The 2020 Senior Review of the Heliophysics Operating Missions

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Executive Summary

In August 2020, the 2020 Heliophysics Senior Review panel undertook a review of 13 missions that are currently in operation. The panel found that all of the missions perform highly valuable observations that are key to world-class scientific research and development of capabilities to understand, monitor, and predict space weather in support of ground-based and space-based assets and systems, as well as crewed missions at low-Earth orbit and beyond.

At the top-level, the panel finds:

- NASA's Heliophysics System Observatory (HSO) encompasses an excellent fleet to study the Sun, the Heliosphere, the magnetosphere, and the ionosphere/thermosphere region. Moreover, the HSO includes missions that examine the couplings at the domain boundaries, both at the lower boundary of the thermosphere-ionosphere to the middle and lower atmosphere and at the outer boundary of the heliosphere to interstellar space. As such, the fleet facilitates studies that range from large-scale system effects to detailed investigations of the physical and chemical processes. The HSO fleet addresses NASA Heliophysics goals as well as the goals set by the Heliophysics Decadal Survey.

- All reviewed missions contribute to the study of the connected Heliophysics system, in addition to scientific objectives proposed by each of the missions. Depending on the mission, these objectives ranged from broadly defined areas of study to specific investigations with well-defined approaches and metrics for closure. In addition, the review especially noted the importance of the "infrastructure missions," which continue to provide valuable contributions to the fleet.

- Although NASA's goals to advance open science through open access publication, open access data, and open-source software are taken seriously by the missions, work remains to be done in each of these areas. Perhaps most notably, the transfer from proprietary, license-based platforms to open-source platforms will not be possible without NASA's contributions to the coordination of these efforts and contribution of NASA's resources toward these efforts.

- The new element of the review focusing on data availability in NASA official archives revealed good progress since the last review, but also revealed that some alarming gaps remain. Some of the problem areas include:
    - The lack of low-level data and calibration information in the Space Physics Data Facility (SPDF)
    - The incompleteness of the Solar Data Analysis Center (SDAC) archives, even if the data are accessible through the Virtual Solar Observatory (VSO)
    - The challenges related to recovering older missions' data and calibration information.

  The last problem is especially urgent for Voyager, and also presents a challenge for missions with an international component.

List of Acronyms

3D	three-Dimensional
3DP	three-Dimensional Plasma and energetic particle investigation
ACA	Antenna Controller Assembly
ACE	Advanced Composition Explorer
AGU	American Geophysical Union
AIA	Atmospheric Imaging Assembly
AIM	Aeronomy of Ice in the Mesosphere
AIME	Assimilative Mapping of Ionospheric Electrodynamics
AIMI	Atmosphere-Ionosphere-Magnetosphere Interactions
AIRS	Atmospheric Infrared Sounder
ALMA	Atacama Large Millimeter/submillimeter Array
API	Application Programming Interface
AR	Active Region
ARTEMIS	Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun
ASCII	American Standard Code for Information Interchange
AU	Astronomical Unit
BFI	Broadband Filter Imager
BSD	Berkeley Software Distribution
CCD	Charge-Coupled Device
CCMC	Community Coordinated Modeling Center
CDAWeb	Coordinated Data Analysis Web
CDE	Cosmic Dust Experiment
CDF	Common Data Format
CIPS	Cloud Imaging and Particle Size
CMAD	Calibration and Measurement Algorithms Document
CME	Coronal Mass Ejection
COR1	Inner Coronagraph (SECCHI)
COR2	Outer Coronagraph (SECCHI)
COSMIC	Constellation Observing System for Meteorology Ionosphere and Climate

CPI	Comprehensive Plasma Instrument
CRS	Cosmic Ray Subsystem
DARTS	Data Archive and Transmission System (Japan)
DEI	Diversity, Equity, and Inclusion
DES	Dual Electron Spectrometers
DIS	Dual Ion Spectrometers
DKIST	Daniel K. Inouye Solar Telescope
DRMS	Data Record Management System
DSCOVR	Deep Space Climate Observatory
DSN	Deep Space Network
EDI	Electron Drift Instruments
EFD	Electric Field monitor
EFI	Electric Field Instrument
EIA	Equatorial Ionization Anomaly
EIS	Extreme-ultraviolet Imaging Spectrometer
ENA	Energetic Neutral Atom
EPA	Energetic Particles Analyzer
EPIC	Energetic Particles and Ion Composition experiment
ERG	Exploration of energization and Radiation in Geospace
ESA	Electrostatic Analyzers
ESA	European Space Agency
EUV	Extreme Ultraviolet
EVE	Extreme ultraviolet Variability Experiment
FG	Filter-Graph
FGM	Fluxgate Magnetometer
FIP	First Ionization Potential
FITS	Flexible Image Transport System
FOSS	Free and Open-Source Software
FOXSI	Focusing Optics X-ray Solar Imager
FPI	Fast Plasma Instrument
FTE	Full Time Equivalent

FUV	Far Ultraviolet
FY	Fiscal Year
GBOs	Ground-Based Observatories
GCRs	Galactic Cosmic Rays
GGS	Global Geospace Science
GNSS	Global Navigation Satellite System
GOES	Geostationary Operational Environmental Satellite
GOLD	Global-scale Observations of the Limb
GONG	Global Oscillation Network Group
GPS	Global Positioning System
GRL	Geophysical Research Letters
GSFC	Goddard Space Flight Center
GSM	Geocentric Solar Magnetospheric
GUI	Graphical User Interface
GUVI	Global Ultraviolet Imager
GW	Gravity Wave
HDS	Heliophysics Decadal Survey
HEK	Heliophysics Events Knowledgebase
HEP	High-Energy Particle monitors
HGI	Heliophysics Guest Investigator
HI	Heliospheric Imager
HMI	Helioseismic and Magnetic Imager
HPD	Heliophysics Division
HSO	Heliophysics System Observatory
IBEX	Interstellar Boundary Explorer
ICME	Interplanetary Coronal Mass Ejection
ICON	Ionospheric Connection explorer
IDL	Interactive Data Language
IHC	Interhemispheric Coupling
IMPACT	In-situ Measurements of Particles and CME Transients
IMU	Inertial Measurement Unit

IN	Intranetwork
IPS	Information Publication Scheme
IRIS	Interface Region Imaging Spectrograph
IS	Infrastructure
ISAS	Institute of Space and Astronautical Science
ISOC	IBEX Science Operations Center
ISTP	International Solar-Terrestrial Physics
ITM	Ionosphere Thermosphere Mesosphere
JAXA	Japan Aerospace Exploration Agency
JGR	Journal of Geophysical Research
JHU/APL	Johns Hopkins University/Applied Physics Laboratory
JPL	Jet Propulsion Laboratory
JSOC	Joint Science Operations Center
KONUS	Gamma Ray Burst Studies Investigation
KSAT	Kongsberg Satellite Services
L2-CPE	L2 Charged Particle Environment
LASCO	Large Angle and Spectrometric Coronagraph
LASP	Laboratory for Atmospheric and Space Physics
LECP	Low Energy Charge Particle
LEP	Low Energy Particles experiment
LISIRD	LASP Interactive Solar IRradiance Datacenter
LISM	Local Interstellar Medium
LISMF	Local Interstellar Magnetic Field
LMSAL	Lockheed Martin Solar and Astrophysics Laboratory
LOS	Line of Sight
MAP	Mission Archive Plan
MAVEN	Mars Atmosphere and Volatile EvolutioN
MFI	Magnetic Field Investigation
MGF	Magnetic Fields Measurement monitor
MHD	Magnetohydrodynamic
MinXSS	Miniature X-ray Solar Spectrometer

MLTI	Mesosphere, Lower Thermosphere and Ionosphere
MMS	Magnetospheric Multiscale
MO&DA	Mission Operations and Data Analysis
MOC	Mission Operations Center
MSG	Major Science Goal
NASA	National Aeronautics and Space Administration
NetCDF	Network Common Data Format
NetDRMS	Network Data Record Management System
NFI	Narrowband Filter Imager
NLC	Noctilucent Cloud
NO	Nitric Oxide
NOAA	National Oceanic and Atmospheric Administration
NRT	Near-Real-Time
NSSDC	National Space Science Data Center
NUV	Near Ultraviolet
PDMP	Project Data Management Plan
PI	Principal Investigator
PLASTIC	PLAsma and SupraThermal Ion Composition
PLS	Plasma Science
PMC	Polar Mesospheric Clouds
PNG	Portable Network Graphics
PRL	Physical Review Letters
PSG	Prioritized Science Goal
PSP	Parker Solar Probe
PUNCH	Polarimeter to Unify the Corona and Heliosphere
PWG	Polar-Wind-Geotail
PWI	Plasma Wave Instrument
PWS	Plasma Wave Subsystem
RAA	Radiance Albedo Anomaly
RF	Radio Frequency
RFA	Research Focus Area

RTG	Radioisotope Thermoelectric Generator
SABER	Sounding of the Atmosphere using Broadband Emission Radiometry
SAO	Smithsonian Astrophysical Observatory
SCM	Search Coil Magnetometers
SDAC	Solar Data Analysis Center
SDO	Solar Dynamic Observatory
SECCHI	Sun Earth Connection Coronal and Heliospheric Investigation
SEE	Solar Extreme ultraviolet Experiment
SEP	Solar Energetic Particle
SES	Société Européenne des Satellites
SES GS	Société Européenne des Satellites Government Solutions
(S)HARP	(Space weather) Active Region Patches
SITL	Scientist-in-the-Loop
SMART	Solving Magnetospheric Acceleration, Reconnection, and Turbulence
SMD	Science Mission Directorate
SMEX	Small Explorers
SMS	Solar Wind and Suprathermal Ion Composition experiment
SO	Science Objective
SOFIE	Solar Occultation For Ice Experiment
SOHO	Solar and Heliospheric Observatory
SolO	Solar Orbiter
SOT	Solar Optical Telescope
SP	Spectropolarimeter
SPASE	Space Physics Archive Search and Extract
SPDF	Space Physics Data Facility
SPEDAS	Space Physics Environment Data Analysis Software
SPICE	Spectral Imaging of the Coronal Environment
SPOF	Science Planning and Operations Facility
SQ	Science Question
SR17	Senior Review 2017
SST	Solid State Telescopes

SSW	SolarSoftware
SSWIDL	SolarSoftware Interactive Data Language
STE	Suprathermal Electron
STEREO	Solar Terrestrial Relations Observatory
STICS	Suprathermal Ion Composition Spectrometer
STEREO	Solar Terrestrial Relations Observatory
STIX	X-ray Spectrometer/Telescope
SW	Solar Wind
SW	Space Weather
SWAVES	STEREO/WAVES
SWE	Solar Wind Experiment
SWFO	Space Weather Follow-On
SWPC	Space Weather Prediction Center
SwRI	Southwest Research Institute
TCI	Thermospheric Climate Index
TEC	Total Electron Current
TGRS	Transient Gamma-Ray Spectrometer
THEMIS	Time History of Events and Macroscale Interactions during Substorms
T-I	Thermosphere-Ionosphere
TID	Traveling Ionospheric Disturbances
TIDI	Thermosphere, Ionosphere Mesosphere, Energetics and Dynamics (TIMED) Doppler Interferometer
TIME-GCM	Thermosphere-Ionosphere-Mesosphere-Electrodynamics – General Circulation model
TIMED	Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics
UCB	University of California, Berkeley
UCLA	University of California, Los Angeles
UK	United Kingdom
UKMet	United Kingdom Meteorological
URL	Uniform Resource Locator
US	United States
UV	Ultraviolet

VAX	Virtual Address Extension
VEPO	Virtual Energetic Particle Observatory
VIM	Voyager Interstellar Mission
VMG	Vector Magnetogram
VSO	Virtual Solar Observatory
WG	Working Group
WSA	Wang-Sheeley-Arge
XRT	X-Ray Telescope

Overview

Introduction

NASA's Science Mission Directorate (SMD) conducts reviews of Mission Operations and Data Analysis programs (MO&DA) on a three-year cycle to maximize the scientific return from these programs within finite resources. MO&DA encompasses operating missions, data analysis from current and past missions, and support of science data processing and archive centers.

Under this call, the budgets for mission extensions beyond the prime mission lifetime/operation period will support the activities required to maintain operations. The missions must continue to produce meaningful and significant science data. In this regime of operations, NASA will accept higher operational risk, lower data collection efficiency, and instrument/mission degradation due to aging. It is therefore anticipated that the cost of implementation will be at a lower level than during the primary mission.

Thirteen missions are part of the Heliophysics 2020 Senior Review: AIM, Geotail, GOLD, Hinode, IBEX, IRIS, MMS, SDO, STEREO, THEMIS, TIMED, Voyager, and Wind.

The 2020 Senior Review allows missions to propose one of two types of mission extensions: a science investigation that presents science objectives, or infrastructure that contributes to the Heliophysics System Observatory. Two of the missions, Geotail and Wind, proposed the infrastructure status.

Regardless of the type of proposal, each mission must meet the Senior Review requirements including: 1) Archive all data in NASA archives immediately; 2) Archive real-time data as originally downlinked and processed; 3) Present a Project Data Management Plan (PDMP) and a Calibration and Measurement Algorithms Document (CMAD); 4) Present a plan for making mission code open source; and 5) Present an End-of-Mission Plan verification letter/memo from Center Safety and Mission Assurance (SMA).

Science investigation proposals must present science objectives that the mission will complete during the extended mission within the in-guide budget, which may assume the use of other Heliophysics System Observatory data. Additional objectives may be proposed with an over-guide request. Science objectives are focused tasks aimed at closing a gap in understanding that the mission will complete during the extended mission (i.e., not broad goals or high-level scientific activities that require several mission contributions).

Infrastructure (IS) proposals focus on contribution to the Heliophysics System Observatory. These proposals may adjust spacecraft orbits/configuration to facilitate synergy with other HSO assets. The infrastructure proposals contain no science objectives, and the science data validation is part of the operations budget.

