# Magnetic Sensor Operation Onboard a UUV: Magnetic Noise Investigation using a Total-Field Gradiometer

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*Abstract*- **To operate a magnetic sensor on board an Unmanned Underwater Vehicle (UUV), it is necessary to provide a means for compensating magnetic noise from a variety of sources. In previous applications involving passively towed platforms, the noise arises from the magnetic fields due to eddy currents and magnetic polarization changes occurring due to rotation of the platform in the earth's magnetic field. It has been demonstrated that this noise can be compensated with a single vector magnetometer that is rigidly attached to the sensor of interest, measuring the rotational changes in the earth's magnetic field. This compensation algorithm has been extended, for passively towed platforms, to provide both motion noise reduction and localization of magnetic dipole targets, in a single process.**

**On a UUV, noise sources are present in addition to those induced by the earth's magnetic field. There are active elements present, such as current loops, motors, actuators, sonars, and electronic devices. To compensate for these additional sources, it is necessary to add additional reference sensors, and to employ more complex compensation models. In a recent MTS/IEEE Oceans paper, a preliminary investigation of such models was made for several prototype UUVs, for both a fluxgate tensor gradiometer and a single-axis total field gradiometer. The total-field gradiometer is the most sensitive of the devices and was operated onboard an active Bluefin BPAUV UUV. The UUV was mounted on a three-axis motion table, and the results obtained were encouraging.**

**In the present paper, we apply a multi-reference sensor magnetic noise compensation algorithm to a single-axis total-field gradiometer operating in the environment of a completely redesigned Bluefin platform, the RELIANT UUV, again mounted on a three-axis motion table. This vehicle has a different configuration from that of the BPAUV, including a very different battery design.**

**We examine in detail the effect of the positioning and number of reference sensors, and show that these issues are critical to performance. We investigate the effect of the positioning of the magnetic sensor relative to other platform systems and find this to be an important issue. Finally we conclude that the performance of the sensor onboard the RELIANT platform using all available reference sensors is roughly the same as that demonstrated onboard the BPAUV.**

**Keywords: Magnetometer, gradiometer, UUV, noise, filters, mitigation, least-squares, SVD**

## I. BACKGROUND

The U. S. Navy, as well as the Navies of other countries, is increasingly looking toward Unmanned Underwater Vehicles (UUVs) to perform tasks in both shallow and deep water. These platforms will carry various types of sensors for the purpose of detection and localization of objects, particularly those buried in the sea bottom [1]. A sensor of particular interest for the detection of ferromagnetic (iron, steel) objects is the magnetometer. This device senses the distortion of the earth's large magnetic field caused by the magnetic polarization of the object. For operation on a platform that moves relative to the earth's magnetic field, special magnetometer types are chosen. In particular, a sensor that responds to the magnetic field total magnitude, known as a total-field sensor, is desirable because it is insensitive to rotations in the earth's main field.

Total-field sensors tend to be so sensitive that fluctuations in the ionospheric currents ringing the earth are an important and often disabling magnetic noise source. Ionospheric magnetic noise can be removed by operating the sensors in pairs, separated by some baseline distance, and subtracting their outputs. The device is then referred to as a magnetic total-field gradiometer. The separation baselines can be selected to be in three orthogonal directions, allowing the measurement of a total-field gradient vector. This quantity has important implications for the localization of magnetic targets [1]. The ionospheric magnetic field variations are spatially homogeneous at lower magnetic latitudes, and are removed by the gradient measurement. The tradeoff is that local sources, whose anomalous magnetic fields vary as the inverse third power of the range to target, have gradients that vary as the inverse fourth power of range. The tradeoff is addressed by creating sensors that have extremely low noise levels [2,3]. The U. S. Navy is actively engaged in research for the installation and operation of vector total-field gradiometers onboard UUVs [1].

