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Specification of Fine-Steering Mirrors For Line-of-Sight Stabilization Systems

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ABSTRACT

Fine-steering mirrors (FSM) are being used in a greater variety of optical systems than ever before. The performance requirements for these systems vary just as widely. It is important for optical system designers, space-based-observation instrument principal investigators, astronomers, tactical weapons seeker designers, and others to understand the capabilities of FSM. It is also necessary for us to be able to specify FSM performance and environments in a manner that effectively communicates system needs to the component manufacturers. If the specification is initially incomplete, major disruption to the program can occur when requirements are understood. This paper introduces the critical and secondary performance and environmental parameters that make up an FSM specification. Also discussed are situations when the various parameters become important.

1. INTRODUCTION: WHY SHOULD I CARE?

The painful fact is that too many pointing systems have failed to meet performance requirements in the last several decades. This paper is presented to aid instrument designers, pointing system specifiers, pointing system designers, and component suppliers during the process of fine-steering mirror (FSM) specification.

FSMs operate in a wide variety of optical systems. There is a tendency for the instrument designer to believe that FSMs were developed specifically for her application. Vendors rarely try to change that idea. Reality dictates that the specification be translated into terms related to the vendor's standard set of performance parameters for the sake of verification.

A complete, properly written FSM specification helps ensure compliance with the system specification. It also helps reduce the costs of excess performance that result from loosely written specifications. When additional requirements are identified too late in a program, at preliminary design review (PDR) for example, the resulting design rework costs money and time. It also compromises performance since the patched design generally does not work as well as it might have.

This paper is not intended to be a primer on system engineering and the specification process. There are already several good ones. It provides specific information related to FSM specifications that most system engineers may not have encountered. It addresses the need for traceability between mission and FSM specifications: it shows that performance matches the need. Communication between user, monitor, prime contractor, and component vendor is encouraged at an interdisciplinary level.

2. PERFORMANCE ISSUES MUST ALL BE ADDRESSED

Fig. 1 illustrates some of the common performance issues.

2.1. Travel

Range of travel must be identified in several terms. The range of accurate operation may be smaller than the maximum useful travel which may in turn be less than the limit switches or physical stops. Don't forget to specify whether the angles are in mechanical or optical coordinates. Optical gain is 2 about the axis perpendicular to the plane of incedence, and less than 2 about other axes. Fig. 2 shows one way to specify travel, rate, and acceleration as a function of frequency.

2.2. Modes of Operation

All operational and nonoperational modes should be called out. These become the basis for all other requirements. The number of modes should be kept to a minimum for simplicity. Remember that each mode can have different requirements and environmental limits. Take advantage of this to make the overall job easier.

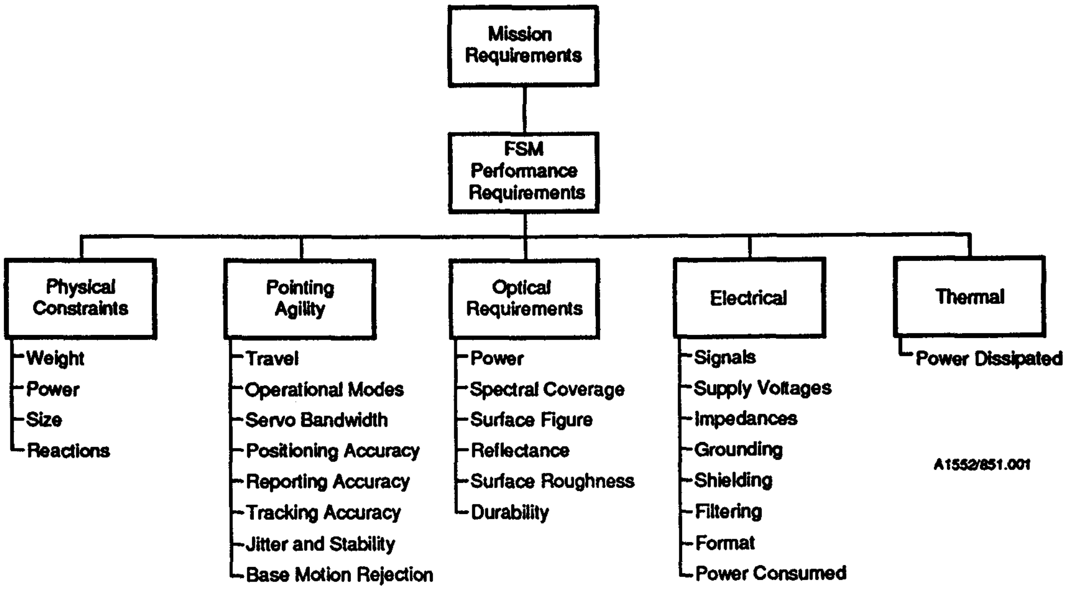

Fig. 1. FSM performance requirements are derived from mission specifications.