Missions Under Review

The following 13 missions are under review in the Heliophysics 2020 Senior Review. The table below summarizes their in-guide budget in the 2017 and 2020 Senior Reviews as well as their FY20 budget and FY21 proposed over-guide budget. The last column indicates the increase in the over-guide budget above the suggested in-guide budget in $k (thousands of dollars).

Mission	Launch year	SR2017 in-guide	FY20 budget	FY21 in-guide	FY21 over-guide	over-guide - in-guide
AIM	2007	$2,982	$2,482	$2,982	$3,262	$280
GEOTAIL (IS)	1992	$222	$433	$433	$493	$60
GOLD	2018	$0	$4,000	$4,000	$5,394	$1,394
HINODE	2006	$6,835	$7,000	$7,000	$7,000	$0
IBEX	2008	$3,400	$2,900	$3,400	$3,400	$0
IRIS	2013	$6,834	$6,100	$6,500	$6,500	$0
MMS	2015	$14,555	$26,000	$18,700	$23,000	$4,300
SDO	2010	$12,000	$12,000	$12,000	$14,538	$2,538
STEREO	2006	$8,250	$7,800	$7,800	$7,800	$0
THEMIS	2007	$5,400	$4,400	$5,000	$5,600	$600
TIMED	2001	$2,551	$2,686	$2,610	$3,260	$650
VOYAGER	1977	$5,587	$5,923	$5,500	$6,472	$972
WIND (IS)	1994	$2,168	$2,200	$2,200	$2,200	$0
Total		$70,784	$83,924	$78,125	$88,919	$10,794

The period for this 2020 Senior Review covers FY2021 to FY2025. Because this Senior Review imposes additional requirements and expectations on the mission data archives, it was indicated that over-guide requests may be included in order to bring the missions' archived data (including metadata and accompanying documentation) up to a consistent standard in the NASA archives.

Charge to the Heliophysics Senior Review Panel

The charge to the Heliophysics Senior Review panel includes three criteria for scientific benefits. The panel was also asked to assess cross-mission synergies and issues, to assess the state of the Heliophysics System Observatory, and to provide feedback and potential improvements for the NASA archives.

The Senior Review assessment criteria are:

A. Completion of previous extended mission science;
B. Compelling nature of proposed science investigations;
C. Contribution to the Heliophysics System Observatory.

The Senior Review Data Archiving Subpanel assessment criterion is:

D. Assess the usefulness and usability of the archived mission data, code, and accompanying documentation, including:
   - The status and plan for data submission to NASA archives;
   - The plan for making mission-funded code/software open source;
   - The quality of the Project Data Management Plan (PDMP), and the Calibration and Measurement Algorithms Document (CMAD).

Review Criteria

The Senior Review panel assessed the scientific merit tied to the Heliophysics mission and assessed the feasibility of implementation described in each mission's proposal. Given the emphasis on the systemic nature of the discipline, the assessment included discussion of the impact of the mission's unique science as well as the mission's contribution to the overall system science performed by the Heliophysics System Observatory.

The Senior Review Data Archive subpanel provided a review of the missions' archived datasets in the NASA facilities in order to determine the datasets' usefulness and usability. The Data Archive subpanel findings will help to improve the missions' archival datasets, particularly in regard to services for the non-NASA, and non-expert science research communities.

The assessment of the missions under consideration is complemented by assessment of the overall strength and ability of the Heliophysics System Observatory–including missions both in operation and in development–to fulfill the Heliophysics Division priorities from FY2021 through FY2023 as represented in the 2014 SMD Science Plan and in the context of the 2013 Heliophysics Decadal Survey.

Detailed assessment criteria included the following:

A. Scientific Success in Previous Mission Investigation (25% weighting)
   - Factor A-1: Success of previous science investigation (i.e., achievement of Prioritized Science Goals in the 2017 Senior Review proposal, for missions included in the 2017 Senior Review; or achievement of prime mission Science Objectives, for missions proposing for their first extended mission)
   - Factor A-2: Performance of addressing any findings in the 2017 Senior Review

B. Overall Evaluation of the Proposed Investigation (35% weighting)
   - Factor B-1: Scientific merit and impact of the proposed in-guide science investigation
   - Factor B-2: Implementation merit of the proposed in-guide science investigation
   - Factor B-3: Relevance of the proposed science investigation to the scientific goals of the Heliophysics Division as defined in the Division's Strategic Objectives and the 2013 Heliophysics Decadal Survey
   - Factor B-4: Cost reasonableness of the proposed science investigation
   - Factor B-5: Scientific merit and impact of any proposed over-guide science investigation (*This factor is informational and does not contribute to the rating of this Criterion.*)
   - Factor B-6: Implementation merit of any proposed over-guide science investigation (*This factor is informational and does not contribute to the rating of this Criterion.*)

C. Contribution to the Heliophysics System Observatory (20% weighting)
   - Factor C-1: Quality of the mission science data collected
   - Factor C-2: Synergy with and benefit to the Heliophysics System Observatory (*This factor applies only to the planned observations, and not to any previous scientific return or proposed mission-funded science investigation.*)
   - Factor C-3: Health of the spacecraft and instruments, and suitability of the mission operating model to maximize its contribution to the Heliophysics System Observatory
   - Factor C-4: Cost reasonableness of the mission's operations model

D. Data and Code Production and Archiving (20% weighting)
   - Factor D-1: Usefulness and usability of the archived mission data
   - Factor D-2: Completeness of the archived mission data
   - Factor D-3: Quality and completeness of the Project Data Management Plan (*This factor includes any plan to produce or update the Project Data Management Plan after the Senior Review process. This factor is informational in the 2020 Senior Review and does not contribute to the rating of this Criterion.*)
   - Factor D-4: Quality and completeness of the Calibration and Measurement Algorithms Document (*This factor includes any plan to produce or update the Calibration and Measurement Algorithms Document after the Senior Review process. This factor is informational in the 2020 Senior Review and does not contribute to the rating of this Criterion.*)
   - Factor D-5: Usefulness, usability, and completeness of the plan for open-source release of mission code (*This factor is informational in the 2020 Senior Review and does not contribute to the rating of this Criterion.*)

Missions that propose as Heliophysics System Observatory Infrastructure were not evaluated on Criterion B. In these cases, the criteria were re-weighted to the following values: Criterion A, 35%; Criterion C, 40%; Criterion D, 25%.

Each evaluation criterion above was assigned an adjectival rating based on the strengths and weaknesses, according to the following table:

Adjectival rating	**Basis**
Excellent	A thorough and compelling proposal of exceptional merit that fully responds to the objectives of this Call as documented by numerous or significant strengths and with no major weaknesses
Very Good	A competent proposal of high merit that fully responds to the objectives of this Call, with strengths that fully out-balance any weaknesses and none of those weaknesses constitute fatal flaws
Good	A competent proposal that represents a credible response to this Call, with strengths and weaknesses that essentially balance each other
Fair	A proposal that provides a nominal response to this Call, but with weaknesses that outweigh any strengths

Poor	A seriously flawed proposal having one or more major weaknesses that constitute fatal flaws

Review Process

Senior Review Panel and Data Archival Subpanel Assessments

Each mission had a primary and secondary reviewer in both the Senior Review panel and in the Data Archival subpanel. Preliminary assessments of criteria A-C made by the Senior Review panelists were shared among the Senior Review panel before the mission interviews. The Data Archival panelists provided for each mission a preliminary assessment of Criterion D before the mission interviews. The Data Archival panel also provided a preliminary summary report to the Senior Review panel before the mission interviews.

Senior Review Panel Meetings

The Senior Review panel met during the week of August 17-21 in virtual format due to the COVID-19 pandemic situation's restriction of face-to-face meetings and travel. The virtual meeting format posed challenges to the scheduling due to the different time zones of panelists, limiting the usable meeting time to six hours per day.

On the first day, the panel was given an introduction of the MO&DA program background by the Heliophysics Division Director.

The panel had a general briefing of the conflicts of interest and the procedures to minimize the impacts of potential conflicts or biases. Prior to mission presentations, the conflicts of interest pertaining to the mission in question were reviewed person by person, and those recusing themselves were removed from the virtual meeting.

Each proposing mission was allotted 20 minutes for their oral presentation. During the presentation, the missions had an opportunity to respond to questions the panelists had submitted during the review process. The presentation was followed by 15 minutes of internal discussion among the panelists, after which the mission team was brought back for 10 minutes to answer any remaining questions.

After the mission interviews were completed, each mission was reviewed by the panel in a 25-minute discussion led by the primary reviewer. The primary reviewers collected input from the entire panel, and the panel discussed common themes that could be raised as general conclusions.

The panel concluded with a question and answer session with the NASA Heliophysics leadership.

Following the assessment week, the Senior Review panel completed the mission-specific reviews and included the Data Archival subpanel material in the draft report. A second virtual meeting was held a week later to hear the Data Archival subpanel report, review the final mission-specific and general findings, and to brief the Heliophysics Division Director on the findings.

During the following two months, the report was finalized and submitted to the Senior Review Program Executive.

Senior Review Findings

Overview

The Senior Review panel and the Data Archive subpanel found that all 13 missions of this assessment are making good progress and are valuable parts of the Heliophysics System Observatory (HSO). The value of the data, data quality, scientific productivity in the past, and the research plans for the future were generally viewed very positively.

A new part of the review assessing the existence and usability of data in the official NASA archives revealed generally good progress, but noted challenges related to recovering old archives stored elsewhere as well as archiving large data volumes of the recent missions. In addition, cultural differences in making data available across the heliophysics subfields persist. All data are generally available to the research community, while some challenges remain in securing a complete archive for long-term future use.

The missions were rated on four individual criteria based on past performance, quality of the research plan, contributions to the HSO, and status of the data archiving. While the panel has rated the missions based on the available facts, the ratings can and must be interpreted in different ways depending upon the rationale in the written report. A lower grade might mean lower quality (and hence, perhaps, lower priority), but such a grade can also indicate lack of performance for reasons that are beyond the control of the mission PI (and therefore may represent a high priority to remedy the situation). Thus, the Senior Review panel would like to remark that it is not possible to use these ratings in a comparative manner without reference to the written assessments and identified strengths and weaknesses.

General Findings

Heliophysics System Observatory

The 2020 Senior Review clearly attests to the great success of the HSO concept. The HSO ideal is truly becoming reality, and no mission among the large fleet stands on its own. The way the community is bringing the observations together is very impressive. Common operating and analysis infrastructure consolidated even further would allow treatment of the fleet as a single system and would facilitate further collaborations and cross-mission analyses.

While all missions contribute to the HSO goals, it is clear that some missions can play a more critical role in the systems science either through a unique location (e.g., Voyager beyond the outer heliosphere) or through data that are used as context in a wide range of studies (e.g., solar images, solar wind parameters). Furthermore, large-scale studies (e.g., on magnetospheric plasma dynamics) require multipoint measurements, and maximizing the number of concurrent measurements from different parts of the system is desirable. The current infrastructure missions continue to make highly valuable contributions in support of the HSO, while also expanding to new areas such as astrophysics, space weather, or the human spaceflight program. The infrastructure category was found to be an excellent vehicle for advancing HSO objectives.

Coordination of mission operations remains an issue. Beyond some observational campaigns, there is no regular process in place to coordinate measurement taking (e.g., operating in high-resolution mode, or pointing limited-view solar imagers toward a common target). The situation is better in data analysis, as many missions provide tools that integrate data from several sources.

Open science

NASA has taken an active role in promoting open science, open data, and open-source codes. These goals are generally well accepted by the missions, but work remains in order to achieve maximal availability and accessibility of publications, data, and analysis tools.

All NASA-funded researchers are required to deposit their peer-reviewed publications to the PubSpace repository, which should open all mission-related publications to the community. This review did not assess how well the missions follow that requirement. In general, the proposals make only a few statements about open access publishing, and most publications appear in forums that are not fully open-access. The golden access publishing option is sometimes used but not always used, and this option is not required by NASA.

The availability and usability of the mission data in NASA official archives is assessed in this review. Great progress has been made over the past few years on this front, and the missions are generally committed to submitting their data in NASA archives. However, this process is still underway with some challenges related to submission of the data itself and submission of supporting metadata and documentation. Well-written software and its robust documentation are essential for scientific research reproducibility, but there is still non-uniformity in the publication and documentation practices related to codes used to process the data to higher-level products. Archiving these codes together with the low-level data is an important element of preserving the value of the HSO observations.

Most, if not all, missions have taken steps toward moving from proprietary, license-based IDLs toward modern, open-access platforms such as Python. While open-source resources such as SunPy are built as a community effort, maintenance of the system at a professional level will require resources beyond the control of individual missions. Such maintenance would focus on controlled transition as well as continued development and user support.

Leadership training

The currently operating missions have an important role in training the next-generation leaders. Furthermore, as many missions continue to operate over several years and even decades, it is necessary to ensure that the core team includes junior researchers who are knowledgeable of the mission’s technical and scientific details. Taking responsibility for mission-critical activities of a mature mission can be excellent training for future leadership roles. One such key activity might be data archiving and documentation of the calibration and processing procedures, which would also give deep insights into the data and their interpretation.

Broader impact

Many missions recognize the public interest in space missions and perform excellent outreach activities. The proposals generally did not present priorities or explicit outreach plans, however, as they were not required to do so. Acknowledging that such activities require time and resources, recognizing the teams' efforts in the form of asking for a short plan and report would help in expanding the public visibility of the HSO fleet and interest in the fleet.

Diversity, Equity and Inclusion

As for many other research disciplines, diversity, equity and inclusion (DEI) are not adequately achieved yet in space and geosciences. Thus, continued work is necessary to increase the number of females, underrepresented minorities, or people with disabilities, especially in leadership positions. Engagement of junior researchers in existing missions can offer experience that is useful in assuming major roles in future mission proposals. Teaming with universities (especially those with diverse student populations) can help to increase the diversity of the future junior researcher community. Including DEI activities as part of future proposals could help proposers to focus time and effort on broadening participation.

