Living With a Star

Pre-Formulation Study

Volume 2
Mission Concept Descriptions

August 1, 2000

Goddard Space Flight Center
Acknowledgement

The Living With a Star (LWS) study management acknowledges with gratitude the significant contributions to this volume made by GSFC engineering team and Integrated Mission Design Center (IMDC) personnel.

A special note of thanks also goes to NASA Jet Propulsion Laboratory personnel who developed the concept for the Far Side Sentinel mission and provided timely input to the mission study team.
Overview

This volume summarizes the results of a 6-month LWS pre-formulation study to develop initial concepts for a set of missions that form the basis for the NASA proposed space weather research network.

Pre-formulation begins the process to define a viable and affordable concept for new NASA programs and projects. This step is followed by a more formal formulation phase to ensure that the program or project is ready to proceed into implementation.

The policy and process are defined in NPD 7120.4A and NPG 7120.5A.
A concerted effort has been made to maintain traceability of concepts and associated costs throughout the LWS program study. This added rigor will allow intelligent trade-offs to be performed and assessed as the program evolves over the months and years ahead.
LWS pre-formulation activities, documented in the GSFC three-volume study summary, were undertaken to accomplish the following:

- Establish preliminary program/mission objectives
- Develop initial concepts
- Explore implementation and access to space options
- Perform systems and supporting analyses
- Identify driving requirements
- Assess technology needs
- Identify risks and mitigation strategies
- Foster opportunities for partnering
- Promote public outreach and education
- Develop rough order of magnitude (ROM) costs
- Report results of initial studies
The methodology adopted for the LWS study is illustrated in the diagram below. Program goals and objectives were first identified. Discipline science teams next determined the type, location, and frequency of measurements to be made. From this information, the engineering team then developed concepts for flight missions that would achieve desired results. Finally, full life-cycle costs were estimated for each mission. See Volume 3 for costing details.
Mission Set

As a result of a broad space weather program assessment of existing national assets (G. Withbroe *et al*), it was determined that certain key mission system elements should be captured in the proposed NASA LWS program. These core missions are listed below and are described herein.

- Solar Dynamics Observatory --------------- Single Spacecraft
- Radiation Belt Mappers --------------------- Small Constellation
- Ionospheric Mappers ---------------------- Small Constellation
- Inner Heliospheric Sentinels --------------- Small Constellation
- Far Side Sentinel -------------------------- Single Spacecraft
As illustrated in the Study Methodology flow chart, the engineering team in concert with the GSFC Integrated Mission Design Center (IMDC) developed an initial concept for each of the proposed LWS missions.

IMDC results have been documented in CD ROM format and are available from the facility operations manager, E. Herring. The mission concept descriptions, presented in what follows, are derivatives of those detailed studies and are suitable for general distribution.
Each mission description includes the following set of charts as applicable:

- Title Page
- Mission Profile
- Mission Time Line
- Mission Objectives
- Instrument Complement
- Instrument Parameters
- System Synopsis
- System Block Diagram
- System Mass Summary
- System Power Summary
- Launch Profile
- Orbit Pictorial
- Orbit Parameters
- Spacecraft Features
- Ground System Concept
- Mission Operations
- Science Data Distribution
- Mission Specific Technology
- Study Options
- Preliminary Risk Assessment
- Study Recommendations

  - Mechanical Subsystem
  - Launch Vehicle Evaluation
  - Launch Configuration
  - Orbit Configuration
  - Power Subsystem
  - Thermal Subsystem
  - Attitude Control Subsystem
  - Propulsion Subsystem
  - C&DH Subsystem
  - Communications Subsystem

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I am also at this point accustomed to reaffirm with emphasis my conviction that the sun is real, and also that it is hot—in fact hot as Hell, and that if the metaphysicians doubt it they should go there and see.

W. Churchill

My friend, the sun, is here, but altered slightly; He acts more cooly than he has been doing; He seems more distant, and he smiles less brightly. I wonder what is brewing.

