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.

Traceability

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.

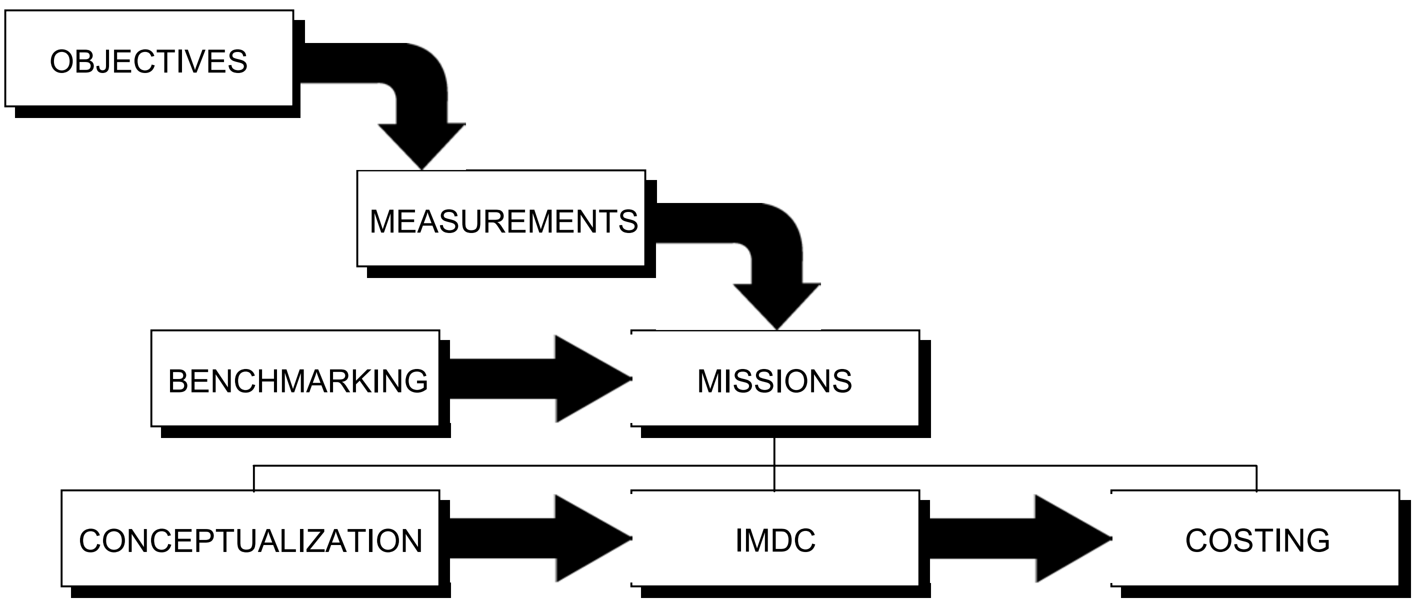
Pre-Formulation Activities

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

Study Methodology

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

Preamble

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.

Mission Study Template

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 --
  - Mechanical Subsystem
  - Launch Vehicle Evaluation
  - Launch Configuration
  - Orbit Configuration
  - Power Subsystem
  - Thermal Subsystem
  - Attitude Control Subsystem
  - Propulsion Subsystem
  - C&DH Subsystem
  - Communications Subsystem
- •Ground System Concept
- •Mission Operations
- •Science Data Distribution
- •Mission Specific Technology
- •Study Options
- •Preliminary Risk Assessment
- •Study Recommendations

Solar Dynamics Observatory

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

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

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

SDO Mission Time Line

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

SDO Instrument Complement

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.

