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Disturbance effects on a ground based precision tracking system

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Abstract

A major concern when considering the design of a ground based precision tracking system, is the optical jitter that will result from various environmental disturbances. This paper considers disturbances including wind, angular seismic, linear seismic, gyroscope noise, electronics noise, and atmospheric turbulence. The disturbances may couple into a tracking system by applying forces or torques directly on the optical components, or by transmitting through the control loops which in turn place jitter into the optical path. The tracking system design can be altered by using different control system configurations to reject the expected disturbances. For instance, if seismic disturbances are large and expected to cause jitter in the optical train it may be desirable to add an autoalignment system to maintain dynamic optical train alignment. A further level of complexity is the selection of a reference for the autoalignment system. It might be a gyroscope stabilized mirror or simply a softly suspended mirror. This paper reports a trade study between the various disturbances and the various hardware configurations that result in some general guidelines when selecting the components in the design of a precision tracking system.

Introduction

A major concern in a precision ground based tracking system is the tracking jitter that will result from various disturbance inputs. Disturbance inputs are considered to include instrument noise and electronic noise as well as the disturbances caused by natural environments such as atmospheric turbulence, wind loading, and seismic vibrations. The designers have many options in choosing the design of the control components that make up the pointing system and alignment control loops.

The pointing system might be one of several types such as a heliostat, a coelostat, or an on-gimbal telescope. The pointing system design is dependent on the selection of the beam expander which is usually based on optical considerations. After a pointing system is selected the control system designers have to decide if an internal optical alignment system is required, and if so should it include an inertial platform as an optical reference. This paper presents the trades done on an on-gimbal telescope and pointing shown in Figure 1. The complete trades on the above mentioned telescopes are very similar to the on gimbal telescope analysis presented in this paper[1]. The selected tracking sensor resides on an isolated platform on the ground and utilizes the full aperture for sensing the target.

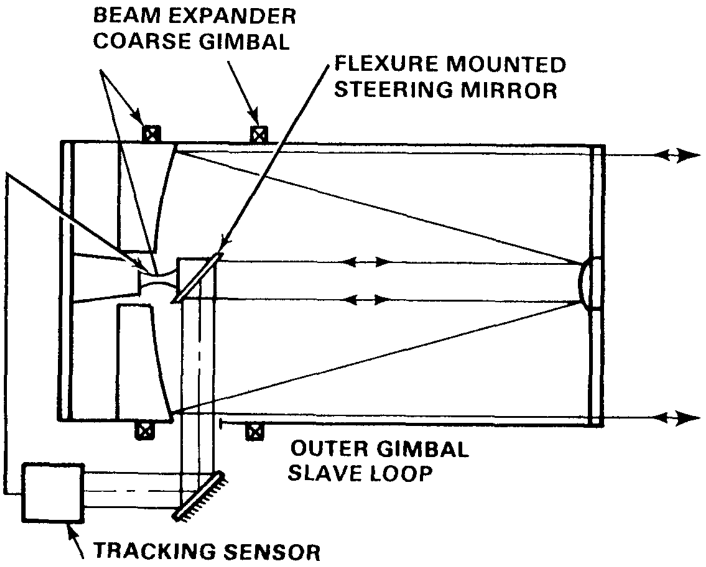

Figure 1 On gimbal telescope with high bandwidth steering mirror

The first upgrade in the system performance is achieved by adding an autoalignment (AA) system to maintain the alignment of the optical train, this is shown as Figure 2. The AA system has an autocollimator to originate an alignment beam that reflects off each optical element, including the reference flat, and then back to a jitter sensor in the autocollimator. The sensed error is used to control a high frequency flexured beam steering mirror. A second possible upgrade is to include inertial gyroscopes and torquers on the reference mirror to provide an inertial platform reference as shown in Figure 3. This upgrade provides an inertial reference for the AA beam and also permits inertial positioning of the telescope by connecting inertial rate commands to the gyroscope torquers. This design is then similar to the design of an inertial platform used for navigation purposes.

This paper will consider several forcing functions and describe the use of a computer simulation to determine the relative magnitude comparisons between the various disturbances.