## II. INTRODUCTION

In a previous OCEANS paper [4], we investigated the operation of a variety of sensors on a variety of prototype UUVs. For the purposes of this paper, we focus on the particular measurements involving the Polatomic P2000 total-field gradiometer and the BLUEFIN BPAUV UUV, and we compare these measurements to measurements made with the same sensor mounted on a completely redesigned vehicle, the BLUEFIN RELIANT UUV. For the BPAUV measurements, the motion table at the Coastal Systems Station, pictured with the BPAUV in Figure 1., was operated in an arbitrary fashion, with the table rotation frequencies changed frequently during the measurement run. This motion is seen in the raw gradient measurement plotted in Figure 2.

For the new measurements involving the RELIANT UUV, we investigated the actual motions observed by the onboard Inertial Navigation System during a programmed BPAUV run made in St. Andrews Bay off Panama City, Florida. The raw roll, pitch, and yaw data are shown in Figure 3. These data were parsed for the straight segments of the run, and the data were used to construct the roll, pitch and yaw amplitude spectra, shown in Figure 4.

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14. ABSTRACT

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Figure 1. P2000-BPAUV on motion table

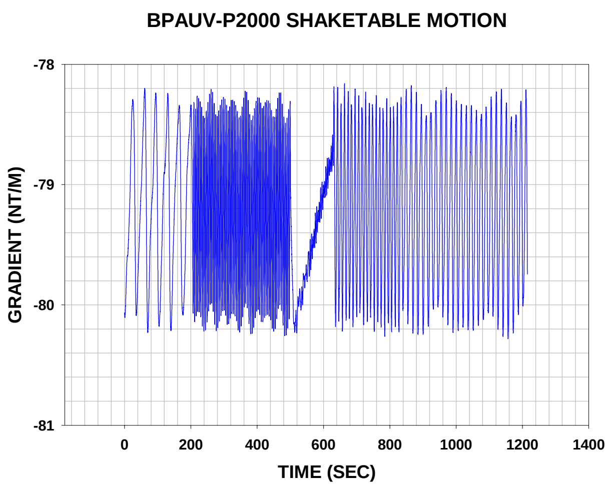


Figure 2. P2000-BPAUV raw gradient during motion

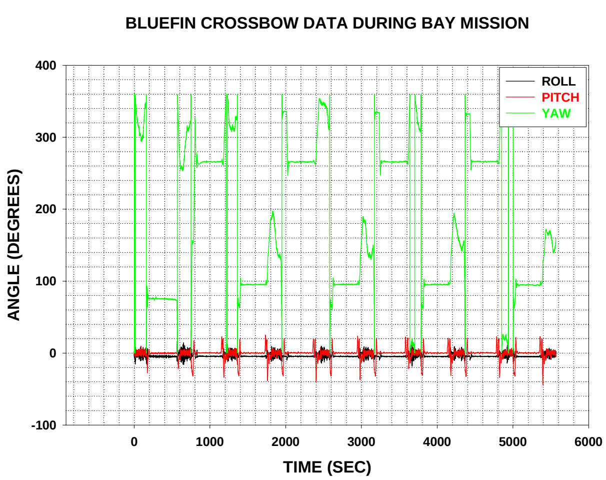


Figure 3. Mission roll, pitch and yaw

Based on these measurements, the roll, pitch and yaw settings for the motion table were 3, 10, and 10 seconds, respectively. The resulting raw gradient for the P2000-RELIANT run is shown in Figure 5.