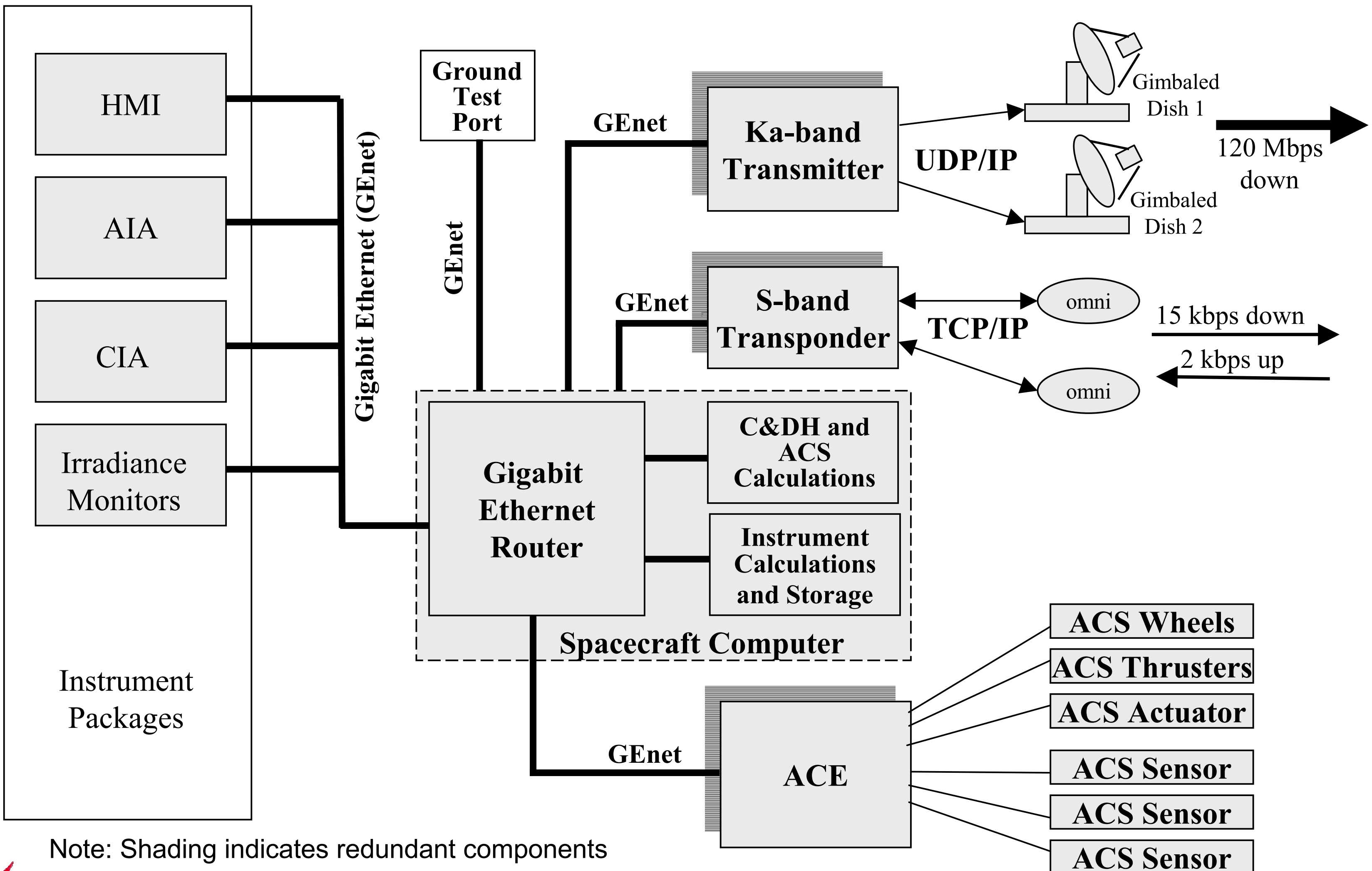
SDO Baseline Instrument Complement

Type/Classification	Size	Mass	Power	Data Rate
	LWH or DH		Avg/Peak	Avg/Peak
	(cm)	(kg)	(W)	(kbps)
HMI Package				
Doppler Imager	40x50x90	24	25	27,000
Magnetograph	15x15x70	Included	10	7,000
Detector Package		5		
AIA Package				
EUV Imager	15x130*	57	35	68,000
UV Imager/Filter Wheel	15x130	10	10	Included
CIA Package				
Inner Coronagraph	6x125	15	10	7,000
Outer Coronagraph	12x125	20	10	7,000
Irradiance Package				
Irradiance Monitor		15	30	0.5
Optics Free Spectrometer	15x30	4	4	0.27
Total		**150**	**134**	**116 Mbps**
* For each of 6 telescope tubes				

SDO System Synopsis

- 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 System Block Diagram



Note: Shading indicates redundant components

SDO Mass Summary

Element					Mass (kg)
Baseline Instruments					150
Instrument Support Structure					50
Modified RSDO Spacecraft Bus					400
	Mechanical/Thermal			114	
	Power			60	
	Attitude Control			54	
	Propulsion			61	
	C&DH/Comm			72	
	Harness			19	
	AKM Adapter			10	
	Balance Mass			10	
Propellant					20
AKM (STAR-30E)					668
Total					**1288**
Delta II 7925-9.5 Lift Capability to GTO					1869
Launch Mass Margin					**45%**
AKM Capability to GEO					830
Integrated Spacecraft-to-Orbit Margin					**34%**

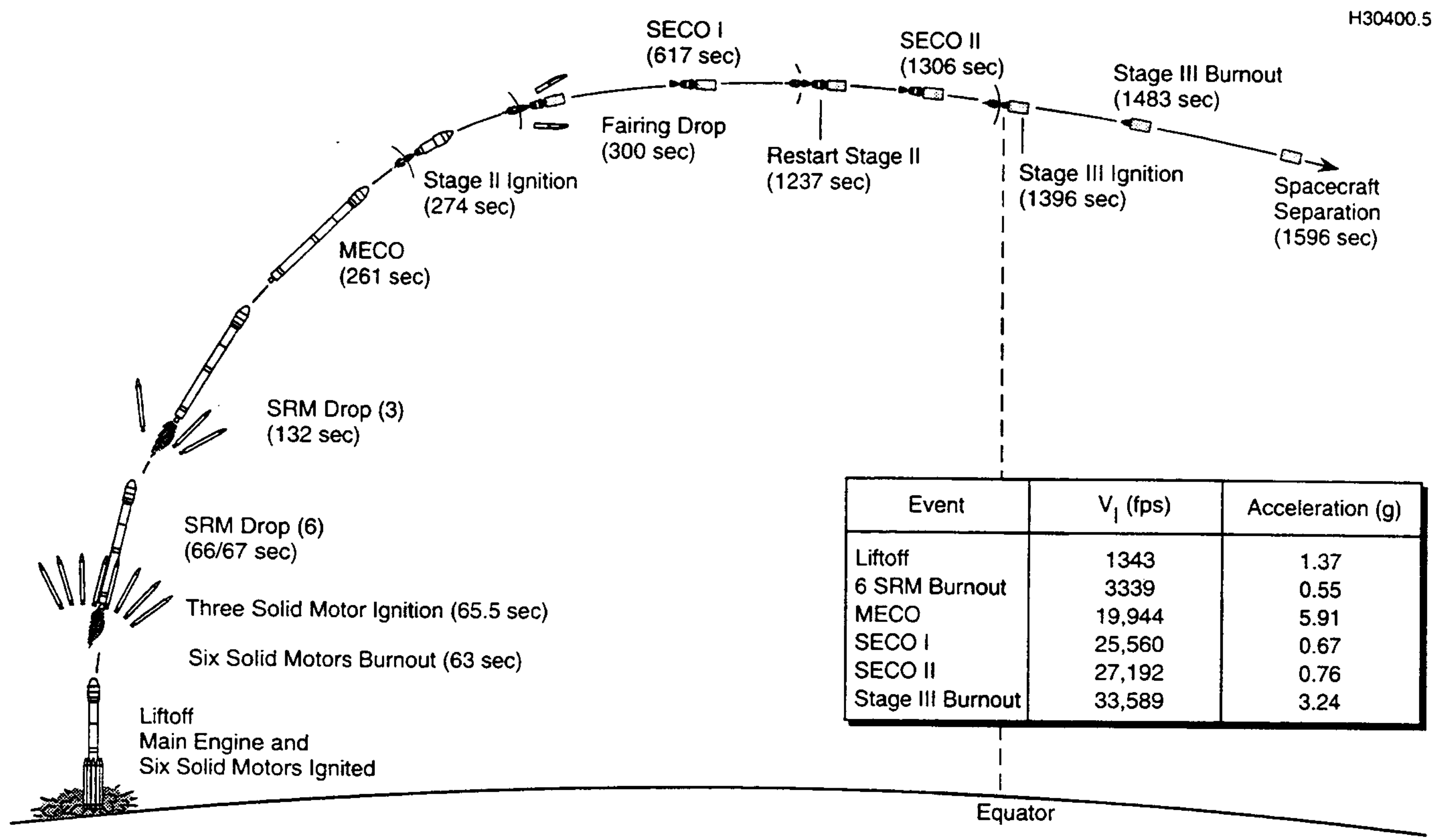
Values are best estimates and do not include contingency.

