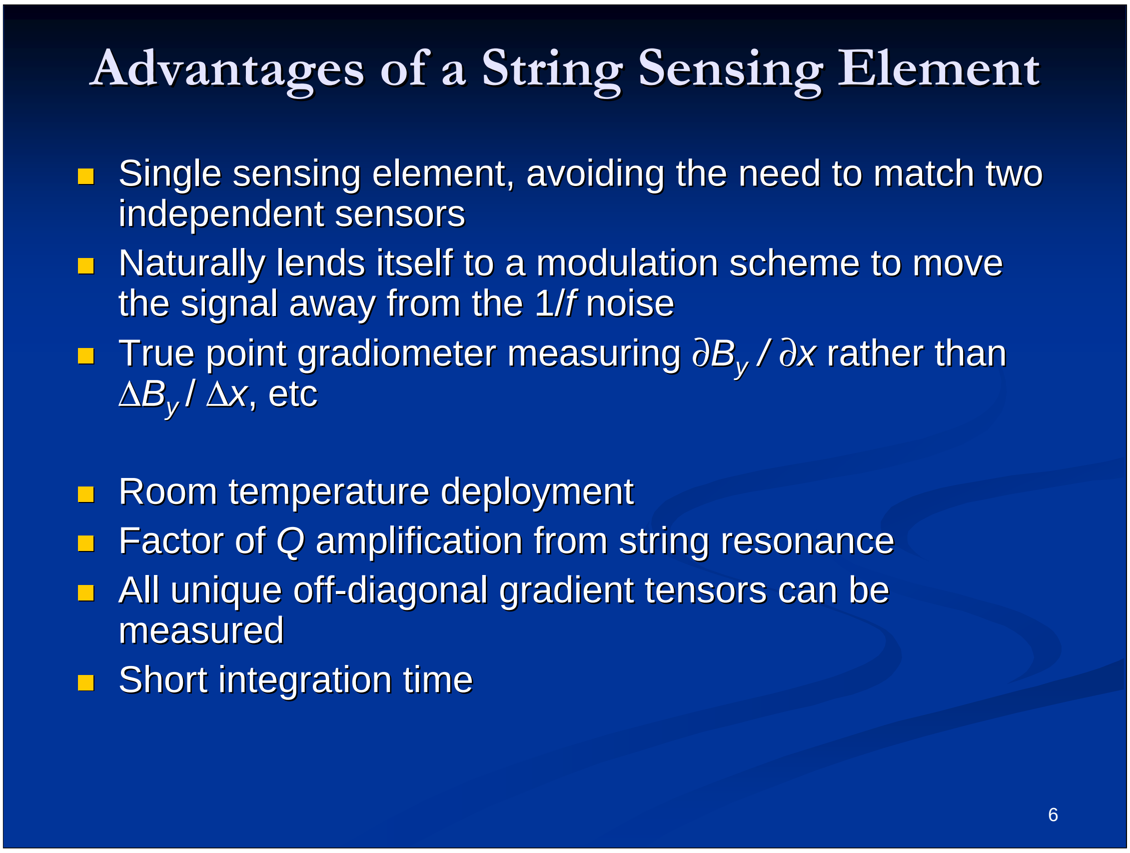
An AC current is passed through the string oscillating at the second mechanical harmonic of the string. In the presence of a gradient field the current drives the string at resonant with the second harmonic frequency. The string has a Q factor of 700 producing mechanical resonant amplification of the vibration by the same factor.

A high frequency carrier signal on the string allows us to detect the gradient field modulation of the string using two pickup coils as part of an LC resonant bridge. The coils are wired in differential mode to reject all but the second harmonic vibration. Modulation of the relative distance between the string and pickup coils modulates the amplitude of the carrier signal in the bridge.

Finally, the much stronger carrier is suppressed at the output giving a double side-band suppressed carrier signal suitable for amplification, demodulation and signal processing.

The signal from the constant magnetic field is suppressed in several ways. First, the second harmonic string drive is off-resonance for the first harmonic oscillation produced by the constant field. Second the differential mode pickup coils reject modulation at the fundamental mode. Finally the subsequent demodulation and filtering of the signal rejects all but the second harmonic, gradient field signal.

Thus the sensor is only sensitive to the gradient field and completely rejects any component of the total field.



Advantages of a String Sensing Element

- Single sensing element, avoiding the need to match two independent sensors
- Naturally lends itself to a modulation scheme to move the signal away from the $1/f$ noise
- True point gradiometer measuring $\partial B_y / \partial x$ rather than $\Delta B_y / \Delta x$, etc

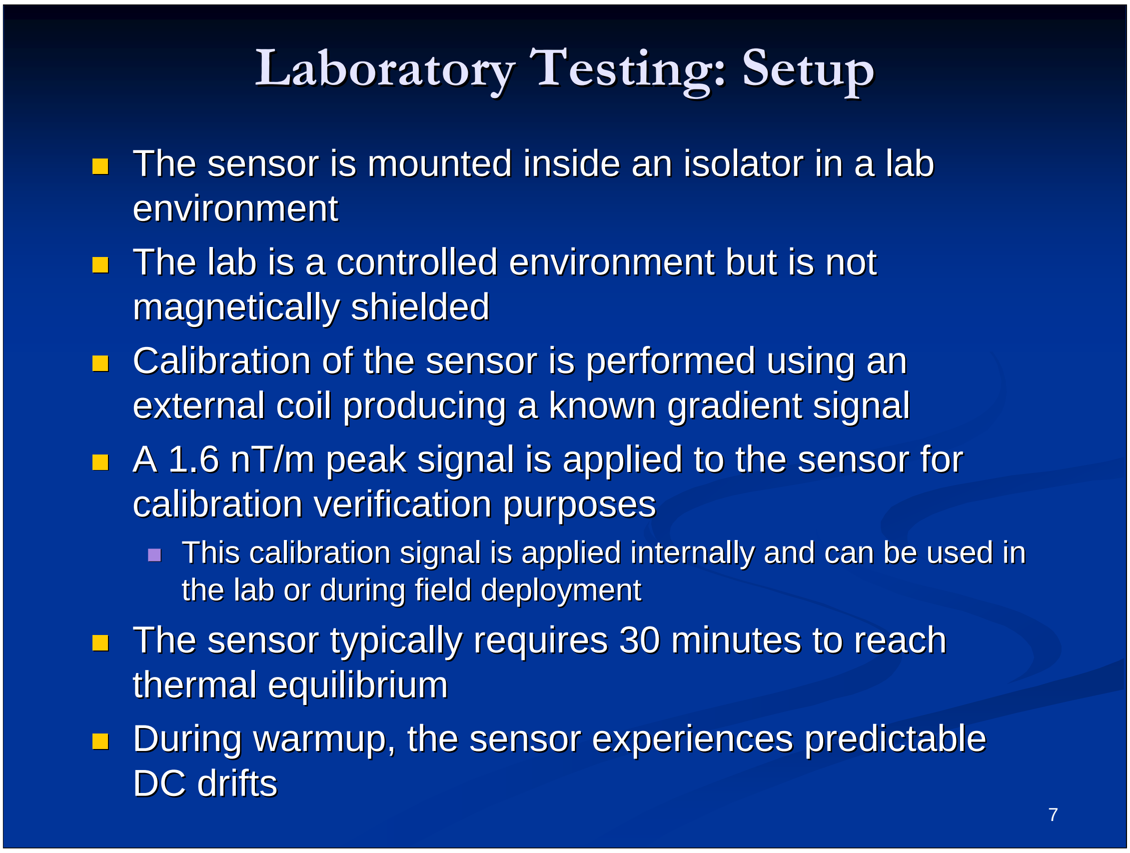
- Room temperature deployment
- Factor of Q amplification from string resonance
- All unique off-diagonal gradient tensors can be measured
- Short integration time

There are several main advantages to having a single string-sensing element. The first and most important is removing the need to match, both in operation characteristics and in orientation, two independent measurement sensors. Having two identical sensors fixed at two positions along a baseline would produce similar results to the single string gradiometer, however it is very challenging to manufacture two identical magnetic sensors to sufficient accuracy and it becomes even more challenging trying to fix the orientation of those two separated sensors, especially in a mobile platform such as an aircraft.

