Specification No. ES519085
CAGE Code 23835
02 May 2003

## Terrestrial Planet Finder (TPF)

# Technology Demonstration Mirror (TDM)

## DETAILED EQUIPMENT SPECIFICATION

05/02/2003

Approved: Eri J. Cohen, TDM Task Manager — Date


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**DOCUMENT CHANGE RECORD**

| Revision Status | | | Paragraphs Affected |
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| **Revision** | **Date** | **Approval** | |
| Basic | 05/02/2003 | Cover | |

Changes to requirements of Specification 519085 are indicated by change bars in the margin.

## 1.0 Scope and Precedence of Requirements

This specification defines the requirements for the design, fabrication, and verification of a deliverable TPF Technology Demonstration Mirror (TDM). The specified mirror constitutes technology demonstration. The essence of this demonstration is to achieve the mid-spatial frequency requirements, both in surface error and in reflectance nonuniformities. Surface error requirements in the mid-spatial frequencies are better than that achieved on Hubble Space Telescope (HST), and in addition, in a more challenging geometry. The TDM is an unobscured section of a steep aspheric profile, on a substrate roughly one-third to one-quarter the areal density of HST, which is why the mid-spatial frequency requirement is very challenging. Furthermore, the TDM goal is 2 times better than required as identified by TPF architecture studies.

While NASA has not identified a flight mission for the TDM, the delivered mirror is to demonstrate the level of technology that can currently be produced to flight standards.

### 1.1. Purpose

The TDM mirror described in this specification is targeted at demonstrating technology relevant to architecture studies for coronagraphic TPF missions.

### 1.2. Conflicting Requirements

Conflicts arising between the requirements of this specification and the requirements of any document referenced herein shall be referred to the TDM Contract Technical Manager (CTM) for resolution.

## 2.0 Relevant documents

The TDM mirror assembly shall be designed, fabricated and tested in compliance to this specification and the documents listed below.

2.1. JPL Guideline D-17868: Design, Verification/Validation and Operations Principles for Flight Systems, Rev. 1

2.2. Specification/Standards Documents

- 2.2.1. MIL-F-48616 - Mild abrasion/Humidity/Adhesion
- 2.2.2. MIL-O-13830 H - General Specification, Manufacture, Assembly, and Inspection
- 2.2.3. ASTM F 1811-97 - Measurement of power spectral density function (PSD).

## 3.0 Definitions

3.1 Coordinate system

3.2.1. The TDM mirror coordinate system is defined in terms X, Y and Z-axis in the following configuration and as shown in Figure 3-1:

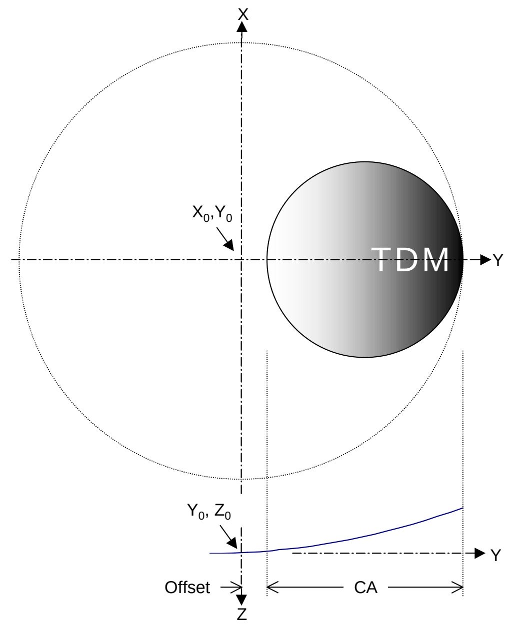



Figure 3-1: Cartesian Coordinate System

3.2.2. Z is the axis normal to the parent vertex and facing into the surface.

3.2.3. Y is the axis along the radius vector of the parent, including both the center of the parent and the center of the TDM.

3.2.4. For data reported to JPL, any alternative coordinates systems evoked must be referenced to this system, and a transformation matrix provided.

3.3. Design Practices

The contractor shall specify the approach to be used and the extent to which metric (SI) units of measurement will be used to meet the requirements of this specification. Use of metric units shall be assumed for new designs unless it can be demonstrated to result in significant inefficiencies.

3.4. Aperture Definitions

3.4.1. Offset Distance: Y1 is the distance between the optical axis (center of the parent) and the nearest edge of the TDM beyond which all specified optical and coating properties are fully satisfied.

3.4.2. Physical Aperture (PA): Includes the maximum physical diametric aperture of TDM front surface, allowing for clear aperture roll off, bezels and non-circularity. The PA is the projection of the plane of the TDM onto the XY plane.

3.4.3. Clear Aperture (CA) is defined as the diameter of the TDM, projected onto the XY plane, within which all specified optical and coating properties are fully satisfied. The TDM surface is inclined to the XY plane. The Clear Aperture Allowance (CAA) is the (PA – CA)/2 which may be anisotropic, and is provided for the convenience of optical fabrication. CAA0 is the CAA along the Y axis nearest the optical axis.

3.4.4. Greatest Lateral Extent (GLE): Includes the TDM Physical Aperture, plus any part of the TDM front or back, projected on the XY plane. The GLE also includes tolerance build-up, and may be anisotropic.

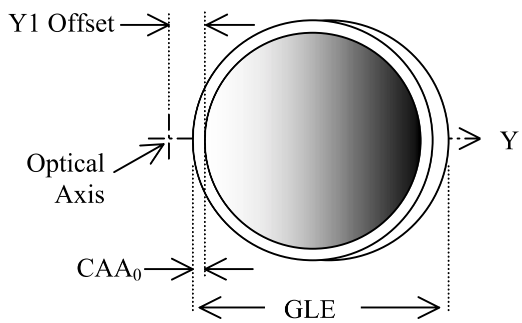


Figure 3-2: Greatest Lateral Extent

3.5. Conic Constant: The conic constant, as used in this document, follows the convention of Malacara (Optical Shop Testing, 2nd edition, 1992, Appendix 1) and is denoted as K. In this convention, a paraboloid has $K = -1$, and an ellipse rotated around its major axis has $-1 < K < 0$.