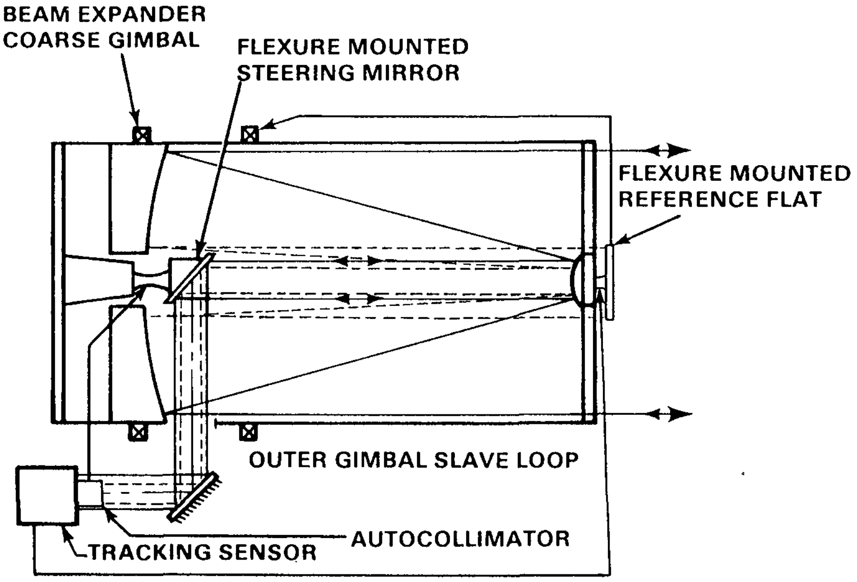

Figure 2 On gimbal telescope with passive stabilized autoalignment system

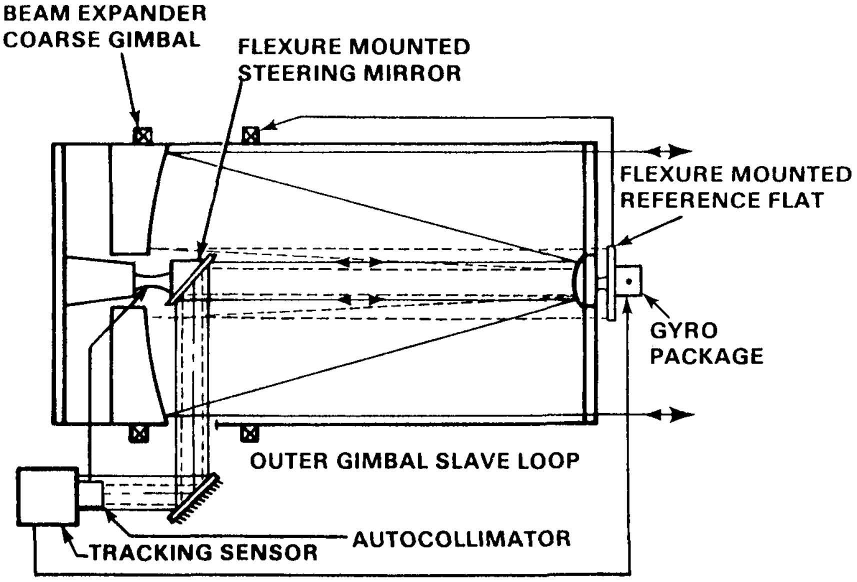

Figure 3 On gimbal telescope with inertial reference autoalignment system

A candidate list of disturbance functions that can degrade the performance of a ground based tracking system are included in Table 1.

Table 1. Disturbance Sources
Wind Forces
Angular Seismic Motion
Linear Seismic Motion
Gyroscope Noise
Electronic Noise
Atmospheric Turbulence

This list may be extended depending on the specific design and use of the tracking system, however, the above sources are adequate to demonstrate the analysis approach described in this paper.

There have been several programs by private companies and by the government to gather disturbance data over the past several years. One program[2] installed considerable special instrumentation in and about an on-gimbal beam expander to measure the force, pressure, and velocity fluctuations due to wind. To measure the force on a flat plate inside the beam expander, a special force meter was constructed with a 4 inch diameter flat plate mounted so that the normal to the flat plate was along the telescope line-of-sight. Force measurements from this device are shown as Figure 4. The resonant peak at 24 Hz was a result of the natural frequency of the measuring device. When this resonance was removed from the data the wind force PSD had an amplitude vs frequency characteristic of -40 dB/decade slope. It was also found that the wind velocity decreased significantly as measurement location moved progressively inside the beam expander housing and away from the entrance aperture.

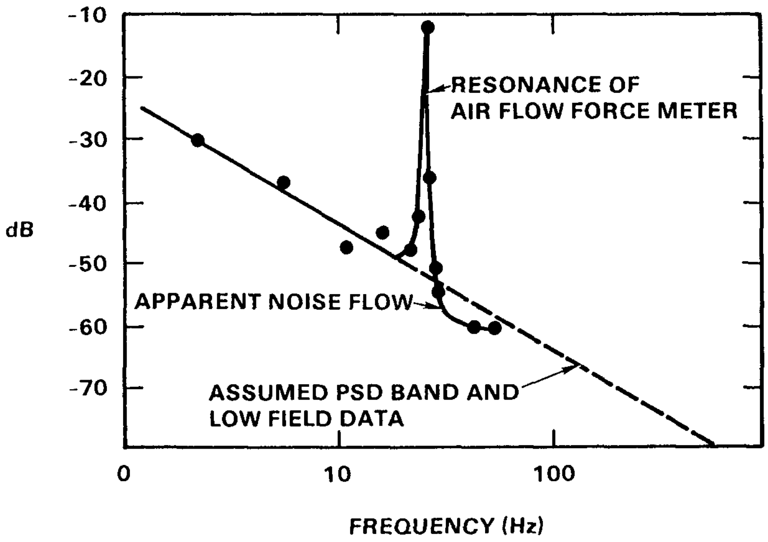

Figure 4 Wind force measurements

These force measurements were used to estimate both force and torque disturbance inputs to the pointing system. Flat surfaces such as the secondary mirror and primary mirror were assumed to be loaded by the measured forcing function scaled to their relative surface area. Torque inputs to flat surfaces were estimated by assuming the force input operated on only one half of the exposed surface area and therefore a lever arm and torque resulted.

The angular seismic disturbance was measured with angular displacement sensing instrumentation at two locations: including Los Angeles, CA, and Albuquerque, New Mexico. The comparison of these two levels as shown in Figure 5 shows considerable level variation, almost 4 decades difference at the peaks. It is interesting to note, however, that the angular seismic frequency content covers similar bandwidths at both locations. The levels above 100 Hz are significantly less that the levels from 1 to 100 Hz. Linear vibration measurements were also gathered and the data from Los Angeles and Albuquerque measurements is shown as Figure 6. Again the levels below 100 Hz are the most significant.

