TMT Telescope structure system – seismic analysis and design

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ABSTRACT

This paper documents the methods used for the seismic design and analysis of the Thirty Meter Telescope (TMT)[2]. The seismic analysis includes response spectrum and nonlinear time history methods. Several seismic restraint design options are considered, both linear and nonlinear, and the seismic performance is presented for these options. The paper addresses several issues specific to large optical telescope seismic design and analysis: generation of appropriate response spectra and time histories; use of operational and survival level earthquakes; selection of damping coefficients; use of reduced degree of freedom models and their calibration with more detailed models; and local response spectra for telescope-mounted systems.

Keywords: Thirty Meter Telescope, TMT, seismic design, seismic restraint, transient analysis, nonlinear, isolation, damping, response spectra

1. OVERVIEW OF TELESCOPE AND MODEL

Given the high-seismicity of the candidate Thirty-Meter-Telescope (TMT) sites [1], it is paramount that sufficient protection be provided for the telescope structure, optics, and instruments against earthquakes. This paper solely discusses the design and analysis work for the seismic restraints. The overall telescope structure design is described in a separate paper in this conference by Szeto et. al [2]

The telescope is formed by two main structural parts, the elevation structure and the azimuth structure, which provide support for the telescope-mounted systems (Figure 1). The elevation structure holds the segmented primary, secondary, and tertiary mirror systems[3] (M1, M2, and M3, respectively) and can rotate about the horizontal elevation axis from zenith to horizon pointing. It is supported by four hydrostatic shoe bearings (HSB) on the azimuth structure. Two Nasmyth platforms located on either side of the elevation structure support various instruments and are tied to the cradle of the azimuth structure. The latter is supported vertically on six HSB around the perimeter of an azimuth track of 17.6m radius, allowing the telescope to rotate about the vertical azimuth axis. Operational lateral loads are transmitted to the ground through the pintle bearing located at the centre of the azimuth structure.

The current TMT finite element model (FEM) representation of the telescope is shown in Figure 2. It is composed of beam, shell, and spring elements. The mass of the telescope is 1800 tonnes, including both structural and non-structural masses. The fundamental mode frequency is 2 Hz. The structure is 55m wide, as measured from the ends of the

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2 The TMT project is a partnership between ACURA (Association of Canadian Universities for Research in Astronomy) in Canada, the University of California and Caltech.
3 In addition of the mirror, each mirror system contains a mirror support system with actuators for figuring control and positioner for alignment control and the associated control electronics.

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Nasmyth platforms, and rises about 50m from the ground. Due to its height and the obscuration limit imposed for the primary mirrors restricting the size of its support structures, the M2 is particularly sensitive to seismic loads.

In the FEM, lateral seismic loads are transmitted from the ground to the structure through springs representing soil stiffness, which are connected to the concrete pintle bearing pier. The latter transfers the load to the pintle bearing springs and seismic restraint springs, which finally pass it to the structure, resulting in inertial loads or structural accelerations.

