MODAL AND OPERATING CHARACTERIZATION OF AN OPTICAL TELESCOPE

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ABSTRACT

As part of the overall assessment of the dynamic characteristics of the Gemini Optical Telescope, an experimental modal test was performed on this structure along with collection of operating data. For the modal testing, multiple reference impact testing was performed to characterize the structure. Time data was acquired and processed to compute multiple referenced frequency response functions. Modal parameters were extracted as part of the overall assessment of this optical telescope.

For the operating assessment, many operating tests were conducted to determine the effects of wind loading on the structure. A variety of different structural configurations were evaluated during a series of tests at the Gemini Optical Telescope. Several days and nights were used to measure the telescope's behavior under a variety of different wind loading conditions. Operating data was collected and reduced for all of the tests conducted to identify wind loading conditions that hinder normal operations of the telescope.

This paper presents some of the significant considerations regarding the data obtained and the determination of the modal and operating mode shapes. Some thoughts on the acquisition of the data and its reduction are presented along with the extraction of modal parameters and operating shapes.

INTRODUCTION

Large optical telescopes are subject to numerous loadings such as normal operation, controls and positioning functions. However, the most critical of all loadings are those due to wind effects. The wind causes structural vibrations which degrade the overall performance of the telescope. Controllers are utilized to assist in the stability of the system and improve overall performance. In order to dynamically characterize the system and optimize the controller design, the modal characteristics of the telescope must be identified.

While a finite element model can be developed and is extremely important for the overall design, the external loadings due to the wind, in particular, are extremely difficult to define. Thus, while a finite element model may exist, its use for prediction of operational response due to the wind is limited. Experimental determination of the system response is the only alternative for the prediction of system performance. In order to fully characterize the performance of a large structure, both operational and modal tests need to be performed.

Figure 1 - Gemini Optical Telescope

The Gemini Telescopes were subjected to a variety of tests to define the dynamic characteristics of these telescopes. Preliminary, feasibility tests were conducted at Mauna Kea, Hawaii (Gemini North) to determine the response characteristics and levels of response on a fully operational unit. Being an operational unit, however, detailed testing with many sensors could not be performed - especially since the primary mirror was in place. However, the companion telescope in Cerro Pachon, Chile (Gemini South) was at a stage in construction where detailed structural tests could be performed. Figure 1 shows the general configuration of the Gemini Optical Telescope.

This paper summarizes some of the modal and operational tests performed. Rather than identify specific performance results obtained, the focus will center on the actual conduct of the test, items considered for the selection of test points, realities of academic vs. practical test considerations, reduction of operating and modal data acquired, and other pertinent considerations for the conduct of this test.

INVESTIGATIVE TESTING AT GEMINI NORTH

In order to justify the effort and expense of a large-scale test on the Gemini Optical Telescope, some preliminary tests were performed at Mauna Kea, Hawaii (Gemini North). These tests were intended to quantify the magnitude of response levels experienced by the telescope during normal operations. Only a handful of highly sensitive PCB seismic accelerometers [1] were judiciously placed in the weldment that houses the primary mirror. Since the telescope was in full operational use, placement of any measuring devices above the mirror of the system was strictly prohibited; this significantly limited the types of measurements that could be acquired. With the use of a very portable 8 channel Bobcat data acquisition system [2], a variety of measurements were made to determine the levels of response to be expected.

The initial tests were directed towards the operation of the telescope as in normal usage. Telescope orientation changes were used as an excitation to the system. In addition to these inputs, the main dome of the telescope was also reconfigured and rotated in order to provide additional inputs to the system. These inputs provided sufficient excitation to allow for adequate response levels to be measured on the telescope. Following these tests, the wind was used as the natural excitation for structural response.

In addition to these operational tests, several impact measurements were made to determine the suitability of using a calibrated impact hammer to acquire frequency response functions. The response of the structure due to these impact excitations was sufficient to allow for reasonably accurate measurements to be made.

While no conclusive design information was expected to be obtained from the acquired measurements, these initial tests provided technical substantiation for a detailed test at Cerro Pachon in Chile to be undertaken.

TEST SETUP AT GEMINI SOUTH

In order to perform a full scale test at Cerro Pachon in Chile, all the equipment and instrumentation needed to be shipped well in advance of the arrival of the engineers at the test site. This proved to be a significant undertaking. Coordination of equipment and instrumentation from several sources and locations proved to be an important and critical administrative task. However, after the initial difficulties, all of the equipment arrived ahead of the test team.