In Coventry
J. J. Daly
## SDO Mission Profile

| **Description:** | Continuous, high cadence observations of the full solar disk and coronal imaging in multiple wavelengths to improve understanding and forecasting of the Sun’s impact on our terrestrial environment |
| **Launch Date:** | December, 2006 |
| **Mission Life:** | 5 years |
| **Orbit:** | Geosynchronous inclined at 28.5 degrees |
| **Space Access:** | One launch from ETR to GTO on a Medium Class ELV |
| **Key Technologies:** | Large format, fast read-out, CCDs and enhancing technologies at the subsystem or component level |

**Instruments:** Four instrument packages including a doppler/magnetograph, EUV and UV imagers, coronagraphs, and irradiance monitors

**Spacecraft:** A single, three-axis stabilized, solar-tracking spacecraft with low jitter that employs an apogee kick motor for orbit circularization and a propulsion system for station-keeping and disposal
The following serial time spans are assumed for mission planning with July 1, 2000 as the initial reference date:

- 15 months for instrument, spacecraft, and ground system accommodation studies as part of the initial project formulation effort
- 12 months for conclusion of project formulation and definitization prior to approval
- 4 years from approval to launch readiness
- December 2006 launch
- 5 years for baseline mission operations
- 2-year mission extension (option for evaluation)
SDO Mission Objectives

The SDO mission employs a three-axis stabilized spacecraft in a geosynchronous orbit with a complement of solar-pointed instruments to make continuous, high-cadence observations of the Sun from its subsurface layers to its outer atmosphere.

Specific mission objectives are as follows:

• Characterize the dynamic state of the Sun on temporal and spatial scales that enhance understanding of solar processes and space weather phenomena
• Explain the evolution, emergence, and decay of magnetic regions and their relationship to the onset of solar flares and coronal mass ejections
• Understand how solar activity affects irradiance and how changes in irradiance affect the Earth
• Improve the predictive capability of large-scale solar events
The baseline SDO instrument complement has been arranged into four distinct measurement packages listed below.

1. Helioseismic and Magnetic Field Imager (HMI)
2. Atmospheric Imager Assembly (AIA)
3. Coronal Imager Assembly (CIA)
4. Irradiance Monitors

Instrument system parameters, shown in the table that follows, are based on direct heritage from the SOHO, TRACE, Solar-B, and STEREO missions.

Accommodation of optional instruments including a spectroscopic imager and a soft x-ray imager with heritage from SOHO, Yohkoh, and GOES was also evaluated.
<table>
<thead>
<tr>
<th>Type/Classification</th>
<th>Size</th>
<th>Mass</th>
<th>Power</th>
<th>Data Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LWH or DH</td>
<td>(kg)</td>
<td>(W)</td>
<td>(kbps)</td>
</tr>
<tr>
<td></td>
<td>(cm)</td>
<td></td>
<td></td>
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<tr>
<td><strong>HMI Package</strong></td>
<td></td>
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<td></td>
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<tr>
<td>Doppler Imager</td>
<td>40x50x90</td>
<td>24</td>
<td>25</td>
<td>27,000</td>
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<tr>
<td>Magnetograph</td>
<td>15x15x70</td>
<td>Included</td>
<td>10</td>
<td>7,000</td>
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<tr>
<td>Detector Package</td>
<td></td>
<td>5</td>
<td></td>
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<tr>
<td><strong>AIA Package</strong></td>
<td></td>
<td></td>
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<tr>
<td>EUV Imager</td>
<td>15x130*</td>
<td>57</td>
<td>35</td>
<td>68,000</td>
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<tr>
<td>UV Imager/Filter Wheel</td>
<td>15x130</td>
<td>10</td>
<td>10</td>
<td>Included</td>
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<tr>
<td><strong>CIA Package</strong></td>
<td></td>
<td></td>
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<tr>
<td>Inner Coronagraph</td>
<td>6x125</td>
<td>15</td>
<td>10</td>
<td>7,000</td>
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<td>Outer Coronagraph</td>
<td>12x125</td>
<td>20</td>
<td>10</td>
<td>7,000</td>
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<td><strong>Irradiance Package</strong></td>
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<tr>
<td>Irradiance Monitor</td>
<td>15x30</td>
<td>4</td>
<td>4</td>
<td>0.27</td>
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<tr>
<td>Optics Free Spectrometer</td>
<td>15x30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>150</td>
<td>134</td>
<td></td>
<td>116 Mbps</td>
</tr>
</tbody>
</table>

* For each of 6 telescope tubes
The nature of the mission requires continuous solar viewing and ground contact that is best accomplished from an inclined geosynchronous orbit.