Findings on Senior Review Requirements

Scientific progress and plans

Reporting scientific publications. While some missions report only publications where the mission data plays a major role, other missions list all papers making use of the mission data even if the data is only used for context. The former speaks mostly for the capacity of the mission to fulfill its scientific mission, while the latter often demonstrates the missions' contributions as part of the HSO. Distinguishing these two types of usage would help assess the achievements in each aspect.

Defining scientific objectives. The proposals contain a wide variety of terminology describing "scientific objectives" (i.e., the knowledge gap to be closed) and "goals" (i.e., the detailed investigation outcomes needed to close the gap). The objectives and goals were given at highly varying levels of detail, ranging from primary objectives from the original mission proposal to highly focused ones that build on reported successes, or entirely new ideas and approaches. There are two distinct aspects of scientific objectives: 1) Scientific directions that the mission is capable of tackling given the past results and the current HSO fleet, and 2) the more focused questions the mission team will target with the proposed funding. It was not always easy to make a distinction between overarching open issues in the field that can be addressed with the mission data, science objectives that the mission team will tackle with the in-guide budget, and the science objectives achievable only within the over-guide budget. Similarly, it was not clear how to value scientific renewal, as some missions presented entirely new scientific objectives and research avenues, while other missions focused on objectives that closely followed from the previous Senior Review period.

Technical status

Mission health. The status of the instruments and expendables are key information in assessing the missions' future usability. The spacecraft and instrument health statements were non-uniform in quality, ranging from general statements such as "all instruments function nominally" to detailed analysis of instrument or spacecraft degradation. A common template for the proposers would help to produce a holistic view of the technical status of the HSO fleet and prospects for the mid-term future.

Cross-calibration. Well-calibrated data are needed for cross-mission studies that are central to the HSO, for long-term trend analyses, and for many machine-learning-based or data-assimilation-based applications. Despite the need, cross-calibration of instruments between different missions remains a poorly attended problem. Including cross-calibration results in the NASA archives would increase the value of the combined HSO dataset.

Error analysis. In many cases, evaluating or even estimating measurement errors can be challenging. Error data is essential not only for interpretation of the measurements but is also a key input to many data assimilation algorithms and machine learning algorithms. More attention should therefore be devoted to quantifying and validating the known and estimated errors in the measurements, and to archiving the results in the NASA archives.

Budgeting

Overall, the budget data provided for the review was often difficult to interpret, and comparisons between the missions were challenging.

In-guide budgets versus over-guide budgets. Many proposals presented an integrated scientific research plan, intertwining elements achievable within the in-guide and over-guide budgets. While this approach builds a coherent view of the exciting science that the mission teams wish to accomplish in case both budgets are granted, it makes it challenging to assess the scientific value and efficiency of the research in case only the in-guide budget is available. Appropriate assessment of the research plan feasibility would require independent research plans and budgets for both the in-guide parts and the supplementing over-guide parts.

As the dollar amounts available for research within the in-guide budgets vary greatly from mission to mission, the quality of the research plans among the missions is not directly comparable.

Operations budget. Costs associated with the mission operations, data taking, and (non-scientific) processing vary greatly between missions. These costs depend upon the spacecraft location, number of instruments and operational modes, data volumes, and other factors contributing to the mission complexity. The Senior Review panel has limited expertise and resources to address the budgetary or personnel needs of operational activities. In general, clear separation of the operational costs from the research costs helps the assessment of the reasonableness of both the operational expenses and research expenses.

In some cases, mandatory mission extension costs (e.g., operations costs or inflation adjustment) were included in the over-guide budgets. Such inclusion complicated the assessment of in-guide-only mission extensions.

External resources. All missions facilitate engagement of scientists outside the mission team, either through guest investigator programs or by providing data access and collaborations to external partners. However, the proposals did not always make a clear separation between research conducted by this funding and investigations performed by external resources. In addition, the

"HSO contributions" were typically interpreted narrowly to mean only multi-spacecraft investigations, rather than use of the mission data by the wider community.

Findings on Data Archiving

All missions are required to fully and completely archive their data products in the Heliophysics Data Archives, SPDF and SDAC. Should a mission not have all data products archived within these databases, the mission team was asked to describe the plan for the transition of those holdings to the SPDF and SDAC archives in the Project Data Management Plan (PDMP) and Calibration and Measurement Algorithms Document (CMAD).

The review focused on the status of mission data in the NASA archives, the documents describing the mission pipeline data processing, data products, and calibration algorithms (PDMP and CMAD), as well as the status of efforts to place well-documented, open-source pipeline processing and analysis software in freely accessible repositories.

NASA archives

While depositing current mission data in NASA archives has long been encouraged, older missions continue to keep complete institutional archives while planning for final data submission at the NASA archives only after mission end-of-life. This causes variance across the missions in the amount and types of data available at the SPDF and SDAC. Some of the older missions in particular suffer from backlogs and have difficulties in recovering the original low-level data and/or calibration documentation with reasonable effort.

Space Physics Data Facility (SPDF). Missions archiving with SPDF deliver data to the archive on a continuous basis. Almost all missions have data available from the current year, and several are fully up to date in their data deliveries (as of 8/2020). The data are available in standard formats (mostly CDF, NetCDF, and ASCII), and software is available to read and plot the data.

Most of the data available through SPDF are level 2 or greater. Level 0 and level 1 data are often available through mission/instrument websites; see below. Many missions have multiple entries in the Heliophysics Data Portal, which provides a wide variety of data options (in one case, there are 136) but makes navigation through the many entries sometimes challenging. For longevity, it would be valuable to also have the original raw data together with the processing algorithms at the official archives.

Solar Data Analysis Center (SDAC). While many of the solar missions have provided at least partial data to SDAC, some missions still rely only on their own archives. In some cases, this is not a choice made by the missions, but caused by the challenges the large data volumes pose on the NASA archiving capacity. This is especially true for SDO. NASA is actively working with the mission teams to seek solutions for facilitation of further data deposition into SDAC. The data are in the FITS format, which is widely used and comes with software support.

Most of the data available in SDAC is level 1 or level 2. Most of this data contains documentation to process the higher-level data products. The VSO provides access to most solar mission data through an interface that links to distributed archives; see below.

Data accessibility

All missions have scientifically useful data and metadata that are identifiable and accessible, although not always through the NASA archives. There are some exceptions to this general condition for individual data products, but the missions' performance is on course overall.

Virtual Solar Observatory (VSO) and Coordinated Data Analysis Web (CDAWeb). The NASA-supported VSO helps to identify and find datasets and provides software for these datasets' analysis. This effort aims at greater ease of use through a single interface and an Application Programming Interface (API) that allows one to search and download functions that then can be called using multiple programming languages (including Python, Java, C, and IDL). In recent years, a large share of the data downloaded from the various archives were identified and accessed via the VSO. It is important to realize that the actual data remain at the mission-specific or instrument-specific archiving sites. The VSO therefore does not constitute an archive that would guarantee long-term maintenance and preservation of these datasets. The CDAWeb offers a similar combined platform for accessing and plotting data from the heliospheric, magnetospheric, and ionospheric missions. The CDAWeb accesses data from the SPDF.

Mission and instrument websites. Many missions' websites give easier access and provide better visualization tools than the official NASA archives. In most cases, the mission websites offer access to the level 0 and level 1 data, providing both software and documentation regarding the calibrations and processing to higher-level products.

Many missions have invested significant efforts in making data, visualization tools, and downloadable software openly available to the research community. In several cases, the tools also allow inclusion of data from other missions or ground-based data sources, further increasing their value to scientific analyses.

Data documentation

Project Data Management Plan (PDMP). The PDMP documentation was required to contain a plan for the process of data transfer to the official NASA archives combined with the necessary documentation. As all missions still have gaps in the data and/or document archiving, and as the value of the archived data critically depends on the quality of the documentation, it is important that these documents be developed further. While some missions have produced highly detailed user guides (most often distributed through mission or instrument websites), this is not universally true.

Calibration and Measurement Algorithms Document (CMAD). Complete documentation of the data, data processing, and calibration are essential information for users outside the core team, for cross-mission studies, and for long-term usability of the data. To some extent, documentation has been archived with the data, and some information is available through the mission websites. It is therefore important that development of these documents and their long-term archiving continues. Producing appropriate-level CMAD documentation requires substantial effort from experienced and knowledgeable scientific personnel and programming personnel. For older missions, a significant part of the effort may involve the search for (and interpretation of) antique source code and paper calibration documents.

Resources for PDMP and CMAD development. Several proposals placed the PDMP and/or CMAD activities in their over-guide budgets. It was not entirely clear whether that placement reflected a change in the budgeting practices or a sentiment that these documents are of lower priority. Given the importance of these documents for future use of the data, these activities should be given high priority regardless of whether such documentation was required when the mission was originally selected.

Because these requirements are new in this Senior Review, the mission teams do not necessarily have resources in their existing budgets to carry out these critically important tasks. Completing these tasks would be especially important for those missions that are close to their end-of-mission, at which point there is a risk of team disintegration and permanent loss of information.

Metadata. The Space Physics Archive Search and Extract (SPASE) metadata are available for the data listed on the Heliophysics Data Portal. These metadata give only a broad overview, however, while detailed, documentation on processing and calibration of the data are missing. Some documentation is available at mission (or instrument) websites, and some teams have written thorough user guides. High-quality metadata greatly increases the value of the archived data. The missions do not seem to have a shared understanding of the SPASE model or of its importance.

Ancillary database information. The PI teams have created ancillary databases that are helpful for the analysis of data from one or more missions. For example, the Heliophysics Event Knowledgebase (HEK) at Lockheed Martin Solar and Astrophysics Laboratory (LMSAL) contains locations of solar active regions, sunspots, coronal holes, and filament channels, as well as events such as flares and coronal mass ejections. Inclusion of appropriate documentation and archiving these ancillary databases together with the data would further increase the value of the archived datasets.

Software development

Transition to open-source platforms. Focusing software development on IDL was an earlier and conscious decision across the missions. Transition from the proprietary IDL codebase to open-source platforms creates a risk that the software pool grows (as there are many open-source platforms beyond Python), which would make cross-mission and cross-instrument analyses more challenging. A maximally usable and interlinked system would build on a common platform that is mastered by recent computer science graduates, is appropriate for data science applications, and offers useful packages for a larger user community. Whatever the choice for the new platform will be, significant resources and commitment to coding, testing, and debugging will be needed in order to reproduce the large IDL codebase in an open-source platform. At the same time, the current users of the old IDL codebase will need support during the transition period.

Community-based code development. An example of a community-based global effort is SunPy, a solar physics free and open-source solar data analysis software package in Python. SunPy offers packages for downloading, analyzing, and visualizing solar data. SunPy is fully integrated with the VSO and is supported by the European Space Agency and other parties. As a true cost-free software environment for solar physics data acquisition and analysis, SunPy is open to researchers worldwide including those in developing countries. Similar efforts are underway for other fields.

Codebase searchability. Several instrument-specific codebases and more general codebases have been identified for their utility and ease of use, but there is no easy way to search such codebases for specific text strings. Such functionality would aid in finding routines that perform certain types of analyses. Searchable metadata in future codebases would help the codebases' searchability. However, an efficient implementation would require a heliophysics-wide common infrastructure.

Cross Mission Findings

All missions have data that are valuable for cross-mission studies. The data are in standard formats (e.g., CDF, NetCDF, FITS, and ASCII) and are accompanied by software for reading the files. More complete documentation and user guides (in some cases available at mission or instrument websites) as well as creation and archiving of metadata and ancillary databases would further facilitate cross-mission research.

Mission-Specific Findings

Infrastructure missions. The reviews of the two infrastructure mission proposals (Geotail and Wind) clearly highlighted the value of this mission category. The long and continuous time series are utilized by a wide range of users, from the heliophysics community to astrophysicists and operational space weather users.

International missions. Participation in international satellite missions has been a key component of NASA's Heliophysics program. The advantages of international collaborations range from increased technological and scientific expertise to new opportunities, given the additional sources of funding. However, it is important to note that just as building and operating the mission should be a joint endeavor, data processing and archiving should also be seen as a joint endeavor. The NASA archives often contain only data from the US-funded instruments, even if the complete dataset containing all instruments would be vitally important for future studies. For example, while collaboration with Japan has been highly successful, the full data of the Geotail and Hinode missions included in this review are not recoverable from a single source.

Legacy missions. As digitalization has progressed, the old missions face challenges in trying to reconstruct the data acquired over the past decades as well as challenges in reconstructing the old calibration and validation documentation. Those data often are not easily reproducible, a prime example being the Voyager mission. Voyager observations throughout the Heliosphere and out of the Heliosphere will be unique at least for the next five decades. If sufficient efforts and investments to recover these data are not made now, there is a danger that the information might be lost or might become unusable. Similarly, continued interest and understanding of the unique series would require financial and intellectual investments in succession planning and education of the younger generation for future leadership positions.