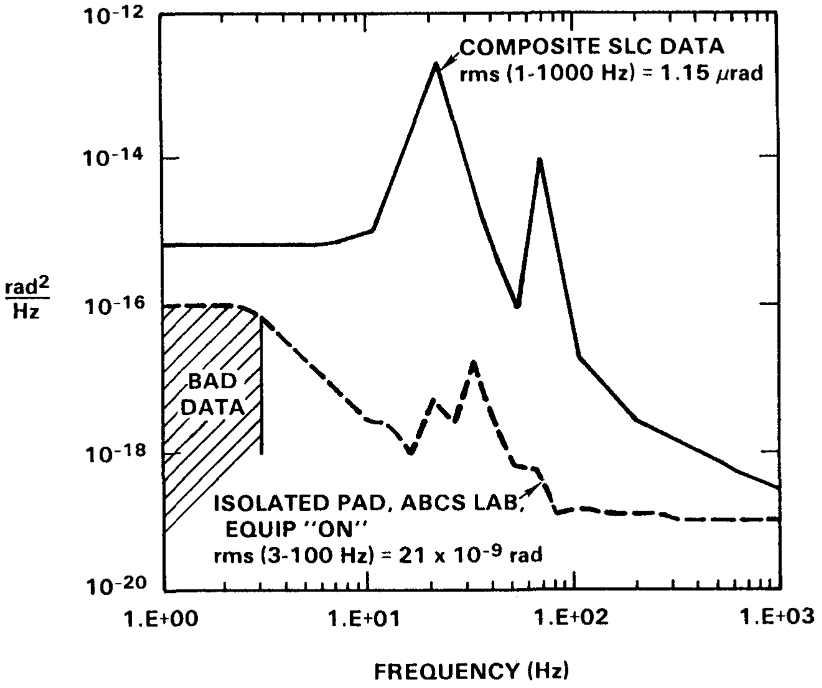

Figure 5 Angular seismic measurements

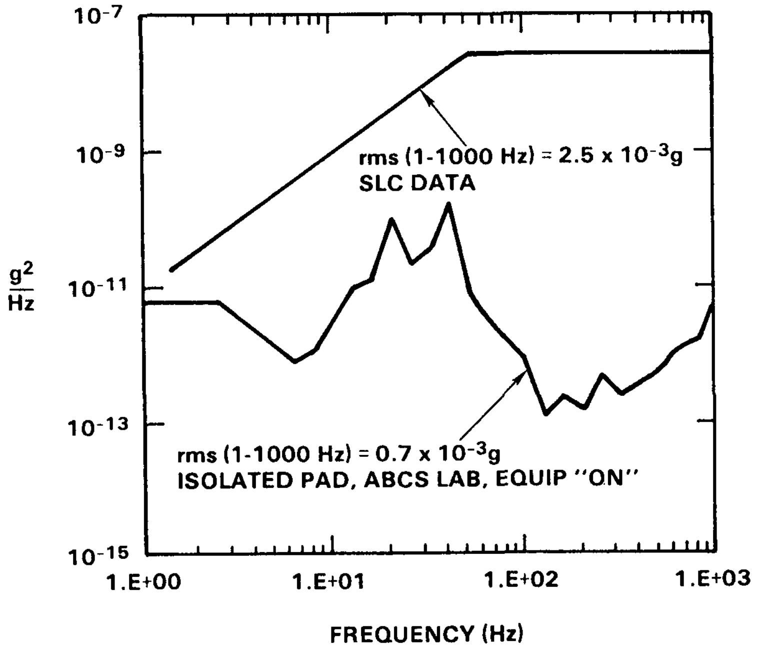

Figure 6 Linear seismic vibrations

Gyroscope noise is obviously dependent upon the specific design of the instrument. In recent years gyroscopes have been produced with very low noise levels. A typical noise measurement is shown as Figure 7, notice that the frequency range is lower than previous data.

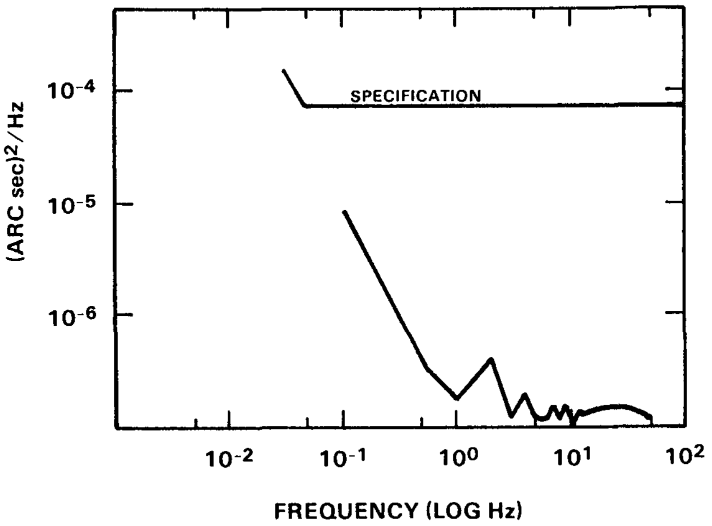

Figure 7 Gyroscope noise

Electronic noise, similar to gyroscope noise, is dependent upon the specific components selected, however good references exist for a variety of electronic components. Figure 8 is typical of the noise spectrum reported by a manufacturer for a specific operational amplifier. Notice that this noise is again more significant below 100 Hz.

