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Vibration Measurements in the Daniel K. Inouye Solar Telescope

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ABSTRACT

The Daniel K. Inouye Solar Telescope (DKIST) will be the largest solar telescope in the world, providing a significant increase in the resolution of solar data available to the scientific community. In large ground-based telescopes, vibration of telescope optics caused by the telescope subsystems is typically the limiting factor of image resolution.[1] The impact of vibration increases with the resolution of the telescope and is therefore a much greater problem in long focal-length telescopes, such as the DKIST. In addition, vibration is a consumer of the adaptive optics image-quality error budget limiting the correction available for atmospheric seeing. In some cases, the adaptive optics might even amplify the vibration at higher frequencies. For all of these reasons, a vibration error budget is a critical component in any large telescope project, and a plan for active vibration management and mitigation is critical to the success of a large telescope project. In the design of a large telescope, finite element analysis is employed and this is historically the only effort put into understanding vibration issues. However, after the telescope mount is constructed and the instruments and ancillary equipment are more clearly defined, there are many opportunities to perform path analyses by directly measuring the low-frequency single-input-single-output (SISO) frequency response function (FRF) between vibration source locations and image motion on the focal plane. These measurements are carried out using inertial-mass shakers along with seismic accelerometers providing an accurate measurement of the image degradation that will be caused by vibration sources in various locations. This allows the designers to determine an appropriate vibration mitigation plan (if needed) long before the vibration source is attached to the telescope. These measurements have proven sensitive enough that they can be performed for equipment not mounted on the telescope structure but located in the telescope building or even in nearby buildings. In a previous paper, techniques were described for measuring vibration which is particularly challenging at frequencies below 10 Hz where accurate measurement requires several noise reduction techniques, including high-performance windows, noise-averaging, tracking filters, and spectral estimation. In this follow-up paper, the development of the DKIST vibration budget detailing the advantages of the shaker measurement technique is described, along with examples of testing performed on the DKIST structures currently under construction at the Haleakala High-Altitude Observatories site in Maui, HI.

Keywords: Vibration, vibration budget, transfer path analysis, TPA, frequency response function, FRF, jitter, shaker, accelerometers

1. INTRODUCTION

The DKIST vibration error budget was based on an approach pioneered by Douglas MacMartin and Hugh Thompson from the Thirty Meter Telescope (TMT).[1] The development of measuring techniques using an inertial mass shaker and high-sensitivity seismic accelerometers to map vibration into units of on-sky image motion has been described previously.[2,3] This paper continues this work by detailing the development of the DKIST vibration budget using the aforementioned measuring techniques. The DKIST vibration budget is a work in progress, and while not complete, the process of detailing the vibration budget is well understood and will be described closely.

The development of the vibration budget began with estimates from the Finite Element Analysis, and as the project moved through factory testing and then into construction, refinements to the vibration budget were made using measured data. In addition, as the adaptive optics (AO) system continued development, a more accurate

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AO transfer function was determined and this new transfer function was used to further refine the vibration budget.

2. TRANSFER PATH ANALYSIS AND TELESCOPES

In order to properly measure and analyze the forces of the telescope system components and the effect they have on image motion, a quasi-Transfer Path Analysis technique will be applied to the data collected. Transfer path analysis (TPA) is well established in the automove and aircraft industries for the reduction of vibration and noise which typically traces the flow of vibro-acoustic engergy from a source. In a telescope, however, the concern is the structure-borne vibration issues as the telescope does not have any specific requirement for air-borne noise. In addition, the frequencies of concern are much lower than in a typical TPA: typically 0.5 - 500Hz as opposed to 300 - 20,000 Hz or more. The goal of a normal TPA is to evaulate the contribution of *source(s)* (instrument/mechanical components) along each path to the *receiver(s)* (optics/image) so that the components along the path can be altered and optimized.

There are also some variations on this technique, such as Operational Transfer Path Analysis (OTPA), which is a method using only data collected under normal operating conditions; no outside forces are imparted to the system. The goal remains the same as in a TPA, to find linearized Transfer Function (TF) matrices between inputs and outputs from a measurement. Other variations include Operational Path Analysis with Exogenous Inputs (OPAX), Gear Noise Propagation, blocked-force TPA, Virtual Acoustic Prototyping, etc. The underlying concepts are very similar and many of these methods have been developed for highly case-specific instances.

It is worth noting that Transfer Path Analysis and all the varying forms of the algorithm have the same basis as the Multiple Input Multiple Output (MIMO) testing technique. MIMO is based on the technique of using multiple input sources (or single input source with extensive fixturing) and collecting data from multiple outputs simultaneously. In Experimental Modal Analysis, both MIMO and TPA methods can be seen as a least squares estimate. This type of testing is also useful in the event that a SDOF (Single Degree of Freedom) is inadequate at distributing the energy required to excite the structure, and MIMO decreases overall testing time since there's no need to change fixturing and orientation of the source.