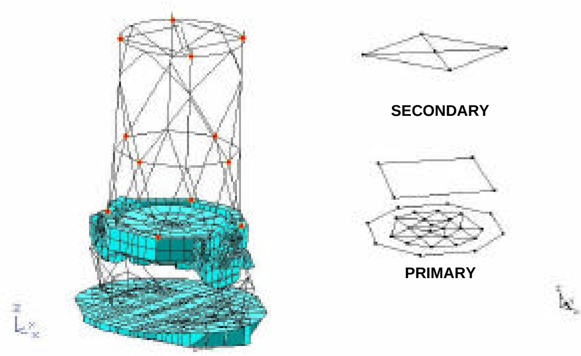

Figure 2 - Measurement Locations

In preparing for the test, several constraints regarding the number of channels of data acquisition and instrumentation were known. A schematic of the test locations are shown in Figure 2; the measurement locations are shown on the existing finite element geometry as well as on the test geometry used.

The telescope was to be instrumented with 75 accelerometers arranged on the primary and secondary portions of the structure along with 24 pressure transducers in the face of the dummy mirror used during the testing. The accelerometers consisted of a variety of PCB seismic accelerometers as well a numerous high sensitivity PCB ICP accelerometers. The seismic accelerometers were used on the primary portion of the structure and the balance of the accelerometers were to be used on the secondary portion of the structure.

One important consideration in the placement of accelerometers on the structure is to be sure that an adequate directional distribution is made to assure that the primary motion is observed. However, the use of some redundant measurement locations was also done in case certain key or important measurement locations were lost during the acquisition phase of the test.

The data acquisition system that was used for the testing performed was a LMS Skalar 88 channel data acquisition system [3] running the LMS MIRAS data acquisition software [4]. In addition to the acquisition system, the LMS CADA-X TMON [5] software was used for additional data reduction.

Once at the test site, the initial task of arranging the instrumentation and cabling was performed. The placement of accelerometers provided the necessary layout of the cabling and patch panels needed to distribute the accelerometers at the desired measurement locations on the telescope. This is an important part of the test setup. Management of the cable runs was extremely important to facilitate easy hookup to the data acquisition system.

More than one-half mile of cable was used to reach all of the sensor locations on the telescope. It was extremely important to maintain proper cable labeling so as to avoid miswiring the instrumentation to the acquisition channels. The management of this large number of cables required careful identification and specification of the cable arrangement. The test setup and instrumentation cabling for the acquisition system is shown in Figure 3a and 3b, respectively.

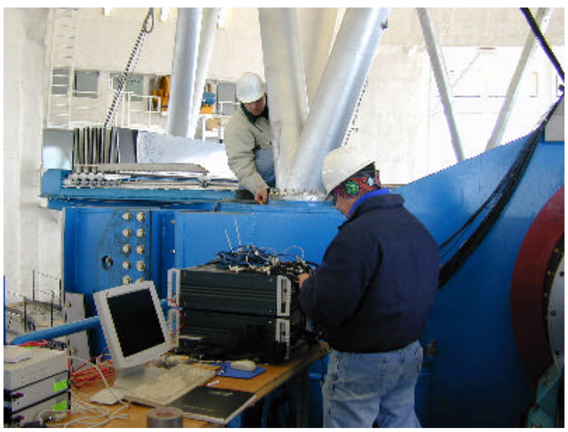

Figure 3a - Picture of Acquisition Setup

Figure 3 - Cable Management

The complete instrumentation setup, system configuration and initial data acquisition system checkout lasted for two long days with four people attending to different tasks associated with the setup of the test. Miscellaneous cables needed to be made at the site to accommodate the patch panel configurations that were available at the site. Actually, making custom length cables saved time when compared to patching together standard length cables.

Once all the transducers were connected to the data acquisition system and ready to acquire data, a measurement system diagnostic test was conducted. Basically, excitations were randomly applied to the telescope through a variety of different mechanisms to assure that all channels were measuring data. Following successful diagnostics, the collection of data was initiated.

DATA COLLECTION AT GEMINI SOUTH

The test data was collected in individual tests for more than 50 configurations of the telescope system. The majority of the tests were collections of operational data due to various wind and geometry configurations of the telescope. Several tests were also conducted using an impact excitation for the development of frequency response functions for modal characterization of the telescope.