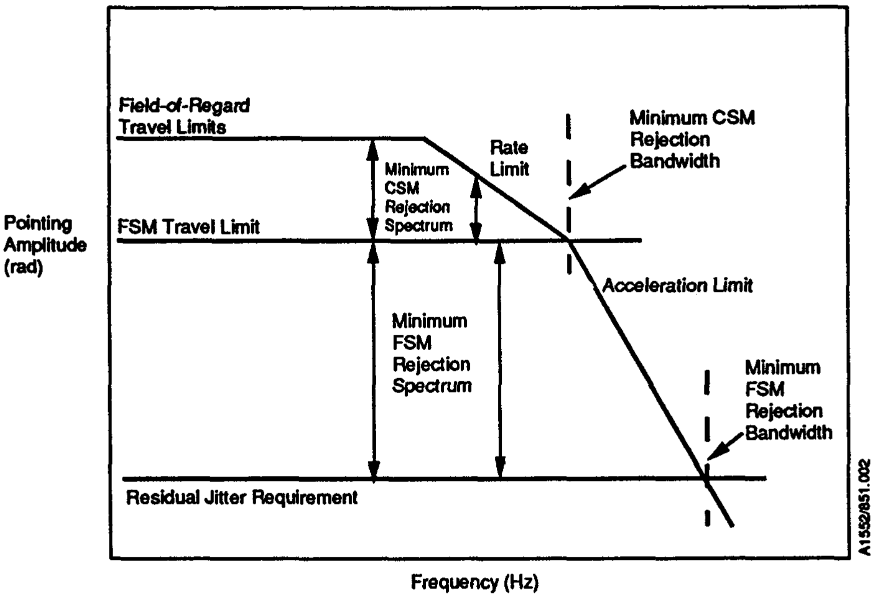

Fig. 2 The combination of rejection bandwidth and large travel can be achieved by coarse and fine-steering mechanisms.

Operating profiles such as scanning, chopping, stabilization, and slew, should be completely defined (Fig. 3). This should include tolerance of variances and the periods during which specifications apply. If some additional following error can be tolerated during the beginning of the linear scan range, for example, the system is much easier to build. If this is not the case, however, the fact that scanning accuracy applies only over the linear scan portion should be included.

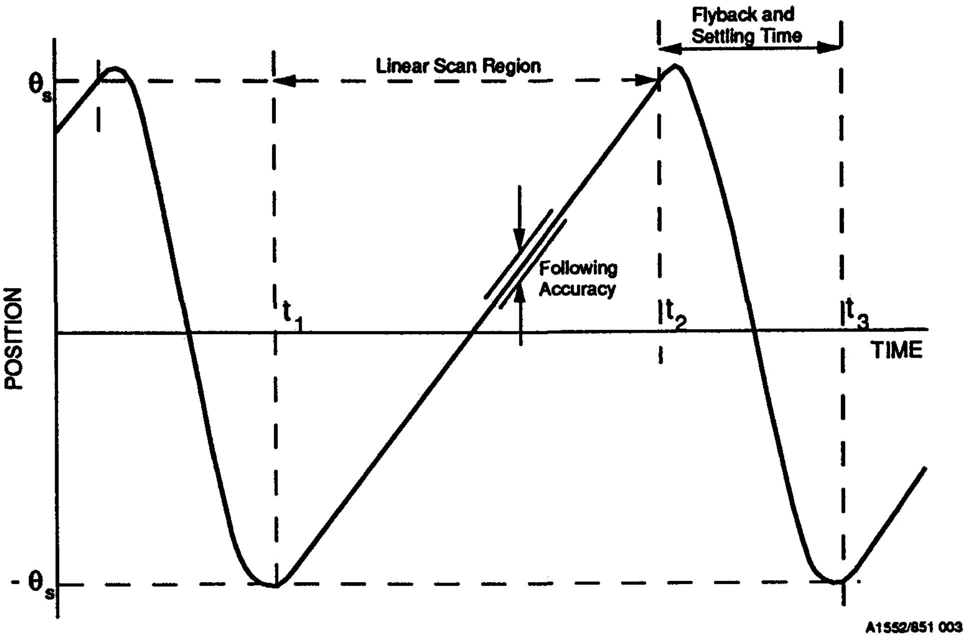

Fig. 3 Scan profile can create following accuracy, slew/settle time, and acceleration requirements.

