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# An Analysis of Airship Acceleration Dynamics for Airborne Gravimetry

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# **An Analysis of Airship acceleration dynamics for airborne gravimetry**

## **Abstract**

A Honeywell three-axis inertial accelerometer was placed on board an Skyship 600B and acceleration data was recorded during a flight. Weather conditions during the flight were windy and turbulent, considered to be near the upper limits of this airship's operational envelope. Power spectra were computed from the acceleration data and showed favorable fall-off at high frequencies, but high power at low frequencies, as compared to a large, multi-engine aircraft used for gravity surveying. The vertical component of the airship accelerations was used as the driving input to model the response of a mechanical, "zero-length spring" style gravimeter. The model shows that the meter would exceed its dynamic limits if it experienced the accelerations recorded on the airship. However, one commercially available gravimeter, the Bell BGM-5, has sufficient dynamic range to operate under these conditions.

## **Introduction**

Airborne gravity measurement has been carried out on a variety of platform vehicles: on helicopters and small and large fixed wing aircraft [Bell at al, 1993; Brozena, 1984; Carson Helicopters, Inc, 1980] These platforms each have advantages and disadvantages for airborne gravimetry. Small aircraft and helicopters can have limited range and small space or limited electrical power for equipment. Larger fixed-wing aircraft have more space, power and a longer range, but as a result of their higher speeds, the noise-reducing filters required for dynamic gravimetry do not give good short wavelength resolution. It has been suggested that airships might be a good platform for airborne gravimetry. The immediately apparent advantages to using an airship are the platform size and carrying capacity, and slower speed (which yields better wavelength resolution). In an effort to investigate the suitability of airships as platforms for airborne gravimetry, in January 2003, the Naval Research Laboratory (NRL) code 7420 installed a Honeywell three axis 986-0035 TRIAX accelerometer on board an Skyship 600B airship, the "Santos Dumont" tail #N606SA. In-flight accelerations of the airship were measured on January 10, 2003, during a 3.5 hour round trip flight from Elizabeth City, North Carolina. Weather conditions during the flight were windy and turbulent, considered to be near the upper limits of this airship's operational envelope, with a maximum sustained wind speed of 15 knots. During the flight, Global Positioning System (GPS) fixes were recorded, and accelerometer data, at 100 Hz, from all 3 axes were recorded from 15:50 UTC to 18:46 UTC.

## **Data processing**

The GPS position fixes were extracted from the GPGGA records of the GPS receiver output (NMEA format). These positions were plotted using the