In analyzing telescope vibration, a typical TPA will not actually be necessary, or plausible. Much of the permanent and pathway components are in place and alterations are very resticted or impossible due to design or integration factors, therefore it is not feasable to use the standard TPA technique. Instead, measurements will be conducted at each mount location with the shaker (making sure to use random noise or sweeps for minimization of coherence between inputs and results) and changes to the movement of the optics will be recorded. Based on the resultant measurements, isolating solutions will be designed and implemented at the source location for vibration reduction, rather than changing components within the telescope structure along paths of transmissibility. Therefore, it could be said that DKIST employs a combination of techniques from the variations of TPA to complete the vibration analysis.

3. DKIST VIBRATION BUDGET DEVELOPMENT

Vibration was not thoroughly considered in the early development of DKIST specifications, but mount jitter was included. In the DKIST optical error budgets, in the seeing-limited coronal-delivered image quality use case, telescope performance is specified to be 50% encircled energy diameter less than 0.7 arcsecond (arcsec). The detailed optical error budget breakdown allocates 140 milli-arcsecond (milli-arcsec) for telescope mount jitter. This is the only allocation in the many telescope specifications for vibration and therefore is considered the limit of all telescope vibration sources. Fortunately, the combined axes of the telescope mount produce a jitter of less than 70 milli-arcsec of on-sky image motion at maximum tracking velocity. Although the specification is without reference to vibrational frequency, it provided a starting point for the development of the telescope vibration budget. Combined with the DKIST AO system, a frequency weighted specification was developed.

Figure 1. DKIST (left) and Pan-STARRS telescopes

3.1 A Frequency Weighted Vibration Budget

The AO system has the ability to correct for low frequency vibration with decreasing correction ability as the frequency increases[*]. Applying frequency weighting to the 140 milli-arcsec specification includes the effects of the AO system in vibration.

Fig. 2 shows three plots of the estimated transfer function for the AO system. *Old TF* was the original plot made when the DKIST AO system was early in development. The other plots show more recent estimates of the AO transfer function with *Stable TF* as the preferred option and *Minimum RMS TF* as the worst-case scenario.

An AO corrected frequency weighted vibration allocation was developed by first simplifying the AO waveform as shown by the red dashed plot line in Fig. 3. Inverting the simplified AO transfer function and multiplying it by 140 milli-arcsec produced a frequency weighted telescope wide vibration limit as shown in Fig. 4.

[*]In fact, the AO system amplifies vibration by a factor of 2 near 100 Hz, making matters slightly worse near this frequency.

