The 2017 Senior Review of the Heliophysics Operating Missions

December 1, 2017

Submitted to:

The Heliophysics Advisory Committee

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Executive Summary

The 2017 Heliophysics Senior Review panel undertook a review of 16 missions currently in operation in October 2017. The panel found that all the missions continue to produce science that is highly valuable to the scientific community and that they are an excellent investment by the public that funds them.

At the top level, the panel finds:

- NASA's Heliophysics Division has an excellent fleet of spacecraft to study the Sun, heliosphere, geospace, and the interaction between the solar system and interstellar space as a *connected system*. The extended missions collectively contribute to all three of the overarching objectives of the Heliophysics Division.
    - Explore the physical processes in the space environment from the Sun to the Earth and throughout the solar system.
    - Advance our understanding of the connections that link the Sun, the Earth, planetary environments, and the outer reaches of our solar system.
    - Develop the knowledge and capability to detect and predict extreme conditions in space to protect life and society and to safeguard human and robotic explorers beyond Earth.
- All the missions reviewed here contribute to study this *connected system*.
- Progress in the collection of high quality data and in the application of these data to computer models to better understand the physics has been exceptional.
- The funds invested in the Mission Operation & Data Analysis (MO&DA) budget are providing an excellent return in terms of our better understanding the geospace environment in which our technological society functions.

The review noted a few serious problems within the portfolio.

- That the large strategic missions are going into extended phase with only a portion of their mission value and prime science output realized.
- That an over-all coordination of mission operations that could enhance the system study of the connected Sun-Earth-Heliosphere system is lacking.
- For the Voyager mission, there are multiple problems regarding succession planning, open data access, and archival storage that need to be addressed.
- There are several missions for which data availability and usability is a concern.
- The archiving of mission data is not well coordinated or controlled by NASA, and the risk to valuable data sets not being fully available is increasing.

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Overview

Introduction

The spacecraft operating under NASA's Heliophysics Division and the science being accomplished with the data from these missions are impressive. Currently there are 16 operating missions using a fleet of 26 spacecraft that allow the study of the interior of the Sun, its generation and evolution of magnetic fields, the generation of solar/magnetic storms, and their evolution through the heliosphere and in geospace. The capability now exists to observe and investigate the physics of magnetic reconnection with unparalleled temporal and spatial resolution, and to study the interaction of the dynamic solar wind with the Earth's magnetosphere and ionosphere, and its interaction with interstellar space. The data produced by these spacecraft are being used extensively in computer models to help us better understand the physics of space.

NASA's Science Mission Directorate (SMD) periodically conducts comparative reviews of Mission Operations and Data Analysis (MO&DA) programs to maximize the scientific return from these programs within finite resources. The acronym MO&DA encompasses operating missions, data analysis from current and past missions, and supporting science data processing and archive centers. NASA uses the findings from these comparative reviews to define an implementation strategy and give programmatic direction and budgetary guidelines to the missions and projects concerned for the next 5 fiscal years (matching the Federal government's budget planning cycle).

Additionally, from the **National Aeronautics and Space Administration Transition Authorization Act of 2017 (PL 115-10; Sec 513 (a) 1)):**

"...The Administrator shall carry out triennial reviews within each of the Science divisions to assess the cost and benefits of extending the date of the termination of data collection for those missions that exceed their planned missions' lifetime."

The 2017 Heliophysics MO&DA review, referred to as the Senior Review, was conducted in October and November of 2017. The Senior Review considered the comparative scientific merit of the various flight programs comprising the Heliophysics System Observatory (HSO) along with the data analysis and archiving programs. The review compared expected scientific returns and contributions to the system observatory relative to program costs under the pressure of reduced resources for the MO&DA program. A set of findings consistent with the 2014 SMD Science Plan and 2012 Decadal Strategy for Solar and Space Physics was developed by the Senior Review panel to help prioritize the resources of the MO&DA program for FY18 and FY19 along with forward-looking findings for FY20–22. This report presents the findings of the 2017 Senior Review.

In general the panel was very favorably impressed with the status of the Heliophysics MO&DA program. There is a strong fleet of spacecraft to do coordinated heliophysics and space weather research. Science accomplished since the last senior review by PI teams and the community is impressive, as is the new science proposed in the mission proposals. There is very good coordination between some missions to develop comprehensive datasets that can guide and be used for modeling.

There are areas of serious concern pointed out in the panel findings: (1) data availability usability, and archival, (2) lack of coordination for mission operations, and (3) length of mission prime phase.

Despite these problem areas, the panel is very favorably impressed with the management of the heliophysics spacecraft system and its future direction.

Missions Considered

The following missions, with their launch dates, in-guide budgets in $M (millions of dollars) for 2018, requested budgets, and their differences considered in this review are shown in the following table:

Mission	Launch	FY18 In-guide	FY18 Request	Delta
ACE	1997	3.000	3.000	0.000
AIM	2007	2.982	3.302	-0.320
Geotail	1992	0.222	0.531	-0.309
Hinode	2006	6.835	6.835	0.000
IBEX	2008	3.400	3.400	0.000
IRIS	2013	6.834	6.834	0.000
MMS	2015	14.555	25.836	-11.281
RHESSI	2002	1.855	1.855	0.000
SDO	2010	12.000	12.908	-0.908
STEREO	2006	8.250	7.800	0.450
THEMIS	2007	5.400	5.400	0.000
TIMED	2001	2.551	2.551	0.000
TWINS	2008	0.604	0.604	0.000
Van Allen	2012	13.000	17.584	-4.584
Voyager	1977	5.587	5.884	-0.297
Wind	1994	2.168	2.168	0.000
Total:		89.243	106.492	-17.249

It was made clear to the panel that there would be no extra money available and that some of the missions, especially MMS (as can be seen in the above table), are requesting significantly more than allocated.

The Charge to the Heliophysics Senior Review Panel

The Senior Review panel to assess for each mission:

(1) In the context of the research objectives and focus areas described in the 2014 SMD Science Plan, rank the scientific merits on the expected returns from the projects reviewed during the period FY18 through FY23. The scientific merits include relevance to the research objectives and focus areas, scientific impact, and promise of future scientific impact, as well as contributing to the system science of heliophysics. It is understood that predicting the science productivity of a mission over such a long period is speculative, but missions are asked to assume the *status quo* operationally; hence, the need for *Prioritized Science Goals* (PSGs) in the proposal. The panel is

requested to assess the progress that each mission has made in achieving their PSGs from the last Senior Review. The panel will provide separate assessments on both the individual project's scientific merit and as a contributor to the Heliophysics System Observatory.

(2) Assess the cost efficiency, data availability and usability, and the vitality of the mission's science team as secondary evaluation criteria.

(3) From the assessments above, provide findings on an implementation strategy for the MO&DA portfolio for FY18 through FY23, based on one of the following:

- Continuation of projects as currently baselined;
- Continuation of projects with either enhancements or reductions to the current baseline;
- Project termination.

(4) Provide an overall assessment of the strength and ability of the MO&DA portfolio to meet the expectations of the HSO from FY18 through FY23, as represented in the 2014 SMD Science Plan and in the context of the 2013 Heliophysics Decadal Survey.

The panel will *not* be asked to evaluate or assess the current utility of real-time data for operational or commercial users. However, the relevance of ongoing or new science investigations that may transition from research to operation in the future, is within the purview of the Senior Review.

Review Criteria:

In providing findings for the Heliophysics Division for each of the missions under review, the panel will be asked to assess all the proposals against the following criteria:

Criterion A: Scientific Merit (40% weighting)

Factor A-1: Overall scientific strength and impact of the mission.

Factor A-2: Expected scientific output and "return on investment" over the requested funding period.

Factor A-3: Incremental and synergistic benefit to the Heliophysics Division mission portfolio.

Factor A-4: Quality of data collection, archiving, distribution, and usability.

Criterion B: Relevance and Responsiveness (30% weighting)

Factor B-1: Relevance to the research objectives and focus areas described in the SMD Science Plan. Relevance to the scientific goals of the Heliophysics Division as defined in the Division's Strategic Objectives and the 2013 Heliophysics Decadal Survey.

Factor B-2: Progress made toward achieving PSGs in the 2015 Senior Review proposal (for missions included in the 2015 SR).

Factor B-3: Performance of addressing any findings in the 2015 Senior Review.

Criterion C: Technical Capability and Cost Reasonableness (30% weighting)

Factor C-1: Cost efficiency of the mission's operating model in terms of meeting the proposed scientific goals.

Factor C-2: Health of the spacecraft and instruments, and suitability of the mission's operating model and science team to maximizing its scientific return.

Factor C-3: Current operating costs.

The following scale will be used to map the number and significance of the strengths and weaknesses to an adjectival description for each of the three criteria above:

Adjectival description	**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, whose strengths 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, whose strengths and weaknesses essentially balance each other.
Fair	A proposal that provides a nominal response to this Call, but whose weaknesses outweigh any strengths.
Poor	A seriously flawed proposal having one or more major weaknesses that constitute fatal flaws.

The findings must take into account the following factors:

- The Panel's assessments of the missions under consideration.
- The overall strength and ability of the resulting mission portfolio, including both the missions under consideration, as well as new missions expected to be launched, to fulfill the Heliophysics Division priorities from FY18 through FY22, as represented in the 2014 SMD Science Plan and in the context of the 2013 Heliophysics Decadal Survey.
- The projected science returns of the missions under review with the potential advances to be gained from an alternative strategy of increased funding for other Division priorities.
- The scientific tradeoffs and opportunity costs involved in extending existing projects versus reducing or terminating them and using that funding for future flight opportunities, most especially in light of new heliophysics missions expected to be launched.

2017 Senior Review Process

The 2017 Senior Review process was interrupted due to changes in the NASA advisory committee policy and structure. As a result, the review was conducted 6 months later, after the fiscal year 2018 had begun, and with an adjusted panel membership. The delay and change in membership was prompted by the requirement that this process be conducted under FACA procedures. Because of the 6-month delay, mission teams were given the opportunity to submit an addendum to update the mission status and include recent science results.

Prior to the review, each panel member was assigned a mission for whom they were responsible to capture and articulate the panel's assessment and findings. The panel members had access to the original proposals and the addenda if submitted. During each mission presentation by the team, the panel members and mission team conducted well-reasoned and open discussions on a wide variety of issues that ranged from budget requirements, to data availability, to the status of the mission team and archival data, to planned mission operations. Questions from the panel were answered in real time, or as needed, answered within 24 hours. After each 45-minute presentation and discussion, the panel conferenced privately for up to 15 minutes, while the mission team waited outside. Then, if needed, the mission team was asked back, for no more than 10 minutes, to clarify any remaining issues for the panel. Not all mission teams were asked back, nor were all mission teams asked additional questions to be answered within 24 hours.

Each mission was assessed and ranked from two perspectives: (1) on its scientific merit, relevance and responsiveness to NASA heliophysics research objectives, and technical capability and cost reasonableness, and (2) on its impact to the coupled Heliophysics System Observatory science. The rankings for each are provided in the plots below, while the rationale will be found in the individual findings for each mission.

Broader Relevance to the Science Mission Directorate

The entire fleet of spacecraft reviewed is an extremely valuable asset to the nation in terms of understanding space weather. In an unconstrained resource environment, a long-term vision for the nation of a fleet of spacecraft dispersed throughout the Sun/space/Earth environment making observations to better understand the physics of space weather could be considered. Even so, the current Heliophysics System Observatory continues its progress to fulfilling that vision. The science results and advancement of the ability to predict space weather and the space environments using this fleet is impressive.

While all of the problems related to space weather are not solved, significant progress is being made. Investigations are making progress in understanding the dynamics of the Sun, its generation and evolution of magnetic fields, the generation of solar/magnetic storms, and their evolution through the heliosphere and in geospace. The capability is now available to observe and investigate the physics of magnetic reconnection with unparalleled temporal and spatial resolution, and to study the interaction of the dynamic solar wind with the Earth's magnetosphere and ionosphere, and its interaction with interstellar space. The data produced by these spacecraft are being used extensively in computer models to help us better understand the physics of space.

The 2017 Senior Review revealed abundant evidence that the recent discoveries facilitated by NASA Heliophysics (HP) extended mission measurements have scientific value beyond the realm of solar and space physics. The science garnered from the current constellation supports the overarching goals of the SMD and addresses some of the specific goals of the three other SMD science divisions.

Collaborative investigations of the Sun-Earth system have yielded important progress in understanding the coupling across various regions. Examples of significant advancement of knowledge and contributions are highlighted in each of the mission assessments.

Senior Review Panel Findings and Recommendations

Overview

The current MO&DA funding is insufficient to provide enhanced support of the proposed science for all missions. Moreover, for some missions due to funding limitations the quality of the proposed data would be compromised such that the science cannot reach its full potential. However, even within the current budget constraints, excellent and compelling science can be accomplished that will advance the field.

The panel conducted an assessment of the value of individual missions to the Heliophysics System Observatory and an associated finding that identifies the missions from a heliophysics system science perspective that would have the least impact should data from those missions not be available at some future date.

The panel found that a significant impediment to readily evaluating the proposals was the non-uniform and often obscure way the proposals relate the science proposed to the labor breakdown. Furthermore, there was generally no discernable distinction of science output between the in-guide and over-guide proposed effort.

General Recommendations

There are six general recommendations not associated with any particular mission.

Title	Recommendation	Context
Extend Prime Mission Phase	Assess extension of prime mission phase up to 5 years for large strategic missions, and 3 years for PI-led missions	The large strategic missions are going into extended phase with only a portion of their mission value and science output realized. Frequently their major prime mission goals are still being actively investigated at the time they enter into the extended phase, with reduced resources. This causes the mission to not fully achieve its science potential and to struggle with resource reductions at the very time when it is reaching its peak performance and science output. The same is true for the PI lead missions, but to a lesser extent. This recommendation will result in substantially more science return at a cost that is likely less than would be incurred if the resources were doled out piecemeal after prime mission phase. Increased mission costs associated with greater reliability for a prolonged prime phase should be considered to ensure that the benefit of increased science is

		worth it.
In-guide and Over-guide Science Output	Require in the next Senior Review call for proposals, a table that articulates (1) what science will be accomplished with the in-guide budget, and (2) what science will be accomplished with a proposed over-guide budget.	Proposed efforts for the senior review frequently elaborate on the great science that will be conducted for the over-guide budget, and have little to no discussion on what will be done if the in-guide budget is awarded. This leaves the review panel with very little information on how to assess and rank each proposal, and what to recommend to the Heliophysics Division. This could be done with a table and or text discussion.
Mission Archive	Establish a team to prepare the Mission Archive presentation	For the past several Senior Reviews, a single individual has expertly prepared the Mission Archive presentation. While this has been accomplished in a remarkable way, a more robust way to ensure that broad perspective of archival efforts is evaluated, that experience with the full range of data sets and types of data can be brought to bear, and that diverse inputs needed for future directions are included, it would be appropriate to have a team compile the content and the presentation.
Heliophysics System Observatory Mission Campaign	Create an opportunity for the community to propose a coordinated HSO observing campaign	Several individual missions proposed adjustments to their mission operations in order to better coordinate with other missions to effectively address a science question. Currently, a few missions coordinate observations, but this is only made possible by members of those missions. The community at large does not have the opportunity to coordinate campaigns, and undoubtedly innovative and important ideas go unfulfilled. There is no opportunity for the community to propose a coordinated campaign-mode science study in which specific missions in the HSO would operate in a given fashion to maximize science return. Creating such an opportunity to propose an HSO campaign team to address system level science would be justified by compelling science. It would be coordinated with and employ appropriate HSO missions.

		Appropriate resources would be made available for mission operations for each participating mission, and for data analysis for the HSO Campaign team.
Data Compatibility	Establish a community-wide, cross-agency workshop to assess options for broad solar and space physics data retrieval	Data access and usability of HSO data was an issue for several missions being reviewed. A common theme that emerged during the assessment was the lack of data compatibility and a cross-referenced and coordinated retrieval system for solar and space physics data. There are pockets of data that are cross-referenced and easily retrievable, but these data are focused.
Mission Data Archival Requirement	Establish a requirement for future Heliophysics AO's that the archived data will be the responsibility of NASA and the responsible mission institution (PI or NASA Center) is required to provide archival mission data in a timely fashion in an appropriate format.	During the review of the missions and associated archival data, it became apparent that there is no set process to ensure that the data is properly archived and made accessible. Some mission data is in jeopardy of being lost because host institutions are not willing to continue to be responsible for data distribution and archival.

Findings and Recommendations

There is one finding regarding several missions entitled **Missions of least impact on Heliophysics System Science**

The panel conducted an assessment of the value of individual missions to the Heliophysics System Observatory shown in the plots below. This finding identifies those missions when considered from a heliophysics system-science perspective, that would have the least impact should future data from those missions not be available. These are RHESSI, Wind, TWINS, and TIMED. Note that these are not necessarily the lowest ranked missions for science or HSO impact. The panel was very intentional and deliberate in assessing the overall system science impact for the HSO, which is distinct from individual mission impact. Consideration by the panel of various aspects was taken into account, such as data usefulness and availability, end-of-mission outlook, and uniqueness of system contribution in the HSO.

The rationale for identifying this set of missions follows. The RHESSI mission provides unique information on hard x-rays of solar events and is complimentary to other solar imaging missions.

However, relative to other solar observing missions, its contribution is very focused. Furthermore the instrument is near its end-of-life with thermal issues that are trending in a worsening direction. The Wind mission provides observations complementary to and overlapping observations with ACE and NOAA's Deep Space Climate Observatory (DSCOVR) mission, but is not cited as often as source of solar wind data as ACE in system-level science investigations and space weather studies. The TWINS mission produces long-term observations of the global magnetosphere, however the data are not used as widely as other magnetospheric missions, and it is difficult for the community to access and use the data without significant involvement of the TWINS science team. Furthermore, one of the two instruments suffered an anomaly over a year ago and has not provided data since, although the failure is still under investigation. TIMED continues to produce valuable data of the ITM system. However, once the GOLD and ICON are launched in 2018, much of the unique value of the TIMED observations will go away.

Additional discussion on the impact of each of these missions is provided in the section entitled "**Missions of least impact on Heliophysics System Science**" located at the end of the document after the Extended Mission Assessment section.

Finding and Recommendation for individual missions

Below is a listing of the findings and recommendations for the individual missions. They are ordered alphabetically by mission. The same findings and recommendations for the missions are also included in the mission assessment.

ACE

Recommendation: The panel recommends that for the next Senior Review the number of papers that derive scientific discoveries principally from ACE data be presented, as opposed to references in which ACE is referenced in general or as context.

AIM

Finding: Although the AIM mission is providing quality data products and documentation, it would be beneficial for these to be served directly from the SPDF Final Archive.

Geotail

Finding: It would be beneficial for the Geotail team to present a plan to NASA HQ that would enable US investigators to engage more heavily in the scientific potential of the HSO.

Hinode

None

IBEX

Finding: The panel finds that most recent skymaps are not easily accessed. The IBEX should ensure that skymaps are easily accessed and useable by the science community.

IRIS

Finding: The Panel is aware that the majority of the IRIS over-guide request is based on the uncertainty in the continued support of ESA.

MMS

Recommendation: The Senior Review recommends that the MMS mission team work towards a lower overall operating cost scenario including developing a new operating paradigm employing more autonomous operations. As MMS moves through extended mission phases, and new HSO missions come on line, current requested costing levels for MMS operations would increasingly become less sustainable. The MMS team is encouraged to begin now to implement such strategies in order to smooth the inevitable transition.

RHESSI

Recommendation: Based on the mission evaluation the panel recommends to (1) develop an end-of-life plan and present to HQ in 2019 prior to the next Senior Review call, and (2) begin archiving data now in anticipation of end-of-life.

SDO

Finding: SDO is a valuable asset to the Heliophysics System Observatory. It provides a breadth of observational information that will enable cutting-edge investigations; the data are presently used by many NASA heliophysics missions, as well as for near-real-time space-weather forecasting by other US and international agencies.

Recommendation 1: It is recommended that for the next Senior Review the team provide a separate number for publications that derive scientific discoveries principally from SDO data, as opposed to papers in which SDO is referenced in general or as context. While the total number of annual publications associated with SDO project is impressive, the Panel feels that in order to better evaluate the impact of SDO data on research in heliophysics that this recommendation should be implemented

Recommendation 2: The Panel recommends that an assessment of the mission requirements, including operations and data timeliness, be made with the intent of reducing mission costs. For example, assess the impact of relaxing the percentage of data that is required to be available in near real time. The panel expresses a concern regarding stated negative impacts of flat funding profile on spacecraft operations, data acquisition, data calibration and data processing described in the proposal under in-guide funding levels. This recommendation if implemented will alleviated the impact of the funding profile.

STEREO

Finding: Many STEREO websites do not spell out acronyms, making it sometimes difficult to get the big picture. The link to the EUVI page does not work:

https://stereo.gsfc.nasa.gov/instruments/instruments.shtml

THEMIS

Finding: the panel recognizes that the full potential of HSO science as proposed by THEMIS will likely not be possible if in-guide budget is awarded.

TIMED

Finding 1: The overall assessment of the TIMED mission is positive. The mission will continue to provide valuable ITM data and will support the upcoming GOLD and ICON missions

Finding 2: There are still issues with the TIMED NetCDF formats and with the final archive strategy. Ongoing discussions with SPDF on these topics should be continued.

Recommendation 1: The panel recommends that the TIMED mission team calibrate the new TIDI Thermospheric Wind product with ground-based wind measurements.

TWINS

Recommendation: It is recommended that images be posted online for the community two weeks after completion. The most recent image found online by the panel was January 2015. As an example, if images take a month to process and 6 months of data are required for each, then each image should be available online to the community within 7.5 months.

Van Allen Probes

Recommendation: The panel recommends that an assessment of the budget profile be conducted to reconcile the planned and executed 2015 Senior Review budget. If needed, this should be followed by a reformulation of the 2018-2019 budget profile that enables mission operations at a level consistent with the current operational level.

Voyager

Recommendation 1: Succession Plan. Given the state of the mission, the panel recommends that a personnel succession plan be developed and presented to HQ and be implemented in near term to ensure that appropriate early career personnel will be trained. This training should occur not only on the science side but on the engineering side, given that the spacecraft currently experience some engineering new challenges (e.g., decreasing power and thermal margins). The Voyager mission is an ageing yet invaluable space research asset, taking *in-situ* data in a region that likely will not be visited for decades to come. The panel is aware of the fragility of the data (some of the instruments operate at the limit of sensitivity) requiring hands-on handling by the PI's and co-I's, and is aware of the aging workforce on this mission. The panel was surprised to find that for such an important and iconic mission that there was no succession plan.

Recommendation 2: Timeliness, Availability and Archival of Data. A data processing and archival plan should be developed and implemented for all the instruments. The panel recognizes that the magnetometer data access and timeliness is being addressed. However, attention should be continued on the magnetometer data and the other data streams. The Voyager data processing and archive require extra care given its legacy approach to managing the data and the ageing instrument/spacecraft coupled with weak signal/noise ratio.

The above mentioned succession plan and archive plan should have the expressed and intentional focus on reduced cost and improved timeliness and availability of the data. The Voyager team should work closely with NASA HQ to ensure that they possess the necessary support (cost associated) to perform such task. Both of these plans should be presented to NASA HQ for approval in the Spring 2018.

Finding 1: While the panel commends the Voyager team for addressing last Senior Review concerns and making the magnetic data available in a timely fashion, one area for improvement of Voyager data handling is the provision of more background corrected data sets from the LECP instruments. Timeliness of data availability and independent insight and validation of data leaves much to be desired.

Finding 2: Voyager relies heavily on interpretation by global models. These global models require the use of supercomputing facilities such as Pleiades. The increased need for supercomputing facilities puts pressure on their time allocation usage. Use of supercomputing facilities should be fully supported.

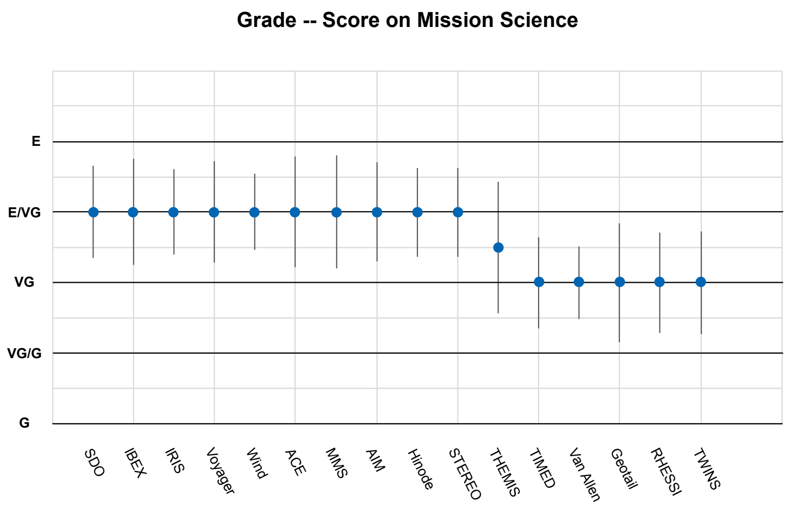
Finding 3: We note that Voyager and IBEX are highly complementary missions exploring the outer edges of the heliosphere. Voyager 1 and 2 are taking in-situ data in two distinct spatial locations while IBEX is taking global Energetic Neutral Atoms maps of the heliosphere. The panel encourages mutual synergetic activities such as joint conferences and collaborations.