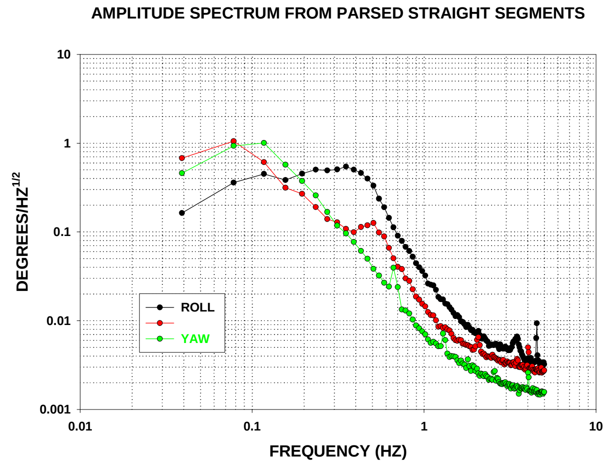


Figure 4. Roll, pitch and yaw amplitude spectra

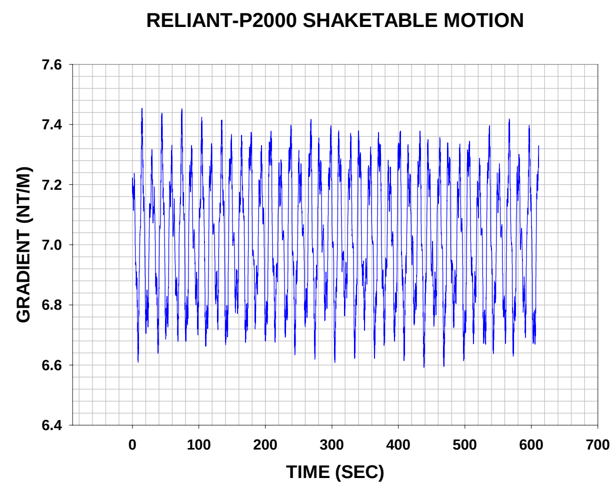


Figure 5. P2000-RELIANT raw gradient during motion

## III. P2000-RELIANT SETUP AND OPERATION

The setup for the P2000 and RELIANT vehicle on the motion table is shown in Figure 6. This arrangement is considerably different than that used by the BPAUV vehicle. The processor is now located in the much smaller spherical housing, and there are three banks of polymer batteries instead of two banks of lead-acid batteries. There are two three-axis magnetometers mounted near the articulated tail cone and ball screws, as shown in Figure 7. There is also an ammeter connected in series with the main battery circuit. The essential components are shown in schematic form in Figure 8.

For the data analyzed in this paper, the vehicle was programmed to move the rudder and elevator in a one-degree amplitude butterfly pattern while running the propulsion motor at 500 RPM. At the same time, the vehicle-sensor assembly underwent motions similar to Figure 5.

Figure 6. P2000 and RELIANT on motion table

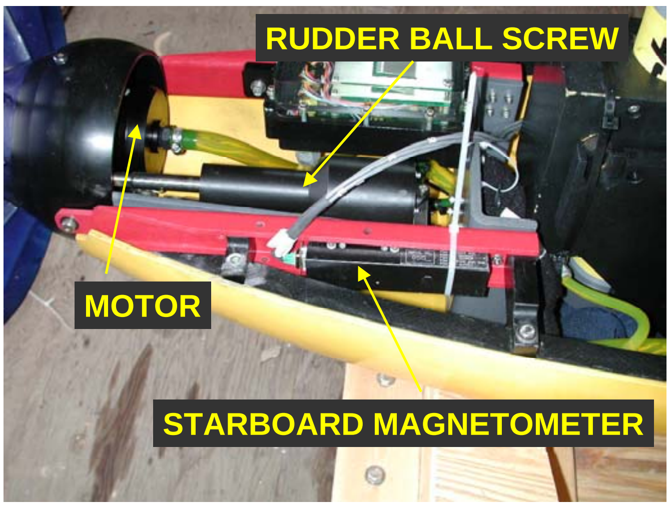


Figure 7. Reference magnetometer location

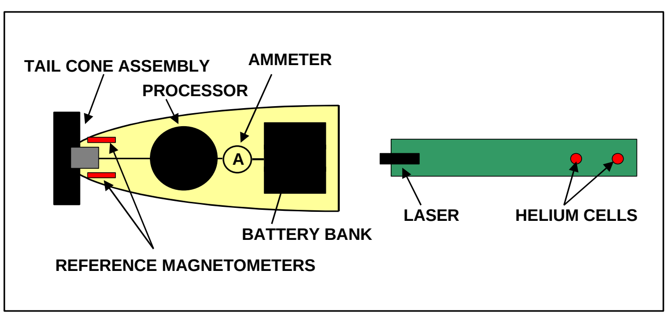


Figure 8. Schematic of vehicle-sensor layout

## IV. DATA COLLECTION

Mission data were collected in 10-minute runs. The P2000 was filtered at 70 hertz, sampled at 432 hertz and stored using the Polatomic data collection system. The magnetometer and current data were collected using a separate VXI system, filtered at 10 hertz and sampled at 27 hertz. The data were synchronized by means of a magnetic coil that was pulsed and seen by the P2000, and the coil current was recorded with the reference magnetometer data. The data were aligned in post processing using correlation, and all data were numerically filtered at five hertz prior to further analysis.

