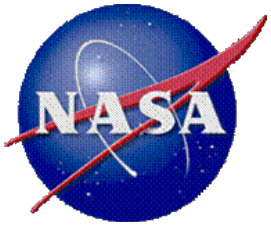
Final End of Mission Plan (EOMP) for the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) Mission

July, 2013

NASA/GSFC Code 444



National Aeronautics and Space Administration

Goddard Space Flight Center

Greenbelt, Maryland

Final End of Mission Plan for TIMED

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This EOM Plan does not contain any known restricted, proprietary, or ITAR related data.

Document Review History

Revision	Date Issued	Changes
-	??/2010	Baseline document – copied from TRACE Mission
1	4/23/2013	First Draft, TIMED Mission
2	6/10/2013	Added Review comments - rfb
3	7/15/2013	Added Review comments - rfb

The following table documents compliance with NASA-STD-8719.14 (Change 4, dated 2009-09-14).

Reqm't #	Compliant or N/A	Not Compliant	Incomplete	Comments
4.3-1.a	■	□	□	TIMED will not shed any debris in LEO during the remainder of the mission or disposal.
4.3-1.b	■	□	□	TIMED will not shed any debris in LEO during the remainder of the mission or disposal.
4.3-2	■	□	□	TIMED will not shed any debris in GEO during the remainder of the mission or disposal.
4.4-1	■	□	□	TIMED does not have any systems susceptible to accidental explosion.
4.4-2	■	□	□	TIMED will be passivated to the maximum extent possible.
4.4-3	■	□	□	There are no planned breakups for the TIMED mission so requirement is not applicable.
4.4-4	■	□	□	There are no planned breakups for the TIMED mission so requirement is not applicable.
4.5-1	■	□	□	The probability of large object collision meets the requirement.
4.5-2	■	□	□	TIMED is not vulnerable to small object collisions, since the disposal is entirely passive.
4.6-1(a)	■	□	□	DAS 2.0.2 predicts that TIMED will reenter within 11 years, meeting the requirement. TIMED has no propulsion system.
4.6-1(b)	■	□	□	This disposal option is not chosen for the TIMED mission.
4.6-1(c)	■	□	□	This disposal option is not chosen for the TIMED mission.
4.6-2	■	□	□	This disposal requirement is not applicable to the TIMED orbit.
4.6-3	■	□	□	This disposal requirement is not applicable to the TIMED orbit.
4.6-4	■	□	□	TIMED meets the disposal reliability, since the disposal is entirely passive.
4.6-5	■	□	□	TIMED will be passivated to the maximum extent possible (see Requirement 4.4-2)
4.7-1	□	■	□	TIMED exceeds the reentry risk requirement with a casualty area of 22.9m^2. A waiver will be requested.
4.8-1	■	□	□	There are no uses of tethers for the TIMED mission so the requirement is not applicable.

1.0 MISSION SUMMARY

The 598 kg Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) spacecraft was launched December 7, 2001 aboard a Delta-II 7920-10C launch vehicle from Vandenberg Air Force Base. It was deployed into a 625 km circular orbit, inclined 74.1º. During its two-year primary mission and 10 years of extended operations, TIMED has collected data on the least explored region of the atmosphere (the Mesosphere, Lower Thermosphere/Ionosphere [MLTI] region) to understand the influence of both the Sun and human activities and to improve the prediction of space weather.

Sponsored by the Science Mission Directorate (SMD) as part of the Heliophysics Division, the Program Executive for TIMED is Dr. Jeffrey Hayes. TIMED was designed and built by Johns Hopkins University's Applied Physics Laboratory (JHU/APL). TIMED is managed by the Space Science Mission Operations (SSMO) Project at GSFC Code 444. The SSMO Project Manager is Patrick Crouse, and the Mission Director is David Quinn.

This End of Mission Plan is intended to represent only the decommissioning and disposal of the TIMED spacecraft vehicle itself. The Delta-II launch vehicle re-entered on January 1, 2002.