SDO Power Summary

Element					**Power**
					(W)
Baseline Instruments					134
Modified RSDO Spacecraft Bus					337
	Thermal			50	
	Power			21	
	Attitude Control			84	
	Propulsion			12	
	C&DH			35	
	Communications			112	
	Harness			23	
Total					**471**
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.

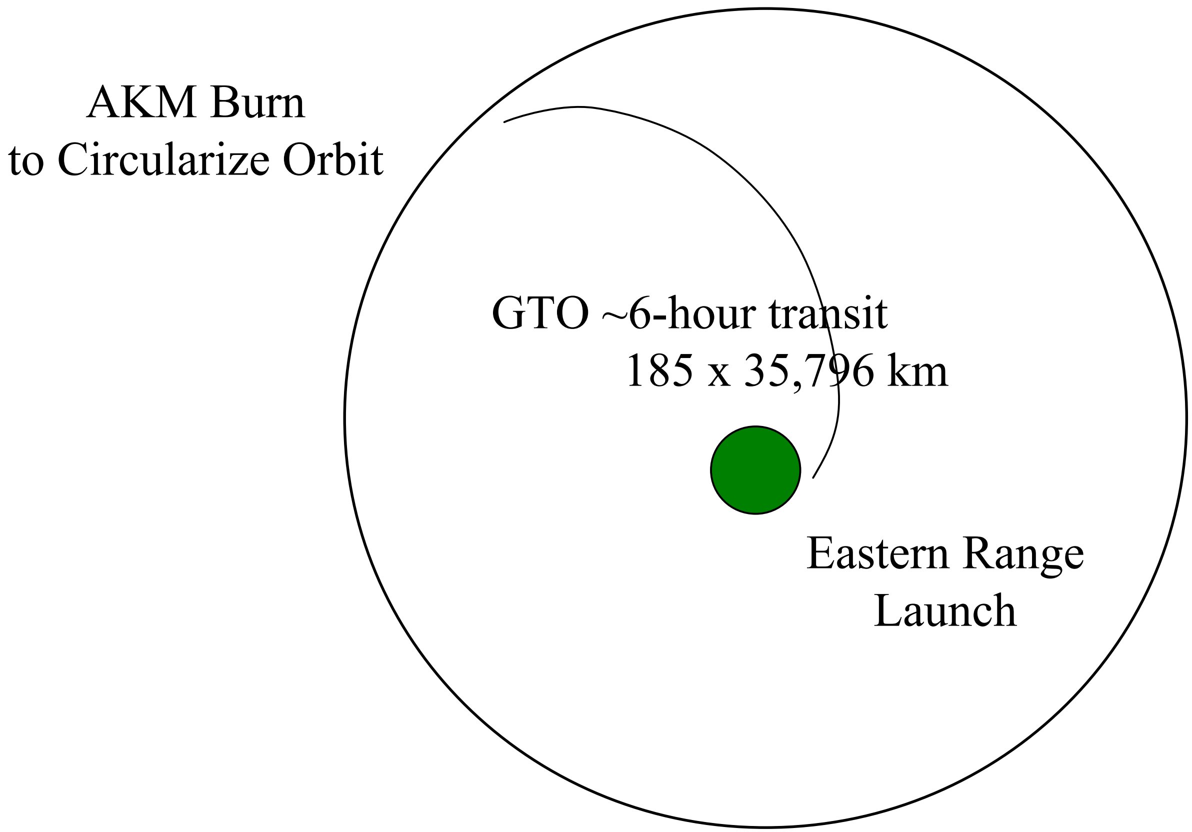
SDO Delta 7925 Launch Profile



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

SDO Orbit Pictorial



SDO Orbit Parameters

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°

SDO Shadow Periods

- 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

SDO Spacecraft Features

The major SDO features include:

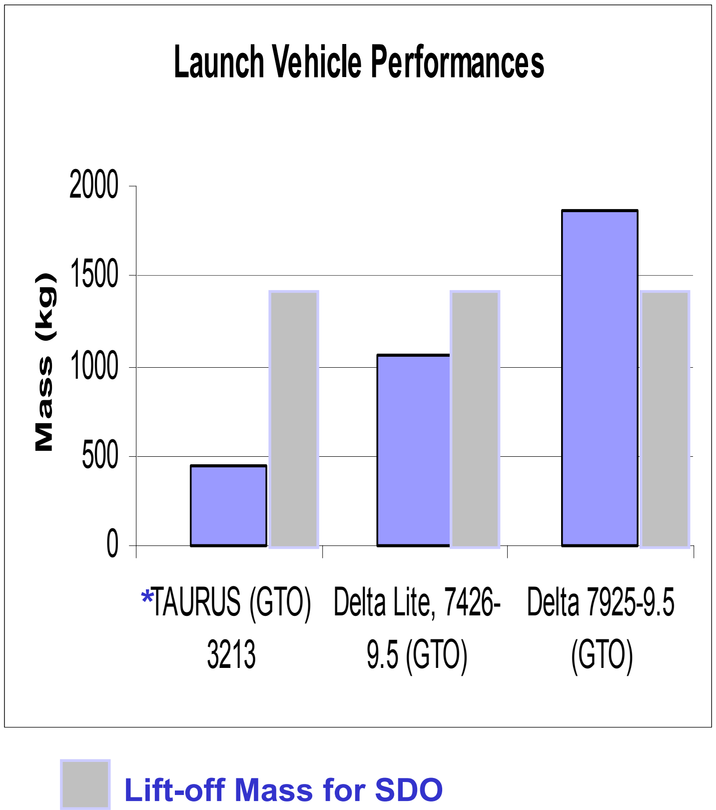
- A three-axis stabilized GEO bus from a future Rapid Spacecraft Development Office (RSDO) inventory with selective redundancy for critical functions
- Subsystem upgrades as appropriate to meet SDO performance and lifetime requirements
- Mission-unique accommodations including a stable support structure, 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