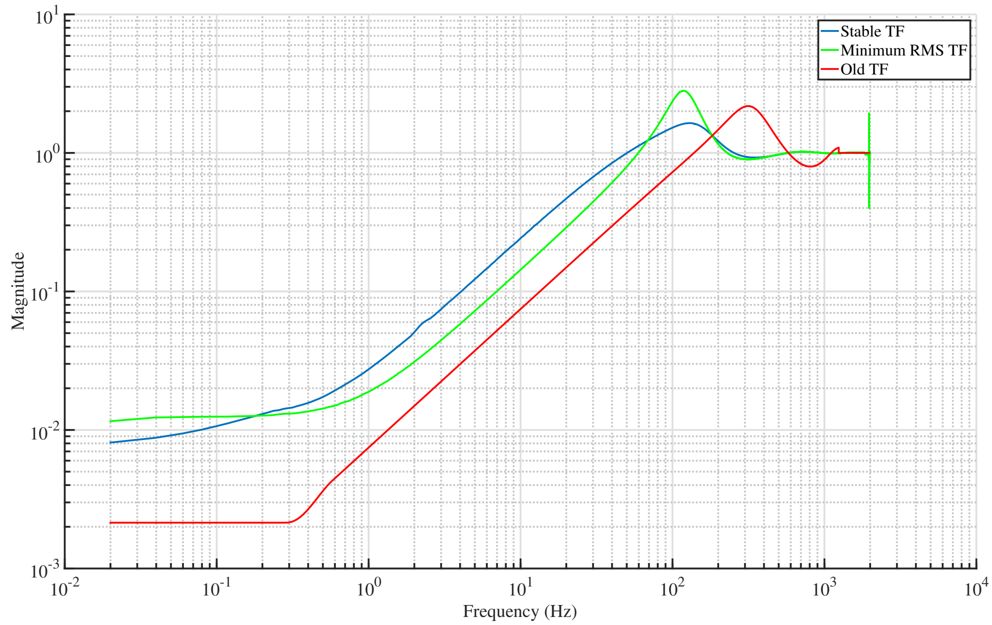

Figure 2. AO Error Magnitude Transfer Functions

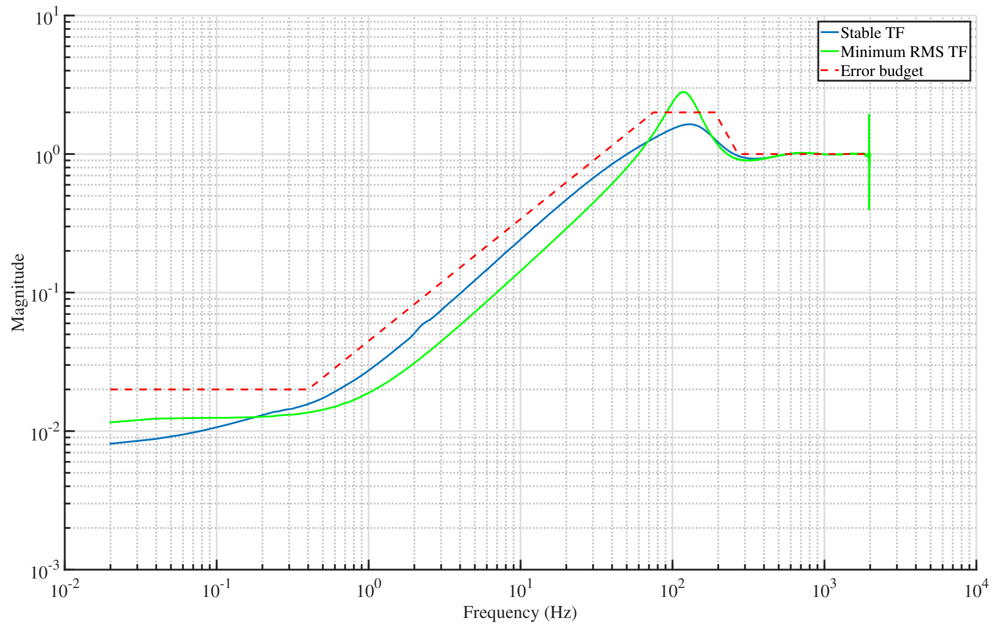

Figure 3. AO Transfer Functions with Approximation

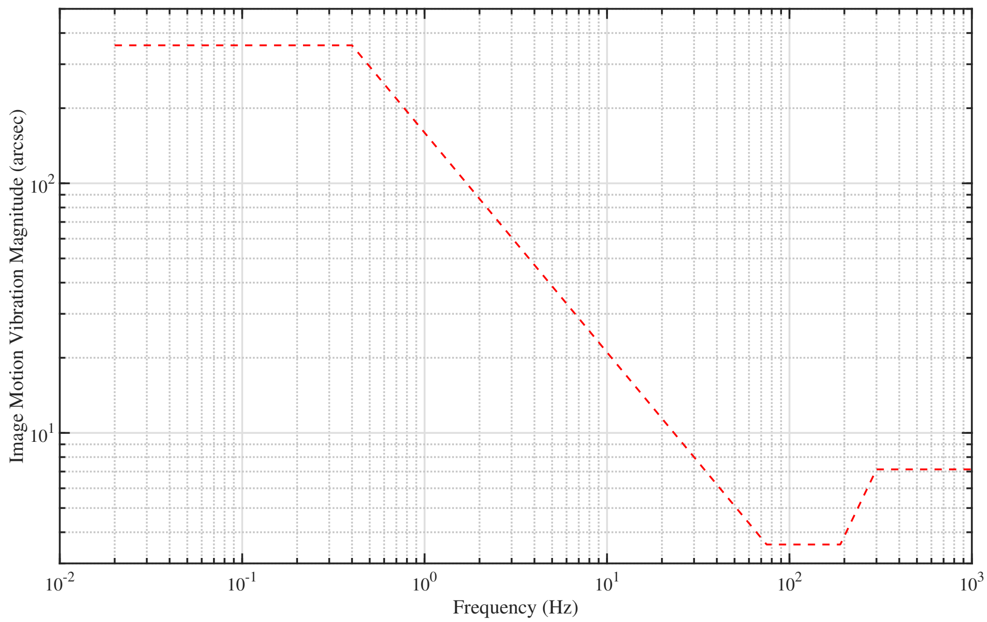

Figure 4. Frequency Weighted Vibration Budget

3.2 Telescope Mount Vibration

The DKIST telescope mount consists of three large drive systems: the telescope azimuth, telescope altitude, and coudé rotator (a rotating instrument lab) as shown in Fig. 5 and Fig. 6. The telescope mount was expected to be a large consumer of the vibration budget.

Azimuth axis: The dominant source of vibration from the telescope mount was found to be the azimuth axis due to direct coupling of the vibration into the most sensitive optics, particularly the primary and secondary mirrors, M1 and M2, respectively.

Altitude axis: The altitude axis uses a pair of direct drive servo motors and therefore contributes significantly less vibration than the azimuth axis.

Coudé rotator: The coudé rotator utilizes a drive similar to the mount azimuth drive, but vibration is attenuated in the image motion conversion when compared to the azimuth axis.

Measured mount vibration was 70 milli-arcsec at maximum tracking velocity. This appeared to be a significant part of the 140 milli-arcsec vibration budget, but when applied to the frequency-weighted budget, the situation was improved as shown in Fig. 7.

Mount vibration is concentrated at low frequencies where the gain of the AO system is good. In the 4-5 Hz range where the mount vibration peaks, the frequency-weighted budget is $\approx$ 800 milli-arcsec. Surprisingly, the mount drive axes are not a dominant contributor to telescope vibration.

