The German airborne SQUID tensor magnetic gradiometer

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Abstract

The German program was started in 1997 at the Institute for Physical High-Technology (IPHT) with the aim of developing a full airborne superconducting quantum interference device (SQUID) magnetic tensor gradiometer using liquid-helium-based thin-film technology. Since that time the sensor, electronics, data acquisition system, and cryogenics have been developed and tested. The first flight trial of a full tensor gradiometer (6 gradient + 3 magnetometer channels), with ancillary sensors (3-axis accelerometer, current sensors, and a real-time differential GPS) was completed in May 2003. This paper describes the system, provides some preliminary results from that experiment, and describes upcoming improvements.

1. Introduction

The German gradiometer program was begun in 1997 to develop a full airborne SQUID magnetic tensor gradiometer using liquid-helium thin-film technology. The concept was to build a light-weight, low-power, high-sensitivity sensor which would be towed on a long cable beneath a helicopter. This would avoid the aircraft-induced noise. Since building the prototype sensor and electronics in the late 1990's, a series of experiments have been completed. These include:

1) the initial lab demonstration of a single component gradiometer (2000),
2) measurement of the helicopter magnetic signature (March 2001),
3) initial flight trial of a single component gradiometer (Oct 2001),
4) a second flight trial of the original system (May 2002),
5) a flight trial of the second generation system (October 2002,
6) a test of their third-generation, full-tensor system (May 2003).

In 2000, DRDC loaned a tow-body to IPHT to allow them to direct their resources towards improving the sensor and data acquisition system. This tow-body was developed during the early 1990's as part of DRDC's now-defunct airborne SQUID program.

The IPHT system consists of a magnetometer/ gradiometer sensor housed in a dewar filled with liquid-helium. The dc-SQUIDs are made from niobium/ aluminum oxide/niobium deposited on silicon wafers. The analog SQUID-controller electronics have a bandwidth of 3 MHz, sit atop the dewar, and are connected to a second box of electronics mounted at the top of the tow-body. These electronics contain the 24-bit A/D's, network communications circuitry, and an Ashtech GPS receiver with built-in differential correction capability. The GPS antenna is mounted at the top of the tow-body. Both sets of electronics are powered from 12 volt batteries mounted at the top of the tow-body. A three-axis accelerometer is mounted on the SQUID controller electronics box, and a reference pressure cell, connected to the liquid-helium reservoir inside the dewar via a short hose, is mounted on top of the second electronics box. Figure 1 shows the tow-body with the electronics, batteries, and various systems mounted on top.

The A/D's measure the following 14 channels of information:

- three magnetometer components (B_x, B_y, B_z)
- six gradient channels (G_1, G_2, G_3, G_4, G_5, G_6)
- three accelerometer channels (A_1, A_2, A_3)
- total current drawn from the batteries (I_T)
- current drawn from the reference cell heater to maintain the same pressure in the dewar as in the reference cell (I_P).

These digitized signals are sent via a fibre-optic cable network cable to a laptop-PC mounted inside the helicopter. The sample rate of these data is 1000 Hz and the data is sent in bursts every 50 ms (20 times per second).

The GPS data is sampled at 20 Hz, send to the laptop via the same cable, and written to a separate file. Each GPS sample is written at the beginning of each burst of A/D data.

For all trials since Oct 2001, a Bell UH-1D helicopter has been used. The kevlar-reinforced tow-cable is approximately 90 m in length.

2. Recent Modifications

The 2002 flights trials showed that the two-component gradiometer system worked well, was relatively immune to EMI, and that the old networking hardware and software was fairly robust. Unfortunately this software was unable to accommodate the extra GPS data stream. For the May 2003 flight trial, the major changes to the system were:

1) the networking hardware and software were changed to a commercial product with UDP instead of TCPIP protocol. The commercial hardware required ~ 1/10th of the electrical current compared to the old hardware,
2) the sensor had 3 magnetometer channels + 6 gradient channels, instead of just 3 magnetometer + 2 gradient channels,
3) the accelerometer, reference pressure cell, total-current measurement, and GPS were added,
4) the present generation of SQUIDs gradiometers have a problem with the rigidity. This will be solved with the next generation of SQUIDs,
5) the probe, on which the SQUIDs were mounted, was changed to accommodate the extra gradient channels,
6) data packets were transferred over the fibre-optic link every 50 ms instead of 500 ms (20 Hz vs 2 Hz).