SDO Launch Vehicle Evaluation



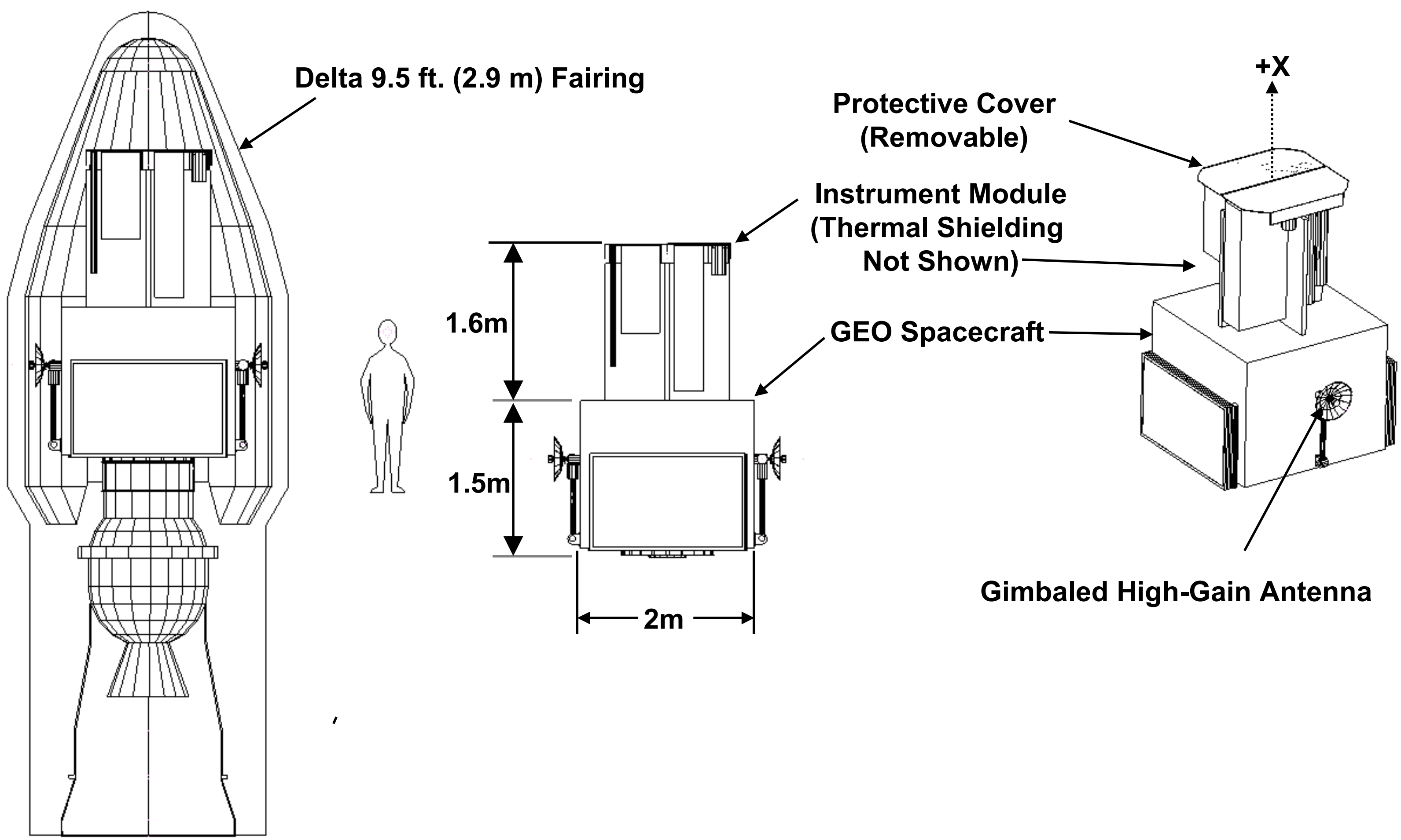
In an effort to minimize launch costs, the capability of several classes of launch vehicles to GTO was evaluated.

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.