3.3 Vibration Budget: Areas, Locations, and Devices

The DKIST vibration budget contains three layers of detail referred to as: *areas, locations,* and *devices.*
The first step in creating vibration budget allocations was to list the major areas where vibration sources were likely to be. Each area is defined with the idea that the severity of vibration anywhere in a given area is approximately the same.

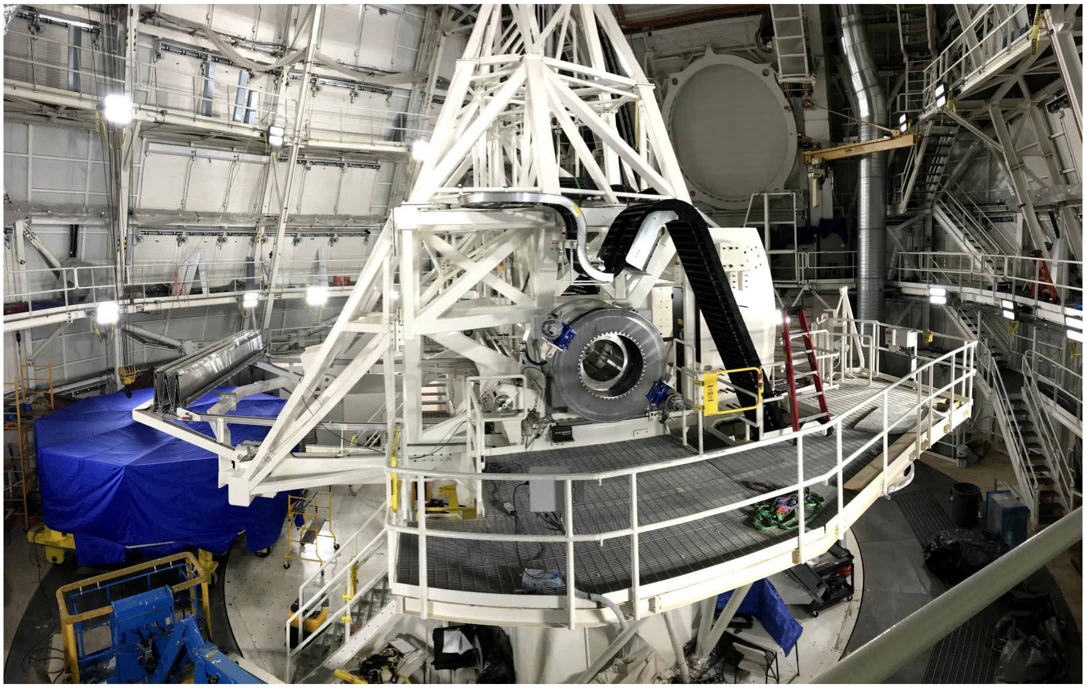

Figure 5. Telescope Mount and Nasmyth Platform

Figure 6. Coudé Rotator Panorama

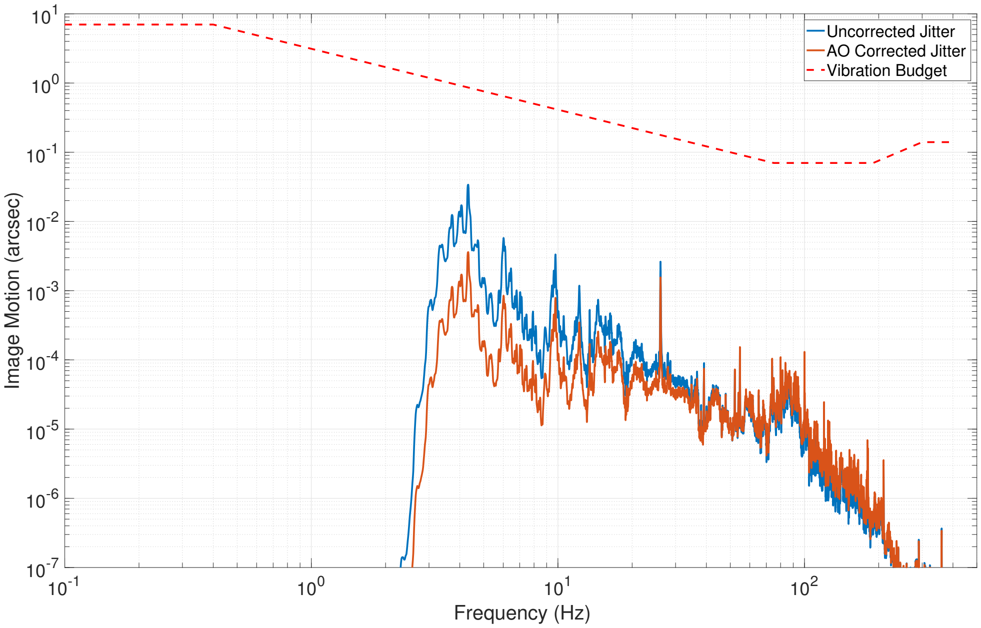

Figure 7. Measured Mount Vibration at Maximum Tracking Velocity. Note: the average vibration is near 30 milli-arcsec. This seems to be at odds with the 70 milli-arcsec reported earlier. The 70 milli-arcsec was peak jitter, but the figure shows an FFT plot which averaged the jitter amplitude and did not catch the occasional peak.