Wind

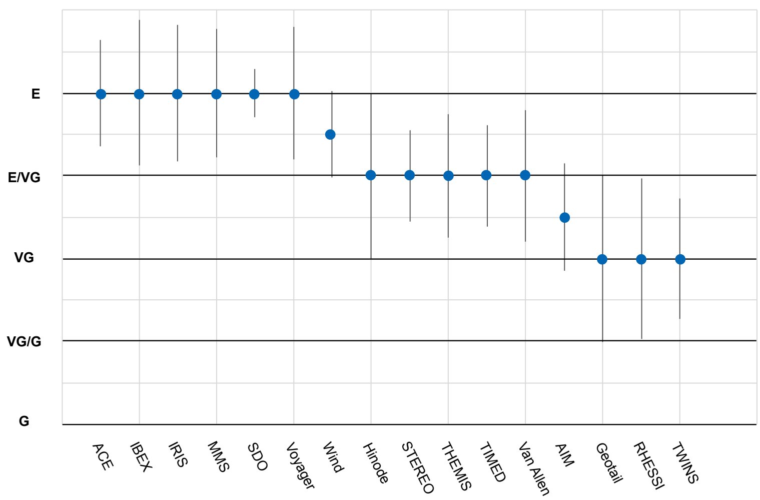
Finding: Wind continues to provide unique, robust, and high-resolution solar wind measurements, important for new science as well as support of other missions in the Heliophysics Observatory. It is unparalleled for low energy particle and radio wave observations of the solar wind by near-Earth spacecraft. Further, it serves as the 1 AU reference for Solar Probe Plus and Solar Orbiter and provides cross-calibration for the DSCOVR and ACE missions. Wind's continues high scientific productivity and high use of its data by other researchers (almost 2 million data access requests in two years).

Mission Grades

Each mission was assessed and graded from two perspectives: (1) on its scientific merit, relevance and responsiveness to NASA Heliophysics research objectives, and technical capability & cost reasonableness, and (2) on its impact to the coupled Heliophysics System Observatory science. The panel considered criteria A, B, C described above for first perspective. The grades for each are provided in the plots below, and the rationale is found in the individual extended mission assessment for each mission in the next section. The plots show the median and the standard deviation of the votes. The ranking indicated in the text for each extended mission summary was determined by the mean of the votes. The number of votes ranged from 14 to 11 depending on the number conflicted panelists for any given mission.



Grade -- Score on HSO Contribution



Extended Mission Assessment

Missions are listed in alphabetical order.

Advanced Composition Explorer (ACE)

Mission synopsis.

The ACE spacecraft, launched in 1997, is one of three in situ solar wind monitoring platforms orbiting the Sun at the L1 Lagrange point, the other two being Wind and DSCOVR. ACE carries a suite of charged particle instruments, spanning the energy range between solar wind plasma and galactic cosmic rays (eV to GeV), and a magnetometer. The CRIS and SIS are two high-energy detectors that measure cosmic rays and SEPs with energies greater than 10 MeV/n. The ULEIS and EPAM detectors measure energetic electrons and ions in the middle of the energy range, from about 50 keV to over 10 MeV. The SWICS and SWEPAM instruments cover the lower end of the energy range and measure solar wind ions and supathermal particles.

The unique feature of the mission is the ability to measure isotopic and charge composition of the solar wind, solar energetic particles, and galactic and anomalous cosmic rays with high precision, owing to the large geometry factor of its instruments. During its 20 years of operation ACE data enabled numerous transformative studies of solar wind processes, charged particle acceleration, turbulence and transport, space weather, and interstellar matter including cosmic rays and pickup ions.

The 2015 SR proposal identified ten PSGs, which were carried over into the 2017 proposal. These are the goals, in priority order, from 1 (the highest) to 10 (the lowest):

3b. Determination of the radial evolution of solar wind and magnetic fields,

2b. Determination of the origin of suprathermal ions and their seed particle populations,

1b. Determination of temporal and spatial evolution of cosmic rays throughout the current unusual solar cycle,

3a. Investigating the rapid distribution of SEPs in the heliosphere,

1c. Understanding the role of seed particles in changing SEP properties over a solar cycle,

3c. Understanding solar wind evolution by combining in situ and remote sensing data,

2a. Studies of evolving magnetic connections to flares and CMEs using multiple spacecraft,

2c. Determination of abundances of rare isotopes in cosmic rays to understand their origin, acceleration, and transport,

1a. Determination of coronal ion temperatures and densities throughout the solar cycle,

4a. Improving the precision of space weather early warning

Eight out of ten ACE PSGs rely on multi-point observations involving the entire heliospheric fleet. With the launch of two new solar wind missions (PSP and SO), the next five years promise to open a new page in coordinated observations by multiple spacecraft, and the ACE investigation will be an important part of these efforts.

Scientific merit (Criterion A)

The ACE research portfolio is unusually diverse. Ongoing ACE science investigations can be broadly classified into (a) studies of the solar wind, (b) studies of solar energetic particles, (c) investigations of galactic and anomalous cosmic rays, and (d) space weather monitoring. ACE has relevance beyond the science of the heliosphere. Its studies of cosmic ray and pickup ion composition help understand the astrophysical processes at their places of origin and en route to the heliosphere, and the properties of interstellar medium.

ACE data continues to be in high demand with over 30,000 downloads each year. ACE has a steady publication record with about 50 publications by the science team per year plus another 250 publications per year that used ACE data, demonstrating its broad relevance. The total number of publications over the mission history is more than 4000. Unfortunately, the citation count was not provided. Nine graduate students whose research involved ACE data received their PhD degrees in the past two years. The team publishes a monthly newsletter to inform the community about new science results. The team is active in organizing conferences, workshops and symposia as well as special sessions at AGU and COSPAR.

The 2017 SR proposal lists the same 10 PSGs as the 2015 proposal. This is understandable: the fields ACE contributes to are quite mature, but contain many difficult unsolved problems. Operating the mission for the next funding period will allow continuing long-term science efforts and enable a number of new investigations.

The next solar minimum will offer an excellent opportunity to study the evolution of CIRs with distance and particle acceleration in progressively steepening compression regions. Future global heliospheric investigation will include studies of heavy element abundances of GCRs and ACRs in order to constrain the galactic environment where GCRs are produced and the properties of the LISM, which is the source of PUIs and ACRs. The team has plans to compare CRIS spectra with PAMELA and AMS-2 to provide better constraints on solar modulation. An advance in understanding the acceleration of ACRs is expected from the study of their response to the deep minimum and weak maximum of the current solar cycle.

A search for cold CME filament material will be conducted and flow reversals in CME sheaths will be investigated during the next funding period. Shock fronts and magnetic flux ropes on scales of a few solar radii will be studied with three spacecraft. Other elements will include continuing studies of electron strahl variability and predicting the depth and duration of the next solar minimum. Operating the mission will help identify the origin of suprathermal ion tails prior to large SEP events. In conjunction with future PSP and SO missions ACE will determine how solar wind structures and suprathermal ion composition evolve from the Sun to 1 AU. A study of large SEP and GLE events involving collaboration with PAMELA will be enabled. A modeling effort will be carried out to evaluate shock and turbulence properties and seed particle populations in large events.

The ACE space weather related work is especially important in predicting the radiation environment of the solar system over the next solar minimum that could turn out to be a grand minimum with record high cosmic-ray intensities due to weak modulation. Over the past two solar cycles ACE has generated an invaluable continuous cosmic ray intensity record and it is essential to continue this record for as long as possible. ACE team developed early warning tools of approaching SEP events using real time solar wind data.

ACE does a commendable job of timely delivering data products to the community. The turnaround is 3 days for L1 data, while the verified L2 data typically becomes available one to four months after acquisition. Data is archived at two places, the ACE Science Center (ASC) at Caltech and at the SPDF. Data is available for direct download in the standard CDF format; in addition, the two ASC web front ends provide ASCII files and plots. Since the last review the data archive has been enhanced by reprocessing some previously available data and releasing new data with a higher temporal resolution. Level 3 data archive provides community added products including useful summary plots, multi-instrument data products, and event databases, providing much added value at no cost. During the current extended period L3 data was enhanced with an addition of magnetic field spectrograms. The data is easy to access, well documented, and highly useful. ACE provides real time data from four instruments for NOAA's SWPC. The proposal includes a detailed plan to complete the mission data archive. Implementing this plan is a currently ongoing effort. Question was raised about the continued unavailability of electron temperature from SWEPAM; this is a historical issue stemming from budget cuts early in the mission.

Relevance and responsiveness (Criterion B)

ACE science has direct relevance to thirteen RFAs within the SMD science plan. ACE contributes to our understanding of fundamental physical processes operating in the heliosphere, such as magnetic reconnection, waves and turbulence, and charged particle acceleration and transport (F1-F5). ACE science helps reveal the properties of the solar atmosphere, the solar wind, and the nature of surrounding interstellar medium by providing solar wind context to missions investigating the distant heliosphere and LISM such as IBEX and Voyager (H1-H4). ACE also has demonstrated capabilities in characterizing the variabilities in space environment and predicting solar activity and space weather (W1-W4). During the past two year period the science team has published numerous papers addressing each of the above RFAs and many more were contributed by the community.

Some highlights of ACEs solar-wind research over the past two years include the discovery that CMEs are over abundant in low first ionization potential elements compared with the solar wind, which suggests that CMEs contain a different kind of solar plasma. ACE measurements of heavy ion temperatures provided important constraints on the turbulent heating mechanisms in the solar wind. In a collaborative effort involving TIMED solar irradiance data the ACE team found that oxygen charge states are affected by photoionization by the solar radiation. ACE investigators reported that the pitch-angle width of the electron strahl varies drastically over the solar cycle, which indicates variability in scattering rates during different phases of the solar cycle.

Noteworthy SEP research includes the study of the breaks in the power laws in the spectra of different SEP species and their charge-to-mass dependence. These results are crucial for understanding turbulent processes associated with CME shocks. Collaboration with STEREO allows a unique opportunity to study the intensities and spectral properties of different SEP species at different positions along the CME shock because of the longitudinal separation between the two spacecraft. An important recent result of such coordinated observations is the clear decrease in longitudinal spread of particles with increasing energy, which might be a result of different injection and acceleration histories of particles, but could also imply more efficient cross-field transport at low energies.

On the heliospheric front ACE instruments provided unique measurements of GCR isotopic intensities during the unusual deep minimum of the solar cycle 23 and the following weak maximum. A paper in Science on Fe-60 isotope in cosmic rays generated significant public interest in the US and abroad; this provides important constraints on the nucleosynthesis in the Galaxy, providing an astrophysical context. Another work of note is the observations of waves excited by the newly born helium pickup ions. Such observations help understand the stability of pickup ion rings under turbulent conditions.

The investigation has made good progress on all ten goals and continues to produce and enable large volumes of important and highly visible new results every year.

The 2015 SR did not identify any significant weaknesses in the mission. The report recommended using all three L1 spacecraft in coordinated observations. This recommendation was not implemented to a full extent, although ACE measurements were used to cross calibrate DSCOVR sensors. One must take into account the delay before DSCOVR started producing data. The proposal provided plans for future observations of several short scale phenomena in the solar wind using all three L1 monitoring platforms. The team demonstrated appropriate responsiveness to the 2015 SR findings.

Technical capability and cost reasonableness (Criterion C)

The mission costs are well optimized and justifiable to support operations, data processing, and reasonable funding of science for 6 instruments. The proposal states that staying under the guideline will result in “significant reduction in science” due to increasing operating costs. The potential reduction in science output under the flat budget was not sufficiently quantified in the proposal. According to the proposal a 5% increase over the guideline over the five years would maintain science funding at a flat level. The ACE mission is facing a situation similar to that experienced by other missions in this review whose operating costs consume a progressively larger portions of their budgets because of a lack of provisions for inflation.

The spacecraft is in overall healthy condition and has sufficient propellant and power for the foreseeable future. The high and intermediate energy detectors and the magnetometer continue to operate with nominal degradation. Two low energy ion and electron detectors (SWEPAM and ULEIS) were not operational at the time of this review. The ACE team expects the instruments will be able to recover in a short period of time. The WIND and DSCOVR spacecraft provide solar wind data from similar vantage points, therefore a temporary loss of solar wind data from ACE would not be critical for the HSO as a whole. However, a permanent failure of these instruments would threaten the mission’s proposed space weather related research and would be detrimental for PSGs 1a, 2b, 3b, 3c, and 4a, including the very important multiple spacecraft observational studies in the next extended period, and will stop the flow of real time solar wind data. The intermediate energy ion spectrometer (SEPICA) had failed in 2011; it is no longer part of the ACE investigation.

Heliophysics Systems Observatory

ACE is an important component of the HSO because of its advantageous position in the solar wind and its comprehensive instrument suite. Of particular importance are coordinated observations of solar events with STEREO. In the next few years coordinated observations with PSP and SO will be critical to understanding the radial evolution of the solar wind and heating processes inside 1 AU, while comparison with New Horizons will enable promising new studies of evolution of solar wind structures beyond 1 AU. However, many of the studies using only solar-wind detectors and the magnetometer could be in principle conducted using WIND observations.

ACE will enable novel shock front and turbulence investigations on short spatial scales in conjunction with the other two L1 spacecraft (WIND and DSCOVR). Extending the mission will enable future studies of shock evolution with heliocentric distance using ACE, MAVEN, and Mars Express data during Mars-Earth alignments. ACE measurements contributes to the synthetic OMNI database of solar wind plasma and magnetic field near Earth. ACE also provides boundary conditions and observational constraints for numerous MHD simulations of solar events and particle acceleration models. In total, ACE data is used by over 60 space missions run by multiple government agencies and the private industry.

Mission Archive Plan

The ACE mission is doing an excellent job of producing, documenting, providing, and archiving its data. New products continue to be produced, enhancing the value of the mission. The many and continually improving data products are made available through many routes, including the SPDF Final Archive via CDAWeb. Documentation is well organized and complete, and thus “archive-ready,” although SPDF and the missions will need to work out what to do with html documentation.

Various suggested improvements:

- Some links are not working (e.g., the SWICS/SWIMS home page when last tried).
- The FTECS EPAM data are difficult to use; much of the data are also available in CDAWeb, and easier to use, but not the highest resolution.
- SWEPAM electron temperature data is referred to as "not yet available." The very useful Level 3 electron pitch angle plots should have all the energy channels provided as numerical data products (with appropriate caveats).
- Level-3 summary plots (etc.) are very helpful, and need to be (functionally) added to the archive and HDP, as planned (and as, e.g., SWEPAM pitch-angle plots are included now in HDP). It is not obvious what "MAG spectrograms" are, although they look interesting.

Overall Assessment

Based on the mission performance during its prior extended phase and the feasibility and promise of its upcoming operational phase, the ACE mission is ranked 6 of 16 missions, and is *considered to be* **Excellent/Very Good**.

Based on its contributions to, and role it plays in achieving the goals of the Heliophysics System Observatory, the ACE mission is ranked 2 of 16 missions, and is considered to be **Excellent**.

Mission Specific Recommendations

The panel recommends that for the next Senior Review the number of papers that derive scientific discoveries principally from ACE data be presented, as opposed to references in which ACE is referenced in general or as context.

Aeronomy of Ice in the Mesosphere (AIM)

Mission Synopsis

Launched in 2007, AIM is a small explorer, which the first satellite mission dedicated to studying Polar Mesospheric Clouds (PMCs), otherwise known as noctilucent clouds, and their formation environment. Two instruments obtain data for this mission, the Cloud Imaging and Particle Size experiment (CIPS) providing nadir imaging of noctilucent clouds and the Solar Occultation For Ice Experiment (SOFIE) observing limb solar occultation. In the early years of AIM, new understandings of PMC formation and variability have been achieved using these observations. As was reported at the last Senior Review, PMC imaging offers a previously unrealized resource to measure dynamics in the upper mesosphere at middle and high latitudes. These measurements along with SOFIE observations of gaseous tracers (e.g. NO and CH4) enabled understanding of coupling between the upper and lower mesosphere and to quantify dynamic connections from one hemisphere to another, and determine that the primary mechanism underlying short term PMC variability (~ days) is variations in global atmospheric dynamics.

Given the proven ability to make measurements of atmospheric dynamics and coupling, this extended mission has been proposed to examine the roles of solar and anthropogenic influence on long term atmospheric change. AIM's orbital precession will offer conditions favoring an extension of CIPS observations beyond summer middle and high latitudes. With this change, observations may be taken anywhere, anytime, along its sunlit track using a newly developed observational technique allowing the study of the atmosphere waves in a truly global context. The new observational technique, imaging Rayleigh scattering from the 50 km region using the nadir-pointing CIPS camera, will provide mapped density fluctuations depicting the gravity and planetary waves, which are actively coupling energy and momentum fluxes vertically in the lower atmosphere. Together with the observations from the Atmospheric Infrared Sounder near 30km, and TIMED/SABER, it is expected to obtain the gradients of energy and momentum flux in the lower mesosphere.

This extended mission will focus on three Prioritized Science Goals to address these outstanding science questions:

PSG-1: How does dynamical variability in the lower atmosphere couple to geospace weather? How do extraterrestrial phenomena propagate into the lower atmosphere?

PSG-2: What are the roles of solar and anthropogenic forcings on PMCs and the structure of the mesosphere?

PSG-3: What are the geographic and temporal distributions of mid-latitude PMCs and how are they influenced by waves and tides in the atmosphere?

Scientific Merit (Criterion A)

The AIM project has done well meeting the science goals set at the time of proposal and for the extensions up to the present time. What began as a task to understand the phenomenon of PMCs has developed into a new methodology to investigate middle and upper mesospheric dynamics. This is a welcome tool in the major investigative need of modern upper atmospheric science to evaluate the mechanisms of vertical transport of momentum and energy. AIM has become a key tool in this quest.

AIM science comprehensively addresses Key Science Goal #2 (KSG-2) of the NAS 2013 Decadal Strategy Report - Solar and Space Physics (2013 DSR): "Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs". This Sun-Earth system perspective also motivates the use of AIM in conjunction with auxiliary ground- and spaced-based measurements to understand upper atmosphere dynamics and vertical atmospheric coupling.

The new observational technique employs an innovative way to image wave motions just above the peak of ozone abundance in the stratosphere. The wave-induced oscillations modulate the densities of the atmosphere and ozone in such a way that the Rayleigh scattered light passes through varying line-of-sight densities of ozone. Since the 265nm filter used in the CIPS imager selects light, which is partially absorbed by ozone, the scene shows darker bands where the line-of-sight ozone densities are greater, thereby showing up the waves. The AIM team has carefully developed this technique and proved its success over the past year. It was not part of the original observing plan at launch.

Since launch, 207 publications have appeared in print journals and 289 presentations at meetings. About one third of the papers were first-authored by AIM team members. Current publishable research includes work on the composition of meteoric smoke, heating of the lower thermosphere observed by SOFIE, solar 27-day control of PMCs and vertical wind, water oscillations of 27-32 days that penetrate from the mesosphere to the stratosphere, and Martian mesospheric clouds.

Relevance and Responsiveness to the Call (Criterion B)

The extended AIM program will advance two out of three of the 2014 NASA Heliophysics goals:

- Explore the physical processes at work in the space environment from the sun to Earth and throughout the solar system.
- Advance our understanding of the connections between the sun, Earth, the planetary space environments, and the outer reaches of our solar system.

AIM observations, past and future, directly support KSG-2 of the 2013 DSR. In addition, the DSR notes that "It is becoming increasingly clear that understanding wave driving from below is critical for predicting large- and small-scale structures in the IT system..." The coupling processes are not well understood, however, leading to the DSR Science Challenge to "Understand how forcing from the lower atmosphere via tidal, planetary and gravity waves influences the ionosphere and thermosphere." AIM observations have played an important role in characterizing tidal and wave-driven variability in the mesosphere PSG-1 and PSG-3 target the origin and vertical propagation of GW and the role of waves and tides in PMC formation. PSG-2 examines the roles of solar and anthropogenic forcings on PMCs and the structure of the mesosphere. It addresses DSR Atmosphere-Ionosphere-Magnetosphere Interactions (AIMI) Science Goal 5, in particular the "singular challenge" of "achieving an understanding of how the whole atmosphere system is coupled to the geospace environment" (DSR Section 8.4.5).

Technical Capabilities and Cost Reasonableness (Criterion C)

The AIM satellite bus is operating satisfactorily, and has just regained normal operation of satellite control with the restoration of bit lock. The Morse code substitute for direct communication used during bit lock failure was workable, but is not expected to be needed again. Each instrument is performing well without significant problems. The satellite system has adequate battery and fuel service to last well beyond the requested extension period. The requested budget is $610k over guideline to pay for additional costs for flight planning to implement the full-sun CIPS observations and unanticipated overhead costs levied since launch by Hampton University. It is recommended that this increment be funded.

Contribution to the HSO

There is synergy with other Heliophysics missions focused on global atmospheric dynamics, such as TIMED, and complementary measurements will support upcoming Heliophysics missions such as ICON and GOLD.

Mission Archive Plan

The AIM mission is producing quality products and documentation, but it is difficult to find simple product help, download what is desired if it is more than a modest collection of files, and to figure out how to analyze the data once retrieved. There are also a number of broken links and missing documents. The Project should begin to serve data from the Final Archive now, rather than wait to see what problems arise at the end of the mission. Serving from SPDF will also put the products where they will be more easily be used in the context of other data, including adding web service (machine-to-machine) access. A new option for preserving IDL tools could be integration with SPEDAS, now a NASA supported integrated suite of access and analysis routines.

Some specific comments:

"Only the final version will be delivered to SPDF." Unaltered original versions plus at least initially functional software (not planned) should also be delivered. Data should be served now from SPDF, rather than waiting to see what the problems will be at the end of mission. Most missions are now doing this.
aAll products are not available to the public. "Users that wish to publish the results derived from AIM data should normally offer co-authorship to the PI". This is not what is in the HP Data Policy, nor is "Investigators supplying data or models may insist that such caveats be published, even if co-authorship is declined." The philosophy in the Data Policy is that the mistakes in a paper are the responsibility of the author, not the provider, and open data is open. It is highly recommended that authors consult with providers, but an offer of co-authorship is not required.

CIPS Level 3B: Seasonal Movies on the LASP website: “Not found.” CIPS Level 3A: Daily Daisies on the LASP website: “Not found.” Given how easy these were to find, it is likely there are many others.

CIPS Level 2, Orbit Strips: "Can’t open page." Same for “Documentation”

One interface has awkward data access via a calendar that requires finding and clicking each file. It seems that email to a person is the only route to larger requests. There are a variety of variegated access routes, none of which seem to be as easy as ftp access from SPDF would be. On LASP AIM-SIPS one has to guess what intervals will be available. In one case, “Downloads are limited to 1 month at a time. If you need more than one season, please contact us for assistance.” This should be made easy?
AIM read routines all seem to be “quick looks.” There don’t seem to be any IDL or other analysis routines, although the MAP says they are available. It is not clear how a user could generate the plots and images found on the various sites based on what is provided. Presumably such software exists. Whatever is used by the team should be available to other users.

It’s very difficult to find simple descriptions of what is in the data products in many cases, although complete descriptions can be found.

SOFIE plots: It takes about ten clicks to get to a plot. There are numerous existing ways to make this easier.

The metadata are not SPASE metadata, but just something similar. Help is available to update this.

Overall Assessment

Based on the mission performance during its prior extended phase and the feasibility and promise of its upcoming operational phase, the AIM mission is ranked 8 of 16 missions, and is considered to be **Excellent/Very Good**

Based on its contributions to, and role it plays in achieving the goals of the Heliophysics System Observatory, the AIM mission is ranked 14 of 16 missions, and is considered to be **Very Good**.

Mission Specific Recommendations

Although the AIM mission is providing quality data products and documentation, it would be beneficial for these be served directly from the SPDF Final Archive.