For all tests performed, time data was collected and written directly to the computer hard drive of the data acquisition system. Data was sampled at a frequency of 200 Hz; for the majority of data to be investigated for the telescope, this was 10 times higher than most of the frequencies to be studied. For the operational data collection tests, data was conducted for approximately 300 seconds. The impact tests, however, consisted of 500 seconds. The data collection lasted for 3 days followed by the breakdown of the test system.

IMPACT TEST DATA COLLECTION

Since it was not feasible to perform shaker excitation testing during construction at Cerro Pachon, an impact testing technique was used. This would require a massive impact device to excite the main telescope weldment and anchor weighing in excess of 200 tons. Since excitation at the base of the structure was not possible, an impact excitation at the extremity of the telescope (where the structure is most flexible) was considered the logical alternative. This approach assumes that the excitation at the flexible extremity of the system will naturally tend to excite the modes of the system. Therefore, rather than use a massive impact device at the massive base of the structure, a more reasonably sized impact at the extremity of the structure should be sufficient to allow the modes of the structure to cause a measurable response of the system so that reasonably good measurements could be made.

Impact locations were selected at two points in the two horizontal directions at the top of the secondary portion of the telescope. A "cherry picker" was used to hoist the hammer and related instrumentation and people to a fixed location on the telescope. During these measurements, only the response of the 75 accelerometers were measured. A typical impact test setup is shown in Figure 4.

Figure 4 - Impact Test Setup

Measured data was acquired for all the channels of the system due to impact excitation. The data acquisition system was setup to capture raw time data due to the impact excitations. A series of consistently placed impacts spaced close to 20 seconds apart were applied for 25 repetitions. This resulted in 500 seconds of time data for 76 channels to be collected on the acquisition system (75 response accelerometers and 1 force excitation). A typical measurement sequence showing the impact and resulting responses of 3 channels is shown in Figure 5.

Figure 5 - Impact/Response Time Data

OPERATING TEST DATA COLLECTION

The impact tests described above were performed during moments when the wind had subsided sufficiently such that collection of operating data was not expected to produce any meaningful results. However, at any other time when substantial wind was available, operating time data was collected with the telescope in a variety of different geometric configurations.

There were structural configurations that are far too numerous to detail in this paper. Suffice it to say that an abundance of data was collected. With all the pressure transducers measuring the response in the dummy mirror along with the balance of the channels in the data acquisition system dedicated to structural response, data was collected in 5-minute increments before reconfiguring the telescope to another geometric configuration. A typical measurement of several records of time data is shown in Figure 6.

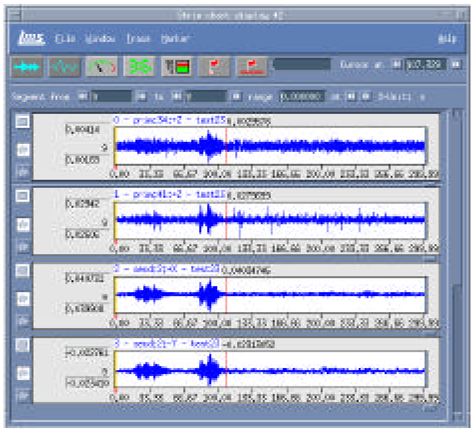

Figure 6 - Operating Time Data

ON-SITE DATA REDUCTION

Due to time constraints, only time data was collected at the test site. In order to assure that reasonable measurements were acquired, one impact data set was reduced (in a preliminary fashion) to assure that the extracted spectra and resulting frequency response functions were of sufficient accuracy to continue with the collection of additional data. Using a preliminary impact test that was conducted during the system diagnostic, a typical measurement reduction was performed. Without getting very particular in terms of trigger conditions, window application, averaging, etc., a set of frequency response functions were computed from auto and cross spectra using the fourier transformed time data relative to the impact excitation force.

In general, the measurement was reasonable but not of the quality needed for extraction of modal parameters. Upon review of the data, very obvious "background" effects could be seen within the measured data. This "noise" on the data basically reduced the accuracy of the measured frequency response functions. The main cause of the noise was due to the normal plant activities that were occurring while the impact tests were being performed. Basically, the instrumentation was sensitive enough that persons walking on the structure were clearly seen in the measurements. These effects were small compared to larger "noise" effects such as the construction crew dropping chain hoists and other related equipment.

The solution to the measurement quality problem was very simple. There could be no activity in the telescope dome during the time when impact measurements were being made. The only way that this could be achieved was to send the construction crew to lunch and lock the doors while these sensitive impact measurements were made.