3.6. Surface Errors

3.6.1. Spatial wavelengths ($\Lambda$) are defined to cover the following ranges:

3.6.1.1. Low spatial wavelengths: $\Lambda > 40$cm

3.6.1.2. Mid spatial wavelengths (critical): $40\text{cm} \geq \Lambda \geq 2\text{cm}$

3.6.1.3. High spatial wavelengths: $2\text{cm} > \Lambda > 1\text{mm}$

3.6.2. The Power Spectral Density (PSD) shall be derived from a surface figure error map inclusive of 100% of the area contained within the clear aperture. PSD will be calculated in a manner consistent with ASTM F 1811-97. Surface error is defined to be parallel to the optical axis.

Surface error (SE) data will be requested by JPL to monitor progress. As the final polishing steps are taking place, at the contractor, SE data shall be sent to JPL electronically for conversion to PSDs."

The optical finishing figure-of-merit over the low, mid, and high spatial frequency regime is the PSD, with piston, tip, tilt, and focus subtracted. A 2-dimensional PSD is to be computed from a residual surface figure map and provided in digital form. The raw surface figure error data shall be provided in digital form as a function of mirror surface coordinates. Coordinates and units shall be identified. Test and data analysis uncertainty shall be allocated in the test error budget.

The contractor is encouraged to over sample to achieve accurate measures of the PSD (Goal is > 5x Nyquist). It is recognized that rich sampling will introduce spurious points. During the study phase, the contractor may offer a schedule of point count that may fall outside the specified PSD, yet not be counted in meeting the specification. JPL reserves the right to modify or reject this approach. The approach must include a rationale for selection of points that will not be included in the PSD. Any such criteria must not result in ignoring a defective zone in either the frequency regime or spatial regime. At least 95% of the data shall be included.

3.6.3. Microroughness is a sampled quantity and represents the contribution to veiling glare resulting from surface error at spatial wavelengths $\sim 1\mu m < \Lambda < 1mm$.

3.6.4. Microroughness shall be measured in mutually agreed locations within the clear aperture. Typically, this measurement is made using a non-contact profilometer, Atomic Force Microscope (AFM) or scatterometer, or some combination of these instruments.

## 3.7. Metrology

The contractor shall provide a detailed test procedure, including an error allocation among various effects covering the full domain of spatial frequencies. These effects may be dependent on the spatial wavelength ($\Lambda$) domain under consideration, and are listed in section 3.8.

## 3.8. Error Budgets

The contractor shall provide a comprehensive error budget as part of the TDM design, defining in depth both random and uncompensated systematic error contributions. The error budget is not merely a high level representation of the TDM, but rather a detailed multi-level tool that may be used to evaluate and understand design trades and sub-tier requirements. At least four error budgets shall be provided for surface errors, and at least one error budget for coating errors. Each shall demonstrate how the requirement is met. The budgets are as follows:

Error Budget (Surface, Λ>40cm)

Error Budget (Surface, 40cm≥Λ≥2cm)

Error Budget (Surface, 2cm>Λ>1mm)

Error Budget (Surface, 1mm>Λ>1μm)

Error Budget (Reflectance, 40cm≥Λ≥2cm)

Error estimates shall recognize both broad spatial frequency effects and anticipated periodic or zonal deviations. Narrow spatial frequency error effects must be noted and included in the error budget. An error budget shall explicitly define how each element is propagated to the next higher level, and state the basis for estimation of the lower tier contributors. If errors cannot be combined automatically, the basis of combination shall be explained. Each error budget shall be delivered as an "active electronic document", preferably as an Excel spreadsheet.

The error budget shall represent effects to at least the 3$^{rd}$ level. Error elements shall include all known relevant random and uncompensated systematic effects, including, but not limited to the following:

- Calibration errors
- Mounting errors
- Test vibration errors
- Test seeing errors
- Sampling errors
- Metrology noise
- Systematic instrument errors
- Mounting repeatability
- Gravity release residual errors
- Uncertainties in combination of observations
- Registration errors
- Temperature offset, gradient and transient errors

- Material inhomogeneity and anisotropy
- Coating stress (global and print through deformation)
- Contamination
- Aging

## 4.0. Optical Characteristics

4.1. Optical prescription

4.1.1. The conic constant shall be (-0.995003) ± 0.0001 (knowledge within ±0.00001).

4.1.2. The vertex radius of curvature shall be 7200 mm ± 2 mm (knowledge within 0.05 mm).

4.1.3. The optical axis of the parent and the center of the TDM mirror shall be separated by 1100 mm ± 2 mm (knowledge within 0.1 mm), in the XY plane.

4.2. Surface definition

4.2.1. Zones

4.2.1.1. The clear aperture (CA), projected on the XY plane, is ≥ 1800mm in diameter in that projection.

4.2.1.2. The clear aperture allowance shall be ≤ 40mm in the plane of the mirror.

4.2.1.3. Greatest Lateral Extent (GLE) shall be ≤ 1930mm along Y.

4.2.1.4. The Physical Aperture shall be ≤ 1900mm along X.

4.2.2. Surface Requirements

The PSD will be derived from surface figure map and includes 100% of the area contained in the clear aperture.

4.2.2.1. Spatial frequency error content

4.2.2.1.1. Over 1mm ≤ Λ ≤ 40cm, residual data points at all frequencies shall be plotted as a function of spatial frequency and shall fall under the required PSD curve sampled at least 2 times the Nyquist frequency with 5 times Nyquist as a measurement goal. Sub-aperture measurement may be necessary to adequately sample the highest spatial frequencies.

The required PSD curve as a function of the spatial frequency, *k*, is defined as:

$$PSD(k) = \frac{A}{1 + \left(\frac{k}{k_o}\right)^n}$$

Where $k = \frac{1}{\Lambda} = \sqrt{\left(k_x^2 + k_y^2\right)}$ cycles/cm

A = 2.4 * $10^5$ $\text{Angstroms}^2$ $\text{cm}^2$

(goal is A = 6 * $10^4$ $\text{Angstroms}^2$ $\text{cm}^2$ between Λ = 40cm and Λ = 2cm)

$k_o$ = 0.04 cycles/cm

n = 3

Over 40cm ≤ Λ ≤ full aperture the surface error shall be 10nm RMS with a goal of 5nm RMS.