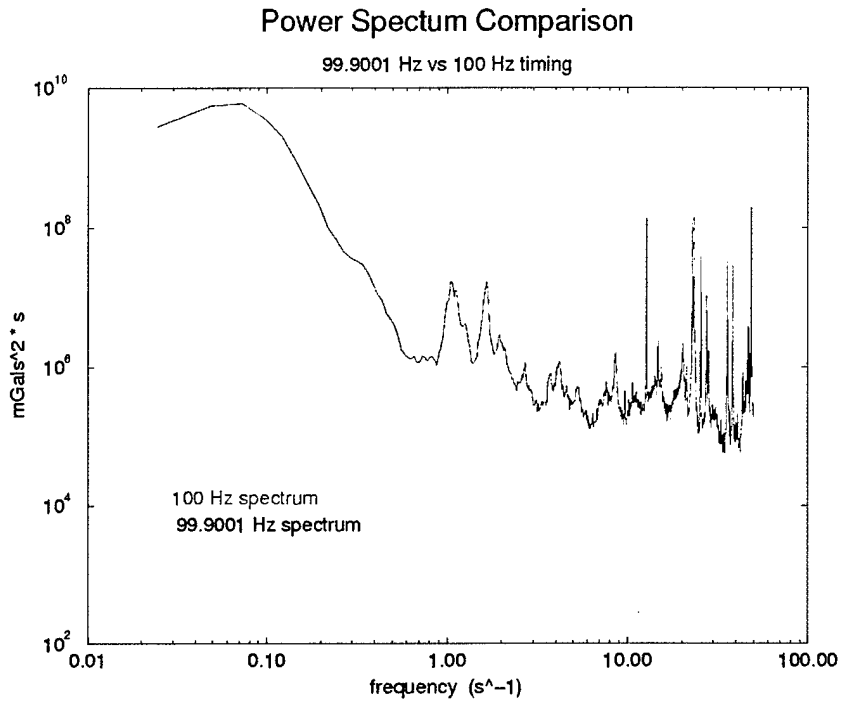


Figure 2: Power spectra comparison, 99.9 Hz vs. 100 Hz

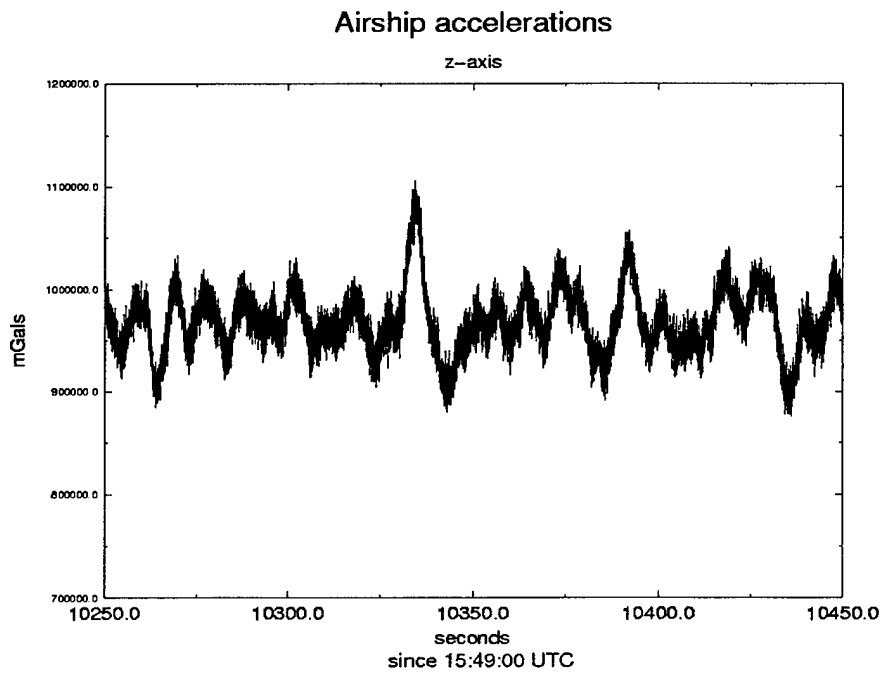


Figure 3: Vertical accelerations (z-axis) from a section of track 3

# Airship -2003 Power spectrum

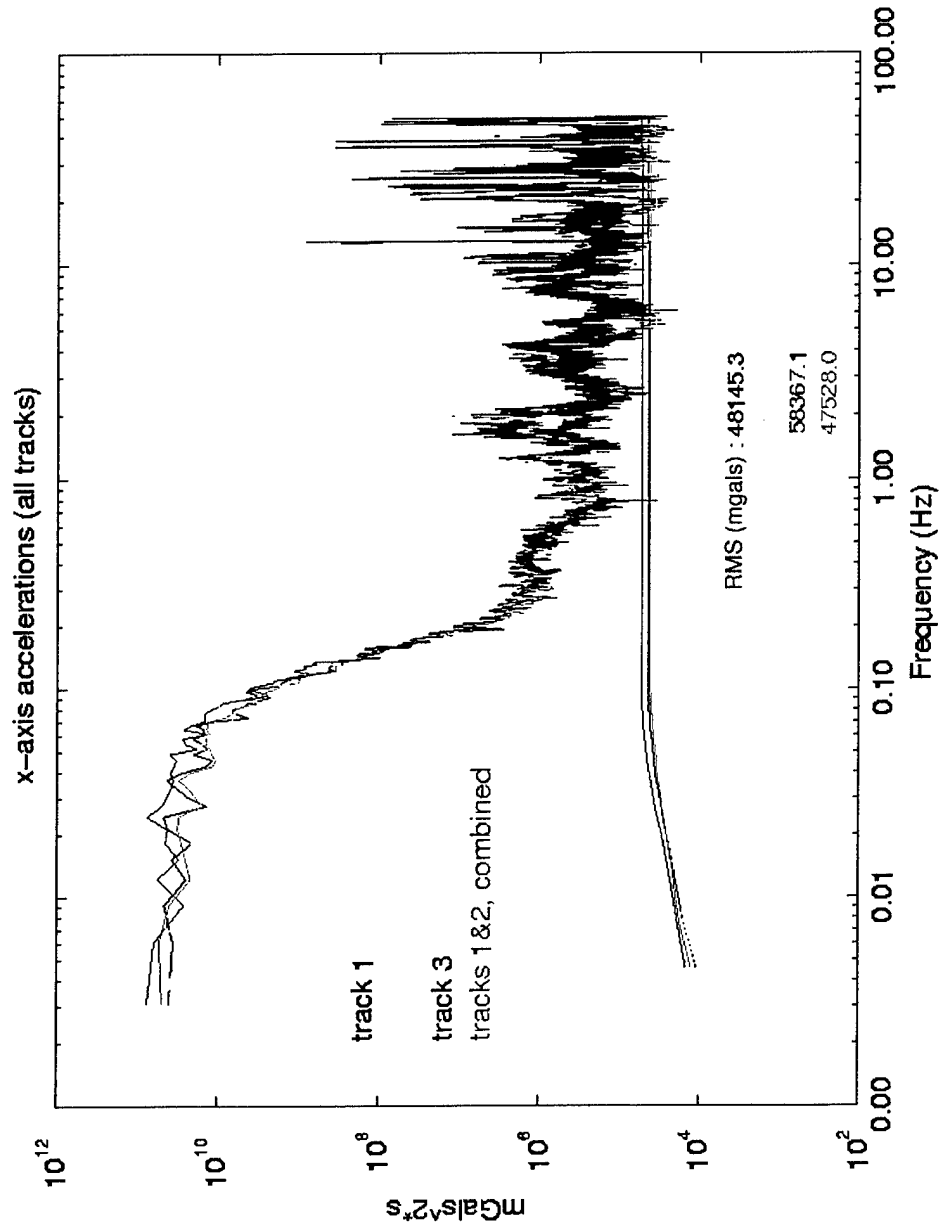


Figure 4: x-axis acceleration power spectra from airship tracks.