Another very important item that needed to be performed using the preliminary processed data was to quickly reduce the measured data using simplistic peak picking techniques to assure that all the channels were configured properly prior to collecting additional data. As it turned out, the drive point measurement did not appear to look like a typical drive point measurement. After several scenarios for this were discussed, the problem was quickly resolved to be a very simple cabling mix-up. Two of the channels were inadvertently switched on the front end of the data acquisition system. This was quickly corrected prior to collecting any additional data.

This quick data reduction and assessment is an extremely important step of the acquisition process. If there are any problems, they can be quickly resolved before collecting additional data.

COMPLETION OF DATA COLLECTION

The data collection window of opportunity was only five days long. At the end of this time, the tedious task of removing all the instrumentation and cabling and repacking all the equipment for return to the appropriate individuals and organizations was not a pleasant task. More time needed to be allotted to this task but often whatever time is available is normally taken up by the desire to "run a few more tests" before breaking down the instrumentation system.

PRELIMINARY DATA ASSESSMENT - DATA CLEANSING

As in most large channel count tests, there are certain channels of data collected that have various problems associated with them. Some channels will appear to be totally incorrect which may be due to instrumentation or hardware problems; these channels need to be removed from the database. Other channels may have bias errors, for instance, that are associated with settling issues related to the acquisition system which may be different between different channels. These effects need to be removed from the individual channels associated with each test otherwise distortion of the transformed data may result.

A particular bias error may be common to a given channel for all tests whereas other bias errors may only be observed for certain individual tests. Effort needs to be carefully expended in this phase to assure that all data channels are modified to remove any such bias error that are seen in the data. Typical bias error from several channels is seen in Figure 7.

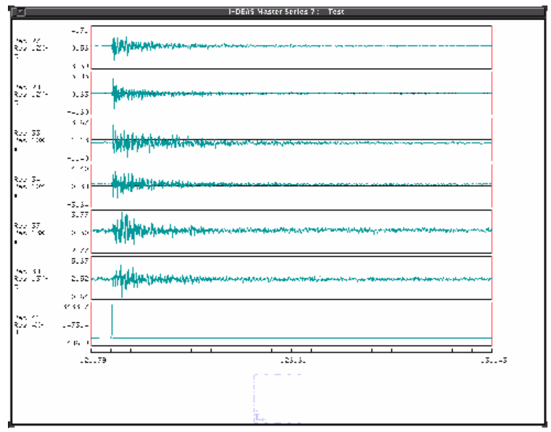

Figure 7 - Bias Errors

In addition to bias errors, there may be other errors that exist based on other operating difficulties (power spikes, plant operations, etc.). Individual tests may need to be excluded if there are too many erroneous excitations causing inconsistent responses. This was the case with several tests that were conducted since the construction of the telescope was still underway during the majority of testing performed. A typical measurement difficulty associated with a power surge or other effect is seen in Figure 8.

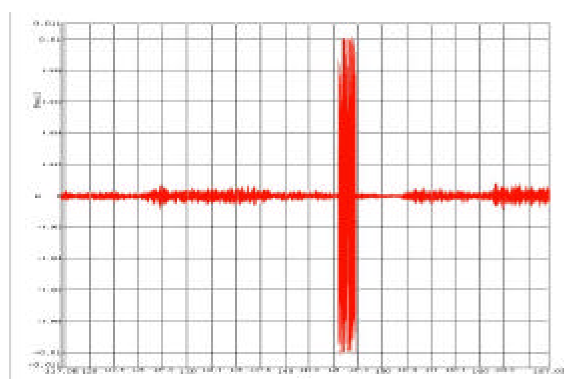

Figure 8 - Measurement Difficulties During a Test

IMPACT TEST DATA REDUCTION

Once the data collection phase was completed, the data sets were made available for reduction of data. The impact data sets were reduced first, in order to help with the reduction of the operating test data sets.

The actual impact measurements are seen to be fairly consistent in amplitude as shown in Figure 9. The response of one of the accelerometers is shown in Figure 10. The impact and response measurements look fairly clean for the measurements acquired.

