GBT MEMO 159

DYNAMIC TESTS ON THE GBT

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Abstract. A means of applying a force of variable amplitude and frequency to a large structure such as the GBT is described. A simple hydraulic servo-mechanism positions a mass in accordance with an electronic command signal, and the resulting reaction force is applied to the structure of interest. The mechanism may have application in the future for damping out vibration in crucial areas of the GBT, but here it is used to excite the structure and to permit measurements on the existing alidade structure of the two principal modes of oscillation and the structural damping associated with these modes.

I. INTRODUCTION

GBT Memorandum No. 133 outlined a method of minimizing a possible problem with vibration in the GBT arm. In that memorandum it was proposed that a moveable mass situated in the vicinity of the receiver room and driven from a device such as a quadrant detector could be used to increase the damping of any oscillation. We have constructed a prototype device based on the design outlined in that memorandum and installed it on the GBT. Very similar hydraulic devices are used to damp out vibrations in tall buildings, and the technology used is mature and easy to apply. Most of the parts used in the system described here are over twenty years old and were purchased to demonstrate the feasibility of building the nutating subreflector for the 140-Foot Telescope.

II. THE MECHANISM

A block diagram of the "shaker" is shown in Figure 1. A 1200-lb. mass mounted on linear bearings is able to slide along two parallel shafts attached to a stationary frame. The mass may be positioned in its permitted direction of motion by a hydraulic cylinder, the shaft of which is attached to the mass via an electronic strain gauge. The position and velocity of the mass are measured by means of transducers which produce bi-directional DC output signals proportional to position and velocity. Electronic circuitry compares the actual position of the mass, as represented by the voltage output of the position transducer, with a voltage corresponding to the desired position. This error voltage is used to drive a spool servo valve that directs hydraulic fluid to the cylinder so as to cause movement to reduce the position error to zero. A hydraulic power supply supplies the necessary flow of fluid—10 gallons per minute at a pressure of 3000 psi. Spool servo valves have fast response times—many tens of Hz—and there is no difficulty in making a loop such as this with a bandwidth of 5 Hz.

The range of movement of the mass was arranged to be approximately ± 2 inches, and the maximum frequency of operation to be 5 Hz, although the two cannot be realised simultaneously.

The input to the position loop is a voltage with a scale of about one inch per volt, so the mass may be positioned conveniently by connecting the position command to a low-frequency signal generator thus giving independent control over amplitude and frequency.

The electronic strain gauge was used only in the early stages of testing to verify the forces that had been calculated. These proved to be correct, and the strain gauge was not used further.