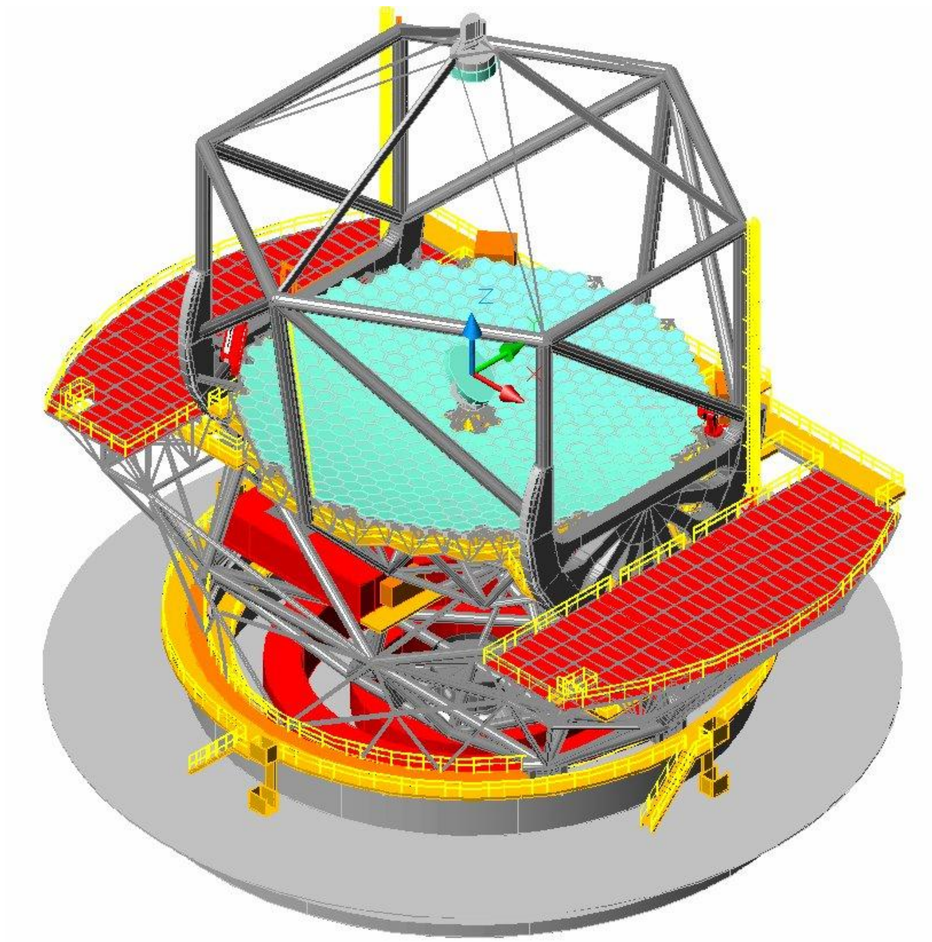

Figure 1: TMT CAD model. The structures supporting the science instruments on the Nasmyth platforms are not shown.

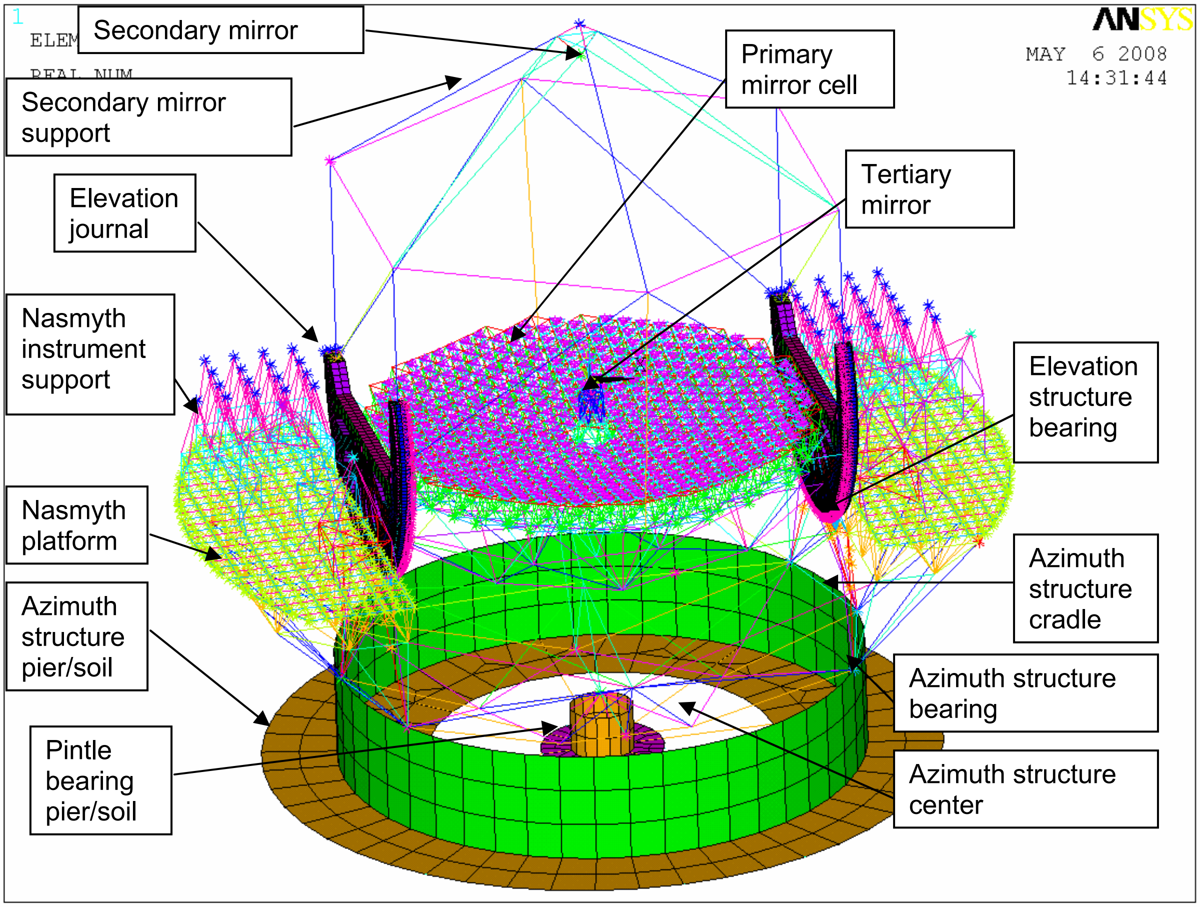

Figure 2: TMT finite element model.

2. DESCRIPTION OF SEISMIC RESTRAINT REQUIREMENTS

Two seismic performance criteria are specified, based on the severity of the earthquake [3]. For an Operational Basis Survival Condition (OBSC) earthquake, which is defined as a seismic event with an average return period of 200 years, the telescope system shall suffer no damage and astronomical observations and regular maintenance operations shall resume after inspection lasting no longer than four hours. For a Maximum Likely Earthquake Condition (MLEC) event, the return period becomes 500 years and operation resumption is five days for the telescope structure system.