If tracking is to be performed, define the reference source. Is it an optical tracking detector with sufficient bandwidth or is the tracking to be done with respect to inertial sensors and navigation data? Specify whether reference sensors are part of the specified system and if sensor errors are included in the accuracies required.

2.3. Servo Bandwidth

Servo performance can be defined in many ways. There are perhaps as many ways as there are servo designers. Control bandwidth should be specified either in open-loop, closed-loop, or disturbance rejection format (Fig. 4). Note that virtually all servos are closed-loop and can still be effectively specified in terms of open-loop bandwidth if desired. Rejection bandwidth is relatively unknown but provides an opportunity to specify a parameter that is directly related to system performance, the relation between disturbances, and the resulting pointing error as seen in Fig. 5.

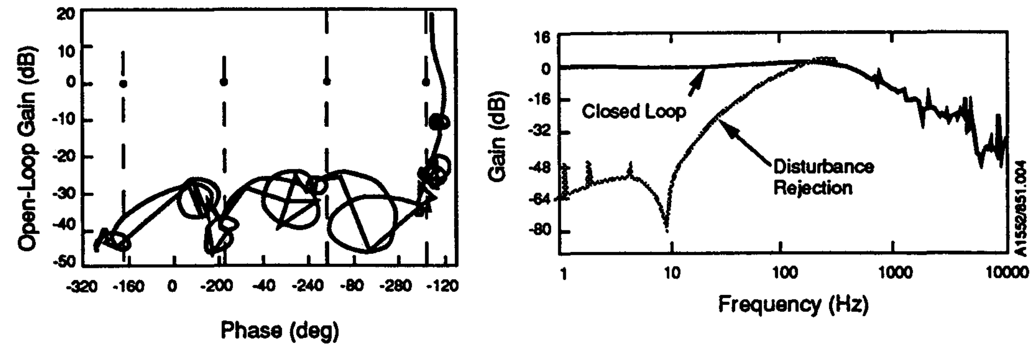

Fig. 4. Example of open-loop, closed-loop, and disturbance rejection curves for a 5-in. FSM.

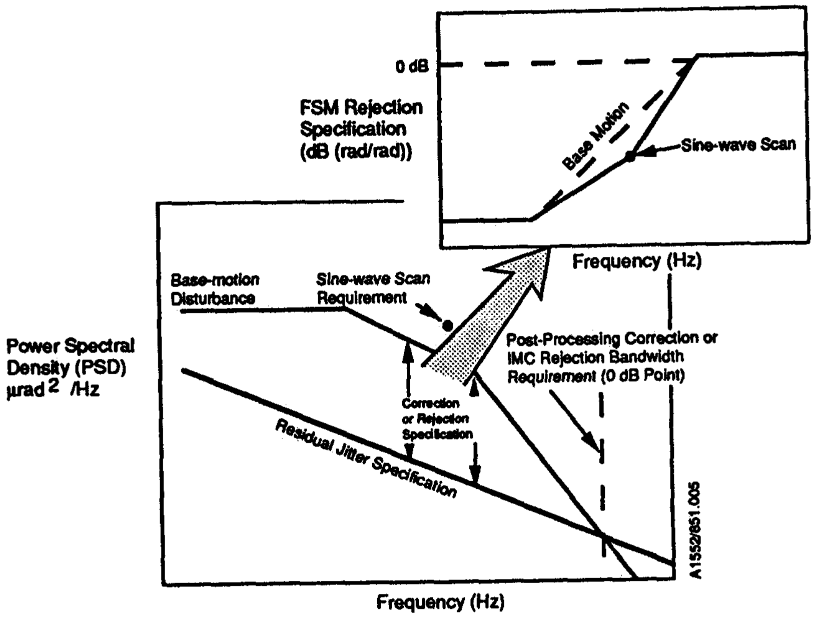

Fig. 5. The FSM rejection spectrum is derived from the residual jitter and disturbance spectrums.

The servo should also be defined in terms of minimum stability margins. These are the amount of parameter variations that can be tolerated before the system oscillates unstably. Since age and temperature variations cause things to change, an adequate amount is needed. Rigid-body margins of 30 to 60 deg of phase and 6 to 10 dB of (high and low) gain are standard. Bending mode margins must also be specified. 60 deg, 10 dB, or the equivalent closest approach has been considered adequate. This is the most-often-overlooked specification and has caused many servos to "sing" at the frequency of structural bending modes during operation. Always request verification by test, perhaps throughout the operating temperature range.