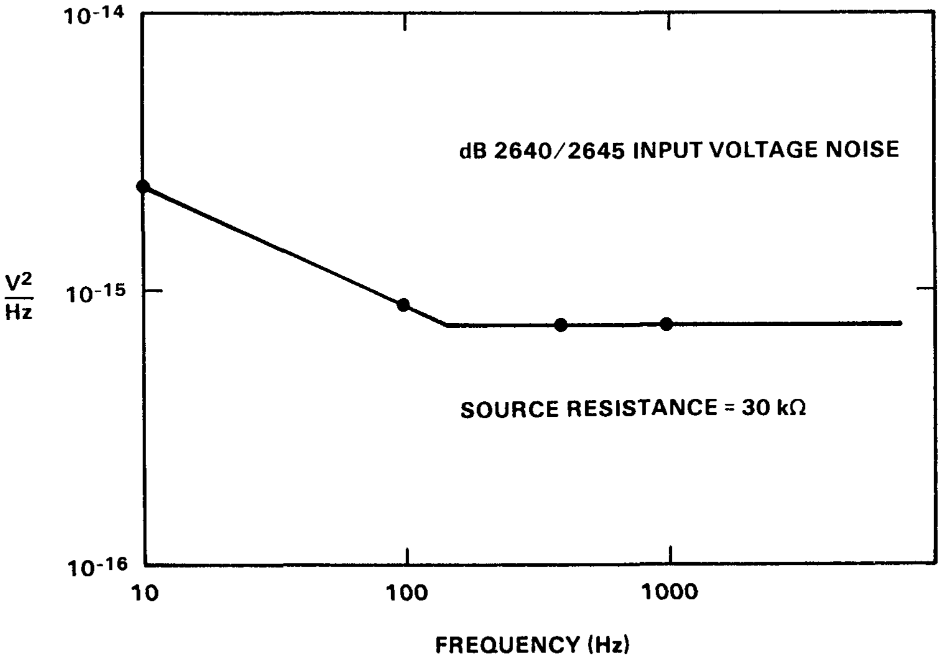

Figure 8 Operational amplifier noise

The last disturbance to be considered in this paper is atmospheric turbulence. This disturbance is somewhat different from the previous ones since it asserts itself by jittering the optical LOS prior to being received by the tracking system. The pointing system will have to suppress jitter caused by turbulence to obtain a jitter free tracking image. Although astronomers have always been affected by the turbulence there is no large bank of turbulence data. There are several available papers on analytic models to predict turbulence. Two of these model outputs are shown in Figure 9. Again, the major power under the curve is contained in the frequency region below 100 Hz.

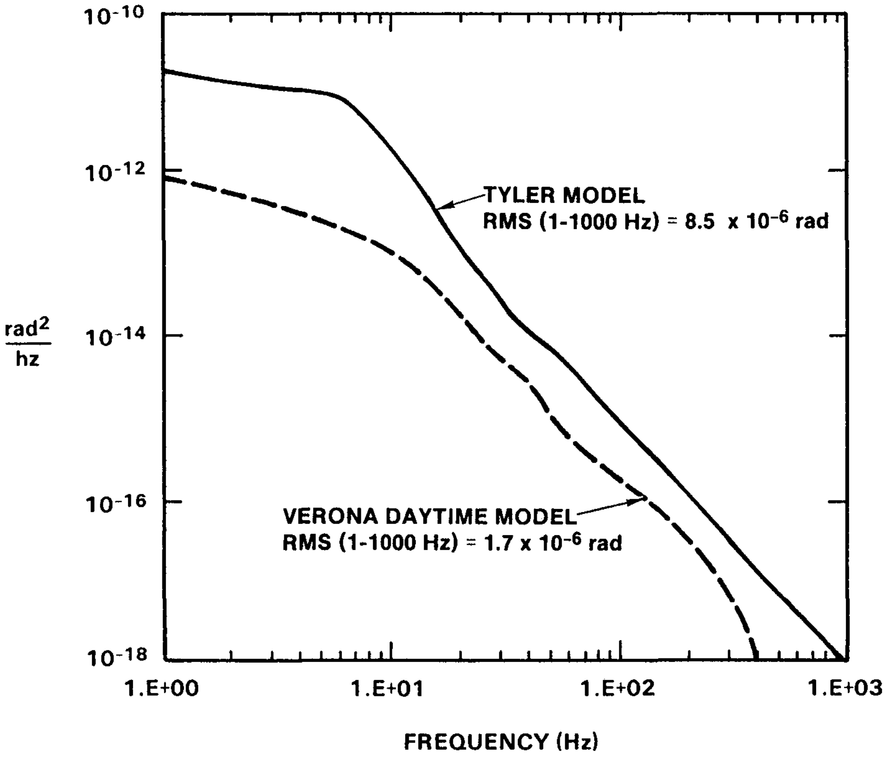

Figure 9 Atmospheric turbulence from computer models

A general summary of the disturbance data reported here is that most of the disturbances are significant in the frequency region of less than 100 Hz. Therefore, the design of a pointing system should permit rejection of disturbances in this range. Of course these disturbances enter the system at different points and will be studied based upon the residual tracking error that they cause.