Surface errors (in RMS) that correspond to the mid and high spatial frequency ranges are 4.8nm and 1.35nm, respectively.

For the high spatial wavelength range, 1mm ≤ Λ ≤ 2cm, the complete mirror does not have to be sampled. Linear scans are acceptable but must be done both radially and azimuthally (referenced to the center of the TDM). 10cm diameter subapertures will be sampled at 5x Nyquist. Subaperture measurements shall be made at 10 independent locations that are mutually agreed upon during the design phase and the results shall be individually RSS'd, after dividing by 10. At least two independent sub-apertures must include the edge of the TDM. Also included in the 10 locations shall be anomalous regions that shall be identified by using a fiber optic illuminator.

The surface figure of the mounted mirror, corrected to zero-gravity conditions, shall be measured in a manner that provides a map of surface figure structure on all spatial scales.

4.2.2.1.2. For the low and mid spatial frequencies a smoothing function shall be applied to the surface figure map to remove by averaging all surface structure on spatial scales smaller than 2 centimeters. The PSD of the surface figure shall be estimated from this filtered surface figure map. The estimated PSD values shall fall below the specified PSD curve over the spatial frequency range from 0.025 to 0.5 cycles / centimeter. Exceptions to this requirement will be allowed, to an extent not to exceed the specified PSD by more than a factor of 2 within a spatial frequency range no greater than 10% of the specified spatial frequency range.

4.2.2.1.3. Over the microroughness regime of ~1μm < Λ < 1mm, the residual surface error must be less than 10Å RMS with a goal of 5Å RMS. Sampled locations will be measured in both radial and azimuthal directions (referenced to the center of the TDM) at ≥ 6 mutually agreed locations defined during the design phase. One of these locations must include the visual "worst" location on the mirror as assessed by high intensity light illumination in a darkened room. Scan length shall be ≥ 10mm, and the spatial filter will be set to yield results comparable to industry standards, and representative of the level of total integrated scatter (TIS) expected from the sample location on the mirror. Derived values may exclude the amplitude of a mapped scratch or dig at the location of the measurement. The level of the mirror is regarded to be the average of the 12 or more measurements above. All measurements shall be reported, and the scans provided in electronic form.

4.2.2.2. Cosmetic quality

The polished clear aperture of the mirror substrate shall meet or exceed a Scratch/Dig of 80/50 per MIL-O-13830H. The "O" indicates the older specification with the visual scratch-dig criteria."

4.2.3. Sequence of optical performance testing

4.2.3.1. Conclusion of optical fabrication prior to coating

4.2.3.2. After coating and prior to mounting

4.2.3.3. After mounting mirror and before environmental tests

4.2.3.4. After thermal cycling and before vibration testing

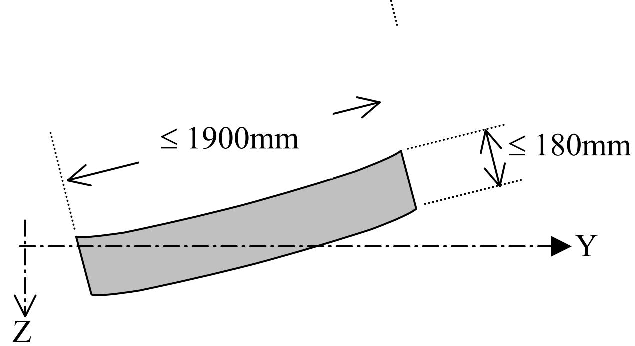
4.2.3.5. After vibration testing

4.3. Reference fiducials: The manufacturer shall design and provide a system of fiducials on the mirror appropriate to aid in post-delivery testing, and in integrating the mirror into a telescope assembly. The design shall be compatible with metrology, and will establish the spatial position of the mirror relative to the parent mirror's vertex and optical axis. It is anticipated that final adjustment of the position of the mirror will be determined by testing optical attributes, and accordingly, the fiducials may not be required to satisfy the full telescope alignment flow down allocated to the Primary Mirror. Alignment fiducials will be either registered to the mirror following a kinematic mounting scheme, or will be integral to the mirror. In either case, accuracy must be met for each Degree-of-Freedom. In the former case, an additional registration repeatability requirement will be satisfied.

| Degrees of Freedom | Accuracy | Repeatability | Units |
|---|---|---|---|
| $\Delta X = \pm$ | 200 | 20 | microns |
| $\Delta Y = \pm$ | 200 | 20 | microns |
| $\Delta Z = \pm$ | 200 | 20 | microns |
| $\theta_X = \pm$ | 26 | 3 | microradians |
| $\theta_Y = \pm$ | 26 | 3 | microradians |
| $\theta_Z = \pm$ | 175 | 20 | microradians |

## 5.0. Mirror Substrate

5.1. The mirror substrate, if fabricated along the off-axis angle of the mirror, shall have a physical aperture in its own plane with a diameter ≤ 1900mm, and thickness at the edge of ≤ 180mm.




5.2. The substrate material must be compatible with maintaining a stable boresight and satisfying surface requirements while exposed to temperatures per section 7.4.

5.3. The substrate material must be compatible with launch and operational loads when implemented on a lightweight structure.

5.4. The substrate material must be dimensionally stable and sustain all optical figure requirements for at least 3 years of storage in earth ambient conditions, and 10 years of space flight.

5.5. The substrate material must be dimensionally stable and sustain a total ionizing dose (TID) per the specifications in section 7.4 while sustaining all optical figure requirements. This specification may be demonstrated by the use of results from radiation testing of a similar substrate.

5.6. The mirror must have a first resonant frequency, in the free-free condition, ≥ 200Hz (300Hz goal). Unsupported sections of the face sheet spanning lightweighting pockets should have a resonant frequency ≥ 2500Hz.

5.7. The substrate areal density, including mounting interfaces, but not bipods, shall be < $60kg/m^2$, with a goal of $30kg/m^2$.