## V. FREQUENCY-DOMAIN FILTERING

The characterization of the platform noise and the analysis of noise reduction via the reference sensors were done in the frequency domain. The filter model is the same as that used previously [4], and is repeated here for convenience.

$$Y^i_{\text{comp}} = Y^i_{raw} - \sum_{j=1}^{N} H^i_j X^i_j \tag{5.1}$$

where $Y^{\text{i}}_{\text{raw}}$ is the measured sensor signal for each frequency $i$, $X^i_j$ and $H^i_j$ are the reference sensor signals and transfer functions for the $j^{\text{th}}$ reference, respectively, and the sum is over all $N$ reference sensor channels ($N$=7 in our case). The equation is applied repeatedly using the fourier transforms of overlapping time windows that have had means and trends removed, and a sufficient number of windows is used to create an over-determined system of equations at each frequency. These equations are solved by least-squares minimization using singular-value decomposition.

## VI. P2000-BPAUV AND P2000-RELIANT COMPARED

The P2000-RELIANT runs were 10 minutes in length, while the previous P2000-BPAUV runs were 20 minutes in length. In the following, we use 1024-point windows for the RELIANT data and 2048-point windows for the BPAUV data, giving different maximum frequency resolutions, but similar sample sizes. The resulting uncompensated and compensated amplitude spectra are shown in Figure 9.

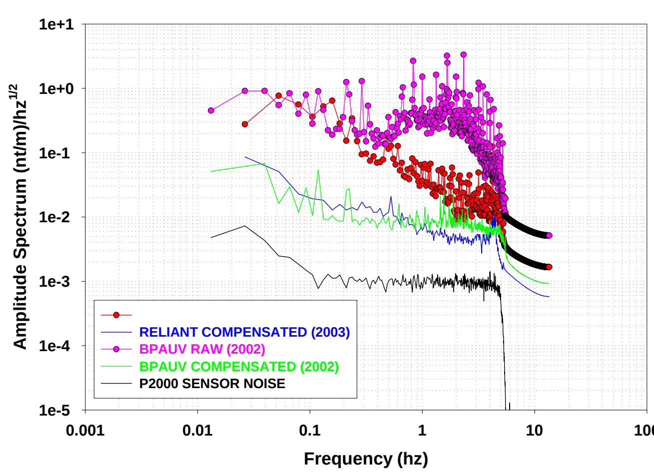


Figure 9. Raw and compensated amplitude spectra

We immediately see that the raw gradient noise above one hertz is much smaller for the RELIANT than that for the BPAUV, while the performance below one hertz is about the same. The reason for the difference is not yet understood. For the compensated gradient, the performance with RELIANT is about the same as that with BPAUV. This is somewhat of a surprise, because it was believed that the battery signature for the RELIANT would be lower than that for BPAUV. We also note that the low-frequency RELIANT compensated performance shows a smoother spectrum than that observed with BPAUV. We believe that this is due to both the difference in motion table operation, and the fact that RELIANT as used on the table was lighter than BPAUV.

## VII. REFERENCE SENSORS SUBSETS

To make an assessment of the importance of the reference sensors, we analyzed the data with the various references dropped from the model. In Figure 10, we show the effects of *dropping* any one of the three reference sensors, and in Figure 11, we show the effects of *keeping* only one of the three reference sensors.