A TIMED Orbital Debris Assessment was performed by Hernandez Engineering of Greenbelt Maryland on 11 December 1997, document number TIMED-7363-9068. That document indicated compliance with all the requirements of NSS 1740.14.

This plan represents the organization and preparation needed to execute termination of the mission due to catastrophic anomaly or termination by the Heliophysics Division at NASA Headquarters. Prior to decommissioning, project management will conduct a Decommissioning Review, which will examine preparedness to execute this EOM Plan.

2.0 SPACECRAFT DESCRIPTION

2.1 Summary Description

A detailed description of the TIMED mission can be found in the Johns Hopkins APL Technical Digest Volume 24, Number 2 (April—June 2003). TIMED is a three-axis stabilized spacecraft, built by Johns-Hopkins University's Applied Physics Laboratory (JHU/APL), as part of the Solar Terrestrial Probes (STP) program. Power is supplied through deployed solar arrays to a nickel-hydrogen battery. TIMED has no propulsion system. The spacecraft payload consists of four instruments: Global Ultraviolet Imager (GUVI), Sounding of the Atmosphere using Broadband Emission Radiometry (SABER), Solar EUV Experiment (SEE), and TIMED Doppler Interferometer (TIDI). The spacecraft mass at launch was 598.2 kg, and the basic spacecraft measures approximately 1.2 m wide by 2.7 m tall (deployed solar arrays are 11.7m tip-to-tip). Below is an overall view of the TIMED Satellite in figure 2-1.