In addition, $1/f$ noise limits the resolution of the individual magnetic sensors unless an additional modulation scheme is used. The string gradiometer lends itself naturally to modulation at a frequency well above $1/f$ noise and aircraft engine noise.

The sensor is a true point gradiometer measuring off diagonal tensor components.

It can be operated at room temperature and features short integration time and responds rapidly to gradient changes.



Laboratory Testing: Setup

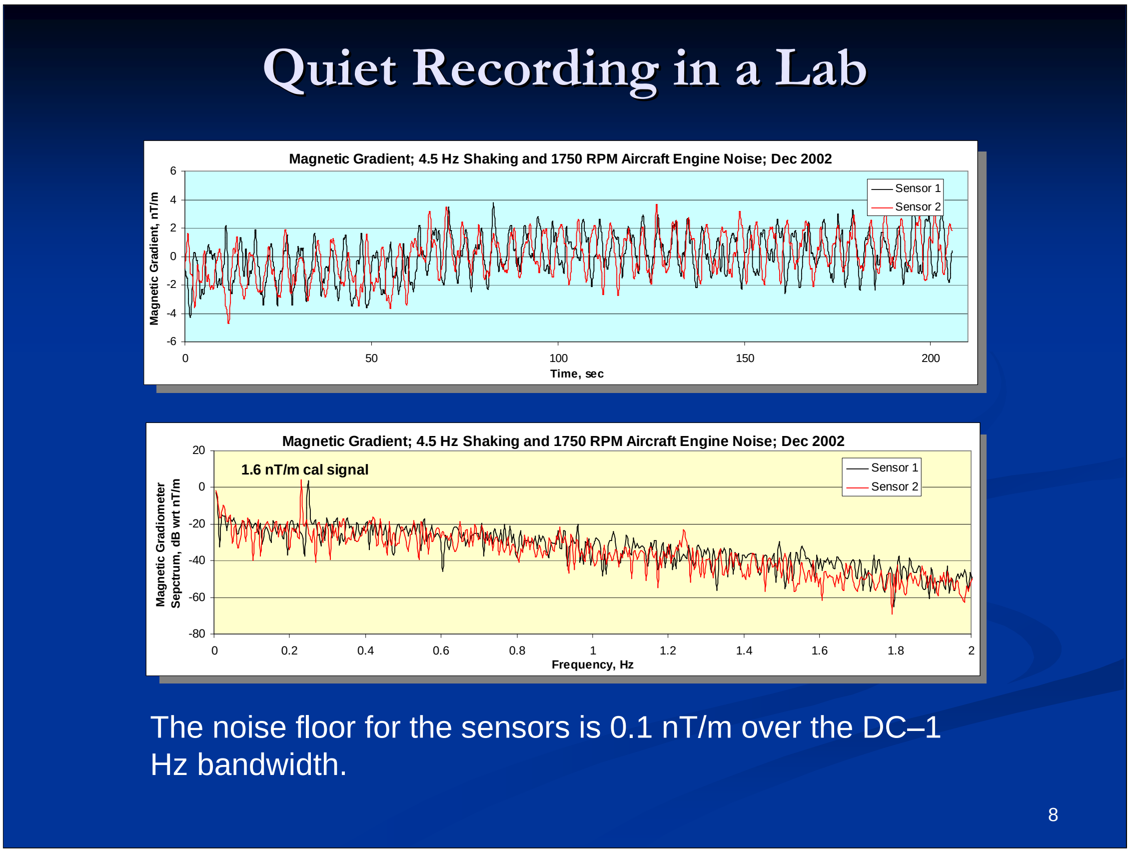
- The sensor is mounted inside an isolator in a lab environment
- The lab is a controlled environment but is not magnetically shielded
- Calibration of the sensor is performed using an external coil producing a known gradient signal
- A 1.6 nT/m peak signal is applied to the sensor for calibration verification purposes
  - This calibration signal is applied internally and can be used in the lab or during field deployment
- The sensor typically requires 30 minutes to reach thermal equilibrium
- During warmup, the sensor experiences predictable DC drifts

The sensor has been extensively tested in a lab environment. The lab was a controlled environment but did not feature any magnetic shielding or special conditions. The sensor was typically mounted either in an isolator or open to the environment sitting on vibration isolation material such as Sorbothane damping material.

The sensor is calibrated in the lab by means or a single loop current-carrying coil positioned a know distance from the centre of the sensor. The gradient field from the loop is calculated and compared with the measured gradient field from the gradiometer.

We can also inject a 1.6 nT/m gradient signal internally. The calibration signal is deployable in the field without the need for a bulky loop coil and allows the sensor performance to be monitored.

The sensor typically requires 30 minutes to reach thermal equilibrium with the environment. After initial start up the sensor experiences slow, well-behaved DC drifts. These drifts can be removed in post processing, or the sensor can be thermally stabilised and allowed time to reach its operating temperature.



Quiet Recording in a Lab

The noise floor for the sensors is 0.1 nT/m over the DC–1 Hz bandwidth.