5.8. Interface pads

5.8.1. Mounting distortion is included in the surface figure requirement, and is to be represented during test

5.8.2. The mirror shall be kinematically mounted via a set of 3 bipods, located at the support points that will minimize gravitational deflection,

5.8.2.1. The mount shall be consistent with the coronagraph instrument packaging and mounting constraints (see figures 5-1, 2, and 3), and maximized support under launch loads. One mirror mount shall lie on the projection of the Y axis, and shall be on the side of the TDM furthest from the optical axis of the parent.

5.9. Venting requirements

5.9.1. Maximum differential pressure shall be < 0.2 atmospheres while depressurizing at the maximum environmental rate.

5.10 TDM Assembly (See figures 5-1, 2, and 3).

5.10.1. The TDM Assembly consists of

5.10.1.1. TDM mirror

5.10.1.2. Mounting pads

5.10.1.3. 3 kinematic bipod mounts, designed / fabricated to protoflight standards

5.10.1.4. A surrogate strong back that will hold the mirror, and represents that structure that, in a hypothetical system, would relate the TDM to the rest of the telescope, to the instrument package, and to the spacecraft. Location of the mount points on the surrogate strong back shall be determined by the contractor.

5.10.2. Testing and validation in the TDM Assembly configuration

5.10.2.1. Performance and environmental tests shall be performed with the TDM in the TDM assembly, with all fasteners at proper torques.

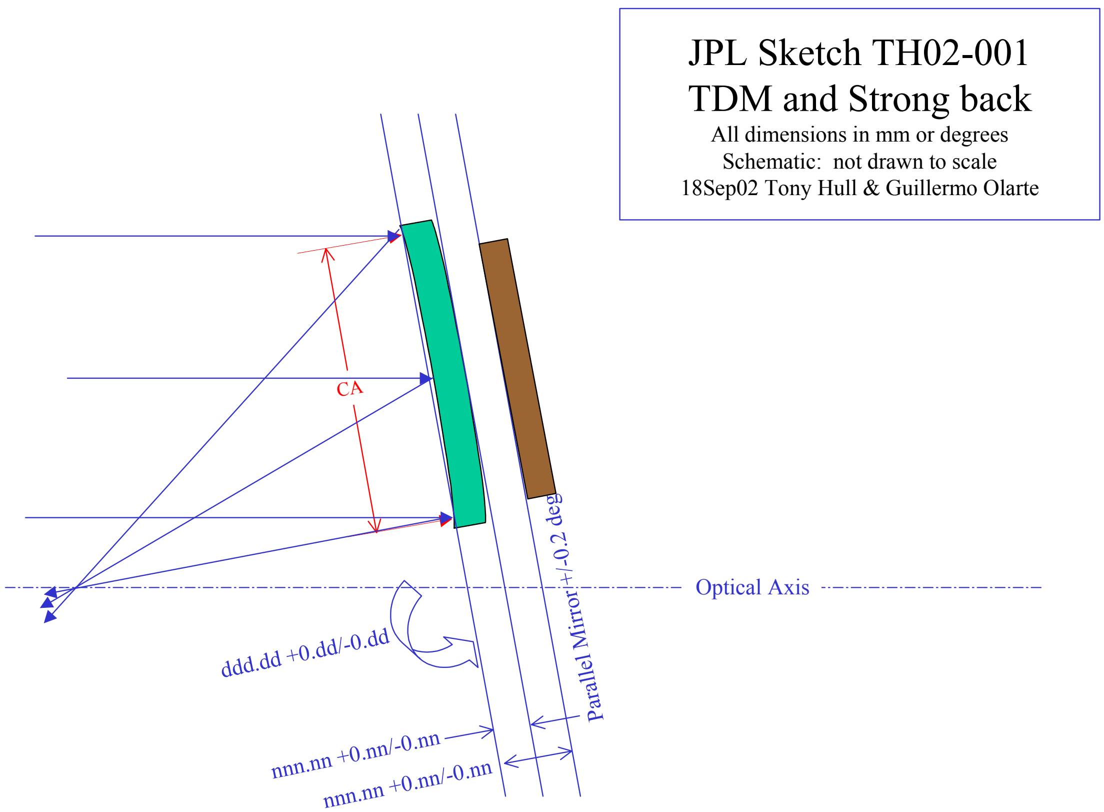
5.10.2.2. Accessory supports for gravity offload tests may be used. Analytic estimates of errors in such offload supports shall be a component in the final mirror error determination.

5.10.3. TDM Assembly Characteristics

5.10.3.1. The TDM assembly (for this specification only, the assembly consists of the TDM mirror, mounting pads, and kinematic bipod mounts) shall have a first resonance frequency ≥ 85 Hz with respect to the strong back with the strong back considered a mechanical ground.

5.11. The TDM shall be compatible with maintaining Class 500 cleanliness requirements. As such, the bevel, edge and backsheet shall be finished in a manner to minimize contamination issues.

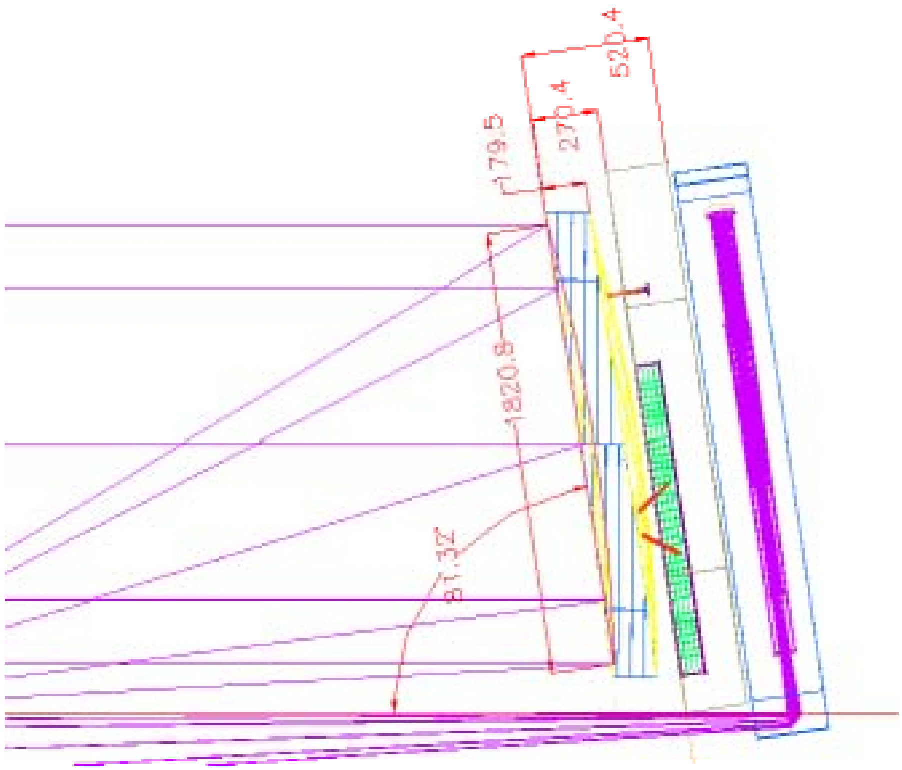
Location Of The Strong Back With Respect To The Mirror #1
Figure 5-1