2.4. Accuracy

While bending mode stability is the most-often-overlooked specification, accuracy is the most misunderstood. This is due to the multitude of variations in what accuracy means to the end user. A thorough treatment of accuracy is beyond the scope of this paper. What is important to each user is what she needs. For this reason Fig. 6 includes a list of "standard" specifications that don't have standard definitions. Feel free to define them to meet your needs.

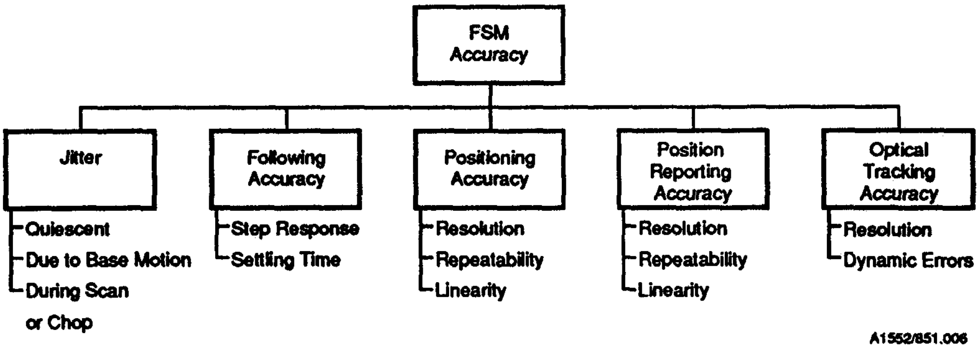

Fig. 6. Accuracy can be specified in many ways.

Remember to define whether you mean root-mean-square (RMS), peak, peak-to-peak, or 3-sigma. You may also be able to apply the specification to an average over a longer period of time, rather than instantaneously, to make it easier to meet.

The reference to which accuracy is defined should also be included. This can be the base, an inertially stable coordinate frame, the target, or a specific value of the position sensor output.

2.4.1. Jitter

LOS jitter, drift, or stability is usually important. Some people think of jitter as the high-frequency LOS motion and stability or drift as a different phenomenon that occurs over longer periods of time. They are in fact the same phenomenon and are separated by a definition of time limits. The most complete method is to define a power spectral density (PSD) function that includes everything. One hertz, plus or minus a factor of ten, is often considered the dividing line between jitter and drift. Once again, have your way with it. An example is shown in Fig. 7 along with base motion test data for Landsat and Olympus satellites.

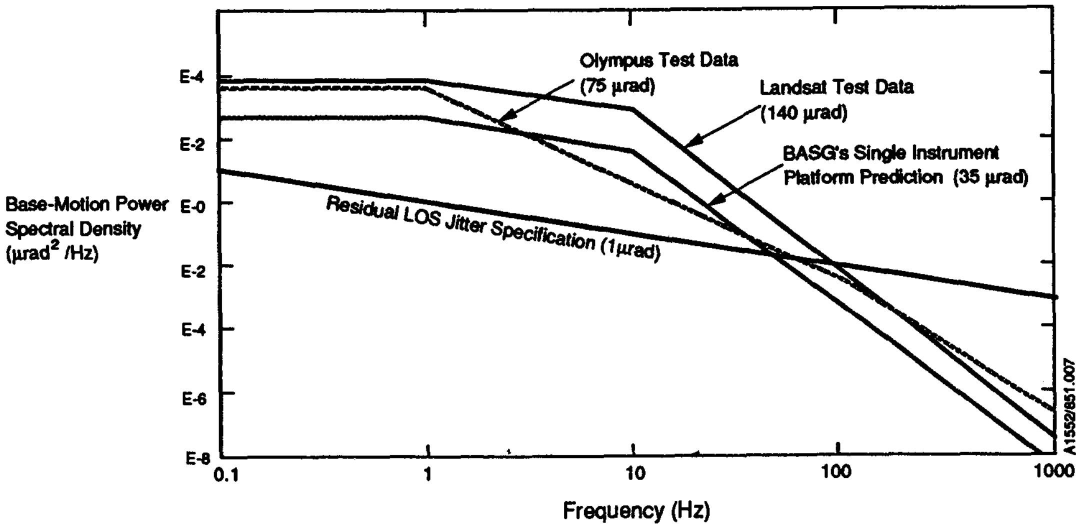

Fig. 7. Base motion PSD data is available for several platforms.