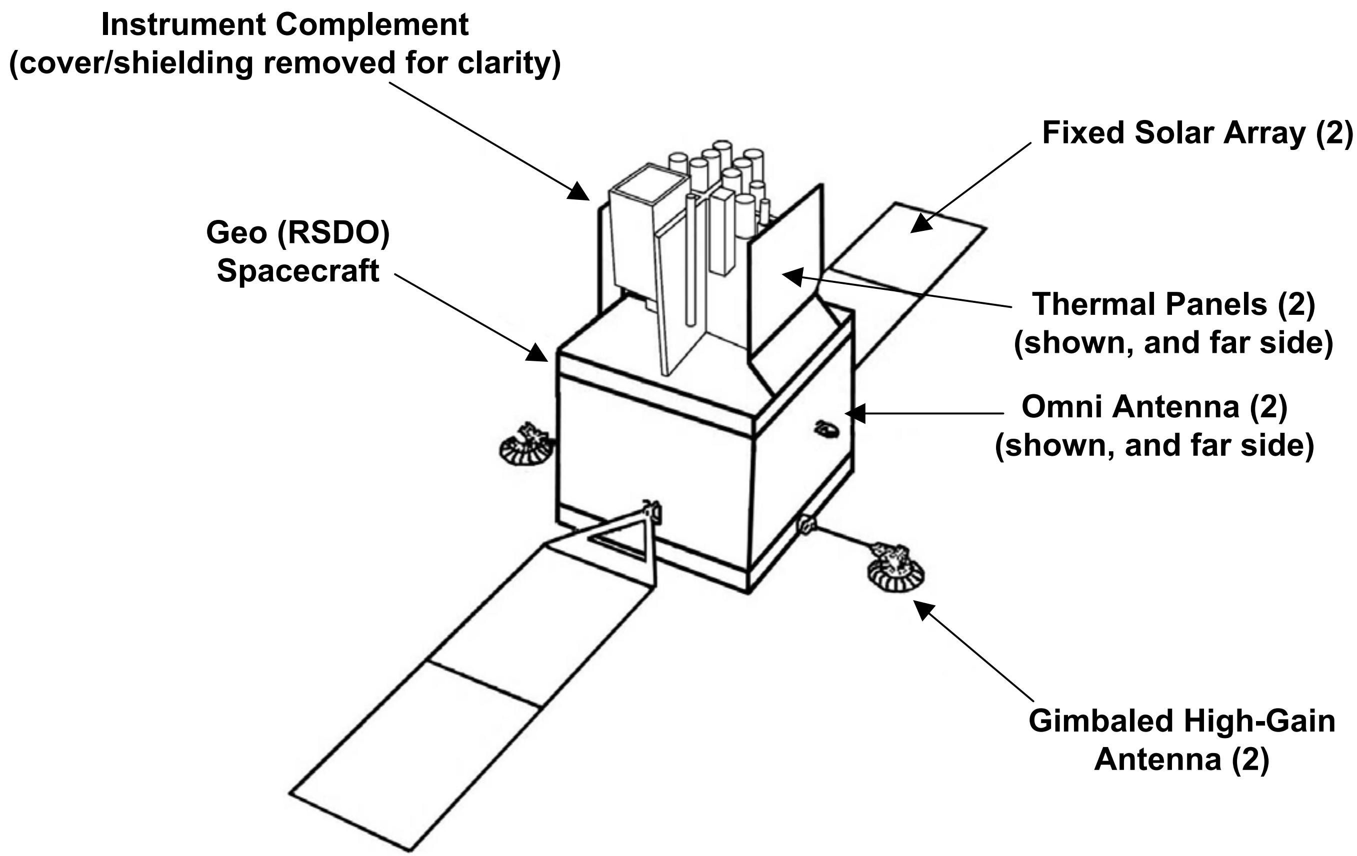
The Delta 7925-9.5 was thus chosen for the concept study.

*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.