Several restraint design criteria are specified in response to the seismic performance requirements:

- The restraints shall not interfere with normal telescope motions and operations
- The restraints shall be the primary lateral-motion resisting and load bearing devices during a MLEC earthquake and protect the rest of the structure and telescope-mounted systems from damage
- The structure and restraints shall both behave elastically during an OBSC earthquake
- The restraints may behave inelastically during a MLEC earthquake to keep the structural elements within the elastic level and the optics & instruments from being damaged
- Restraint against uplift shall be provided if necessary
- The restraints shall retain sufficient stiffness and strength to also protect the structure against aftershocks

3. ANALYSIS

This section describes the analysis method implemented to support the seismic restraint design. It is important to choose a suitable method to capture the dynamic and potentially nonlinear behavior of the seismic restraints.

3.1 Methods

There are several popular seismic analysis methods, namely: 1) equivalent static load procedure, 2) spectrum analysis, and 3) time-history (transient) analysis. The first procedure will be used only as an order of magnitude level verification since it lacks accuracy for complex, irregular structures. The spectrum analysis is appropriate only for structures behaving linearly. Since it is anticipated that the restraints will behave in a nonlinear manner, time-history analysis is selected as the primary analysis method. It is also the most flexible method in terms of the type of structural behaviors and load scenarios allowed.

The downside of transient analyses is long computational time. With over 20,000 nodes and 35,000 elements, the current TMT FEM requires over nine hours to perform one analysis over 1500 time points (15-sec total) on a high-end PC workstation. The long run-time may be mitigated by the use of the substructuring technique, which effectively allows the simplification of the linear-behaving portion of the FE model to a single "super-element" and thus significantly cuts down run time. Although the stiffness of the simplified model would be maintained during this process, the mass and mass moment of inertia of the original model need to be redistributed by assigning "master nodes", which are nodal locations where original structural masses are lumped.

There is no specific rule for master node assignment, but it is found that putting master nodes at locations of concentrated masses and at the interface of the super-element and the original elements would preserve the dynamic characteristics of the original structure. This is judged by comparing both the time-domain transient analysis and the frequency-domain harmonic analysis results, the latter involving the evaluation of frequency responses of the two models with unit seismic loads applied. Currently, about 250 master nodes are assigned to the simplified model. A transient analysis of this model is drastically reduced to about one hour.

The accelerations of non-structural components (e.g. the secondary mirror subsystem) due to seismic loads are dependent on their own natural frequencies. Specifically, if the natural frequencies of an instrument are similar to those of the dominant modes of the telescope structure, the resulting resonance effect can amplify the instrument's accelerations. To examine this effect, a local response spectrum can be developed for any telescope-mounted system. Using the secondary mirror system as an example, one can extract the time-history response at M2's mounting point and then convert these results into the frequency-domain to derive a local response spectrum. With this information, the M2 design team can then determine which frequencies are sensitive to seismic loads and modify their design accordingly, if necessary. This also forms the basis of seismic loads interface requirements between the telescope structure and the telescope-mounted systems.

3.2 Assumptions

Damping is a major source of uncertainty in seismic design due to lack of suitable experimental data. Table 1[4] lists several damping sources relevant to telescope structure design. For transient analyses, Rayleigh damping will be employed, which involves modification of the mass and stiffness matrices by factors alpha & beta, respectively, to incorporate these damping sources. In relation to the more commonly used (but not applicable for transient analyses) damping ratio concept, the two factors can be used to generate a V-shaped damping ratio vs. frequency graph. Initially, alpha & beta damping coefficients will be conservatively chosen so that the constant damping ratio between 2 and 10 Hz, where the dominant vibration modes lie, is 1% or less (Figure 3). In addition, beta damping is defined locally for the springs representing soil. With alpha equals 0, a linear damping ratio vs. frequency relationship is generated where the soil damping ratio is 10% at 10 Hz. Further investigations will be conducted to determine whether higher damping values for the overall structure or specific components (e.g. bearings) is warranted, which would reduce structural accelerations and restraint load demand.

Table 1: Damping mechanisms

Damping Type	Energy Absorption Mechanism
Base/soil damping	Frictional interactions or movement between soil particles and/or the foundation
Frictional damping	Friction between bolted joints, restraints, attached walkways, cables and hoses, etc.
Viscous damping	Drag from air or wind as the structure vibrates in a medium
Control system damping	Mechanical, magnetic or hydraulic damping mechanisms (active or passive)
Structural damping	Inter-molecular interactions in the material from which the structure is made