# Airship – 2003 Power spectrum

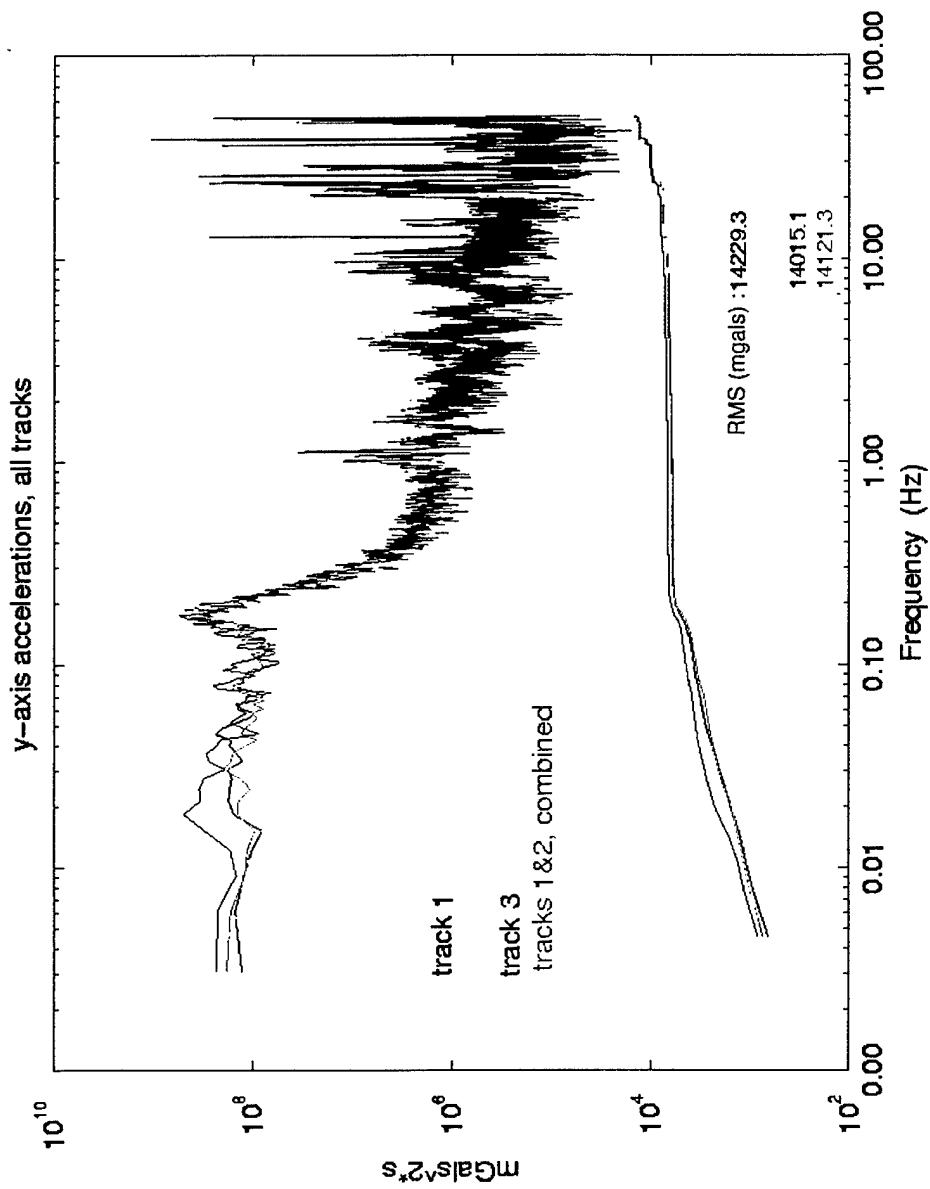


Figure 5: y-axis acceleration power spectra from airship tracks

# Airship – 2003 Power spectrum

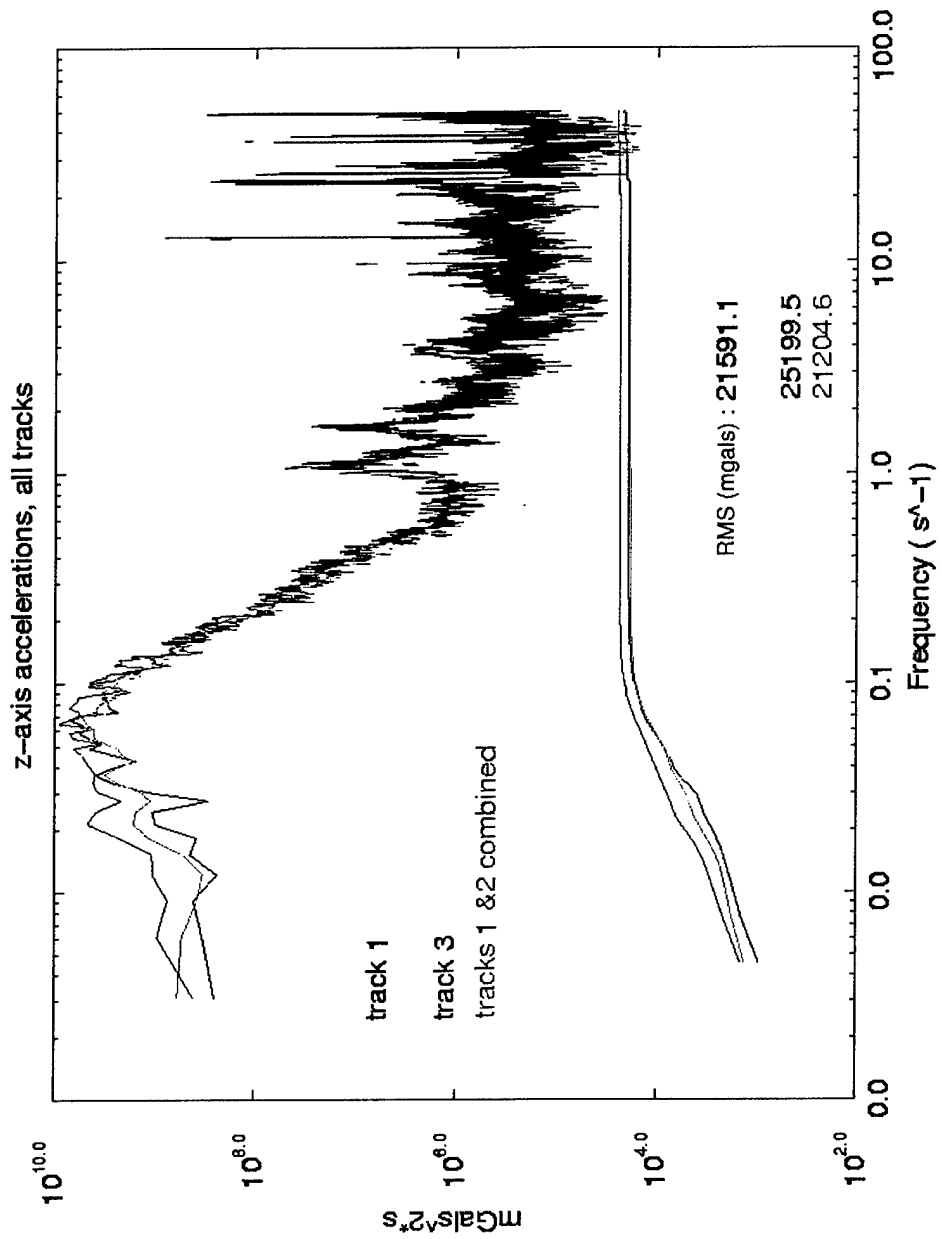


Figure 6: z-axis acceleration power spectra from airship tracks.

## **Spectral Analysis**

For each of the tracks (1,1a,2,and 3) the spectrum1d routine in the GMT package was used to compute spectral density estimates by ensemble averaging of multiple overlapping windows. The windows were 32768 points long (approximately 328 seconds at 100 Hz) and spectra were computed for the x, y and z-axis accelerations, as shown in Figures 3,4, and 5, along with the square root of integrated power (the root mean square) for each track and axis.

For comparison, four long flight-tracks of open-water radar altimetry data from the NRL SST airborne experiment in 2000 over the Gulf of Mexico were analyzed. The aircraft flown was one of NRL's research P-3, the radar altimeter was built at NRL [Brozena et al., 1986]. As part of the survey gravity processing, the altitude time series had been splined, filtered and twice numerically differentiated to give a 2Hz vertical acceleration time series. The response function for the filter employed is shown in Figure 7. Power spectral density estimates were obtained using GMT's spectrum1d script using 1024 point windows. Figure 8 shows the power spectra for the vertical accelerations of the four tracks, and the integrated power. The effects of the gravimetry processing filter can be seen by the steep roll-off commencing at 0.25 Hz (4 seconds or 520 meters at typical P-3 speed). Figure 9 shows that by 0.2 Hz the airship vertical acceleration power spectrum is already well below the P-3 spectrum, indicating that the pass band for a processing filter for gravimetry on an airship could be moved to include higher frequencies. But even the filter designed for gravimetry processing from a P-3 survey would begin to cut-off at just 36 meters ( 0.25 Hz or 4 seconds at airship speed of approximately 9 m/s). At low frequency, however, it is apparent that the airship has much more power than the P-3: it is subject to greater, long trending accelerations. What is a gravity meter's response to this low frequency, high power, acceleration?