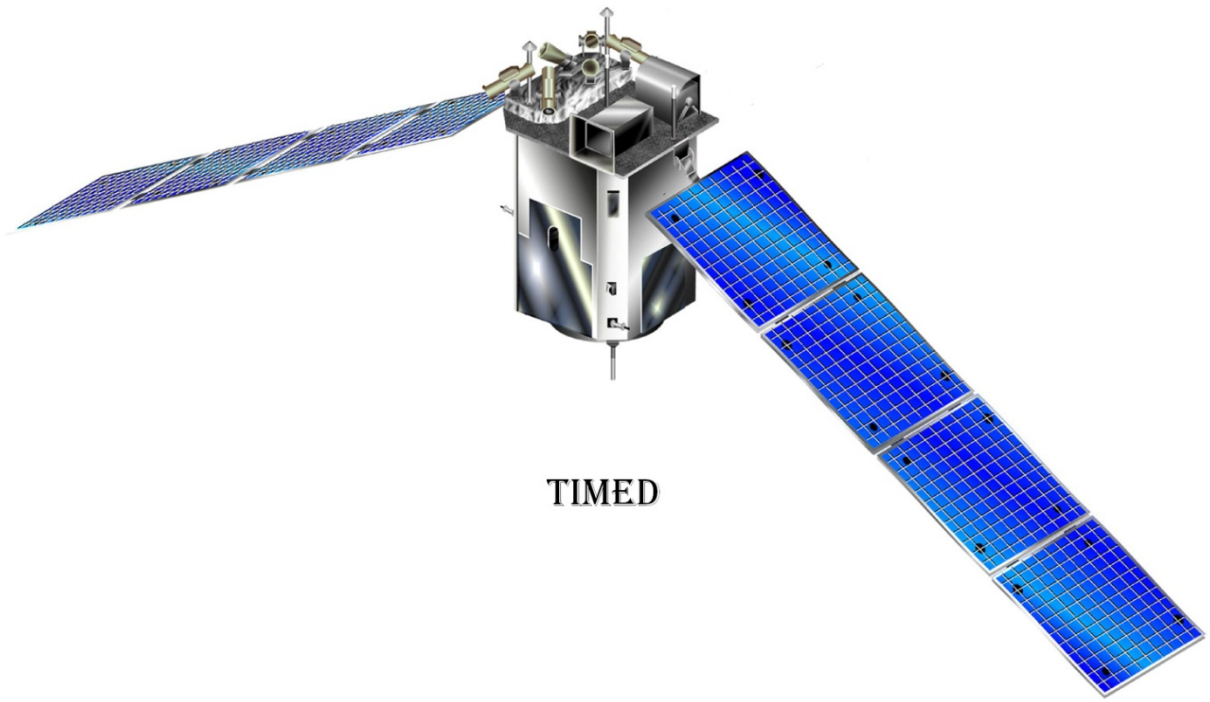

Figure 2-1. Overall view of TIMED

2.2 Passivation Table

Description	Identification	Prior to Passivation	After Passivation
Fluids	(none)	N/A	N/A
Mechanical Energy	Four Reaction Wheels	Three Wheels Operational	Remaining wheels powered down
Mechanical Energy	Saber Mechanical cooler and Scan motor	Operational	Energy Drained to maximum extent
Mechanical Energy	TIDI telescope motors SEE Scan motor	Operational	Energy Drained to maximum extent
Electrical Generation and Storage	Solar Arrays	Operational	Minimize Illumination
Electrical Generation and Storage	NiH2 Battery	Operational	Energy Drained to maximum extent
Thermal Energy	Heat Pipes for SEE and Reaction Wheels	Operational	Energy drained to maximum extent
Experiment Gases	(none)	N/A	N/A
Radioactive Materials	(none)	N/A	N/A

2.3 TIMED Status

TIMED is currently on-orbit and operational, collecting science in its twelfth year of operation. All systems are operational, including the battery.

3.0 ASSESSMENT OF SPACECRAFT DEBRIS RELEASED DURING AND AFTER PASSIVATION

3.1 Requirements

Requirement 4.3-1: Debris passing through LEO: For missions leaving debris in orbits passing through LEO, released debris with diameters of 1 mm or larger shall satisfy both Requirement 4.3-1a and Requirement 4.3-1b (Requirement 56397).

a. Requirement 4.3-1a: All debris released during the deployment, operation, and disposal phases shall be limited to a maximum orbital lifetime of 25 years from date of release (Requirement 56398).

b. Requirement 4.3-1b: The total object-time product shall be no larger than 100 object-years per mission (Requirement 56399). The object-time product is the sum of all debris of the total time spent below 2000 km altitude during the orbital lifetime of each object. (See section 4.3.4.2 for methods to calculate the object-time product.)

Requirement 4.3-2: Debris passing near GEO: For missions leaving debris in orbits with the potential of traversing GEO (GEO altitude +/- 200 km and +/- 15 degrees latitude), released debris with diameters of 5 cm or greater shall be left in orbits which will ensure that within 25 years after release the apogee will no longer exceed GEO - 200 km (Requirement 56400).

3.2 Compliance

No debris is to be released by TIMED during the remainder of, or after, the mission. As such, the spacecraft is fully compliant with NASA-STD 8719.14 Requirement 4.3.-1. Requirement 4.3-2 is not applicable to the TIMED orbit.

4.0 ASSESSMENT OF SPACECRAFT POTENTIAL FOR EXPLOSIONS AND INTENTIONAL BREAKUPS

After science operations, passivation and disposal must be completed. In accordance with the requirements below, all sources of on-board stored energy (pressure, mechanical, chemical, etc.) must be eliminated to the maximum extent possible in order to reduce the potential for post-mission explosion, which would produce a debris field obstruction for future missions through that orbit. In addition, it is beneficial to the rest of the on-orbit community for the spacecraft to not produce any further radio frequency transmissions, if possible. (See table 2.2)

4.1 Requirements

Requirement 4.4-1: Limiting the risk to other space systems from accidental explosions during deployment and mission operations while in orbit about Earth or the Moon: For each spacecraft and launch vehicle orbital stage employed for a mission, the program or project shall demonstrate, via failure mode and effects analyses or equivalent analyses, that the integrated probability of explosion for all credible failure modes of each spacecraft and launch vehicle is less than 0.001 (excluding small particle impacts) (Requirement 56449).