3.3.1 Areas

The four identified *areas* in and around the telescope are:

Telescope Foundation: The DKIST telescope and coudé rotator sit on concrete piers cast into the deep concrete telescope foundation. Since they share the same foundation, all vibration sources on the telescope and coudé piers couple directly into the telescope mount and therefore the telescope optics. For this reason, the telescope foundation and everything attached to it is the most critical area.

Enclosure Foundation: The enclosure pier is cast into the enclosure foundation which encircles the telescope foundation. The telescope enclosure and operations portions of the telescope are built on the enclosure pier and are therefore mechanically coupled to each other. The use of a foundation separate from the telescope foundation allows a level of decoupling from the mount for equipment vibration and wind shake buffeting the enclosure. All piping and electrical connections crossing the boundary from the enclosure pier to the telescope pier utilize flexible sections to limit the transfer of vibration; and, although the enclosure pier is mechanically separate from the telescope pier, it still couples through the soil to some extent. This area is therefore the second most sensitive area.

Utility Building: The large pumps and compressors are located inside the Utility Building some distance from the telescope piers. The cooling fluids and electrical circuits are connected to the telescope through an underground tunnel. Like the enclosure pier, the utility foundation is coupled to the telescope pier through the soil, although the physical distance dampens this coupling to a large extent.

Outside Areas: The outside areas consists of the roadway, parking lots, walking trails, concrete aprons, and construction buildings. During operation, these areas are expected to be quiet with the exceptions of an occasional car on the roadway or in the parking lots. Cars driving past the telescope can easily be seen in the vibration measurements and quantifying the level of these areas is planned.

3.3.2 Locations

The *locations* of possible vibration sources in each of the four areas are shown in Table 1.

Table 1. Vibration Source Locations.

Mount	**Coudé**	**Enclosure**	**Other**
TEOA	Rotating Floor	Pier	Utility Bldg Upper Floor
Gregorian Station	Rotating Racks	Top Arch Girder	Utility Bldg Lower Floor
Right Nasmyth	Outer Ring	Mid Level	Roadway
Left Nasmyth	Cable Wrap	Floor Level	Parking Lot
Bridge	Fixed Floor	Service Ring	Loading Bay
M5/M6 Tower		Utility Level	Apron
Telescope Floor		Mezzanine Level	High Bay
M1 Cell		Ground Level N.	
Service Ring		Ground Level S.	
Utility Level			

3.3.3 Devices

Vibration sources are referred to as *devices* in the vibration budget and this convention is used here. A *device* is any vibration source in the vicinity of the telescope and can be a single coolant pump or a rack full of equipment. A device can be thought of as a discrete package that will be installed onto the telescope as a single object and not part of a subsystem (such as a fan inside a rack of equipment).

3.4 Types of Vibration

Vibration is more-or-less stochastic (random), so vibration sources are generally added in quadrature as shown in Equation 1. This statement is approximately accurate for fluid flow, bearing noise, and even induction motors. In induction motors, rotor slip prevents phase synchronization between motors if the motors are not mechanically coupled. Synchronous motors are phase coherent, but the phases are likely to be random in relation to each other and so fall into a gray area. Models of synchronous motors running at the same frequency but with random phase alignment show that the amplitude of the vibration adds in quadrature, however, experience indicates otherwise. A possible explanation is that if two motors couple into a structural mode, they are coupled through the structure and tend toward self-synchronization. The vibration of motors that are self synchronized add directly (not in quadrature) and this can be problematic. Best practice is not to have synchronous motors at all or to put all motors on variable frequency drives (VFD) so they can be set to slightly different rotational velocities to minimize vibration issues arising from an excess of vibrational energy at fixed frequencies.

For stochastic vibration sources, the vibration from n sources s add in quadrature.

$$Vibration_{total} = \sqrt{(s_1)^2 + (s_2)^2 + ... + (s_n)^2} \tag{1}$$

3.5 Vibration Budget Allocations

The list of DKIST vibration locations listed in Table 1 totals 31 locations. Calculating the allowable contribution from each souce can be done by normalizing each source amplitude to 1, where

$$Vibration_{total} = \sqrt{s_1^2 + s_2^2 + ... + s_n^2} \tag{2}$$

$$Vibration_{total} = \sqrt{1 + 1 + ... + 1} \tag{3}$$

$$Vibration_{total} = \sqrt{number\ of\ sources.} \tag{4}$$

Inverting Equation 4 gives the fractional contribution of each source for $Vibration_{total} = 1$, where

$$\frac{1}{\sqrt{number\ of\ sources}} = contribution\ per\ source. \tag{5}$$

For DKIST where there are 31 locations,

$$\frac{1}{\sqrt{31}} = contribution\ per\ source. \tag{6}$$

$$contribution\ per\ source = 0.180 = 18.0\%. \tag{7}$$

For DKIST, the source locations each have an amplitude of 18% of the total budget as shown in Equation (7). Using the DKIST vibration budget, if each of the 31 locations contribute 25.2 milli-arcsec (18% of 140 milli-arcsec), the total telescope vibration will be 140 milli-arcsec. Therefore the first step in allocating the vibration budget is to limit each of the 31 locations an equal share of the vibration (25.2 milli-arcsec in the DKIST vibration budget).