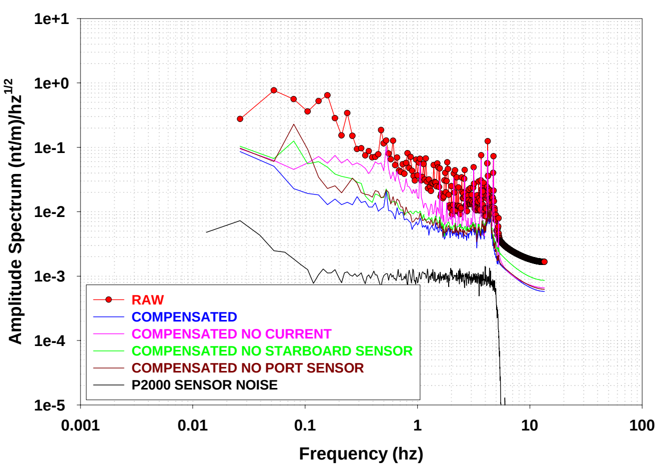


Figure 10. Removal of any one reference sensor

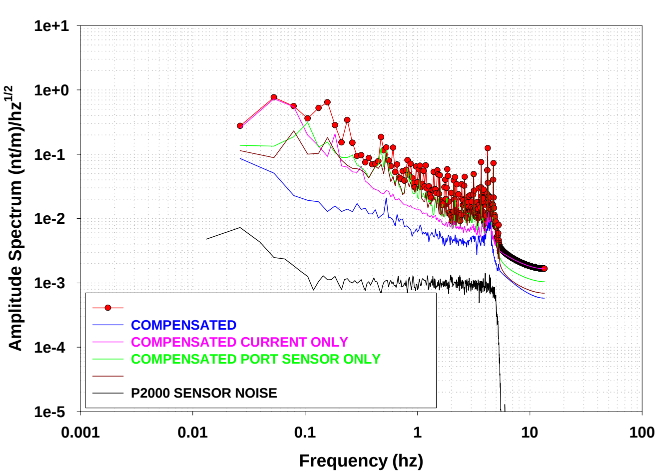


Figure 11. Retention of only one reference sensor

In Figure 10 we see that removal of the current sensor increases the noise level significantly except at the lowest frequency, while removal of one magnetometer predominantly affects the frequency range 0.1-0.4 hertz. These reductions in performance are all important, as we expect signal frequencies to be predominantly below one hertz.

Examination of Figure 11 shows that the use of only one of the reference sensors results in a performance loss of almost 20 dB over the frequency range of most interest. Multiple reference sensors are essential to performance.

## VIII. REFERENCE RELOCATION

We relocated the port magnetometer to a position adjacent to the spherical processor housing, but still relatively near to the tail cone area. The rearrangement is shown in Figure 12 and the result is shown in Figure 13.