3. Purpose of the May 2003 Trial

The aims of the most recent flight trial were:

1) verify the new SQUIDs were working properly,
2) test the GPS during flight,
3) test the modified network electronics during flight,
4) determine the noise levels on all gradient channels during flight,
5) test compensation/noise reduction algorithms,

Figure 2 shows the gradiometer and tow-body in flight.

4. Results from the flight trial

4.1 EMI & magnetometer sensitivity

Neither the three magnetometer channels nor the six gradiometer channels showed any flux jumps. (When the system loses lock, then re-acquires lock, there may be a jump. These jumps come in quantized units known as Φ_o's.) This is a problem that has plagued other airborne SQUID systems and it is important to note that the IPHT design has overcome this difficulty.

The magnetometer SQUIDs were intentionally "spoiled" to suppress their sensitivity, but they were not de-sensitized quite enough. In order to avoid exceeding the dynamic range of the magnetometer A/D channels, the pilots were asked to keep the bank angle of the helicopter (and thus the tow-body) to less than 10°. Subsequent magnetometer SQUIDs will be desensitized further to avoid this operational limit.

4.2 GPS

The Ashtech GPS system automatically applied differential corrections from a WAAS satellite, but it was unable to automatically detect and apply corrections from the Danish Coastal Beacons. It is unclear if the signals from these beacons were too small to be detected, or if the Ashtech system failed. Even without these corrections, the WAAS-corrected GPS was accurate to within approximately 1 metre.

4.3 New network hardware/software

Unfortunately the new networking hardware/software package dropped some data points. On average, it missed ~ 0.1 seconds of data every 100 seconds. This is a "missed data" rate of only 0.1%. Because the data stream was time stamped, it was possible to interpolate over this missing data and did not lead to any serious problems with the analysis of these data. This problem has already been overcome with the latest software release from the network software supplier.

4.4 Raw noise levels on the gradient channels

Figures 3a,b show the raw gradiometer and magnetometer data along a single straight flight line.

The old network hardware drew a substantial current that produced a distinct magnetic waveform in the gradiometer data. A noise stacking technique was used to estimate this waveform from data collected when the gradiometer was stationary. It was then subtracted from the gradient data at the beginning of each network transfer. Because the new network hardware required approximately 1/10th of the electrical current, this "network transfer waveform" was not evident in the raw gradient data.

4.5 Compensation

IPHT uses a 3-term model for modeling and removing noise due to permanent and induced magnetic sources and have found that these coefficients change very little over long periods of time. These terms are simply the three SQUID magnetometer signals. (A fourth-term DC can be added or one can remove the means of all the gradient and magnetometer channels prior to calculating the coefficients.) They have found very little further improvement results if the eddy-current sources are modeled with magnetometer derivative terms, except in the case where data from a single long straight line is analysed. If an entire flight with many heading and altitude changes is analysed, the improvement is minimal. This suggests that high-dynamic manoeuvres produce magnetic noise which does not fit the standard eddy-current model.

Figure 4 shows a portion of the power spectral density (PSD) of the raw, 4-term (permanent + induced magnetization), and 7-term (permanent + induced + eddy current sources) compensated G_1 data along a single straight line. The 7-term model clearly removes noise in the band near 1 Hz. This noise has previously been attributed to the natural pitch and roll motions of the tow-body.

Figure 5 shows the power spectrum of the raw and 7-term compensated gradients G_1 through G_5. (The reader should compare similar coloured traces to determine the degree of compensation achieved.) The remaining noise is ~ .005 nT/m across the band 3 – 25 Hz for each of the five gradients and ~ 0.01 nT/m from 0-3 Hz. Both of these values are considerably above the design specification of 0.0002 nT/m (200 fT/m), which IPHT has achieved when the system is stationary. Notice the strong line at 20 Hz in the green trace (G_4). This suggests that the 20 Hz networking transfer waveform is still detectable and that it should be removed to obtain the best noise levels.

Additional methods for traditional compensation were tried, including three extra terms for the acceleration components, and terms for the total current and pressure sensor. This resulted in no appreciable improvement.