Geotail

Mission Synopsis

Geotail science instrument suite consists of six plasma, energetic ion composition, and fields (both electric and magnetic) instruments. Geotail has been in a 9 x 30 Re equatorial orbit since February 1995, placing it in regions where it passes through all boundaries through which solar wind energy, momentum and particles must pass to enter the magnetosphere. Geotail makes observations that define the location and physics of tail magnetic reconnection and particle acceleration.

Scientific Merit (Criterion A)

Geotail is a low-cost mission that will provide a highly valuable contribution to the HSO. The Geotail orbit is ideal for measuring the mid-tail dynamics, including the field and flow properties associated with near-Earth and distant reconnection. The 9x30 Re orbit also allows Geotail to spend a significant amount of time skimming the dayside magnetopause and measuring dayside reconnection, and skimming the dawn and dusk boundary layers that are key regions of magnetosheath plasma entry and energy coupling with the solar wind. In addition, when apogee is in the dayside regions, Geotail will spend 35% of its time in the solar wind, enabling the accurate measurement of the solar wind conditions that are driving the magnetosphere.

The perspective Geotail provides of the upstream solar wind is very different from ACE owing to its location nearer to Earth when in the upstream Solar Wind (SW). Therefore its SW measurements provide complementary observations that are frequently important in understanding SW-magnetosphere interactions

Multi-spacecraft studies are recognized as a very exciting and a powerful tool for understanding the space environment. The Geotail team realizes that Geotail, together with MMS, THEMIS/ARTEMIS and ground-based networks, can contribute significantly to this novel way of looking at magnetospheric dynamics. Five PSGs are based on multispacecraft studies. The 6th PSG is accomplished with Geotail data alone to conduct long-term studies of magnetospheric processes

The specific extended mission PSGs are:

- Long-term trend of magnetospheric processes (PSG #6)
  - Crucial for understanding localized or transient phenomena (e.g., substorm, storm)
  - Important to reveal the trends and construct models for recent relatively quiet solar cycles
- Conjunctions with MMS and THEMIS/ARTEMIS (PSGs #3-4)
  - Multiscale measurements of magnetic reconnection, Kelvin-Helmholtz instability, etc.
- Conjunctions with ARASE(ERG) and Van Allen Probes (PSGs #1-2)
  - Particle injection into radiation belts & VLF wave excitation
  - Role of ultra low frequency waves in particle acceleration & radial diffusion
- Conjunctive observations with other satellites in HSO (PSG #5)
  - Energetic particle leakage

Scientifically, mission impact has been high as revealed by a mission-long publication count of 1150 publications. Over the past ten years the annual publication rate has leveled off to between 25 and 50 per year.

Data collection, archiving, distribution, and usability Over the years, close collaborations have developed among the Japan and US groups, spurred by more modern technology. Geotail data handling has evolved and data from the 6 experiments on Geotail are now available from a variety of sources as described in the proposal. Today's large storage devices and easy data transfer via the Internet make Geotail data widely available to scientists worldwide. Geotail data are readily available via CDAWeb, the Japanese DARTS, and US Web sites. SPDF/CDAWeb, DARTS and STARS also serve as active archives

<u>Relevance and Responsiveness to the Call (Criterion B)</u>

The Geotail extended mission proposal is responsive and relevant to the call.

Geotail's science contribution is relevant to the research objectives and focus areas described in the SMD Science Plan, to the scientific goals of the Heliophysics Division as defined in the Division's Strategic Objectives, and to the 2013 Heliophysics Decadal Survey.

Since Geotail was last considered in the 2008 senior review, the panel has been unable to track progress on specific scientific goals that were anticipated approximately a decade ago. Nevertheless, as described in Criterion A, above, Geotail's importance to the HSO is perhaps enhanced relative to the past owing to its potential to add to multipoint observations as MMS, Van Allen Probes have come on line, and as continued operations of THEMIS/ARTEMIS are being folded into the HSO.

There were no findings in the 2008 Senior Review that needed to be addressed.

<u>Technical Capabilities and cost reasonableness (Criterion C)</u>

The Geotail spacecraft remains very healthy after more than two decades in space (launched in 1992). Geotail has been continuously operated for more than two solar cycles. Although all the fuel has been exhausted, the spacecraft system is still in good condition and most of the onboard science instruments are in normal operation. Gradual degradation of batteries and solar arrays is being continuously monitored and are projected to remain viable for another 10 or more years.

Geotail was last considered in the 2008 senior review. Changes to instrument and spacecraft status since then include the loss of one of the two s/c tape recorders, which failed on December 25, 2012.

There is no reason to believe that the spacecraft cannot operate for many more years. The two U.S. instruments along with all other Geotail instruments, with the exception of the high-energy particle instrument, continue to provide excellent data. The US instruments are the Comprehensive Plasma Instrumentation (CPI) and the Energetic Particles and Ion Composition (EPIC) instrument.

Geotail operations are supported by Japan. ISAS/JAXA has approved the Geotail operation extension until the end of March 2019. The present extended mission proposal requests NASA's continuing support for Geotail-specific DSN data download operations and minimal funds to support two US instrument investigations. The current data coverage (~85% of time) is possible only if data are received by NASA's DSN. Only 10% of Geotail data comes through JAXA ground stations.

<u>Cost Realism.</u> The in-guide request seeks operations costs that are reasonable and appropriate in view of the scientific merit of Geotail's continued participation in the HSO. For FY18-FY22 some inflation adjustment to continue the production of Geotail data has been requested. The in-guide budget would only fund the mission operations (ground system) and project science support at GSFC necessary to continue the operations of the Geotail mission and does not include support for the two US PIs to monitor their instruments and produce/validate Geotail data. (The proposal points out that funding to support US Instrument PIs has not been in the in-guide budget since the last Geotail senior review in 2008, although HQ has been providing funding at constant level of ~ $100k/year to each US PI from other sources.)

Relative to the in-guide budget, the overguide request represents additional funding to support two US instrument PIs for instrument monitoring and data reduction/validation, as well as scientific research. The PI overguide is comprised of two components: 1) A portion for data processing for the two US PIs, which is inflation-adjusted amount at ~ $125k/year/instrument (FY18), represents an essentially constant level of fund since 2008. Such level of support will minimally allow them to continue to monitor their instruments and produce Geotail data for the scientific community. 2) A portion for scientific research for the two US PIs, which is at $17k/year for U. Iowa and $31k/year for JHU/APL (FY18), allowing them to conduct scientific research in association with Geotail data validations.

The panel feels that the requested overguide is reasonable and is a cost-effective use of HSO funds.

Contribution to the HSO

Multipoint observations are crucial in the quest to understand and predict the geospace environment. Geotail is well positioned to support MMS, THEMIS/ARTEMIS and Van Allen Probes in their respective extended missions. Geotail's contribution includes unique Solar Wind and mid-tail measurements that full complement other elements of the HSO.

Geotail data represents a continuous, and continuing 25-year record of measurements that continues to be widely used by the worldwide scientific community. The strong involvement of the Japan Geotail community brings significant value to the HSO that comes that comes without additional costs from the U.S.

Mission Archive Plan

Geotail is a joint NASA/JAXA mission, but over the years the degree of sharing between the two parties has increased to the point that data are being prepared for and served from both CDAWeb and DARTS. [NSSDC is named, at times, as the parent of CDAWeb rather than SPDF, but there is no functional confusion. NSSDC is improperly identified as the US Final Archive, but the presence of the data at CDAWeb means this is not a problem.] The US CPI data has been progressively improved such that now it includes not just high-resolution moments but also particle distribution functions. The other US instrument (EPIC), as well as the data from the Japanese instruments, either are or are planned to be at CDAWeb. Japanese sites provide specialized tools (via DARTS and STARS) for analysis in a multi-mission context complementary to that of the US instruments. The above, along with extensive documentation, ensure that Geotail data will be well archived for the long term.

It will be important to follow through on the plans in the MAP for completing the NASA Final Archive for Geotail, and resources should be supplied, as possible, to guarantee this is the case to the extent possible given the international nature of the mission. The lack of a schedule for some of the archiving tasks is a concern that should be addressed.

It would be useful to eventually archive at SPDF such things as the summary plots provided at the Iowa site unless these are already included in GIF-walk plots.

Overall Assessment

Based on the mission performance during the prior extended phases and the feasibility and promise of the upcoming operational phase, the Geotail mission is ranked 14 of 16 missions, and is considered to be **Very Good.**

Based on its contributions to, and role it plays in achieving the goals of the Heliophysics System Observatory, the Geotail mission is ranked 15 of 16 missions, and is considered to be **Very Good.**

Mission specific recommendations/findings

The Panel finds that it would be beneficial for the Geotail team to present a plan to NASA HQ that would enable US investigators to engage more heavily in the scientific potential of the HSO.

Hinode

Mission Synopsis

The Hinode mission was launched in 2006 as a Japan/US/UK collaboration to study transient, high-energy solar events, magnetic fields that drive solar activity, and energy transport through the solar atmosphere. After completing its three-year prime mission, Hinode was granted mission extensions in 2010, 2013, and 2015. With reference to the 2012 Heliophysics Decadal Survey Science Challenges and the 2014 Heliophysics Roadmap Research Focus Areas, the Hinode mission established four Prioritized Science Goals (PSGs) for the 2015 Senior Review:

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

These PSGs have been retained for the 2017 Senior Review.

Hinode comprises three instruments. The Extreme-ultraviolet Imaging Spectrometer (EIS) obtains high-resolution spectra and monochromatic images with 1-arcsec pixels in two wavelength bands: 17.0–21.0 nm and 25.0– 29.0 nm, sampling plasma temperatures in the broad range 0.1–20 MK. The X-ray telescope (XRT) images the solar corona with 1-arcsec pixels, rapid cadence (as short as 2 s), broad temperature sensitivity (1–32 MK), and wide dynamic range. The Solar Optical Telescope (SOT) consists of the diffraction-limited 50-cm Optical Telescope Assembly (OTA) and the Focal Plane Package (FPP), which includes the Spectro-Polarimeter (SP) and the Correlation Tracker (CT). SP is a scanning-slit instrument that obtains full Stokes (polarized) spectra of magnetically sensitive photospheric spectral lines at high angular (0.3 arcsec) and spectral (3 pm) resolution. A third element of the FPP, the Filtergraph (FG), failed in February 2016. FG comprised the Broadband (0.3–0.7 nm) Filter Imager (BFI) and Narrowband (10 pm) Filter Imager (NFI), both of which sampled the full angular resolution of the OTA. XRT images the full Sun, while the other instruments have more limited fields of view on the scale of active regions.

The proposal describes recent mission achievements with respect to each of these goals and forward investigations underway or proposed for the extension period. Hinode remains unique within the Heliophysics System Observatory (HSO) by virtue of its ability to observe magnetic fields near the smallest spatial scales achievable while also providing full-Sun coronal context over a very broad range of temperature. Hinode has forged strong and scientifically productive ties with other missions, including SDO, RHESSI, STEREO, and ground-based observatories (GBOs). The relationship between Hinode and the IRIS mission has become so close that the observing proposal structure is now merged into the IRIS-Hinode Operations Plan (IHOP). Hinode continues to expand its collaborative reach to include the NuSTAR mission, the Atacama Large Millimeter Array (ALMA), and within the proposed extension period, Parker Solar Probe, Solar Orbiter, and the 4-m Daniel K. Inouye Solar Telescope (DKIST).

Scientific Merit (Criterion A)

The multi-faceted Hinode observatory has significantly advanced the state of knowledge with respect to each of its Primary Science Goals during its prime mission and extended phases.

The Spectro-Polarimeter has redefined the state of the art for the observation of small-scale vector magnetic fields as a result of its sensitivity and high and unvarying angular resolution. These characteristics have enabled SP both to probe the physics of small-scale flux concentrations such as solar bright points and to track the large-scale behavior of polar magnetic fields through the solar cycle. High-quality SP magnetograms, combined with non-linear force-free magnetic field modeling and MHD simulations constrained by XRT and other coronal data, have provided the first rigorous tests of fully three-dimensional flare models. More generally, the Hinode instrument suite has no rival in its ability to study the magnetic topology of solar active regions.

EIS is uniquely able to provide comprehensive physical diagnostics of coronal plasma, including temperature, density, line-of-sight velocity, spectral line broadening, and abundances, all with high spatial resolution. This capability has been used, in conjunction with other HSO instruments and numerical modeling, to constrain the sources of the fast solar wind, to explore possible abundance variations through the solar cycle, to study the propagation and dissipation of MHD waves, and to characterize explosive chromospheric evaporation in flares—among many other consequential studies.

In the proposed extension period, the additional telemetry allocated to SP, EIS and XRT as a result of the failure of the FG instrument will be exploited to obtain more full-resolution SP rasters, more EIS line profiles, and higher-cadence XRT sequences. The loss of unique FG capabilities, such as Ca II images at the limb and high-cadence, high-resolution, large-area magnetograms, will preclude some studies that were previously possible; but, with serviceable data from other HSO assets to replace FG data, the observatory retains the capability to make significant progress on all its PSGs. Also, the loss of FG-enabled science can be compensated (in a rough sense) by telemetry-enabled "deep-dive" programs with the remaining, fully functional instruments.

As of February 2017, Hinode science data have been used in at least 1095 refereed journal articles from scientists in more than 20 nations. Although refereed publications have declined by about one third since their peak in 2009–2012, they are still at ~100/year and may well increase when the full effect of collaborations with IRIS, NuSTAR, and ALMA is felt. Involvement by early-career scientists remains strong, with over 80 Ph.D. theses and 40 Master's theses based substantially on Hinode data.

The Hinode mission is doing a good job of producing, documenting, providing, and archiving its data. The many and continually improving data products are made available through several portals, including the SDAC Final Archive. Extensive analysis software is provided and implicitly preserved via SolarSoft. The latter is IDL-based, but this limitation may be mitigated as SolarSoft is ported to Python (SunPy). The use of Helioviewer for at least some products is a very useful addition, as is the co-alignment database.

Currently, Hinode does not make Level-1 or higher-level data uniformly available for convenient download. Providing these data would be highly valuable to potential users who do not have access to specialized software. Although continuing calibration refinements would require periodic reprocessing and therefore impose additional effort on the mission team, this is an activity routinely undertaken by many other missions and should be strongly considered.

Relevance and Responsiveness (Criterion B)

The Hinode PSGs map closely to 2012 NRC Decadal Survey Science Challenges (DSCs) and to the Research Focus Areas (RFAs) in the 2014 NASA Heliophysics Roadmap. In particular, all the PSGs support the DSC, "Determine how magnetic energy is stored and explosively released and how the resultant disturbances propagate through the heliosphere" as well as the RFA, "Understand the origin and dynamic evolution of solar plasmas and magnetic fields throughout the heliosphere." PSGs 1-3 also support the DSC, "Determine how the Sun's magnetism creates its hot, dynamic atmosphere," and PSG 4 also supports the DSC, "Understand how the Sun generates the quasi-cyclical magnetic field that extends throughout the heliosphere." Other RFAs, including "Understand magnetic reconnection," "Understand the plasma processes that accelerate and transport particles," "Understand the creation and variability of solar and stellar magnetic dynamos," and "Understand the role of turbulence and waves in the transport of mass, momentum, and energy," are supported by one or more PSGs. In short, the proposal demonstrates strong links between nationally-defined science goals and both the achievements thus far and the plan for future investigations.

The proposal and addendum present 18 recent science results distributed across the 4 PSGs. Future work is also discussed with emphasis on synergies between Hinode and other components of the Heliophysics System Observatory. An illustrative subset of these examples is noted here.

A study of a surge in a large flare exploited Hinode (EIS and XRT), RHESSI, and SDO to show that multi-stranded loop structures are needed to explain the combined data (PSG-1). Hinode/XRT, SDO/AIA, and NuSTAR data were combined to determine the temperature profile of a microflare over a broad range, finding that the emission during the impulsive phase of this small event nevertheless extended to 10 MK (PSG-1). The ability of Hinode/XRT to reveal the hottest loops in active regions has made it a key asset for constraining non-linear force-free field (NLFFF) models of the coronal magnetic field, which are in turn critical for testing modern three-dimensional flare models (PSG-2). A recent analysis of Hinode Stokes profiles resolved a longstanding controversy about the orientation of weak internetwork magnetic fields by demonstrating that they are predominantly horizontal, in agreement with MHD simulations (PSG-2). Hinode/EIS spectra have demonstrated that some small regions near sunspots exhibit the inverse first ionization potential (FIP) effect, which heretofore has been seen only in stars with large starspots; the FIP effect is an important but not fully understood diagnostic of the source (coronal or photospheric) of solar or stellar plasma (PSG-3). One of the first Ph.D. theses to be based on joint spectroscopic observations from Hinode and IRIS found clear evidence for heating to transition-region temperatures in spicules, in good agreement with radiative MHD simulations (PSG-3). The Hinode XRT and EIS instruments have now accumulated nearly a full solar cycle of full-disk irradiance observations (PSG-4). These observations are unique in two ways: they span the full range of solar plasma conditions, extending from the chromosphere to the hottest AR plasmas; and they have spatial resolution, making it possible to study the magnetic origins of solar irradiance variability. The unique ability of Hinode SP to observe strong magnetic flux concentrations in the Sun's polar regions has brought into question the pole-peaked ("top-knot") flux distributions that have been inferred from lower-resolution synoptic data (PSG-4). It will be important to resolve this question through continued observations and future analysis of data from SP, SDO/HMI, and GBOs.

The proposal presented a wide range of prospective investigations that address each of the PSGs and are fully responsive to the Senior Review call.

The 2015 Senior Review did not include any specific findings that the Hinode mission was asked to address.

Technical Capability and Cost Reasonableness (Criterion C)

The SOT Filtergraph (FG) stopped working on 25 February 2016. After detailed analysis, the mission team, sponsoring agencies, and the Hinode Science Working Group agreed to leave FG unpowered for the remainder of the mission. The other instruments are functioning well and are fully capable of addressing the Priority Science Goals. The spacecraft functions nominally and has sufficient fuel to continue observations for at least ten more years in its current 680-km polar orbit.

The mission team has achieved cost efficiencies through adjustments such as Focused Mode operations during eclipse seasons (reducing science planning to once a week) and an automated routine for dynamically allocating telemetry. However, Hinode is a multi-faceted observatory, and its integration with the HSO requires a high level of daily international coordination. The proposed operating model is well justified and can be executed with in-guide funding.

Value to the Heliophysics System Observatory

Hinode instruments provide data in unique parts of parameter space that complement other solar missions. XRT presents a unique bridge between SDO/AIA and RHESSI, especially for studies of high-energy events that can severely impact the heliosphere and the near-Earth environment. XRT presently represents the sole HSO capability for imaging the hottest coronal plasmas. The spectral coverage of EIS is unique in the HSO but is also powerfully complemented by the chromosphere-focused IRIS spectrograph. SP provides "ground truth" measurements of the structure of the photospheric magnetic field, which for example, is viewed in only an averaged sense with SDO/HMI.

Faced with the failure of the FG instrument and constrained funding, yet expanding opportunities for synergistic observations, the Hinode instrument teams have developed new observing modes and collaborations to contribute uniquely to HSO system science while reducing planning and operations requirements. For example, SP now obtains high-cadence vector magnetic observations of a narrow field of view co-aligned with IRIS. EIS routinely takes full-disk spectroscopic observations to identify and investigate sources of the solar wind—a vital boundary condition information for the heliospheric system. A higher telemetry allocation will allow XRT to exploit fully its unique ability to acquire high-cadence image sequences of high-temperature plasma in flares and non-flaring heating events, with complementary temperature coverage from SDO/AIA.

In summary, the Hinode team has made a concerted and successful effort to integrate the Hinode Operational Plans (HOPs) with the HSO, as evidenced by over 300 HOPs coordinated with other HSO assets.

Mission Archive Plan

The Hinode mission is doing an excellent job of producing, documenting, providing, and archiving its data. The many and continually improving data products are made available through many routes, including the SDAC Final Archive. [It is incorrectly stated that NSSDC is the Final Archive for the data; NSSDC is now only a Planetary Archive. The fact that SDAC mirrors DARTS makes the issue of data safety largely moot.] Extensive analysis software is provided and implicitly preserved via SolarSoft. The latter is IDL-based, but this limitation may be circumvented as SolarSoft is ported to Python (SunPy). The use of Helioviewer for at least some products is a very useful addition, as is the co-alignment database. Hopefully the later is used in conjunction with the former.

At some point, probably sooner rather than later, it would be useful to apply "prep" routines to all the files to produce a Level 1 (etc.) product that could be used independently of specialized software. This seemingly is done already for at least some of the products. The supplied png browse data is quite helpful; these should be in the final archive if they aren't already.

Overall Assessment

Based on the mission performance during its prior extended phase and the feasibility and promise of its upcoming operational phase, the Hinode mission is ranked 9 of 16 missions, and is considered to be **Excellent/Very Good.**

Based on its contributions to, and role it plays in achieving the goals of the Heliophysics System Observatory, the Hinode mission is ranked 9 of 16 missions, and is considered to be **Excellent/Very Good**.

Interstellar Boundary Explorer (IBEX)

Mission Synopsis

IBEX was launched on October 19, 2008, with an Orbital Sciences Pegasus XL Rocket near the Reagan Test Site in the Kwajalein Atoll. IBEX is part of NASA's Small Explorers (SMEX) program, with a Prime Mission start date of February 11, 2009, and a duration of 2 years. IBEX is now proposing a 3rd extension.

The overarching objective of the mission is to explore and map the complex boundary between the heliosphere and the local interstellar medium (LISM). It does so by detecting and measuring, in near-Earth space, energetic neutral atoms (ENAs) coming from or through the boundary region and travelling inward from interstellar space. IBEX has made numerous fundamental discoveries, many unanticipated, spanning questions about the local interstellar magnetic field (LISMF) and its influences, the boundaries of our solar system, their spatial structure, and the properties of the LISM. In the 1st and 2nd extended mission (EM), IBEX continued 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.

In this, the proposed 3rd mission extension, the prioritized science goals (PSG) are:

- PSG1: What is the physical origin of the Ribbon?
- PSG2: What are the basic physical properties of our global heliosphere and how are they regulated?
- PSG3: What are the field, flow properties and composition of the Local Interstellar Medium
- (LISM), and how does it interact with the global heliosphere?

A Science Traceability Matrix is provided in the EM3 proposal, linking the PSGs to IBEX data products, SMD-Heliophysics goals, and 2012 Decadal Survey Key Science Goals.

Science Merit (Criterion A)

The IBEX team has made numerous groundbreaking discoveries and accomplishments, which address each of the PSGs. 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 pursuit to allow the resolution of the controversies that now exist concerning the global heliosphere and interstellar interactions. During the Prime Mission Phase and the first two EMs, the following was accomplished:

- Accomplishment 1: The IBEX Ribbon. IBEX discovered the completely unanticipated Ribbon emission from the first set of observations in 2009. Currently, only IBEX is capable of observing the Ribbon, providing the data needed to resolve the questions of its underlying processes, and to understand the Ribbon's broader implications for heliophysics and astrophysics. The extended mission will provide the means to test the physical processes controlling the Ribbon's formation through the solar cycle.
- Accomplishment 2: The Ribbon and TeV Cosmic Rays. During the initial observations of the Ribbon, it was realized that the Ribbon is likely ordered by the LISMF vector direction, with ENA emission coming from radial directions perpendicular to the LISMF.
- Accomplishment 3: Determination of the LISM field direction and strength. The pristine LISMF direction is offset from the Ribbon center by ~8° toward the LISM inflow direction and supports the concept that Voyager 1 is observing the draped LISMF.
- Accomplishment 4: Parallax Measurements of the Ribbon. A model-independent method was used to identify the distance from the Sun to the Ribbon emission via the parallax motion of the Ribbon as viewed from the Earth (and IBEX) as it orbits the Sun.
- Accomplishment 5: Ribbon Evolution Different than the Globally Distributed Flux (GDF) - Support for Secondary ENA Ribbon Source.
- Accomplishment 6: Asymmetric Heliosheath and Heliotail Geometry. Besides the Ribbon, IBEX observations of the globally distributed flux have provided a wealth of new insights into the structure and characteristics of the heliosheath.
- Accomplishment 7: Energy and latitudinal dependence of global ENA spectrum was established.
- Accomplishment 8: Roll-over of the low energy ENA spectrum. A roll-over in the heliospheric ENA spectrum below 0.1 keV was observed in the downwind hemisphere
- Accomplishment 9: Polar heliospheric boundary manifestations of the 11-year solar cycle was observed.
- Accomplishment 10: 11-year solar cycle and PUI extinction influences on Heliotail structure are observed.

- Accomplishment 11: Voyager 1 and a plasma depletion layer outside the HP investigated.
- Accomplishment 12: Disappearance of latitudinal ordering of the Ribbon and GDF. The first three to five years of IBEX observations revealed a clear latitudinal ordering of the Ribbon and GDF with the SW.