## **Meter modeling**

While NRL has used a variety of gravity meters for airborne gravimetry, most of our experience has been with highly over-damped mechanical spring-type accelerometer sensors such as the LaCoste & Romberg model S meter. The S meter is a relative gravity meter, measuring changes in acceleration from a known reference, and the sensor is mounted on a stabilized platform designed to keep it nearly level and oriented to measure in the z-axis. The dynamic range of a model S meter has 3 components: long period changes of up to 12000 mGals are compensated by varying spring tension, which the control system adjusts to null the beam position supported by the spring tension. Shorter period acceleration are proportional to the velocity of the beam, and the

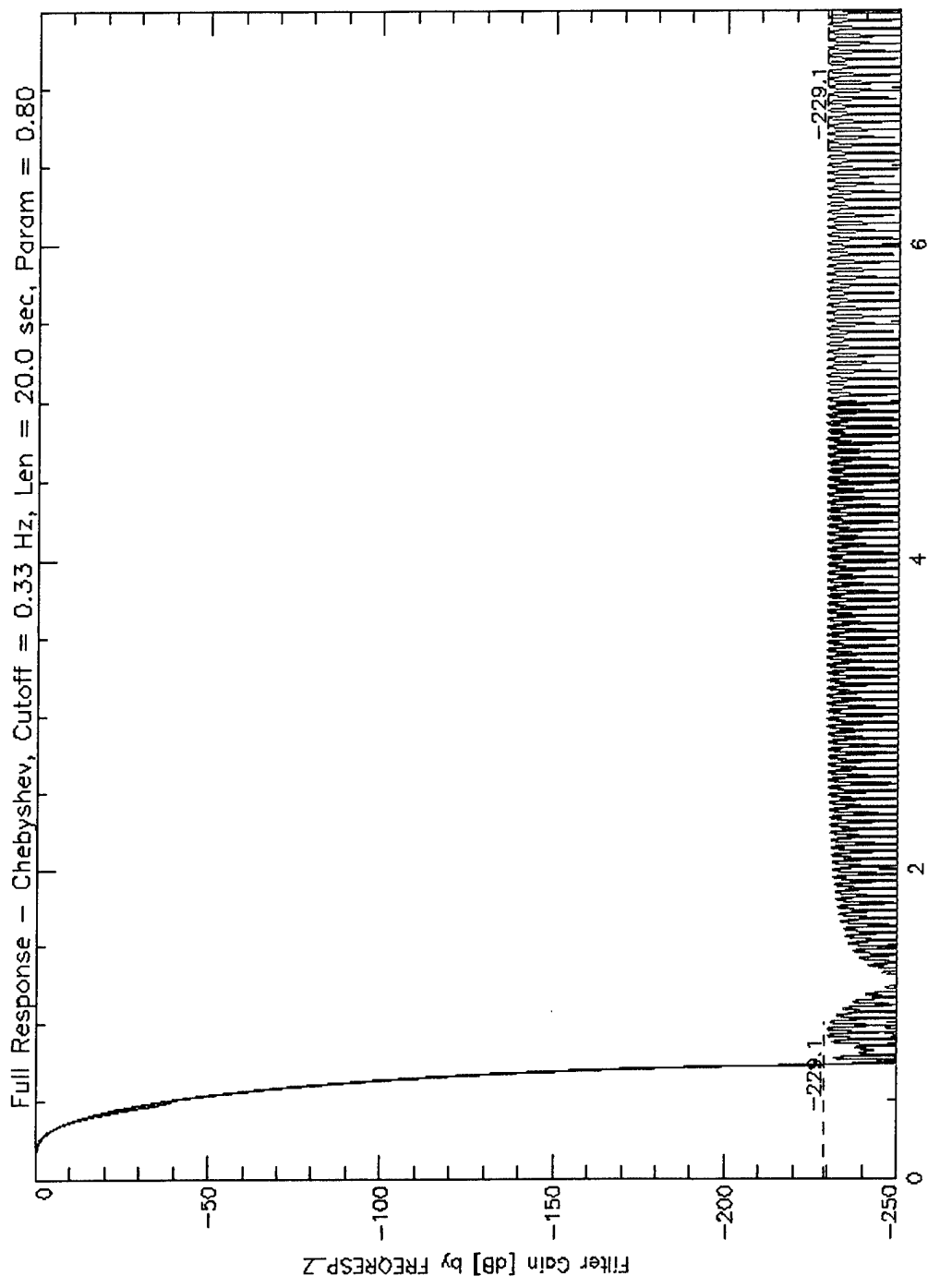


Figure 7: radar altimetry processing filter response

### P3: power spectra and integrated power

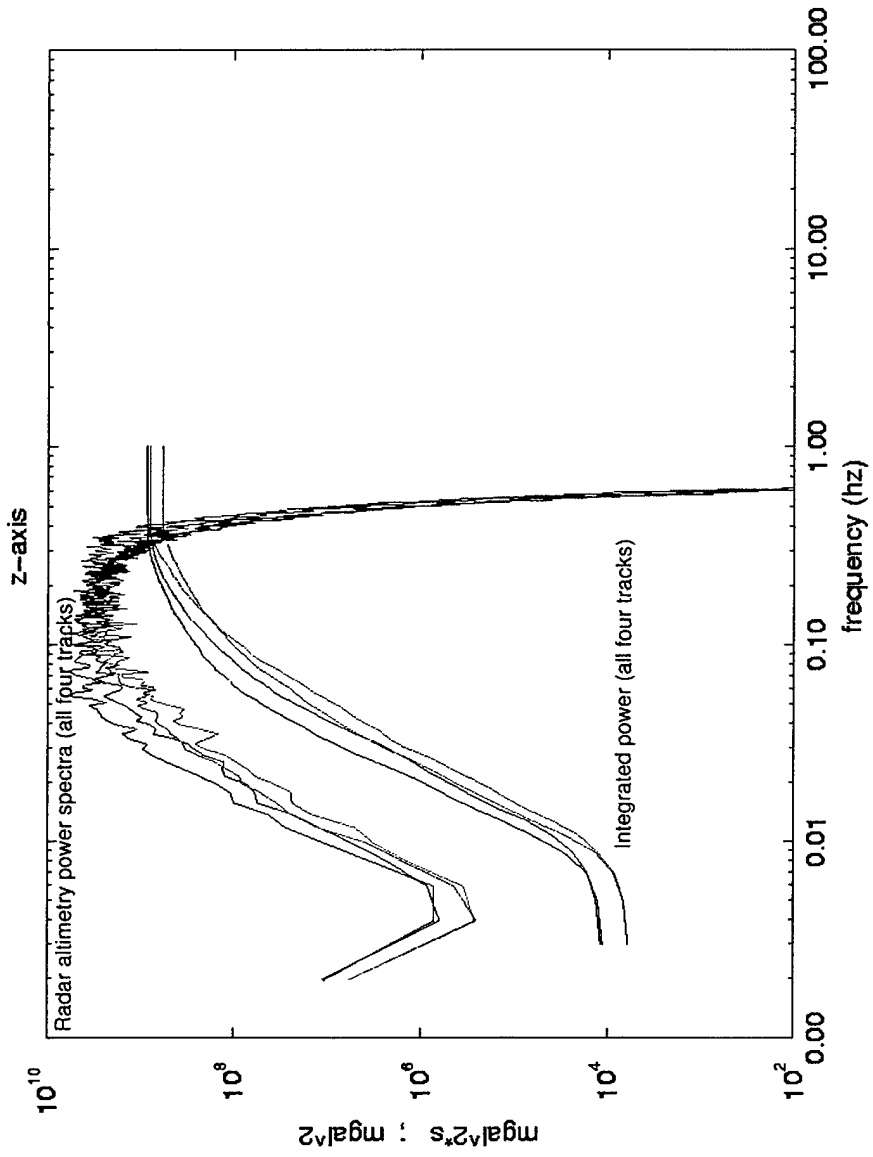


Figure 8: Power spectra from four tracks of radar altimetry flown on a P-3

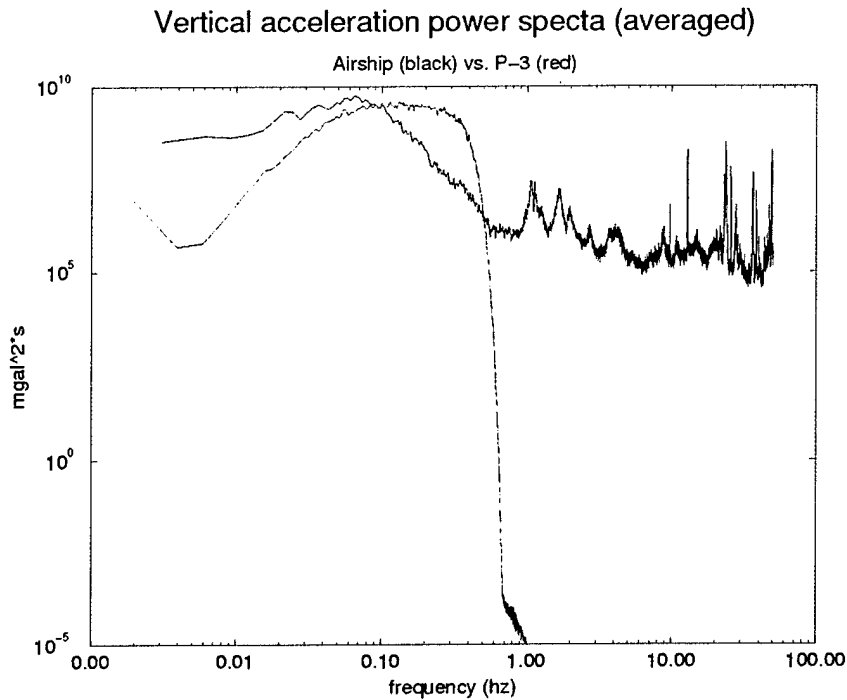


Figure 9: Comparison of Airship and P-3 z-axis acceleration power spectra

shortest period accelerations are (mostly) eliminated by air dampers attached to the beam. The sensed acceleration is

$$\text{acceleration} = \text{spring tension} + k \cdot d \frac{(\text{beam position})}{dt} + \text{cross coupling}$$

where k is a scale factor. Since an increased acceleration of 1 mGal corresponds to a -2 mVolt/min change in beam position,  $k = -1./30000$ . when working in mGals and volts. The cross coupling term is an error term and small (< 2 mGals usually for aircraft measurements) so it will be ignored.

The limiting range of the beam on the meter corresponds to the limits -10V to +10 V on the A-to-D; and the rate of spring tension change in the control system is limited to about 9 mGals/second. The spring tension control loop issues a new set level every second, and the meter recording system samples the spring tension every 10 seconds. A first, simple model then is to ignore the spring tension, which is reasonable for very short periods of time.

$$\text{acceleration} = k \cdot d \frac{(\text{beam position})}{dt} \quad \text{or}$$

$$\text{beam position} = 1/k \int \text{acceleration} + C$$