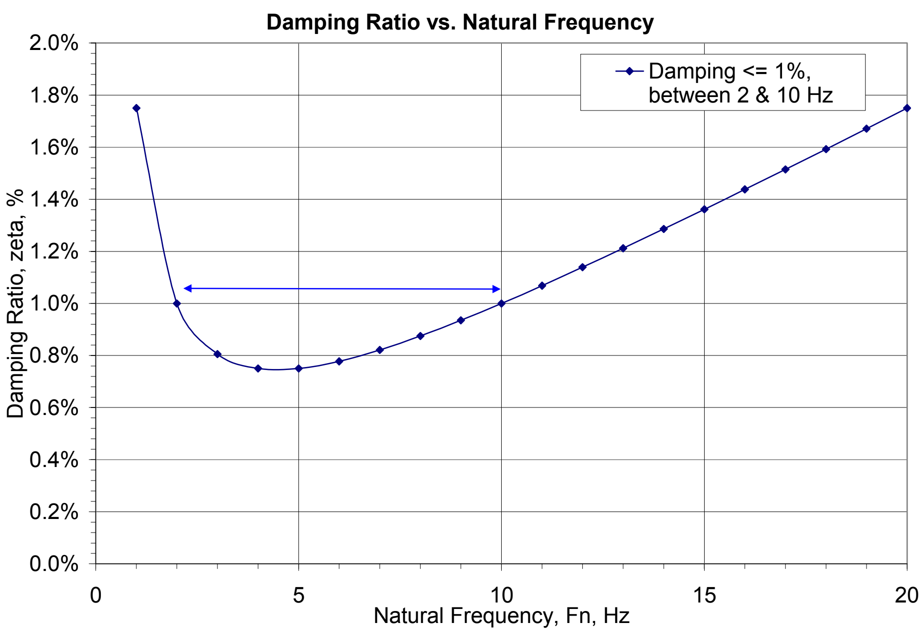

Figure 3: Damping ratio vs. frequency curve generated with the Rayleigh damping method.

Because a final observatory site has not been selected for TMT, site- and soil- specific ground motion time histories are not available for analysis. Instead, synthesized ground acceleration time histories based on a 500-yr return period earthquake in Mauna Loa, Hawaii are used [5]. This data set contains 40 seconds of motion in 0.01-second increments for all three orthogonal directions. It was used for the seismic analysis of the Gemini Observatories. The peak ground acceleration is 0.30g in the horizontal directions and 0.22g in the vertical direction.

3.3 Seismic loads

Seismic loads are applied simultaneously in three orthogonal directions as constrained displacements at the ground nodes. These loads are transmitted upward to the rest of the structure as described previously. Displacement inputs are constructed from the ground acceleration data by double-integration over time. Although 40 seconds' worth of data is available, peak structural responses can be captured with only 15 seconds of data and thus analysis times can be reduced by about half.

Currently, only one set of ground motion data (Hawaii) is being used. In the final analysis, multiple sets of ground motions will be employed. These ground motions will be generated by commercial software which incorporates local soil and seismology information. This includes soil stiffness, soil type, seismic event probability, and fault types & locations in the surrounding area.

3.4 Load cases

A large number of load cases need to be run to sufficiently understand the behavior of seismic restraints under various operational scenarios and restraint parameters.

The telescope is a dynamic structure that operates in multiple configurations. The zenith angle of the elevation structure is among the most important parameters, for several reasons: 1) the stiffness of the elevation structure journals (and thus the overall elevation structure) varies with zenith angle, 2) the height of telescope-mounted systems relative to the ground changes, and 3) the acceleration direction of telescope-mounted systems changes, which results in the need to consider inertial loads on the telescope optics in multiple directions. Other loading parameters include: HSB on or off oil (which alters bearing stiffness), elevation and azimuth structure brakes on or off (which affects rotational stiffness), Nasmyth platform instruments installed or not (which alters system mass and mass eccentricity), etc.

A major restraint design choice is whether to utilize nonlinear material behavior. The primary benefits of designing for elastic restraints, which deform proportionally to the applied forces, are quicker recovery from seismic events (since no damage) and simpler analyses. However, because maintaining elasticity implies constant restraint stiffness during an earthquake event, the resulting structural loads and instrument accelerations may become excessive, which would disqualify the elastic restraints from being a feasible solution. On the other hand, by utilizing nonlinear behavior, the restraints deflect linearly up to an elastic force limit, then displace with no (or low) stiffness afterwards while dissipating the seismic energy. The restraints themselves may require repair or replacements after the earthquake, but their ability to limit seismic loads on the structure helps maintain elasticity of the structural members. Examples of nonlinear devices include friction dampers, buckling-restrained braces, and yielded members. To further reduce seismic load, the brakes that resist elevation and azimuth structure rotations may be designed to allow slippage. The nonlinearity characteristics of the restraints and brakes are important parameters to be investigated.

The seismic restraints are co-located with the pintle bearing at the central base of the azimuth structure. The selection of load path is another design choice. The two lateral-load resisting devices (bearings and seismic restraints) can be loaded in series or in parallel. In the case of serial loading, seismic load flows from the ground to the restraints, then to the pintle hydrostatic bearing pads. In the case of parallel loading, seismic load is transmitted simultaneously to both components. Generally, parallel load paths result in restraints with higher load-resisting capacity and stiffness since stiffness of the components is additive. On the other hand, serially-loaded restraints are easier to install and align.

Tables 2 and 3 provide additional comparisons of linear vs. nonlinear restraints; and of restraints loaded in series vs. in parallel.

Table 2: Comparison of linear vs. nonlinear seismic restraints

	Linear Restraint	**Nonlinear Restraint**
Force transmitted to structure	Higher	Lower, since seismic load is limited by nonlinear behaviour
Required load capacity of the lateral HSB	Higher	Lower
Analysis complexity	Lower	Higher, requires use of time-consuming transient analysis
Analysis accuracy	Use standard analysis methods with confidence	More work is needed to verify result accuracy
Fabrication tolerance requirements	Similar	
Installation tolerance requirements	Similar	
Downtime	Short, since no damage	Longer, to repair/replace components
Relative cost	Lower	Higher repair/replacement costs[4]

[4] The higher costs may be offset by the lower telescope-mounted system costs which may be designed for lower seismic loads.