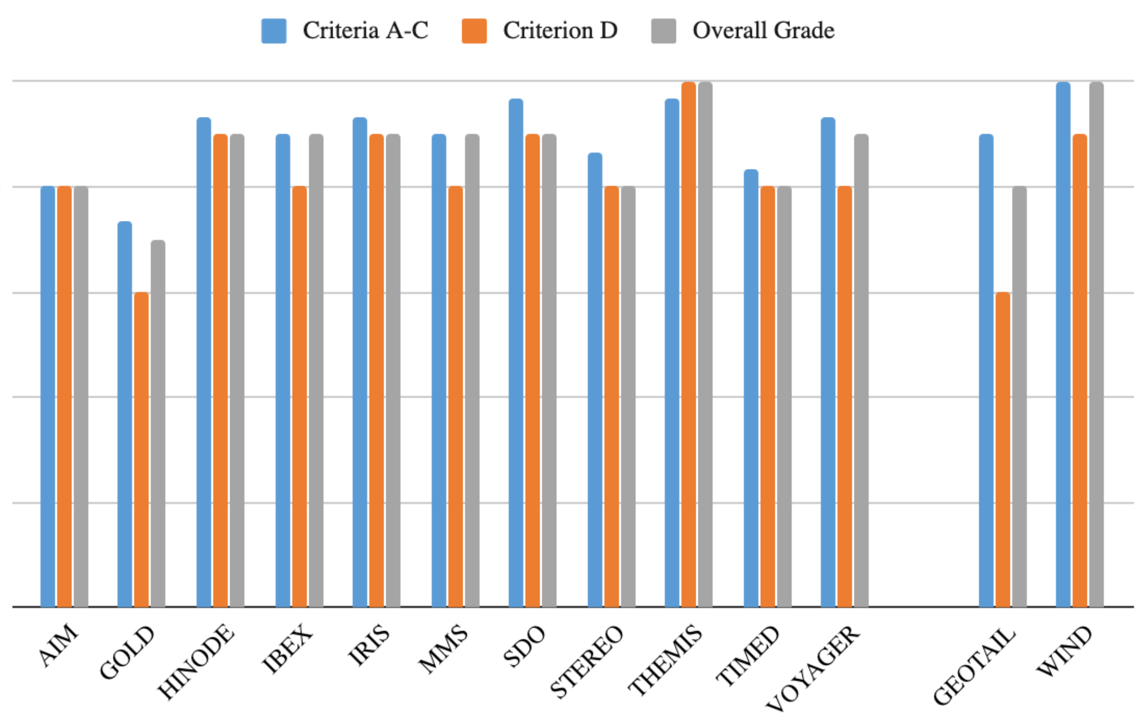
Models vs. data. Indirect measurements require complex modeling to derive physical parameters from the original data. If these models are not archived along with the data, it is impossible to reproduce the higher-level data products from the original observations. This is especially relevant for missions such as IBEX, which makes use of energetic neutral atom imaging techniques to remotely sense distant ion populations.

Mission Ratings

Each mission was rated based on scientific productivity, quality of the research plan, and contributions to the Heliophysics observatory (Criteria A-C) as well as the status of data archiving and documentation at NASA archives (Criterion D). With different weighting of each criterion (see section "Review Criteria"), each mission was assigned an overall grade.

The table below summarizes the science, data archiving, and overall rating of the missions by taking a weighted average over Criteria A-C. Criterion B is not assessed for the infrastructure category mission proposals (Geotail and Wind). For those missions, the science is therefore assessed by Criteria A and C only.

As noted in the General Findings, the ratings must be used only in conjunction with the written assessments that give the factual justifications for the ratings. It is not possible to use these ratings in a directly comparative manner, since lower ratings may arise from factors beyond the control of the mission PI.



Extended Mission Assessment

This section provides a synopsis of the missions and the panel's overall assessment and findings. A more detailed assessment of the strengths and weaknesses of each of the criteria and their sub-questions has been provided separately to NASA and the missions.

AIM: Aeronomy of Ice in the Mesosphere

Mission Synopsis

Launched in 2007, the Aeronomy of Ice in Mesosphere (AIM) mission is dedicated to studying the Polar Mesospheric Clouds (PMCs). PMCs include the Noctilucent Clouds (NLCs), a very visible phenomenon in the polar summers when ice crystals create the luminescent clouds near 83 km altitude. AIM studies PMCs using a suite of three instruments: Solar Occultation For Ice Experiment (SOFIE), Cloud Imaging and Particle Size (CIPS), and Cosmic Dust Experiment (CDE). SOFIE and CIPS are currently operating nominally.

While the original science goal of AIM was to study the formation of and variations in PMCs with relation to the mesospheric climate change and its relation to global change, the mission data has been used to study the underlying global atmospheric dynamics that produce PMCs. AIM observations are suited for studies of gravity waves and planetary waves associated with processes in the troposphere and stratosphere, in turn impacting PMCs and their variability.

The importance of coupling between various atmospheric regions has been well established in the Decadal survey for Heliophysics (2013), and AIM continues to provide key measurements towards this topic. The prioritized science goals from the 2017 extended mission were: 1) How does dynamical variability in the lower atmosphere couple to geospace weather? How do extraterrestrial phenomena propagate into the lower atmosphere? 2) What are the roles of solar forcing and anthropogenic forcing on PMCs and the structure of the mesosphere? 3) What are the geographic and temporal distributions of mid-latitude PMCs, and how are they influenced by waves and tides? For 1), CIPS observations are used to investigate hot spots of gravity wave activity around the globe, while SOFIE profiles provide vertical measurements. Significant progress has been made towards goals 1) and 2), while goal 3) was more exploratory in nature without reporting much progress. Key highlights from this prior work include the discovery of the absence of solar cycle variation signature in PMC in the 21st century compared to prior years, and a much-needed estimate of the meteoric flux input into the atmosphere.

The proposed science goals for the current extended mission build upon the prior accomplishments, and are described as follows:

1) What is the morphology of gravity waves entering the mesosphere and lower thermosphere?
2) How does the planetary wave activity influence PMCs and composition in the mesosphere?
3) How does anthropogenic and extraterrestrial forcing impact the polar mesosphere?

Overall Assessment

The proposed science objectives are all rooted in fundamental science questions that are identified in the geospace community as important and timely. The AIM team has demonstrated significant success and productivity with science goals from the past extended missions, even if objective 3) bears significant resemblance to goal 2) from the previous extended mission.

During the last extended mission period, the AIM orbit changed from sun-synchronous noon/midnight to sweeping through -90º. While SOFIE wasn't able to collect science data for months due to the change in solar illumination, CIPS obtained data from multiple latitudes during this period. For the next extended mission period, both instruments will return to their normal orbit and data collection, with CIPS continuing to provide near-global maps of Radiance Albedo Anomaly (RAA) that aid in gravity wave studies, and SOFIE will make PMC measurements in the polar regions. This configuration is poised to serve the extended mission science objectives well.

The data from the SOFIE and CIPS instruments are archived in SPDF. Quick-look images and routines to read the data files are also available.

The publication record of the AIM primary mission team remains reasonable (125 publications since launch), and the data are used widely in publications by the broader science community.

The AIM spacecraft is in good health and continues to operate nominally, even if the proposal outlines some minor receiver issues with the spacecraft.

Focused Findings

For the previous extended mission, the AIM team showed significant progress on the two first Prioritized Science Goals. Prioritized Science Goal PSG-3, "What are the geographic and temporal distributions of mid-latitude PMCs, and how are they influenced by waves and tides?" was proposed as an exploratory investigation in nature due to the low signal-to-noise for PMCs at mid-latitudes but has not yielded significant progress.

For the upcoming extended mission, the AIM team plans to work with global models, existing TIMED Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument data, and newly available datasets from ICON and GOLD in order to further investigate gravity wave signatures and planetary wave activity. Science Objectives 1 and 2 represent new science for the AIM mission. While Science Objective 3 is similar to Prioritized Science Goal 2 from the previous extended mission, it is justified by the benefits from more data in the new solar cycle given the key finding of an absence of solar cycle impact on PMC variability.

While it may be worthwhile to work with the global models, the proposal did not provide a convincing case for using the indirect measurements of gravity wave activity from the CIPS instrument (RAA) as input for global models or validation of these models.

The proposal presents highly valuable science investigations but does not fully discuss the investigations' implementation. While the AIM team mentions using global models to use towards achievement of the objectives, the proposal does not mention local models of propagation that could help identify specific lower atmospheric sources for the gravity waves. The proposal did not make a convincing case for the use of RAA data in gravity wave studies, given that RAA data provide a view that is limited to a specific altitude.

The AIM discussion of archiving is not consistent with the Senior Review requirements. The AIM archive in SPDF only includes level 1 and higher data, with the lower-level data to be archived as part of mission closeout. Further, the mission PDMP outlines how to access data through the mission websites but does not describe SPDF holdings. Lastly, as the SOFIE data processing is quite complex, the documentation provided in the proposal is not sufficient to allow an independent researcher to interpret the data processing steps or to replicate these steps.

The proposal demonstrates that AIM continues to provide valuable insights into lower-upper atmospheric coupling science by itself and by combining the measurements with those measurements coming from the TIMED, ICON, and GOLD missions. AIM thus remains an important part of the HSO.

Geotail

Mission Synopsis

Geotail is a joint mission between Japan's Institute of Space and Astronautical Science (ISAS) and NASA. Geotail is in its 28^{th} year of operation. The Japan Aerospace Exploration Agency (JAXA) has been the cognizant agency in Japan managing Geotail since 2003. Geotail was originally part of the International Solar-Terrestrial Physics (ISTP) Science Initiative that also included the Polar spacecraft (until April 2008) and the still-operating Wind spacecraft.

JAXA supports the operation and data handling for six instruments on board Geotail, and NASA provides similar support for two instruments. JAXA has approved operational support through the end of March 2022. The scientific objective of Geotail at launch was to study the tail structure and dynamics of the magnetotail.

The Geotail spacecraft was placed in a 9 X 30 R_E, low inclination (~7°) orbit in 1995. Geotail will remain in that orbit with an inclination of ~11° through 2025, with an orbital period of ~5.2 days. The satellite carries these seven instruments and instrument packages: Magnetic Fields Measurement Monitor (MGF), Low Energy Particles (LEP) experiment, Electric Field (EFD) monitor, Energetic Particles and Ion Composition Experiment (EPIC), High-Energy Particle (HEP) monitors, Plasma Wave Instrument (PWI), and Comprehensive Plasma Instrument (CPI).

The proposal is in the HSO infrastructure category, and hence presents no science objectives.

Overall Assessment

Three aspects of the extended Geotail mission make the mission a particularly strong asset for the HSO. 1) Continuing Geotail measurements to three full solar cycles forms an unparalleled dataset of the equatorial magnetosphere climatology, which has intrinsic value toward unraveling the physical processes under different driving conditions. 2) Geotail provides unique solar wind data just outside the bow shock, and synergistic orbital conjunctions with MMS and THEMIS. 3) Geotail provides charge-state data that contribute to information on ion source populations. This is a measurement that is otherwise only available from MMS within the HSO.

Geotail has provided invaluable data to radiation environment models of the magnetotail, solar wind, and the lunar environment. Geotail data and these L1, L2, lunar, and magnetosheath models have played an important role in the hardening and operational sustenance of many space-based assets.

Geotail instruments are healthy. Successful operation for five more years is likely. Of the instruments, only the HEP experiment is no longer functional. HEP was decommissioned in 2006. The other six instruments including the data-handling subsystems are operational with little degradation in data quality. The two US experiments (i.e., CPI and EPIC) are expected to continue producing high-quality data beyond 2025. Due to the failure of one of two onboard data recorders in 2012, uninterrupted 24-hour data stream coverage was reduced to 85% coverage. This reduction forms the greatest risk for the mission extension. The hydrazine fuel cells are expended and were purged in 2004 to preclude bursting during eclipse.

The information provided in the proposal suggests a lack of long-term continuity of the data analysis algorithms and codes, calibration procedures, past measurements, and the more recent (beyond 2015) high-cadence observations from the JAXA instruments.

Focused Findings

Capturing the full value of the Geotail mission will require special outreach and planning from NASA in order to ensure that the Japanese and US teams are motivated and appropriately funded to capture the information for the PDMP and CMAD, as well as the low-level mission archive (especially data since 2015). With the evident value of the Geotail dataset covering three solar cycles, an easily accessible collection of analysis, calibration codes, and broad descriptions of instrument functionality would represent a significant contribution for posterity. The proposal notes that the very small in-guide budget at present cannot fund modernization and development of the PDMP and CMAD documents in order to meet current standards. Data or related calibration information can be permanently lost without such an effort, which would constitute a major loss for the HSO dataset.

The Geotail budget request is modest and appropriate. Satellite operations, US instrument operations, data analysis, data dissemination, and data access coordination with JAXA are managed by two PIs. A total of 2.1 FTEs/year for this mission contracts to NASA Center ground operations and DSN scheduling services, with 0.3 FTE of civil servant support. No support is requested for science operations. The greatest technical risk for the mission is the absence of a redundant onboard data recorder.

Geotail is an important component of HSO infrastructure, but operating in an infrastructure funding model and with international partners, the Geotail mission needs additional attention from NASA in order to ensure that its mission archives achieve the same depth and quality of newer missions.

The Geotail data archiving strategy is not consistent with the Senior Review requirements, which is largely due to the age and the international nature of the mission. Lower-level data are hard to find and difficult to access, and some data sets are only available on NSSDC hard media or on individual instrument websites. The refresh rate for data on SPDF varies from two days to two years. The higher-resolution processed data was only found on DARTS (JAXA’s data archive), and even there only through 2015.

GOLD: Global-scale Oscillations of the Limb and Disk

Mission Synopsis

The Global-scale Observations of the Limb and Disk (GOLD) mission is designed to study how Earth's ionosphere-thermosphere system responds to geomagnetic storms, solar radiation, and upward-propagating tides. GOLD measures key state variables such as thermospheric temperature and composition. The instrument was launched into geostationary orbit on 25 January 2018 aboard an SES communications satellite. Nominal operations and observations started on 9 October 2018. Full science operations have been conducted since 17 October 2018.

The GOLD instrument is a dual-channel spectral imager recording the Far Ultraviolet (FUV) spectrum of the Earth's atmosphere. From these measurements, thermospheric temperature and neutral composition ratios (i.e., integrated O to N_2, column density ratio) are derived at a half-hour cadence during daytime full-disk observations. Daytime limb observations are used to derive exospheric temperatures. At night, GOLD images the low-latitude ionosphere, where instability-driven, depleted density regions are frequently observed. Molecular oxygen (O_2) density profiles are obtained at all local times from stellar occultations.