The second step is to identify the number of devices (vibration sources) in each of the 31 locations. For example, if one of the 31 locations contains 10 individual devices, each device will be allowed to contribute $1/\sqrt{10} = 31.6\%$ of the 25.2 milli-arcsec from the previous paragraph. 140 milli-arcsec $\times 18.0\% \times 31.6\% \approx 8$ milli-arcsec. When each location has been determined and the expected number of devices estimated, the vibration budget has become a list of the maximum image degradation allowed by each device.

The list of allowable image motion degradation allocated to each device is not useful to the device design team. To be useful, the sensitivity of the location where the device is mounted must be understood. In other words, how much force at a given location does it take to create a given level of image motion. For this, we need a path analysis between the location and the telescope optics. This analysis is performed by measuring the Frequency Response Function (FRF) between the location and image motion.

3.6 Path Analysis using the Frequency Response Function

Performing a path analysis by measuring the FRF involves the use of an inertial-mass shaker moved to each location and accelerometers located at the telescope optics. The units of the FRF are *Newtons of input force* to units of *arcseconds of on-sky image motion*. Details on the equipment and techniques to perform these measurements have been developed and described in detail.[2,3]

The FRF is the function that maps input force to image motion for each location in three dimensions. An example of a measured FRF from one of the DKIST Nasmyth Platforms is shown in Fig. 8. DKIST will need 31 of these measurements, one from each vibration location. Grouping the devices into locations saves measuring the transfer path from each individual device, although some locations may need more than one transfer path (checks should be made at various places in a large or complex location to ensure that the FRF captures the transfer path throughout the location). Given the results of past measurements, so far, moving the shaker to different places in a given location typically has little effect.

The FRF plot in Fig. 8 contains three plot lines, one for each orientation of the shaker (the plot lines are intentionally made fuzzy where the FRF coherence is less than 80%). The FRF plots create the needed sensitivity and frequency weighted connection between each vibration source location and the vibration budget.

The DKIST Nasymth platform is shown in Fig. 9. The Nasmyth platform is one of the 31 locations and so has a vibration budget allocation of 25.2 milli-arcsec (18% of 140 milli-arcsec) allocation. But this 25.2 milli-arcsec budget must be divided between the four racks of equipment and the coolant lines for a total allocation of 1/5 of the 25.2 milli-arcsec per device. $1/\sqrt{5} \times 25.2 = 11.3$ *milli-arcsec.* Fig. 10 Shows the Nasmyth FRF plotted again in a log-log scale along with the vibration budget developed above and scaled to 11.3 milli-arcsec.

To calculate the force that will equal the budget allocation, the budget is divided by the FRF value at any given frequency. In this example, at 55 Hz, the budget is 7.5 milli-arcsec and the FRF is 5 milli-arcsec $\frac{7.5 milli-arcsec}{5 milli-arcsec/N} = 1.5N$.