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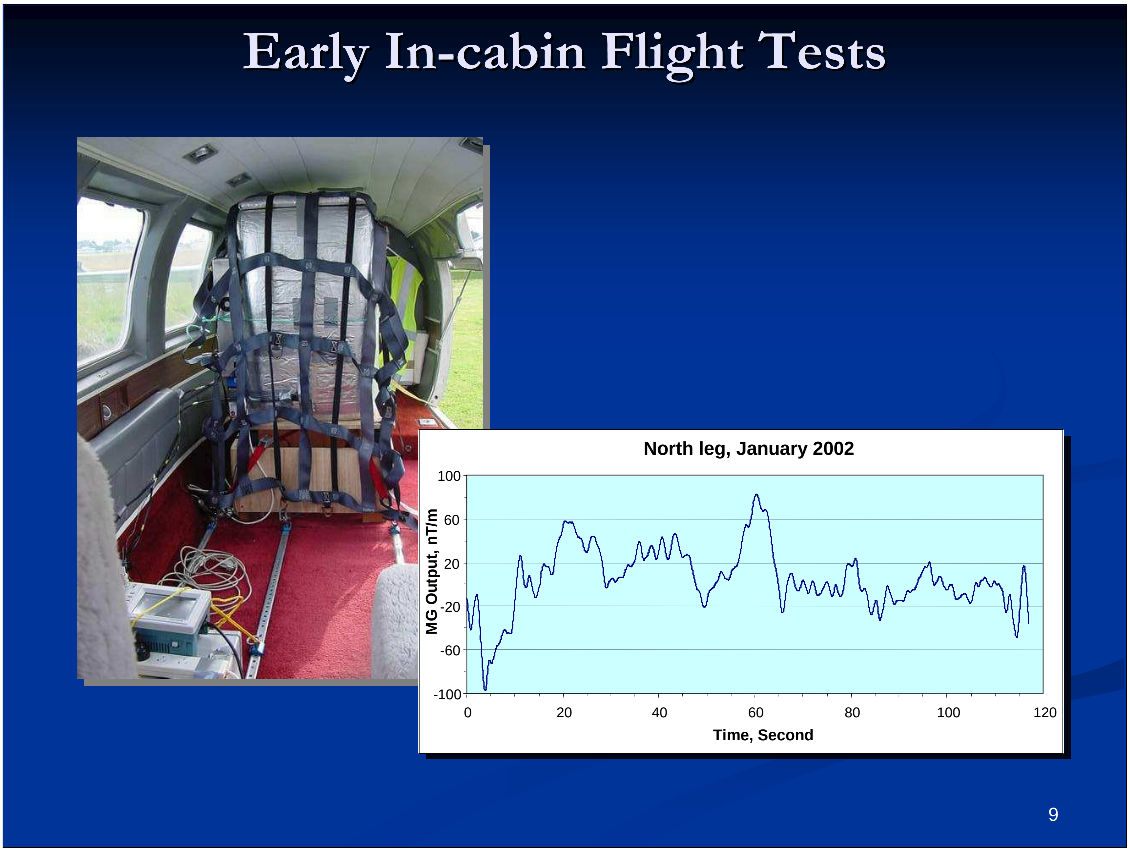
The time domain graph shows simultaneous output from two independent gradiometers in lab conditions. The sensors have almost reached thermal equilibrium with the environment and the 1.6 nT/m calibration signal is active. To make it more difficult, the sensors were being shaken at 4.5 Hz, 0.1g and in the presence of high volume 1750 RPM aircraft engine noise.

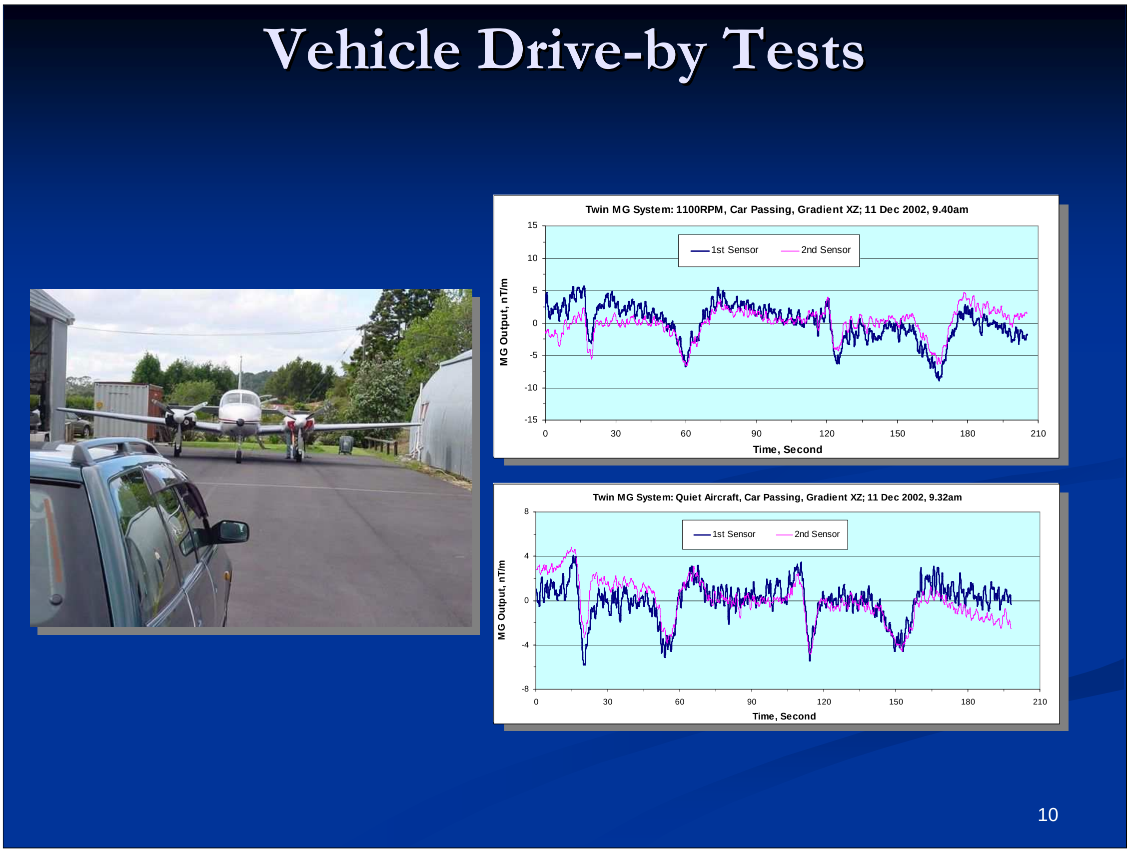
The spectrum is calibrated relative to 1 nT/m and shows the flat response of the sensor for the DC–1 Hz bandwidth. The noise floor is 0.1 nT/m measured in the quiet environment of the lab.



Early In-cabin Flight Tests

North leg, January 2002

Early in-cabin flight experiments showed that even in the relatively quiet environment of the aircraft cabin the noise floor was 3 orders of magnitude above the target of 0.1 nT/m even when housed in a large padded container. The majority of the noise, especially inside the cabin, is attributed to heading error and other magnetic noise. However, additional experience in the field showed that vibration and acoustic noise played a significant role in the deployed sensor noise.