Further accomplishments (30 altogether) addressing properties of the Interstellar Medium and additional science observations with IBEX are listed in the EM3 proposal.

IBEX's scientific productivity has been substantial: over 260 refereed publications with more than 5500 citations, 77 new publications and 2345 citations since the last senior review, including the initial discovery papers in Science, a total of 8 papers in Science, and 25 papers in Astrophysical Journal Supplements.

Relevance and Responsiveness to the Call (Criterion B)

The IBEX 3rd extended phase is highly relevant to the SMD science plan. Each of the three 2014 NASA Science Plan Goals for Heliophysics is addressed by this phase of the mission. IBEX all-sky maps provide a fundamental source of knowledge about how our Sun's activity influences the global structure of the heliosphere and its interactions with the LISM, thereby addressing NASA's fundamental science question, "How do geospace, planetary space environments and the heliosphere respond?" to variations from the Sun and LISM.

Addressing the three Heliophysics Goals:

1. IBEX maps of the global heliosphere and energy spectra resolve fundamental dynamic processes that control the changes to our global heliosphere and the particle populations including energetic particles and cosmic rays that help define the space environment at the planets and throughout our solar system.
2. IBEX globally images the direct manifestations of solar changes at the farthest reaches of the Sun's influence in the local galactic medium.
3. IBEX determines the source of variations to cosmic rays that present the most significant hazard to long duration space travel, and over the long-term, influence Earth, other planetary systems, and their habitability.

High-quality IBEX data and user-friendly analysis tools are accessible to scientists and the public via the IBEX website, the Space Physics Data Facility (SPDF) and the National Space Science Data Center (NSSDC). The IBEX website details the mission's objectives, launch, data acquisition strategy, history, research team, educational materials, and 12 Level-3 final data product releases. These releases are archived to SPDF and NSSDC for further access via the Virtual Heliophysics Observatory.

Technical capabilities and cost reasonableness (Criterion C)

The IBEX spacecraft bus and payload are in excellent health, and an additional five years or more of operations is fully expected. Three mission-long trend analyses of the spacecraft bus subsystems and one mission-long trend analysis of the payload subsystems have been performed since launch. All indicate degradation far less than pre-launch predicts. The IBEX-Lo configuration changed in 2012, and the current settings allow non-degraded data collection throughout the period covered in the continued EM. Key life-limiting factors are radiation and battery loading due to long eclipses. Both of these were greatly minimized by the June 2011 orbit change maneuver.

The FY 2018 - 2023 budgets are identical to the current FY17 budget, so the real spending power of the mission degrades with inflation; for 3% inflation per year, a nearly 20% cumulative reduction will occur over the six-year period. In order to continue to operate the mission and to make ground-breaking science with a decreasing budget, IBEX plans to find efficiencies and reduce capabilities on the operations side and by accepting some increased risk.

IBEX remains a low-risk, low-cost mission with huge science return.

Contribution to the HSO

IBEX connects to all major components of the HSO and to other NASA missions (MMS, STEREO, New Horizons, Juno, MESSENGER, LRO) and addresses all three Heliophysics science objectives of the 2014 Science Plan for NASA's Science Mission Directorate (SMD) and all four goals from the 2012 Solar and Space Physics Decadal Survey.

Mission Archive Plan

The IBEX mission is doing a good job of producing and archiving its data. However the most recent skymaps are not easily accessed. New products are archived in multiple places as they are produced. Data are stored and served through many routes, including the SPDF Final Archive. [The SPDF Archive seems to be misidentified as NSSDC, which is no longer an HP archive.] Both low level and fully vetted final data products are produced and made available, and relevant software is part of the planned set of final products. The team will easily achieve the goal of an independently useful and complete set of products and documentation for the long term.

One possible concern is the use of just ASCII files and IDL savesets. In addition, it would be useful to consider either or both CDF and FITS as formats to provide more direct access from various software packages to be able to use the data more easily in multi-mission contexts.

The IBEX entries in the HDP need to be updated, since they only cover up to Release 3. This should be coordinated with the SPASE group at UCLA and GSFC.

Overall Assessment

Based on the mission performance during its prior extended phase and the feasibility and promise of upcoming operational phase, the IBEX mission is ranked 2 of 16 missions, and is considered to be **Excellent/Very Good**.

Based on its contributions to, and role it plays in achieving the goals of the Heliophysics System Observatory, the IBEX mission is ranked 6 of 16 missions, and is considered to be **Excellent**.

Mission specific recommendations/findings:

The panel finds that most recent skymaps are not easily accessed. The IBEX should ensure that skymaps are easily accessed and useable by the science community.

Interface Region Imaging Spectrograph (IRIS)

Mission Synopsis

The Interface Region Imaging Spectrograph (IRIS) is the highest resolution observatory to provide seamless coverage of spectra and images from the photosphere into the corona. IRIS is designed to provide spectra and images of the Sun from the photosphere to the low corona, at high spatial, spectral, and temporal resolution. It has an effective spatial resolution between 0.33 and 0.44 arc seconds, and a maximum field of view of 120 arc seconds. The IRIS consists of a 20 cm telescope that feeds far (FUV) and near ultraviolet (NUV) light into a high-resolution spectrograph that obtains solar spectra and images at very high cadence (down to 2 s) and resolution both spatially (0.3300 in FUV, 0.400 in NUV) and spectrally (3 km/s pixels), allowing flexible rastering of active region size fields-of-view. The spectral ranges for the slit--jaw are similar to those of the far--UV (4.0~nm bandpass) and near--UV (0.4 nm bandpass). The high data rate of IRIS allows images to be taken every 5-10 s and spectra every 1-2 s. IRIS is a NASA small Explorer that was launched on 27 June 2013 into a circular, Sun-synchronous, polar, low-Earth orbit. The prime mission started at the end of July 2013 and finished late July 2015. IRIS has been in extended mission for nearly 2 years since August 2015.

The primary objective of IRIS is to understand the processes that energize the solar atmosphere. Examples include: The detection of non-thermal electrons in coronal nano-flares provides new insight into mechanisms behind non--thermal energy generation specifically, which dominate in the chromosphere and corona. The IRIS high resolution spectra have shown for the first time the existence of regions of very dense plasma in the photosphere and low chromosphere that are rapidly accelerated and heated to 80,000 K.

IRIS combines observations of the solar chromosphere and transition region with advanced numerical simulations, including the development of publicly available sophisticated radiative transfer codes. IRIS science goals for the next five years will address a broad range of unsolved questions pertinent to the physics of the solar chromosphere and low corona, such as which physical processes dominate the heating of the chromosphere, which mechanisms drive white light flares and initiate coronal mass ejections, and how jets supply mass to the corona and to the fast/slow solar wind. IRIS team proposes, for the next mission extension, to continue monitoring flares and CMEs to obtain a statistical ensemble of observations required to make breakthroughs in understanding these eruptions. The following are the prioritized science goals of IRIS during the proposed extended mission:

1. Study fundamental physical processes in the solar atmosphere
2. Investigate the (in)stability of the magnetized atmosphere
3. Analyze energy and mass transfer between photosphere, chromosphere and corona
4. Quantify variations of far and near ultraviolet solar radiation over the solar cycle
5. Explore the solar-stellar connection

During its extended phase, the *IRIS* mission will focus in further developing advanced numerical simulations to improve the diagnostic value of its observations, and further strengthening collaborations with other space- and ground-based observatories.

31 refereed papers published in the 16 months since the data became public. Nearly 25 Ph. D. students worldwide use IRIS data for their dissertation. Since the last senior review, 162 refereed

IRIS-related papers published. IRIS had 8 major media events and more than 51,000 downloads by many hundreds of scientists worldwide.

Science Merit (Criterion A)

One of the most challenging problems in solar physics is to better understand the nature of solar flares and coronal mass ejections (CMEs). The subarcsecond spatial resolution combined with the very high temporal cadence of the observations makes IRIS a unique instrument for detailed studies of the magnetic field reconnection and its thermodynamic effects in flares.

During the first mission extension, IRIS has continued to provide new insight into many physical processes and discovered new phenomena that challenge current models and provide novel avenues for future research. The IRIS team proposes to continue confronting new developments of a wide range of numerical models with observations from IRIS (often specially tailored and on new targets in response to earlier findings) and other space-based (HSO) or ground-based instruments to capitalize on the promise of earlier discoveries.

Science objectives in the proposed extended phase: Through a combination of novel inversion techniques, advanced numerical simulations,and coordinated IRIS, ALMA and other ground-based observations, the US and broader IRIS team will advance our understanding of the processes, including ion-neutral interactions, that dominate the heating of the chromosphere. The IRIS team will use 37 and HSO observations and 3D numerical models to investigate the role of field line braiding in heating magnetic loops, with several HGI teams studying the effects of nonequilibrium ionization in such loops. The IRIS team and HGI teams will exploit the novel diagnostic potential of loop footpoint brightenings observed with IRIS to investigate the presence and properties of non-thermal particles in nanoflare sized events in the non-flaring corona. The IRIS team and several HGI or HGCR teams will exploit IRIS and HSO observations and 3D numerical models to advance the current understanding of reconnection in the partially ionized chromosphere, the onset of fast reconnection, particle acceleration in flares, the mechanism driving white light flares and the initiation of coronal mass ejections. Coordinated ground-based HSO and IRIS observations will be obtained by the IRIS and HGI teams to study how jets supply mass to the corona or solar wind, determine the chromospheric origins of the solar wind and how small-scale flux emergence impacts the lower atmosphere. The IRIS team will study the physical origins and cyclical variations of the Mg II index, and search for precursor signatures of the next solar cycle. The high spectral resolution of IRIS will be used by the IRIS team to benchmark stellar synthesis codes and study white light flares on other stars, addressing key issues in stellar astrophysics.

The IRIS mission provides an excellent set of searchable, accessible, and well-documented products. IRIS has considerable coordination with other missions, which is very productive. Users are provided with a number of routes to data, all well documented. The data are safe and well served.

However, whether their excellent data search tool can be preserved on a long-term basis is yet to be considered and taken adequate measured to ensure it. It is also of concern that if SDAC is already mirroring the primary IRIS archives and if not, the plan for this should be started soon rather than waiting for the end of the mission. It should be noted that NASA is no longer maintaining Resident Archives in general, and the level of resources that was expected for such efforts was never expected to be large (e.g. $50K/year for two years). This makes planning for long-term archiving somewhat more urgent than indicated in the MAP.

Relevance and Responsiveness to the Call (Criterion B)

The IRIS mission is relevant to the SMD Science Plan and for achieving NASA's strategic goal for Heliophysics to Understand the Sun and its interactions with the Earth and the solar system. The PSGs of IRIS addresses the science goals of Heliophysics Roadmap Research Focus Areas (RFAs) and 2012 Decadal Survey Challenges (DSCs) and Key Science Goals (KSGs) and the proposal provides in depth details of how each of their PSGs address these science goals.

As in the previous SR, the current Panel did not notice anything of concern regarding the spacecraft health, operations, data archival or their science goals. The panel found the *IRIS* mission to be outstanding and addressing compelling science in the proposed extended mission and the proposal well presented.

Technical Capabilities and Cost Reasonableness (Criterion C)

Lockheed Martin Space Systems Company developed the IRIS spacecraft in-house under management by LMSAL. The IRIS spacecraft and the instruments on board are in excellent health. All spacecraft systems are performing nominally with minimal intervention from the engineering staff, contains no consumables and has performed almost flawlessly on orbit so far. No subsystem shows signs of significant degradation. Attitude control, mechanisms, throughput and optical performance are expected to continue to allow IRIS to obtain data of the highest quality, and provide well-calibrated data within a few days of observing.

All the instrument calibrations have been well incorporated into the data products provided to the science community. The main challenges for the extended mission are to keep all calibrations current, and to improve their quality as future science may rely on more sophisticated analysis. Continued adequate funding of the calibration work is essential for the future scientific return of the mission.

IRIS has been managed within budget since launch. However, since the in-guide funding for FY 19-23 includes a significant drop in funding and does not correct for inflation while costs for X-band are budgeted to increase significantly. As a result, science operations funding is reduced to below 5 FTE (for science planning and coordination, data processing, archiving and validation, and calibration), and science analysis to below 3.5 FTE leading to loss of key personnel. This poses a significant risk of lower quality calibration of data, substantial cuts in coordination with other instruments, and reduces the availability of unique stably-pointed ("sit-and-stare") observing sequences (because of reduced frequency of wobble calibration). This reduction would also impact science analysis, severely cutting the involvement of early career scientists and removing support for PSGs 3-5. The over-guide request of IRIS includes inflation correction (3% per year) and support for X-band passes after December 2018.

Since launch, eight of the 14 IRIS X-band passes per day have been provided by ESA, which is guaranteed until December 2018 and may continue (on a 2-year decision cycle). Therefore we have budgeted for replacement of this downlink capability by NASA (not-in-kind, i.e., in addition to existing in-kind NEN passes) in the event ESA support is not continued. We note that while the total budget in this "Request" is Over-Guideline, it would maintain science operations and analysis (excl. X-band, incl. 3% inflation) at 75% of the prime mission budget. The higher budget of the "Request" will maintain the funding at the level required for continued availability of well-calibrated, stably-pointed spectra and images, and allow science at adequate levels to address the PSGs. If ESA X-band support continues beyond 2018, the increased costs to NASA would be modest.

International support - ESA has agreed to continue IRIS support with funding for European workshops and 8 data downlinks/day until December 2018 and the team is awaiting ESA decision on their continued support.

Contribution to the HSO

IRIS has an excellent track record of coordinating with HSO missions such as SDO, Hinode, RHESSI and STEREO. With its high-resolution images and spectra, IRIS provides a critical capability in the HSO by delivering rich photospheric, chromospheric, transition region and coronal diagnostics that no other HSO instrument can provide. During the proposed extended phase, coordinated observations with the HSO and ground-based observatories will be a primary goal for IRIS science operations.

The chromospheric and transition region spectra and images of IRIS form a perfect complement to Hinode's photospheric magnetograms and coronal spectra and images, SDO's full-disk magnetograms and coronal images, STEREO's full-disk coronal views, and RHESSI's hard X-ray observations. IRIS observations of the destabilization, response to energy release, and hot plasma in flares provide excellent high-resolution diagnostics of the reconnection process that complement the coronal observables from SDO, Hinode, RHESSI, LASCO and STEREO. Future collaboration/coordination plans include ground-based instrumentation that will soon be operational, such as the Atacama Large Millimeter/submillimeter Array (ALMA), the German GREGOR 1.6 m telescope, and the NSF-funded 4 m Daniel K. Inouye Solar Telescope (DKIST).

Mission Archive Plans

The IRIS mission provides an excellent set of searchable, accessible, and well-documented products. The considerable coordination with other missions is very useful. Users are given a number of routes to data, all documented. The data are safe and well-served.

A long-term concern is whether the very nice data search tool can be preserved; this problem should be given some thought.

It is not clear whether the SDAC mirrors the primary IRIS archives. If not, the plan for this should be started soon rather than waiting for the end of the mission. It should be noted that NASA is no longer maintaining Resident Archives in general, and the level of resources that was expected for such efforts was never expected to be large (e.g. $50K/year for two years). This makes planning for long-term archiving somewhat more urgent than indicated in the MAP.

Overall Assessment

Based on the mission performance during its prior extended phase and the feasibility and promise of its upcoming operational phase, the IRIS mission is ranked 3 of 16 missions, and is considered to be **Excellent/Very Good.**

Based on its contributions to, and role it plays in achieving the goals of the Heliophysics System Observatory, the IRIS mission is ranked 7 of 16 missions, and is considered to be **Excellent**

Mission Specific Recommendations/Findings

Findings: The Panel is aware that the majority of the IRIS over-guide request is based on the uncertainty in the continued support of ESA.

Magnetospheric Multiscale (MMS)

Mission Synopsis

The Magnetospheric Multiscale Mission (MMS) operates four spacecraft in high-altitude, low-inclination orbits in the magnetosphere, reaching an apogee that has been raised from 12 to 25 Re. One hundred instruments across the four spacecraft comprise the instrument suite spanning a wide range of particle energies, together with electric and magnetic field sensors. The primary objective of MMS is to investigate magnetic reconnection in the boundary regions of the Earth's magnetosphere, with particular emphasis on the microphysics of reconnection. This microscope view is achieved through precision control of the orbits of each of the highly instrumented spacecraft to achieve very close inter-satellite spacing in regions of expected scientific interest.

The MMS science mission commenced on Sept. 1, 2015 after six months of instrument commissioning. MMS completed its two-year prime mission in September 2017, having met all level 1 requirements. This is the mission's first proposal for extended phase operations.

The MMS mission timeline is comprised of mission Phases, each delineated by the location of the line of apsides of the S/C cluster as the cluster moves successively through different regions of geospace. Following a commissioning and several months of near Earth nightside orbits at 12 Re apogee, the prime mission Phase 1 focused on the dayside magnetopause, lasting thru early February of 2017. Apogee raise to 25 Re set up MMS for detailed investigation of tail reconnection (prime mission Phase 2), which was only completed in September 2017.

The two phases of the prime mission (dayside reconnection with apogee at 12 Re; nighside neutral sheet reconnection with 25 Re apogee) captured in total more than twice the number of quality reconnection events at specific magnetic shear orientations and density levels than needed to fulfill MMS Mission Level 1 requirements.

Extended Mission - During extended mission, lessons learned from Phases 1 and 2 will be used to implement optimum tetrahedron sizes while modifying the on-board burst quality indices to increase the number of reconnection events that are captured. Opportunity for new science to emerge from this extended mission derives from MMS apogee now being at 25 Re placing it in the turbulent near-Earth upstream region well forward of the magnetopause and bow shock when at apogee on the dayside.

The MMS extended mission has 4 Prioritized Science Goals (PSGs): (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, and (4) investigate the microphysics of collisionless shocks. The four prioritized science goals are to be accomplished in four focused measurement campaigns during each year of the extended mission as summarized in the following table.

Measurement Campaign	Spacecraft Location	PSGs addressed
A	Duskside bow shock, solar wind, and dusk flank magnetopause	1, 2, 3, 4
B	Dawnside bow shock and fore- shock region	1, 3, 4
C	Dawn flank magnetopause	1, 2
D	Magnetotail	1, 2

Scientific Merit (Criterion A)

MMS has made significant science contributions, including high impact new discoveries during its prime mission. MMS contributions provide enlightenment on the complexity of the energy flow into, through, and out of the magnetosphere. Its extreme success has provided us new understanding on the microphysics of reconnection as well as insights into other important mechanisms that govern the exchange of mass and energy through and around the magnetopause. New discoveries have been made in addition to confirmations of some theoretical predictions. The long list of discoveries and confirmations have been reported in over 400 publications including a soon to be published 60-paper special issue of the Journal of Geophysical Research (JGR). That about 1/3 of the JGR special issue papers are first-authored by members of the scientific community outside of the MMS Science Working Team is evidence of the widespread interest in the MMS measurements. More than 16 different journals have published MMS results including high-impact journals Nature, Science, and Physical Review Letters.

Since the prime mission magnetotail pass has just been completed, the first tail papers are in process. The analysis of prime mission phase 2 measurements is revealing new and unexpected insights on energy conversion in the magnetotail. Distribution function "crescents" are being seen as well in the tail reconnection, despite the difference in plasma beta with respect to the dayside. These were not predicted.

During the extended mission the focus of MMS research on reconnection will be to:

- Continue research on tail reconnection during a second tail pass using lessons learned from the first pass.
- Investigate reconnection in environments and configurations either undersampled (turbulent magnetosheath) or not available (dawnside flank) during the prime mission.
- Verify knowledge from prime mission research regarding universality and applicability to additional regimes and environments.

The expected scientific output and "return on investment" over the requested funding period is expected to be very high, as MMS continues to apply it's sophisticated capabilities into new regions of the coupled Heliophysics system not previously observed by MMS during its prime mission, including in-depth probing of the turbulent region upstream of the magnetopause (enabled by higher apogee as compared to the prime mission). There is a very high expectation of synergistic benefit to the Heliophysics Division mission portfolio by continuing operation of MMS through an extended mission phase.

Since March 2016 MMS has a completely open data set. Level 2 data are posted on a public site within 30 days of data acquisition in formats, including the Common Data Format (CDF) format that can be read and plotted with various software packages such as IDL, Python, Matlab, and Autoplot. In addition, MMS maintains a comprehensive software package known as SPEDAS (Space Environment Data Analysis System), which is inherited from the THEMIS program but which has specific procedures for MMS. MMS maintains one of the largest open data sets in space science. Calibrated data at the highest resolution are available to the science community and the general public within 30 days of acquisition. Burst-mode data is available for 33 dayside electron diffusion region encounters (EDR) with tail EDRs still being accumulated. Interest in MMS data is reflected by 55 guest investigator proposals limited to archived data (10 selected) with another AO due in 2018. Data downloads have occurred from 75 countries with numerous publications by outside scientists. The MMS team is engaging the broader heliophysics community through ongoing MMS Science Community Workshops held annually beginning in 2016.

Relevance and Responsiveness to the Call (Criterion B)

The MMS extended mission proposal was responsive and relevant to the call.

MMS science is extremely relevant to the research objectives and focus areas described in the SMD Science Plan, to the scientific goals of the Heliophysics Division as defined in the Division's Strategic Objectives, and to the 2013 Heliophysics Decadal Survey.

The extended mission offers opportunities to improve on the statistics of electron diffusion region (EDR) encounters and investigate important aspects of particle acceleration, reconnection, and turbulence that were not possible or were limited in the prime mission. Additional relevance derives from high-value synergistic measurements planned with THEMIS/ARTEMIS, Van Allen Probes, Geotail, and other operating missions

Since MMS was not included in the 2015 Senior Review there is nothing to be said about 2015 Senior Review responsiveness or actions taken. It is noteworthy that the MMS prime mission has met Level 1 Mission Requirements and has demonstrated high scientific productivity with high impact science. PSGs delineated for the extended mission hold high promise of continuing this admirable record of accomplishments.

Technical Capabilities and cost reasonableness (Criterion C)

The observatories are in excellent health. Of the one hundred instruments across the four identical spacecraft all but three are operating at their design capability. For those three instruments, operations continue, however, with minor limitations: One of four the Energetic Ion Spectrometer (EIS) has been repurposed to provide high-resolution electron measurements, one of eight Electron Drift Instruments (EDI) is limited to passive mode, and one of 16 electric-field double probes has lower sensitivity owing to a meteor impact.

Following the recently completed apogee raise maneuver, sufficient fuel remains to maintain orbits and tetrahedrons for more than thirty years, however reentry is predicted to occur around 2030. The current projection is that the planned orbit with accurate tetrahedron formations can be maintained for at least 8.5 years after completion of Phase 2B.

The MMS mission, with four spacecraft under active control to produce a tight formation in the regions of high scientific interest, and with one hundred sophisticated state-of-the-art instruments, requires highly experienced spacecraft operators and extremely knowledgeable instrumentors to maintain health and safety of the spacecraft and the vitality of the science measurements. Limitations on the amount of data that can be brought to the ground require trained scientists working daily to assure that only the most valuable data be retrieved. During the MMS prime mission this continuous-involvement, Scientist-in-the-Loop (SITL) activity has assured optimization of high value science return. Thus the four-spacecraft MMS mission as currently operated requires a cadre of highly trained individuals to produce the sophisticated measurements that are leading to scientific impacts that reach far beyond mere understanding of local heliophysical processes. Collectively, this hands-on operation has come with costs that are not out of line with the scientific value of MMS.

Contribution to the HSO

MMS has become an important contributor to the HSO as it provides detailed insight into the transformation of energy impinging on the dayside magnetosphere and the conversion of energy on the nightside. The processes driving this energy conversion are at the heart of heliospheric system dynamics throughout the connected sun-earth system. Through the synergy with other elements of the HSO, the continuation of MMS into its first extended mission phase brings high value to the HSO collaboration.

Mission Archive Plan

The MMS mission is doing an excellent job of producing, documenting, providing, and archiving its data. New products continue to be produced, enhancing the value of the mission. The many and continually improving data products are made available through many routes, including the SPDF Final Archive via CDAWeb.

While the Fast Plasma Instrument (FPI) has a complete and very well documented Data Products Guide in the CDF, it would be good to make it available on the Internet.

Some thought should be put into how features of the useful quick look facility could be preserved past the end of the mission, perhaps via SPEDAS. Sets of "png-walk" files could be produced and served by various means.

Resident Archives have not been offered in the most recent HDEE competitions; data are passing to Final Archives effectively, such that the small funding offered for RAs no longer seems useful. This policy could, in principle, be revisited.