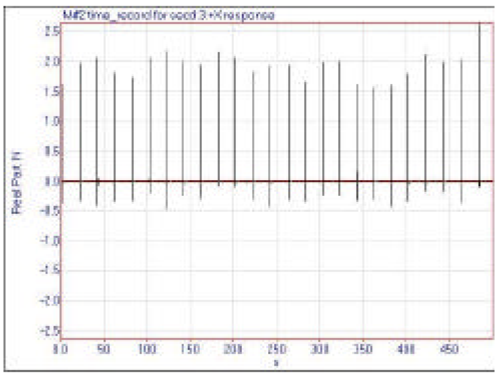

Figure 9 - Impact Time Data

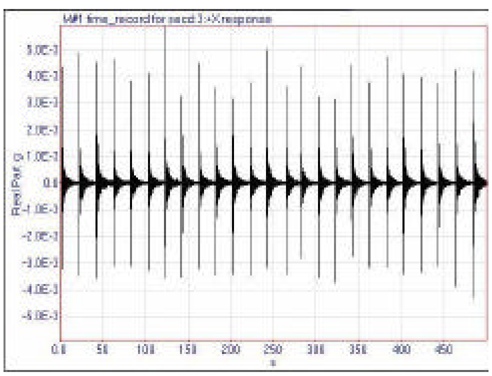

Figure 10 - Response Time Data from Impact

The reduction of this data was performed as typically done with any impact measurement such as with a dual channel FFT analyzer. The only difference is that the time data that was acquired and saved on disk is used instead of data collected live. The time data was inspected for any inconsistencies; data channels were either adjusted through filtering techniques or removed from the data set.

The impact channel was reviewed to determine the maximum amplitude of the impact excitation so that a suitable impact trigger level could be specified. A pre-trigger delay was also specified as normally done in impact testing. Once these parameters were specified along with the normal signal processing parameters (frequency bandwidth, time step, block size, number of averages, etc.), the auto and cross spectral measurements (necessary for the development of the frequency response function and coherence) were computed. Since the response signals have clearly decayed to essentially zero by the end of the block size sample interval, no exponential window was needed for the processing of this data. Had this not been the case, an exponential window would have been needed.

The computed frequency response and coherence functions are shown in Figure 11 and 12, respectively, for one of the impact measurements acquired at a drive point location. The measurements are considered to be of reasonable quality considering that only a small sledge impact hammer was used for the excitation of the large telescope structure. The coherence drops, as expected, at frequencies where the response is very small.

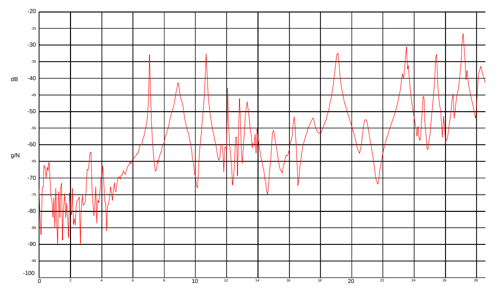

Figure 11 - Impact Frequency Response Function

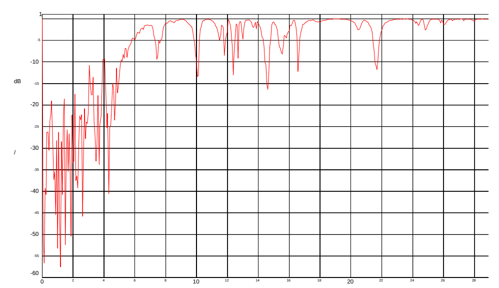

Figure 12 - Impact Coherence Function

OPERATING TEST DATA REDUCTION

Using the response data collected from the available wind excitation, cross spectral measurements were computed. These cross spectra were computed relative to a number of references. The references were selected based on the results of the modal test (ie, points where significant response was noted for the majority of the shapes to be extracted). Only the tests with the most significant response were used for the initial investigation of the operating modes.

The most significant tests were identified based on their auto spectra considering the entire energy distribution for all of the measurements and using subsets of measurement points associated with the main components of the telescope (ie, primary and secondary). Figure 13 shows a typical summation of the auto spectra for the telescope for the primary and secondary in the upper and lower traces, respectively. Table 1 shows the frequency regions where significant responses were observed.