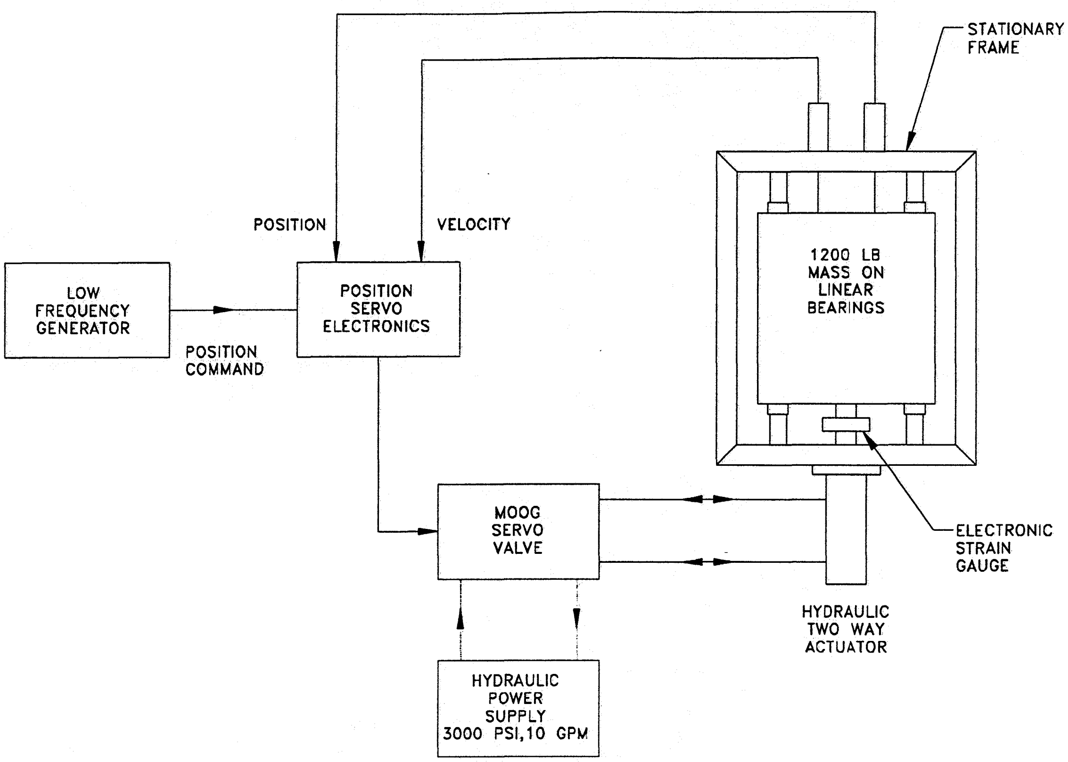

Figure 1. Block diagram of the "shaker".

For a fixed displacement, the maximum force goes as the square of the operating frequency. The maximum force rating of the various components is 3000 lbs.; the mechanism can apply a force of around 500 lbs. peak at 1 Hz and up to 3000 lbs. peak at 2.5 Hz, beyond which the amplitude should be reduced to avoid overstressing the components.

III. Tests on the GBT

After testing in the laboratory, the shaker and its associated power supply were hoisted up onto the GBT and placed into position on the elevation platform. The shaker was welded to the platform at an angle of 45 degrees, as shown in Figure 2. Accelerometers were mounted to the massive elevation bearing housing so as to monitor the movement of the housing in two directions: along the elevation axle and perpendicular to it. In this way, we were able to monitor the two lowest-frequency modes of oscillation of the alidade structure.

Our measurements were taken during the nighttime of October 4 and the afternoon of October 5, 1996—over a weekend period when construction workers were not present at the site. As of this date, the alidade structure, the box structure, and the elevation wheel assembly had been completed (and completely welded). In addition, all counterweight boxes were in place, but none had been filled with concrete. One section of the horizontal feed-arm structure had been bolted, but not welded, to the box structure and was partially supported by cables which were connected to a crane.

The sensitivity of the accelerometers was 10 volts out for 0.1 G in. Our data-taking scheme varied from monitoring the output voltage on an oscilloscope, to using the Hewlett–Packard low-frequency spectrum analyser (Model 3561A), to a simple digital recording system.