Overall Assessment

Based on the mission performance during its just completed prime mission and the feasibility and promise of continued operations during its first extended mission the MMS mission is ranked 7 of 16 missions and is considered to be **Excellent/Very Good**

Based on its contributions to, and role it plays in achieving the goals of the Heliophysics System Observatory, the MMS mission is ranked 3 of 16 missions, and is considered to be **Excellent.**

Mission specific recommendations/findings

Recommendation: The Senior Review recommends that the MMS mission team work towards a lower overall operating cost scenario including developing a new operating paradigm employing more autonomous operations. As MMS moves through extended mission phases, and new HSO missions come on line, current requested costing levels for MMS operations would increasingly become less sustainable. The MMS team is encouraged to begin now to implement such strategies in order to smooth the inevitable transition.

Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI)

Mission Synopsis

Launched in 2002, the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) has provided diagnostic observations of high-energy processes in solar flares for the past 15 years.

These observations address the key Heliophysics goal of understanding the fundamental processes of energy release and particle acceleration in solar eruptions, both flares and coronal mass ejections (CMEs). RHESSI continues to be the only instrument providing X-ray imaging spectroscopy of solar flares (until the launch of Solar Orbiter in 2019). The single instrument makes imaging and spectroscopy measurements with a few arc second angular resolution and one- to a few- keV energy resolution at energies from soft X-rays to gamma-rays (3 keV to 17 MeV). The RHESSI team aims to achieve the missions overall science goal of understanding solar flare energy release and particle acceleration by addressing the following prioritized science goals (PSGs):

1. Evolution of solar eruptive events (SEEs)
2. Acceleration of electrons
3. Acceleration of ions
4. Origin of thermal plasma
5. Optical Sun
6. X-ray and gamma-ray sources of both terrestrial and astrophysical origin.

The last two objectives takes advantage of RHESSI's non-solar observing capabilities.

RHESSI observations have contributed to nearly 2,000 refereed papers, of which 200 papers were published during the last extended phase, over 100 Ph.D. and master's theses and about 4,000 citations per year. The RHESSI *Science Nuggets* is a novel endeavor by the RHESSI team, started in 2005, consisting of brief reports introducing various aspects of the scientific material to a technically competent audience, often including as-yet-unpublished insights. So far, there have been over 290 RHESSI Science Nuggets reported.

Science Merit (Criterion A)

During the past two years of its extended operation RHESSI has made fundamental discoveries in the areas of solar, terrestrial, and astrophysical studies. The fundamental new information obtained on the energy release, electron and ion acceleration, and plasma heating processes in flares is especially notable. Other areas where RHESSI provided significant advancement of knowledge and understanding include: global energy budget, quiescent filament eruptions, HXR emissions from CMEs, electron propagation, location and extent of gamma-ray source(s), characterization of "super-hot" flare plasma, solar oblateness, terrestrial gamma-ray flashes and cosmic gamma-ray bursts.

Since 2002, RHESSI has detected over 114,000 events, which are included in the RHESSI Flare List. Almost 22,000 of them have detectable emission above 12 keV, 610 above 50 keV, 199 above 100 keV, and 42 above 300 keV; 27 events show gamma-ray line emission. All the data and the analysis software have been made immediately available to the scientific community.

RHESSI observations are complementary to SDO, STEREO, Hinode and IRIS missions in the Heliospheric System Observatories (HSO); Fermi/LAT and Fermi/GBM in the astrophysics missions; and ground-based optical and radio observatories such as Very Large Array and Expanded Owen's Valley Solar Array (EOVSA). A recent study of the September 2017 flares using the combined data from RHESSI and EOVSA seems particularly promising. The coordinated observations with these missions have provided critical information regarding SEEs (PSG 1) and origin of thermal plasmas (PSG 4). Another significant result based on the observations made by RHESSI and Fermi revealed how electrons and ions are accelerated, trapped and transported when the solar eruptive events evolves into very large spatial scales.

The data archive contains the full Level-0 telemetry data, the RHESSI flare list, and quick look light curves, spectra, images, and housekeeping plots for the entire mission. The archive, currently about 9 TB, resides on a private server at SSL and two public servers, one at Goddard and the other at FHNW in Switzerland. RHESSI also provides an extensive documentation with comprehensive descriptions of the mission, the instrument, the science objectives, data analysis techniques, the software, and the data archive. Moreover, support personnel are available at all three data sites to guide scientists in using the software and interpreting the results. The complete RHESSI software package necessary for the analysis of all RHESSI data is available online as part of the Solar Software (SSW) tree. The software generates image cubes (in time and energy), spectra (either spatially-integrated or feature-specific), and light curves, and provides support for comparisons with data products from other missions.

<u>Relevance and Responsiveness to the Call (Criterion B)</u>

RHESSI is directly relevant to the SMD Science Plan and for achieving NASA's strategic goal for Heliophysics to "Understand the Sun and its interactions with the Earth and the solar system." It addresses the SMD Science Question – "What causes the Sun to vary?"

It was mentioned in the last SR that the primary issue regarding the spacecraft health and continued operation was the need for detector annealing but as this procedure would strain the cryocooler, it might not be possible to be repeated. The current Panel notes that the RHESSI team seems still undecided, as reflected in their proposal, whether they want to go for another annealing or not.

<u>Technical Capabilities and Cost Reasonableness (Criterion C)</u>

RHESSI seems to have some issues regarding the spacecraft health and continued operation. The team assures that RHESSI is still capable of making science quality observation and data acquisition, and though the solar array power output has declined it is not affecting the battery charging during each daylight period. However, the Panel has serious concerns about the health of the spacecraft and particularly the detector temperature. To reduce the heat load on the cryocooler and hence keep the detector temperature at the lowest possible level, RHESSI is currently operating with only two of the nine germanium detectors activated. Nevertheless, the RHESSI team expects that operations can continue well into 2019, with a possible sixth anneal sometime in 2017 or 2018, at the expense of performance but with the core HXR imaging spectroscopy capability retained. The RHESSI team ascertains that the rapid rise of the detector temperature will have no effect on their PSGs and the team will turn off the mission when they cannot detect a C-class flare any more.

However, the panel is concerned that the temperature may well increase faster than the team anticipates, making it difficult to achieve their PSGs. In Section 1.2 of their proposal, the RHESSI team estimates the number of flares that will be detected above 6 keV in FY 2018 and FY 2019. The panel feels that the extended mission plan should be reassessed if the detector sensitivity decreases to a degree that the number of detectable flares is expected to be significantly lower than the estimates in the proposal.

Contribution to the HSO

RHESSI contributes significantly to the Heliophysics System Observatory as the observations are complementary to SDO, STEREO and Hinode. The coordinated observations with these missions have provided critical information regarding SEEs (PSG 1) and origin of thermal plasmas (PSG 4). RHESSI is the only existing hard X-ray imaging mission in the HSO. During the proposed extended phase of the mission, the RHESSI team aims at coordinating observations with MinXSS, NuSTAR, and ALMA in addition to EOVSA, SDO, IRIS, STEREO and Hinode.

Mission Archive Plan

RHESSI has an impressive array of products from those useful to anyone who can read FITS files to ones that require SolarSoft routines that are continually upgraded and maintained. Products at all levels are documented and plans are in place to improve these as needed. Innovative approaches such as visibilities will further increase the value of the data. The longevity of SolarSoft provides a way of maintaining the RHESSI software into the future, and the team has given considerable thought to the possible transitioning of routines to Python (a problem that needs to be address by many groups).

One concern is that there is frequent mention of a “Resident Archive” phase; this is not a routine part of the current HP plan, and it was never a part of the plan at the level of $1M/year. It would seem that the team should work on beginning the transition to an archival state now, before the end of mission. A number of efforts already support this, but either an agreement needs to be worked out for RHESSI to have a two-year ramp down phase or earlier planning needs to take place. It is admirable that this mission has explicitly taken on issues such as the preservation of tools that many missions have largely ignored.

Overall Assessment

Based on the mission performance during its prior extended phase and the feasibility and promise of its upcoming operational phase, the RHESSI mission is ranked 15 of 16 missions, and is considered to be **Very Good.**

Based on its contributions to, and role it plays in achieving the goals of the Heliophysics System Observatory, the RHESSI mission is ranked 13 of 16 missions, and is considered to be **Very Good.**

Mission specific recommendations/findings

Recommendation: Based on the mission evaluation the panel recommends to (1) develop an end-of-life plan and present to HQ in 2019 prior to the next Senior Review call, and (2) begin archiving data now in anticipation of end-of-life.

Solar Dynamics Observatory (SDO)

Mission Synopsis:

The Solar Dynamics Observatory (SDO) is a LWS flagship mission, with three instruments on-board. The Heliosesmic and Magnetic Imager (HMI) is an imaging instrument, which takes full-disk Doppler- and magneto- grams with which helioseismic analysis and magnetic field estimates (both line-of-sight and vector) can be obtained. The spatial sampling of solar disk is done at 0.6", with cadence of 45s (Dopplergrams and line-of-sight magnetic field maps) and 12 min (vector magnetic field maps). The Extreme-ultraviolet Variability Experiment (EVE) provides EUV spectral irradiance measurements in the Soft X-ray (0.1—10nm) and EUV (10-122nm) wavelength intervals, with up to 0.25s cadence and moderate spectral resolution; EVE also includes a low-resolution Solar Aspect Monitor (SAM) that provides full-disk context images. The Atmospheric Imaging Assembly (AIA) captures full-disk coronal images in 7 wavelength regimes every 12 seconds at 1" resolution and two chromospheric-wavelength images alternating between 12 second cycles. The SDO is in a geosynchronous orbit with near continuous science downlink.

The prioritized science goals (PSGs) presented in SDO proposal emphasize seven broad areas of particular importance in solar physics.

PSG 1: Tracking Subsurface Flows and Structures as Activity Fades
PSG 2: Magnetic Variability and the Solar Cycle
PSG 3: The Magnetic Connection Between the Sun and the Heliosphere
PSG 4: Revealing the Fundamental Physics of Solar Eruptive Events
PSG 5: Understanding Solar Drivers for Geospace and Planetary Atmospheres
PSG 6: SDO Cooperative Research for Heliophysics and Astrophysics
PSG 7: Special Observing Opportunities and Rare Events

During its first Extended Mission, SDO continued taking a comprehensive set of solar observations needed by the community. Definitive data products are routinely generated along with some "near-real –time" (NRT) products that are useful for scientific research, space weather applications and also as a broad context information in operations planning for other solar missions. The team enabled easy access to the data by developing tools for browsing, searching, and exporting subsets of data from the SDO Data Centers. SDO made significant progress in addressing five previously identified PSGs including developing better understanding of large-scale subsurface flow patterns, the relation between properties of subphotospheric flows and the photospheric magnetic fields, the role of surface distribution of magnetic fields in polar field reversals, wave propagation through solar atmosphere, the topology of magnetic field and its evolution from the photosphere to the corona. SDO observations played a key role in advancing our understanding of the impact of solar activity on planetary atmospheres and magnetospheres (e.g. EVE data were used as an input for Total

Electron Content (TEC) modeling and validation of EUV SSI modeling in the COSPAR Thermospheric Ionospheric GEospheric Research (TIGER) Program, for studying the evolution of Mars' upper atmosphere from the NASA MAVEN mission, and in modeling of the ionosphere of Titan), and enabled in-depth studies of the solar drivers for the ionosphere/troposphere (IT) missions in the HSO (AIM, TIMED).

The second extended mission will continue in-depth exploration of PSGs with new questions that arose from the recent research, and the timeliness of the science with respect to the phase of the solar cycle. The outcome of the mission will be enriched with addition of collaborative research in Heliophysics and Astrophysics, and special observing opportunities and rare events (planetary transits, sungrazing comets, solar eclipses).

The SDO mission plays an important role in advancing our capabilities to predict and mitigate adverse Space Weather effects of the near-Earth radiation environment. The data from all three SDO instruments are routinely provided to two centers for operational space weather forecast: NOAA's Space Weather Prediction Center (SWPC) and the forecast center run by the US Airforce 557th Weather Wing.

Scientific Merit (Criterion A)

During its first extended mission phase, SDO provided rich information necessary for characterizing the progression of cycle 24, the overall magnetic and thermodynamic environment in solar atmosphere from the photosphere to the corona, and the effects of solar activity on heliosphere and near-Earth environment. SDO improved our understanding of properties of large-scale flows and their evolution with the phase of solar cycle; explored the relation between properties of subphotospheric flows and the photospheric magnetic fields. The data were used to improve the understanding of eruptive activity (flares and CMEs) and wave propagation through solar atmosphere, the large-scale connectivity in solar atmosphere and solar irradiance. The impact of SDO on solar and space physics research is evidenced by the number of published scientific papers: about 850 articles in 2016 (about 500 in peer reviewed journals). The results from the SDO mission are routinely featured in high-impact journals, and in many major news outlets. In addition to its strong contribution to the research, SDO makes a major impact in areas of public outreach, education and promotion of heliophysics research to general public around the world. SDO data enable and support research in many areas of heliophysics, planetary studies and astrophysics.

Given the importance and timeliness of proposed PSGs, it is expected that high scientific output that we witnessed during the first extended mission will continue during the second extended mission. The data accumulated during that period will provide the complete coverage of entire cycle 24 from its rising, maximum and declining phases. These data will be indispensable for characterizing the properties of this unusual cycle, for understanding the origin of solar eruptive activity and predicting flare/CME activity and future cycles.

The mission embraced open-data policy, with data released to public with a minimum delay. Instrument teams continue being proactive in identifying and addressing the issues with the quality data.

Relevance and Responsiveness (Criterion B)

The significance of SDO science to the Heliophysics Science Program is reflected in the 2014

Roadmap for Heliophysics, which identifies SDO as important to 9 of the 13 Roadmap Research Focus Areas and 11 of 12 Heliophysics Decadal Survey Challenges. SDO observations play a key role in advancing our understanding of the origin of solar activity and its impact on planetary atmospheres and magnetospheres. Overall, SDO makes strong contribution to the science goals of all four NASA SMD Divisions: the Heliophysics, Earth Science, Astrophysics and Planetary Science.

The mission made a good progress in achieving PSGs identified in the 2015 Senior Review. As the result, it has developed a better understanding of subphotospheric flows including the meridional circulation pattern and zonal flows. New approaches for far-side imaging are being tested. SDO data allowed for a better characterization of magnetic properties of active regions including active region tilt and helicity (twist) and their possible relation with helicity properties of subphotospheric flows. The team continues improving the quality of the vector field data. Progress was also made in the non-linear force free field (NLFFF) modeling and representation of coronal structures, understanding the properties of Sun's global and polar fields, and further development of the coronal dimming as proxy for detection of the coronal mass ejections (CMEs).

The 2015 Senior Review had several finding specific to the SDO. In one of the findings the Panel noted that the SDO mission was designed and built to an extremely tight data capture and quality specification dating from circa 2001. It had been suggested that perhaps, "a review of this specification, in light of NASA's extended mission paradigm, could highlight areas of cost savings in mission operations and ground system maintenance and at the same keep the data quality at acceptable levels scientifically." To partially address this finding, the team is exploring an option of transferring the ownership of one antenna dish located on the NASA White Sands Complex in New Mexico. Other finding called for a clear and thorough assessment of the orbital effects on all HMI data products accompanied by a plan for testing possible mitigation algorithms and evaluating the results. While the effect of orbital motions on HMI data remains unsolved, the team had identified some possible solutions and is working towards their implementation. Some tests (including taking observations with different orientation of spacecraft) had been conducted. This work needs to continue until proper solution or sufficient mitigation is found.

Technical Capability and Cost Reasonableness (Criterion C)

The spacecraft and instruments are healthy and continue to operate in their nominal science mode with no new anomalies identified during the First Extended Mission. The SDO-dedicated ground station in New Mexico captures the continuous stream of science data and uplinks commands to the spacecraft. The team had identified areas of potential issues and is working on mitigating such issues with planned hardware and software upgrades.

The project funding is approaching a level that might be insufficient to continue delivering high quality of data and data products at the current level. The Panel expresses concerns that under a flat funding scenario the staffing at Joint Science and Operations Center (JSOC) at Stanford University could fall below a sustainable level as early as FY2020. This may, potentially, have a damaging effect on the ability of the team to deliver the data to the community in a timely manner. In the past, the HMI and AIA teams had seen a departure of several key members, which was related to insufficient level of funding. The above mentioned hardware upgrades must be completely covered by the SDO budget, which further reduces funding availability for scientific analysis of data and development of new data products. The Panel finds that the requested modest (3%) increase in funding level is highly desirable for providing support for one additional postdoctoral researcher (in each institution) and partial support for the new SunPy software library currently developed. A compromise needs to be found to ensure a support for these efforts with the constraints of the available budget.

Contribution to the HSO

SDO is a great asset to the HSO: its full-disk imaging and high-cadence irradiance data are employed as context observations for many heliophysics missions. The data are used for missions' planning (e.g., IRIS, Hinode and future NASA's Parker Solar Probe and ESA's Solar Orbiter), to assist the data analysis (e.g., TIMED, AIM, IBEX, RHESSI, STEREO and future missions: GOLD, ICON), and to model the effects of space weather on Earth and other planets. SDO data are now the organic part of the research landscape in heliophysics. The data are used as modeling input for various parts of heliophysics system, as context information for mission operation planning, as input for space weather operational forecast. SDO promotes interdisciplinary research in astrophysics and heliophysics and its data are widely used in public education activities and outreach programs.

Mission Archive Plan

As is fitting for the mission that is producing more data than the rest of Heliophysics combined, SDO produces, documents, and serves an excellent and complete set of data products. There are many routes to the data, with guides to all of them, ranging from web service access from applications to the easy movie making capabilities of Helioviewer. The SDO mission is in excellent shape for the foreseeable future.

In this year's MAP the team has made a major step forward in addressing the question of how to make a permanent archive for SDO data. The plan envisions a multi-year Resident Archive phase. This will be unlike the small and now largely obsolete RA phase for other missions in which data already flow to final archives, often as they are made, so no RA is needed. The issue is less in moving the data, although that will take some time, and more in preserving capabilities. The plan begins the work of deciding what is essential and most cost effective, but this will clearly be an issue for some time to come. As implied in the plan, it is likely that the best route will be to decide on the final architecture and to begin to implement it well before the mission's end. SDAC is the current most obvious choice for a Final Archive, but it will not look the same after it acquires its new role. We can only hope that what we learn from this will help with DKIST.

Overall Assessment

Based on the mission performance during its prior extended phase and the feasibility and promise of its upcoming operational phase, the SDO mission is ranked 1 of 16 missions, and is considered to be **Excellent/Very Good.**

Based on its contributions to, and role it plays in achieving the goals of the Heliophysics System Observatory, the SDO mission is ranked 1 of 16 missions, and is considered to be **Excellent.**

Deleted: 5

Mission specific recommendations/findings

Finding: SDO is a valuable asset to the Heliophysics System Observatory. It provides a breadth of observational information that will enable cutting-edge investigations; the data are presently used by many NASA Heliophysics missions, as well as for near-real-time space-weather forecasting by other

US and international agencies.

Recommendation 1: It is recommended that for the next Senior Review the team provide a separate number for publications that derive scientific discoveries principally from SDO data, as opposed to papers in which SDO is referenced in general or as context. While the total number of annual publications associated with SDO project is impressive, the Panel feels that in order to better evaluate the impact of SDO data on research in Heliophysics that this recommendation should be implemented

Recommendation 2: The Panel recommends that an assessment of the mission requirements, including operations and data timeliness, be made with the intent of reducing mission costs. The panel expresses a concern regarding stated negative impacts of flat funding profile on spacecraft operations, data acquisition, data calibration and data processing described in the proposal under in-guide funding levels. This recommendation if implemented will alleviated the impact of the funding profile.

SOlar TErrestrial Relations Observatory (STEREO)

Mission Synopsis

The SOlar TErrestrial Relations Observatory (STEREO) is part of the NASA Solar Terrestrial Probes program (STP). Launched in 2006, it consists of two identical spacecraft in ~1AU solar orbits with STEREO-A moving ahead of Earth and STEREO-B trailing behind. The mission provides the first-ever stereoscopic images of the corona and heliosphere and acquires in-situ solar wind observations over a wide longitudinal range. STEREO carries multiple imaging instruments to record the solar corona in four EUV wavelengths, the white light corona from 1.5 to ~15 Rsun, and the first-ever images of the heliosphere out to ~1AU. Two in-situ instruments measure the interplanetary magnetic field (IMF), solar energetic particle (SEPs), solar wind plasma, alphas and heavy ions. A radio burst tracker covers a wide range of frequencies.

The primary mission science goal focused on the 3-D structure of coronal mass ejections (CMEs) that are a major driver of space weather. STEREO completed its prime mission phase in January 2009. The prioritized science goals (PSGs) of the current extended mission take full advantage of the unique orbital positions of STEREO in the extended phase. The PSGs fall into three broad categories:

PSG1: Understand space weather throughout the inner heliosphere
PSG2: Study the corona over 360 degrees
PSG3: What can we learn from full heliosphere coverage?

There has been significant progress on all PSGs. Use of STEREO data has resulted in many scientific findings, a few of which are included in this document. Multipoint STEREO imaging, combined with observations from L1, have shown the topology of flux ropes relative to the outer shell of a CME and provided reliable estimates of CME trajectories in interplanetary space. STEREO in-situ observations have shown that CMEs continue to evolve dynamically as they interact with surrounding solar wind structures. STEREO has detected CME-shocks with wide longitudinal extent, which has important implications for understanding and predicting SEP events. STEREO (along with observations from SDO) has made possible the first 360-degree view of the solar corona that has led to the discovery of ROSSBY waves on the Sun and provided unambiguous determinations of solar structure lifetimes. Combined STEREO and Voyager data have shown that the very energetic CME of July 2012 generated a solar system scale 'tsunami'. PLASTIC data have yielded pitch-angle distributions of heavy pick-up ions that do not show the expected mass-per-charge dependence from standard wave-particle interaction theory.

STEREO-B operation was lost in 2016. Impacts on the mission are discussed under Criterion B. STEREO-A is still able to provide some 3-D information about the Sun, CMEs and solar wind in conjunction with SDO, LASCO and other Earth-Sun line observations. STEREO continues to provide the only far side view of the Sun, currently imaging 2/3 of the far side disk. It is approaching the L5 point making it uniquely and ideally positioned to view Earth-directed CMEs and provide a test bed for optimizing future L5 missions. STEREO will also provide unique observations for the upcoming Parker Solar Probe (PSP) and Solar Orbiter (SO) Missions.

Science Merit (Criterion A)

STEREO has revolutionized our ability to consider and understand the Sun and heliosphere as an integrated system. Its unique location and capabilities (e.g. heliospheric imagers) have made possible new investigations into the structure, evolution and origins of the solar wind. Multipoint CME observations from STEREO have improved the Space Weather Prediction Center forecasts of CME arrival times by 6 to 7 hours. *STEREO is the only mission able to view the far side of the Sun.* Full sun coverage has led to the discovery of ROSSBY waves on the Sun, recently reported in Nature. It has advanced our understanding of CME evolution in the solar wind. Full Sun observations have been used to demonstrate that active region lifetimes are self-similar and their light curves scale directly with their peak He+ 304 A emission. The directional finding capability of the STEREO S/WAVES experiment has been extremely useful in understanding the dynamics of shocks and electron beams.

The PSGs in the next extension phase will take advantage of STEREO's unique location approaching L5 to study Earth directed CMEs, and provide (in combination with SDO) near full coverage of the solar EUV corona in the approach to minimum activity. STEREO results from the new extension phase should be significant. Observations from STEREO's unique location will enhance scientific return from the upcoming PSP and SO missions. Near-Sun observations from PSP and SO used with STEREO data at 1AU can help constrain models of particle acceleration and transport, and further our understanding of suprathermal seed populations.

STEREO data are widely used by the community. There are 1434 refereed publications using STEREO. Community use of the data continues to be very high. All STEREO data are available to the community from the STEREO Science Center (SSC), the Heliophysics Data Portal and the VSO. Beacon data provide near realtime observations from the STEREO webpage and are an integral component of Space Weather Prediction Center forecasts. PLASTIC and IMPACT data are also accessible from the VHO. A number of online browse tools, interactive plots, and movies are available. Mission documentation is in a special issue (V 136) of Space Science Reviews. Data analysis software is available from the Solar Software Library. The emphasis is on IDL software but source code for other languages is also distributed. Software documentation can be found from the SSC page from the 'software' link under the 'Analysis' sidebar. Documentation is accessible under the individual instrument links.