The solid model of the mirror was simplified as follows. A shell representing the front surface was generated and then duplicated. The identical second surface was offset from the first and in this drawing represents the back surface of the mirror. The offset was set to ~18cm per specification 5.1. (At the edge of the physical surface of the mirror this distance is 17.95cm and at the thickest point it is 18.06cm. This distance is measured along a perpendicular to the plane defined by the front surface of the mirror.)

Note that the full physical extent of the mirror is represented including the clear aperture allowance (CAA) which is defined in specification 3.4.3.

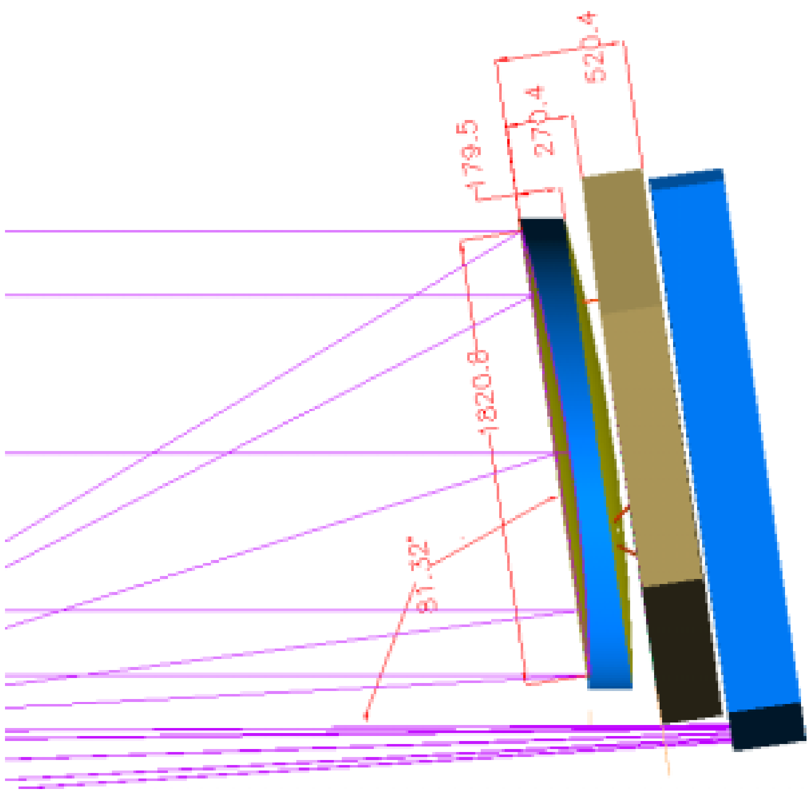
Location Of The Strong Back With Respect To The Mirror #2
Figure 5-2




The strong back is represented by the rectangle outlined in gray and the focal plane optics is in the box outlined in blue. The most critical dimension is the 520.4mm which is the distance from the back of the strong back to the front edge of the mirror and 270.4mm from the front of the strong back to the front edge of the mirror. (Edge, in this case, is the edge of the clear aperture and not the physical aperture.).

The gray box, representing the strong back is 250mm thick and the bipods are mounted roughly at the mid-point (125mm from the top and back).

Location Of The Strong Back With Respect To The Mirror #3
Figure 5-3



## 6.0 Mirror Coating Definitions

The requirement for the mirror coating shall be an unprotected reflective metallic film, and the reflectance will be equal to freshly deposited pure gold. A protected coating will be considered but the uniformity of the phase variation in the overcoat must be treated as a surface error due to the path delay in the overcoat and be part of the surface error budget. The uniformity of reflectance over the clear aperture, not the absolute value of the reflectance, is the essence of the coating requirement.

In the specifications that follow, reference is made to both witness samples and test coupons. Witness samples are coated along with the TDM while test coupons are coated during special coating runs that are identical in all coating parameters to the coating run used to coat the TDM. The location of each witness sample, with respect to the TDM, shall be recorded. The location of the test coupons with respect to the geometry to be used to coat the TDM shall be recorded.

**6.1. Spectral Characteristics.** The reflectance of the TDM mirror's specular surface is equivalent to the reflectance of Au without overcoat. The TDM mirror will operate over a spectral wavelength band from 0.50μm to 2.50μm. Tests shall cover this spectral range. The coating shall be optimized for the spectral wavelength band from 0.55μm to 0.95μm. The coating reflectance shall be ≥ reflectance of bare freshly deposited gold minus 1% at Beginning of Life (BOL), and within minus 2% of bare freshly deposited gold at End of Life (EOL).

6.2 **Coating Area.** Coating shall extend beyond the clear aperture but not across an edge onto any edge bevel. Within the clear aperture, coating reflectance uniformity and reflectance requirements shall be satisfied.

6.3 **Coating Deposition Process.** The coating deposition process shall be consistent with satisfying all TDM requirements, with emphasis on lifetime, reflectance uniformity, low scatter, and minimal surface error over all spatial frequencies. The supplier's ability to clean the reflective surface of molecular and particle contamination by a process the supplier provides, is a TDM goal. Any induced polarization or phase retardance will be included in the reflectance uniformity and surface error uniformity requirements to the extent they affect these attributes.