4.6 Frequency-Domain Coherence

Figures 6a-c illustrate the PSD's of the accelerometer, I_T and I_P signals. Visual inspection showed that accelerometer and I_T PSDs closely resemble that of the compensated G_1 residual. Frequency-domain coherence was used to determine if the noise level could be further reduced with this technique. Figure 7a shows the result for the entire bandwidth and Figure 7b shows only the 0-30 Hz region. Clearly there has been a dramatic improvement in the noise level after frequency-domain coherence processing. The largest improvement was brought about by the accelerometer signals but the total current was also important. There did not appear to be any improvement when the pressure current signal was used. However, this particular line was flown at the same height so there would be very little change in pressure. Other flight data where altitude changes took place would be needed to verify this result. It is interesting to note that there was no appreciable improvement when coherence processing was applied to the magnetometer channels, suggesting that the 7-term perm + induced + eddy model is the best model involving those signals already.

It should be noted that once the noise associated with accelerometer signals was removed, the 20 Hz network transfer noise became apparent. This appears to have been removed, or at least significantly reduced, by coherence processing vs the total current. Whether it is easier to remove this noise with waveform subtraction, or with the coherence processing, in a real-time system is a topic for further research. The remaining noise appears to be resonance frequencies not picked up by the accelerometers, possibly the bending of the thin substrates. Thick substrates may reduce this noise.

5. Future Improvements

Although this flight trial successfully demonstrated a full tensor gradiometer, IPHT will soon produce another system with the new generation of SQUIDs. These SQUIDs should be less sensitive to vibration and thus reduce the overall system noise. Also, the SQUID heater will be deposited directly on the substrate instead of wire-wound, and a fourth (redundant) magnetometer will be added.

The networking difficulties encountered in this trial (0.1% lost data transfers) have already been corrected in the latest release of the commercial software.

The analysis in Sections 4.5 and 4.6 suggest that a considerable reduction in noise level is achievable with methods other than the simple 3-term model presently used by IPHT. Coding a time-domain version of the coherence-processing algorithms may lead to the greatest noise reduction.

Although the Canadian tow-body has been a valuable asset to the program, it was designed for a larger, more massive, dewar. It has some natural modes of motion (pitch and roll) that produce unwanted noise around 1 Hz. A new tow-body, designed especially for the IPHT dewar, which eliminates these unwanted motions is required. It is hoped that a new dewar will be available by late 2003.

Finally, in order to take full advantage of the tensor gradiometer capability, it is necessary to know not only the position of the sensor, but the orientation. One solution is to change the Ashtech GPS system to an integrated GPS/INS unit such as the C-MIGITS III. Work is already underway in this area.

Figure 1. Electronics and sensors mounted on above the dewar: 1) SQUID controller electronics, 2) second electronics box, 3) accelerometer, 4) batteries, 5) pressure reference cell, 6) GPS antenna.

Figure 2. DRDC tow-body, containing the SQUID sensor and electronics, if flight.

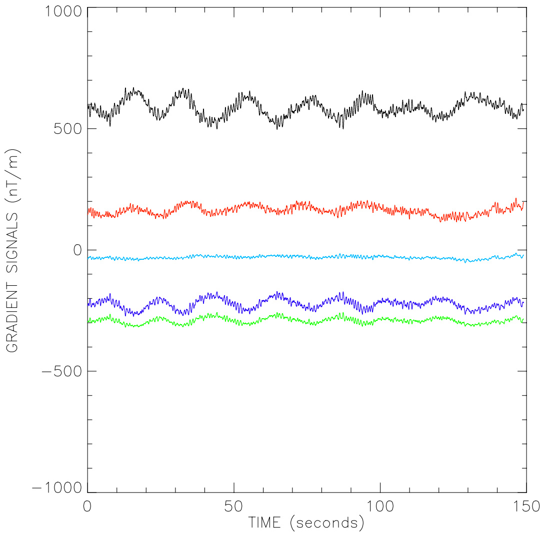

Figure 3a. Raw gradiometer data collected in straight, level flight. Black = G_1; dark blue = G_2; light blue = G_3; green=G_4, and red=G_5.