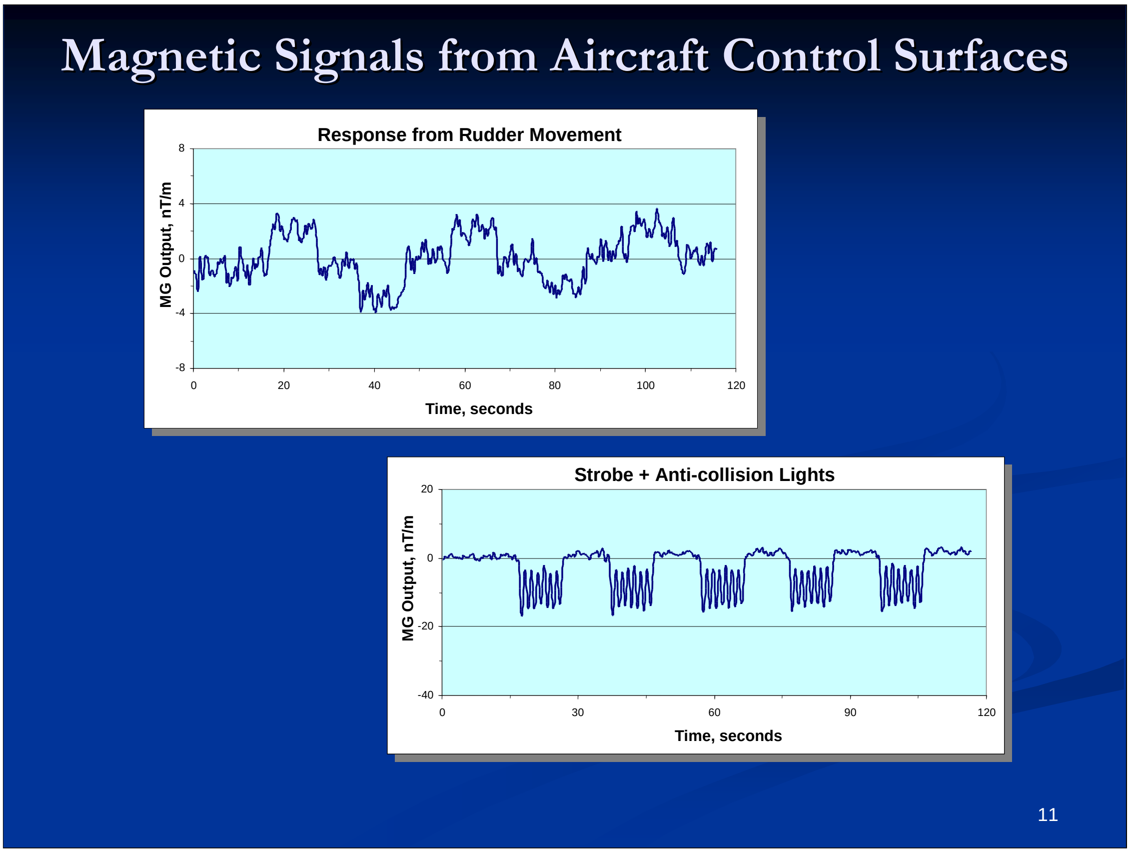
Vehicle Drive-by Tests

Twin MG System: 1100RPM, Car Passing, Gradient XZ; 11 Dec 2002, 9.40am

Twin MG System: Quiet Aircraft, Car Passing, Gradient XZ; 11 Dec 2002, 9.32am

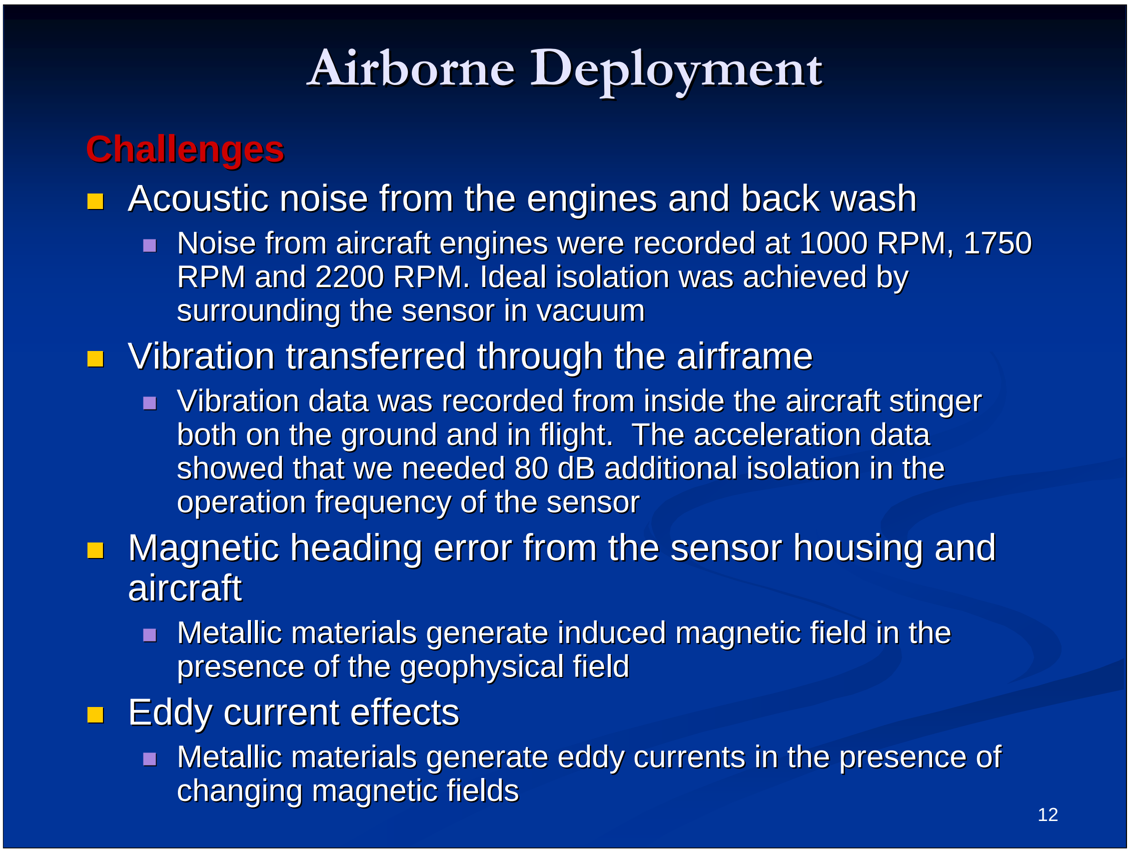
The in-cabin experiments did show us that the sensors could detect a magnetic anomaly from an aircraft flying 60 m above the ground.

We placed the sensor in the cabin of an aircraft and ran the engines at 1750 RPM. A car drove past the wing of the aircraft approaching to within 10 m of the sensor. The magnetic gradient was recorded simultaneously on two sensors for BXZ and BYZ gradient components. The signatures detected for the vehicle are consistent with the calculated magnitude and profile of a 100 nT magnetic anomaly of 400 m length located 100 m below the aircraft.



Magnetic Signals from Aircraft Control Surfaces

Movement of the control surfaces of an aircraft produce gradient signatures in the sensor. Typically the signatures are minor and current post-processing algorithms are capable of removing the features from the raw data. In cabin recordings on an unmodified aircraft show that the effect from full movement of the rudder is only ~7 nT/m. The strobe and anti-collision lights, which are normally turned off during surveys, produce a similar magnetic signature. For a degaussed survey aircraft in flight the effect from the control surfaces would be much less.