Table 3: Comparison of seismic restraints with serial and parallel load paths

	Serial	Parallel
Force transmitted to structure	Same if linear behaviour	
Required load capacity of the lateral HSB	Higher, since lateral HSB takes the same load as the restraint	Lower, since the restraint can be designed to take the majority of loads
Analysis complexity	Lower	Higher; need to be concerned about load sequence
Analysis accuracy	Use standard analysis methods with confidence	More work is needed to verify result accuracy
Fabrication tolerance requirements	Lower	Greater precision is required
Installation tolerance requirements	Lower	Greater effort required to align components so they are loaded as intended
Downtime from seismic event	Similar	
Relative cost	Lower	Higher

4. RESULTS

With transient analyses, an extensive amount of result data is generally generated over the time-history. However, the simplifications made by the substructuring technique can restrict the result extraction. Without resorting to time-consuming "expansion pass" analysis which essentially expands the simplified model back to the full model, nodal results are only available for nodes assigned as "master nodes" and elemental results can be extracted only from elements that are not part of the "super-element". However, with judicious selection of master nodes and exclusion of certain elements from the super-element, this restriction is not a major impediment.

Table 4 lists the results to be extracted from the time-history analysis which provide quantitative comparisons to guide the development and optimization of the seismic restraint design. Displacements, accelerations, and element forces are reported in three orthogonal directions where applicable in the component's local coordinate system. For member stress, results at only selected time points will be determined using expansion pass analyses. The time points will be selected based on the instances of high structural accelerations or restraint forces. For all other result types, time-history series of outputs will be determined.

As the seismic restraint design and analysis work is in progress, only representative results are provided in this paper. Figure 4 shows the Mauna Loa ground acceleration time history which constitutes the x-component of seismic load, peaking at 0.3g as mentioned. (The y- and z-components of loads are also applied, but not shown) The next two figures show the preliminary results for x-direction accelerations of M2 and M3 support points for both linear[5] and nonlinear models[6]. Table 5 summarizes the peak results of both cases. It can be seen that, comparing to the linear model, utilizing a nonlinear restraint in the nonlinear model results in lower peak accelerations. It should be understood that these results are preliminary and the current seismic restraint parameters have not yet been optimized for seismic performance. The following design and modeling strategies will be implemented to refine the telescope-mounted system seismic acceleration predictions:

- Utilization of component-specific damping ratios for bearings, restraints, and soil, where warranted

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[5] For the linear FE model, the restraint is modeled as a linear spring with a stiffness value of 1×10^9 N/m.
[6] For the nonlinear FE model, the restraint is modeled as a bi-linear spring with the same stiffness value of 1×10^9 N/m, but with an elastic force limit of 2000 kN at which point stiffness becomes zero. Similarly, the brakes are modeled as bi-linear springs to allow slippage upon exceedance of brake capacity.

- Optimization of seismic restraint parameters, e.g. stiffness, elastic force limit, nonlinearity, load path, energy-dissipation mechanism
- Optimization of the support towers for the telescope-mounted systems, e.g. stiffening of the M3 support structure will reduce M3 accelerations
- Integration of the M2 & M3 system structural designs with the support towers to minimize the acceleration amplification effect by structure

Table 4: Transient analysis results

Result type	**Item**
Nodal displacement Nodal acceleration	Both ends of seismic restraint elements Base of segment handling cranes Edges of Nasmyth platforms Selected M1 segment support points M2/M3 support points Centre of gravity locations of: Selected M1 segments M2/M3 Nasmyth platform instruments Laser guide star facility components
Element force	Elevation and azimuth structure hydrostatic shoe bearings Elevation and azimuth structure drives Elevation structure guideshoes Pintle bearing Seismic restraints
Sliding distance	Seismic restraints (if nonlinear)
Member stress	All elements where applicable, at selected time points