The science questions of the prime mission were: 1) How do geomagnetic storms alter the temperature and composition structure of the thermosphere? 2) What is the global-scale response of the thermosphere to solar extreme-ultraviolet variability? 3) How significant are the effects of atmospheric waves and tides propagating from below on the thermospheric temperature structure, and how does the structure of the equatorial ionosphere influence the formation and evolution of equatorial plasma density irregularities? The proposed new objectives for the first extended mission are as follows:

1) What factors control the morphology of the Equatorial Ionization Anomaly (EIA), the generation and characteristics of plasma depletions, and the relationship between these items?
2) How are geomagnetic storm responses affected by solar and seasonal cycles to drive thermospheric composition and temperature variation?
3) What are the sources and effects of the small-scale and medium-scale atmospheric waves that GOLD observes?
4) How do altitude profiles of composition and temperature vary with solar activity?

The science objectives are organized in terms of 13 sub-objectives, which are split between in-guide budget, over-guide budget, and research done outside the instrument team.

Overall Assessment

GOLD provides valuable new observations of the thermosphere-ionosphere system, which is insufficiently mapped at present. In the ascending phase of the solar cycle, GOLD will conduct high-quality measurements of the upper atmosphere.

The initial science mission has produced important contributions to several topics of the prime mission, such as magnetic storm effects, observations of waves, and image analysis of the equatorial ionosphere anomaly. GOLD observations overlap with ICON and TIMED's Global Ultraviolet Imager (GUVI) instrument, providing an opportunity for synergistic observations. The over-guide mission extension adds additional campaigns to facilitate coincident measurements with other HSO missions.

GOLD is highly relevant for the research objectives and the scientific goals of the NASA Heliophysics Division, as well as for the 2013 Heliophysics Decadal Survey. GOLD's observations of the thermosphere and ionosphere system are of great importance to HSO.

The GOLD Public Science Data Products Guide on the SPDF archive provides a thorough description of the file/data format and content, metadata, and updates/release notes. However, the CMAD and PDMP documentation do not address issues related to clear labeling (or removal) of erroneous data. Addressing these issues would make data usage easier. Level 1c and 2 data products are available at the SPDF, and those data are complete from 2018 through the current date in 2020.

GOLD instruments operate nominally and do not exhibit any health issues.

Focused Findings

The GOLD mission provides measurements that are of great value to the HSO. However, the proposed GOLD objectives do not present a compelling extended mission investigation: Several of GOLD's proposed objectives describe work without reference to what specific understanding of the system would result from the investigations; these objectives are focused on merely gathering data, observing morphology, or searching for correlations. Furthermore, the in-guide research for Science Objective 1 is essentially an extension and expansion of the prime science mission's Science Question 4.

The proposal does not sufficiently discuss the implementation of some of the proposed tasks. The proposal states that GOLD provides a unique perspective for observing lower atmospheric wave effects on neutral composition. However, the proposal does not demonstrate that GOLD alone would be able to distinguish between in situ waves and lower atmospheric waves. Assimilation of the GOLD observations into models presents new and unique challenges. The proposal does not clarify how the various assimilation challenges will be overcome or how the data assimilation capability will be achieved and implemented.

The extended GOLD mission is vitally dependent on the over-guide budget and cannot fully function as described in the proposal with only the in-guide budget. The GOLD implementation is unique within the HSO fleet, as the instrument is mounted on a commercial satellite that is owned and operated by SES GS. While this was an optimal way to realize the mission, the SES GS hosting fees must be included in the GOLD operations budget in order to extend the GOLD mission. The GOLD mission extension proposal includes the SES GS-related cost in the over-guide budget and mentions that this inclusion was made by direction of NASA (proposal page 26).

The GOLD data archiving proposal is not consistent with the Senior Review requirements. Only L1c, L1d, and L2 data products are available at either SPDF or the mission website. GOLD release notes on SPDF illustrate details of the current release including limitations and errors within the data files, but neither those, the PDMP, nor the CMAD provide a concise summary and/or to label the data accordingly. The PDMP includes L3 data products and identifies requirements for these data products' availability, but also notes that L3 products are not being produced and indicates that such products have not been defined.

The GOLD mission could further increase its value by engaging in careful cross-calibration between missions, which would allow the community to more easily integrate, e.g., the long-term TIMED/GUVI record with the GOLD observations.

Hinode

Mission Synopsis

Hinode was launched in 2006 into a sun-synchronous orbit, which allows near-continuous observation of the Sun. The mission was originally scheduled for three years, but it has continued to produce high-quality data for 14 years. Hinode is fully capable of operating through the upcoming solar cycle.

Hinode is an international solar mission led by Japan, with major contributions from NASA, the UK Space Agency, and ESA. JAXA has approved funding through 2025 for its agreed-upon contributed tasks, which include spacecraft operations, station passes, instrument planning and support, and data archival. ESA and the Norwegian Space Council are conducting a review for the confirmation of an extension to 2022 and a follow-up extension until 2025. The tasks agreed by these organizations include passes at KSAT stations Svalbard and Troll and use of the Hinode Science Data Center at the University of Oslo. A positive recommendation has been advanced for the committee's decision in October 2020. The UK Space Agency will hold its next review in the summer of 2021. The UK Hinode team maintains the planning software for instrument operations and validation of uploads, provides about 10 weeks per year of instrument planning, and maintains the primary web repository for EIS MO&DA.

Hinode carries three main instruments. The Solar Optical Telescope (SOT) has a focal plane package consisting of a Broadband Filter Imager (BFI) that produces images of the solar photosphere and chromosphere in six wide-band interference filters, a Narrowband Filter Imager (NFI) that produces magnetogram and dopplergram images of the photosphere, and a Spectropolarimeter (SP) that produces high-resolution vector magnetograph maps of sections of the photosphere. The X-Ray Telescope (XRT) uses grazing incidence optics to image the X-ray full disk and low corona. The Extreme-ultraviolet Imaging Spectrometer (EIS) wavelength bands include emission lines at temperatures ranging from 50,000 K to 20 million K.

The mission continues its science objectives:

1) Study the sources and evolution of highly energetic dynamic events
2) Characterize cross-scale magnetic field topology and stability
3) Trace mass and energy flow from the photosphere to the corona
4) Continue long term synoptic support to quantify cycle variability

Overall Assessment

The spacecraft and instruments are in good health. The losses of the high gain antenna and the SOT Filter-Graph (FG) have been adequately compensated and have actually opened opportunities for new, scientifically productive observing modes (e.g., high cadence EIS pre-flare scans).

The results of the last mission extension are largely incremental. These results include advances in the analysis of the dynamics of network and internetwork fields, the low first ionization potential element evolution during an active region lifetime, the detection of strong horizontal magnetic fields in umbral filaments, and the discovery of the power-law relationship between X-ray intensity and surface magnetic field strength over more than a single magnetic cycle. However, XRT provided essential X-ray images for the groundbreaking detection of hard X-ray emission from bright X-ray loops in the corona. This detection was made by the Focusing Optics X-ray Solar Imager-2 (FOXSI-2) sounding rocket and was published in Nature: Astronomy in 2017.

Hinode's proposed in-guide scientific investigations for the three-year mission extension are meaningful and address new avenues within Hinode's four science objectives. The research exploits the opportunity offered by the upcoming solar maximum for detailed study of large and small dynamic events on the Sun. Examples include the study of reconnection in flares through high-data-rate EIS (and IRIS) rasters complemented with XRT images, as well as the study of active region "hot clouds," which are diffuse X-ray emissions from active regions that account for a significant fraction of their total emission. The proposed observations are performed with very low-risk, well-established procedures, often in close collaboration with other spacecraft and Ground-Based Observatories (GBOs). In particular, Hinode and IRIS operate as practically one instrument. This operation increases the value of each mission synergistically.

Each of the proposed studies in the Hinode extension proposal is unambiguously linked to the 2014 Heliophysics Roadmap Research Focus Areas and 2012 Decadal Survey Heliospheric Major Science Goals. The proposal also lists a number of interesting investigations carried by the international partners.

Hinode data are well archived in multiple locations and are easily accessible. The data format is FITS, which is widely readable. The FITS headers and keywords are well organized and commented. Units are provided for all quantities, and the units are appropriate and standard at each data level. Level 0 data are available through VSO. Open-source code (via SolarSoft) is available to create level 1 and level 2 data products, and these routines are clearly identified in the PDMP (Project Data Management Plan). All three User Guides are comprehensive and explain how to retrieve and process their respective data. The Hinode data system is integrated with that of IRIS.

Focused Findings

Hinode is a key element in the HSO's large array of instruments for recording the upcoming solar maximum. Never before has such an armada of missions observed the solar maximum. The recent additions of the Daniel K. Inouye Solar Telescope (DKIST), Parker Solar Probe, and Solar Orbiter, as well as an upgraded Sac Peak and GONG, add an entirely new dimension to the detection space.

Hinode XRT plays a crucial role in the HSO because it provides the only full-disk, high resolution, high cadence X-ray images of the Sun. SOT/FG provides partial disk, very high-resolution Vector Magnetograms (VMGs) that perfectly extend in time (prior to and after DKIST) the even higher-resolution DKIST VMGs. EIS and IRIS, together with the Spectral Imaging of the Coronal Environment (SPICE) and the X-ray Spectrometer/Telescope (STIX) instruments on Solar Orbiter, provide a unique multi-angle spectroscopic capability for the first time during the upcoming solar maximum. In addition, Hinode's VMGs are a perfect complement to the magnetograms of polar regions obtained by the Solar Orbiter, both for verification and for additional polar coverage. These magnetograms are especially complementary during occasions when there is a substantial angle between the Solar Orbiter, the Sun, and Hinode.

The discussion provided on the HINODE software is not consistent with the Senior Review requirements and may not be sustainable in the long-term as the community moves towards open-source platforms. The Hinode data requires that the user perform the calibration for level 0 to level

1 and/or level 2 and within SolarSoft and IDL. There is no plan presented for archiving all of the relevant data analysis routines on NASA servers, which would better enable the reproduction of the full analysis pipeline

IBEX: Interstellar Boundary Explorer

Mission Synopsis

IBEX was launched on October 19, 2008 via an Orbital Sciences Pegasus XL Rocket as part of NASA's Small Explorers (SMEX) program. The Prime Mission started on February 11, 2009, targeting a duration of two years. The overarching objective of the IBEX mission is to explore and map the complex boundary between the heliosphere and the Local Interstellar Medium (LISM). This is achieved by detecting and measuring, in near Earth space, Energetic Neutral Atoms (ENAs) coming from or through the heliospheric boundary region and travelling inward from interstellar space.

In the extended mission, IBEX continues to discover the evolving properties of interstellar interactions, stimulating fundamental controversies. In addition, IBEX observations reveal new information about global magnetospheric and lunar interactions with the solar wind. The scientific objectives for the extended missions are the following:

1) Determine the origin of the Ribbon.
2) Study the physical properties of our global heliosphere and understand how they are regulated.
3) Understand the field, flow properties, and composition of the LISM, and how the LISM interacts with the heliosphere.

Overall Assessment

IBEX has made numerous fundamental discoveries, many of which were unanticipated. These discoveries span questions about the Local Interstellar Magnetic Field (LISMF) and its influences, the boundaries of our solar system, the spatial structure, and the properties of the LISM.

The proposal makes a strong case for the importance of the proposed science objectives. The primary mission of IBEX was during the solar minima. During the extended mission, the IBEX team is utilizing temporal changes in the solar wind to test hypotheses concerning the origin of the IBEX Ribbon, the influences of the LISMF, and the underlying physical mechanisms that operate in the LISM/heliosphere interaction. IBEX will tackle questions such as how the heliospheric boundaries respond to changing solar wind conditions.

IBEX mission is a very productive mission (over 296 refereed publications; 44 new since the last senior review). The team has identified new opportunities for science, as IBEX captures the response of the interstellar boundaries to the changing structure of the solar wind in its decline from solar maximum to the next solar minimum.

IBEX observations have been analyzed in the context of numerous competing models and theories, ushering in the present era of heliospheric research. As the mission proceeds, testable predictions are pursued to allow the resolution of the controversies that now exist concerning the global heliosphere and interstellar interactions.

Focused Findings

The proposal makes a strong case for the importance of the extended mission. During the next period, IBEX will complete ENA maps that then will cover a full solar cycle. These unique data would allow closing the science understanding gap of the charge exchange, transport, and microphysical processes in space plasmas. Future ENA maps will provide further insight into the global structure of the heliosphere including the inner and outer heliosheaths and their evolution over the solar cycle. The extended mission will improve understanding of the interstellar medium properties, magnetic fields, turbulence, and flow patterns.

There are currently several controversies explored by IBEX as identified by the proposal. The ENA data are line-of-sight integrated flux that is usually calculated in post-processing after Magnetohydrodynamics (MHD) modeling. The proposal stresses that the differences in the modeling and observational results point to weaknesses in our understanding of the inner heliosheath plasma processes. However, the proposal did not make a convincing case of how the IBEX team engages the larger modeling and theoretical heliospheric community to gain insights, observations, and methods for resolving these controversies and for providing testable predictions.

The proposal does not make it clear that the IBEX mission would take full advantage of the broader HSO community. Examples of open issues warranting broader discussion engaging a diverse set of views include the conflicting interpretations in recent literature of the same datasets, or the varying interpretations of the ENA maps regarding the shape of the heliosphere and the origin of the emission. The proposal does not provide sufficient discussion on the collaboration between the HSO missions and mission teams, even if some of the open questions posed in the proposal can likely only be resolved through collaboration across several missions.

Together with data from ACE, STEREO, MMS, the Voyagers, and other elements of the Heliophysics System Observatory (HSO), IBEX provides an unprecedented picture of the global evolution of the heliosphere and magnetosphere over the solar cycle.