Relevance and Responsiveness to the Call (Criterion B)

STEREO science plan and strategic objectives are directly relevant to many of the research focus areas of the Heliophysics Roadmap, 2014-2033. STEREO has played a major role in developing the capability to predict the onset of hazardous space weather events at Earth and directly led to improvements in space weather forecasting of solar disturbance arrival times. STEREO observations are helping to characterize space weather effects are providing a better understanding of the origin and dynamic evolution of solar plasma and fields in the heliosphere. STEREO has contributed to better understanding of the plasma processes that accelerate and transport particles, and understanding the role of turbulence and waves in energy and mass transport.STEREO detected nanoscale dust particles in addition to the known families of micron-sized dust. The levels were significantly different between the orbital positions of STEREO-A and STEREO-B. STEREO-A will be traversing the flight path of STEREO-B on the next extended mission enabling it to reassess the nanodust measurements in that locale. Identifying and assessing a new population of dust is directly relevant to Heliophysics decadal survey goals.

STEREO-A trajectory is bringing it back toward Earth, resulting in an increase in telemetry. In addition, the loss of STEREO-B has allowed that telemetry to be used by STEREO-A providing more cadence for observations and enhancing science discovery possibilities.

The 2015 Senior Heliophysics Review panel assessed the potential impact of the loss of STEREO-B on the mission. The panel found that STEREO-A can provide good coverage to complete scientific objectives and, alone, is a valuable asset to the Heliophysics Observatory. The demise of STEREO-B translates into a loss of observations of SEP events originating on the west limb of the Sun as well as a loss of multipoint observations from SWAVES. It also reduces full 360-degree coverage of the Sun. The current coverage from STEREO and AIA is ~300 degrees. Impact on mission goals is small.

Technical Capabilities and Cost Reasonableness (Criterion C)

The STEREO-A spacecraft is healthy, aside from the loss of the primary Inertial Measurement Unit (IMU). The four reaction wheels and Sun sensors are nominal and the propulsion systems retains ~50 years of fuel for momentum management. The spacecraft is operating in gyroless mode. Solar panel performance remains nominal. All SECCHI instruments are operating. The team is addressing two COR1 minor issues that do not otherwise effect observations. SWAVES and IMPACT are functioning nominally. PLASTIC had a 10 mA reduction in the current, but it does not impact solar wind measurements.

The budget for a one spacecraft mission is sufficient to operate in the next extended phase due to the loss of STEREO-B. The team, along with APL mission operations, is able to produce some cost savings for a single-spacecraft mission. The STEREO team is seeking cost-of-living increases for the extended mission. At this time, all teams need to work within a fixed cost budget. There does not appear to be extenuating circumstances that warrant an increase in funding at this time.

Contribution to the HSO

The unique vantage point of STEREO and its unprecedented views of the heliosphere make it a key component of the Heliophysics System Observatory (HSO) fleet and expand the fleet's scope through the inner heliosphere. STEREO has strong synergy with the HSO fleet. STEREO is an identified contributor to multiple ongoing scientific investigations by 11 of the 15 mission teams participating in this review. STEREO provides the additional line-of-sight observations that significantly improve space weather forecasts of CME arrival times, which is a primary goal of the heliophysics progam. Its trajectory is bringing it toward the L5 point, making it ideally suited for observing Earth-directed CMEs. STEREO data continue to produce scientific discoveries, such as the recent discovery of ROSSBY waves on the Sun. Observations from STEREO will enhance the scientific return of the upcoming PSP and SO missions.

Mission Archive Plan

The STEREO mission is producing data and making it readily available for all of its in situ and remote sensing instruments. The STEREO Science Center at SDAC is preserving all the data products, and serves the SECCHI images. The in-situ data is served from instrument sites, but most of it is also already at and served by SPDF/CDAWeb. SolarSoft/VSO access and CDAWeb access provide web service connections to the data. Generally, the STEREO archives are in good shape, although it can be difficult to find specific items (e.g., link to the SSR special issue). The use of SPEDAS (TPLOT) is a plus, as are the many images and movies from NRL. It would be good to archive the "Level 2+" products from NRL.

Some concerns:

Some Level-3 event list products are currently in pdf and Excel. HP has put together a standard for such event lists, in ASCII, but this has not been well advertised, so it is not surprising that it is not implemented here. (See http://spase-group.org/docs/.) There is a helpful page that links to STEREO Event Lists but it does not seem to include the ICMEs and other events that are mentioned in the MAP (under IMPACT).

There is no simple location that points to detailed documentation; the SSC page gives links, but many are to low level explanations. Considerable information is seemingly in the headers to CDF files, and while this is useful, it is not obvious to the user that is where to look.

Many sites do not spell out acronyms, making it sometimes difficult to get the big picture. Also, the link to the EUVI page did not work.

Overall Assessment

Based on the mission performance during its prior extended phase and the feasibility and promise of its upcoming operational phase assuming only STEREO-A is operating, the mission is ranked 10 of 16 missions, and is considered to be **Excellent/Very Good.**

Based on its contributions to, and role it plays in achieving the goals of the Heliophysics System Observatory, the STEREO mission is ranked 8 of 16 missions, and is considered to be **Excellent/Very Good.**

Mission specific recommendations / findings:

Finding: Many STEREO websites do not spell out acronyms, making it sometimes difficult to get the big picture. The link to the EUVI page does not work:

https://stereo.gsfc.nasa.gov/instruments/instruments.shtml

Time History of Events and Macroscale Interactions during Substorms (THEMIS)

Mission Synopsis

THEMIS is a MIDEX mission consisting of a five-satellite constellation. THEMIS, a five-satellite mission, was launched in February 2007 into orbits. These orbits vary in apogee and the spacecraft regularly becoming radially aligned at distances between 12 Earth radius (R_E) and 30 R_E. After completing the prime mission in 2010, the THEMIS proposed and implemented a split into three Earth-orbiting (THEMIS-low, inside of 15 R_E) and two lunar orbiting (ARTEMIS) spacecraft groups. In 2013 the team proposed to optimized observations with MMS, Cluster, Geotail, and the Heliophysics System Observatory (HSO). During the upcoming 5 years the THEMIS/ARTEMIS team proposes to co-ordinate this resources with HSO to address questions related to the nature, regional drivers and global consequences of reconnection being the dominant driver of convection and particle acceleration in Earth's environment.

The associated prioritized science goals (PSG) are:

- PSG1: During FY18-19 the emphasis will be on understanding global connections with THEMIS "low" in opposition to MMS, Geotail and Cluster on the other side of the magnetosphere. Day-night conjunctions will explore the connections between magnetopause and magnetotail reconnection. Dawn-dusk conjunctions will explore reconnection, viscous interaction, ULF wave driving, and boundary layer formation on the flanks.

- PSG#2 goal: In FY18-FY20 THEMIS will raise its apogee to the intermediate altitude region from 13.2-15.8 RE. To explore the nature, regional drivers, and global consequences of reconnection from equatorial orbits with apogees of 13.2-15.8R_E.

During the first two years Day-night conjunctions will explore the connections between magnetopause and magnetotail reconnection. Dawn-dusk conjunctions will explore reconnection, viscous interaction, ULF wave driving, and boundary layer formation on the flanks of the magnetosphere. In FY20-22 the emphasis will be on global connections but with THEMIS "low" in conjunction (on the same side of the Earth) with MMS, Geotail and Cluster. On the dayside, this grand HSO constellation will explore the formation, evolution, driving and consequences of regional activations. ARTEMIS, at 60R_E, will provide pristine solar wind observations or magnetotail observations of lobe flux, energy transport, reconnection, and tailward flowing mass, energy, and momentum. Arase, VAP and GOES will explore from the inner-magnetosphere the consequences of regional magnetopause/tail activations together with one on more THEMIS probes during the in- or out-bound orbits.

Over the last few years THEMIS "low" and ARTEMIS have made significant discoveries that provided significant new insight in the understanding of how the magnetosphere couples to the solar wind and ionosphere.

THEMIS plays and important role in the HSO co-ordination efforts and the THEMIS software (TDAS) provides a strong support for the research community. The Geospace Environment Modeling (GEM) executive council has endorsed THEMIS's HSO optimization and coordination efforts. THEMIS was also highlighted by the 2016 National Academy of Sciences study (NAS2016).

Science Merit (Criterion A)

THEMIS "low" and ARTEMIS have made significant discoveries that illuminated and, in some cases, changed our understanding of how the magnetosphere couples to the solar wind and ionosphere. These studies provide strong motivation not only for adjusting our own mission's plans, but also for designing observation strategies for NASA's HSO, shaping NASA Heliophysics partnerships with the NSF, NOAA, and international space agencies, and informing NASA's future mission planning. THEMIS (in conjunction with MMS and ground based observations) has made significant science discoveries in its prime missions and it its extended mission phases. Most recently showed the association of bursty bulk flows with depolarization fronts in the magnetotail. THEMIS provided strong evidence that ion and electron injection associated with depolarizing flux bundles and fast flows. THEMIS provided significant new insights into the foreshock topology and foreshock structures (Foreshock bubbles, transients, and rotational discontinuities). THEMIS also revealed properties of Spontaneous Hot Flow Anomalies, sheath cavities, and dynamic pressure pulses. These findings and the Aurora investigation received significant media attention and where subjects of Journal cover pages. The success of this mission is evidenced by more than 148 publications/year in the last 3 years, including a number of articles in high-profile journals.

This extended phase is focused on conjunctions with MMS, VAP, Geotail, Cluster, and Ground Based Observations (GOBs) to investigates global reconnection phenomena, and coordinated measurements on MHD and kinetic scales. For instance, simultaneous day-night conjunctions will explore the connections between magnetopause and magnetotail reconnection. Dawn-dusk conjunctions will explore reconnection, viscous interaction, ULF wave driving, and boundary layer formation on the flanks.

Relevance and Responsiveness to the Call (Criterion B)

This extended phase is highly relevant to the SMD science plan. The goal is to understand the fundamental processes that occur in the space environment; to determine how planetary habitability is affected by solar variability, and to provide the knowledge needed to improve space weather forecasting. THEMIS targets understanding energy transformation, energy partitioning and transport at reconnection fronts, particle acceleration upstream at foreshock bubbles, and phase space density evolution in the inner magnetosphere due to wave-particle interactions. These processes are ubiquitous across planetary space environments and at the Sun, yet also have tremendous importance for space weather understanding and prediction. Finally, THEMIS is completely aligned with the recommendation of the Heliophysics Decadal Survey to enable and optimize a powerful HSO.

Technical Capabilities and cost reasonableness (Criterion C)

The THEMIS/ARTEMIS constellation is presently in excellent health and is performing nominally. All subsystems are in excellent condition (with the exception of the loss of a sphere on TH-B, which has had negligible effect on science). The technical issues that have appeared since the last senior review have been resolved and have resulted in no science degradation.

All data processing and software continue to function reliably. All flight dynamics systems are nominal. Mission design runs with the latest orbit solutions occur months in advance for nominal planned maneuvers with a quick turnaround reaffirming conjunctions, shadows, and fuel budget. Product generation based on updated ephemerides is fully automated. GSFC flight dynamics provide backup orbit solutions for each probe.

Contribution to the HSO

THEMIS contributes significantly to the Heliophysics System Observatory (HSO). It is operating inside the magnetosphere and in the solar wind and provides unique solar wind measurements. its sidereal-resonant and MMS-resonant orbits will optimize HSO science yield by enabling orbit conjunctions with ground-based observatories and MMS. Its all-purpose analysis tools enable optimal cross-mission (HSO) data analysis. The analysis tools being developed by THEMIS can ingest data from dozens of other space and ground assets. "Plug-ins" for instruments on MMS, ERG (now renamed Arase), the Van Allen Probes, GOES and POES spacecraft, >100 ground-based observatories, and all SuperDARN sites exist.

The MMS-THEMIS coordination will be used to enable an optimized HSO network.

Mission Archive Plan

The THEMIS mission is doing an excellent job of producing, documenting, providing, and archiving its data. New products continue to be produced, enhancing the value of the mission. The many and continually improving data products are made available through many routes, including the SPDF Final Archive via CDAWeb; the latter aspect largely satisfies long-term archiving requirements. Documentation is systematic, easily accessed from one location, and available in many forms. Ground based instruments are also supported, including for archiving.

The team produced the IDL-based TDAS analysis tools that have become the generally applicable SPEDAS suite, now supported by NASA as an HPDE infrastructure project; this will be a useful service to the community in many ways. Many of its features can be used without an IDL license, which opens the software to a wider community.

The THEMIS mission needs to determine how best to permanently archive documentation, but this is a common issue that must be worked on with the Final Archives.

Overall Assessment

Based on the mission performance during its prior extended phase and the feasibility and promise of its upcoming operational phase, the THEMIS mission is ranked 13 of 16 missions, and is considered to be **Very Good.**

Based on its contributions to, and role it plays in achieving the goals of the Heliophysics System Observatory, the THEMIS mission is ranked 12 of 16 missions, and is considered to be **Excellent/Very Good.**

Mission specific recommendations/findings:

Finding: the panel recognizes that the full potential of HSO science as proposed by THEMIS will likely not be possible if in-guide budget is awarded.

Thermosphere, Ionosphere Mesosphere, Energetics and Dynamics (TIMED)

Mission Synopsis

The TIMED mission was launched in 2001 with the primary goal of determining the basic states and energy balance of the mesosphere and lower thermosphere in the region between 60 and 180 km. To enable this goal, the TIMED mission has a solar flux monitor (SEE) and three earth oriented remote sensing instruments (SABER, GUVI and TIDI) designed to measure the temperature, composition, dynamics and energetics of the Earth's ionosphere, thermosphere and mesosphere (ITM). To date, TIMED has accumulated one of the most significant databases of solar and ITM measurements beginning during the second half of SC-23 (solar minimum) and continuing through the peak of SC-24. For this extension, the experiment team proposes to continue their observations through 2020, allowing the characterization of the declining phase of solar cycle SC-24.

TIMED has transformed our understanding of the ITM and its connections to internal and external influences. Having the long-term data series of TIMED measurements is critical for long-term trend studies. An extended TIMED dataset will allow the effects of natural variability (e.g. solar, weather) to be more precisely separated from the increasing trends being measured for CO_2 and other gases. Significant findings of the TIMED mission to date include observations that illustrate how tropospheric weather and climate strongly affect not only the mesosphere, but also the thermosphere and ionosphere. TIMED measurements have also demonstrated the connection between the temporal and spatial changes of ITM structure and the observed variability of the lower atmosphere and ocean, such as Sudden Stratospheric Warming (SSW) events, Quasi-Biennial Oscillation (QBO), and the El-Nino Southern Oscillation (ENSO).

The extended mission is enriched by four new measurements from the TIMED suite of instruments: 1) a new SABER H2O product, vertical profiles of water vapor volume mixing ratios extending from the tropopause to ~ 90 km, providing global H_2O time and space variations with 2 km vertical resolution; 2) a new TIDI Thermospheric Wind Product, which extends the TIMED/TIDI neutral wind measurements up to 300 km; 3) a new GUVI NO Column Density data set derived from the NO-ε band emission (172-182 nm) present in the routine GUVI spectrographic, and 4) an improved and spectrally extended SEE Solar Spectral Irradiance Product. These data products will be collected in addition to TIMED's standard data products. Calibration of these products, and in particular, the wind product should be undertaken.

For this coming extension, three Prioritized Science Goals (PSGs) have been identified by the TIMED team motivated by Goal 2 (*Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs*) and Goal 4 (*Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe*) of the 2012 National Research Council Heliophysics Decadal Strategy (HDS). These PSGs are:

(1) Investigate geospace coupling in the context of geomagnetic storms during the new era of GOLD and ICON mission operations,
(2) Determine and understand the ITM long-term decadal-scale changes and the contribution of different forcing processes,
(3) Characterize, compare, and study the differences in the ITM system behavior between two solar minima.

Science Merit (Criterion A)

The TIMED mission has been and continues to be an invaluable resource for expanding scientific understanding of the ITM system. Important discoveries and advances in understanding have occurred over the course of the mission. Publication statistics document the ever-increasing use of TIMED data by the worldwide ITM community. In 2016, the total number of refereed papers was 192 and of which 9% were first authored by TIMED team members. Over the course of the mission, more than 2100 papers with over 100 authors and co-authors have published using TIMED data products.

Understanding the causes and effects of decadal and long-term ITM changes is a fundamental goal of the extended TIMED mission. TIMED observations of thermal structure, composition, and energetics provide the requisite data needed by the ITM community to achieve this understanding. The uninterrupted continuity of TIMED measurements also provides the ability to better discriminate solar cycle contributions from the long-term decadal changes in the ITM (PSG-2). Studies of some of the least-understood ITM properties namely decadal-scale changes in the atmosphere in response to slow-varying drivers, e.g. CO_2 changes and ocean temperature ENSO cycles. will be enabled with the additional TIMED data. TIMED/SABER has also provided the first comprehensive global gravity wave climatology. Gravity wave breaking induces eddy mixing or turbulence in the MLT.

In addition, because TIMED has collected over 11-years of ITM observations, from one solar maximum to another, variations in solar cycles can be studied, as well as the periodic behavior observed in the ITM at all time scales (from hours, days, to years).

It is important to maintain continuity of record across two solar cycles for studying long-term decadal changes.

Most importantly, the extension of the TIMED mission will overlap with the new Heliophysics missions ICON and GOLD that are scheduled to launch in 2017-2018. This overlap will allow enhanced ITM studies beyond what a single mission could provide, the continuation of the ITM record without any gaps, and more comprehensive validation of the ITM record. The addition of ICON and GOLD provide high confidence for continued scientific discovery for TIMED and Heliophysics enabling new scientific inquiries.

<u>Relevance and Responsiveness to the Call (Criterion B)</u>

The TIMED phase proposal was fully responsive to the Senior Review call.

The prioritized science goals of this extended phase of the TIMED mission are highly relevant to all four Atmosphere Ionosphere Magnetosphere Interactions (AIMI) challenges listed in the 2012 Heliophysics Decadal Strategy (HDS), listed here:

AIMI-1: Understand how the ionosphere thermosphere system responds to, and regulates, magnetospheric forcing over global, regional and local scales.
AIMI-2: Understand the plasma-neutral coupling processes that give rise to local, regional, and global scale structures and dynamics in the AIM system.
AIMI-3: Understand how forcing from the lower atmosphere via tidal, planetary, and gravity waves, influences the ionosphere and thermosphere.
AIMI-4: Determine and identify the causes for long-term (multi-decadal) changes in the AIM system

The TIMED PSGs are also closely coupled to several of the Research Focus Areas (RFA) in the 2014 Heliophysics Road Map, including these three high priority targets:

STP – Lower Atmosphere Driving: To provide a comprehensive understanding of the variability in space weather driven by lower-atmosphere weather on Earth.
STP – Magnetosphere-Ionosphere-thermosphere Coupling: To determine how the magnetosphere-ionosphere-thermosphere system is coupled and how it responds to solar and magnetospheric forcing.
LWS – Geospace Dynamics Coupling: To study in an integrated fashion how the ionosphere-thermosphere-mesosphere system responds to dynamical forcing

TIMED GUVI data were recently used to improve the OVATION model, which has been an operational model used by NOAA SWPC since 2014. TIMED data can directly address issues related to long-term trends in the atmosphere, and complements other missions, e.g. GOLD by providing a complementary view of all hemispheres and high- and low-latitudes. TIMED products continue to be jointly analyzed with measurements from other HSO missions (e.g. ACE, AIM, MMS, SDO, STEREO, TWINS, and Van Allen Probes).

The last Senior Review identified these weaknesses with the mission:

"This mission is becoming a one-sensor mission with SABER as the dominant sensor. The role of the other instruments, TIDI, SEE and GUVI is limited. SEE has only a 3% duty cycle and it is not clear of the importance of SEE data to the overall mission. GUVI can only view at a single look angle and its value to the mission is limited."

In response to this, the team has attempted to resurrect the wind measurement capability on TIDI. Three other "new" measurements are being provided in the extended mission: the new SABER H2O product; a new GUVI NO Column Density data set; and an improved and spectrally extended SEE solar spectral irradiance product. These new measurements have the potential to make significant contributions to the mission.

Of the three satellites: TIMED, ICON, GOLD, TIMED is the only one that can provide high latitude measurements.

Technical Capabilities and Cost reasonableness (Criterion C)

The TIMED spacecraft, instruments, and ground systems are working well, providing operations and data flow with no loss of science data and quality needed to meet the goals of this extended mission.

The TIMED team will continue to supply the standard ITM and solar data products and continue to improve capabilities. This includes the new data products: the new SABER H_2O product; a new TIDI Thermospheric Wind Product extends the TIMED/TIDI neutral wind measurements up to 300 km; a new GUVI NO Column Density data set; and an improved and spectrally extended SEE solar spectral irradiance product.

In-guide costs are reasonable. No over-guide costs were requested.

Contribution to the HSO

The TIMED 15+ year record of the ITM and solar UV irradiance is the anchor for the HSO measurements for Earth's upper atmosphere. TIMED has accumulated a significant database of solar and ITM measurements from the second half of SC-23 up through the peak of SC-24. The experiment team proposes to continue their observations through 2020, which will allow characterization of the declining phase of solar cycle SC-24. All of the science products from each of the instruments are being produced on a continual basis. The plan is to transition all the data to the SPDF within 150 days after the end of the mission.

During the next 2-3 years, TIMED data will be used to help calibrate the instruments on GOLD and ICON. TIMED data will also help to collect data needed for long-term trend studies and for comparison of two solar minimum periods. TIMED also provides measurements of the polar auroral and high latitude region at all local solar times. ICON and GOLD do not provide data in these regions because of their orbits, however some of this information is provided by AIM, which is in a high inclination orbit.

Mission Archive Plan

Currently TIMED produces and serves many levels of well-calibrated and documented data that are used for unique scientific investigations. Distribution is through various web sites and the virtual ITM Observatory (VITMO). The plan is that the TIMED Science Data Center (SDC) will continue to be integrated with the VITMO and SPDF to support the needs of the community scientists. New products continue to be devised and produced, enhancing the utility of the mission. However, except in the case of SEE, it is not completely clear what the final archive of these very useful data will look like. A bare set of files will not be sufficient. Working with the Final Archives, and perhaps with the newly supported SPEDAS suite of tools, can hopefully lead to a set of products that will be both useful for the long term and easily used in a multi-mission context.

The SEE instrument has web pages that provide data access (albeit through a day-by-day interface and in a unique NetCDF version), a documented set of software, an organized set of documents about the instrument and data, and a nicely organized web site for access to everything. Thus, they are well situated to produce a final archive.

SABER data are available in NetCDF from an ftp site that is easy to use. They also provide a "custom data tool" for subsetting the data; this (oddly) requires a username and password, and seems to only allow four variables to be selected. It is slow to respond, although the files are probably not that large by modern standards. (One request never came back.) There seems to be very little analysis software, so it is not clear what to do with downloaded files. Working to serve data from SPDF could both enhance the exposure of the data and improve the wait times.

TIDI only provides VITMO as a link to data in the description in the MAP. See below on VITMO. A UNIX command line download is provided on a link from the main TIMED data site. It is not clear what to do with the files once accessed. TIDI has a very useful quick look plot capability that should be preserved, if only through producing a complete set of plots. Working with SPDF to serve data in the near term, rather than waiting for the mission to end, should give better results for the legacy of these data.

GUVI provides good documentation and IDL (2002) software that seems to just read the files. The most useful tool available is the GUVI online image browser, or more generally the "galleries," which worked well. This seems to be the only simple route to useful data products, and it is essential to preserve the "gallery" capabilities in a long-term archive. A simple approach would be to produce and archive high-resolution image files of all the galleries, which could be presented in a number of ways. There is a discussion of what sound like very positive improvements in GUVI products for "version 13," but no clear source of software. It is possible to find links for files of data, which work to bring data to the user, but it is not clear what to do next. As with the other instruments, working to serve data from SPDF/CDAWeb before mission end would be helpful.

The TIMED data policy states: "Users that wish to publish the results derived from AIM data should normally offer co-authorship to the PI" This is not what is in the HP Data Policy, nor is "Investigators supplying data or models may insist that such caveats be published, even if co-authorship is declined." The philosophy in the HP Data Policy is that the mistakes in a paper are the responsibility of the author, not the provider, and open data is open. It is highly recommended that authors consult with providers, but an offer of co-authorship is not required.

VITMO is described as a major portal for TIMED data distribution. A number of VITMO searches for GUVI data came up empty. There was no obvious way of finding available time ranges. A search for ACE MAG data came up with HDF files, which are never used, whereas a SWEPAM data request came up with parameter by parameter gif files. A query for all TIMED quantities yielded nested lists of files in various formats, which had to be downloaded one file at a time or all at once as a zip file that did not unzip properly. When downloaded, a TIDI file came through as "Unknown.dms." The TIDI LOS file was 168MB of what was seemingly some unknown binary format, although it said "CDF" at the top, so it was presumably NetCDF. No preview plots or images were available for any of the products. It is understandable that software (VITMO) that has not been funded for some time does not work efficiently, but it should not be advertised as if it provided a particularly useful service. VITMO provided some useful beginnings, but at this stage working with standard formats, APIs, and tools will be more helpful. This process should be initiated with SPDF and perhaps with SPEDAS.