Assuming the meter starts with the beam in the null position,  $C=0$ . Therefore, gravity meter beam position can be modeled as the scaled integral of the airship vertical acceleration, or, incorporating the time series data rate (100 Hz = 0.01 s)

$$\text{beam position}(T) = -1/30000 \cdot (0.01) \sum_{t=0}^T \text{acceleration}(t)$$

to see if this exceeds the physical limits of the beam.

The z-axis accelerations shown in Figure 10, from track 3, were chosen to represent a short period "worst case" for the meter. Assuming an initial beam position corresponding to 0 Volts, then the resulting model beam position for this acceleration series is also shown in figure 10. The beam would stay in limits, if it had started out null. But for longer periods, it is clear that the effect of the spring must be considered, as can be seen in figure 11, which shows what the beam position, for this overly simple model, would be for an entire track.

To keep the beam within limits, the meter must adjust the spring tension as the measured acceleration changes. Since

$$\text{acceleration} = \text{spring tension} + -1/30000 \frac{d}{dt}(\text{beam position})$$

$$\text{spring tension} \sim 1/30000 \frac{d}{dt}(\text{beam position})$$

and so, adjusting the spring tension setting changes beam velocity, and consequently, over time, the beam position.

The control loop of an S meter adjusts the spring tension at fixed time intervals to null the beam (position and velocity) and thereby compensate for (some) long period changes in acceleration. The change in spring tension is determined by both beam position, and beam velocity, with the limitation that the change cannot be greater than the maximum motor speed of 9 mGals/sec. The S-type gravity meter control software calculates an incremental adjustment to the spring tension:

$$\text{adjust} = \text{scale}_{\text{restore}} \cdot \text{position} + \text{scale}_{\text{damp}} \cdot \text{velocity}$$

where the position restorative scale and velocity damping scale factors are meter dependent. Sample values for two such meters, S93 and S34 are:

	restore (position in mVolts)	damp
S34	-0.005	-0.06
S93	-0.0105	-0.07455

In practice, a value of about 90% of the maximum motor speed, or 8 mGals/s, is used to limit spring tension adjustments, so that the magnitude of the