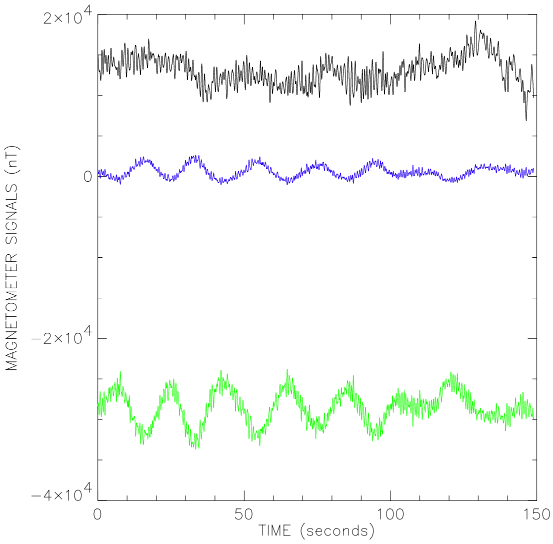

Figure 3b. Raw magnetometer data collected in straight, level flight. Black = B_1; dark blue = B_2; light blue = B_3;

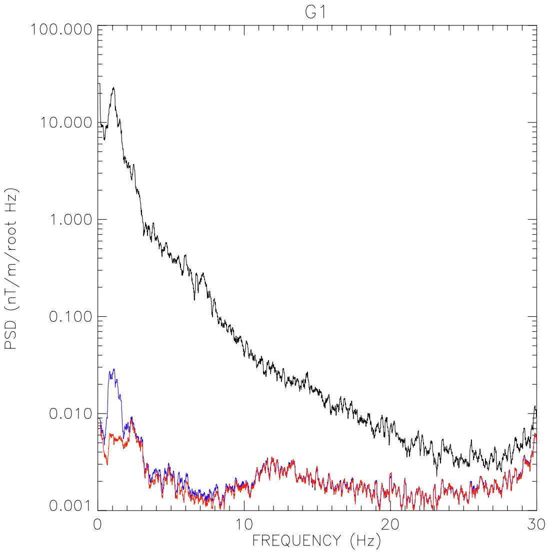

Figure 4. PSD of raw (black), 4-term (blue), and 7-term (red) compensated G_1 along a single flight line.

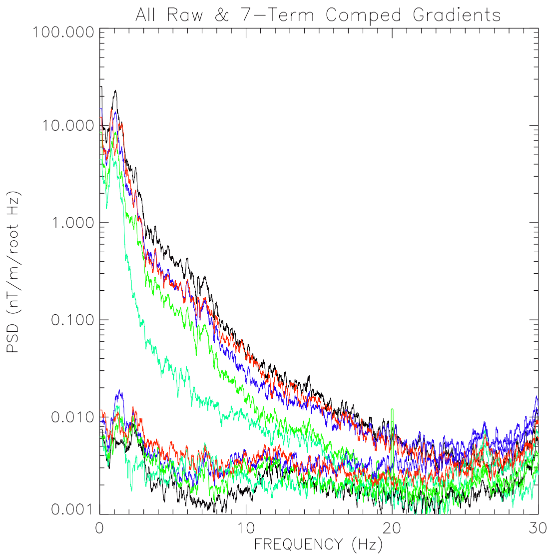

Figure 5. PSD of all raw and 7-term compensated gradients along a single flight line. Black = G_1; dark blue = G_2; light blue = G_3; green=G_4, and red=G_5.

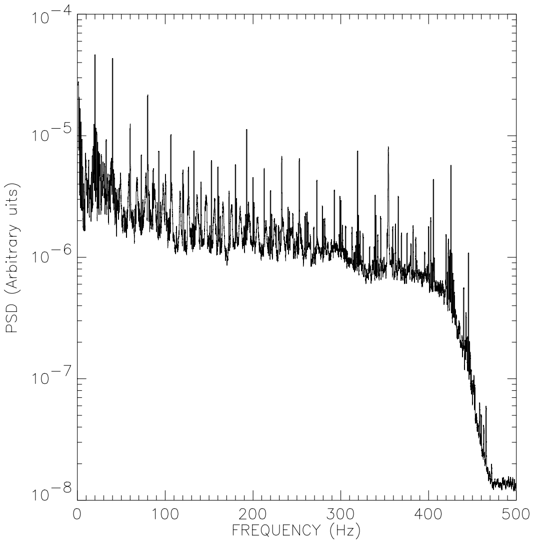

Figure 6b. PSD of total current (I_T) signals.