Continuous downlink of high-rate telemetry strongly influences the flight data and communications systems as well as the ground operations approach.

A 5-year mission design life requires some level of system and subsystem redundancy.

Accommodation of optical instruments with a pointing accuracy of 10 arc-seconds and low jitter places additional demands on spacecraft subsystems and the ground test program.
# SDO Mass Summary

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass (kg)</th>
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<tbody>
<tr>
<td>Baseline Instruments</td>
<td>150</td>
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<tr>
<td>Instrument Support Structure</td>
<td>50</td>
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<tr>
<td>Modified RSDO Spacecraft Bus</td>
<td>400</td>
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<tr>
<td>Mechanical/Thermal</td>
<td>114</td>
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<tr>
<td>Power</td>
<td>60</td>
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<tr>
<td>Attitude Control</td>
<td>54</td>
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<tr>
<td>Propulsion</td>
<td>61</td>
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<tr>
<td>C&amp;DH/Comm</td>
<td>72</td>
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<tr>
<td>Harness</td>
<td>19</td>
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<tr>
<td>AKM Adapter</td>
<td>10</td>
</tr>
<tr>
<td>Balance Mass</td>
<td>10</td>
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<tr>
<td>Propellant</td>
<td>20</td>
</tr>
<tr>
<td>AKM (STAR-30E)</td>
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<td><strong>Total</strong></td>
<td><strong>1288</strong></td>
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<td>Delta II 7925-9.5 Lift Capability to GTO</td>
<td>1869</td>
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<tr>
<td>Launch Mass Margin</td>
<td>45%</td>
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<tr>
<td>AKM Capability to GEO</td>
<td>830</td>
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<tr>
<td><strong>Integrated Spacecraft-to-Orbit Margin</strong></td>
<td><strong>34%</strong></td>
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Values are best estimates and do not include contingency.
## SDO Power Summary

<table>
<thead>
<tr>
<th>Element</th>
<th>Power (W)</th>
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<tbody>
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<td>Baseline Instruments</td>
<td>134</td>
</tr>
<tr>
<td>Modified RSDO Spacecraft Bus</td>
<td>337</td>
</tr>
<tr>
<td>Thermal</td>
<td>50</td>
</tr>
<tr>
<td>Power</td>
<td>21</td>
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<tr>
<td>Attitude Control</td>
<td>84</td>
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<tr>
<td>Propulsion</td>
<td>12</td>
</tr>
<tr>
<td>C&amp;DH</td>
<td>35</td>
</tr>
<tr>
<td>Communications</td>
<td>112</td>
</tr>
<tr>
<td>Harness</td>
<td>23</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>471</strong></td>
</tr>
</tbody>
</table>

**Solar Array Capability (BOL):** 1025

**Power Margin (BOL):** 118%

**Solar Array Capability (EOL):** 920

**Power Margin (EOL):** 95%

Values are best estimates and do not include contingency.
SDO Delta 7925 Launch Profile

Event | $V_i$ (fps) | Acceleration (g)
--- | --- | ---
Liftoff | 1343 | 1.37
6 SRM Burnout | 3339 | 0.55
MECO | 19,944 | 5.91
SECO I | 25,560 | 0.67
SECO II | 27,192 | 0.76
Stage III Burnout | 33,589 | 3.24

Eastern Range launch site, flight azimuth 95 deg; maximum capability to 28.7-deg inclined GTO, 100-nmi perigee
AKM Burn
to Circularize Orbit

GTO ~6-hour transit
185 x 35,796 km

Eastern Range
Launch
The parameters for the final mission orbit are given below:

- **Altitude:** 35,796 km (Geosynchronous)
- **Inclination:** 28.5° to the Equator
- **Longitude:** 102° W
- **Period:** 24 hours
- **Epoch:** December, 2006
- **Right Ascension of the Ascending Node (RAAN):** 346°
• There are two 3-week Earth shadow periods per year:
  – Maximum shadow duration: 73 minutes
  – Total duration for 1 year: 2701 minutes

• There are three Lunar shadow events per year:
  – Maximum shadow: 60%
  – Duration ranges from ≈ 27 to 30 minutes
The major SDO features include:

- A three-axis stabilized GEO bus from a future Rapid Spacecraft Development Office (RSDO) inventory with selective redundancy for critical functions
- Subsystem upgrades as appropriate to meet SDO performance and lifetime requirements
- Mission-unique accommodations including a stable support structure, a master control computer, and a large capacity image handling system for the instrument complement
- One standard observing mode for simplicity of operations
SDO Mechanical Subsystem

- The SDO Mechanical Subsystem relies on standard aerospace materials and fabrication techniques for both spacecraft and instrument support structures. Aluminum and/or composites may be used to accommodate mass, thermal, or electrical constraints. Kinematic mounting of instruments is proposed in order to meet on-orbit alignment requirements.

- A number of critical deployments are required for the following elements:
  - Folded solar array
  - Gimbaled high-gain antennas
  - Instrument covers
In an effort to minimize launch costs, the capability of several classes of launch vehicles to GTO was evaluated.

The chart on the left illustrates that the Taurus XL (3213) and Delta 7425-9.5 (Lite 7426) do not have adequate lift capability. Although not shown, the Taurus XL also does not meet SDO volume requirements.

The Delta 7925-9.5 was thus chosen for the concept study.

*Note: Performance quotes are based on expiring NASA ELV contracts and their associated numbering system. Future performance can be obtained through the NASA Launch Services (NLS) contract.
SDO Orbit Configuration

Instrument Complement (cover/shielding removed for clarity)

Geo (RSDO) Spacecraft

Fixed Solar Array (2)

Thermal Panels (2) (shown, and far side)

Omni Antenna (2) (shown, and far side)

Gimbaled High-Gain Antenna (2)
SDO Assembly Sequence

Instrument Support Structure (Typical)

Instrument Packages

Instrument Packages Integrated to Support Structure

Instrument Module Integrated onto Geo Bus
The SDO Power Subsystem is a 28-volt direct energy transfer system that can support a load of 695 watts at the beginning of life. It consists of the following elements:

- Two fixed solar array wings with a total triple junction GaAs cell area of 4.5 m²
- A single 70 ampere-hour Li-ion battery sized to handle transfer orbit, worst-case shadow period, and peak power load conditions
- Power electronics

Solar array degradation over the life of the mission due to UV exposure, ionizing radiation, thermal cycling, and system losses has been taken into account in the array sizing.
SDO Power Subsystem (continued)

SDO Mission Over 5 Yr Life With Deployable Panel; 24% Efficiency; Average Load During Day=694.2W; Average Load During Night=694.2W

Power Margin for 4.5-m² Solar Array

Same Day and Night Power 695 Watts
SDO Thermal Subsystem

- The instrument module, containing the scientific instruments and their support structure, is thermally isolated from the spacecraft bus.
- Standard techniques including multi-layer insulation blankets, coatings, heaters, fixed radiators, and heat pipes are used for thermal control of the instrument module.
- The instruments are mounted to a conductive support structure that is temperature controlled in the range of 0° to 20° C by an external radiator.
- Instrument electronics are maintained between 0° and 30° C.
- Instrument CCDs are cooled to 200 K or lower by connecting them with heat pipes to a separate radiator and have heater circuitry for precision control at the desired temperature.
- Spacecraft components are maintained between 0° and 40° C. Batteries, however, are kept between 0° and 20° C for long life.
- Heater power is provided for thermal control during eclipse seasons.
The Attitude Control Subsystem (ACS) proposed for SDO can accommodate a number of solar viewing instruments with the following general pointing requirements:

- **Accuracy (1 \( \sigma \))**:  
  - Pitch/Yaw: 10 arcsec

- **Stability/Jitter (1 \( \sigma \))**:
  - Pitch/Yaw: 0.25 arcsec over 45-second time interval
  - Roll: 50 arcsec over 45-second time interval

- **Knowledge (1 \( \sigma \))**:
  - Roll: 30 arcsec
The ACS integrates the following complement of hardware to achieve the required pointing accuracy, stability/jitter, and knowledge:

- Redundant Attitude Control Electronics
- Coarse Sun Sensors
- Digital Sun Sensor
- Four-Axis Inertial Reference Unit
- Star Tracker
- Pyramidal Reaction Wheel Assembly
- Guide Telescope (part of instrument package)
The Propulsion Subsystem includes a STAR-30E AKM for orbit circularization after GTO is achieved and a liquid hydrazine system for dispersion correction, station-keeping, and disposal.

Delta-V requirements are itemized below:
- Orbit circularization 1479 m/sec
- Station-keeping 0.16 m/sec per year
- Disposal 12.7 m/sec

The hydrazine propellant mass was estimated to be about 20 kg for an extended mission life of 7 years including a substantial allotment for dispersion correction.
The SDO flight Command and Data Handling/Communications Subsystem has the following features:

- A spacecraft computer sized to accommodate the aggregate instrument data rate
- Two S-band transponders and omni-directional antennas for commanding, tracking, and low-rate telemetry as well as for spacecraft control in emergencies
- Two gimbaled 12-inch diameter Ka-band antennas for downlink of science data to avoid complex GEO maneuvers and to provide limited redundancy
- Convolutional and Reed-Solomon encoding
- Data system bit error rate of $10^{-8}$
The proposed ground system accommodations take advantage of existing infrastructure and include the following features:

• A dedicated 5-meter ground terminal at GSFC to ensure a continuous communications link
• Ranging from Deep Space Network (DSN)/Goldstone and Ground Network (GN)/Merritt Island Launch Annex (MILA) ground stations (two contacts/day) to minimize complexity at the prime site
• Distribution of data to three candidate locations:
  - 50 Mbps to West Coast/U.S.
  - 50 Mbps to East Coast/U.S.
  - 25 Mbps to Middle U.S.
• Links and lines to achieve a data latency of minutes to hours
SDO Ground System Concept

- **DSN 26-m Station at Goldstone**
- **MILA 9-m Station**

**50-Mbps Science Data**
- West Coast
- East Coast

**25-Mbps Science Data**
- Middle U.S.

**S-band Command @ 2 kbps**

**120 Mbps Ka-band Down (Science Data and Housekeeping)**

**Housekeeping Telemetry @ 15 kbps**

**15 kbps Telemetry and Ranging**

- ATM Network

**2-kbps Command**

- **SDO MSOC @ GSFC**

- **Ranging through 26-m/9-m Antennas**
  - Two passes per day
  - Back-up telemetry and command

**Goddard Space Flight Center**
A mission operations concept has been chosen that encourages automation of routine spacecraft functions and makes use of commercial off-the-shelf (COTS) products.

Salient features include the following:

- Combined Mission and Science Operations Center (MSOC) co-located with dedicated ground station at GSFC
- Automated mission operations using COTS command and control system
- Science data processed to Level Zero and short-term archival at MSOC
- Real-time science data distribution to Principal Investigators (PIs) at East Coast, West Coast, and Middle U.S. locations
- On-board recording of health and safety data to support anomaly resolution
- Hot backups for command/telemetry servers and MSOC science data processor
The SDO mission concept incorporates new technology that is expected to be available in the near term. Such items include:

- Radiation resistant, fast read-out, 4096 x 4096 monolithic CCD arrays
- High-efficiency, triple-junction, GaAs solar cells
- Li-ion battery
- Small Explorer (SMEX)-Lite reaction wheels
- Ka-band antenna system
The advantages and disadvantages of a number of viable orbit options were assessed as part of the SDO concept study. Orbits evaluated included geosynchronous, sun-synchronous, highly elliptical, and L1. It was concluded that an inclined geosynchronous orbit provided the best match for the driving SDO requirement of continuous contact for high rate data to a single ground station and also provided near constant solar viewing with very little eclipse time.