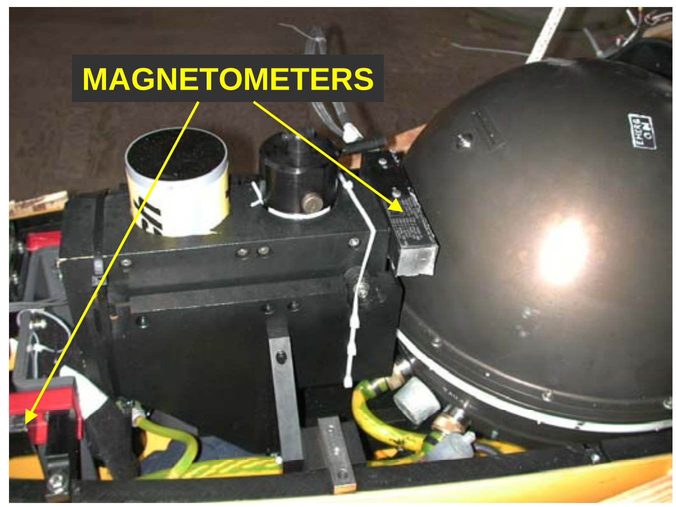


Figure 12. Port magnetometer relocation

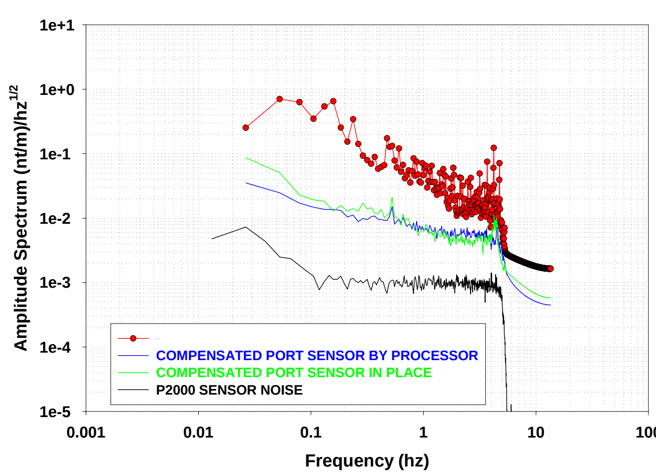


Figure 13. Residual for new magnetometer location

We see from Figure 13 that there is a slight improvement in the total-field gradiometer performance.

## IX. TOTAL-FIELD GRADIOMETER RELOCATION

In a final experiment, we placed the P2000 sensor in a reversed position in the cradle, as shown in Figure 14, and, schematically in Figure 15. The resulting spectra are shown in Figure 16.

Figure 14. P2000 reversed in cradle

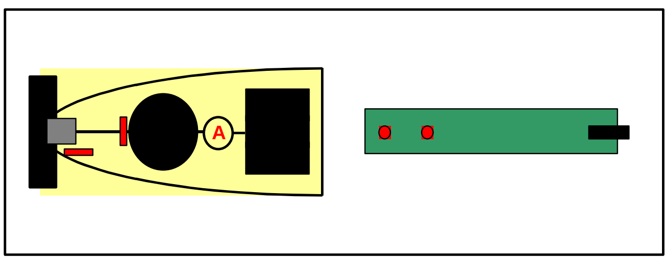


Figure 15. Schematic view corresponding to Figure 14

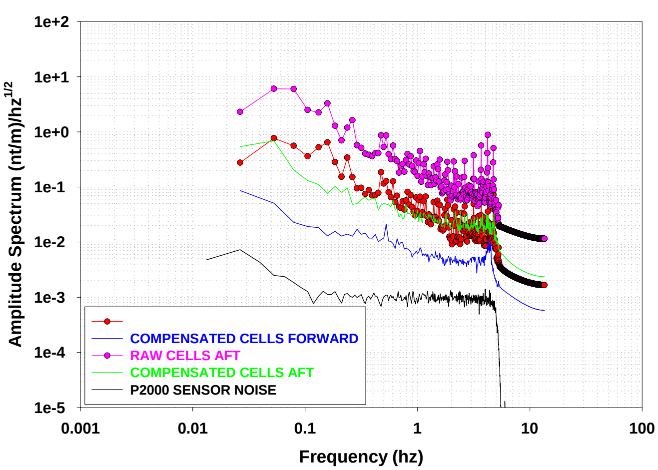


Figure 16. Two sensor positions compared

The reversal of the P2000 in its cradle moves the center of the gradiometer from about 4.5 feet forward of the batteries to about 1.5 feet forward of the batteries, or a reduction in distance by about a factor of 3. Inspection of the spectra in Figure 16 shows that the compensated amplitude spectrum is roughly 8-10 times larger for the reversed geometry. If the noise source were a point dipole at the face of the batteries, we would expect the gradient to increase by $3^4$=81. This means that the actual sources are distributed, and located further to the rear of the platform. What we conclude here is that placing the sensor well forward of the active components is crucial to performance, and in some applications, it might be worthwhile to use an especially long extended vehicle to push sensor performance closer to its ultimate level.

## X. CONCLUSIONS

We have established that multiple reference sensors at multiple locations are essential for the mitigation of magnetic noise on active, moving platforms. The results obtained here suggest that experiments with additional reference sensors at additional locations might be useful. We intend to perform such measurements in the future.

The result obtained by repositioning the total field gradiometer provides valuable guidance for systems under design. There is a continuing conflict between the magnetic sensor users (further is better) and the vehicle designers (shorter is better).

The best result obtained in the present experiment is a sensor noise floor of 18-24 dB above intrinsic sensor noise in the 0.1-1.0 hertz range. As large as this seems, it is 20+ dB better than the best noise level we have obtained with fluxgate tensor gradiometers.

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