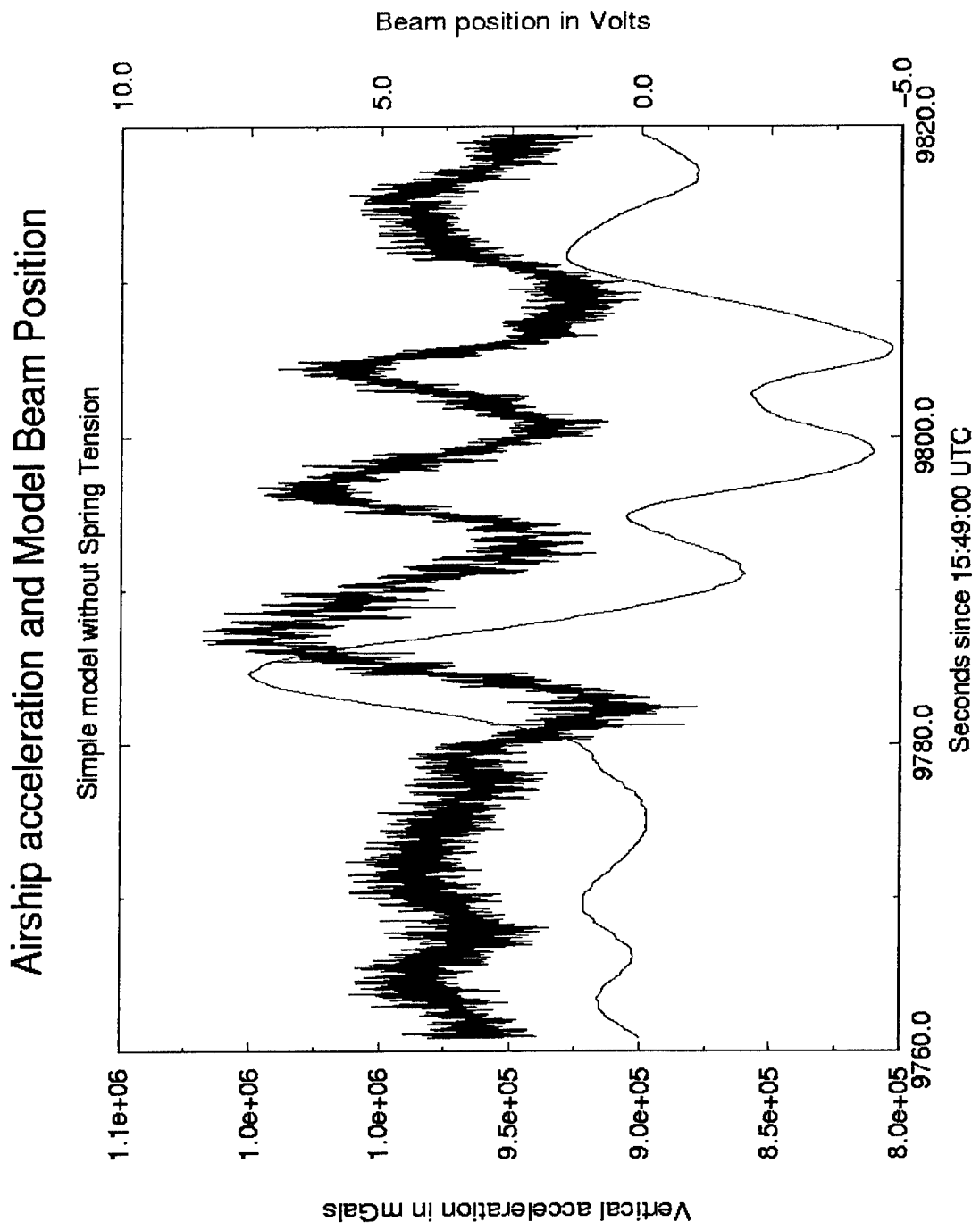


Figure 10: a sample section of vertical acceleration data from track 3 and the resulting simple beam position model

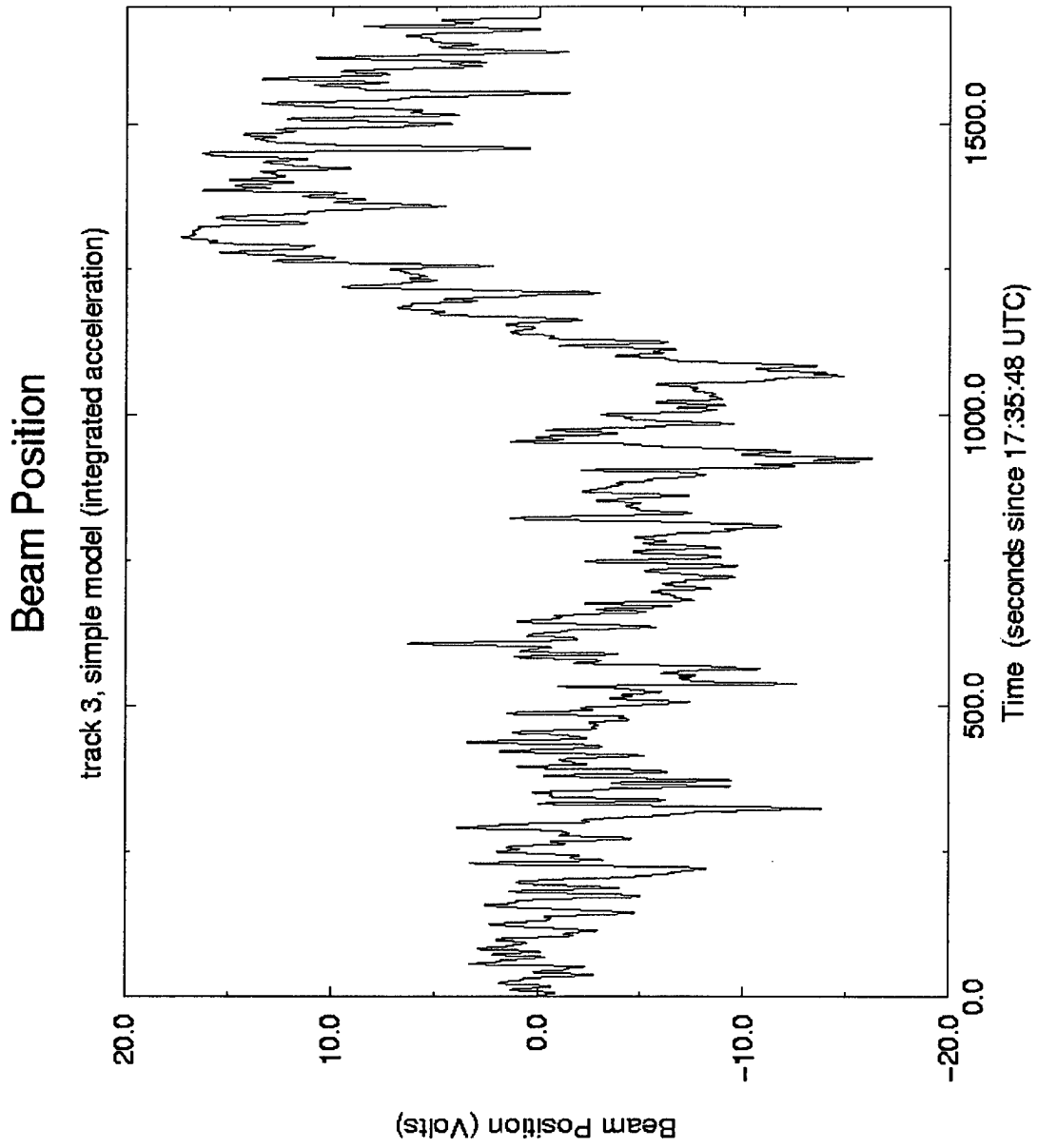


Figure 11: Simple (integrated acceleration) model beam position for entire track 3

adjustment is capped at  $8 \cdot \text{control increment}$ , the control increment being measured in seconds. Software was written to emulate the spring tension control system, taking as input a z-axis acceleration time series, a time spacing or rate, and restoring and damping scales. The 100Hz airship vertical accelerations were averaged and decimated to produce a 10Hz series that was used as accelerations in the model. The initial beam position and velocity were set to 0, as was the initial model spring tension.

$$\text{position}(0) = 0, \text{velocity}(0) = 0, \text{spring tension}(0) = 0 .$$

Then, at each epoch (0.1 s), velocity was set to vertical acceleration minus the current spring tension, and the position was set to the last position plus the scaled multiple of velocity with the epoch time interval.