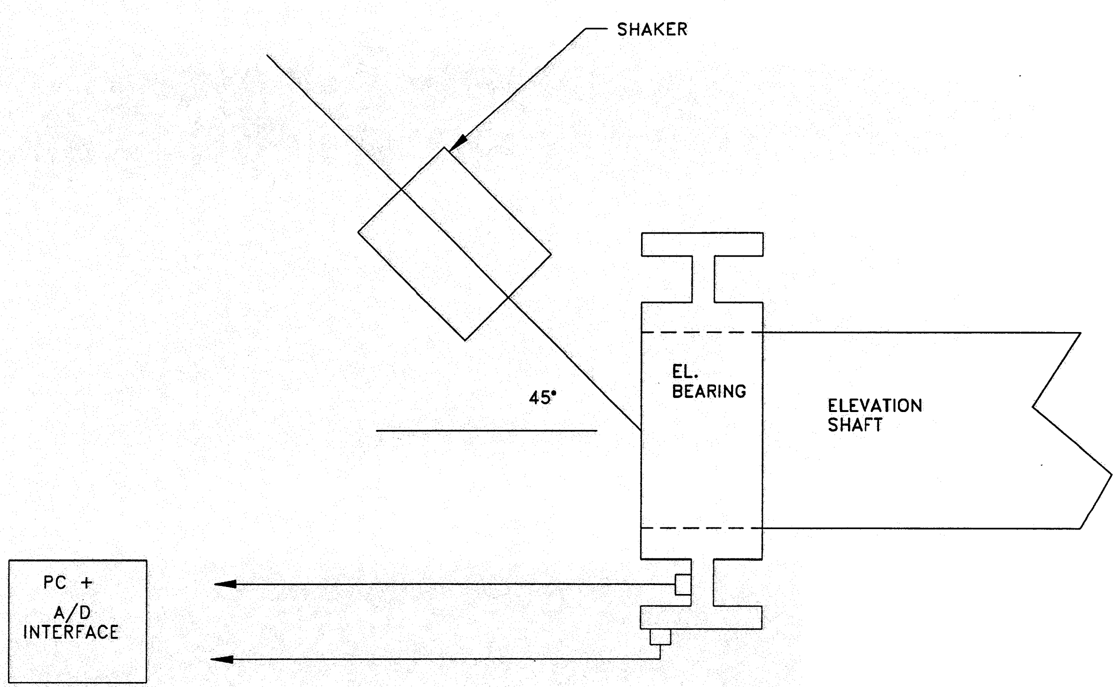

Figure 2. Experimental setup on the GBT.

By slowly varying the frequency of the shaker and recording the output of the accelerometer, we were able to measure the frequencies of the two modes mentioned quite accurately. Due to limited time on the structure and the keen interest in obtaining a good estimate for the damping coefficient, we concentrated our efforts on obtaining high-quality data on the mode along the elevation axle.

IV. Results

1. Mode Frequencies. The results for the two lowest frequency modes in the alidade structure are as follows:

- Along the elevation axle — 1.23 Hz;
- Perpendicular to the elevation axle — 2.26 Hz.

2. Damping. The damping coefficient, Z, associated with a given modal frequency of a structure is related to the amplitudes of successive cycles in the decay of the corresponding modal resonance, according to

$$\frac{X_n}{X_{n+1}} = e^{2\pi Z} ,$$

where X_n is the amplitude of the n^{th} cycle and X_{n+1} the amplitude of the next. For a steel structure, the damping coefficient is typically around 0.01 (often the value is quoted in percent; i.e., in this case, 1%).

The basic measurement technique for determining the damping of the GBT alidade structure was as follows: The structure was excited on resonance for several minutes. At the end of this time, the amplitude of the induced vibration at the accelerometer was about 800 microns peak-to-peak, the shaker was switched off, and the time-sequence recorder was started. Every 9.95 ms the output of the accelerometer was converted to a 12-bit number and stored in computer memory. After 100 seconds the sequence was halted and the results