Airborne Deployment

Challenges

- Acoustic noise from the engines and back wash
  - Noise from aircraft engines were recorded at 1000 RPM, 1750 RPM and 2200 RPM. Ideal isolation was achieved by surrounding the sensor in vacuum
- Vibration transferred through the airframe
  - Vibration data was recorded from inside the aircraft stinger both on the ground and in flight. The acceleration data showed that we needed 80 dB additional isolation in the operation frequency of the sensor
- Magnetic heading error from the sensor housing and aircraft
  - Metallic materials generate induced magnetic field in the presence of the geophysical field
- Eddy current effects
  - Metallic materials generate eddy currents in the presence of changing magnetic fields

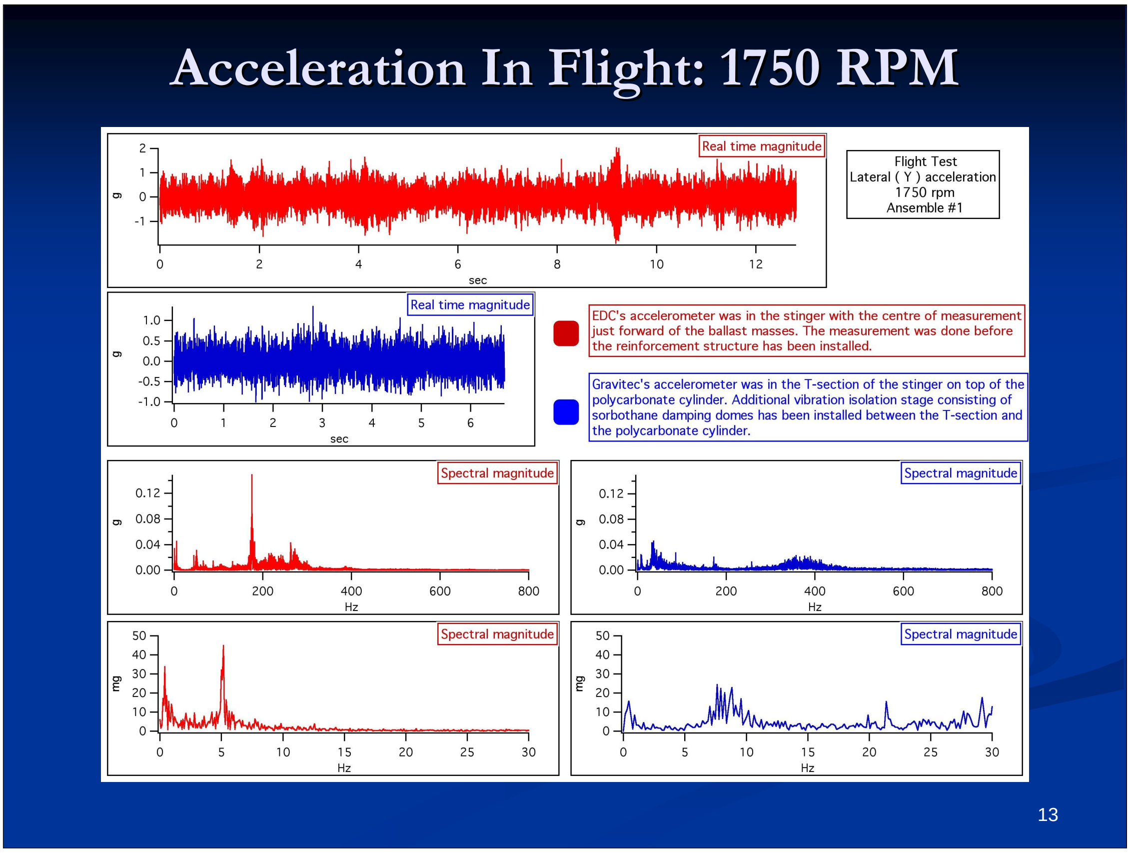
The environment is considerably more difficult to work in on board an aircraft than it is in a lab.

Acoustic noise from the engines and backwash from the props was characterised by recording engine noise at 1000 RPM, 1750 RPM and 2200 RPM. The noise was played back on a stereo system at full volume, allowing us to test the response of the sensor to the noise.

Vibration transferred by the airframe to the sensor was characterised by recording the acceleration in the stringer from DC to 1 kHz.

Magnetic heading error from magnetically contaminated materials in the aircraft and in the sensor housing was characterised by rotating the sensor out in the field well away from know magnetic sources. High altitude flight tests verified the results from ground tests.

Eddy currents generated in the sensor housing have only become evident after reducing the noise from sound, vibration and magnetic noise from the sensor frame.



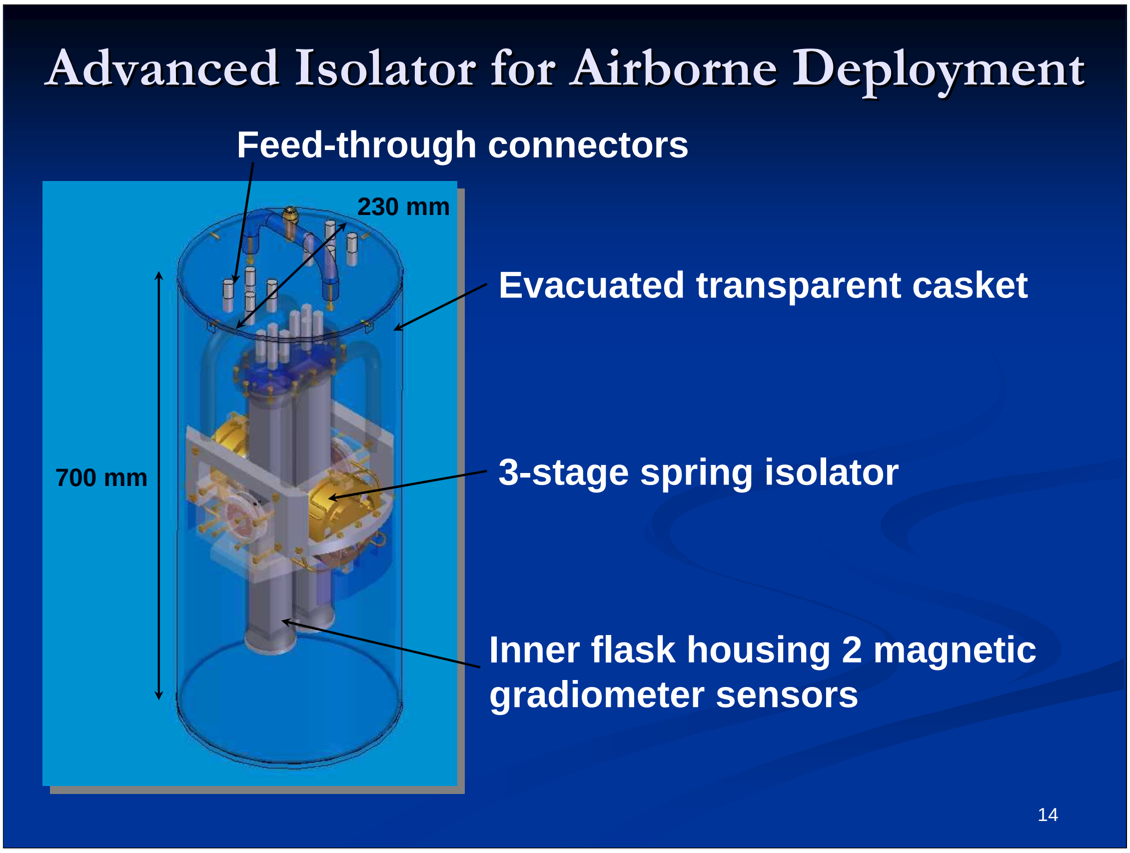
Acceleration In Flight: 1750 RPM

Flight Test
Lateral (Y) acceleration
1750 rpm
Ansemble #1

🟥 EDC's accelerometer was in the stinger with the centre of measurement just forward of the ballast masses. The measurement was done before the reinforcement structure has been installed.

🟦 Gravitec's accelerometer was in the T-section of the stinger on top of the polycarbonate cylinder. Additional vibration isolation stage consisting of sorbothane damping domes has been installed between the T-section and the polycarbonate cylinder.