Control system concepts

As mentioned previously, to limit the scope of this paper it was decided to report results only for the on-axis, on-gimbal beam expanding pointing system. However, the controls design for this pointing system has many alternatives. If the tracking error was used to drive the entire gimbal assembly only a very low frequency tracking system could be achieved due to the large inertia of the gimbals and telescope. If higher bandwidth control is desired the designer must include a high bandwidth steering mirror in the optical train. Steering mirrors are available that can respond to several hundred Hz as required for this application. The basic tracking loop which includes a high frequency steering mirror would appear as shown in Figure 1. One limitation with this design is the signal-to-noise characteristics of the tracker. If the bandwidth of the tracker is increased when the target has poor signal-to-noise, the tracking jitter due to tracker noise may be worse than the jitter due to turbulence[3]. Figure 10 shows graphically how turbulence induced jitter and tracker noise combine. In the case of Figure 10, the tracking bandwidth would be optimum at 32 Hz to obtain minimum tracking jitter.

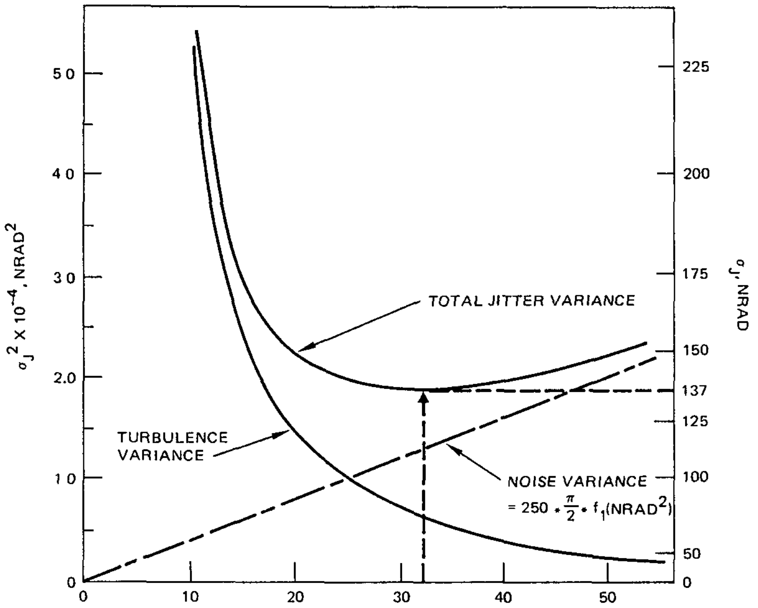

Figure 10 Sensor noise vs turbulence rejection tradeoff curves

Other design options have also been mentioned. If the optical train between the aperture and the tracker contains the majority of jitter it would be good practice to remove that jitter prior to the tracking error measurement. This is possible by using a system configuration such as in Figure 2. In this case an auto alignment beam traverses the optical train and reflects off a reference flat back beam to a jitter sensor. For this design to be effective the reference mirror and the AA sensor must be isolated from large jitter disturbances. This design can be successful if the disturbances to the mirror and sensor are high enough in frequency that an isolation system can be effective. This concept is referred to as "Passive Stabilization AA System" since the reference is passively stabilized.

A second alternative for reducing jitter at the track sensor is to augment the AA by making the reference mirror reside on an inertially stabilized platform. This option is shown as Figure 3. This configuration should be effective even if low frequency seismic angular motion disturbs the telescope. Ideally, the gyroscopes keep the small platform stable in the presence of low frequency disturbances. The draw back with this system is that the gyroscopes themselves are a source of jitter. If the gyroscopes have a significant noise level, the noise will drive the platform resulting in this noise being inserted into the optical path.

These three configurations were evaluated to determine the relative tradeoffs. To accomplish this evaluation the control systems were simulated using a frequency domain computer program. The three configurations were first conceptualized as block diagrams as are shown in Figures 11, 12, and 13. These simulations were defined with control loop parameters that represent the present state-of-the art in control loop performance. For example, the small inertial platform for the AA reference was set to have an open loop crossover frequency of 100Hz. The auto alignment system was simulated to have an open loop crossover of 500Hz and the track loop was set to have a bandwidth of 90Hz. The beam expander magnification was selected to be 3, which is important, since the angular deviations of the LOS beyond the beam expander are reduced by the magnification of the beam expander. The disturbances that have been described were input to the simulation model as shown in Table 2.

Table 2. Disturbance Coupling

Source	Input Locations
Wind Force	Secondary Mirror & Inertial Platform
Wind Torque	Secondary, inertial platform, primary
Angular Seismic	Outer gimbal base, track sensor, auto-alignment,
Linear Seismic	Gimbal base, beam expander, small platform
Gyroscope Noise	Inertial platform
Electronic Noise	Track loop, inertial platform loop
Atmospheric Turbulence	Track loop