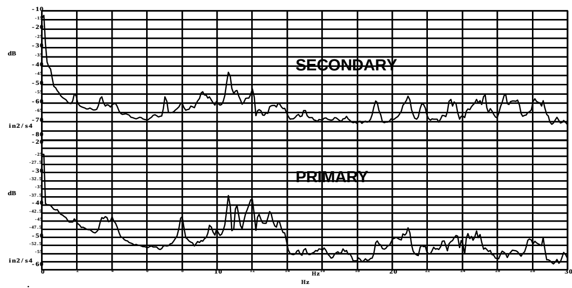

Figure 13 - Summed Spectra for Primary and Secondary

Secondary	Primary
1.855	1.855
3.418	3.418
	3.613
3.711	
	4.004
4.199	
7.031	
8.008	8.008
8.496	
9.18	
9.57	9.57
9.961	9.961
10.645	10.645
11.133	11.133
12.012	12.012
12.402	12.402
	12.989
13.281	
13.477	

Table 1 - Significant Frequencies Observed

This data was reduced as typically done with any spectrum analyzer (as previously mentioned in the impact section on data reduction). Typical signal processing parameters were specified (frequency bandwidth, time step, block size, number of averages, etc.) for the computation of the auto and cross spectral measurements. Since the input wind and resulting response of the system was random in nature, a Hanning window with 50% overlap was used for all processing performed. A typical measurement is shown in Figure 14. This data was used for the extraction of operating modes of the telescope.

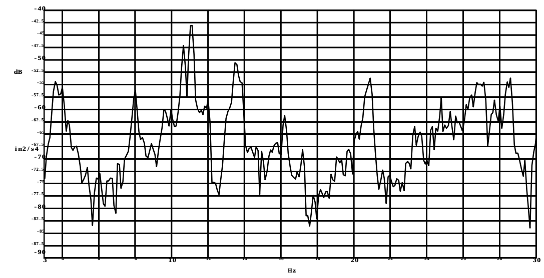

Figure 14 - Typical Cross Spectra

EXTRACTION OF MODAL DATA FROM IMPACT MEASUREMENTS

Using the computed frequency response functions from the measured time data, the modal parameter estimation process was performed. The telescope contained some very directional modes due to the nature of its configuration. The methodology for extracting the modes is discussed next; the detailed extraction of all the modal parameters is well beyond the scope of this paper.

Several different references were used for the generation of frequency response functions. While many references were available, not all of the references were used for the extraction of each of the poles of the system. In fact, not all of the measurements were used for the estimation of a particular pole. The main reason for being very selective in the estimation of poles is due to the fact that the measurements for all of the response channels do not always show good response over the entire frequency range of interest.

Of course, this is very reasonable since the response of the system is strongly controlled by the mode shapes of the system. If the telescope has a predominate x- direction motion for the first mode of the system, then the response of the telescope in the y- and z-directions may not show any significant response. In this case (as was the case for many of the major telescope modes), the use of all of the measurements to extract poles for that particular mode of the system may not produce very good results. This is mainly due to the fact that a good portion of the measurements may not be sufficiently accurate and may in fact be extremely sensitive to noise since the structural response is very small in these directions. Inclusion of these measurements adds noise onto the pole estimation process, thereby contaminating the extraction process. (Figure 15 shows a schematic of the typical measurement selection process for pole extraction. The figure shows a typical collection of FRFs that might be used for pole extraction.)