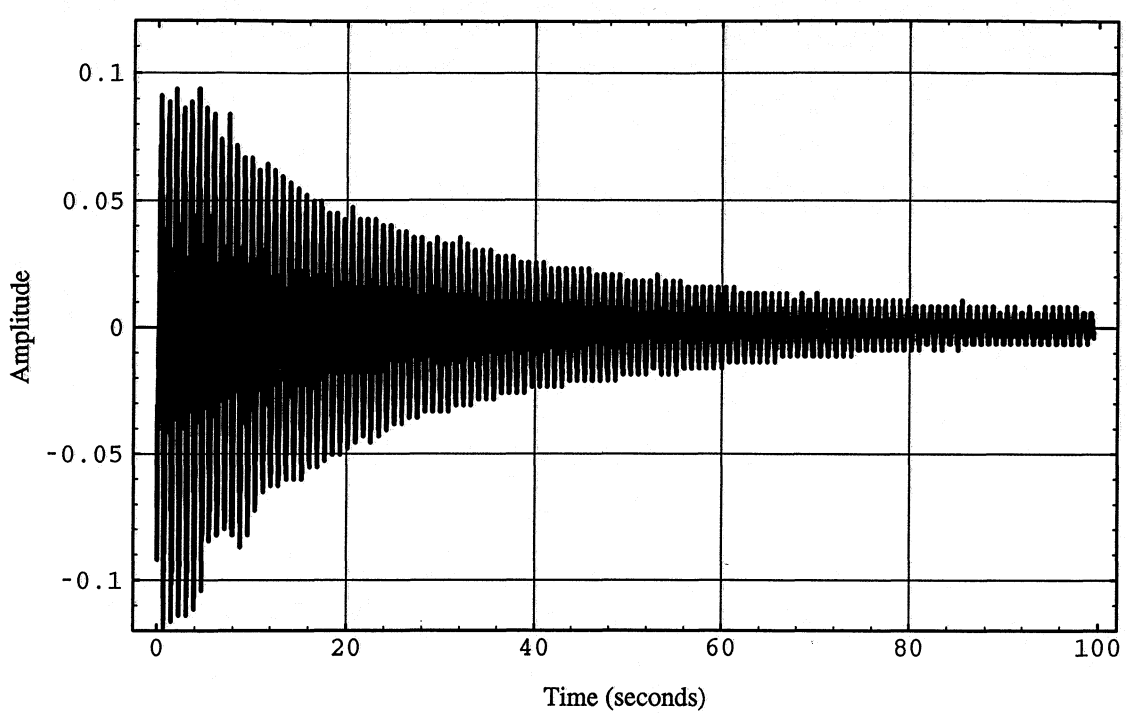

Figure 3. Time series of modal resonance decay, as measured by the accelerometer that was mounted parallel to the elevation axle.

transferred to a floppy disc. One such time series has been analyzed in detail and is shown in Figure 3.

This 100-second time series of decay data, which was obtained following sinusoidal excitation, at 1.26 Hz, of the lowest resonant frequency, was analyzed in two ways: (1) by fitting the data, by nonlinear least squares, to an exponentially-damped-sine-wave model; and (2) by spectral analysis, via the fast Fourier transform (FFT) algorithm. A nonlinear least-squares fit of the data to the model

$$f(t) = ae^{-bt}\sin(2\pi f_r t - c)$$

yielded parameter estimates $a = 0.0759$, $b = 0.0289$, $f_r = 1.23$ Hz, and $c = -5.871$ radians (with t measured in seconds). The corresponding estimate of the structural damping coefficient is given by $b/(2\pi f_r) \approx 0.00374$. Figure 4 shows the data, which are plotted in green, and the best-fitting model plotted in red.

The spectral analysis was performed by Welch's method of weighted and overlapped, segmented averaging of periodograms (WOSA) [**2,3**]. (This is the method implemented in the VLBA correlator.) The sampling interval of $\Delta t = 9.95$ ms allows the estimation of spectral components at frequencies up to $1/(2\Delta t) \approx 50$ Hz. To obtain a high-dynamic-range estimate of the spectrum, we first applied heavy tapering to the data. Figure 5 shows the spectral estimate derived by segmenting the 10,000-point time series into $L = 1024$-point pieces, applying a moderately heavy prolate-spheroidal wave function taper, and utilizing 67% fractional overlap of the segments. In addition to the dominant spectral feature at 1.23 Hz, a number of features appear between approximately 7 Hz and 20 Hz; the prominent feature at ~40 Hz is probably an alias of 60-Hz power line interference. No