6.4. **Coating Reflectance Uniformity.** Within the TDM clear aperture, and over spatial wavelength bands between 2cm $\leq \Lambda \leq$ 40cm, the RMS residual reflectance shall be ≤ 0.3%, with ≤ 0.1% the goal. The error in the measurement of the reflectivity shall be to ≤ 0.1%. Metrology directly on the TDM mirror is preferred. However, as a less favorable option, the supplier may extrapolate the reflectance uniformity of the mirror from a dense set of planar test coupons set at a comparable angle and spacing to the source, and exposed immediately before or after the TDM under identical deposition conditions. In the case of the less preferred option, test coupons shall represent the entire TDM surface. JPL will consider sampling strategies to reduce the number of measurements needed, provided that the full surface sampled in this strategy is justified based on coating technique and/or on coating demonstrations.

6.5. **Straylight**. Any contribution of the mirror coating to stray light shall be included in the microroughness specification. The TDM mirror will be subjectively inspected in a dark room with a collimated high intensity light. Areas that exhibit anomalous brightness shall be included in sampling should metrology directly on the TDM mirror be possible.

6.6. **Ionizing Radiation**. The mirror coating shall show no signs of degradation, cloudiness or discoloration after test coupons are subjected to 1.5 times the TID level specified. After irradiation the mirror coating on the sample shall be examined with 10X microscope and shall show no evidence of flaking, peeling, cracking or blistering. This specification can be demonstrated by the use of results from a similar coating.

6.7. **Humidity Resistance.** The mirror coating shall show no signs of deterioration such as tarnishing after witness samples are subjected to tests specified in MIL-F-48616.

6.8. **Adhesion.** The mirror coating shall show adhesion when subjected to tests specified in MIL-F-48616. Witness samples shall be used for this test.

6.9. **Mirror Coating Stress**. The mirror optical coating shall not produce significant stresses in the mirror. The optical surface of the mirror shall meet all requirements in section 4.2.2 after mirror coating. This shall be determined by comparing full aperture phase maps taken of the TDM optical surface before and after coating.

6.10. **Mirror Coating Surface Quality**. The finished TDM mirror coating shall comply with MIL-0-13830 H. The mirror coatings shall exhibit no structural non-uniformity, sleeks, or scratches larger than 80/50 when inspected with the unaided eye.

6.11. **Mirror Witness Samples.** The contractor shall manufacture an appropriate number of the witness samples. The witness samples shall be 50mm x 50mm size, fabricated using the same mirror substrate material; polished by the same process as the mirror substrate is polished, and coated with an identical mirror coating process as the TDM mirror. The test lot size shall be > 20 pieces.

6.12. **Contamination Control**. The coated TDM shall be kept in a contamination controlled area during metrology/storage/shipping at a Class 500 cleanliness level. During storage and shipping the TDM shall be kept in a non-condensing environment.

6.13. **Grounding.** Provision for grounding the coated surface must be provided**.** Any point on the coated surface to the ground point shall have a resistance of less than 100Ω.

## 7.0. Environment Compatibility Verification

7.1. TDM Lifetime

7.1.1. The pre-launch storage lifetime (within shipping container) is 2 years.

7.1.2. The pre-launch telescope integration lifetime is 3 years, at integration environment.

7.1.3. The space flight lifetime shall be 5 years, with a goal of 10 years.

7.2. The TDM shall survive the following launch environment (non-operating) conditions

7.2.1. Temperature: -10°C to +60°C

7.2.2. Pressure: 15 psi to < $10^{-6}$ Torr

7.2.3. Pressure change: Specified range above over a 5 minute period

7.2.4. Humidity: 0 to 50% RH

7.3. Protoflight Qualification Requirements:

7.3.1. **Structural Loads**: The TDM and supporting struts shall be designed to 2.5 times the limit load value of 12 gs applied in the worst single direction through the center of gravity of the TDM. Pass/fail testing shall be done on the bipods and the bipod to the mirror bond at a level of 1.25 times the limit load. The latter test shall use a surrogate mirror. Loads may be applied by a static loads test, a centrifuge test, or a shaker pulse test.

7.3.2. **Random Vibration**: The TDM assembly (bipods and strongback included) shall be subject to the random vibration qualification levels given below. The test duration is one minute (since the TDM is protoflight hardware) in each of three orthogonal axes. The test may be force limited to reduce over-test at hard mounted resonance frequencies. The upper bound force spectrum below may be used to limit the input acceleration to the test article. Additional notching of the input acceleration spectrum may be applied if necessary to keep the interface force from exceeding the structural limit load. The random vibration test will be preceded by a low level random vibration test from which the frequencies to be notched can be determined.

Primary Mirror Random Vibration Qualification Test Acceleration Input

| Frequency, Hz | Acceleration Spectral Density Level |
|---|---|
| 20<br>20 – 80<br>80 – 500<br>500 – 2000<br>2000<br>Overall | $0.015 g^2$ / Hz<br>+ 3 dB / Octave<br>$0.06\ g^2$ / Hz<br>-6 dB / Octave<br>$0.00375\ g^2$ / Hz<br>7.1 g RMS |
| | |

1g = standard acceleration due to gravity = 9.81 $m/s^2$

Duration: 1 minute in each of three orthogonal axes

Primary Mirror Random Vibration Qualification Test Force Limit Specifications

| Frequency, Hz | Force Spectral Density Level |
|---|---|
| 20 – 1.1 Fn<br>1.1 Fn - 1000 | 480 $FN^2$ / Hz<br>- 6 dB / Octave |

Where Fn is the first predominate resonance frequency in the axis of test, F is the product of the acceleration spectrum times the square of the total mass of the test article in kg, N is the unit Newtons

7.3.3. **Thermal:** The TDM shall be exposed to 3 cycles over the survival temperature range (see section 7.4) with a temperature ramp ≤ 1ºC/minute.

7.4. Operational Space Flight Environment

7.4.1. Gravity environment 0g

7.4.2. Operating temperature 20 ±2 °C

7.4.3. Survival temperature range -30°C to +60°C

7.4.4. TDM thermal gradients Front to back < 2°C, Radial <1°C

7.4.5. TDM thermal transients dT/dt < 1°C/minute

7.4.6. Pressure < $10^{-6}$ Torr. Results of a test on a similar mirror is acceptable.

7.4.7. Ionizing radiation 20,000 rad (Si) total dose (TBR) in 5 years (witness sample includes materials in addition to substrate and coating that were not included in other sections). This specification may be demonstrated by the use of results from the radiation testing of similar material.