Requirement 4.4-2: Design for passivation after completion of mission operations while in orbit about Earth or the Moon: Design of all spacecraft and launch vehicle orbital stages shall include the ability to deplete all onboard sources of stored energy and disconnect all energy generation sources when they are no longer required for mission operations or postmission disposal or control to a level which cannot cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft (Requirement 56450).

Requirement 4.4-3. Limiting the long-term risk to other space systems from planned breakups: Planned explosions or intentional collisions shall:

a) Be conducted at an altitude such that for orbital debris fragments larger than 10 cm the object-time product does not exceed 100 object-years (Requirement 56453). For example, if the debris fragments greater than 10 cm decay in the maximum allowed 1 year, a maximum of 100 such fragments can be generated by the breakup.

b) Not generate debris larger than 1 mm that shall remain in Earth orbit longer than one year (Requirement 56454).

Requirement 4.4-4: Limiting the short-term risk to other space systems from planned breakups: Immediately before a planned explosion or intentional collision, the probability of debris, orbital or ballistic, larger than 1 mm colliding with any operating spacecraft within 24 hours of the breakup shall be verified to not exceed 10^{-6} (Requirement 56455).

4.2 Safe Mode Disabled

The TIMED SAFE mode points the solar arrays at the sun. It will be disabled. Attitude sensors will be powered down to prevent the vehicle from determining sun position. The reaction wheels will be powered down to induce tumbling and further prevent the vehicle achieving SAFE attitude.

4.3 Passivation Tasks for TIMED

The following hardware may contain or produce energy at the end of the mission, and must be considered for passivation if possible:

NiH2 Battery
Solar Arrays
Transponder
Reaction Wheels
Heat pipes for SEE and reaction wheels
SABER mechanical cooler and scan motor
TIDI telescope motors
SEE scan motor

4.4 Passivation Potential for TIMED

The following addresses the current passivation potential for each of the above hardware components:

NiH2 Battery - The battery charge rate will be set to its minimum charge level. It will be drained to the maximum extent possible.

Solar Arrays – Illumination will be minimized to the greatest extent possible.

Transponder - The transmitter will be powered off at the end of the passivation process.
Reaction Wheels – All remaining reaction wheels will be powered down.

4.5 Compliance

Requirement 4.4-1 concerns explosion potential during the mission, and is not applicable to Final EOM Plans. Requirement 4.4-2 will be met by draining all possible energy from the spacecraft. Since there are no intentional breakups planned for the TIMED mission, Requirements 4.4-3 and 4.4-4 are not applicable.

5.0 ASSESSMENT OF SPACECRAFT POTENTIAL FOR ON-ORBIT COLLISIONS

5.1 Requirements

Requirement 4.5-1. Limiting debris generated by collisions with large objects when operating in Earth orbit: For each spacecraft and launch vehicle orbital stage in or passing through LEO, the program or project shall demonstrate that, during the orbital lifetime of each spacecraft and orbital stage, the probability of accidental collision with space objects larger than 10 cm in diameter is less than 0.001 (Requirement 56506).

Requirement 4.5-2. Limiting debris generated by collisions with small objects when operating in Earth or lunar orbit: For each spacecraft, the program or project shall demonstrate that, during the mission of the spacecraft, the probability of accidental collision with orbital debris and meteoroids sufficient to prevent compliance with the applicable postmission disposal requirements is less than 0.01 (Requirement 56507).

5.2 Vulnerability to Collisions Which Might Prevent Disposal

Since the disposal of the TIMED spacecraft is entirely passive, and requires no active maneuvering or intervention, there is no practical probability for small objects to prevent the eventual disposal by atmospheric reentry.

5.3 Vulnerability to Collisions Post-Disposal

The probability of collision with large objects (>10cm diameter) has been calculated using DAS 2.0.2 (Debris Assessment Software) as 0.00025 over the remaining orbital lifetime of the TIMED mission.