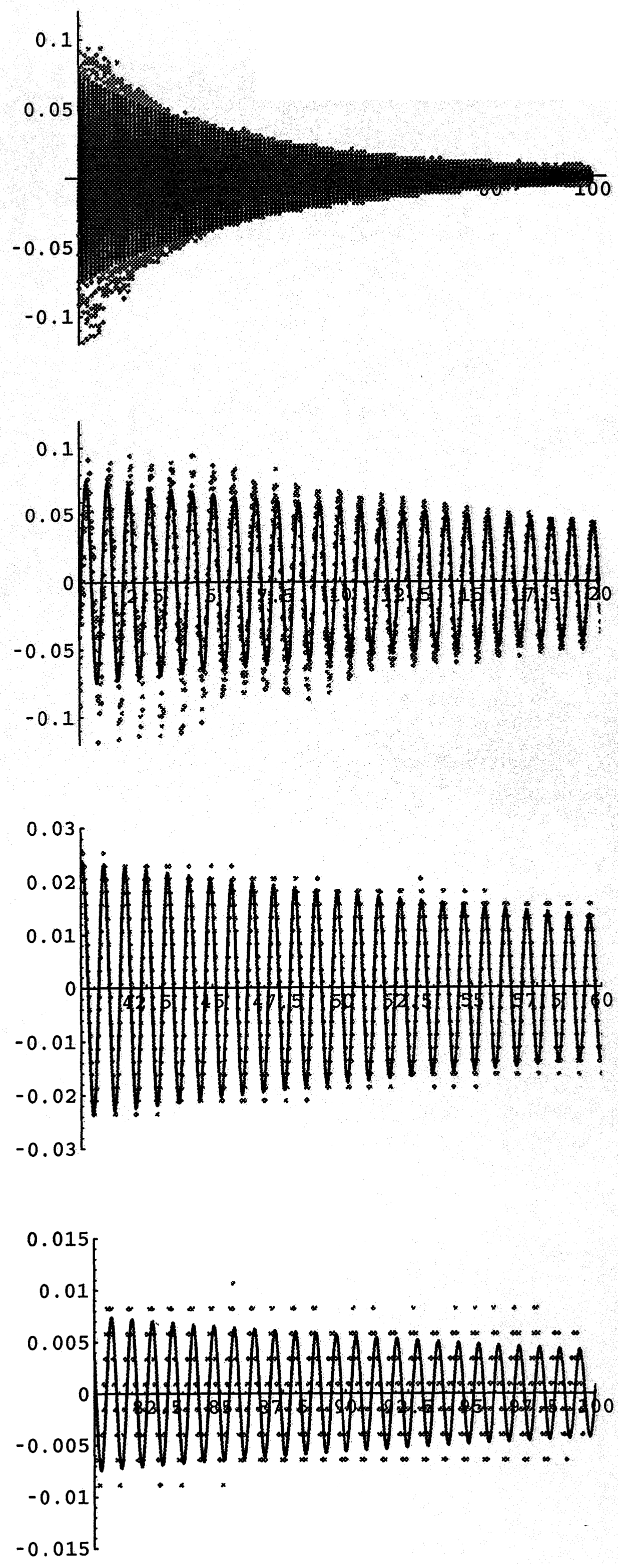

Figure 4. The 100-second time series of decay data (green), plotted together with the best-fitting exponentially-damped-sine-wave model (red). *(Top panel),* all data; *(second panel),* first 20 seconds; *(third panel),* middle 20 seconds; *(fourth panel),* final 20 seconds.

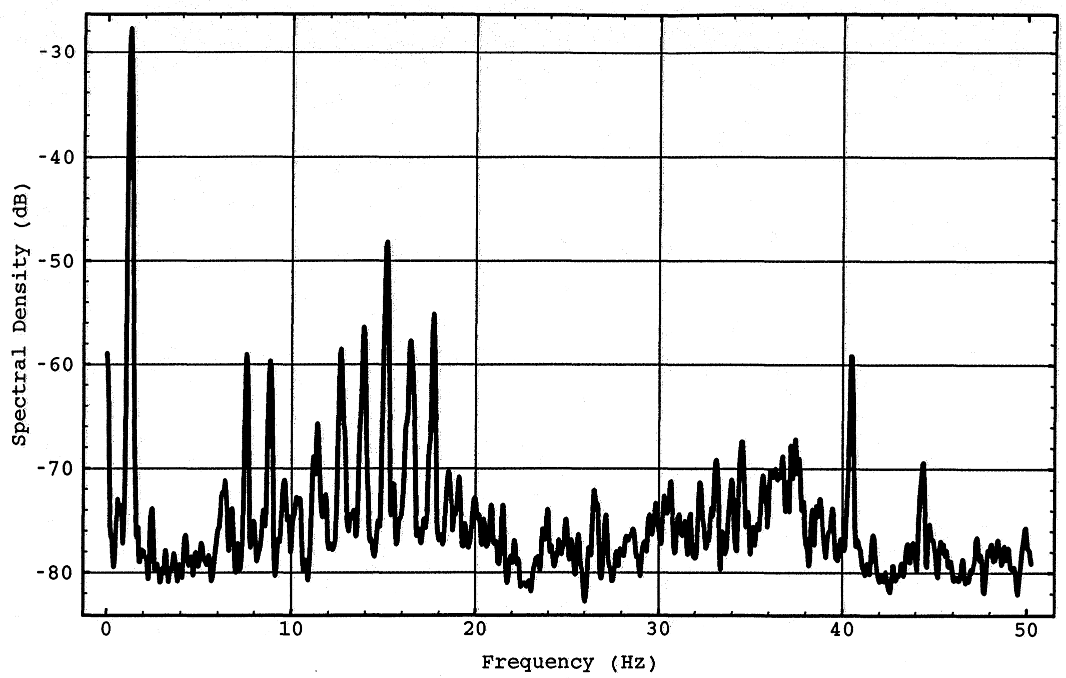

Figure 5. High-dynamic-range spectral estimate, 0 to 50 Hz.

useful estimate of the spectral widths may be derived from this spectral estimate, because of the heavy tapering and the coarseness of the frequency mesh (the points are spaced by $\Delta f = 1/(2L\Delta t) \approx 0.05$ Hz). The spectral estimates computed by software were found to be in agreement with those from the HP spectral analyser.