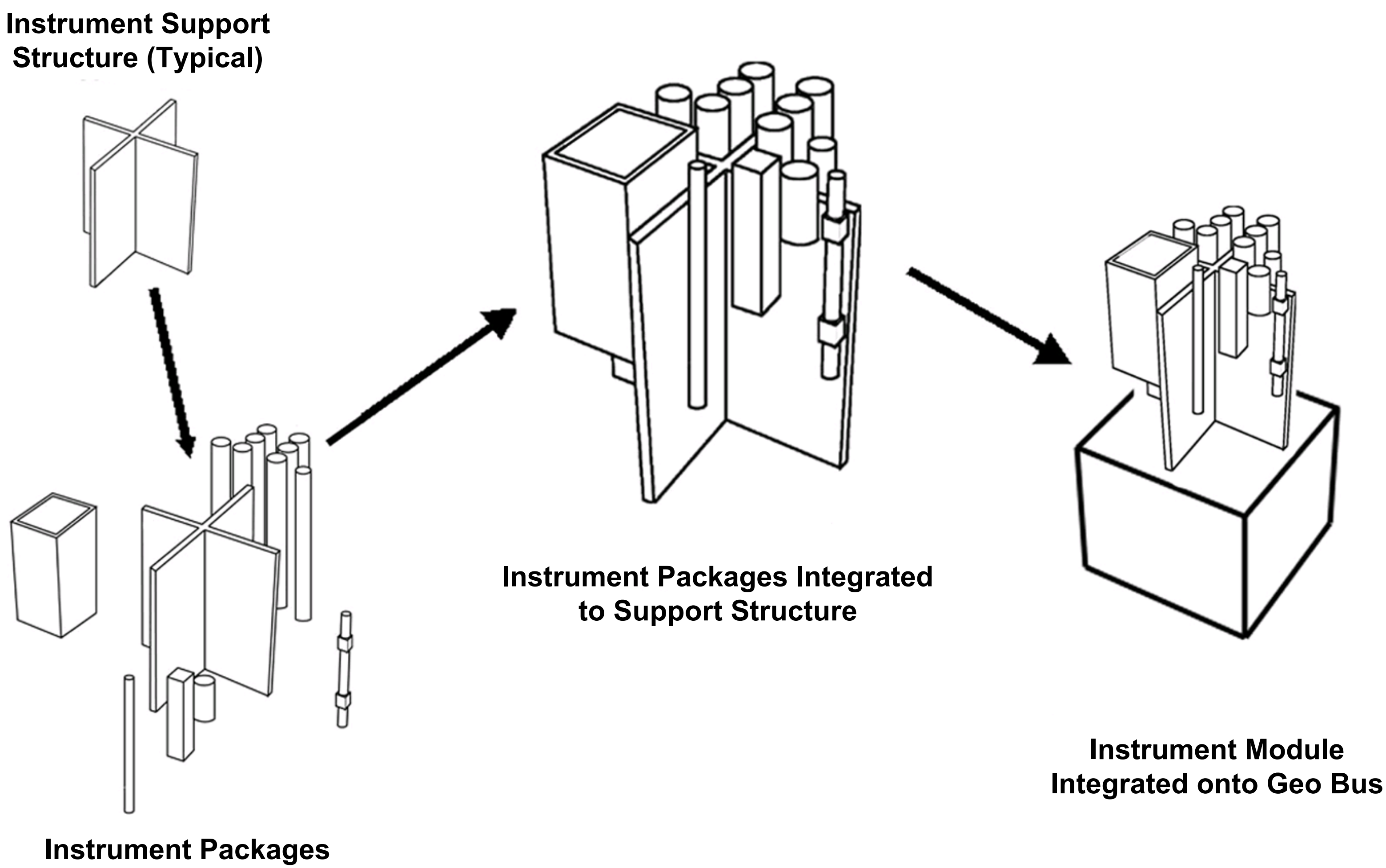
SDO Launch Configuration



SDO Orbit Configuration



SDO Assembly Sequence



SDO Power Subsystem

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:

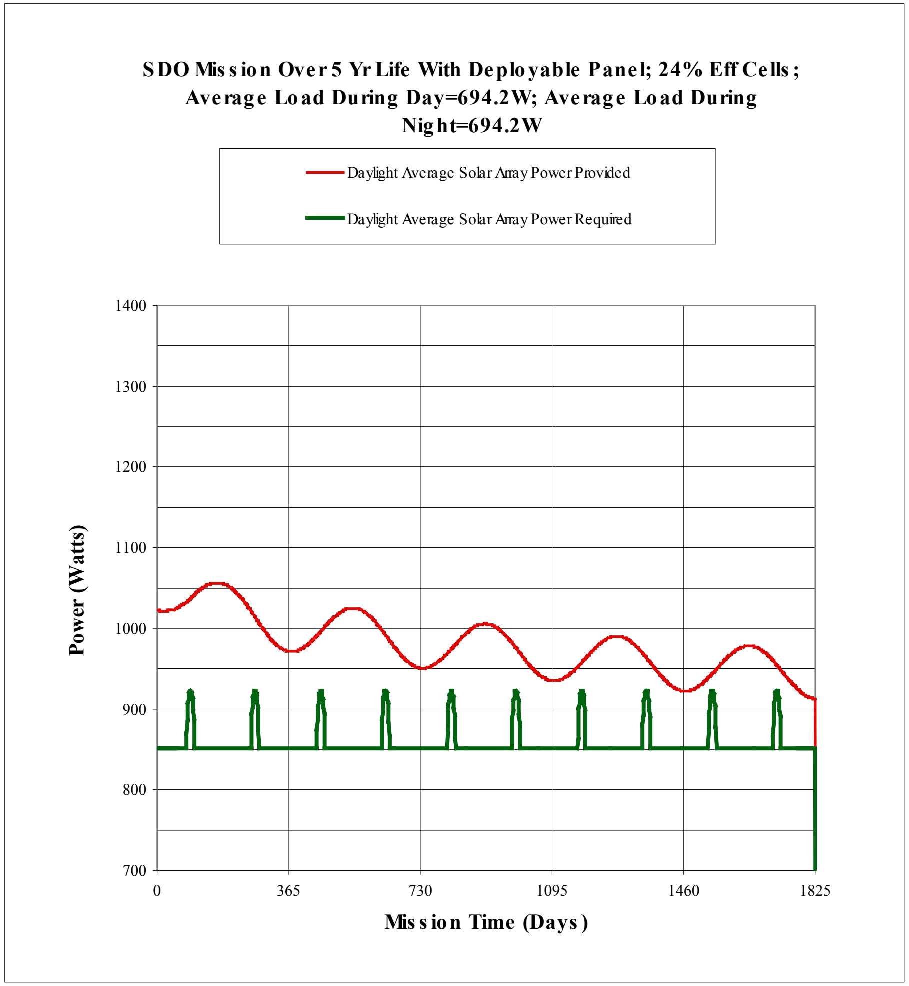
- Two fixed solar array wings with a total triple junction GaAs cell area of 4.5 m^2
- A single 70 ampere-hour Li-ion battery sized to handle transfer orbit, worst-case shadow period, and peak power load conditions
- Power electronics

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)

Power Margin for 4.5-m^2 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.

SDO Attitude Control Subsystem

The Attitude Control Subsystem (ACS) proposed for SDO can accommodate a number of solar viewing instruments with the following general pointing requirements:

- Accuracy (1 σ):
  - Pitch/Yaw: 10 arcsec
- Stability/Jitter (1 σ):
  - Pitch/Yaw: 0.25 arcsec over 45-second time interval
  - Roll: 50 arcsec over 45-second time interval
- Knowledge (1 σ):
  - Roll: 30 arcsec

SDO Attitude Control Subsystem (continued)

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)