7.5. Storage

Temperature between 10 and 30 degrees C, at less than 5% relative humidity

7.6. Integration

Temperature between 5 and 35 degrees C, at less than 80% relative humidity

## 8.0. Quality Assurance

## 8.1. Responsibility for Quality Assurance

Primary responsibility for quality assurance of delivered hardware, processes, tests, or services is placed on the contractor, who is responsible for offering only those hardware, processes, tests, or services that conform to specified requirements. The contractor shall implement a quality assurance program to assure that the requirements of this specification are met.

## 8.2. Materials and Processes

Materials and processes employed in designing producing the TDM are to be consistent with space flight practices. Specifically, compliance under vacuum conditions, survival temperature range and survival launch loads shall be demonstrated on either the TDM, or a representative surrogate of the TDM. Materials and processes used shall be consistent with an ionizing radiation environment and meet flight standards for outgassing. The TDM optical performance shall be evaluated before and after testing at specified vibration levels and depressurization rates, and demonstrate no resulting degradation. Performance shall also be demonstrated over the operational temperature range.

### 8.2.1. Traceability

All materials shall be identified with a material lot number. Traceability shall be provided by identifying materials in a particular serialized assembly or subassembly by a procured lot number. This identification shall remain with the material at all times and provide complete traceability information from the procurement source.

### 8.2.2. Material Review Boards (MRB)

The contractor shall notify JPL in advance of any MRBs including:

a. Type I MRBs that consider issues affecting form, fit, or function relative to the TDM specifications. The contractor shall include JPL in the MRB. The MRB shall be final only after JPL approval.

b. Type II MRBs that consider issues affecting contractor imposed sub-tier requirements. JPL does not necessarily have to be included in the MRB, however, the disposition of the MRB shall be reported to JPL, electronically, within 24 hours of closure.

## 8.3. Anomaly Reporting and Corrective Action

The contractor shall notify JPL of any manufacturing failures or anomalies that put at risk the timely completion of deliverables. The contractor shall contact and consult with the JPL CTM in order to plan and gain authorization for corrective action.

## 8.4. Quality Conformance Inspections and Tests.

TDM compliance with the requirements of this specification shall be verified by one or more of the following methods as indicated in Table 8.4.

a. Inspection - A visual observation, examination, or direct measurement of the physical characteristics of the deliverable item with a comparison to the applicable requirement, yielding a subjective pass / fail evaluation.

b. Analysis - A calculated prediction showing that the deliverable hardware complies with the stated requirements based on measured properties including relevant test data together with analytical models based on the applicable engineering and physical governing equations.

c. Test – A laboratory procedure under controlled conditions yielding multi-valued experimental data, and subsequent data reduction, to provide quantitative data that are directly compared to prescribed requirements.

8.5. Test Documentation

Prior to the conduct of any testing called for by this specification, the contractor shall prepare a test procedure including the testing sequence, the test methods, and the pass/fail criteria for each test. The test procedure shall be submitted to JPL for approval prior to testing. Complete records of all tests shall be kept and made available to JPL. The records shall include the data for each test conducted. A JPL representative shall be notified of test dates so that tests may be witnessed by JPL.

8.6. Test Equipment Accuracies

Unless otherwise agreed to, equipment used to measure unit parameters shall not introduce an error greater than ten percent of the tolerance of the parameter being measured.

Table 8.4 Product Verification Matrix

| Paragraph | Parameter | Inspection | Analysis | Test |
|---|---|---|---|---|
| **4.1** | **Optical Prescription** | | | |
| 4.1.1 | Conic constant | | | FA |
| 4.1.2 | Vertex radius of curvature | | | X |
| 4.1.3 | Pupil Offset | | | X |
| **4.2** | **Surface Definition** | | | |
| 4.2.1.1 | Clear Aperture | X | | |
| 4.2.1.2 | Clear Aperture Allowance | X | | |
| 4.2.1.3 | Greatest Lateral Extent | X | | |
| 4.2.1.4 | Physical Aperture | X | | |
| **4.2.2** | **Surface Requirements** | | | |
| 4.2.2.1.1 | Surface Phase Map | | | FA |
| 4.2.2.1.2 | PSD Curve | | | X |
| 4.2.2.1.3 | Microroughness | | | SS |
| 4.2.2.2. | Cosmetic Quality | X | | |
| 4.2.3 | Sequence of optical testing | X | | |
| 4.3 | Reference Fiducials | X | | |
| **5.0** | **Mirror Substrate** | | | |
| 5.1 | Mirror Dimensions | X | | |
| 5.2 | Thermal Stability | | X | |
| 5.3 | Launch Compatibility | | X | |
| 5.4 | Lifetime | | X | |
| 5.5 | Ionizing Radiation | | X | |
| 5.6 | Resonant Frequency | | X | |
| 5.7 | Mass | | X | |
| 5.8 | Interface Pads | | X | |
| 5.9 | Venting | | X | |
| 5.10 | TDM Assembly | | X | |
| 5.11 | Cleanliness | X | | |
| **6.0** | **Mirror Coating** | | | |
| 6.1 | Spectral Characteristics | | | WS |
| 6.2 | Coating Area | X | | |
| 6.3 | Coating Process | X | | |
| 6.4 | Reflectance Uniformity | | | TC |
| 6.5 | Straylight | X | | |
| 6.6 | Ionizing Radiation | | X | |
| 6.7 | Humidity | | | TC |

| Paragraph | Parameter | Inspection | Analysis | Test |
|---|---|---|---|---|
| 6.8 | Adhesion | | | TC |
| 6.9 | Coating Stress | | | FA |
| 6.10 | Coating Surface Quality | | | FA |
| 6.11 | Witness Samples | X | | |
| 6.12 | Contamination Control | X | | |

| | | | | |
|---|---|---|---|---|
| 7.0 | **Environment Compatibility Verification** | | | |
| 7.1 | Lifetime | | X | |
| 7.3 | Protoflight Qualification Requirements | | | |
| 7.3.1 | Structural Loads | | | X |
| 7.3.2 | Random Vibration | | | X |
| 7.3.3 | Thermal | | | X |
| 7.4 | Operational Space Flight Environment | | | |
| 7.4.1 | Gravity Environment | | | FA |
| 7.4.2 | Operating Temperature | | | X |
| 7.4.3 | Survival Temperature | | | X |
| 7.4.4 | TDM Thermal gradients | | X | |
| 7.4.5 | TDM Thermal transients | | X | |
| 7.4.6 | Pressure | | X | |
| 7.4.7 | Ionizing Radiation | | X | |
| 7.5 | Storage | | X | |
| 7.6 | Integration | | X | |