To achieve sufficient spectral resolution to estimate the width of the 1.23-Hz spectral feature, it was necessary to dispense with data tapering and with segmentation of the time series. The periodogram of the 10,000-point time series (computed by means of a 20,000-point FFT) yields a spectral resolution of $\Delta f = 1/(20000\Delta t) \approx 0.005$ Hz. Figure 6(a) shows this spectral estimate over the frequency range 0–5 Hz. Figure 6(b) is an expanded plot of the 1.23-Hz spectral feature, enabling the 3-dB width, or full width at half-maximum (FWHM), to be measured. The approximate value of this width, 0.012 Hz, yields an estimate of $\frac{1}{2}\frac{0.012}{f_r} \approx 0.0049$ for the structural damping coefficient,[1] which is considerably larger than our previous estimate of ~0.0037. This discrepancy is explained by the fact that the high-resolution spectral estimate derived from the 100-second time series is artificially broadened by convolution with a function whose FWHM is about 0.009 Hz. (See, e.g., [**3**, pp. 198 ff.].) This is illustrated in Figure 7. Indeed, the periodogram of the exponentially-damped-sine-wave model has a FWHM which measures approximately 0.0115 Hz. When this is taken into account the two methods of analysis are seen to be in nearly perfect agreement. If a longer time series (say, 200–400 seconds) had been recorded, then the inherent spectral resolution would have been great enough that this broadening could have been largely ignored.

V. Discussion of Results

The value obtained for the damping of the structure at the present stage of construction is consistent with that of a very high-quality welded steel structure. The values for the

[1]The relationship between the damping coefficient, Z, and the quality factor, Q, of the system is $Z = 1/(2Q)$, where Q is given by the resonant frequency divided by the FWHM of the resonance line.

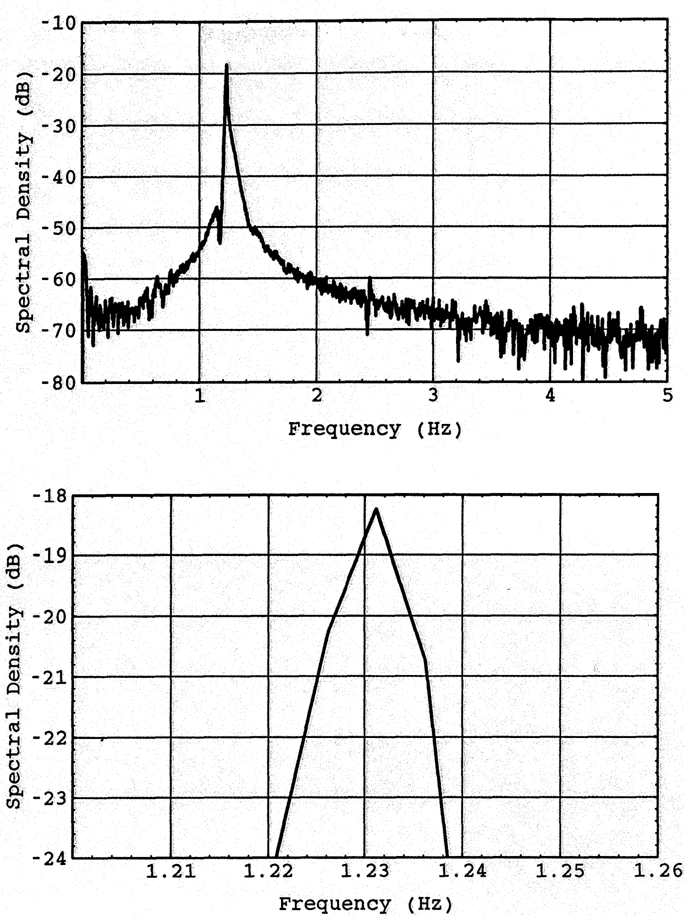

Figure 6. *(Top)* High-resolution spectral estimate, 0 to 5 Hz; *(Bottom)* Magnified view of the 1.23-Hz resonance line, allowing the 3-dB width (0.012 Hz) to be measured.

damping of a large structure such as the GBT are generally taken to be 0.01 and are based on measurements on completed structures which generally have additional damping from sources such as friction components in heavily loaded bearings. The literature quotes a wide range of values for the damping in steel structures. For example in [**1**], we find the following:

- Steel material — 0.001;
- Welded steel structure — 0.005–0.008;
- Bolted steel structure — 0.008–0.025.