SDO Propulsion Subsystem

- 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

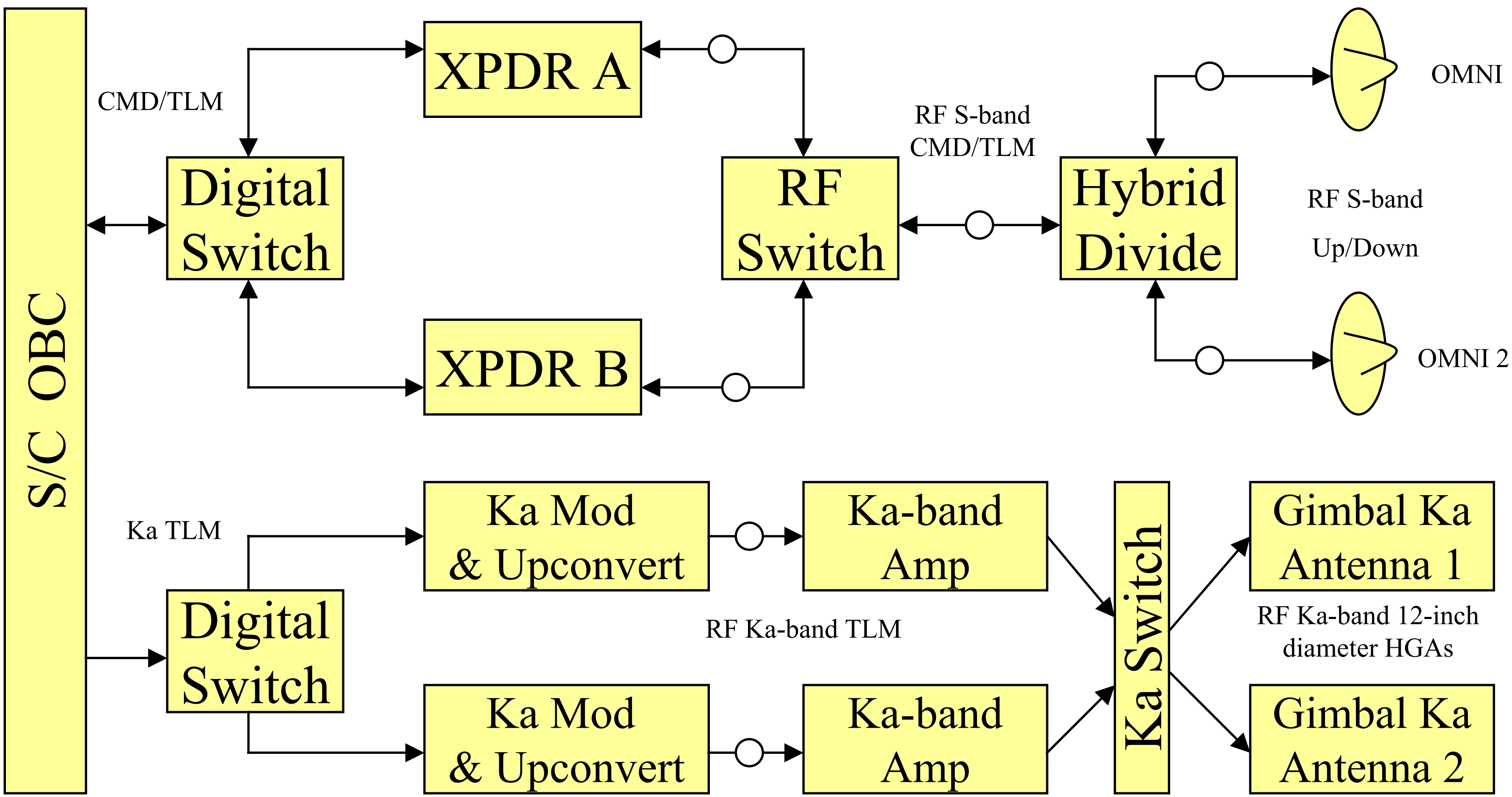
- The hydrazine propellant mass was estimated to be about 20 kg for an extended mission life of 7 years including a substantial allotment for dispersion correction.

SDO C&DH / Communications Subsystem

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}

SDO Communications Subsystem



SDO Ground System

The proposed ground system accommodations take advantage of existing infrastructure and include the following features:

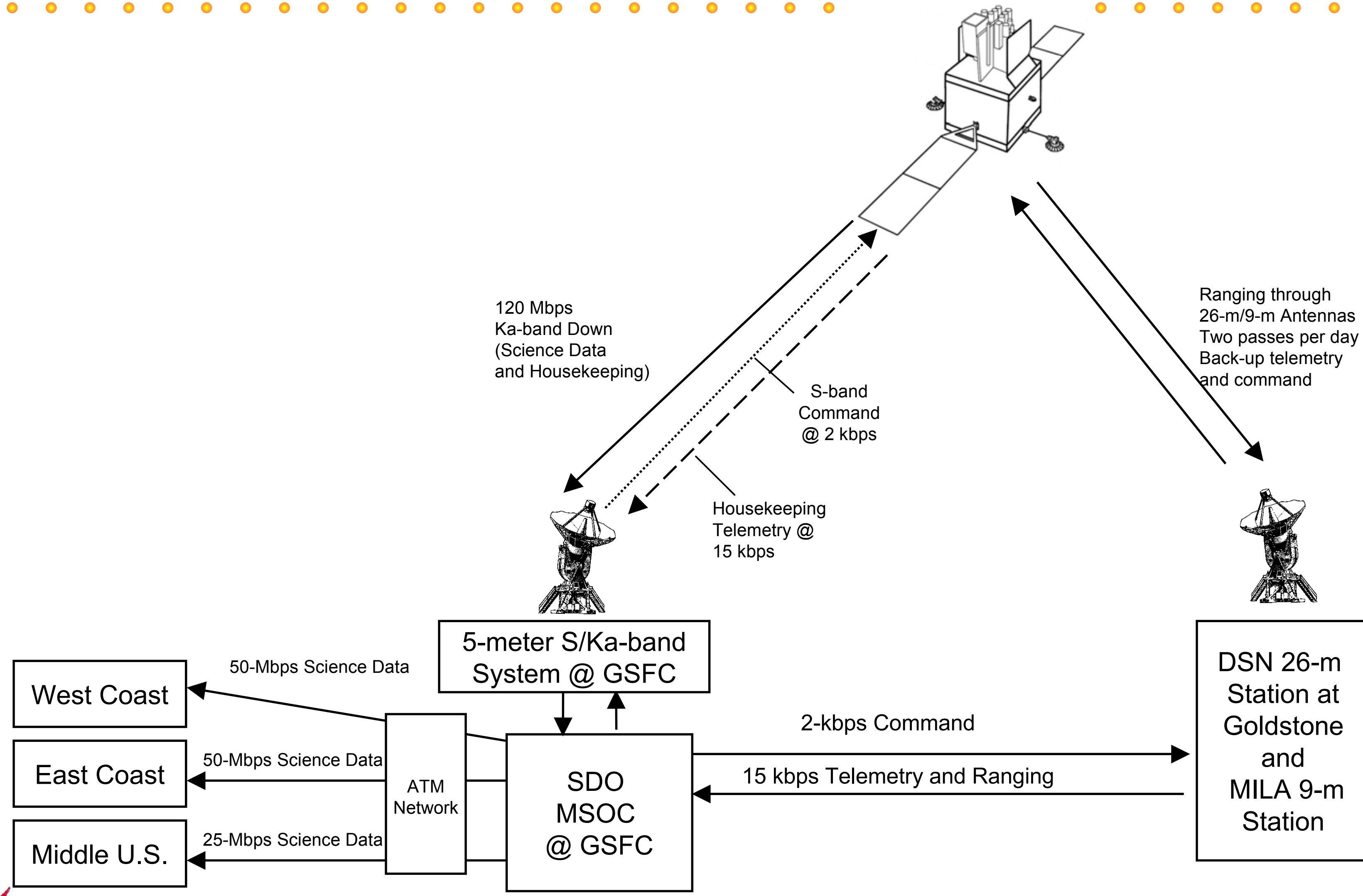
- A dedicated 5-meter ground terminal at GSFC to ensure a continuous communications link
- Ranging from Deep Space Network (DSN)/Goldstone and Ground Network (GN)/Merritt Island Launch Annex (MILA) ground stations (two contacts/day) to minimize complexity at the prime site
- Distribution of data to three 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