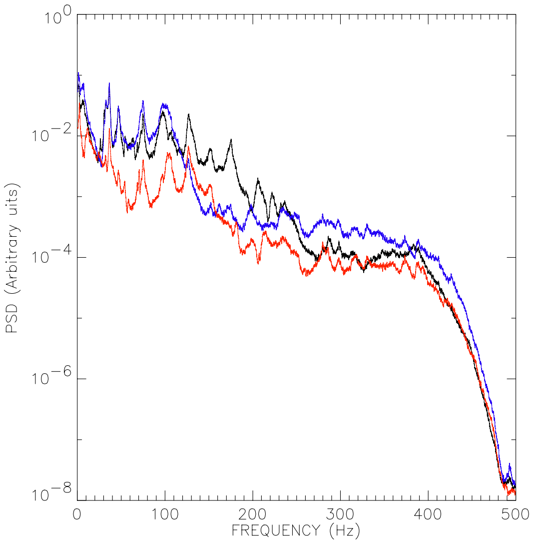

Figure 6a. PSD of accelerometer signals. Black = X, blue = Y, red = Z.

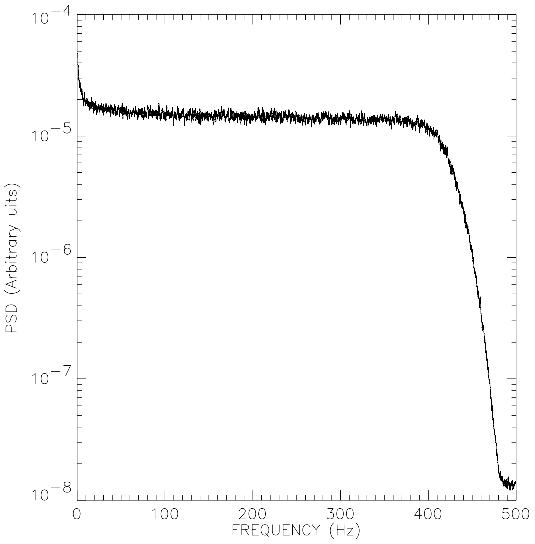

Figure 6c. PSD of pressure current (I_P) signals.

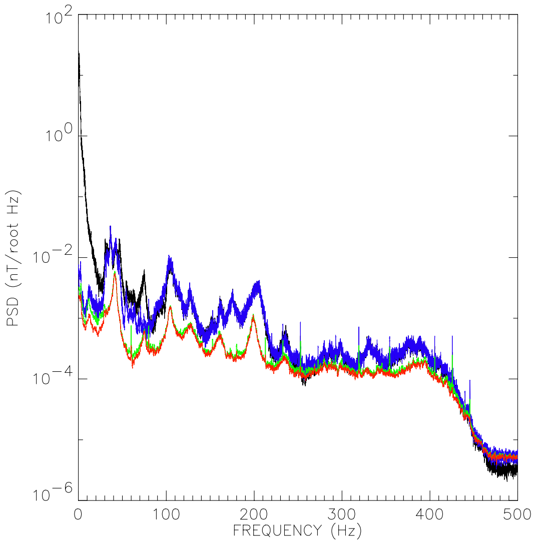

Figure 7a. PSD of residuals after various levels of coherence processing. Black = G_1; dark blue = compensated G_1; green = coherence processing with only accelerometers; red = coherence processing vs accelerometers and total current.

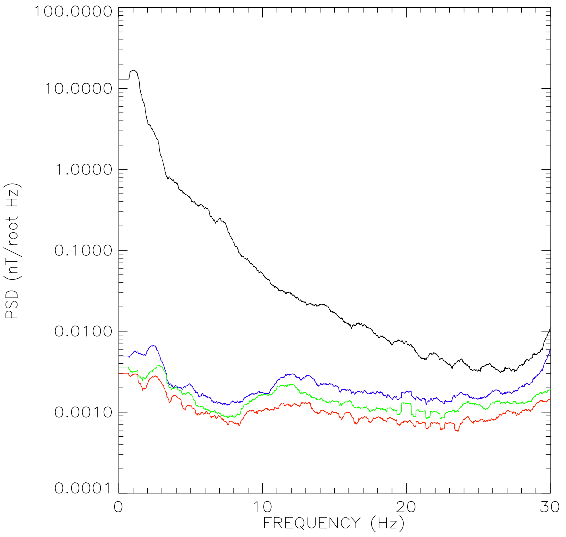

Figure 7b. PSD of residuals after coherence processing as in Figure 6a, but displaying only 0-30 Hz. (Spectra have been smoothed with a 101 pt boxcar for display purposes.)