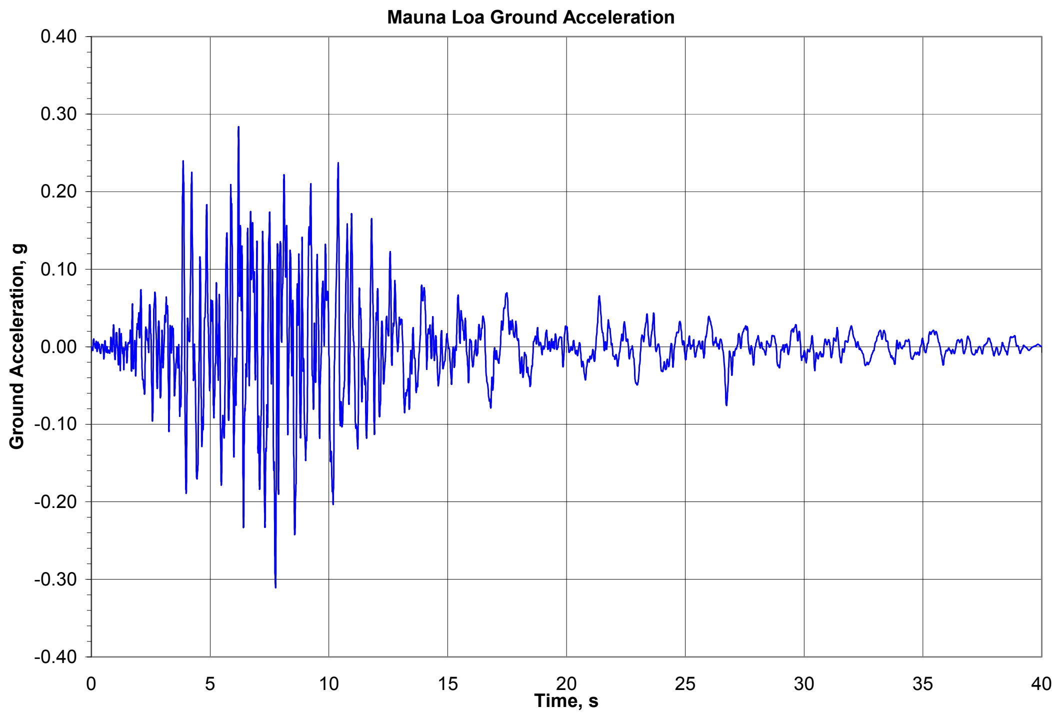

Figure 4: Lateral ground acceleration time-history, applied as constrained displacement in x-direction after double-integration over time. Only the first 15 seconds of data is used in the analysis. [Maximum = 0.30g]

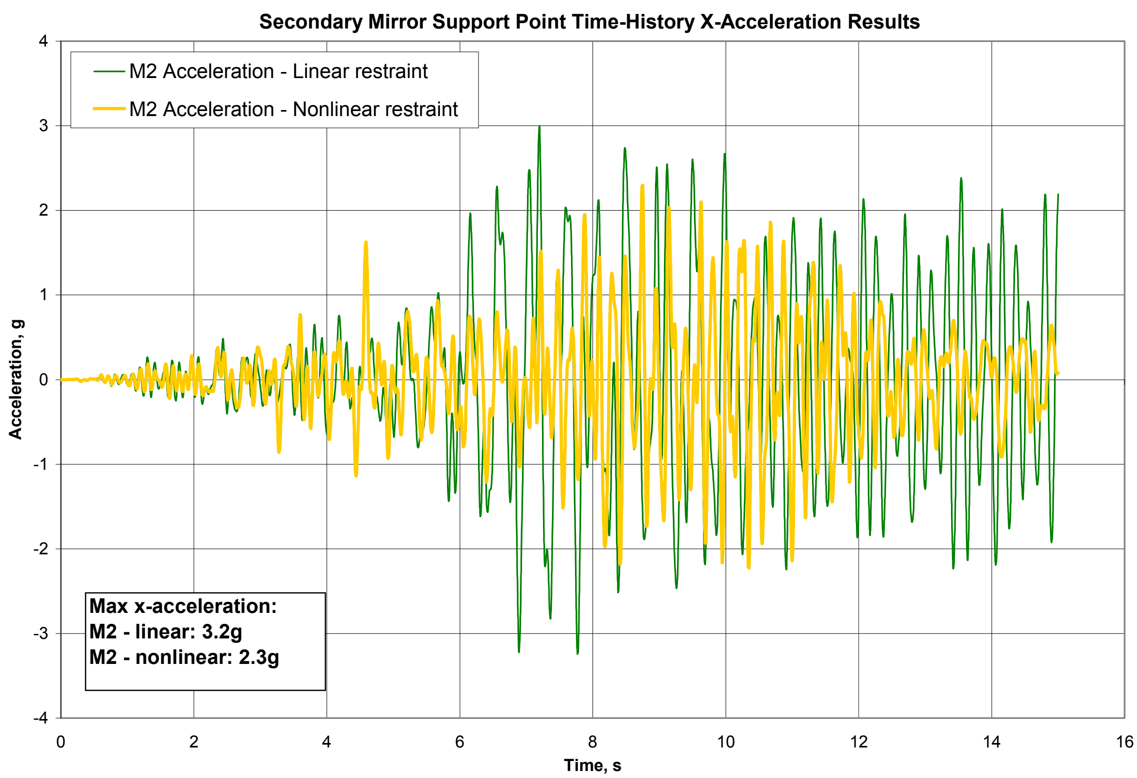

Figure 5: Comparison of M2 support point x-acceleration between models with linear vs. nonlinear restraints.