The drift specification should be limited to apply only over a specific time period. This can be anywhere from 0.1 second to years. Shorter periods are, of course, easier and less costly so specify only what is needed.

2.4.2 Following Accuracy

Following accuracy often refers to the ability to follow a scan, chop, or slew profile. It can also apply to any other dynamic condition.

2.4.3. Positioning Accuracy

The accuracy to which a pointing system can be positioned is often critical. It may be defined as positioning resolution, repeatability, or linearity. Webster does as well as anyone in defining these terms if you need guidance. The important thing is to be specific. Include which modes and operating conditions it applies to and under what environmental ranges.

2.4.4. Position Reporting Accuracy

The accuracy to which reporting, or knowledge, can be accomplished is sometimes the important issue. If so, resolution, repeatability, or linearity can be used as above.

2.4.5. Optical Tracking Accuracy

The accuracy to which a target can be tracked with an optical photodetector may also be important. Following error, jitter, drift, resolution, repeatability, and linearity can apply. The dynamic conditions for each are also necessary. Local platform motion as well as target motion must be considered. Acquisition, if applicable, requires an additional set of requirements. As a minimum, stable transition between caged and tracking modes within a specified time interval upon discreet command is essential.

2.5. Mechanical Envelope

Size, weight, and mounting interface limitations are important. Specify minimum angular clear access to the clear aperture. Also include the envelope of the mirror at extremes of travel. Can the mechanism extend beyond the edges of the mirror? In front of the first surface? Mechanical accuracy of the mounting interfaces may also be an issue. The mechanism and electronics box must each be specified.

2.6. Optical Quality

The surface figure should be defined as peak to valley (PV) or RMS, surface or wavefront error, and at what wavelength. Conversion to a 0.632 uM figure is standard for verification purposes. If the accurate portion of the surface is less than the total area, cost can be reduced. Reflectance and surface roughness or scatter should be specified over the required wavelength range and at the operating angles of incedence. Durability should take into account the incident optical power, cleaning method, and debris in the operating environment.

2.7. Electrical

The electrical interface should be specified in terms of signals required, available voltages, impedances, grounding and shielding, filtering, format, protocol, signal gains and ranges, connectors, and others. It is costly to assume that everybody builds electronics the same way.

2.8. Power

Power must be defined as total electronic consumption and dissipation at the mechanism and within the electronics. Consumption can be maximum instantaneous peak, RMS, or average over a cycle time. All three must be defined for each operating mode or condition.

As Fig. 8 illustrates, power consumed in the actuator is dependent on total acceleration capability as well as the amount of acceleration being used. This is due to the additional actuator size required and the power used to accelerate the additional actuator mass. Fig. 9 illustrates the total power consumed, including electronics, as a function of acceleration used when the total acceleration capability is changed by modifying only the power supply voltage.

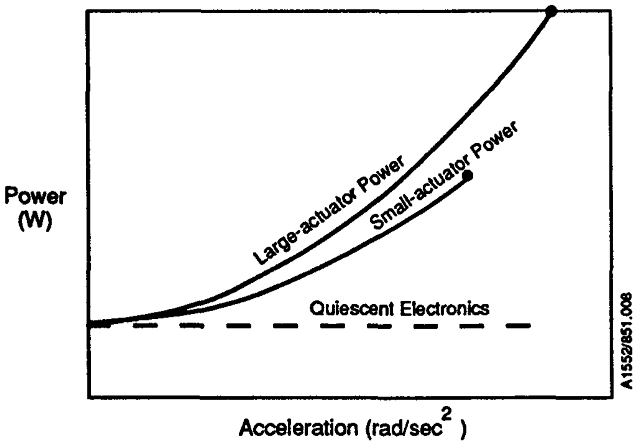

Fig. 8. Actuator power consumption is related to actuator size/capability if the actuator inertia is significant.