Overall Assessment

Based on the mission performance during its prior extended phase and the feasibility and promise of its upcoming operational phase, the TIMED mission is ranked 11 of 16 missions, and is considered to be **Very Good.**

Based on its contributions to, and role it plays in achieving the goals of the Heliophysics System Observatory, the TIMED mission is ranked 10 of 16 missions, and is considered to be **Excellent/Very Good.**

Mission specific recommendations/findings

Finding 1: The overall assessment of the TIMED mission is positive. The mission will continue to provide valuable ITM data and will support the upcoming GOLD and ICON missions

Finding 2: There are still issues with the TIMED NetCDF formats and with the final archive strategy. Ongoing discussions with SPDF on these topics should be continued.

Recommendation 1: The panel recommends that the TIMED mission team calibrate the new TIDI Thermospheric Wind product with ground-based wind measurements.

Two Wide-angle Image Neutral-atom Spectrometers (TWINS)

Mission Synopsis

TWINS was launched in 2008 into a molniya orbit, with an apogee of 7.2 Re to study ring currents (RC) and low altitude emissions. TWINS has discovered new global properties of geospace plasmas and neutrals, fostered understanding of causal relationships, confirmed theories and predictions based on in situ data, and yielded key insights needed to improve geospace models.

There are two instruments onboard TWINS. The Energetic Neutral Atom (ENA) imagers observe energetic neutrals produced from the global magnetospheric ion population, over a broad energy range (1– 100 keV) with high angular ($4^\circ \times 4^\circ$) and time (about 1-minute) resolution. TWINS also provides Lyman-α geocoronal imaging to monitor cold exospheric hydrogen atoms that produce ENAs from ions via charge exchange. TWINS1 is reporting no issues. However, in July 2017, there was an electronic anomaly on TWINS2. It is currently not available, but efforts are still underway to recover TWINS2. The loss of TWINS2 means there is a decrease in dimensionality and a moderate science decrease in the inversion images, but the core mission can still be fulfilled by a single imager. Additionally, the pitch angle measurements will be of a lower resolution with only one instrument.

In the coming five years TWINS will continue to observe the geospace as it responds to a sequence of Sun and solar wind drivers. TWINS is the only operating magnetospheric imager and is a valuable asset to study the long-term magnetospheric response to such an unusual solar cycle. In its extended mission, TWINS will continue to visualize 3D global ion dynamics, composition, origins, and densities. Below are the top level Prioritized Science Goals for 2018-2023.

1) The Global 5-Dimensional Ring Current
    a) Determine 3D spatial distribution of ring current ion intensity and pitch angle
    b) Determine relative importance of different physical mechanisms governing RC formation and decay
2) Ring Current and Plasma Sheet Energization
    a) Determine how RC and plasma sheet respond to different types of storms
    b) Determine how RC and plasma sheet response varies throughout the solar cycle
3) Ion Precipitation
    a) Determine global distribution of ion precipitation
    b) Uncover casual relationships linking the dynamics and energetics of precipitating and trapped ions
4) Ion Temperature
    a) Determine local time and radial dependence of magnetospheric ion temperature
    b) Discover the global dynamical connection between plasma sheet and RC temperature
5) Neutral Hydrogen Exosphere
    a) Determine global 3D spatial dependence of exospheric H atoms
    b) Understand physical processes that control the exospheric distribution
6) Ion Composition
    a) Discover the altitude dependence of ion composition
    b) Determine the dynamic linkages among, ionospheric, RC, and PS ion composition

Scientific Merit (Criterion A)

The TWINS extended mission includes eight overlapping science investigations (see below) that address twelve prioritized science goals, covering the science topics. Each investigation plays a role in achieving one or more of the PSGs, and supports several other related PSGs. The last two science investigations (#7 and 8 below) are studies with other missions including THEMIS, Van Allen Probes, MMS, and IBEX. The TWINS team has laid out a very detailed list of new science investigations, including the approach, methodology, impact, and relevance for each.

2018-2023 Science Investigations to answer the PSGs

1. ENA Inversions: Time Evolution of Pressure, Energy, and Pitch Angle
2. Observational Study of Ion Precipitation Using TWINS ENA Images
3. Ion Temperatures in the Ring Current and Plasma Sheet
4. Ion Composition: Species-Dependent Transport and Loss
5. Neutral Exospheric Hydrogen (Geocorona)
6. Global Modeling: Physical Mechanisms Controlling the Ring Current
7. TWINS plus THEMIS, Van Allen Probes, and MMS: Imaging and In-Situ Constellations
8. TWINS-IBEX: Multi-mission Magnetospheric ENA Imaging

The TWINS mission has provided observations beginning at a modest level of solar activity in 2008. The subsequent solar maximum was usually low with only a "handful" of large storms. TWINS continues to image into the declining phase of solar cycle 24 and will continue to contribute new information. The ENA imaging is an asset to the Heliophysics System Observatory (HSO) that allows for observing the response of the geospace to solar driving events.

The TWINS project is producing high-quality products that are already available through the SPDF Final Archive. The data are completely open and accessible, and thus much of the long-term archiving task is complete nearly as the data are produced.

It was not clear where to find IDL savesets and ASCII files, and, more importantly, there was no obvious link from the home page or the proposal to the lists of documentation and software in Table 9 of the proposal. Presumably the data are well documented, but that is currently not able to be assessed. CDAWeb does contain some documentation, but not much detail. Likewise, little information seems to be available on possible inversions of the data to retrieve physical variables; this would be extremely useful, despite the limitations of these procedures. The browsing tool is quite helpful. It would be useful to consider ways to retain this capability in an archive.

Relevance and Responsiveness (Criterion B)

TWINS is a valuable asset to study the long-term magnetospheric response. It is the only operating magnetospheric imager and will continue to observe the geospace environment as it responds to the Sun and solar wind drivers. Table 6 of the proposal is a detailed relevance matrix of the PSGs and their mapping to three of the NASA Heliophysics science goals, namely explore fundamental physical processes, advance understanding of solar-to-geospace dynamical connections, and develop knowledge of variability of space weather. The table also shows the mapping to two of the Heliophysics decadal survey topics, those being: determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs (response to the Sun and solar wind; variability and extremes) and discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe (particle acceleration and transport).

Described below are highlights of the previous extended mission and progress towards the prioritized science goals.

- The first 3-mission study between TWINS, THEMIS, and Van Allen Probes (RBSP) captured cross-scale structure of the ring current (*Goldstein et al.*, 2017). Globally, the partial RC intensifies and migrates. Locally, injection is bursty and structured.
- TWINS and RBSP both observed two stormtime flux peaks, each with its own pitch angle anisotropy (*Perez et al.*, 2016). The CIMI and Tsyganenko models explained the anisotropy structure.
- Low-altitude ENA imaging provided new insight into global ion precipitation dynamics and energetics during major storms (*Goldstein et al.*, 2017; *Valek et al.*, 2017). Simple physical models of ENA viewing geometry and energy loss improved low-altitude ENA analysis (*Goldstein et al.*, 2016; *LLera et al.*, 2017).
- TWINS-derived global ion temperature maps (validated with Geotail & LANL data) from 48 storms highlight dramatic system-level heating and cooling, and show clear differences between CIR vs CME storms (*Katus et al.*, 2017; *Keesee et al.*, 2017).
- New data have doubled the upper energy limit of TWINS oxygen imaging (*Delmonico*, 2015). The new analysis shows that O+ enrichment depends strongly on energy (*Valek et al.*, 2017).
- Analysis of Lyman-α imaging data revealed the solar-cycle-driven expansion and contraction of the exosphere, and found a definitive link to solar wind pressure (*Zoennchen et al.*, 2015, 2017).
- Global BATSRUS-CRCM simulations were compared with AMPERE-derived field-aligned current maps to explain why both TWINS and RBSP observed evidence of ion flux dropouts across a broad range of energy (*Buzulukova et al.*, 2017). Monte Carlo simulations modeled the pitch angle distributions of low altitude ENAs (*Goldstein et al.*, 2016).

Unfortunately, not all primary science goals from the previous Senior Review were able to be implemented. Due to a funding issue, the team reduced core science to accommodate inflation increases in operational work, dropped two science investigations and four proposed science goals (PSGs), and shut down science activities outside Goddard when FY16 funding from NASA HQ was not sent to the rest of the TWINS science team.

TWINS has gathered 4,776,895 one-minute ENA images, including 776,079 minutes of stereo viewing as of 1 January 2017. TWINS data are accessible via twins.swri.edu, and are also hosted by CDAWeb. The TWINS Mission Archive Plan has been fully implemented since the 2013 Senior Review. Since 2014 the TWINS mission has hosted the TWINS Storm Catalog at http://twinsstorms.swri.edu/, where members of the community can access highest-level TWINS analysis from an ensemble of large storms. Since 2015, improvements have been made to the content, format, and navigation capabilities. The TWINS science team has published approximately 66 peer reviewed papers, and graduated 14 Masters and Ph.D. students.

Technical Capability & Cost Reasonableness (Criterion C)

The submitted budget and In-line budget are the same, no additional budget was requested. Labor is requested for the project scientist, a contractor, instrument team, and a travel budget. The level of effort requested is appropriate for personnel to make steady progress towards completion of the proposed science goals.

The TWINS host spacecraft is expected to continue to perform nominally through the next 5-years. The ENA sensor on TWINS 1 is operating well and continues to return high quality data. In late 2016 an anomaly in the TWINS 2 electronics occurred that is still under active investigation and may be recoverable. The TWINS 1 ENA sensor and LAD continue to function nominally and are fully

Deleted: anisotropy structure was explained by the CIMI and Tsyganenko models adequate to support continued science from the TWINS mission, although with single-perspective viewing.

Contribution to the HSO

TWINS performs a special function within the HSO by providing quantitative contextual information that ties together the in situ observations while the local measurements of particles and fields provide a more detailed view into the physical processes at work.

Mission Archive Plan

The TWINS project is producing high-quality products that are available through the SPDF Final Archive. The data are completely open and accessible, and thus much of the long-term archiving task is complete nearly as the data are produced. However, the most recent image found online by the panel was January 2015.

It was not clear where to find IDL savesets and ASCII files, and, more importantly, there was no obvious link from the home page or the proposal to the lists of documentation and software in Table 9. Presumably the data are well documented, but it is currently hard to tell. CDAWeb does contain some documentation, but not much detail. Likewise, little information seems to be available on possible inversions of the data to retrieve physical variables; this would be extremely useful, despite the limitations of these procedures.

The browsing tool is quite helpful. It would be useful to consider ways to retain this capability in an archive.

Overall Assessment

Based on the mission performance during its prior extended phase and the feasibility and promise of its upcoming operational phase, the TWINS mission is ranked 16 of 16 missions, and is considered to be **Very Good.**

Based on its contributions to, and role it plays in achieving the goals of the Heliophysics System Observatory, the TWINS mission is ranked 16 of 16 missions, and is considered to be **Very Good.**

Recommendations/findings

Recommendation: It is recommended that images be posted online for the community two weeks after completion. The most recent image found online by the panel was January 2015. As an example, if images take a month to process and 6 months of data are required for each, then each image should be available online to the community within 7.5 months.

Van Allen Probes

Mission Synopsis

The twin spacecraft of the Van Allen Probes Mission were launched on 30 August 2012 to advance the goals of the Living with a Star Program and NASA's Science Plan by improving predictive understanding of how radiation belts and ring current particle populations in near-Earth space form and change in response to variable inputs of energy from the Sun. The Probes entered their prime science mission on 1 November 2012. The Probes began their extended mission on 1 November 2015 with a new overarching objective and a set of Prioritized Science Goals (PSGs) for a five-year investigation, which continue to drive the ongoing and future Van Allen Probes science activities. The overarching objective of the extended phase is to quantify the processes governing the Earth's radiation belt and ring current environment as the solar cycle transitions from solar maximum through the declining phase. The associated prioritized science goals (PSG) are:

- PSG1: To perfect understanding of the relative roles of local versus transport mechanisms of particle acceleration and the role that nonlinear mechanisms play in the acceleration processes.
- PSG2: To perfect understanding of the relative importance of precipitation and magnetopause losses of energetic particles in the inner magnetosphere and provide more definitive information about the causes and consequences of the precipitation.
- PSG3: To perfect understanding of the relative roles of global-scale transport processes and mesoscale dynamic injections in the inner magnetosphere and their respective roles in the production of geoeffective waves.

During the first two years of the extended mission the Van Allen Probes have made significant progress in addressing the PSGs, including a number of important discoveries in the physics of the radiation belts and ring current, and in advanced systems understanding of Earth's inner magnetosphere. The Van Allen Probes second extended mission will continue through the expected lifetime of the probes, roughly until mid 2019, to fully address the PSGs that would bring much closer a predictive understanding of the dynamic variability of the ring current and radiation belts.

The extended mission is enriched by a number of new elements including: (1) modified spacecraft and instrument operations; (2) a modified orbital configuration; (3) coordination with new assets of the Heliophysics System Observatory (HSO); and (4) a new updated centralized Science Gateway for interactive access to Van Allen Probes data and high-level modeling tools for data analysis, science planning, and coordination.

The Van Allen Probes, as the second Living With a Star spacecraft mission, plays an important role in advancing our capabilities to predict and mitigate adverse Space Weather effects of the near-Earth radiation environment. In the first extended mission it established close collaboration with the Space Weather Prediction Center (SWPC), which continuously broadcasts a subset of Van Allen Probes data in near-real time.

<u>Science Merit (Criterion A)</u>

The Van Allen Probes have made significant science impacts during its prime mission phase and its first extended mission phase. During its first extended mission phase, Van Allen Probes has enriched our understanding of Earth's inner magnetosphere and radiation belts. The unprecedented length of time it has been able to observe the mechanisms driving the dynamic nature of the radiation belts enables a deeper understanding of the physics of this key region of Geospace. This is evidenced by the over 350 publications, including a number of articles in high-profile journals that have received substantial press interest, such as Nature (6 articles), Nature Physics (2 articles), Nature Communications (3 articles), Science (2 articles), Physical Review Letters (2 articles).

The second extended phase is focused on quantifying the processes governing the Earth's radiation belt and ring current environment as the solar cycle transitions from solar maximum through the declining phase. Multiple collaborations are planed with existing NASA and NOAA space missions including MMS, THEMIS, and GOES, various ground observations such as HAARP and GPS networks, unique laboratory experiments at UCLA and NRL, and with soon-to-be-launched missions such as Arse (ERG), DSX, and ICON. The impact of this mission is expected to continue to be just as significant as it has been. The science return on investment for continuing the mission at a successful level will be (1) a better understanding of this key region during the declining phase of the solar cycle, (2) a valuable probe of a key region of the coupled Sun-Earth system, and (3) valuable input toward a better predictive capability for space weather forecasts.

The recent establishment of the Van Allen Probes Science Gateway in which the mission data is easily accessible to the scientific community, is expected to enable an increased number of investigations using mission data and thus, an increased number of publications.

By continuing the mission into the extended phase until the expected end-of-mission in mid 2019, a comprehensive two-spacecraft coverage of the inner magnetosphere over more than a half of the solar cycle enables for the first time, a systems understanding of the inner magnetosphere. Van Allen Probes plan to closely collaborate with other missions of the Heliophysics System Observatory, low-altitude spacecraft, and ground-based measurements, including new assets that will become available within next two years. Together, it will advance the goal of attaining predictive understanding of how Earth's radiation belts and ring current respond to varying energy input from the Sun.

Relevance and Responsiveness to the Call (Criterion B)

The Van Allen Probes second extended phase is highly relevant to the SMD science plan. Each of the 2014 NASA Science Plan goals for Heliophysics is addressed by this phase of the mission. It will continue to make progress toward exploring the physical processes in the space environment in the inner magnetosphere and radiation belts, it will make advancements in the understanding of the connections that link the Sun and the Earth, and by extension to planetary space environments around magnetized bodies, and it will enable improved predictions of extreme conditions in space that impact human and robotic explorers.

Following the success of the first extended phase, in which significant progress was made toward the prioritized science goals, a good case was made in the proposal that further progress toward achieving the prioritized science goals will be made during these last two years of operation. This is in part due to a new orbit strategy that increases the MLT separation between the two spacecraft, and collaborations with additional space-based and ground-based assets.

The Van Allen Probes second extended phase proposal was fully responsive to the Senior Review call.

Technical Capabilities and cost reasonableness (Criterion C)

The technical health and status of the Van Allen Probes spacecraft and ground system is very good. Considering the more than six-year mission operations, the instruments and spacecraft are in very good condition, with very few anomalies. The lack of fuel is anticipated to be the cause of end-of-mission, and is expected to occur in middle of 2019.

However, an adequate exposition of the impact of operating within budget guidelines was not made in the proposal or by the team presentation. It was not made clear why steps could not be taken to operate within guide while continuing to meet current mission requirements until the expected end-of-mission in mid-2019. The statement that the mission would be terminated early unless the over-guide budget was approved was made without substantial justification or discussion of possible operational adjustments that were or could be considered.

Contribution to the HSO

The Van Allen Probes mission contributes significantly to the Heliophysics System Observatory. It is the only mission operating in and focused on the inner magnetosphere and radiation belts. It collaborates in an effective and synergistic manner with many US and international space missions and ground-based assets to enable a better understanding of the coupled Sun-Earth system. The Prioritized Science Goals (PSGs) of the extended mission improve systems understanding of how Earth's radiation belts and ring current respond to varying energy input from the Sun. To that end, Van Allen Probes rely on close collaboration and coordination with other missions of the HSO, low-altitude spacecraft, and ground-based observatories. Positioned ideally and uniquely in the heart of the inner magnetosphere, Van Allen Probes serve as a comprehensive monitor of mid-latitude electrodynamics, an essential input for understanding ionosphere-thermosphere dynamics, necessary to advance the science of TIMED, ICON, GOLD, and CINDY. By addressing fundamental aspects of charged particle energization Van Allen Probes also have a strong scientific overlap with IBEX, RHESSI, and Voyager.

Furthermore, the Van Allen Probes play an important role in advancing our capabilities to predict and mitigate adverse Space Weather effects of the near-Earth radiation environment. International collaboration with receiving stations around the planet enables the extensive observational coverage of Earth's radiation belt and ring current. The data and associated analysis enables the further development of empirical and first principle models for the Earth's radiation belts. These models feed other efforts to provide space weather forecasts. The same data and analysis also feed engineering design standards that improve spacecraft and instrument radiation mitigation methodologies.

Mission Archive Plan

The Van Allen Probes mission is doing an excellent job of producing, documenting, providing, and archiving its data. New products continue to be produced, enhancing the value of the mission. The many and continually improving data products are made available through many routes, including the SPDF Final Archive via CDAWeb, thus satisfying the major requirements for producing a Final Archive.

It will be useful to seek to identify aspects of the Science Gateway that are worth preserving and/or incorporating into other tools such as SPEDAS. In addition, the publication of the Mission Book goes a long way toward providing long-term preservation of the details of the instruments and data products.

Overall Assessment

Based on the mission performance during the first extended phase and the feasibility and promise of the final operational phase, the Van Allen Probes mission is ranked 12 of 16 missions, and is considered to be **Very Good.**

Based on its contributions to, and role it plays in achieving the goals of the Heliophysics System Observatory, the Van Allen Probes mission is ranked 11 of 16 missions, and is considered to be **Excellent/Very Good.**

Mission specific recommendations/findings

The panel recommends that an assessment of the budget profile be conducted to reconcile the planned and executed 2015 Senior Review budget. If needed, this should be followed by a reformulation of the 2018-2019 budget profile that enables mission operations at a level consistent with the current operational level.

Voyager

Mission Synopsis

Voyager 1 and 2 were launched in 1977 and have been sending data for 40 years from space. After their grand tour around the planets, they entered a new phase of Interstellar mission. The Voyager Interstellar Mission explores the interaction of the heliosphere with the local interstellar medium (LISM).

Voyager 1 crossed the heliopause in 2012 and is making the first *in-situ* measurements of the LISM. Voyager 2 is in the heliosheath and is expected to cross the HP and enter the LISM within a few years. Voyager 2 will observe the heliopause at a different time and location and for the first time directly observe the plasma in the heliopause region and LISM. These new data should clarify many of the outstanding questions that remain from the Voyager 1 observations. The goal of the Voyager Interstellar Mission is to observe the environment outside the heliosphere. We already know from the measurements generated by V1 that the LISM is a very dynamic region.

Their 2017 prioritized science goals are

1. Determine the characteristics of the energetic particles, solar wind plasma, and magnetic field in the heliosheath and identify the underlying physical processes that produce these characteristics.
2. Determine the nature of the heliopause at two locations (V1 and V2).
3. Determine accurate energy spectra, composition, gradients, and pitch-angle anisotropies of GCRs in the LISM.
4. Determine the strength, direction, draping, turbulence, and evolution of the LISM magnetic field; search for the predicted magnetic sector crossing that would indicate that V1 was still in the heliosheath.
5. Determine the density, speed, temperature, and variations of the ionized component of the LISM.
6. Determine the effects of solar induced disturbances in the heliosheath and LISM.
7. Determine the effects of the solar cycle progression on the heliosheath and on generation of transients in the LISM.
8. Provide in situ observations in support of Heliospheric System Observatory studies of global heliospheric processes and mappings of the heliospheric interaction with the LISM.

Voyager 1 has observed four plasma wave events in the LISM. All of these events are associated with dropouts of GCRs perpendicular to the magnetic field, but the physics of this relationship is not yet understood. Based on V2 observations of a large merged interaction region (MIR) in 2015 we predict another plasma wave event will arrive at V1 in early 2018.

The heliosheath characteristics at Voyager 2 are very different from those observed at V1. Whereas V1 observed a slowdown of the flow and entered a quasi-stagnation region before encountering the HP, the flow at V2 has turned tailward but maintained a constant speed. Numerous energetic electron dropouts have been observed at V2 but the electron intensity was smooth at V1. Data from different heliosheath locations are critical for understanding the global morphology of the heliosheath plasma and energetic particle flows. Data from the working plasma instrument on Voyager 2 will increase our understanding of the heliopause boundary region.

In addition to the most recent data, the V1 and V2 HSH observations have provided many other surprises. Outstanding problems are the acceleration mechanism and source location of the anomalous cosmic rays (ACRs) and the role of reconnection in the HSH both near the heliospheric current sheet and at the HP. V2 data should help resolve these issues. The Voyagers are now observing the declining phase of the solar cycle and are viewing the effects of interplanetary coronal mass ejections (ICMEs), MIRs, and corotating interaction regions on the HSH and the LISM.

Science Merit (Criterion A):

Voyager is in a unique position in the Heliospheric Solar Observatory – being the only spacecraft taking *in-situ* plasma data at the boundary of the heliosphere. Its science impact is invaluable and most likely will be the only flagship mission for years to come to visit such region taking *in-situ* data. It is a discovery mission in the sense that no other mission was in that region prior. Its uncovered and continue uncovering a number of unexpected surprises. Its observations showed how little we understand the outer regions of the heliosphere. The observations at Voyager 1 and 2 do not agree showing that the heliosheath vary tremendously spatially (and temporaly). The heliosheath characteristics at Voyager 2 are very different from those observed at Voyager 1. An example are the flows that remain high, differently than the flows at Voyager 1 that decreased steadily from the termination shock. Voyager 1 also encountered a "stagnation region" ahead of the heliopause; what so far seem not present at Voyager 2. Another differences between the two spacecrafts are the numerous energetic electron dropouts that have been observed at Voyager 2 but not present at Voyager 1. Neither of these observations and differences between the two spacecrafts was predicted by theories and models.

Outstanding theoretical puzzles are the acceleration mechanism and source location of the anomalous cosmic rays (ACRs) and the role of reconnection in the heliosheath both near the heliospheric current sheet and at the Heliopause. Voyager 2 data (the only spacecraft among the two that has working plasma instrument) should help resolve these issues.

In September of 2012, Voyager 1 is believed to have crossed the heliopause. That crossing proved to be much more complex than previously thought. Voyager 1 is now exploring the local interstellar medium, in the region "mediated" by the solar wind. Such region proven to be much more dynamic than previously thought. In the last 5 years (or 18 AU ahead of the heliopause), Voyager 1 has detected several shocks (four) believed to be driven by the solar activity. Such shocks were accompanied with anisotropy in the Galactic Cosmic Rays (GCRs). Moreover, Voyager 1 is measuring the plasma conditions (such as interstellar magnetic field) that are affected by the proximity of the heliopause (such as draping). These conditions are different than the conditions in interstellar medium as we move farther away.