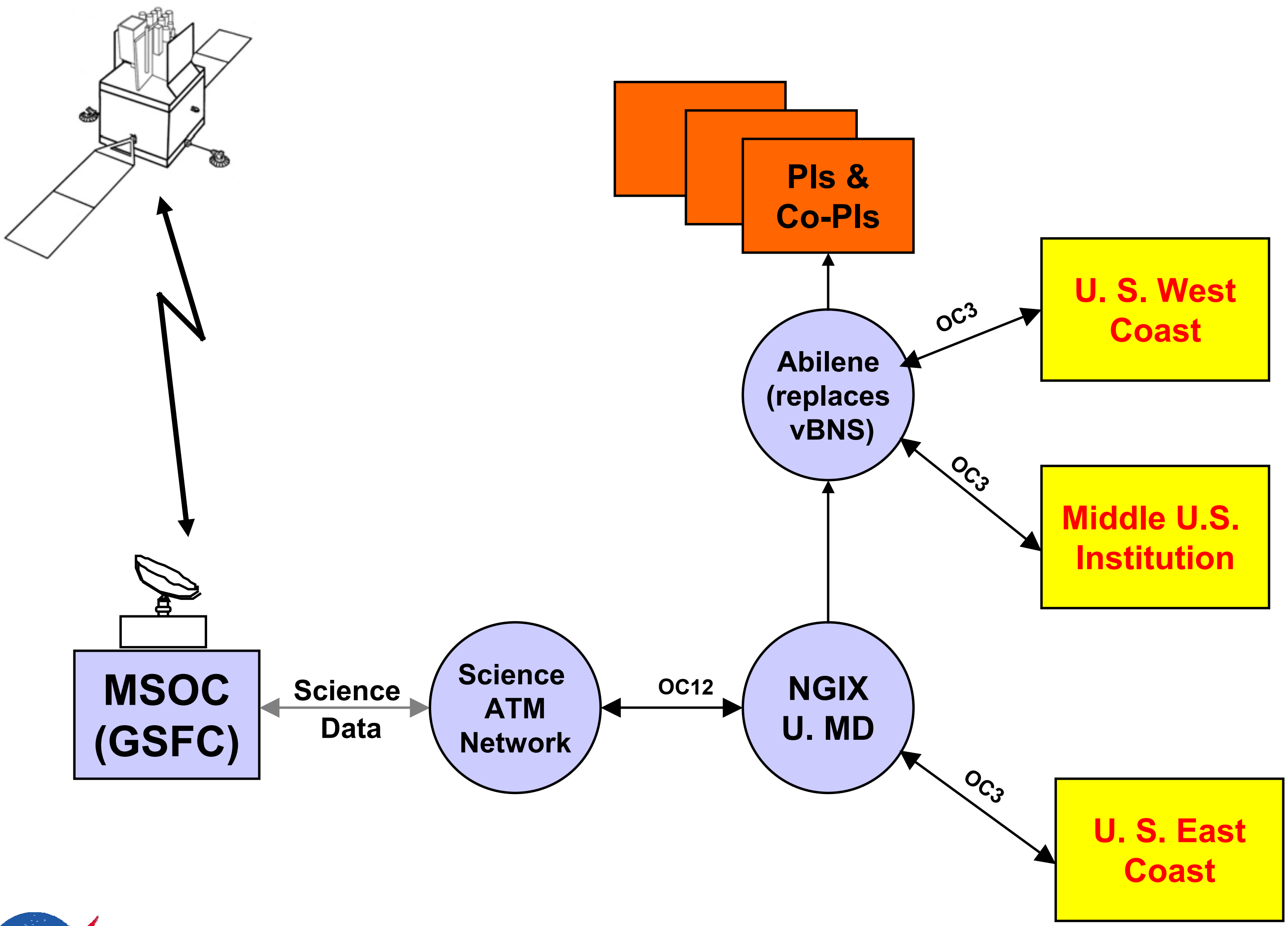
SDO Mission Operations

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

SDO Science Data Distribution



Notes:

OC3 -155 Mbps

OC12-622 Mbps

SDO Mission Specific Technology

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

SDO Study Options

- 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.

Preliminary Risk Assessment

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.

Acronyms

ACE	Attitude Control Electronics
ACS	Attitude Control Subsystem
AIA	Atmospheric Imager Assembly
AKM	Apogee Kick Motor
BOL	Beginning Of Life
C&DH	Command and Data Handling
CCD	Charge-Coupled Device
CIA	Coronal Imager Assembly
COTS	Commercial Off-The-Shelf
DSN	Deep Space Network
ELV	Expendable Launch Vehicle
EOL	End Of Life
ETR	Eastern Test Range

Acronyms

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

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