5.4 Compliance

TIMED meets both Requirements 4.5-1 and 4.5-2

6.0 ASSESSMENT OF SPACECRAFT POST-MISSION DISPOSAL PLANS AND PROCEDURES

6.1 Requirements

Requirement 4.6-1. Disposal for space structures passing through LEO: A spacecraft or orbital stage with a perigee altitude below 2000 km shall be disposed of by one of three methods: (Requirement 56557)

a. Atmospheric reentry option:

- Leave the space structure in an orbit in which natural forces will lead to atmospheric reentry within 25 years after the completion of mission but no more than 30 years after launch; or
- Maneuver the space structure into a controlled de-orbit trajectory as soon as practical after completion of mission.

b. Storage orbit option: Maneuver the space structure into an orbit with perigee altitude greater than 2000 km and apogee less than GEO - 500 km.

c. Direct retrieval: Retrieve the space structure and remove it from orbit within 10 years after completion of mission.

Requirement 4.6-2. Disposal for space structures near GEO: A spacecraft or orbital stage in an orbit near GEO shall be maneuvered at EOM to a disposal orbit above GEO with a predicted minimum altitude of GEO +200 km (35,986 km) for a period of at least 100 years after disposal (Requirement 56563).

Requirement 4.6-3. Disposal for space structures between LEO and GEO:

a) A spacecraft or orbital stage may be left in any orbit between 2000 km above the Earth's surface and 500 km below GEO (Requirement 56565).

b) A spacecraft or orbital stage shall not use nearly circular disposal orbits near regions of high value operational space structures, such as between 19,100 km and 20,200 km (Requirement 56566).

Requirement 4.6-4. Reliability of postmission disposal operations in Earth orbit: NASA space programs and projects shall ensure that all post-mission disposal operations are designed for a probability of success as follows: (Requirement 56567)

a. For disposal maneuvers not associated with controlled reentry, the probability of success shall be no less than 0.90 at EOM.

b. For controlled reentry, the probability of success at the time of reentry burn shall be sufficiently high so as not to cause a violation of Requirement 4.7-1 pertaining to limiting the risk of human casualty.

Requirement 4.6-5. Operational design for EOM passivation:

a) All NASA spacecraft and launch vehicles in Earth and lunar orbit shall be passivated at EOM to the extent necessary to prevent breakup or further generation of orbital debris (Requirement 56571).

b) The timing, order, procedures, and verification methods for performing all depletions identified for Requirement 4.4-2 shall have been developed prior to launch (Requirement 56572).

c) The level of passivation shall be updated prior to implementation of the EOMP (Requirement 56573).

d) Passivation shall occur as soon as this operation(s) does not pose an unacceptable risk to the payload after EOM has been commenced (Requirement 56574).

e) Spacecraft and launch vehicles not operating in orbit about Earth or its moon are not required to be passivated at EOM, however passivation is recommended.

6.2 TIMED Disposal Orbit

Since there is no propulsion system on-board the TIMED spacecraft, its orbit cannot practically be altered. Any alteration of the TIMED orbit would require the development of a robotic retrieval vehicle. The plan is to dispose of TIMED on-orbit. The current TIMED orbit is 612 x 613km x 74.08˚. The average cross sectional area (calculated per NASA-STD 8719.14A) is 10.85 m^2, so that the area to mass ratio for the 598 kg spacecraft is 0.018. From that orbit, reentry is predicted by DAS 2.0.2 in 10.8 years (from May 2013). According to predictions by the GSFC Flight Dynamics Facility, however, the reentry will occur no earlier than August 2037.

6.3 Reliability of Post-mission Disposal

Since the disposal of TIMED is entirely passive, the reliability of post-mission disposal is almost 1.0. The only practical alteration to the disposal is from a large object collision, the minute probability of which is reported in section 5.3 above.

6.4 TIMED Post-mission Disposal Procedure

The detailed procedure for accomplishing TIMED post-mission passivation is included as Appendix A.

6.5 Compliance

The TIMED mission complies with Requirement 4.6-1, using DAS 2.0.2. Requirements 4.6-2 and 4.6-3 are not applicable to the TIMED mission orbit. The TIMED mission meets Requirement 4.6-4, and will meet Requirement 4.6-5, using the plans and procedure outlined in Appendix A.