The IBEX proposal archiving strategy is not consistent with the Senior Review requirements. The PDMP states that lower-level and raw data are also archived at SPDF, yet the data are not publicly available except during a short period from 2008/12 to 2009/06. The proposal conveys an expectation that only level 3 (final) products will be used by the community, and there is no open-source software available to the community that could perform calibration of the low-level products. The PDMP includes no discussion or a user guide on how to implement the complex processing from level 0 to level 3 data. The lack of robust readme files in the SPDF archive leaves the user with a large number of files with no clear guidance on their content and organization (while this information is available from the mission data website, it has inconsistent documentation on where the correct information resides). Furthermore, the archival dataset should explicitly include information related to IBEX's orbit, ephemeris, and attitude information.

It is not clear from the proposal whether the modeling software to produce the ENA maps is openly available to the scientific community, or how and if the MHD models used to derive the final fluxes are archived with the data products. This information is necessary for reproducing the processing from the original data to the physical quantities, and therefore would form an integral part of the archival dataset.

IRIS: Interface Region Imaging Spectrograph

Mission synopsis

The Interface Region Imaging Spectrograph (IRIS) is a solar physics Small Explorer (SMEX) launched on June 27, 2013 into a circular, Sun-synchronous, polar, low-Earth orbit. The prime mission finished in July 2015. The overarching science goal is to study the region of the solar atmosphere in which the temperature rapidly increases with height, providing insight into the heating of the solar corona. The instrumentation comprises a high-resolution Far Ultraviolet (FUV)/Near Ultraviolet (NUV) spectrograph with two bandpasses and a slit-jaw camera. In addition to high spectral resolution (26-53 mÅ), IRIS images have high spatial resolution (0.4″), are free of atmospheric seeing, and can be obtained at a high temporal cadence (10 s).

During the first extended mission that started in 2017, the prioritized science goals were to study fundamental physical processes in the solar atmosphere, investigate the (in)stability of the magnetized atmosphere, analyze energy and mass transfer between photosphere, chromosphere, and corona, quantify variations of far and near ultraviolet solar radiation over the solar cycle, and explore the solar-stellar connection.

For the next extended mission phase, the IRIS team will continue to address the five prioritized science goals listed above with 19 studies that extend the current results and add some novel approaches. Some of the new studies include:

1) Dissipation of Alfvén waves
2) Initiation of Coronal Mass Ejections (CMEs)
3) Energy deposition process during flares
4) Quantify variations of FUV/NUV solar radiation over the solar cycle
5) The First Ionization Potential (FIP) effect
6) Machine learning to search for flare precursors.

Overall assessment

The IRIS science team is very productive. To address the science goals of the previous extended mission, the IRIS team has produced 216 refereed publications. Some of the major results include direct evidence for the generation of Alfven waves from reconnection, discovery of small-scale jets from small-angle reconnection, establishment of relationship between Ellerman bombs and Ultraviolet (UV) bursts to current sheets, and observations showing that cancellation of internetwork flux is insufficient to power the quiet chromosphere. Furthermore, they have improved flare predictions using machine learning based on Mg II spectra and demonstrated that the observed Mg II index differences between the quiet Sun and coronal holes can have significant impact on irradiance modeling.

IRIS is an essential part of the HSO, providing unique observations to probe the interface region where the solar temperature increases rapidly with altitude. The instrumentation on IRIS is simple compared to most other solar remote-sensing missions. For full exploitation of the data, the IRIS small spatial coverage of the solar disk requires supporting measurements of the surrounding regions to provide context. In addition, the measurement of other observables such as the magnetic field are essential to completely understand the IRIS spectra and images.

The IRIS team is continually interacting with groups involved in other space missions as well as ground-based assets. The project is especially strong in the integration of the observational data with sophisticated numerical modeling.

The data system and calibration methods for IRIS are thoroughly documented in the PDMP and the CMAD. The IRIS datasets are heavily used, and the resulting experience has produced a useful interface and calibration tool set. The IRIS data is accessible through the VSO, but only level 2 data are archived in the SDAC. Access to the data via the IRIS interface is quite good and is integrated with access to Hinode data.

While the proposal did not present much technical detail on the critical past and projected instrument performance parameters, it appears that the IRIS instruments and platform are in excellent technical health and should have no problem operating throughout the next extended mission.

The proposal budget did not provide sufficient information on the in-guide budget effort. The science operations presented in the proposal seem expensive (7.9 FTE), but arise from the complexity of planning, coordinating, and implementing the operations. The proposal mentions ESA ground-station support that is worth $1.5M annually. The ESA support is provisionally approved through December 2022. A new extension through December 2025 has been requested.

Focused Findings

While the high-cost operational approach including complex calibration, validation and archiving tasks distributed to multiple team members does provide back-up solutions through cross-training, there might be ways to adopt modern (e.g., machine learning) methodologies to build a more efficient and robust system.

The proposal does not clearly state whether the Bitfrost model and the simulation results are available to the wider research community. One solution might be to include Bitfrost in the NASA Community Coordinated Modeling Center (CCMC).

The IRIS data archiving strategy is not consistent with the Senior Review requirements. The SDAC archive does not contain the low level data products, and the complete IRIS dataset not being available through the SDAC archive inhibits full utilization of the complementary solar space missions and ground-based assets. The IRIS team advertises their search tool for community access to the IRIS data and related data resources and is currently seeking long-term support for the maintenance of this tool.

MMS: Magnetospheric Multiscale

Mission Synopsis

The Magnetospheric Multiscale (MMS) mission consists of four identically instrumented spacecraft in a tetrahedral formation. MMS was launched in 2015 as part of the NASA Solar-Terrestrial Probes program. Nearly 100 instrumentation components across the four spacecraft comprise suites of plasma analyzers, energetic particle detectors, electric and magnetic field instruments, as well as an Active Spacecraft Potential Control device. The instruments measure the ion and electron distributions and the full three-Dimensional (3D) electric and magnetic fields with unprecedented high (i.e., millisecond) time resolution and accuracy. These measurements by four closely spaced spacecraft enable MMS to identify and study the small (i.e., tens of km) electron diffusion regions, therefore achieving MMS' primary goal of using the Earth's magnetosphere to investigate magnetic reconnection and its microphysics.

After completing its two-year prime mission, MMS was granted a mission extension in 2017 with four prioritized science goals: 1) Investigate magnetic reconnection in all near-Earth environments. 2) Determine the processes that heat plasma populations and accelerate particles to large energies. 3) Study the way turbulent processes interact on kinetic scales. 4) Investigate the microphysics of collisionless shocks. The second mission extension has the following science goals:

1) Understand how reconnection works in all boundary regions in Geospace.
2) Understand particle acceleration processes in the outer magnetosphere and bow shock and the possible relationship of these processes to magnetic reconnection.
3) Determine the nature of kinetic-scale turbulence and its role in reconnection and particle acceleration.

The three goals are to be addressed in four focused measurement campaigns: a) duskside flank; b) dayside; c) dawnside flank; and d) magnetotail. During campaign b), MMS will explore the magnetopause at increasing latitudes. MMS will encounter the southern magnetospheric cusp in 2023 and return to the ecliptic plane by 2025. The over-guide proposal includes an orbit maneuver after 2023 from the tetrahedron to other configurations such as "string-of-pearls."

Overall Assessment

During the first extended mission, MMS has made significant advances in our understanding of the magnetic reconnection process and many other aspects of magnetospheric physics. MMS has achieved significant progress within previous Senior Review prioritized goals and has made additional discoveries. The achievements are evident in a vast number of scientific publications, including three Science Reports and two Nature Letters. The broad community use of MMS data has produced novel results on details of reconnection, collisionless shocks, kinetic turbulence, and wave-particle interactions. Optimization of the tetrahedral formation to achieve progress on the science goals has demonstrated new physical insights with respect to kinetic scales. These insights come largely from the MMS data.

The extended MMS mission makes a strong contribution to the HSO through scientific relevance, measurement quality, and good opportunities for cross-mission science. MMS is likely to become an HSO centerpiece, providing synergistic context and data to the science goals of other missions. MMS is unique in providing the ion and electron distributions and the full 3D electric and magnetic fields with unprecedented high (i.e., millisecond) time resolution and accuracy. Furthermore, proposed studies of cold He and O ion species on reconnection processes and the effects of turbulence and transients on the reconnection process are at the heart of NASA's Heliophysics goals. The proposed research topics are well suited for the MMS instrumentation, and the team has demonstrated ability to address key issues with the mission.

The proposal makes a convincing case that MMS is an extremely complex mission that requires precision control of the orbits of four closely spaced spacecraft with 100 instrument components onboard, but the high cost-to-science ratio remains a concern. The scientific merit of the over-guide budget is excellent and brings major additions to the in-guide budget proposal, in terms of addressing the same questions but in more ways or in more detail, and also in terms of bringing whole new questions that are not addressed in the in-guide plan. Change of the orbital configuration would allow study in electron, ion, and MHD scales simultaneously, which has not been possible for any of the previous missions.

Data from all four MMS satellites are available from the mission website and SPDF, and the data are nearly current. The SPDF archive contains level 2 data products in CDF format. Level 0, level 1, or level 3 products mentioned in the CMAD are not available. The mission site supports the IDL-based SPEDAS package. Although observations from the four satellites are frequently analyzed together, the CMAD and PDMP documentation do not provide sufficient information on calibration and validation, and error information and documentation are available only for the electric fields instrument. The provided documentation is not sufficient to reproduce figures in published papers using data either from the MMS website or from the SPDF archive.

All four MMS spacecraft are in excellent health and can complete the proposed five-year extended mission with sufficient fuel reserve for re-entry. All instruments continue to meet level 1 measurement requirements with minor limitations:

- Two of the four MMS4 Dual Electron Spectrometers (DES) are no longer operational since the summer of 2018.
- Two of eight Electron Drift Instruments (EDI) are limited to passive mode.
- Two of 16 electric-field double probes have lower sensitivity due to micro-meteor impacts.
- One of four MMS3 Dual Ion Spectrometers (DIS) is limited to 11 keV maximum energy.

Focused Findings

MMS is a valuable mission with exceptional scientific output. The proposed science investigation is at the heart of NASA's Heliophysics goals and possible within the in-guide budget. The extended MMS mission makes a strong contribution to the HSO through scientific relevance, measurement quality, and good opportunities for cross-mission science.

While the mission prioritized science goals presented to the 2017 Senior Review were too general and broad for well-defined closure, there is little doubt that MMS has achieved significant progress within each of the stated 2017 goals. The very similar goals in the 2020 Senior Review proposal illustrates that the achievements are works in progress.

The MMS discussion on data archiving and software efforts are not fully consistent with the Senior Review requirements. The CMAD and PDMP documents do not offer an easy introduction for MMS data users that would provide an overview of the different types of data products, details on error analysis/uncertainty estimation for all data products, methods to navigate among datasets from different instruments, or information on cross-spacecraft calibration and validation.

There are minor discrepancies between the statements in the PDMP document and implemented archiving activities. The PDMP asserts that quick-look data are available within 24 hours, but as checked, the most recent data were from four days prior. Similarly, the level 3 data products and modeling data are not available on either NASA CDAWeb or the mission website, even if listed in the PDMP as available.

SDO: Solar Dynamics Observatory

Mission Synopsis

SDO is one of NASA's large strategic missions aimed at addressing multiple strategic priorities in science. SDO has three instruments onboard. The Helioseismic and Magnetic Imager (HMI) imager takes full-disk Doppler and magnetograms (longitudinal and vector) that provide helioseismic and magnetic field information. The Atmospheric Imaging Assembly (AIA) captures full-disk coronal images in seven wavelength bands and two chromospheric images alternating between 12 second cycles. The Extreme Ultraviolet Variability Experiment (EVE) provides EUV spectral irradiance measurements in the Soft X-ray and EUV wavelengths. SDO is in a geosynchronous orbit with near-continuous science downlink. The science objectives emphasize five broad areas of particular importance in solar physics:

1) Track subsurface flows and structures as activity rises.
2) Unmask magnetic variability of the solar cycle.
3) Explore magnetic connections from the Sun throughout the heliosphere.
4) Reveal the fundamental physics of solar atmospheric dynamics and eruptive events.
5) Understand space weather and space climate for Earth and other planets.

The third extended mission will continue in-depth exploration of the objectives with new questions posed by recent research. Data from all three SDO instruments are routinely provided to space weather monitoring and prediction users including NOAA and the US Air Force, as well as to NASA for space weather and mission planning purposes.

Overall Assessment

The SDO science teams made significant progress in addressing all goals from the 2017 Senior Review, increasing understanding of the following:

1) Properties of the sub-photospheric flows critical for the operations of the solar dynamo
2) Energy flow and wave propagation through the atmosphere
3) Fundamental physics of solar eruptive events
4) The solar drivers for space weather

Activities facilitated by the SDO have led to creation of several new data products and event catalogs and have stimulated collaborative research with (stellar) astrophysics. SDO data are utilized in a significant number of publications including more than 4,500 refereed papers, 2,900 papers in conference proceedings, and 62 PhD dissertations.

The objectives described in the proposal are both compelling and realistic. These objectives capitalize on the fact that SDO will be observing its second solar maximum, which makes it possible to contrast the two. This comparison will allow, for example, the physical reasons for the (expected) differences in dynamo processes between the maxima. The proposal has a strong data-driven and data-constrained modeling component, including machine learning. The proposal has clearly identified key questions upon which the mission will focus in order to reach the science objectives. The proposal provides a comprehensive implementation plan and task list, differentiating tasks to be performed by SDO team members from those that can only be addressed using external researchers and external sources of funding. The proposed objectives contribute to the research focus areas listed in the 2013 Heliophysics Decadal Survey and the NASA Heliophysics Division's strategic objectives. The in-guide budget is sufficient to ensure continuation of observations, these observations' calibration and validation, and about 75% of the proposed science investigations.