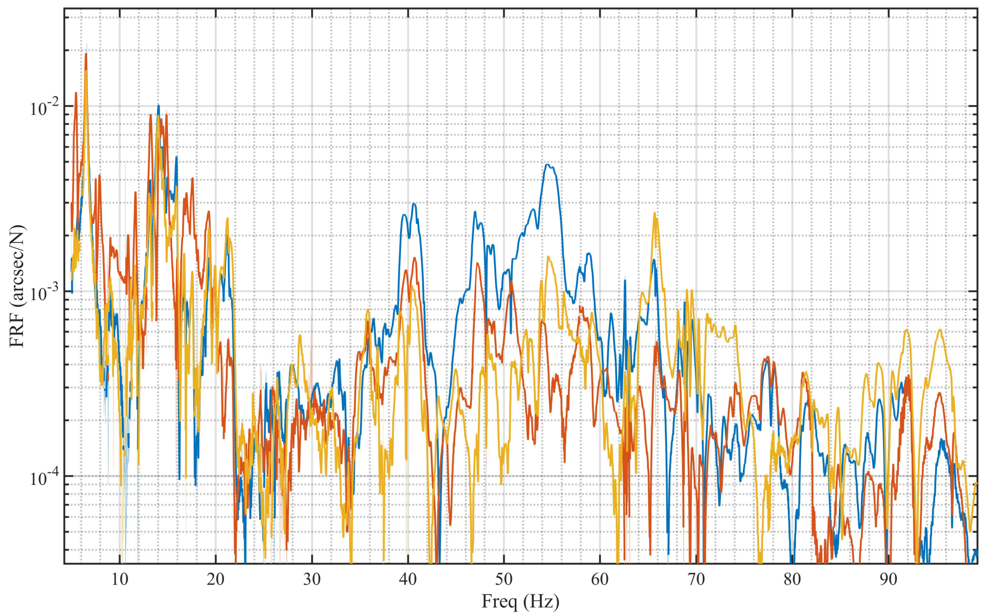

Figure 8. FRF of the -X Nasmyth Plaform

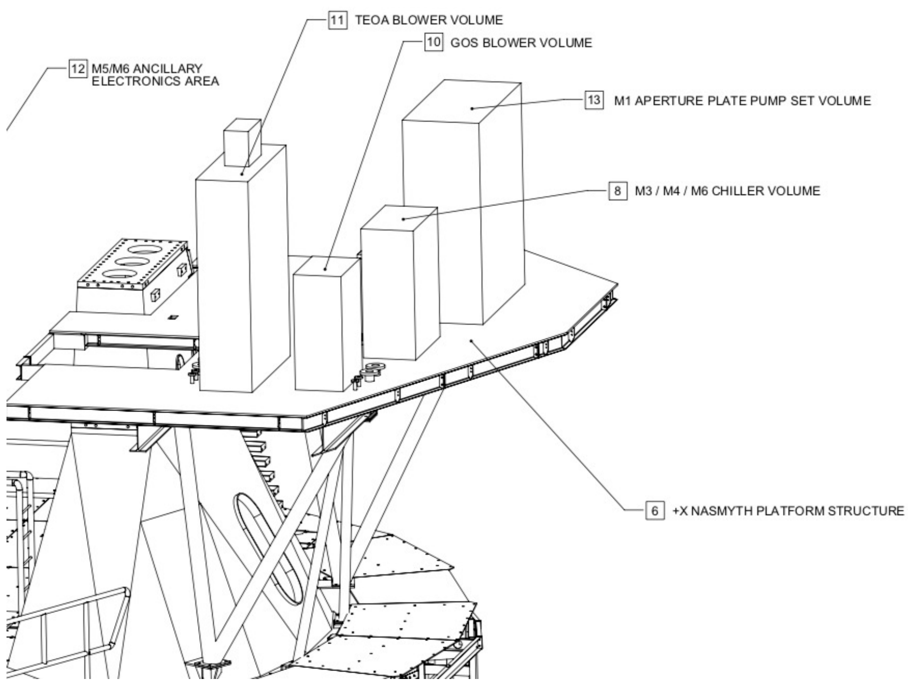

Figure 9. DKIST Nasmyth Plaform

This means that each device on the Nasymth platform must transmit less than 1.5N of force to the Nasmyth Platform location at this frequency.

A specification in units of force vs frequency is easily measured by a partner or contractor building a device, long before the device is delivered to the telescope. This approach gives time for vibration mitigation to be

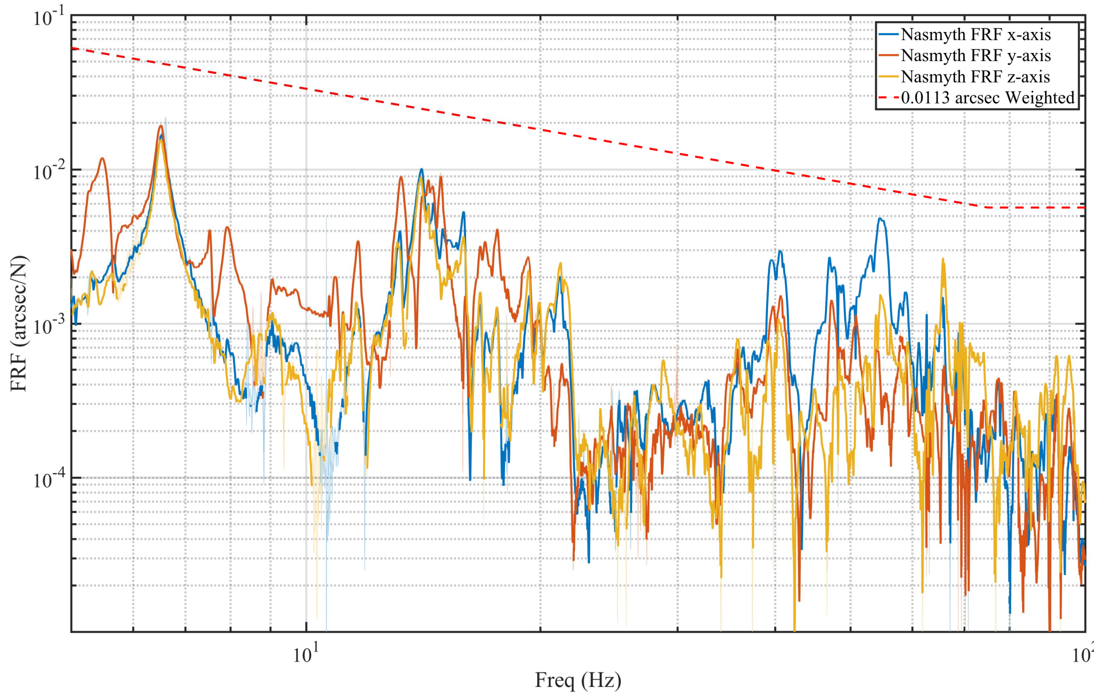

Figure 10. FRF of the -X Nasmyth Platform with Budget

implemented before the device arrives at the telescope and panic ensues. Measuring a device simply entails placing the device on load cells and measuring the forces in various orientations. A simple Fourier transform will convert the load cell data into a function of force vs frequency which can be directly compared to the FRF.