7.0 ASSESSMENT OF SPACECRAFT REENTRY HAZARDS

7.1 Requirement

Requirement 4.7-1. Limit the risk of human casualty: The potential for human casualty is assumed for any object with an impacting kinetic energy in excess of 15 joules:
a) For uncontrolled reentry, the risk of human casualty from surviving debris shall not exceed 0.0001 (1:10,000) (Requirement 56626).

b) For controlled reentry, the selected trajectory shall ensure that no surviving debris impact with a kinetic energy greater than 15 joules is closer than 370 km from foreign landmasses, or is within 50 km from the continental U.S., territories of the U.S., and the permanent ice pack of Antarctica (Requirement 56627).
c) For controlled reentries, the product of the probability of failure of the reentry burn (from Requirement 4.6-4.b) and the risk of human casualty assuming uncontrolled reentry shall not exceed 0.0001 (1:10,000) (Requirement 56628).

7.2 TIMED Atmospheric Reentry Risk

A reentry risk assessment utilizing DAS 2.0.2 was performed for TIMED by Scott Hull, GSFC on June 4, 2013. It calculated a Debris Casualty Area of 22.9 m^2. That equates to a reentry risk of 1 in 3650. This exceeds the NASA reentry risk requirement of 1 in 10,000.

7.3 Compliance

TIMED does not meet Requirement 4.7-1. A waiver request will be submitted.

8.0 ASSESSMENT FOR TETHERS

8.1 Requirement

Requirement 4.8-1. Mitigate the collision hazards of space tethers in Earth or Lunar orbits: Intact tether systems in Earth and lunar orbit shall meet the requirements limiting the generation of orbital debris from on-orbit collisions (Requirements 4.5-1 and 4.5-2) and the requirements governing post-mission disposal (Requirements 4.6-1 through 4.6-4) to the limits specified in those paragraphs. Due to the potential of tether systems being severed by orbital debris or meteoroids, all possible remnants of a severed tether system shall be compliant with the requirements for the collision, debris, and disposal of space structures (Requirement 56652).

8.2 Compliance

No tethers are employed by the TIMED mission. As such, NASA-STD 8719.14 Requirement Group 4.8 is not applicable to this mission.

APPENDIX A

TIMED End of Mission Plan Execution

Note: This Appendix will be amended and edited as necessary to reflect the development of the End of Mission operations. As such, it is intended that the text included here is for reference only, and that the most recent update be obtained from the Project in order to clarify any details.

A1.1 **Operations Related Tasks** The project will convene a decommissioning review, organized and led by the TIMED Mission Director, to approve the passivation steps of the TIMED S/C.

A1.1.1 Passivate the spacecraft, to the maximum extent possible.

A1.1.1.1 Disable autonomy rules which could impede passivation. Modify autonomy rules which could assist passivation.

A1.1.1.2 Set all three VT levels to zero.

A1.1.1.3 Turn off battery heater circuits.

A1.1.1.4 Disable peak power tracking.

A1.1.1.5 Continuously reset coulometer to 100% .

A1.1.1.6 Turn on all loads via PDU.

A1.1.1.7 Disable HLVS and Soft LVS.

A1.1.1.8 Rotate solar arrays 90 degrees to the sun vector.

A1.1.1.9 Disable all sun keepout checks.

A1.1.1.10 SAFE mode will be disabled, attitude sensors and reaction wheels will be powered off, preventing SAFE mode attitude and initiating a tumble.

A1.1.1.11 Transmitter powered off.

A1.1.2 Monitor the spacecraft downlink frequencies once per day for one week to ensure no RF transmission. Continue to monitor once per week for 3 months and attempt to command the vehicle on.

A1.1.3 Release ground stations from further tasking responsibilities.