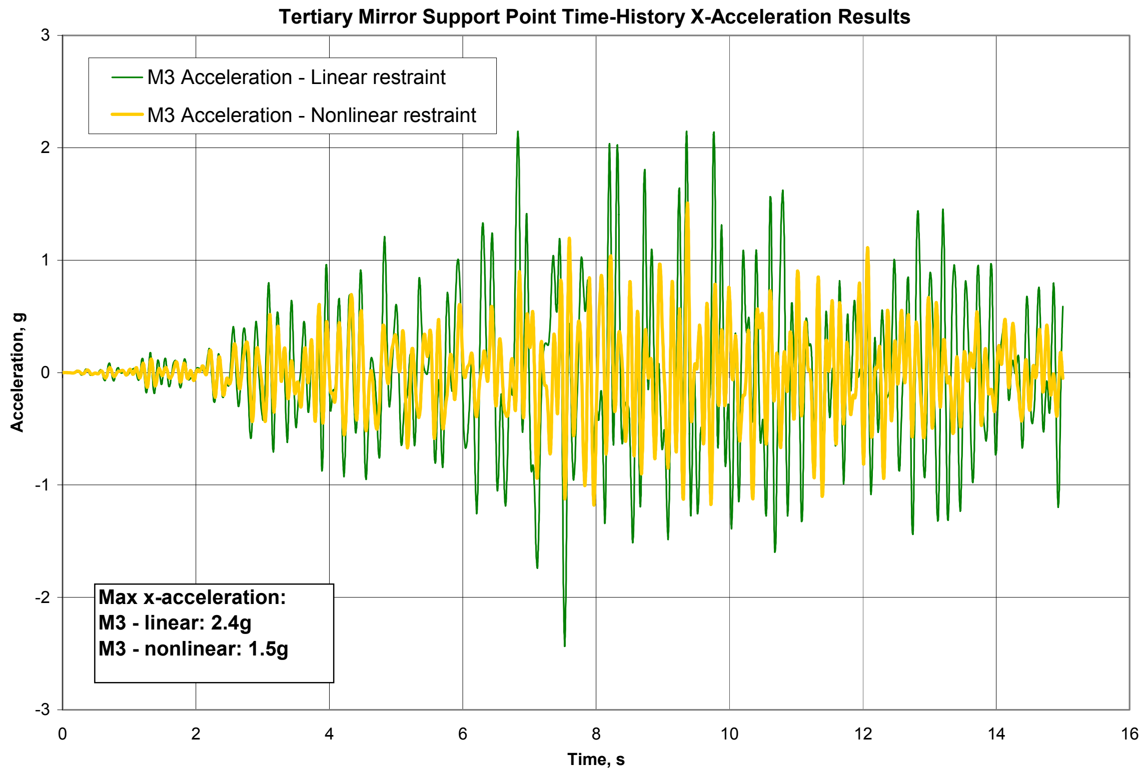

Figure 6: Comparison of M3 support point x-acceleration between models with linear vs. nonlinear restraints.

Table 5: Seismic accelerations of telescope-mounted systems, for linear and nonlinear FE models (in units of g)

Description	**Linear Model**			**Nonlinear Model**		
	x	**y**	**z**	**x**	**y**	**z**
M1 support frame	1.7	1.9	1.9	0.9	0.7	1.4
Nasmyth platform	1.3	2.1	1.4	0.7	1.0	1.4
M3 support point	2.4	3.8	1.5	1.5	2.3	1.4
M3 centre of gravity	3.0	4.6	2.5	2.1	3.0	2.4
M2 support point	3.2	5.0	1.5	2.3	2.0	1.5
M2 centre of gravity	3.7	6.1	2.8	3.1	3.1	2.8

5. IMPLEMENTATION CONSIDERATIONS FOR THE SEISMIC RESTRAINT CONCEPTS

Broadly speaking, there are two main methods of protecting structures from earthquakes and they may be termed restraint and isolation. The restraint method uses a structural tie that reduces a degree of freedom between two otherwise moving parts; for example, the pintle bearing assembly is a restraint between the azimuth structure and the azimuth track. The isolation method uses a spring, damper, or gap device that reduces the transmission of ground acceleration motion to a structure. Both types of devices may be sacrificial, i.e. damaged during a MLEC earthquake, provided the time needed to replace them is within the recovery specification of five days.

5.1 Pintle bearing assembly

The baseline design places five hydrostatic shoe bearings mated to a cylindrical steel track at the top of a structural column referred to as the pintle bearing assembly. By definition, the pintle bearing assembly provides the center of rotation for the telescope and reacts to forces only in the horizontal plane. Thus it serves as the lateral seismic restraint for the telescope structure by preventing it from sliding off the azimuth track. In so doing, the ground motions and seismic forces are transmitted through the bearings to the telescope. Currently, two implementations are under consideration:

5.1.1 Restraint in parallel with pintle bearings

An alternate pintle bearing configuration with three pairs of two bearings with each pair mounted to a load dividing bogie is shown in Figure 7. This concept, as shown in Figure 7, places a second structural load path beside the pintle bearings to protect them from earthquake forces that would otherwise damage them.

5.1.2 Isolation in series with pintle bearings

This concept places springs or slip-able elements at any one of the interfaces along the horizontal seismic load path between the pintle bearing pier support column and where the pintle bearing assembly contacts the azimuth structure. Ideas under study include tailoring the spring rate of the pintle column itself, installing industrial slip devices between the bearing assemble and the azimuth structure, and, mounting the pintle bearings on force-limiting bogies.