$$\begin{aligned} \text{velocity}(i) &= z \text{ acceleration}(i) - \text{spring tension}(i) \\ \text{position}(i+1) &= \text{position}(i) + dt \cdot (\text{velocity}(i) + \text{velocity}(i+1))/2 \end{aligned}$$

The spring tension is adjusted using

$$\begin{aligned} \text{spring tension}(i+1) &= \text{spring tension}(i) + \text{adjustment} \quad \text{if } i \equiv 0 \text{ mod } 10 \\ &= \text{spring tension}(i) \quad , \text{ otherwise} \end{aligned}$$

so that spring tension is adjusted every second (10 epochs). The adjustment was calculated by

$$\text{adjustment} = \text{scale}_{\text{restore}} \cdot (\text{average recent position}) + \text{scale}_{\text{damping}} \cdot (\text{smoothed velocity})$$

with the provision that if the calculation was larger in magnitude than 8 mGals, then the adjustment would be set to +/- 8 mGals. The average position is the average over the previous second, and 3 minutes of past velocities were filtered. Finally, the model beam position was calculated as

$$\text{model beam position} = -1/30000 \cdot \int (z \text{ acceleration} - \text{spring tension}) dt$$

and both the beam position and spring tension were compared to the physical limits of real meters. In particular, beam position should stay in the range -10 V to 10 V and the physical range of the spring tension is limited to 12000 mGals.

Several modeling runs were made with this software using the accelerations from the airship tracks as well as different damping and restoring parameters. The results for tracks 1 and 2, combined, are shown graphically in figure 12 which clearly demonstrates that given the limits on the speed of the spring tension motors, the beam could not be kept within the physical limits of an operative S-type meter during the weather conditions of the test flight. As an experiment, the model was run with an increased motor speed limit of 40 mGal/s, and consequently increased limits on the size of the spring tension adjustment, with the results shown in figure 13. Here also, the beam was not kept within physical limits, even though the spring tension changes come close to exceeding the physical limits of such meters.

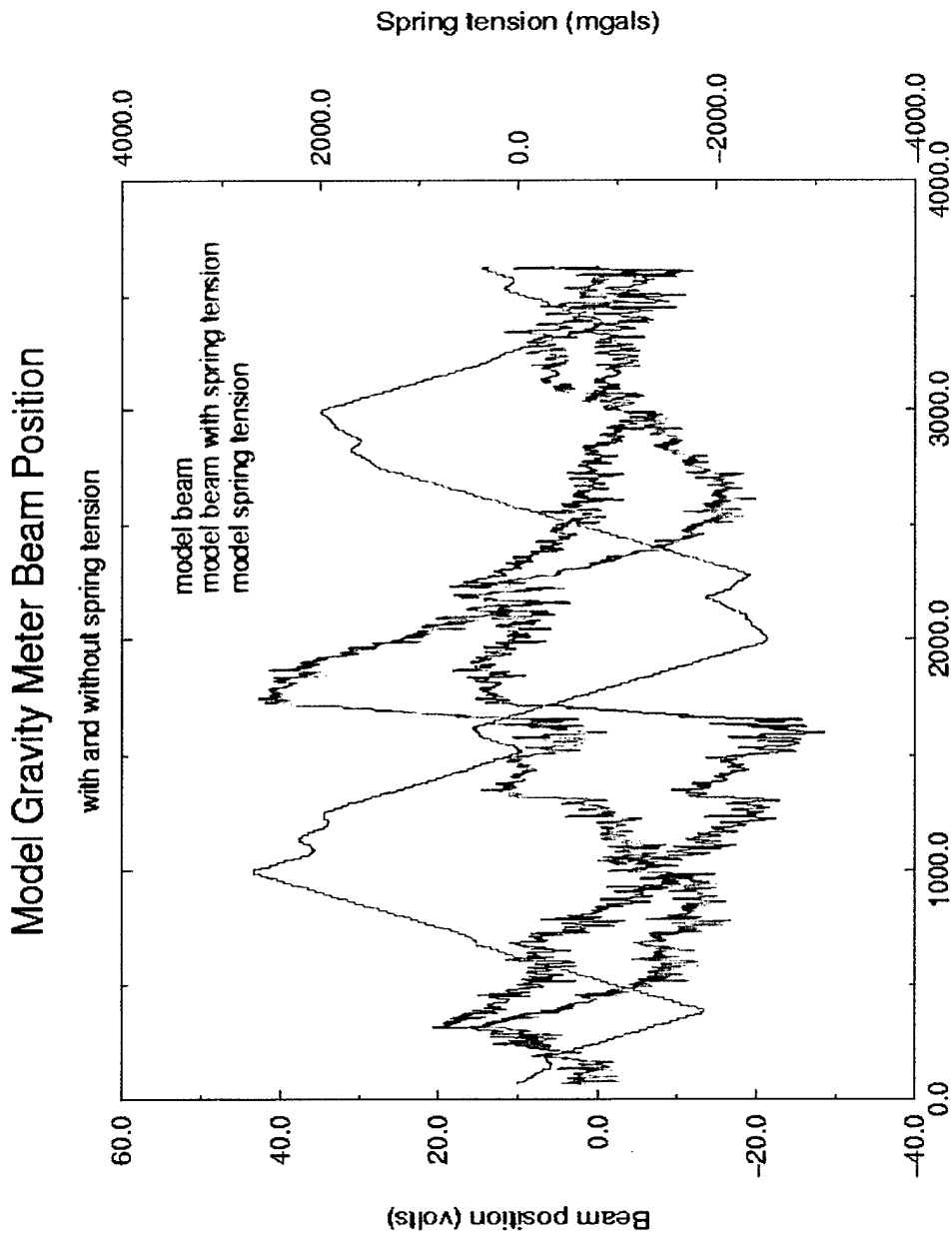


Figure 12: Beam position model for tracks 1 and 2 combined, assuming a spring tension change rate of 8 mGal/s. The damping (beam velocity) and restorative (beam position) coefficients used were from gravity meter S34.