While the SDO team provides excellent access to the data, the data can only be accessed from mission resources (i.e., Joint Science Operations Center [JSOC] and VSO), and not through the official NASA SDAC archive. The proposal acknowledges the lack of well-developed CMAD and PDMP documentation and presents an over-guide request to produce them. The proposal mentions plans for release of an open-source mission code but gives no timeline for that release.

The spacecraft and all instruments are in excellent health. The plans for continued operations are clear. Degradation of all three instruments is within the expected range, and the proposal presents realistic plans for evaluation and mitigation of continuing instrument degradation. The proposal mentions a continuing effort to better understand the source of the 12-hour and 24-hour variations in Doppler and magnetic field measurements.

The SDO team strongly supports community engagement by organizing special events and scientific conferences, supporting Working Groups (WG) such as the EUV Irradiance WG, and through a highly successful public outreach program.

Focused Findings

SDO addresses key science questions about the origin and evolution of solar activity and provides vast amounts of observations that enable cutting-edge research and public outreach. SDO is the only space-based mission delivering full-disk magnetograms of the solar photosphere. Moreover, SDO provides high-resolution imaging data of the solar corona, solar irradiance measurements, and will be probing the interior of the Sun during the upcoming solar maximum. The magnetograms are widely used by HSO for context, direct comparison, and in modeling of various solar and heliospheric phenomena.

The planned flare and eruptive event observations during the solar maximum (with the context of high-resolution vector magnetograph data of flaring and non-flaring active regions) will roughly double the flare database that can be used by machine-learning algorithms that target flare prediction. This is important since machine-learning algorithms need large amounts of data to be effective, while the most important features for space weather (i.e., the X- and M-class flares) are relatively rare. Accurate prediction of flares and CMEs is of major importance for planned NASA manned missions beyond the Earth's magnetosphere.

Rapid data access enables monitoring of the solar conditions pertinent to space weather. SDO magnetic field observations and the models driven or constrained by these observations are critical for the proposed collaborative investigations with other NASA spacecraft (e.g., Hinode, TIMED, MinXSS, IRIS, Parker Solar Probe, Solar Orbiter, STEREO) and several ground-based observatories (DKIST, Atacama Large Millimeter/submillimeter Array ALMA).

The in-guide budget would likely not enable the mission to achieve repair and replacement of the aging ground communication facilities, delivery of high-quality data to the research community and space weather users, and the ambitious scientific goals. These facilities are maintained and operated by the mission (in contrast to many missions whose downlink services are provided by NASA without financial implications to the projects).

STEREO: Solar TErrestrial RElations Observatory

Mission Synopsis

The STEREO spacecraft were launched on October 25, 2006 and inserted into heliocentric orbits. Subsequently, the two spacecraft were allowed to drift in opposite directions from the Earth-Sun line by 22º per year. The prime mission was designed for a two-year operational period beginning with the STEREO-B heliocentric orbit insertion, with engineering sufficient to sustain an extended mission of up to five years. This extended mission has been far exceeded.

The mission instrumentation consists of:

- The Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) is a remote-imaging suite that images from the Sun to 1 AU and beyond with a combination of a solar EUV imager, two coronagraphs, and two heliospheric imagers.
- The In-situ Measurements of Particles and CME Transients (IMPACT) suite samples the 3D distribution of solar wind plasma electrons, the characteristics of Solar Energetic Particle (SEP) ions and electrons, and the local vector magnetic field.
- PLAsma and SupraThermal Ion Composition (PLASTIC) measures the properties of the bulk solar wind, in particular the plasma characteristics of protons, alpha particles, and heavy ions.
- STEREO/WAVES (S/WAVES) is an interplanetary radio burst tracker that traces the generation and evolution of traveling radio disturbances from the Sun to the orbit of Earth.

The spacecraft subsystem failures include the loss and aging of the Inertial Measurement Units (IMUs), and the loss of STEREO-B in 2014 due to IMU failure after nearly eight years of successful operation. Attempts were made to regain contact with STEREO-B. Despite one contact period in 2016, these attempts have been unsuccessful. Thus, the STEREO mission presently consists of only the STEREO-A spacecraft. Over the five-year period covered by this proposal, STEREO-A will move from a separation angle from Earth of 61° on October 2020, swing through the Earth-Sun line in August 2023. By the end of September 2025, STEREO-A will then move ahead of the Earth again to a separation of 48°. This range of locations will allow STEREO-A to make unique contributions to heliophysics.

The primary science focus of the mission is understanding Coronal Mass Ejections (CMEs), SEPs, and the solar wind, and in particular the effects of these phenomena on space weather. The goal sets addressed in the assessment of scientific progress in the period from FY2017 to FY2020 included the following: 1) Characterize Space Weather Throughout the Inner Heliosphere, 2) What Can We Learn from 360° Coverage of the Solar Corona? and 3) What Can We Learn from Coverage of the Full Hemisphere? The Science Objectives planned to be addressed from FY2020 to FY2023 include the following:

1) The Structure and Magnetic Morphology of CMEs, Active Regions, and the Solar Wind as Revealed by Multi-point Measurements
2) Applying STEREO Observations Toward Evaluating Off-L1 Location Space Weather Research
3) Understanding the Effects of Solar Cycle Variations on the Corona and Heliosphere

Overall Assessment

The STEREO mission has continued to produce compelling science, achieving many advances within the past three years. The proposed science for the next three years is strong, revisiting the original goals of STEREO as well as strengthening the connection to the HSO. STEREO highly leverages and enhances the science return of the HSO due to STEREO's unique orbit and comprehensive set of instruments. The loss of STEREO-B has further tightened the already strong collaborations with other missions.

The STEREO-A spacecraft is healthy, aside from the loss of the primary IMU and degradation of the backup IMU. The risk to the planned five-year mission therefore remains low. While most instruments continue to operate nominally, there are some long-standing instrument issues such as STE-U blinding by sunlight, as well as more recent issues such as problems with PLASTIC that still require resolution.

Focused Findings

The Science Objectives listed in the proposal are broad in nature, which leads to difficulty in assessing how science closure will be achieved and demonstrated in the next Senior Review. For example, the subject of Science Objective B2 "How accurate is the assumption of corotating solar wind structure in the face of increasing solar magnetic complexity?" has already been comprehensively studied, and while the proposal aims to predict the solar wind during the presence of small transients, it does not detail how this will be achieved. On the other hand, Science Objective C1 "How do coronal and heliospheric transients during the new cycle 25 rising phase compare to the rising phase for cycles 23 and 24?" is more of a survey than a scientific analysis, even if the provided and continued catalogs are frequently used by the scientific community.

STEREO is a mission of key importance to the HSO, and a significant asset for maximizing the science return from recently launched or upcoming missions. As STEREO-A completes its first revolution of the Sun, the lessons learned from the first revolution can be applied to the coming five-year interval that will also include a conjunction with the Earth. STEREO's trajectory will take it from L5 to sub-L1 to L4, providing data important for space weather forecasting questions as well as for the HSO.

STEREO launched into the deepest solar minimum of the past 100 years in 2008. This led to a paucity of events such as CMEs, flares, and SEP events. STEREO is fortunate to be returning to the near-Earth environment as solar cycle 25 builds and nears its maximum. Studies focusing on events of solar activity during the part of the trajectory between L5 and L4 can replicate the experiments that are planned for the prime phase, with the exception that the expected number of transient events is significantly higher.

Even without STEREO-B, STEREO contributions to space weather operations remain significant. The most accurate characterization of CME properties for running the Wang-Sheeley-Arge (WSA)-Enlil model requires STEREO SECCHI images. These images are used by NASA/CCMC, NOAA/SWPC, UKMet, the Korean Space Weather Center, and the Australian IPS to forecast space weather. The PLASTIC and IMPACT magnetometer data are used by all of these centers to improve forecasting of co-rotating structures. The IMPACT particle data is used to assist in SEP forecasting. In addition, SECCHI is the only mitigation against the loss of Solar and Heliospheric Observatory (SOHO) Large Angle and Spectrometric Coronagraph (LASCO). Ensuring maximum scientific and operational use of the STEREO PLASTIC, the instrument's science and beacon data should be corrected to as high quality as possible.

The STEREO data archiving strategy is substantially complete, though some minor issues remain to be fully consistent with the Senior Review requirements. The PDMP is well written and thorough. There is no CMAD document currently in place. While the proposal asserts that a CMAD document should be available by 2021, the plan for creating this document is not clearly described.

The proposal does not present a clear documentation or mission code or a clear open-source plan. There is no strategy for the long-term archiving of SSWIDL routines. Key documentation for the software such as the SECCHI Data User Guide is not currently available in a NASA archive. The mission code for processing from raw data to higher levels is not well documented on the mission website or NASA archives.

THEMIS: Time History of Events and Macroscale Interactions during Substorms

Mission Synopsis

Launched in 2007, THEMIS consists of five identical probes (i.e., A, B, C, D, and E). Two of the probes (A and B) have been dispatched to a lunar orbit and are designated as the ARTEMIS mission. The three Earth-orbiting probes (C, D, and E) have low-inclination orbits that are ideal for studying the equatorial magnetosphere.

Each THEMIS probe carries five sensors including an Electric Field Instrument (EFI; for DC electric fields), a Fluxgate Magnetometer (FGM; for DC magnetic fields), Search Coil Magnetometers (SCM; for AC magnetic fields), Electrostatic Analyzers (ESA; for plasma electrons and ions), and Solid State Telescopes (SST; for energetic electrons and ions up to MeV). In addition to the flight sensors, the mission also supports Ground-Based Observatories (GBO) consisting of a network of 20 All-Sky white-light Imagers (ASI) and nearly two dozen fluxgate magnetometers (GMAGS) based in North America.

Much of the community accesses and analyzes THEMIS data through the Space Physics Environment Data Analysis Software (SPEDAS) IDL software, which has also been adopted by other missions. This software is being ported to Python for even wider open-access use. This is especially important since THEMIS is used for numerous conjunction studies with other missions such as MMS.

In the proposed extended mission, the orbits of the three Earth-orbiting probes will be modified through one-year campaigns in order to provide equilateral triangular configurations in the Geocentric Solar Magnetospheric (GSM) XY, YZ, or XZ planes for observations of dayside phenomena and nightside phenomena. These configurations allow separation of spatial and temporal features at least in one plane, and also enable curlometry to determine one component of the electric current. These observations serve two overarching science objectives:

1) Understand how the solar wind energy, having entered Earth's magnetotail, is dissipated into near-Earth plasma heating and powers the auroral ionosphere.
2) Understand how dayside transients (i.e., foreshock transients and magnetosheath jets) interact with Earth's bow shock, magnetosheath, and magnetopause to alter geoeffectiveness of the solar wind.

Overall Assessment

THEMIS has been a high-impact mission since the last senior review, and the mission has successfully addressed its prioritized science goals. The new proposed science investigation includes one compelling question (i.e., nightside energy conversion at the tail-dipole interface) for which THEMIS is uniquely positioned, and one important question (i.e., the outsized impact of dayside transients on geoeffectiveness of solar wind) for which THEMIS will provide valuable data. The data are widely used by the community and play a broad role in the HSO.

The mission data archives are thorough and complete at the mission data website, and these archives are accompanied by high quality documentation. However, the NASA archives are not as complete.

The NASA archives do not yet include the level 0 and level 1 data that are useful for certain kinds of analysis, and these archives do not include as much of the documentation.

All (minor) sensor anomalies have been recovered or are using a successful workaround plan so that the sensors are returning full science capability on all probes.

Focused Findings

THEMIS is proposing exciting science, provides a valuable contribution to the HSO, and supports the lunar program through its ARTEMIS component. The proposal presents three sets of objectives. In order of importance, these objectives include nightside research, dayside studies, and cis-lunar studies.

The proposed budget is appropriate for the mission operations and proposed science. The over-guide budget would enhance the main science investigation and HSO support by funding a broader team of scientists, completing the CMAD, and funding reconfiguration of the ARTEMIS probes to support Lunar Gateway with near-real-time MeV ion measurements.

The proposal clearly describes data archiving and software efforts consistent with the Senior Review requirements. It anticipates completion of the migration of data and especially documentation to the NASA SPDF archive during the upcoming extended mission. The IDL-based SPEDAS software is very usable and successful, and this software will likely become more widely usable with a Python implementation that is in development.

TIMED: Thermosphere, Ionosphere Mesosphere, Energetics and Dynamics

Mission Synopsis

The TIMED mission was launched in 2001, with the primary goal of determining the basic states and energy balance of the Mesosphere, Lower Thermosphere and Ionosphere (MLTI) by making observations covering altitudes between 60 and 180 km. The TIMED instrument suite consists of four instruments: The Global Ultraviolet Imager (GUVI), a far-ultraviolet spectrograph observing composition and temperature; The Solar Extreme Ultraviolet Experiment (SEE), a sun-pointing spectrograph/photometer combination measuring solar radiance from the soft X-rays to the far-ultraviolet; The TIMED Doppler Interferometer (TIDI), a limb sounding interferometer measuring wind and temperature profiles; and Sounding of the Atmosphere using Broadband Emission Radiometry (SABER), a multichannel limb-scanning radiometer measuring broadband infrared emission to obtain altitude profiles of temperature, pressure, geopotential height, volume mixing ratios for a number of trace species, and atmospheric cooling and heating rates.

The overall objectives of the TIMED two-year, nominal mission were to perform a comprehensive, global study of the MLTI region and to establish a baseline against which to compare future measurements. TIMED has delivered quality science data since early 2002. Despite nearly 19 years on orbit, TIMED is still able to routinely produce most of its original data products as well as some additional ones that were added during the mission. The mission started at the declining phase of solar cycle 23 and has covered the entirety of cycle 24. The current mission extension will cover five years of the increasing solar activity phase of cycle 25.