As part of the task of isolating the sensor from the noise of the aircraft we needed to characterise the level of noise on the ground and during flight. The flight recordings were the most interesting and useful of the recordings made. They showed that the noise is typically ~0.2 m/s2 but can peak to over 1 m/s2 at frequencies below 400 Hz. Even though the sensor operates at frequencies above 400 Hz, we needed 80 dB additional isolation in order to reach our target sensor noise floor.



Advanced Isolator for Airborne Deployment

Feed-through connectors

Evacuated transparent casket

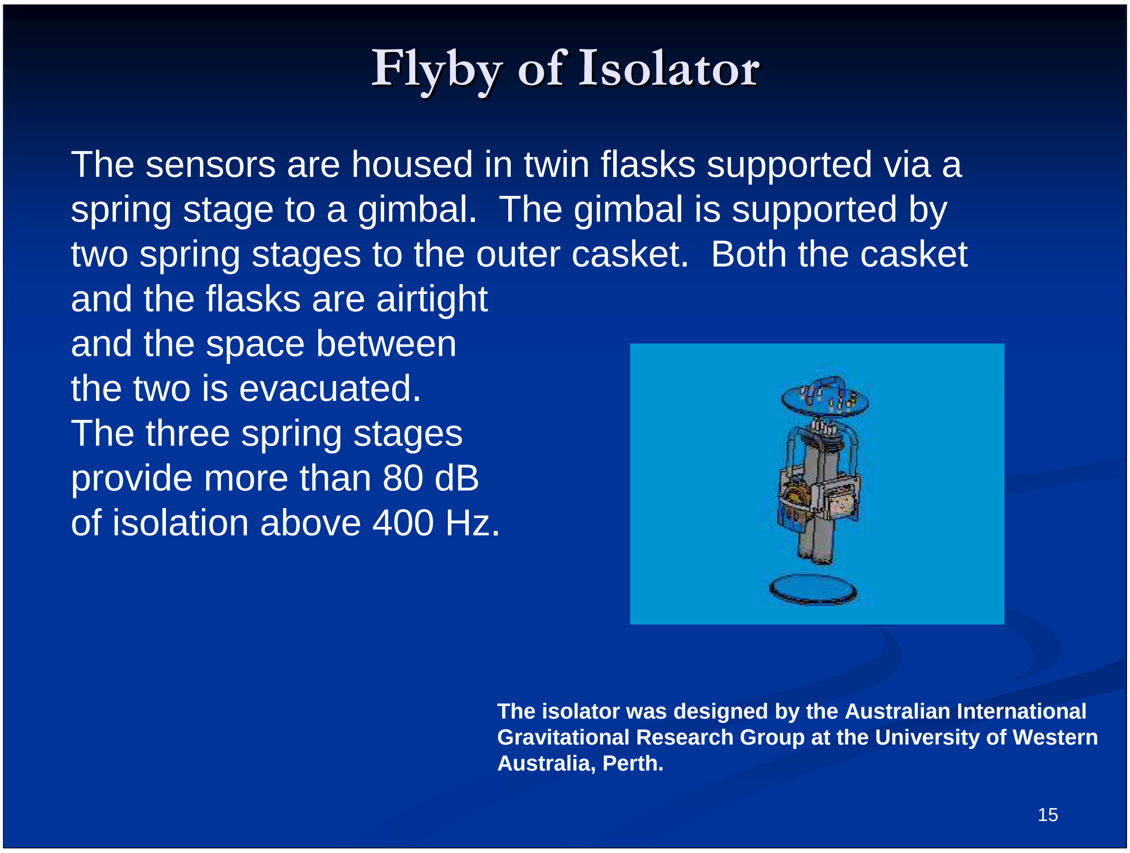
3-stage spring isolator

Inner flask housing 2 magnetic gradiometer sensors

In order to achieve this level of isolation we worked with the Australian International Gravitational Research Group at the University of Western Australia on an advanced passive isolator capable of working in the available stringer section.

The isolator needed to be able to hold 2 sensors operating under atmospheric pressure and fit in the stinger T-section already constructed for the aircraft.

The isolator consists of a transparent polycarbonate outer casket. An inner flask houses two sensors at atmospheric pressure. The flask is suspended inside the casket by a 3-stage spring suspension system.



Flyby of Isolator

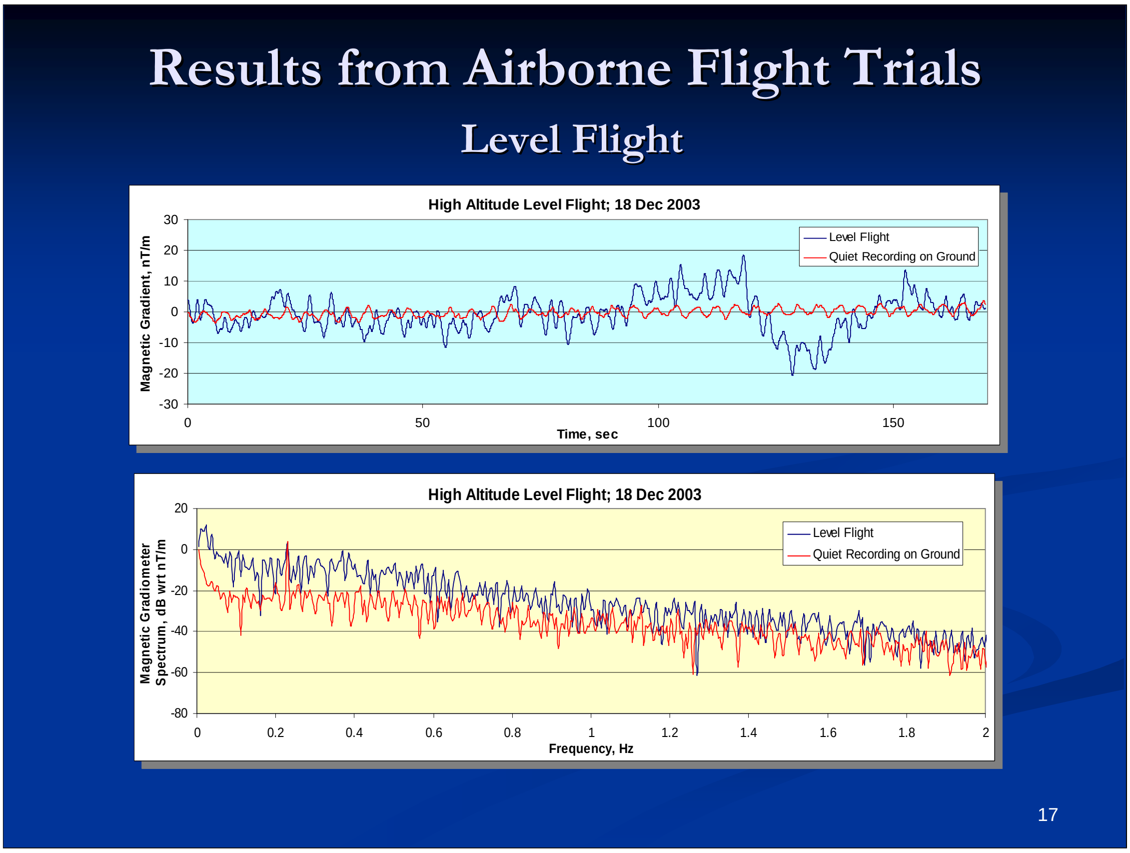
The sensors are housed in twin flasks supported via a spring stage to a gimbal. The gimbal is supported by two spring stages to the outer casket. Both the casket and the flasks are airtight and the space between the two is evacuated. The three spring stages provide more than 80 dB of isolation above 400 Hz.