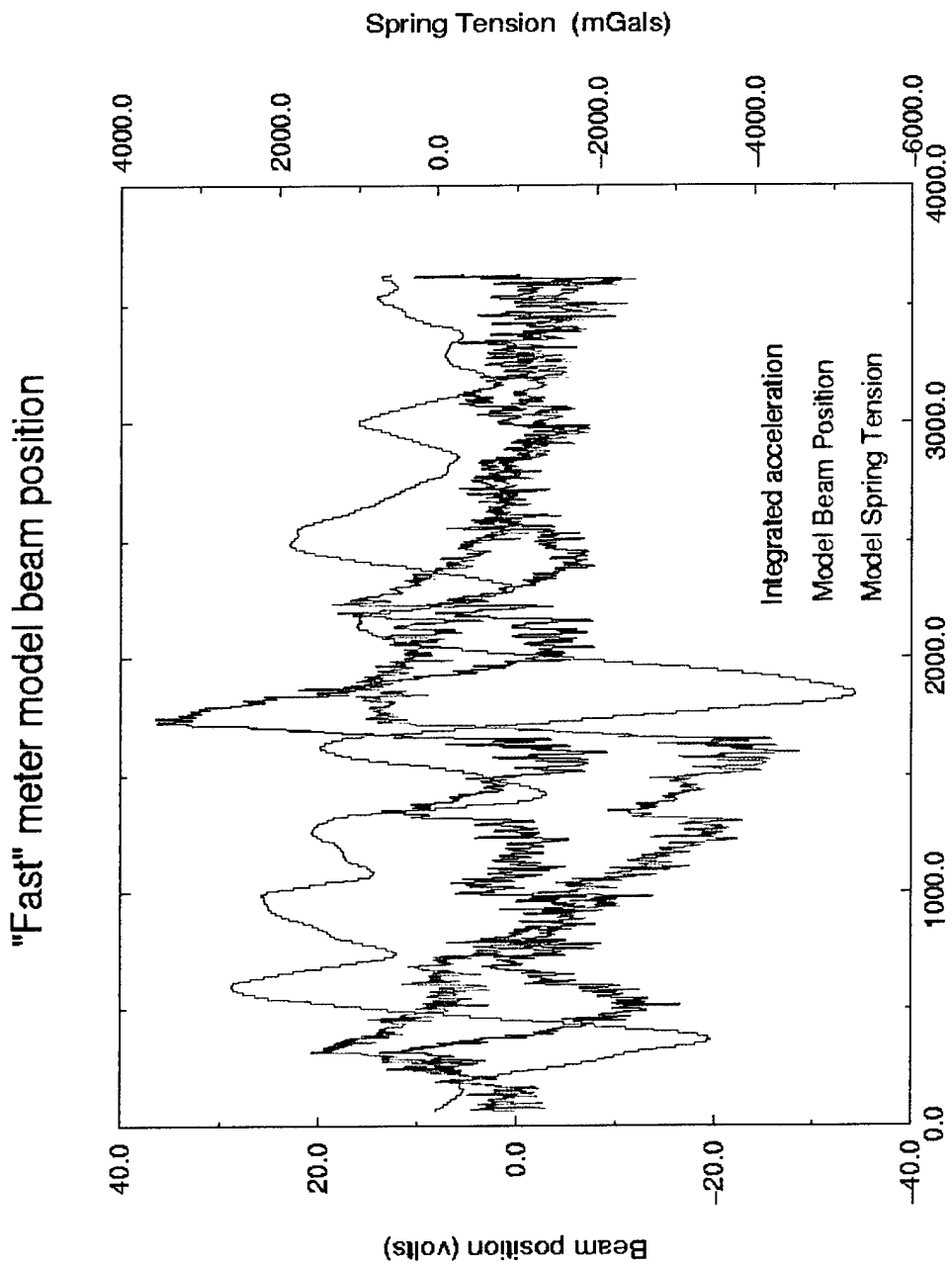
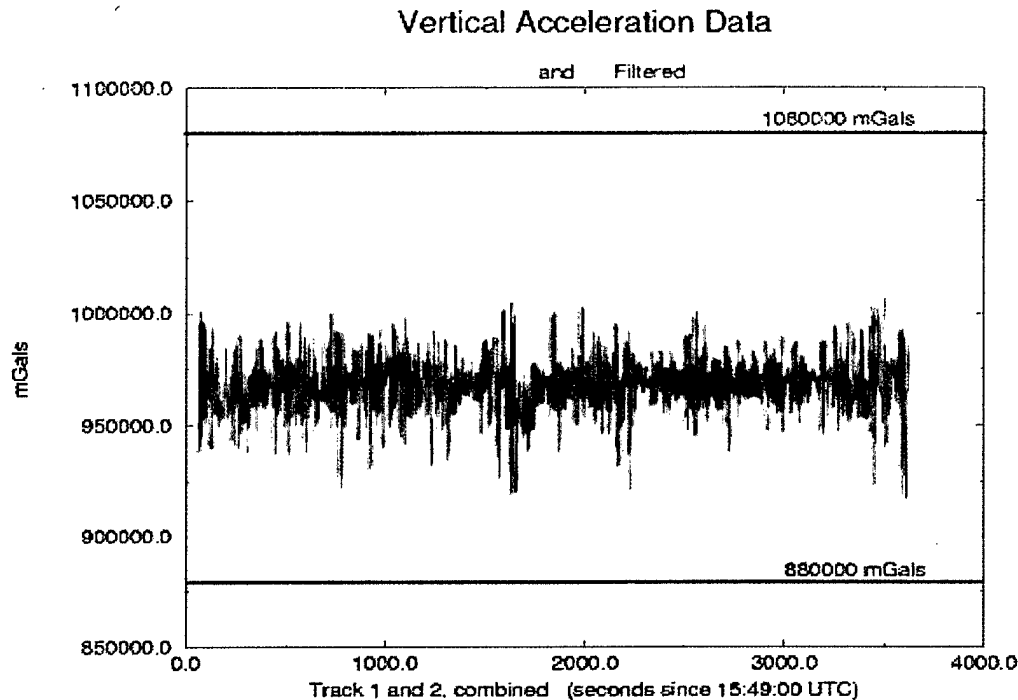


Figure 13: Beam position model, for tracks 1 and 2 combined, assuming "fast" spring tension motors (up to 40 mGal/s).



*Figure 14: Measured Vertical accelerations from outbound (tracks 1 and 2) and inbound leg (track 3) of flight. Filtered accelerations are super-imposed (red) on the raw measurements.*

The S-meter design is not the only commercially available meter design. Bell Aerospace has built meters that measure changes in acceleration based on changes in electric current required to generate a sufficiently strong magnetic field to stabilize a charged proof mass. The Bell BGM-5 uses such a design and has a reported sustained dynamic range of plus and minus 0.10 G, or approximately  $\pm 100,000$  mGals [R. Herr, NAVOCEANO; personal communication, 2003]. To quickly assess the suitability of such meters for use on airships, the measured airship accelerations were plotted versus time. Since the BGM-5 has an internal resistance/capacitance (RC) filter with time constant 3 seconds, the acceleration data was also digitally filtered with a digital implementation of an RC filter. The plots in Figure 14 show how the airship accelerations compare to the limits of 880,000 and 1,080,000 mgals, which nominally 0.9 G and 1.1 G (using  $1G = 980,000$  mGals). These graphs suggest that the BGM-5 is dynamically suited to use on airships.

## Conclusion

The modeling we have done using the airship acceleration data from January 2003 shows that, for these relatively extreme weather conditions, a mechanical spring-type gravity meter would exceed its mechanical limits of travel if employed on board the airship. This would be true even if unrealistically fast motors could be used to adjust the spring tension. However, meters of different design have dramatically different dynamic

responses and ranges, which should be investigated. This would include meters like the Bell BGM-5, which has a sustained dynamic range of +/- 0.1 G.

### **Acknowledgments**

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