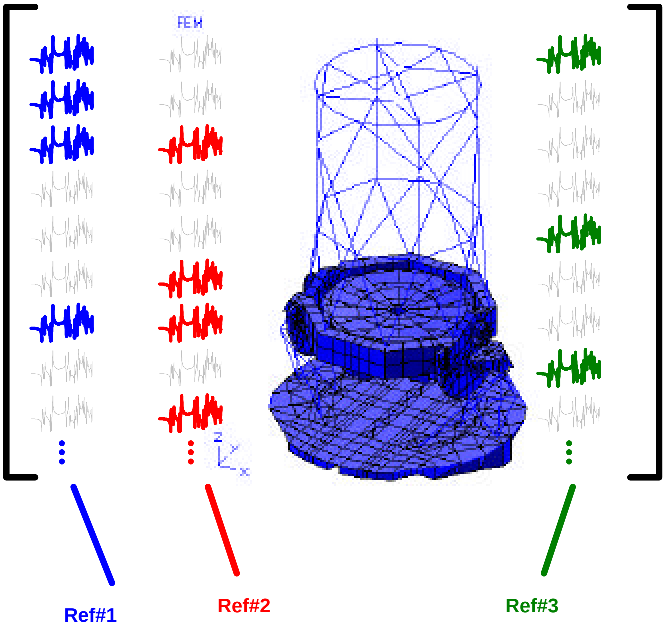

Figure 15 - Typical Measurement Selection for Pole Estimation

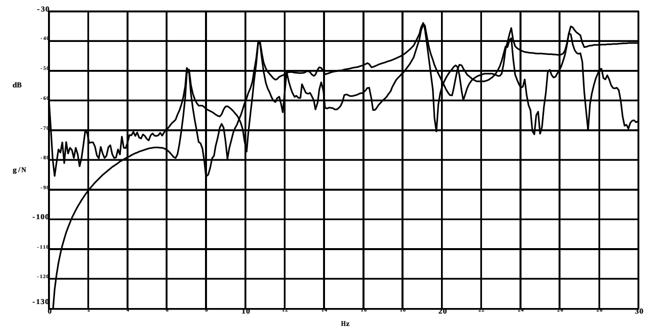

Figure 16a - Poor Extraction and Synthesis of FRFs

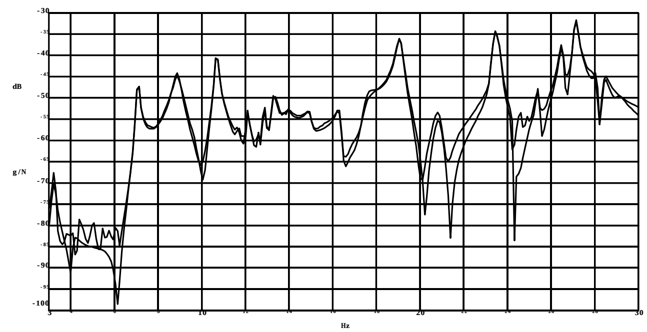

Figure 16b - Good Extraction and Synthesis of FRFs

If these measurements are excluded from the pole estimation process, then there is a much higher probability that better pole estimates will be obtained. Since there were directional modes to be extracted, care was exercised to assure that the measurements that show the highest modal participation were used for the estimation of poles and then the residues for the telescope. This approach was used for all of the modes of the system (following a preliminary analysis to determine the modal participation for each of the modes).

While this approach is much more time consuming, the estimated poles and subsequently, the residues, are much more accurate and are a better representation of the system. While not discussed in this paper, a less stringent approach to parameter estimation (utilizing all of the measurements for all of the references for the pole and residue approximation) clearly yielded modal parameters that were less accurate. One very clear indication of the adequacy of the extracted modal parameters is through the comparison of the synthesized measurements with the actual measured functions. Figure 16a shows a marginal comparison when care is not taken to extract the best possible poles and residues for the system. In contrast, Figure 16b shows a very good comparison when extreme care is utilized in extracting parameters.

While not specifically detailed and presented herein, the major modes of interest in the telescope were extracted from the measured frequency response data. The modes consisted of the typical bending, nodding and torsional modes expected in this type of structure. These modes are used for comparison with the operating data discussed next.

EXTRACTION OF OPERATING DATA FROM OPERATING MEASUREMENTS

Using the cross spectra that were processed for a number of references, operating modal deflections were computed for a number of frequencies. The majority of these frequencies coincided with the frequencies observed from the modal tests, as expected. Using a standard peak picking approach, operating deformation patterns were obtained for a number of frequencies and for a number of different references. A significant amount of additional processing was performed using singular value decomposition techniques to assist in the identification of reference locations and extraction of operating modes; discussion of this supporting data is well beyond the scope of this paper.

As expected, the telescope has some significant motion that visually appears to be very similar to the major modes of the system. These operating deflections consisted of the typical bending, nodding and torsional modes expected. While not specifically presented herein, these modes were used for correlation with the modes obtained from the experimental modal analysis that was performed. This is presented in the next section.

CORRELATION OF MODAL AND OPERATING DATA

Using the experimental mode shapes and the operating modes, a correlation study was performed. Basically, the MAC was used to enable a quick validation of the operating and modal information extracted from the measured data. Again, many different tests and configurations were evaluated and the results of one typical case are presented herein. The results of the MAC are presented in graphical form in Figure 17 and in tabular form in Table 2. Clearly, there is good agreement between the modal data and operating modes of the telescope. (Note: Columns in Table 2 that show no correlation are expected due to the directional nature of the modes of the system.)

It is important to note that the geometric configuration of the telescope for modal data and all of the operating data is different. Modal data was collected with the telescope "parked" in the vertical upright configuration. All of the operating data was collected in configurations that were different than the modal test configuration. Therefore, there is expected to be some differences in the mode shapes due to this configuration difference.

The modal data used here was based on the very careful extraction of modes from measured data described earlier; if care was not exercised in extracting parameters, then the correlation results clearly diminished.