Future years will have exciting science: Voyager 2 is still in the heliosheath taking invaluable data that will help us understand the nature of the heliosheath. Voyager 2 will cross into the interstellar medium with a working plasma instruments what will be invaluable.

Additional data by Voyager 1 is required as it continue in its trajectory into the LISM. Voyager 1 showed that we need a better understanding of the LISM the region mediated by the solar wind. Additionally, there are current several new controversies including a) the global shape of the heliosphere; b) the direction and intensity of the interstellar magnetic field; and c) the origin of the anisotropies of the GCRs; all require additional data that will be provided by Voyager 1 and 2 in future years.

The output of papers is large. Their papers are classic papers using these unique data set sets. A large portion of the science interpretation is done the Guest Investigators not supported by the mission. Therefore, it is crucial the support of HGI program.

There is great public interest in Voyager, as evidenced by the several press releases and coverage. Examples are all the celebration around the 40th year of Voyager. https://voyager.jpl.nasa.gov

Relevance and Responsiveness to the Call (Criterion B)

Voyager 1 and 2 are the only spacecraft positioned to directly observe the boundaries of the heliosphere and to directly sample the LISM, a part of the SMD goal 2. They address directly the Heliophysics research objectives and focus areas to "study the interaction of the solar system with the interstellar medium". Additionally, they are probing micro-physics such as reconnection, turbulence and acceleration of particles in a regime of plasma different than close to the Sun (e.g., high beta plasma of the heliosheath). Therefore, they provide additional regime to probe these phenomena.

The Voyager proposal was fully responsive to the Senior Review call. The team solved most of the problems raised in the last senior review making the magnetic data timely available (although the panel is aware of the difficulty with the magnetometer working close to the noise level). In response to the previous Senior Review Findings of Special Concern, the Magnetometer Science Team was reorganized with Dr. Norman Ness continuing as Principal Investigator, and Dr. Adam Szabo appointed Task Manager with the financial responsibility for the MAG effort funded by the Voyager project. The other instruments data is also readily available.

Technical Capabilities and cost reasonableness (Criterion C)

The spacecraft will have sufficient power to operate all instruments until the early 2020s; after this time, the instruments will be turned off serially, which will extend the useful life of the spacecraft to approximately 2030.

The team solved most of the problems raised in the last senior review making the magnetic data timely available (although the panel is aware of the difficulty with the magnetometer working close to the noise level). In response to the previous Senior Review Findings of Special Concern, the Magnetometer Science Team was reorganized with Dr. Norman Ness continuing as Principal Investigator, and Dr. Adam Szabo appointed Task Manager with the financial responsibility for the

MAG effort funded by the Voyager project. The other instruments data is also readily available.

Regarding the vitality of the science team there should be training of a next generation both in the engineering side as well as in the science data analysis side. There should be direct support for training younger scientist – see recommendations bellow

Voyager mission is an "aging" mission; and therefore requires extra care in the handling of the data and output of science. Both the founding PI's; co-I's and engineers possess unique understanding of the mission that must be transferred to a younger team, who can be brought in *immediately* to chaperone the team and guarantee continuity.

The Voyager missions have generated and will continue to generate invaluable data. There is a knowledge loss and increased project risk that will occur when some long-time current flight team members are longer on the team.

Additionally, the mission has become more demanding to operate. The in-guide budget barely maintains the level of science done currently. As stated by the project "Decreasing power and thermal margins have required increased engineering effort to keep the spacecraft operating safely while maximizing the science return. In the last year, two additional part time engineers have joined the project to perform thermal analysis and system level trades. Supporting them has required a decrease in support to other areas, primarily ground system support, in order to stay within the budget envelope."

Contribution to the HSO

Its scientific impact is unique from its advantage point. Its measurements put in context and complement the global ENA maps from IBEX. Voyager has strong synergies with solar and heliospheric missions such as STEREO, ACE, Wind in order to constrain the solar activity seen at Voyager. Moreover, it will benefit greatly future missions such as IMAP

Mission Archive Plan

Many earlier weaknesses in the Voyager MAP have been largely rectified, and MAG, PLS, and some PWS data are now served in useful forms from various archives including SPDF as the Final Archive. CRS should begin the process of producing archival products rather than waiting for the closeout phase. It would also be helpful for LECP data to be archived in and served from SPDF/CDAWeb. There are a number of datasets in the Voyager set where it will be a challenge to figure out the best way to provide the community with scientific access that is now provided through specialized tools; this process should begin as a dialogue between the mission, SPDF, and perhaps via the new route of SPEDAS. See recommendations below.

Various comments:

VEPO products and tools are useful, but somewhat divorced from the main set of SPDF files and capabilities, e.g., at CDAWeb. They should be integrated into that environment, as many of the other Voyager HP-relevant sets now are.

A plan to move the (very complete) LECP products to CDAWeb would be useful. There currently seems to be no plan to serve the data from SPDF, which would be very useful as a final archive in addition to the PDS archive.

Note that some PWS and PLS data have been added to CDAWeb by SPDF, with the consent of the PIs. SPASE metadata was also produced.

Overall Assessment

Based on the mission performance during its prior extended phase and the feasibility and promise of its upcoming operational phase, the Voyager mission is ranked 4 of 16 missions, and is considered to be **Excellent/Very Good.**

Based on its contributions to, and role it plays in achieving the goals of the Heliophysics System Observatory, the Voyager mission is ranked 4 of 16 missions, and is considered to be **Excellent.**

Mission specific recommendations/findings

Recommendation 1: Succession Plan. Given the state of the mission, the panel recommends that a personnel succession plan be developed and presented to HQ and be implemented in near term to ensure that appropriate younger personnel will be trained. This training should occur not only on the science side but on the engineering side, given that the spacecraft currently experience some engineering new challenges (e.g., decreasing power and thermal margins). The Voyager mission is an ageing yet invaluable space research asset, taking *in-situ* data in a region that likely will not be visited for decades to come. The panel is aware of the fragility of the data (some of the instruments operate at the limit of sensitivity) requiring hands-on handling by the PI's and co-I's, and is aware of the ageing workforce on this mission. The panel was surprised to find that for such an important and iconic mission that there was no succession plan.

Recommendation2: Timeliness, Availability and Archival of Data. A data processing and archival plan should be developed and implemented for all the instruments. The panel recognizes that the magnetometer data access and timeliness is being addressed. However, attention should be continued on the magnetometer data and the other data streams. The Voyager data processing and archive require extra care given its legacy approach to managing the data and the ageing instrument/spacecraft coupled with weak signal/noise ratio.

The above mentioned succession plan and archive plan should have the expressed and intentional focus on reduced cost and improved timeliness and availability of the data. The Voyager team should work closely with NASA HQ to ensure that they possess the necessary support (cost associated) to perform such task. Both of these plans should be presented to NASA HQ for approval in the Spring 2018.

Finding 1: The panel commends the Voyager team for addressing last Senior Review concerns and making the magnetic data available in a timely fashion. One area for improvement of Voyager data handling would be providing more background corrected data sets from the LECP instruments. However, timeliness availability of data and independent insight and validation of data leaves much to be desired.

Finding 2: Voyager relies heavily on interpretation by global models. Such global models require the use of supercomputing facilities such as Pleiades. The increase pressure of high computing facilities put pressure on time allocation. Such use should be fully supported.

Finding 3: We note that Voyager and IBEX satellites are highly complementary missions exploring the outer edges of the heliosphere. Voyager 1 and 2 are taking in-situ data in two distinct spatial locations while IBEX is taking global Energetic Neutral Atoms maps of the heliosphere. The panel encourages mutual synergetic activities such as joint conferences and collaborations.

Wind

Mission Synopsis

The Wind satellite was launched in November, 1994 as part of NASA's International Solar Terrestrial Physics program. The instruments gather high time resolution, accurate solar wind measurements including magnetic field, solar wind particles and speed, and plasma waves. After 23 years, seven of the eight instruments continue to work very well with the exception of the gamma ray sensor, which no longer has any coolant. This spin stabilized satellite is currently executing halo orbits at L1.

The mission is very productive as evidenced by over 1,825,000 data access requests in 2015 and 2016. All of the data are accessible to the public in a timely manner. Wind continues to remain a relevant mission as evidenced by recent press releases and high impact publications (i.e., 12 in Nature and 7 in Phys. Rev. Lett. since 2015.

Wind also contributes critically to multi-mission research, as part of the Heliophysics System Observatory (HSO). With its ample fuel reserves, sufficient for >50 years, Wind will continue to provide accurate solar wind observations for magnetospheric studies (supporting MMS, THEMIS, and Van Allen Probes), serve as the 1 AU reference point for outer heliospheric (e.g., Voyager, MAVEN, JUNO) investigations, and provide critical support for other NASA missions (e.g., STEREO, ACE, DSCOVR, etc.). Moreover, new Wind results will continue to improve theories of solar wind heating, acceleration, and energetic particle processes and serves as the "anchor" at L1 for comparisons with observations from future solar missions that will gather data closer to the sun (e.g., Solar Probe Plus and Solar Orbiter).

Wind addressed exceptionally well all of the prior science goals of the previous senior review and is well poised to address the new prioritized science goals (PSG) as outlined in the proposal. These include:
PSG 1. Wave- and/or Turbulence-Particle Studies
PSG 2. Unusual Solar Cycle
PSG 3. Particle Acceleration
PSG 4. Long-Term Dust Science

Wind contributes significantly to NASA's science and space weather goals of understanding the solar wind and its interactions with the earth's magnetosphere and can be expected to continue to provide excellent scientific research for years to come.

Science Merit (Criterion A)

Measurements from the Wind spacecraft have made significant science impacts during its mission lifetime, and in particular during the last Senior Review cycle. These include studies of solar transients and their relationship to coronal mass ejections, including small transients for which high resolution, continuous measurements are needed, energetic particle acceleration in the solar wind particularly with respect to shocks, and dust physics, which address the interaction of the solar wind and the interstellar medium. Wind is well poised to continue these studies with new prioritized science goals that build on this previous work. For example, recently, Wind's high resolution measurements have revealed turbulence embedded in weak shock structures where laminar conditions were expected.

Wind continues to remain a highly relevant mission for NASA. It has yielded over 600 publications in peer-reviewed science journals since the last Senior Review (out of over 4300 refereed publications since launch). Further, since 2015, it has had many press releases and high impact publications (i.e., 12 in Nature and 7 in Phys. Rev. Lett.). It has also supported 15 PhD theses since 2015 with 16 more in progress.

<u>Relevance and Responsiveness to the Call (Criterion B)</u>

Wind's extended phase is highly relevant to the NASA Science Mission Directorate science plan. It can be expected to contribute to our understanding of the solar wind and its interactions with the magnetospheres of the earth and other planets. Its data will enable improved space weather predictions. Wind's response to this Senior Review was fully responsive to the Senior Review call. Significant progress was made to all of the prioritized science goals of the previous senior review and we can expect continued excellent scientific productivity during the upcoming period of performance.

<u>Technical Capabilities and cost reasonableness (Criterion C)</u>

All instruments are working well except the gamma ray instrument that ran out of fuel. There are some instrument degradations, but all contribute very meaningful data and many, such as the magnetometer, the 3D plasma detector, the Solar Wind Experiment Faraday Cup Strahl experiment, and the plasma wave instrument, are working in their fully "nominal" operational mode. The spacecraft is in good health.

From the operations standpoint, Wind requires one two-hour DSN support every other day. Note that DSN and associated communication costs are "in kind" and do not contribute the Wind Budget.

Costs are very reasonable. In fact, it is tempting to ask to what extent additional funds might further the already high scientific productivity of the mission by fostering more in depth scientific research with some of the data products.

<u>Contribution to the HSO</u>

Wind is highly relevant to Heliophysics System Observatory (HSO) and contributes to inner heliospheric missions, such as STEREO, ACE, and Discovr, missions to other planets such as the MAVEN mission at Mars, and upcoming missions close to the sun such as Solar Probe and Solar Orbiter. Wind is essential for providing solar wind information for magnetospheric missions such as MMS, the Van Allen Probes, and THEMIS. Its solar wind data supports a number of other missions (such as IBEX and Voyager) as well as ground-based radars and other instruments as well.

Furthermore, Wind and ACE satellites are highly complementary missions, both executing halo orbits at L1, that include some common instruments as well as some instruments that are unique to each mission. It is hoped that beyond the cross-calibrations of the common instruments on the two satellites, in addition mutual, synergistic observations of the two complete data sets are encouraged, at least for science questions where this makes sense.

<u>Mission Archive Plan</u>

The Wind project is doing an excellent job of producing, documenting, providing, and archiving its data. New products continue to be produced, enhancing the value of the mission. The use of SPDF for the serving of data means that Wind continually does most of what is needed to produce a Final Archive. The documentation is complete and well-organized, and thus archive-ready.

The Wind data products are available to the community directly from the instrument team sites (as well as the CDAWeb), with a single project webpage containing links to and descriptions of the large number of Wind data products.

<u>Overall Assessment</u>

Based on the mission performance during its prior extended phase and the feasibility and promise of its upcoming operational phase, the Wind mission is ranked 5 of 16 missions, and is considered to be **Excellent/Very Good.**

Based on its contributions to, and role it plays in achieving the goals of the Heliophysics System Observatory, the Wind mission is ranked 5 of 16 missions, and is considered to be **Excellent.**

<u>Mission specific recommendations/findings</u>

Finding: Wind continues to provide unique, robust, and high-resolution solar wind measurements, important for new science as well as support of other missions in the Heliophysics Observatory. It is unparalleled for low energy particle and radio wave observations of the solar wind by near-Earth spacecraft. Further, it serves as the 1 AU reference for Solar Probe Plus and Solar Orbiter and provides cross-calibration for the DSCOVR and ACE missions. Wind's continues high scientific productivity and remarkably high use of its data by other researchers (almost 2 million data access requests in two years).

Missions of least impact on Heliophysics System Science

Below is an assessment of four missions that were assessed to have the least impact on heliophysics system science should their future data not be available.

Impact of not having RHESSI data

The Panel was asked to evaluate the relative impact on the HSO in case one of the solar missions was lost. The missions in question are SDO, IRIS, STEREO, Hinode and RHESSI. All of these missions provide unique information about the Sun, which are critical to the Solar Terrestrial interaction studies. The Panel concluded that losing RHESSI would have the least impact HSO.

RHESSI is the only instrument providing high resolution X-ray and gamma ray imaging spectroscopy of solar flares. This information is critical in locating reconnection sites which no other mission to date can do. Further, RHESSI obtains spectra, which are critical diagnostics of particle acceleration and energy dissipation. However, the detectors are degrading to a level where soon RHESSI will likely be unable to detect weak flares below C class. Moreover, the Sun is approaching solar minimum during which time the major energetic events are expected to be rare. While valuable research can still be done with smaller flares, the absence of larger energetic events significantly narrows the scope of mission research. From the point of view of HSO, data from other missions such as GOES and Hinode and ground-based instruments such as ALMA and EOVSA could mitigate the loss of RHESSI to a certain extent.

Therefore, while RHESSI continues to produce valuable science quality data, the Panel concludes that the impact of losing RHESSI on HSO will be less significant science in comparison to other solar missions SDO, IRIS, STEREO and Hinode.

Impact of not having Wind data

Terminating the Wind satellite would result in the loss of a number of significant capabilities, which are not provided by other missions:

- High resolution magnetic field measurements at L1 critical to understanding shocks, turbulence, and transient events and the mechanisms associated particle acceleration
- High energy particle measurements with high geometric factor and directional observation capability
- Plasma wave measurements, which provide the only absolute plasma density information at L1 (needed by ACE and DSCOVR)
- Two-point interferometry with STEREO of radio waves produced by electron beams
- Thermal electron moment measurements with much higher time resolution compared to ACE
- Thermal ion measurements as well as 3D low energy ion measurements of the solar wind thermal core at high time resolution
- Continuous record of over 2 solar cycle of solar wind variability, critical to understanding space climate

A loss of Wind's investigations of the kinetic processes of the solar wind will have severe impact on research in the broader field of plasma physics. This includes studies of plasma instabilities and wave excitation caused by VDF anisotropies enables by Wind's ability to measure 3D distributions in velocity space.

Despite its important contributions to the Heliophysics System Observatory, losing the Wind spacecraft would have slightly less impact than terminating ACE, IBEX, or Voyager at this particular time.

Impact of not having TWINS data

The Panel was asked to evaluate the relative impact on the HSO and mission specific science of the magnetospheric missions: TWINS, Geotail, MMS, THEMIS, and the Van Allen Probes. All of these missions provide unique information about the magnetosphere, which are critical to the geospace knowledge set. After thorough review, the panel agrees that the HSO will be impacted less by the loss of TWINS.

TWINS provides imaging of ring current and measurements of low altitude emissions. The Energetic Neutral Atom (ENA) imagers observe energetic neutrals produced from the global magnetospheric ion population, over a broad energy range (1– 100 keV) with high angular ($4^{\circ} \times 4^{\circ}$) and time (about 1-minute) resolution. TWINS also provides Lyman-α geocoronal imaging to monitor cold exospheric hydrogen atoms that produce ENAs from ions via charge exchange. TWINS supplies a unique set of images of the global structure of the magnetosphere, while other missions provide localized observations. TWINS is capable of taking a full image in 60s taken every 82s. As of January 1, 2017, TWINS (both instruments together) has taken approximately 9 years' worth of 1 minute images. However, not all of the images are available online to the community. The loss of TWINS2 means there is no longer the ability to have "stereo" images and the pitch angle observations will be of limited resolution (as compared to the dual spacecraft pitch angle measurements).

Should the TWINS mission be lost, HSO will lose imaging of the magnetosphere using neutral atoms (ENAs). There is no replacement planned for imaging the ring current region. Therefore, the global picture coincident with local measurements will not be obtained. The magnetospheric community and the HSO will lose the ability to do campaigns with other satellites that emphasize the correlation of the global and micro structure of the ring currents as we approach solar minimum.

Note: If the action is deferred, the Van Allen Probes will naturally exit the HSO platform in mid 2019.

Therefore, while TWINS continues to produce valuable science quality data, the panel concludes that the impact of losing TWINS on the HSO will be less significant science in comparison to the missions performing in situ plasma particle and fields observations, which study the dynamics of the magnetosphere, specifically Van Allen Probes, MMS, THEMIS, and Geotail.

Impact of not having TIMED data

As of November 2017, there are two NASA Heliophysics satellites collecting measurements in the important ionosphere-thermosphere-mesosphere (ITM) region: TIMED and AIM. In the near future, two new ITM satellites will be launched: ICON in December 2017 or early 2018 and GOLD in mid-2018 or later. As a suite, these four satellites will monitor the exchange of energy and momentum between the ITM and the magnetosphere-solar wind from above and the troposphere-mesosphere from below.

TIMED has been the workhorse for ITM science since 2001. During the next 2-3 years it will be collecting critical data ITM data to be used to characterize the long-term trend effects of the solar minimum and to cross-calibrate instruments on ICON and GOLD.

TIMED is in a high inclination orbit (inclination = 74.0722º) at approximately 600 km.

The TIMED instrumentation includes:

GUVI, a far-ultraviolet spectrograph, which globally measures the composition and temperature of the mesosphere-lower thermosphere region and its auroral energy inputs. This includes the columnar measurements of O/N_2 ratio and the column of NO, H, and O^+, as well as UV/Visible airglow.

SABER, a multichannel radiometer designed to measure heat emitted by the atmosphere over a broad altitude and spectral range, as well as global temperature profiles and sources of atmospheric cooling. Ozone, water vapor, and carbon dioxide are important gases that warm and cool the ITM region through absorption of solar radiation and emission of infrared radiation (heat energy). SABER measures the vertical distribution of H, O, O_3, CO_2, OH, H_2O down to 60 km along the path of the satellite by directly observing the infrared energy they emit. It also measures the temperature profiles and heating and cooling rates.

TIDI, a Doppler interferometer designed to globally measure the wind and temperature profiles of the MLT region. TIDI provides inverted wind profiles, airglow brightness, and O2 atmospheric band volume rates.

SEE, a spectrometer and a suite of photometers designed to measure the solar soft X-rays, extreme-ultraviolet and far-ultraviolet radiation that is deposited into the MLT region. SEE provides fully calibrated and daily averaged EGX and XPS irradiances.

To understand the impact of ITM measurements without TIMED, the measurements of AIM, ICON, and GOLD are reviewed here.

AIM, Aeronomy of Ice in the Mesosphere satellite is in a near polar orbit at approximately 530 km. The AIM mission has three instruments, CIPS, cloud imaging and particles size, CDE, cosmic dust experiment, and SOFIE the solar occultation for Ice experiment. Of these three instruments, SOFIE has the most overlap with TIMED instrumentation. SOFIE uses the technique of solar occultation to measure solar energy passing through the limb of the earth's atmosphere as the sun rises or sets relative to the spacecraft. These measurements are accomplished using differential absorption radiometry with eight band pairs covering wavelengths from 0.29 to 5.26 microns. The SOFIE instrument on AIM measurements are used to retrieve PMC extinction, $\boldsymbol{\beta(\lambda)}$ □ at eleven wavelengths $\boldsymbol{(\lambda)}$ from 0.330 to 5.01$\boldsymbol{\mu}$m, in addition to temperature and the abundance of five gaseous species (O3, H_2O, CO_2, CH_4, and NO).

ICON, the Ionospheric Connection Explorer, which will be launched in the near future will fly in a low earth orbit at around 575 km. Its orbital inclination is predicted to be about 27 degrees, and so it is confined to viewing the equatorial region and the lower mid-latitudes.

It has four instruments on board:

MIGHTI: The Michelson Interferometer for Global High-resolution Thermospheric Imaging instrument, which observes the temperature and speed of the neutral atmosphere. These winds and temperature fluctuations are driven by weather patterns closer to Earth's surface. In turn, the neutral winds drive the motions of the charged particles in space.

IVM: The Ion Velocity Meter, which will observe the speed of the charged particle motions, in response to the push of the high altitude winds and the electric fields they generate.

EUV: The Extreme Ultra-Violet instrument, which will capture images of oxygen glowing in the upper atmosphere, in order to measure the height and density of the daytime ionosphere. This helps track the response of the space environment to weather in the lower atmosphere.

FUV: The Far Ultra-Violet instrument, which will capture images of the upper atmosphere in the far ultraviolet light range. At night, FUV measures the density of the ionosphere, tracking how it responds to weather in the lower atmosphere. During the day, FUV measures changes in the chemistry of the upper atmosphere -- the source for the charged gases found higher up in space.

GOLD, the Global-scale Observations of the Limb and Disk mission, which will be launched in the near future, is an ultraviolet imaging spectrograph that will fly on a commercial communications satellite in geostationary orbit to image the Earth's thermosphere and ionosphere. GOLD will make measurements from a longitude of 47.5ºW during two years of on-orbit prime mission operations. GOLD measurements will therefore cover one region at all times and all periods. It will not provide global measurements.

The GOLD instrument is a dual channel imaging spectrograph, each capable of all measurements. Each channel contains an ultraviolet spectrograph equipped with an imaging detector that covers 132 to 162 nm. This wavelength range contains important emissions from the main constituents of the thermosphere—atomic oxygen (135.6 nm) and molecular nitrogen (the Lyman-Birge-Hopfield (LBH) band system 132 – 162 nm). Two selectable entrance slits, which are 0.2 mm and 0.4 mm wide, respectively, enable the two spectral resolutions of 0.2 nm and 0.4 nm required for measuring temperature and composition, which it measures simultaneously. On the dayside, it measures T and O/N_2. On the nightside, it measures the O^+ density. It also measures the O_2 profile on limb from stellar occultations.

During the next 2-3 years, TIMED data will be used to help calibrate the instruments on GOLD and ICON. TIMED data will also help to collect data needed for long-term trend studies and for comparison of two solar minimum periods. TIMED also provides measurements of the polar auroral and high latitude region at all local solar times. ICON and GOLD do not provide data in these regions because of their orbits, however some of this information is provided by AIM, which is in a high inclination orbit.

Below is a list of some of the measurements available in the different missions.

O/N_2: TIMED/GUVI, GOLD
NO: TIMED/GUVI, TIMED/SABER, AIM/SOFIE
H: TIMED/GUVI, TIMED/SABER
O^+: TIMED/GUVI, ICON FUV/EUV, GOLD
O: TIMED/SABER, ICON FUV/EUV
O_3: TIMED/SABER, AIM/SOFIE
CO_2: TIMED/SABER, AIM/SOFIE
OH: TIMED/SABER
H_2O: TIMED/SABER, AIM/SOFIE
Temperature: TIMED/SABER, ICON/MIGHTI

Winds: : TIMED/TIDI, ICON/MIGHTI