The isolator was designed by the Australian International Gravitational Research Group at the University of Western Australia, Perth.

The space between the casket and flask is evacuated in order to provide complete isolation from sound and improve the vibration provided by the suspension. The spring stages are designed to provide more than 80 dB isolation above 400 Hz in 6 degrees of freedom. Due to the harshness of the environment, the isolator was designed to withstand up to 3 g shock and maximum sustained accelerations of 1 g.

Stinger Section with Sensor Installed

The sensor is mounted in a stinger T-section of a Cessna 404 aircraft, approximately 2 meters from the tail. The preamps are clamped inside the stinger 40cm from the sensor and DSP sits inside the cabin of the aircraft. Sorbothane domes, not shown in these pictures, provide additional isolation between the stinger and isolator, improving performance of the sensor.



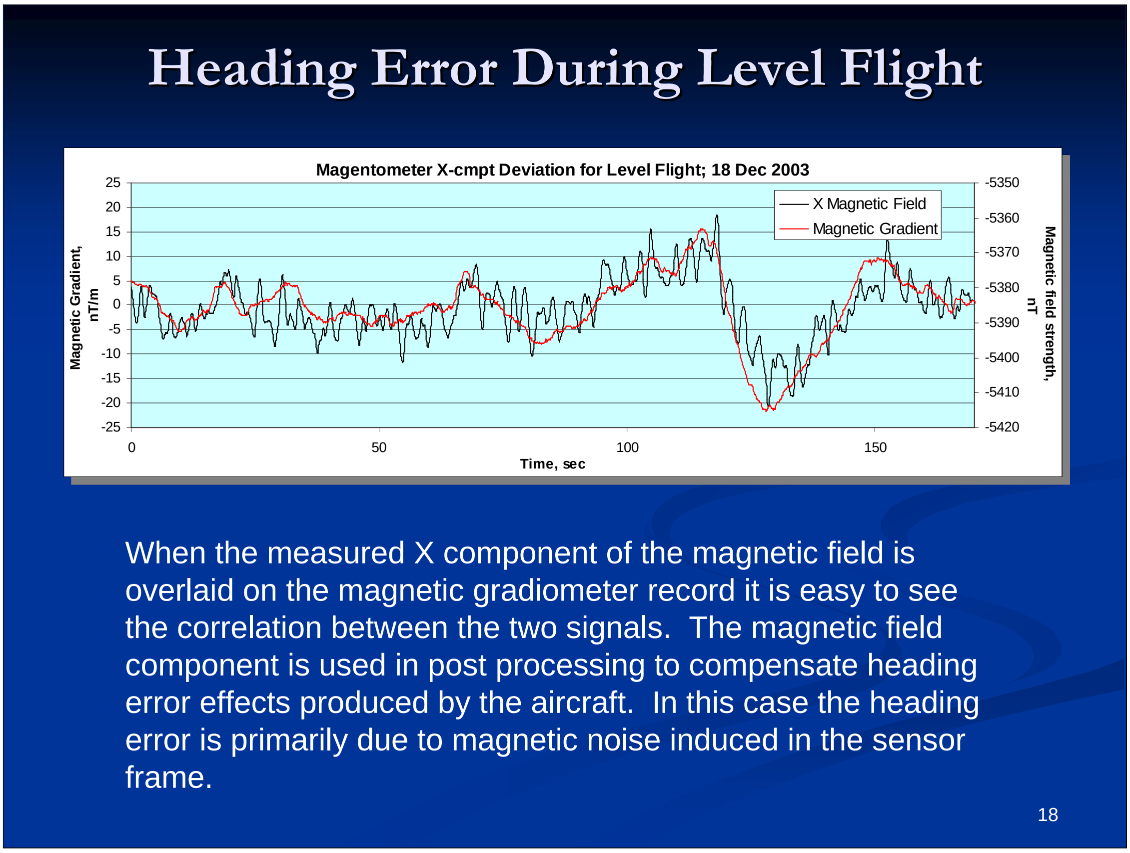
Results from Airborne Flight Trials

Level Flight

The most recent data was recorded in flight in the stinger section of the survey aircraft. The aircraft was flying at high altitude along level North-South lines. Due to lack of availability of the aircraft we were unable to record more recent data for the sensors.

In flight the sensor is operating at 0.5–1 nT/m wideband noise, some 5–10 times larger than the target noise floor for the sensor. Most of the noise above 0.1 Hz is attributed to eddy current effects in the frame of the sensor head. Eddy currents produced in the frame typically produce spikes of ~5 nT/m magnitude, resulting in broadband noise.

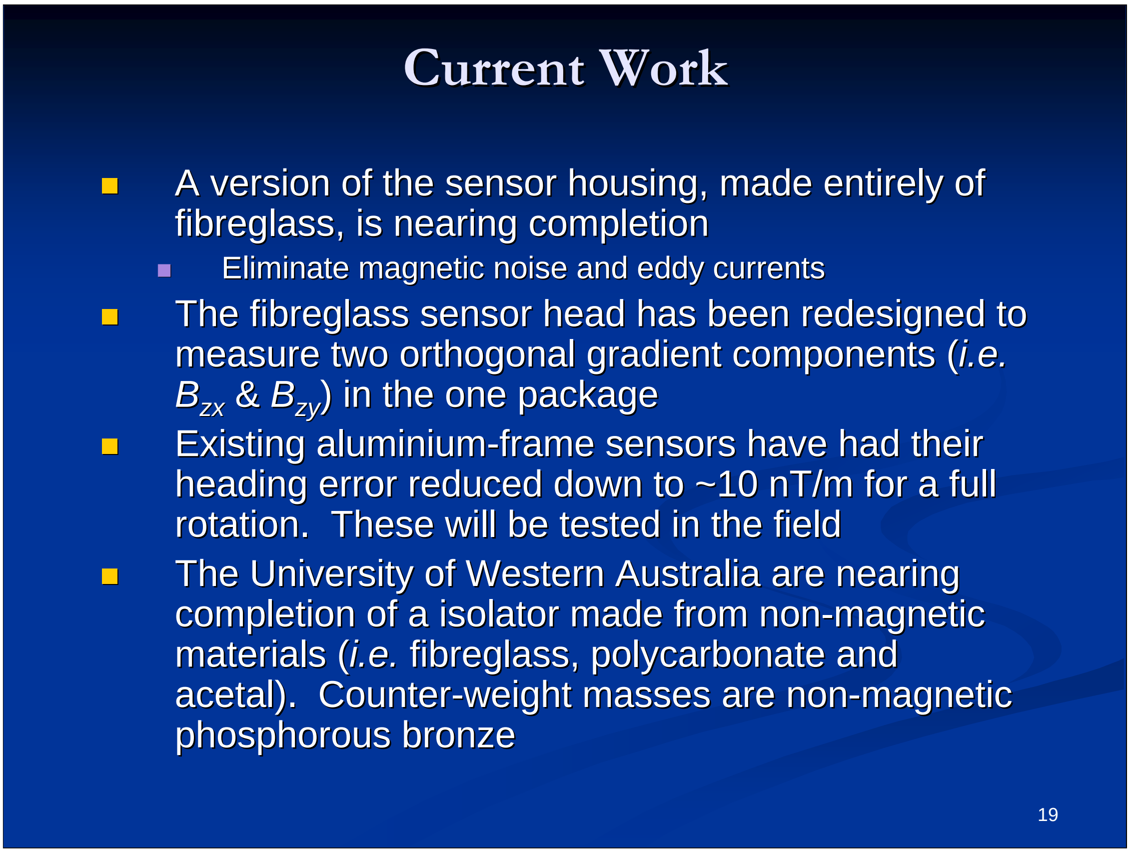
The longer-term features are due to heading error effects from the sensor housing.