Defining the budget for the Nasymth platform location as a flat 1.5N of force for each piece of equipment is the simple solution, and will certainly suffice for less sensitive areas in the telescope, but a frequency weighted specification is a refinement that allows the device engineers more flexibility. In the Nasymth example, a frequency weighted specification could be written as shown in Table 2.

Table 2. Frequency weighted Location Budget.

0 - 50 Hz	2.5N
50 - 60 Hz	1.5 N
60 - 70 Hz	2.5 N
above 70 Hz	5 N

A better alternative for very sensitive locations such as our example Nasmyth platform is to provide the device designers with the FRF and allow them to ensure that they don't exceed their budget.

An example of where this might be valuable: Assume the device engineers had a small 3600 rpm induction motor coolant pump that they found was producing 3N of vibration at 55 Hz (the most sensitive frequency for the Nasmyth Platform). Armed with the FRF, the device engineers might choose to replace the motor with a larger 1800 rpm unit moving the rotational frequency from 55 Hz to 27 Hz where 300N of force produces less image motion than 3N at 55 Hz. Another solution might be to keep the 3600 rpm motor but ensure that the orientation of the vibration is in the y-axis or z-axis. If the vibration is aligned to minimize the force on the x-axis, 3N meets the vibration budget.

The use of the FRF is a powerful tool in vibration planning and mitigation. It gives the project the ability to create a very detailed set of vibration specifications to provide to teams developing the subsystems, and it gives the development teams a powerful tool that allows them a broad range of options to mitigate vibration problems.

3.6.1 Conclusion

The methodology and measurement techniques have been developed and described for the DKIST vibration budget. A few measurements have been made, mostly in the factory test phases, but enough to gain confidence in the approach and validity of the measuring techniques. It was hoped that some of the on-site measurements would be finished at this point, but schedule pressure in the construction phase has derailed these efforts to date. Nevertheless, plans and resources have been allocated to perform the location measurements and to provide the device providers with useful vibration budgets. Some of these budgets will come too late, and the task of vibration mitigation will fall on the project. But attempts will be made to quantify and mitigate the issues before the equipment is mounted to the telescope. The vibration budget as described in this report has proven to be a powerful tool to identify and mitigate vibration issues long before they surprise everyone on the day the telescope achieves first-light.

APPENDIX A. IMAGE MOTION TO WAVEFRONT TILT CONVERSION

Given:
$D = 4m$ (DKIST telescope aperture)
$a =$ radians of image motion
$x =$ meters P-V wavefront tilt.

$x = D \times a = 4 \times a$

Converting from P-V wavefront tilt to rms wavefront tilt:
Let X = RMS wavefront tilt
Since the ratio between P-V and RMS for tilt on a circular aperture is 4
$4 \times X = 4 \times a$
thus,
$X = a$

Where X is in units of meters of rms wavefront tilt
And a is radians of angular image motion

Conversion to more useful units:
X (rms radians)$\times 206265 =$(rms arcseconds)
a (radians) $= X$ (meters)$\times 1e9 =$(nm)
so the conversions are,

$2.06265 \times 10^4 (\frac{\text{arcsec}}{\text{nm rms wavefront}} = 0.206265 \frac{\text{milli-arcsec}}{\text{nm rms wavefront error}}$
or,
$4.84814 \frac{\text{nm rms wavefront tilt}}{\text{milli-arcsec image motion}}$

The DKIST vibration allocation of 140 milli-arcsec equates to ≈ 680 nm rms wavefront tilt.

ACKNOWLEDGMENTS

The authors would like to thank Luke Johnson for Appendix A and for developing the AO transfer functions. The authors would also like to thank Doug MacMartin and Hugh Thompson for the very idea of a vibration budget, and express that we do hope to work more closely with TMT (schedule pressure is the only excuse we can give for our terrible lack of communication, but we do plan to do better).

Other telescope projects interested in further developing the ideas in this paper are encouraged to contact the authors. Vibration is the limiting factor in large ground-based telescope performance and we feel it is important that vibration error budgets become as common as optical error budgets. The research reported herein is based in part on data collected with the Daniel K. Inouye Solar Telescope (DKIST), a facility of the National Solar Observatory (NSO). NSO is managed by the Association of Universities for Research in Astronomy, Inc., and is funded by the National Science Foundation. Any opinions, findings and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the National Science Foundation or the Association of Universities for Research in Astronomy, Inc.

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