A1.2 **Administrative Tasks**

A1.2.1 Final Engineering Report

As a part of spacecraft termination, a brief history and final status of the principle spacecraft systems shall be documented in a final engineering report. The report is to be compiled by the SSMO Lead Systems Engineer or his/her designee, and should be issued within 60 days of mission termination. The report shall contain significant milestones, spacecraft anomalies, and achievements of the TIMED mission, as well as the final locations of the mission data archives and ground support equipment.

A1.2.2 Mission Archive

The final TIMED spacecraft engineering and science data will be stored at GSFC in the Flight Projects Directorate library. Materials to be included in the archive include (but are not limited to) spacecraft drawings, SDR information package, operations manuals, basic science and engineering telemetry, any anomaly or failure review reports, and a copy of the final engineering report. Storage of the archive will be in electronic format when available, unless some of the documentation is only available in hard copy. The location of this archive will be included in the final engineering report for reference. Mission records and material will be archived per NASA and GSFC directives.

A1.2.3 Ground Hardware Disposition

The final disposition of the ground support hardware (operations consoles, test beds, etc.) shall be specified by the Project Manager no later than 30 days after mission termination. At least one operations console should be retained intact until the spacecraft has been proven to be permanently inert. The disposition of this equipment will be included in the final engineering report for reference.

A1.3 **Responsibilities**

In order to effectively conduct the required activities during the mission's End of Mission phase, all of the primary groups described in this section will need to follow through with their defined responsibilities. These groups include the Flight Operations Team (FOT), GSFC civil servant Applied Engineering Technology Directorate (AETD), the Space Science Mission Operations (SSMO) management team, and a contractor support team as needed.

A1.3.1 Flight Operations Team

The FOT has the primary responsibility to monitor the spacecraft.
The FOT will, with the Mission Director's consent, start the EOM procedure.
As always, the FOT will be responsible for conducting any trending data and for reporting anomalous behavior to AETD. The FOT will also be responsible for coordinating all activities and efforts between the parties in this section as they pertain to operations, including the generation of operations timelines of events, and for scheduling all necessary communication support.

A1.3.2 Applied Engineering Technology Directorate (AETD)

The SSMO Lead Systems Engineer will poll the systems branches within AETD for any requested EOM characterization tests, and determine whether those tests might endanger the safe disposal of TIMED. The Orbital Debris Technical Lead, will ensure that an acceptable EOM Plan has been assembled and submitted. The EOM process will then be followed through completion, to ensure safe disposal of TIMED.

A1.3.3 SSMO Management and Mission Director

SSMO management, primarily through the Mission Director (MD), will be responsible for authorizing and approving all End of Mission activities and ensuring that funding and infrastructure is in place to ensure adequate support. The MD will lead End of Mission (EOM) meetings and ensure that all action items are being addressed. The responsibilities and activities outlined in this document will also need to be approved by SSMO management prior to implementation. Any coordination, communication, or responsibility issues between the responsible parties outlined in this section will be directed by SSMO management, including requests from the science community. In addition, SSMO will be the source of all information releases to end-users and will coordinate with NASA Headquarters regarding information for the general media.

APPENDIX B

Acronyms

Acronym	Definition
ACS	Attitude Control System
AETD	Applied Engineering and Technology Directorate (at GSFC)
DAS	Debris Assessment Software (provided by JSC/ODPO, current version is 2.0.2)
DCA	Debris Casualty Area
EOM	End of Mission
EOMP	End of Mission Plan
FOT	Flight Operations Team
GSFC	Goddard Space Flight Center
ITAR	International Traffic in Arms Regulations
MD	Mission Director
N/A	Not Applicable
NASA	National Aeronautics and Space Administration
NSS	NASA Safety Standard
ODA	Orbital Debris Assessment
ODAR	Orbital Debris Assessment Report
RF	Radio Frequency
SCS	Spacecraft Computer System
SDO	Solar Dynamics Observatory
SDR	Single Design Review
SMD	Science Mission Directorate (at HQ)
SSMO	Space Science Mission Operations
TIMED	Thermosphere Ionosphere Mesosphere Energetics Dynamics