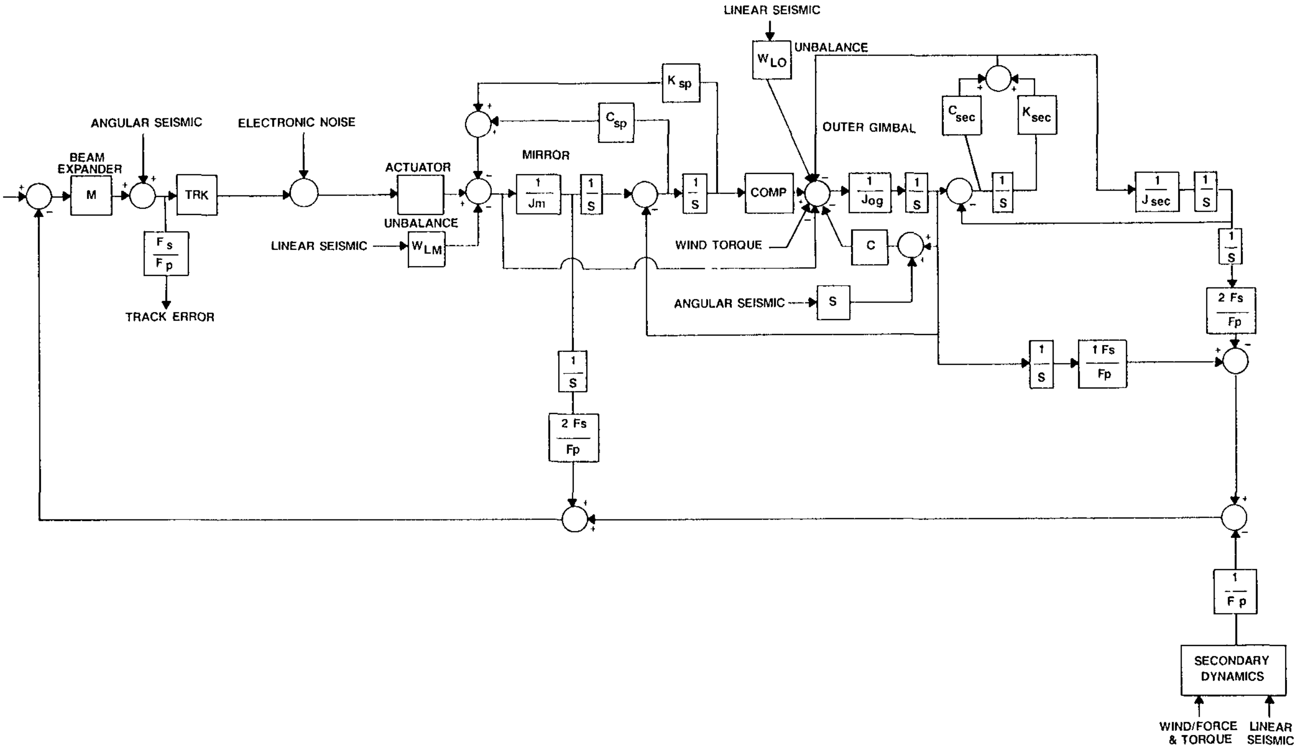

Figure 11 Block diagram of on gimbal telescope with high bandwidth steering mirror and disturbances

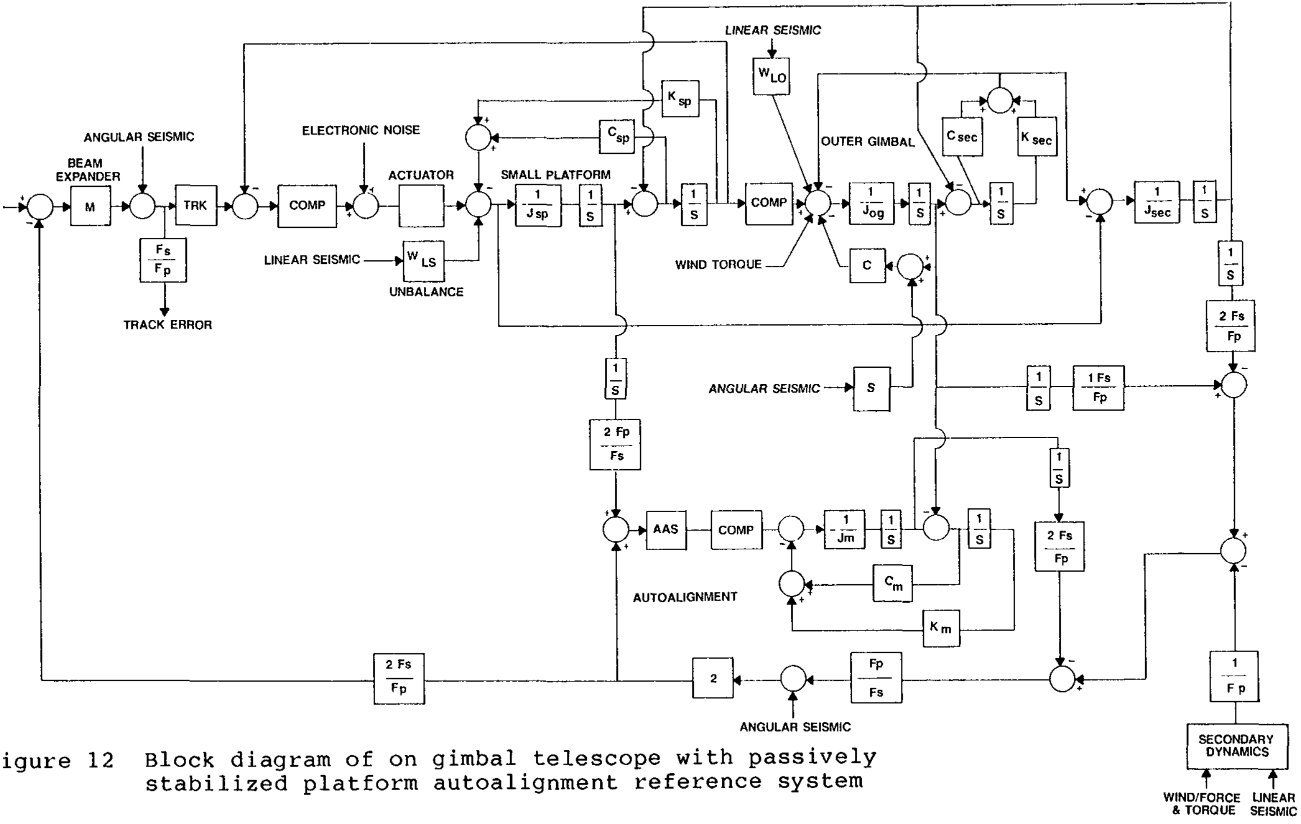

Figure 12 Block diagram of on gimbal telescope with passively stabilized platform autoalignment reference system