The most recent mission extension pursued the following science goals: 1) Investigate geospace coupling in the context of geomagnetic storms during the new era of GOLD and ICON operations. 2) Determine and understand the Ionosphere Thermosphere Mesosphere (ITM) region long-term decadal-scale changes and contribution between different forcing processes. 3) Characterize, compare, and study the ITM drivers and response differences between two solar minima. The mission extension proposal includes the following science objectives:

1) Understand the causes for the hemispheric and longitudinal variations in storm-time neutral response.
2) Investigate how middle atmospheric meteorological disturbances influence the thermosphere.
3) Determine the ongoing effect of weaker solar cycles on the thermal structure, composition, and dynamics of the ITM region.

Overall Assessment

During the last mission extension period, the team made significant progress in the prioritized science goals. The TIMED mission continues to provide valuable and unique data to the investigation of the mesosphere/lower thermosphere/ionosphere region and its coupling to drivers from above (solar) and below (troposphere/stratosphere). The number of TIMED-related, peer-reviewed publications continues to be high, exceeding 160 per year. The majority of publications have been by first authors from outside of the mission team.

The science objectives proposed for the next five years are broad areas of investigations that are highly relevant to documented NASA science priorities. Several of the objectives effectively leverage newly available data from the recently launched GOLD and ICON missions. However, the broad definition of these objectives will complicate a clear assessment of closure.

The continuation of TIMED observations is expected to contribute significant value to the HSO, given that the data products are largely complementary to the data from the GOLD and ICON missions. Common measurements, such as the O/N2 ratio (TIMED/GUVI, GOLD, and ICON) can be used to provide careful cross-mission calibration that will be essential for improving data quality and for continuing the long-term TIMED dataset into the future.

The TIMED spacecraft and instruments are in operating condition overall, despite TIMED's advanced age. GUVI continues to be limited to its spectrographic mode due to a failure of the scanning mechanism, but successful steps were taken to recover from a reaction wheel failure and to build resilience in case of another wheel failure.

Focused Findings

TIMED observations constitute a highly valuable, long-term dataset for conducting high-priority MLTI research. The measurements are largely complementary to ICON and GOLD in both latitude, longitude, and altitude coverage. Moreover, the coincident measurements (e.g., O/N2 ratio) present a unique opportunity for cross-mission calibration that is essential for future continuation of some of the long-term TIMED datasets.

The broadly defined Science Objectives do not contain sufficient explanation, detailed approaches, or metrics of success to show that they will lead to focused advances in scientific understanding. For example, in discussing Objective 1 "Understand the causes for the hemispheric and longitudinal variations in storm-time neutral response", the proposal does not adequately address whether closure can be achieved within the in-guide effort and the available data. Similarly, the presentation of Objective 2 "Investigate how middle atmospheric meteorological disturbances influence the thermosphere" does not pose a focused scientific question to be answered, even if it is expected to yield "new scientific knowledge and vastly improved forecasting skill". Lastly, Objective 3 "Determine the ongoing effect of weaker solar cycles on the thermal structure, composition, and dynamics of the ITM region" is not accompanied by an adequate description of the importance or necessity of adding another solar cycle to the current measurement set.

The proposal does not provide supporting information about the rationale for or benefit from prioritizing in-guide science investigations over continued TIDI operations. The termination of TIDI operations would result in an unrecoverable loss of data for the HSO. The cost for continuing TIDI operations is given as ~6.5% of the in-guide science data analysis budget, meaning that terminating its operations would not free a significant fraction of mission resources for additional science investigations.

The TIMED data archiving is not consistent with the Senior Review requirements. The archive in SPDF lacks some data as well as detailed documentation on calibration and processing. For example, level 3 data for v13 are not available on SPDF, TIDI level 1 data are given only as unretrieved line-of-sight data, and GUVI level 3 data are only available on the JHU/APL website. Furthermore, the critical calibration information that is available on the GUVI website has not been submitted to the SPDF archive, and documentation on SABER or TIDI software version changes could not be found on SPDF.

The PDMP has some deficiencies regarding the GUVI data products: There is no description of how to incorporate three new GUVI data products into the SPDF archive, and the final archive plan lacks details regarding GUVI data. Furthermore, the plan for final archiving does not provide a schedule for delivery after the end of the mission, nor does the plan identify the nature of any products, tools, or documentation that have not yet been delivered to SPDF final archive. On the CMAD side, there is contradicting information on the resource allocation between the proposal body and the budget tables.

The proposal makes only a brief mention of code management and does not provide a clear plan for open-source code. Also, there is no budget specifically identified for open-source code transition. The proposal states that "because some key data processing software utilizes commercial and proprietary code packages [...], the TIMED archive will not include calibration and processing codes that implement the algorithms described in the TIMED CMAD."

Voyager

Mission Synopsis

The twin Voyager space probes (V1/V2) were launched in 1977, making the pair the longest operating space mission of all time. After completing the encounters with the giant planets of the solar system, the program was refocused as the Voyager Interstellar Mission (VIM) with a primary objective to study the plasma and energetic particle environment of the distant solar wind, heliosheath, and the Local Interstellar Medium (LISM). Voyager trajectories took the spacecraft past the solar wind termination shock and eventually past the heliopause (i.e., the magnetic boundary of the solar system) in 2012 for V1 and 2018 for V2. The VIM has produced a multitude of discoveries that greatly advance our understanding of the outer heliosphere and the Sun's interstellar environment. The Voyagers are the only man-made platforms outside the heliosphere. Given the large cost and long transit times of the proposed future missions, the Voyagers will remain humanity's only source of in-situ information about interstellar space for decades to come.

Each space probe currently operates five instruments. The Cosmic Ray Subsystem (CRS) measures high-energy ions and electrons, including galactic and anomalous cosmic rays. The Low Energy Charge Particle (LECP) detector detects lower-energy ions mainly of heliospheric origin. The Fluxgate Magnetometer (MAG), the Plasma Science Instrument (PLS; only operational on Voyager 2), and the Plasma Wave Subsystem (PWS) detect high frequency radio and plasma waves. Forced by the decline in power outputs from the Radioisotope Thermoelectric Generators (RTGs), the mission plans to gradually switch off instruments and the respective heaters in order to ensure that at least one instrument on each spacecraft is operational through the year 2028. Communication using Deep Space Network (DSN) provides about eight hours of continuous coverage per day for each space probe at a cost of about $40M/year.

Current mission science objectives are aimed at closing the understanding gaps on:

1) The magnetic field heliopause draping pattern, the nature, origin, and evolution of turbulence in the LISM, and the physics of transient events in the LISM
2) The density and temperature of interstellar material near the heliopause
3) The properties of the pristine (i.e., unmodulated) interstellar spectra of multiple ion species, and the mechanism behind Galactic Cosmic Rays (GCR) anisotropy events
4) The properties and structure of the heliopause boundary

Overall Assessment

The Voyager mission has delivered outstanding science since the last Senior Review. The crossing of the heliopause by V2 allows a detailed comparison between the properties of the heliopause boundary in two directions separated by about 100 AU. The results show that these boundary layers are far more complex than previously thought. V1's continued exploration of the space around the heliopause has brought forth theories and models of the origin of magnetic fluctuations in the LISM and the puzzling long-lasting periods of enhanced GCR anisotropy. Significant progress was made in interpreting the transient events, including their unusual width. V2 made the first-ever direct observation of interstellar plasma, finally confirming beyond doubt that the space probe is outside the solar system.

In response to the 2017 Senior Review, the mission team has initiated activities aimed to increase synergy with IBEX and Cassini remote sensing observations, which complement the Voyagers' in-situ measurements. The Voyager data continues to be in high demand, resulting in about 150 publications since 2017. About 45 of these papers were published by the Voyager team. The mission owes a great deal of its success to its active involvement with the Heliophysics Guest Investigator (HGI) community that provides much of the modeling support for the mission.

The Voyager mission team proposes a compelling investigation of the heliosheath, heliopause region, the LISM, and GCRs, promising unique new data and high discovery potential. The Voyagers are an essential component of the HSO, providing a unique perspective of the heliosphere on the largest scales.

The mission data archive is usable and contains up-to-date, high-level data, although some of the interfaces are difficult to navigate. Level 0 and 1 data is generally not available in the archives, with the exception of the MAG data and the V2 PLS current since the heliopause crossing.

All instruments continue to operate nominally and return data. Despite reduced frequency of the roll maneuvers, MAG continues to deliver good data at a 48-second resolution aided by a stronger magnetic field in the LISM. The PLS instrument on V2 that was not designed for interstellar observations only provides the current in the detector (rather than the distribution moments) after the heliopause crossing. The team is successfully mitigating the adverse effects of decreasing RTG power outputs and the cooling of the spacecraft as a result of heater turn-offs.

Focused Findings

Voyagers are a source of unique data and an irreplaceable part of the HSO fleet. The proposal states that the mission will come to an end sometime before the end of the 2020s due to the decaying RTG power. Thus, the coming years are critically important for making the unique observations, as well as for ensuring the appropriate archiving and documentation of the data from the past decades.

The mission has partially addressed the 2017 Senior Review findings regarding succession planning. The mission has trained three early-career scientists to perform data processing for PWS, LECP, and MAG. However, the proposal provides no succession plan for the CRS instrument or the overall Project Scientist.

While the proposal lists an impressive number of science goals, the proposal's definition of science objectives and goals is not in line with NASA's definition. Rather, the objectives described in the proposal are specific action items, which are not appropriately linked to outstanding questions. Furthermore, the proposal does not clearly identify which objectives will be addressed under the over-guide budget rather than the in-guide budget.

The proposed in-guide budget will permit achieving the essential data collection objectives but is dominated by the operating costs of supporting 11 FTEs of engineering services. As the budget outlook is flat, retaining this workforce will consume an increasing part of the available funding in future years. Over time, this will severely hamper the team's ability to continue analyzing the data and publishing the findings.

The proposal makes it clear that the in-guide budget level is insufficient to support full scientific utilization, implementation of a program management succession plan, and implementation of the management succession plan for PLS and CRS instruments. These activities are central to the continued success of this unique mission.

The Voyager data archiving is not consistent with the Senior Review requirements. Low-level data are not generally available in the SPDF archive and the PDMP documentation does not include a consistent level of information for each instrument. Furthermore, the JPL Voyager data access page links to a number of different pages, which do not include adequate explanations or information in an easily accessible format.

Wind

Mission Synopsis

The Wind spacecraft was launched in November 1994 to the Earth's L1 Lagrange point as the interplanetary component of the Global Geospace Science (GGS) Program within the International Solar Terrestrial Physics (ISTP) program. The instrument suite of the spin-stabilized spacecraft provides comprehensive and unique measurements of high time resolution solar wind (Solar Wind Experiment [SWE]), thermal to solar energetic particles (SMS, EPA), Magnetic Field Investigation (MFI), radio and plasma waves (WAVES), and gamma rays (TGRS and KONUS).

The proposal is in the HSO infrastructure category, and hence presents no science objectives.

Overall Assessment

Wind contributes significantly to NASA's science and space weather goals by addressing the solar wind, solar energetic particles, and the interactions of these phenomena with the Earth. Wind data are widely used not only in the heliospheric community but also in the astrophysical community. This usage is underlined by Wind's high data access rate, by recent press releases, and especially by its exceptional track record of publications including more than 1000 refereed publications since 2017. Approximately 40-60% of those publications are based predominantly on Wind data. These publications, including high impact papers (nine in Nature, three in Physical Review Letters [PRL]), also prove the successful progress that was made toward previous science goals that were focused on wave-particle and/or turbulence-particle studies, unusual solar cycles, particle acceleration, and long-term dust science.

The greatest strength of the Wind mission to date is its contribution to NASA's HSO, justifying its implementation as an infrastructure. Wind contributes to the HSO with many unique data products and baseline measurements for inner and outer heliospheric missions. Wind provides reliable solar wind measurements close to Earth, and frequently participates in multi-spacecraft investigations. Several of Wind's numerous and robust data products are unique either at Wind's orbit or among operating spacecraft (e.g., heavy ion solar wind data from STICS, energetic particle anisotropies by 3DP, and radio observations near Earth in the 4 kHz-to-14 MHz range).

Wind is a very cost-efficient mission. Software was implemented in 2016 to automate operations of WAVES and the Solar Wind Experiment (SWE). Smaller issues due to excess charging of batteries were mitigated by recent mode changes in order to reduce the maximum charge voltage, which is also anticipated to extend the battery lifetimes and reduce operations. Wind's large fuel reserve will allow the spacecraft to continue operating for another 50 years.

Data from the Wind mission is largely available from SPDF either in CDF or ASCII format, and is documented by SPASE metadata. However, no level 0 or level 1 data are stored in the archive. Data sources and analysis software are logically organized, described, and linked. However, the large number of different datasets listed on the Heliophysics Data Portal makes it difficult to identify the desired ones.

The proposal does not present CMAD or PDMP documentation but asserts that the construction of this documentation is underway. Because the proposal lacks sufficient detail on that process, it is not clear whether or when the lower-level Wind data and associated documentation, calibration, and software needed for deeper analyses will become available to scientists outside the team.

The Wind spacecraft is in good health and operates stably. Except from the gamma-ray sensor that has run out of coolant, all instruments are operating well. On June 26, 2020, the flight operations team completed the first maneuver to move Wind from a Lissajous orbit into a halo orbit around L1. Two further maneuvers are required for completion, with the second maneuver being scheduled for August 2020 and the third maneuver afterward. No major changes to the data products have appeared since 2015.

Focused Findings

The Wind mission constitutes a particularly important component of the HSO due to its robust, long-term, and partly unique measurements that are frequently used in multi-spacecraft studies. This usage is underlined by a remarkably high number of publications using Wind observations and Wind's high data access rate.

The lacking PDMP and CMAD documentation noted in the proposal poses challenges for the use of the data. The PDMP should provide an overview of the different types of data products and should list data products that are still maintained and updated separately from those that are not maintained and updated. This information would ease the use of the data, which now is complicated by the large number of available data products including approximately 58 selectable data types with approximately 1118 total data products. The team's plan for gathering current versions of the calibration codes in lieu of a formal CMAD is an acceptable starting point, per the Senior Review requirements.