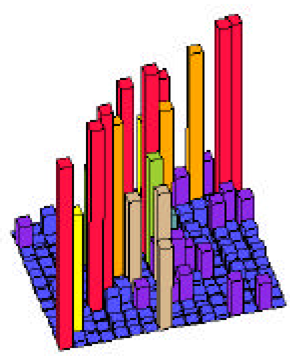

Figure 17 - Typical MAC Correlation Results

96.9	3	0.7	0.1	0.3	0.4	0.3	43	0.4	0.3	3.6	2.1	18.2	0.3	14	0.3
0.2	64.1	1.6	0.1	3.2	3.3	2.7	0.3	2.6	2.7	0.3	2	0.3	1.2	0.5	0.2
1.8	0.5	3.8	0.7	11.4	1.5	13.2	1.4	12.7	15.7	3.8	2.7	1.6	1.8	1.1	0.4
0.2	0.6	1.2	96.4	5.1	9.4	0.5	0	0.3	8.7	5.8	0	0	6.9	0	0.1
0.2	0.8	0.5	0.6	98.3	4.7	48.8	2.2	49.5	24.7	0.9	14.5	0.1	2.4	0.9	0.9
0.8	4.2	0.7	5.2	22.8	85.5	16.6	0.5	17.5	7.4	12.9	12.5	0.4	5.1	0.8	3.9
1.9	0.3	0.4	0.5	47.7	2.4	98.4	0.1	57	25.6	11.1	7.1	2	2.7	0.3	1.5
0.8	0.6	1.4	0.7	50.9	3	59	1.6	97.9	76.9	3.8	9.2	0.4	3.5	0	4.5
0.2	0.1	2.3	17.2	18.6	0.8	17.8	0.6	66.5	88.4	4.8	5	0.1	16.2	0.3	15.5
2.3	0.1	0.1	0.3	3.7	0.8	1.1	8.9	2.1	1.1	6.6	8.4	9.8	11.2	15.7	0.5
12.6	2.2	0.8	0.1	1	0.8	0	55.5	0.5	0.4	5.4	23	86.9	2.8	97.4	0.4
0.3	2	10.1	1	0.2	1.7	4.1	0.2	10.5	17.8	14.6	0.6	0.2	22.7	1	92.8

Table 2 - Typical MAC Correlation Results

OBSERVATIONS

A good deal of effort was expended in the measurement and reduction of this data for the Gemini Optical Telescope. One very important item to be emphasized here is that the collection of data was performed by capturing time data at the site location. While some reduction of that data was performed at the site to assure that adequate measurements were being made, the majority of the data was reduced long after leaving the test site of the telescope. The use of captured time data permitted the more in-depth evaluation of the data collected. If all the data collected were processed to capture frequency averaged data at the site (without having the time data available), then there would be no possibility of further processing the data in a multitude of different scenarios. The ability of processing the time data in a variety of ways allows for a tremendous flexibility which would not be possible if only averaged frequency data was obtained.

SUMMARY

This paper presented an overview of the collection of operating and modal data for the Gemini Optical Telescope. The overall test plan and setup were described. Aspects of test setup and data collection were presented. Considerations for the data cleansing prior to further use was discussed. The reduction and use of time data to estimate the telescope's modal characteristics and operating deflection shapes was presented. A comparison of the operating shapes and extracted mode shapes was shown.

REFERENCES

1) PCB Seismic Accelerometers (Model 393) and ICP Accelerometers (Model 336, 356, 308), PCB Piezotronics, Depew, NY
2) Bobcat eight channel data acquisition system, Spectral Dynamics, San Jose, California
3) LMS Skalar modular, multichannel data acquisition system, Leuven Measurement Systems, LMS N.America, Troy, Michigan
4) LMS MIRAS Acquisition Software, Leuven Measurement Systems, LMS N.America, Troy, Michigan
5) LMS TMON Acquisition/Reduction Software, Leuven Measurement Systems, LMS N.America, Troy, Michigan
6) LMS FMON Acquisition/Reduction Software, Leuven Measurement Systems, LMS N.America, Troy, Michigan
7) LMS Modal Analysis Software, Leuven Measurement Systems, LMS N.America, Troy, Michigan
8) MTS/SDRC I-DEAS Test Software, Mechanical Testing & Simulation, Minneapolis, Minnesota
9) Vibrant Technology ME'scope Modal Analysis Software, Jamestown, California