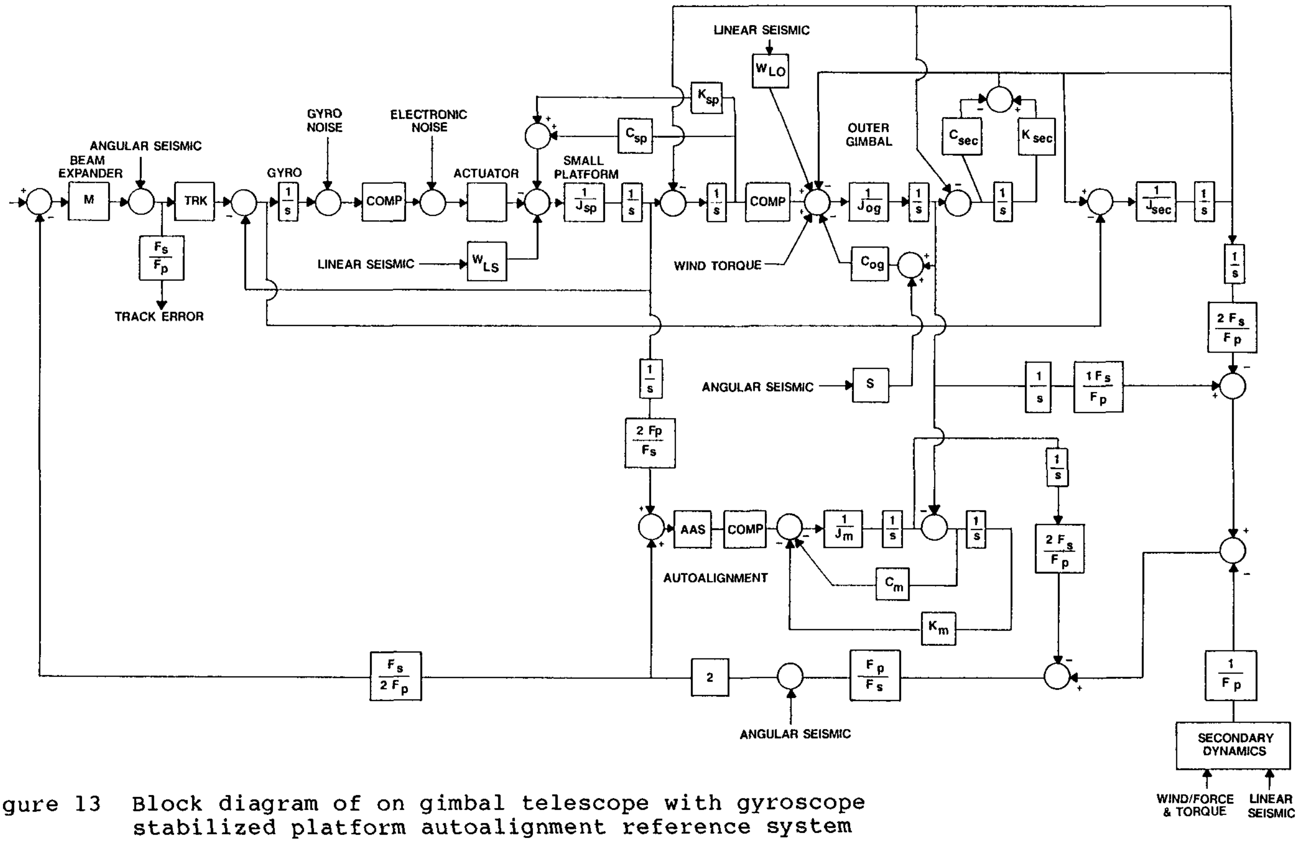

Figure 13 Block diagram of on gimbal telescope with gyroscope stabilized platform autoalignment reference system

Error estimates

To determine the major disturbances that limit performance it is necessary to define realistic RMS levels for the disturbances. Table 3 lists levels that are considered possible.

Table 3 - RMS Disturbance Level

Disturbance	RMS Level
Wind Pressure	3.6×10^{-5} psi
Angular Seismic Motion	20×10^{-9} to 1.0×10^{-6} rad
Linear Seismic Motion	1×10^{-3}g to 3×10^{-3}g
Gyroscope Noise	100×10^{-9} rad
Electronic Noise	3×10^{-6} volts
Atmospheric Turbulence	$2 \times 10-^{6}$ rad

These disturbances were input into the computer simulation and the track error was calculated for each disturbance. The relative magnitudes of the resulting errors are shown in Figure 14, 15, and 16. The combined shaded and unshaded area of the curves were the results with high seismic inputs as measured in Los Angeles; the unshaded results from the seismic data were the low seismic levels measured in Albuquerque.