5.2 Azimuth bearings and azimuth track

Due to the 17.6m vertical offset between the telescope centre of mass and the pintle bearing assembly, the horizontal ground acceleration will create reactions at the azimuth bearing locations which subtract from and add to the static weight reactions. Upstops can be used to prevent uplift of the azimuth bearings if the compressive load falls below zero.

The FE simulation will provide the peak compressive reactions at each azimuth bearing during the earthquake and determine whether the current size and number of bearings is sufficient to survive the MLEC earthquake. Alternate configurations under study with greater load capacity for the azimuth bearings are six pairs of HSB600 size bearings with each pair mounted to a load dividing bogie, or alternatively, four sets of 3 at four corners, where each set of 3 bearings is mounted on a load dividing bogie.

In this case seismic restraints are needed to prevent the telescope from lifting up off the azimuth track. A current concept uses a mechanical upstop restraint shaped like a hook that reaches under the azimuth track plate's edge and runs with a small amount of clearance during normal operation (Figure 8). Again FE analysis will be used to establish the need for and strength required of the upstops, their connections, and the azimuth track.

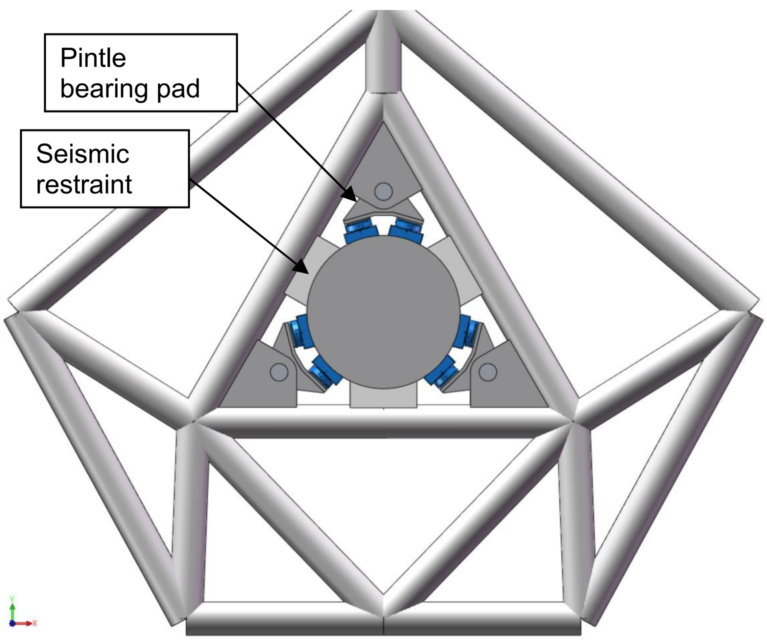

Figure 7: Plan view of azimuth structure seismic restraints and pintle bearing pads in parallel load path.

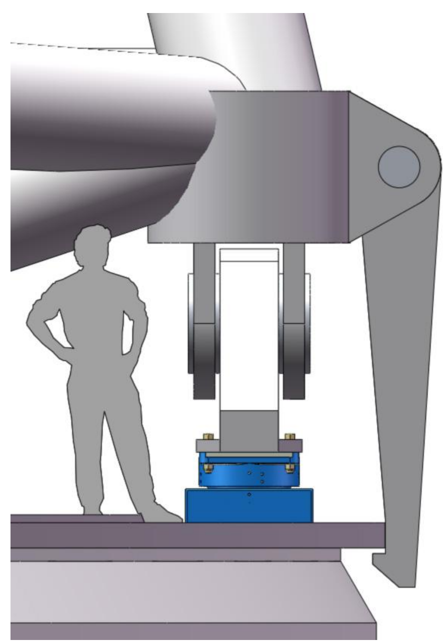

Figure 8: Elevation view of an upstop device.

5.3 Elevation bearings and rockers

The current design mates 2 HSB600 hydrostatic shoe bearings to each of the two 10.75m radius elevation journals, with each bearing placed 25° off of vertical to cradle the journal. This gravity-organized bearing system requires static and seismic restraint in the direction of the elevation axis. The current design places additional hydrostatic shoe bearings against the flat faces of the journals to provide this constraint. The baseline assumption is that the elevation seismic restraint is expected to be linear system. FE simulation will be used to size these bearings and determine if additional restraint or isolation is required and to determine if upstops are needed to prevent the elevation journals from lifting off of the main elevation bearings.

6. CONCLUSION & FUTURE WORK

The seismic restraint design is in progress. Upon generation of the full first set of transient analysis results, the restraint design space (stiffness, nonlinearity mechanism, load path, etc) can be considerably narrowed. Further analyses will then be conducted with a point design to examine a comprehensive set of load cases to ensure that the telescope structure and the telescope-mounted systems will be sufficiently protected under various telescope configurations and load scenarios. For these analyses, site- and soil-specific ground motion data, and realistic global & component-specific damping values will be defined to obtain accurate responses.

Finally, the seismic design and analysis methodology will enable an integrated telescope structure and seismic restraint system to be optimized efficiently and to ensure that the telescope-mounted systems maintain safe acceleration values.

ACKNOWLEDGEMENT

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