Legend:

FA – Full aperture
WS – Witness Sample
SS – Subsample
TC – Test Coupon

## 9.0 Demonstration Phase Contract Data Requirements List

Each CDRL item should contain sufficient details to define the engineering results. Documentation (e.g., QA reports, drawing sets, lists) shall be complete.

| No. | Item | Due Date |
|---|---|---|
| 1.0 | Blank production plan (include substrate acquisition plan)<br>Material requirements<br>CTE, homogeneity, CTE anisotropy<br>Facesheet seeds, voids, and inclusions<br>Stress and annealing<br>Fracture mechanics plan<br>Structural design<br>Mirror mount design<br>Fabrication plan<br>Slumping requirements<br>Percentage of complete bonds<br>Surface error of the blank<br>Facility plan<br>Blank handling equipment | Delta PDR |
| 1.1 | Pre-shipping review presentation package (blank) | |
| 1.2 | Blank acceptance data package<br>Pre-ship surface error<br>Inspection reports | |
| 1.3 | Results of the tests on the substrate facesheet witness pieces (material properties such as CTE, modulus, etc.) | |
| 1.4 | Results of the tests on the core witness pieces measured (material properties such as CTE, modulus, etc.) | |
| 2.0 | Structural Design Review presentation package | CDR |
| 2.1 | Full parts list (including mirror handling, gravity off-load, measurement system, packaging) | |
| 2.2 | Full drawings list (including all items in 2.1) | |
| 2.3 | Full set of as-designed drawings (including all items in 2.1) | |
| 2.4 | Analysis reports (structural design and model, depressurization analysis, thermal model - as designed) | |
| 2.6 | Gravity release report<br>Calculated distortion due to gravity with the TDM<br>in the optical test configuration<br>Design of the gravity release system<br>Assumptions and analysis of this system<br>Test to verify the assumptions and analysis | |

| | | |
|---|---|---|
| 2.6.1 | Gravity release residual error study<br>Errors determined both by analysis and measurement | |

| | | |
|---|---|---|
| 3.0 | Coating plan<br>Process to be used for coating<br>Plan to verify coating facility | CDR |
| 3.1 | Coating metrology plan | |
| 3.2 | Coating aging study (uniformity with time) | |
| 3.3 | Pre-shipping review presentation package (to coating facility) | |
| 3.4 | Cleaning plan | |
| 3.5 | Test coupons<br>Results for reflectivity, reflectivity uniformity, adhesion, humidity and radiation sensitivity, and coating stress | |
| 3.6 | Coating readiness review presentation package | |
| 4.0 | Test plan | CDR |
| 4.1 | Test Readiness Review<br>Verification of metrology system | TRR |
| 4.2 | Optical performance test procedures | |
| 4.3 | Environmental test procedures<br>Verification of temperature control and vibration isolation system<br>Identification of residual errors due to temperature variations and vibrations | |
| 4.4 | Test equipment calibration reports | |
| 4.5 | Mirror vertex and directional reference<br>Procedure to be used for verification of the mirror | |
| 4.6 | Mirror alignment plan (for test and telescope recommendations) | |
| 4.7 | Special test equipment (null lenses, etc.) design | |
| 4.8 | Test data (primary and reduced)<br>Surface maps and PSD<br>Modal frequencies | |
| 5.0 | Final controlled version of detailed manufacturing plan | PSR |
| 5.1 | Manufacturing flow diagram | |
| 5.2 | Tooling drawings | |
| 5.3 | Handling fixture design - as built | |
| 6.0 | TPF Primary Mirror Development Plan | PSR |
| 7.0 | TDM Analysis reports (structural, depressurization, thermal - as built) | PSR |
| 7.1 | Full set of as-built drawings (red lines acceptable) | |
| 7.2 | QA report | |

## 10.0. Acronyms and definitions

| | |
|---|---|
| AFM | **A**tomic **F**orce **M**icroscope |
| BOL | **B**eginning **O**f **L**ife |
| CA | **C**lear **A**perture |
| CAA | **C**lear **A**perture **A**llowance |
| CDR | **C**ritical **D**esign **R**eview |
| CDRL | **C**ontract **D**ata **R**equirements **L**ist |
| CTM | **C**ontract **T**echnical **M**anager |
| CTE | **C**oefficient of **E**xpansion |
| EOL | **E**nd **O**f **L**ife |
| GLE | **G**reatest **L**ateral **E**xtent |
| HST | **H**ubble **S**pace **T**elescope |
| MRB | **M**aterial **R**eview **B**oards |
| PA | **P**hysical **A**perture |
| PDR | **P**reliminary **D**esign **R**eview |
| PSD | **P**ower **S**pectral **D**ensity |
| PSR | **P**re-**S**hip **R**eview |
| QA | **Q**uality **A**ssurance |
| RH | **R**elative **H**umidity |
| SE | **S**urface **E**rror |
| SOW | **S**tatement **O**f **W**ork |
| TA | **T**echnology **A**nnouncement |
| TDM | **T**echnology **D**emonstration **M**irror |
| TID | **T**otal **I**onizing **D**ose |
| TIS | **T**otal **I**ntegrated **S**catter |
| TPF | **T**errestrial **P**lanet **F**inder |
| TRR | **T**est **R**eadiness **R**eview |

Definitions

| | |
|---|---|
| k | Spatial Frequency in Cycles Per Centimeter |
| K | Conic Constant |
| $\Lambda$ | Spatial Wavelength |