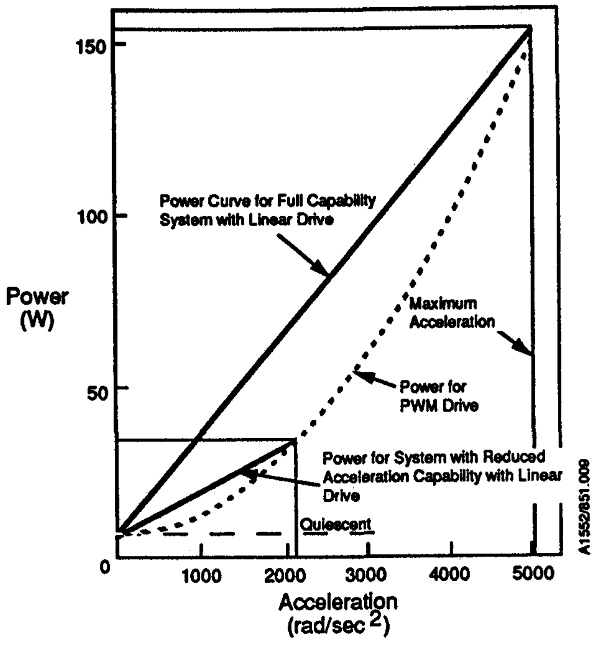

Fig. 9. Power consumption is related to acceleration, type of driver, and acceleration capability.

2.9. Reaction Forces and Torques

The host platform should be disturbed minimally for most precision pointing systems. Reaction forces and torques should therefore be limited to prevent unacceptable motion of the platform. The limitations should be formatted as a function of frequency as shown in Fig. 10 and Fig. 11 taken from Ref. 1. Uncompensated momentum may also require limitation. Accurate reaction cancellation is needed to achieve these values during scanning, chopping, or slewing.

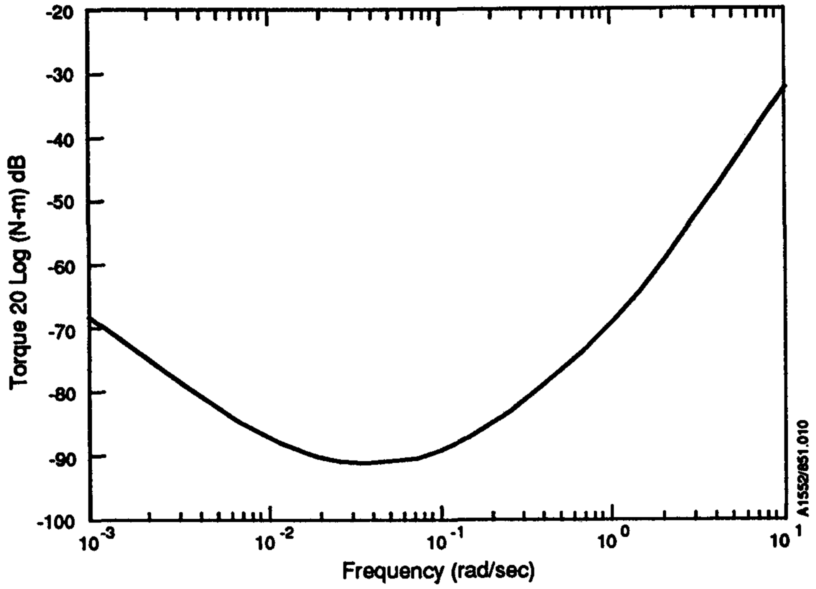

Fig. 10. Example of allowable sinusoidal torque

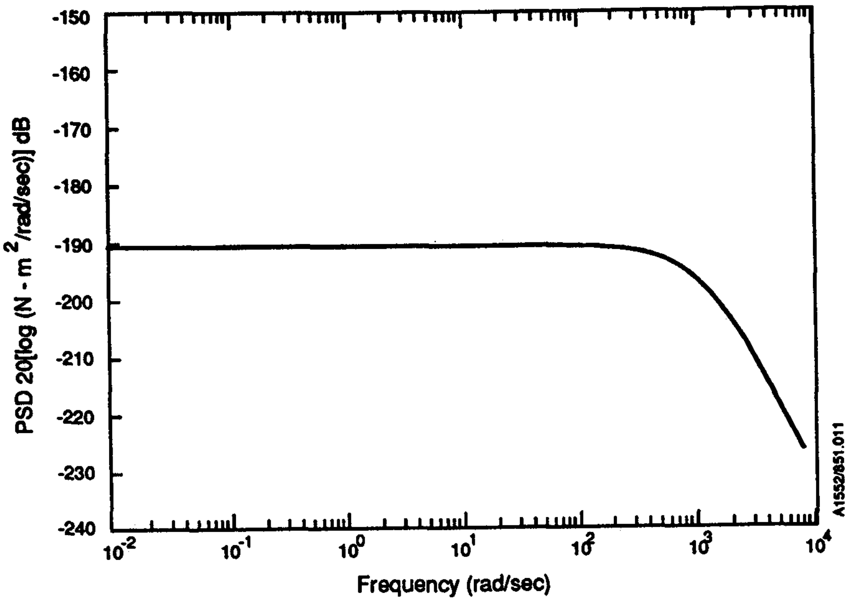

Fig. 11. Example allowable white noise torque

2.10. Turn-on Characteristics

In certain applications performance is required shortly after application of power. In such cases stability may need to be assured under various combinations of worst-case environmental conditions. Thermal time constants and stabilization time are primary candidates for specification in such cases. Other systems may find it necessary to limit the electrical power surge at power application.