The damping in a steel structure depends almost entirely on the nature of the joints, as these are the only regions where significant energy can be dissipated. The higher the joint quality, the less energy is dissipated and the lower the damping. From this it follows that the GBT number of 0.004 represents an extremely high-quality structure.

Due to the excellent agreement between the values of damping obtained by measurement of the decay time and a computation of the width of the modal resonance line, we have available to us a simple tool for the continuous measurement of the structural damping during construction.

The sensitivity of the accelerometers is such that random excitations, particularly during the day, result in significant accelerometer output. We are assembling a simple data-

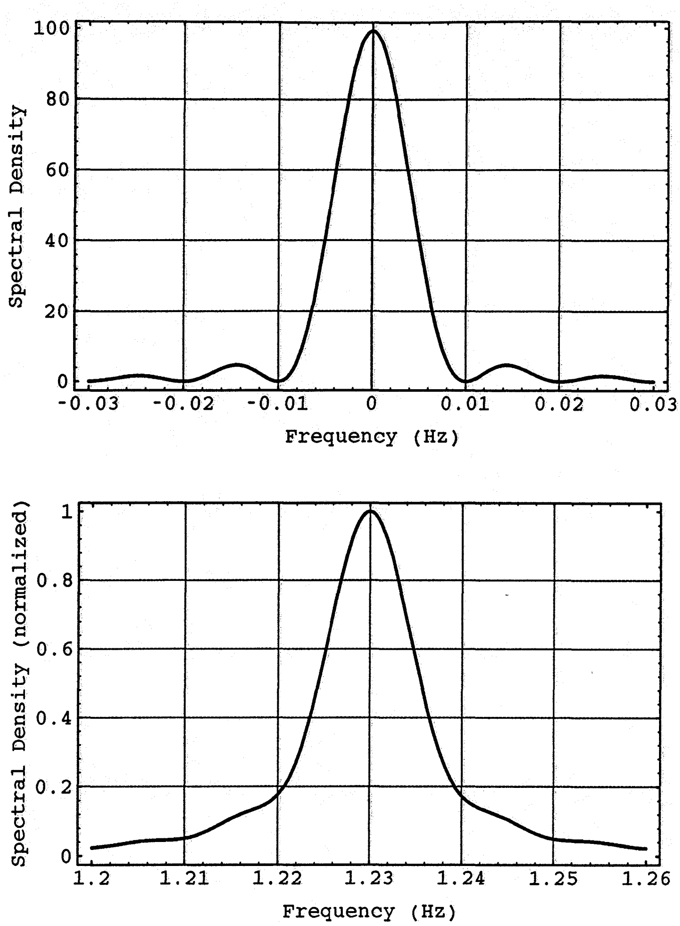

Figure 7. *(Top)* The high-resolution spectral estimate derived from the 100-second time series is actually an estimate of the true spectrum convolved with the function which is plotted here—a scaled sinc^2 function whose FWHM measures approximately 0.0089 Hz; *(Bottom)* Here, the analytically computed 100-second periodogram of the exponentially-damped-sine-wave model (b = 0.0289, f_r = 1.23 Hz) is plotted. Its FWHM measures approximately 0.0115 Hz, which is in excellent agreement with the line width shown in Figure 6(b).

collection system that will produce a time series of around an hour's worth of data per day from accelerometer(s) on the structure. As the construction progresses, we expect the spectral line width to broaden as the damping in the structure increases. We hope to implement this system within the next month or so. In addition we anticipate the installation of the ground-based laser systems in the next six months, and vibrations at any point on the structure then may be monitored to confirm and augment the accelerometer recordings.

Acknowledgments

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References

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