In addition to the baseline instrument packages, accommodation of a soft x-ray imager and a spectrometer was also evaluated. These two additional instruments increased payload mass by about 110 kg, power by 120 W, and data rate by 2.1 Mbps respectively. In order to retain acceptable system mass, power, and cost margins for the baseline configuration, the science definition team decided to remove these lower priority instruments from further consideration.
During the course of the SDO concept study, a number of risk areas were identified and are listed below. Further study will be required to fully assess these risks, their potential impact, and mitigation strategies.

- Development of a robust flight data and image handling system
- Development of a stable optical bench for the instrument packages
- Maintenance of co-alignment of instruments with the inner coronagraph
- Control of molecular and particulate contamination during ground testing and flight operations
- Spin balancing of the integrated system as required for Delta 3rd stage and AKM launch phases
- Availability of anticipated technology enhancements
SDO Study Recommendations

- Conduct a survey of solar viewing instruments now under development or planned for future development to ensure adequacy of assumed SDO instrument resource requirements.
- Develop an initial set of requirements for the Instrument Support Structure.
- Perform an accommodation study to determine the suitability of RSDO spacecraft for the SDO mission.
- Outline the functions to be performed by the master computer and size the image handling system.
- Determine the proper balance between on-board and on-ground instrument data processing.
- Assess the ability of soft x-ray imagers and spectrometers planned for other flight missions to complement the SDO baseline measurements.
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACE</td>
<td>Attitude Control Electronics</td>
</tr>
<tr>
<td>ACS</td>
<td>Attitude Control Subsystem</td>
</tr>
<tr>
<td>AIA</td>
<td>Atmospheric Imager Assembly</td>
</tr>
<tr>
<td>AKM</td>
<td>Apogee Kick Motor</td>
</tr>
<tr>
<td>BOL</td>
<td>Beginning Of Life</td>
</tr>
<tr>
<td>C&amp;DH</td>
<td>Command and Data Handling</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge-Coupled Device</td>
</tr>
<tr>
<td>CIA</td>
<td>Coronal Imager Assembly</td>
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<td>COTS</td>
<td>Commercial Off-The-Shelf</td>
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<tr>
<td>DSN</td>
<td>Deep Space Network</td>
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<tr>
<td>ELV</td>
<td>Expendable Launch Vehicle</td>
</tr>
<tr>
<td>EOL</td>
<td>End Of Life</td>
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<tr>
<td>ETR</td>
<td>Eastern Test Range</td>
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### Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>EUV</td>
<td>Extreme Ultraviolet</td>
</tr>
<tr>
<td>GaAs</td>
<td>Gallium Arsenide</td>
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<td>GN</td>
<td>Ground Network</td>
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<tr>
<td>GOES</td>
<td>Geosynchronous Operational Environmental Satellite</td>
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<tr>
<td>GSFC</td>
<td>Goddard Space Flight Center</td>
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<tr>
<td>GTO</td>
<td>Geosynchronous Transfer Orbit</td>
</tr>
<tr>
<td>HMI</td>
<td>Helioseismic and Magnetic Field Imager</td>
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<tr>
<td>LWS</td>
<td>Living With a Star</td>
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<tr>
<td>MECO</td>
<td>Main Engine Cut-Off</td>
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<td>MILA</td>
<td>Merritt Island Launch Annex</td>
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<td>Mission and Science Operations Center</td>
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<td>NLS</td>
<td>NASA Launch Services</td>
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<tr>
<td>OBC</td>
<td>Onboard Computer</td>
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Acronyms

PI  Principal Investigator
RAAN Right Ascension of the Ascending Node
RF  Radio Frequency
RSDO Rapid Spacecraft Development Office
SDO  Solar Dynamics Observatory
SECO Secondary Engine Cut-Off
SMEX Small Explorer
SOHO Solar and Heliospheric Observatory
SRM Solid Rocket Motor
STEREO Solar Terrestrial Relations Observatory
TRACE Transition Region And Coronal Explorer
UV Ultraviolet
XPDR Transponder