3. NONPERFORMANCE ASPECTS NEED ATTENTION TOO

A summary of some nonperformance issues is shown in Fig. 12.

3.1. Interface

Interface control drawings should be generated to control mechanical and optical characteristics. Surface finish, angular accuracies and ranges should be clearly specified.

The thermal, electrical, and electromagnetic interfaces must also be defined. All modes and operating conditions can be specified separately if necessary. In some cases solar heating of the mirror needs to be considered. It is necessary to specify which team member is responsible for control of the thermal environment as well as the range of operation.

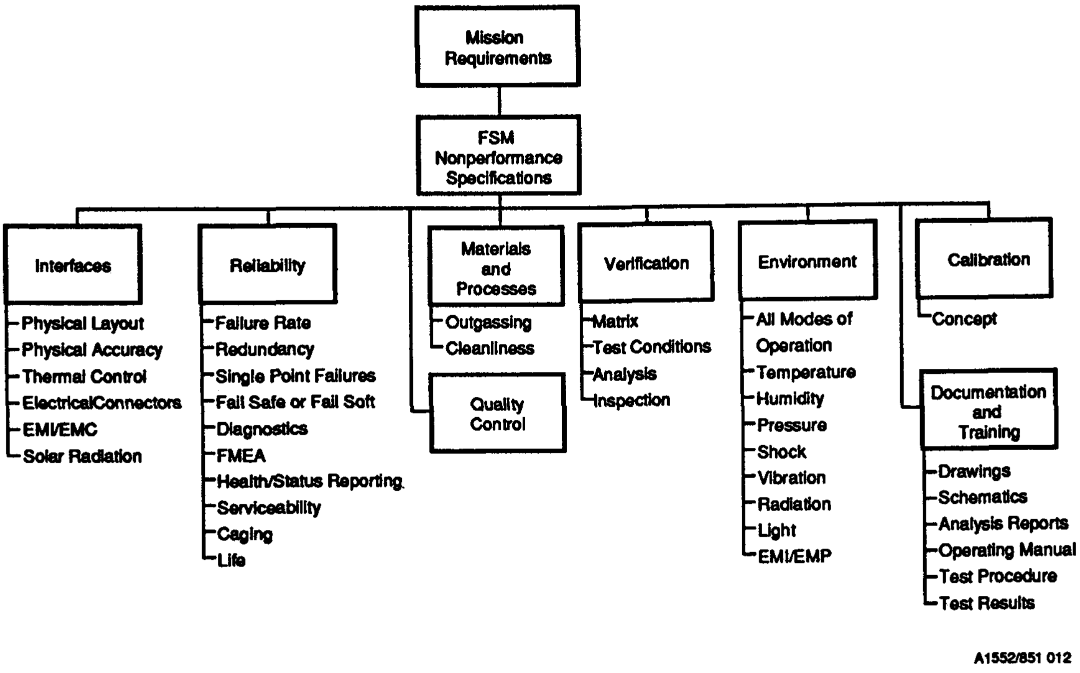

Fig. 12. Nonperformance issues must also be addressed.

3.2. Reliability

In addition to probability of failure over a specified time or mean time between failures (MTBF), it may be advisable to specify redundancy, elimination of single-point failures, or fail-safe operation. Fail-soft features can ensure graceful degradation and minimal operation in the event of common or high-probability failures. Internal diagnostics may also be useful for self-checking in inaccessable environments.

The specification can require an analysis to predict failure modes and to evaluate associated mission implications. If human safety is involved, additional risk scenarios must be considered. Special measures such as the replacement of bonded joints with those that rely on mechanical constraint may be appropriate.

Various health-indication signals can be generated such as temperature, mechanical travel limit, signal-out-of-range, high current, and excessive servo error indicators.