Conclusions

It is seen from the results that the seismic and turbulence disturbances are the most significant.* If the local seismic motion is small, the choice of configuration would be the simplest and least expensive which is the system shown in Figure 1. In the presence of large seismic disturbances the AA system is justified to attenuate the beam path disturbances. However, comparing the results of Figures 15 and 16 shows that the inertial referenced platform does not improve LOS stabilization over the passive stabilized system. This configuration is not only cheaper but may perform with less error by avoiding the gyroscope induced noise. However, if inertial pointing is required, the gyro stabilized platform reference to the AA system is the necesary choice. From this evaluation it appears that electronic noise, linear seismic, and wind effects will not be primary disturbance inputs to a Ground based precision tracking system.

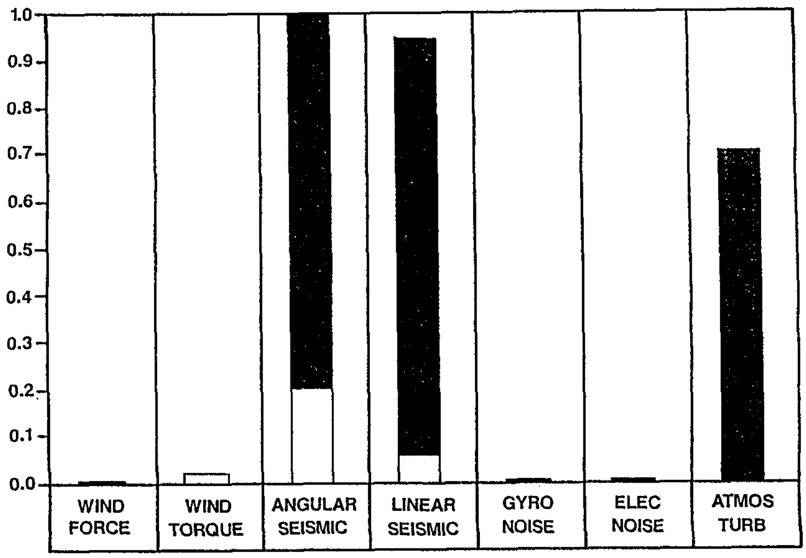

Figure 14 Performance results for on gimbal telescope with high bandwidth steering mirror

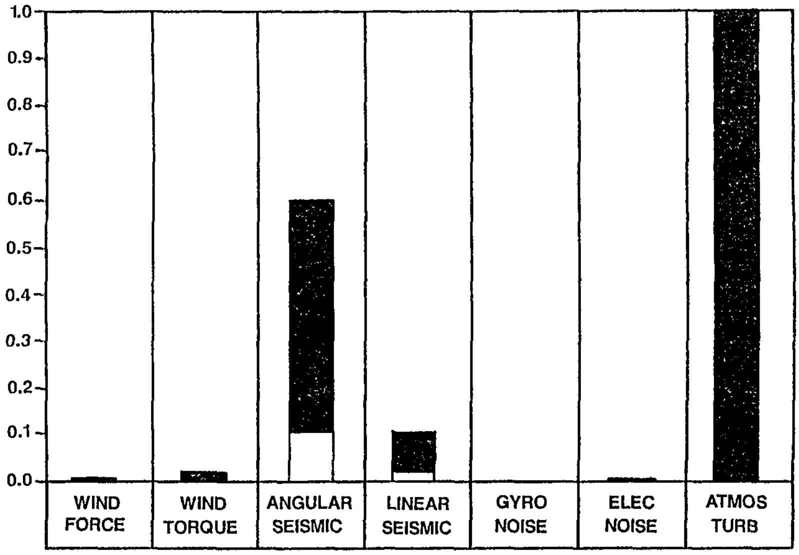

Figure 15 Performance results for on gimbal telescope with passive stabilized autoalignment reference

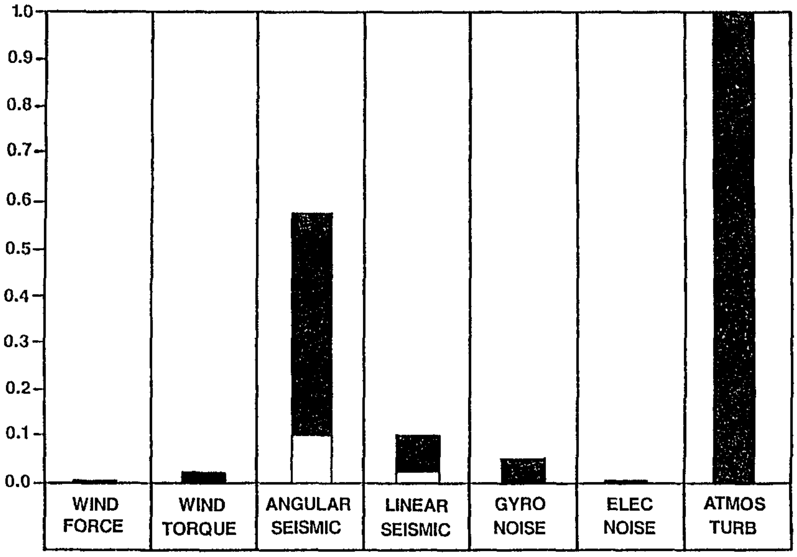

Figure 16 Performance results for on gimbal telescope with inertial reference autoalignment

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