Heading Error During Level Flight

When the measured X component of the magnetic field is overlaid on the magnetic gradiometer record it is easy to see the correlation between the two signals. The magnetic field component is used in post processing to compensate heading error effects produced by the aircraft. In this case the heading error is primarily due to magnetic noise induced in the sensor frame.

By comparing the x component of the magnetic field measured in the stinger with the gradient field measured by the sensor is it easy to see the correspondence between long-term features. The magnetic heading error is a little too large to deal with in post-mission compensation. However, both the eddy current noise and heading error noise have a common source in the aluminium alloy used for the sensor housing. The material was chosen to reduce the effect of thermal expansion on the string resonant frequency. Alternate non-metallic materials with coefficients of expansion close to that of the aluminium alloy would eliminate heading error and eddy current noise and significantly improve the in-flight noise performance of the sensor.



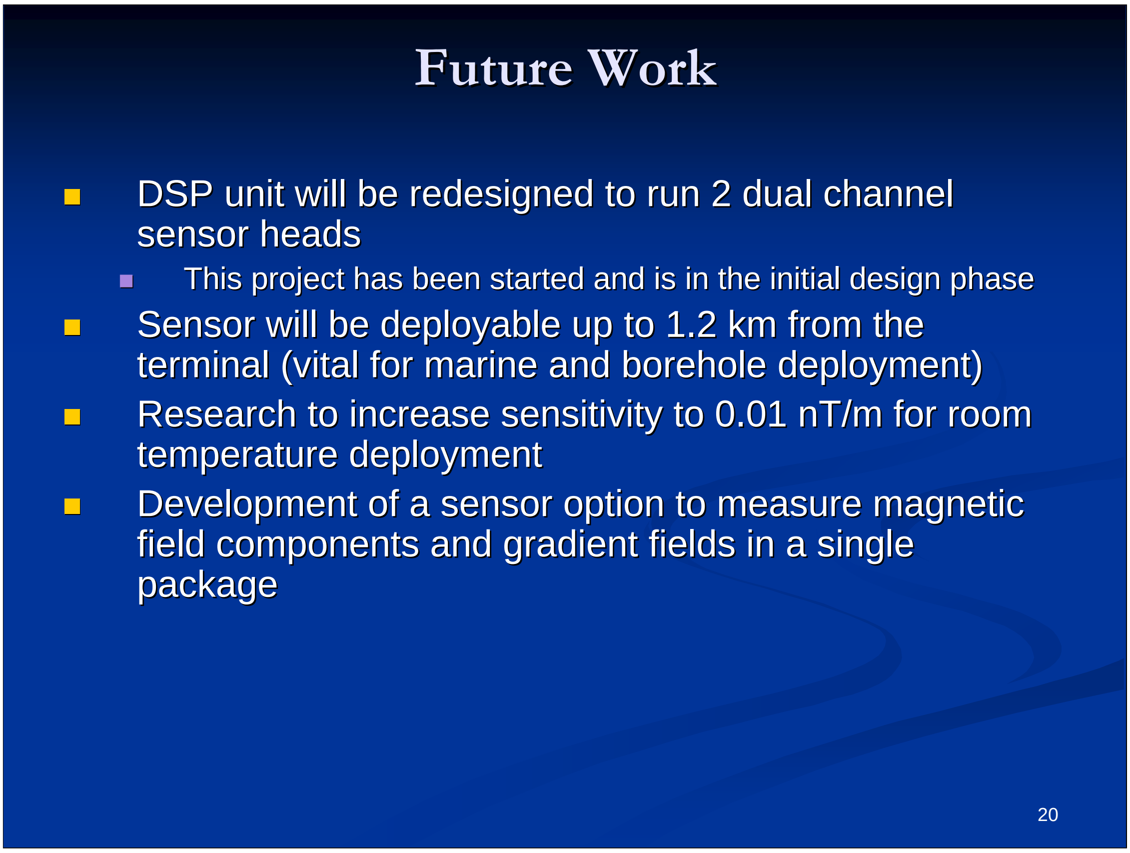
Current Work

- A version of the sensor housing, made entirely of fibreglass, is nearing completion
  - Eliminate magnetic noise and eddy currents
- The fibreglass sensor head has been redesigned to measure two orthogonal gradient components (*i.e.* B_{zx} & B_{zy}) in the one package
- Existing aluminium-frame sensors have had their heading error reduced down to ~10 nT/m for a full rotation. These will be tested in the field
- The University of Western Australia are nearing completion of a isolator made from non-magnetic materials (*i.e.* fibreglass, polycarbonate and acetal). Counter-weight masses are non-magnetic phosphorous bronze

Gravitec is working on the next generation sensor, which will incorporate improvements in design and ease of use. The first and most important improvement is the use of fibreglass in the sensor frame. This will eliminate the remaining eddy current and heading error effects preventing commercial deployment of the sensor. At the same time we are working on a sensor head design that will measure string deflection in 2 orthogonal directions, allowing a single sensor package to simultaneously measure two gradient tensors (BZX and BZY for instance).

Work is progressing on the existing aluminium frame sensors to reduce the heading error to ~10 nT/m for a 360 rotation. We will run flight tests with these sensors before the end of the year.

The University of Western Australia have nearly completed a new isolator made almost entirely of non-magnetic materials. This isolator will give the same level of isolation as the original prototype isolator, but should eliminate heading error noise from the isolator.



Future Work

- DSP unit will be redesigned to run 2 dual channel sensor heads
  - This project has been started and is in the initial design phase
- Sensor will be deployable up to 1.2 km from the terminal (vital for marine and borehole deployment)
- Research to increase sensitivity to 0.01 nT/m for room temperature deployment
- Development of a sensor option to measure magnetic field components and gradient fields in a single package

The dual-channel sensor head will be deployed with a DSP capable of running 2 dual-channel sensor heads, for a total of 4 channels.

The new sensor and DSP package will be deployable up to 1.2 km from the operator, making it ideal for marine deployment.

Gravitec will be working with UWA on a third generation isolator providing better isolation in a smaller package. In addition, we will be working with them on an improved sensor detection method that is expected to decrease the noise floor to 0.01 nT/m.

And we are looking at combined package capable of measuring component magnetic and gradient fields all from the one string sensing-element.