3.3. Life

The operational, nonoperational, and storage life can be specified. Include all testing time. Separate identification of periods of stressful performance can reduce cost. An alternate method is to specify the number of on/off cycles. Limitations on maintenance cycles and downtime are required of some systems. The use of recyclable materials is increasingly important.

3.4. Serviceability

Is the device to be serviced in the field, at a depot, or at the factory? Is the mirror substrate to be replaceable in the field? Such requirements can have large impact since balancing or accurate sensor calibration may be difficult with the equipment available at such locations.

3.5. Mechanism Hidden Behind Mirror

In some applications, such as when the FSM is to be used as the secondary optic of a cassegrain telescope, it may be necessary to locate the actuators, suspension, and position sensors entirely behind the mirrored surface.

3.6. Caging

If the FSM is to be subjected to harsh vibration or lateral loading during launch, takeoff or landing, it may be necessary to specify mechanical or electronic caging of the moving assembly. Caging can be either single operation or repeatable depending on reliability and mission needs.

3.7. Materials and Processes

Standard M&P issues include outgassing of volatile materials under low-pressure and high-temperature conditions. Cleanliness during fabrication and assembly may also need to be specified.

3.8. Test and Verification Methods

A matrix should be included to identify which requirements are to be verified by test, inspection, or analysis. The ranges of conditions under which each test is to be conducted should be included.

The specification should identify the desired analyses and can include stress, mass properties, structural bending modes and loads, servo performance, reliability, and failure modes and effects. The accuracy required of each analysis can be defined, as well as the level of confidence expected. The format of the output data can also be included.

3.9. Calibration Method

In some cases cost can be reduced by performing calibration in the operational environment. This is the case for some space-based systems that must undergo gravity and temperature changes during launch. The cost of on-orbit calibration can be less than that of ensuring accuracy from ground calibration through launch. It is therefore desirable to specify the conditions and limitations on calibration procedures. This can include the customer-furnished equipment and integration facilities available for calibration. If calibration software or processing hardware can be provided as part of the larger system, costs may be reduced.

3.10. Environment

The environment must be specified for the FSM mechanism as well as the electronics box. All modes of operation and nonoperation including integration testing, launch, takeoff, landing, storage, and transportation should be included. Parameters specified should address temperature, humidity, pressure, shock, vibration, radiation, light, and electromagnetic interference and pulse (EMI/EMP).

3.11. Quality Control

Many plans exist for quality assurance. The best may be the one that is operating effectively at the vendor's facility.

3.12. Documentation and Training

A variety of documentation formats are available. Perhaps the most effective include a complete set of as-built drawings and schematics, analysis reports, an operating manual, a test procedure, and test results.

4. COMPONENT SPECIFICATIONS

The specifications for component parts of an FSM are as important to the proper operation of an FSM as its own specification. The basic parts often include:

- polished mirror substrate,
- position sensors,
- flexure suspension, and
- actuators.

The line of communication should continue through to the component part suppliers. Each item of the FSM specification should be checked for applicability to part specifications.

5. EVOLUTION OF THE SPECIFICATION

A specification is a "living" document. It continues to evolve as program understanding matures. Even as we have attempted to make it complete we must continue to use it as a tool for solving current challenges.

The process starts with identification of the need. This can be at program conception or during the development of a new product concept. Although no more than a framework in a state of flux at this time, the specification should have all the basic pieces.

During the concept planning phase the critical requirements are identified and used in feasibility analyses to determine viability. Alternate concept options may be generated at this time having slightly different FSM specifications.

A trade study research program is then conducted. Demonstration or test hardware may be fabricated. The purpose at this time is to accurately determine which configuration concept option is most effective for the application. The specification is well understood at the end of this phase, but may still be in table format.

During the detailed design phase the specification is fleshed out into a well-defined document. As additional team members contribute new viewpoints, verbal descriptions of the requirements are needed to accurately create a common understanding. The document looks complete at this time, and hopefully is.

Through the course of fabrication, assembly, testing, and system integration the specification is fine tuned. Any lessons learned become expensive modifications to the specification. This is the time when the quality of previous effort is seen and the program is vulnerable to major cost impact due to schedule slips that can result from an incomplete specification.

The final rating of specification quality occurs during use and logistic support. At this time we determine if predictions for performance over life, under a variety of operating conditions, and in the presence of human factors come true. Much of the system cost is incurred at this time, providing an additional rating.

6. REFERENCES

1. General Instrument Interface Specification for the EOS Observatory, UID101, GE Aerospace Astro-Space Division/Nassau Park, 12 Oct 1990.