Wind 2023 Senior Review Proposal

Lynn B. Wilson III
NASA GSFC
Project Scientist

Executive Summary: Infrastructure Proposal

NASA launched the *Wind* spacecraft in November, 1994 to the Earth's L1 Lagrange point as the interplanetary component of the Global Geospace Science (GGS) Program within the International Solar Terrestrial Physics (ISTP) program. The spin stabilized spacecraft – spin axis aligned with ecliptic south – carries eight instrument suites that provide comprehensive measurements of thermal to solar energetic particles, quasi-static fields to high frequency radio waves, and γ-rays. In particular, the *Wind* instrument suite provides comprehensive and unique high time resolution (HTR) in-situ solar wind measurements that enable the investigation of wave-particle interactions. *Wind* is also the only near-Earth spacecraft equipped with radio waves instrumentation. All instrument suites continue to provide valuable scientific observations completely available to the public (except TGRS, now without coolant).

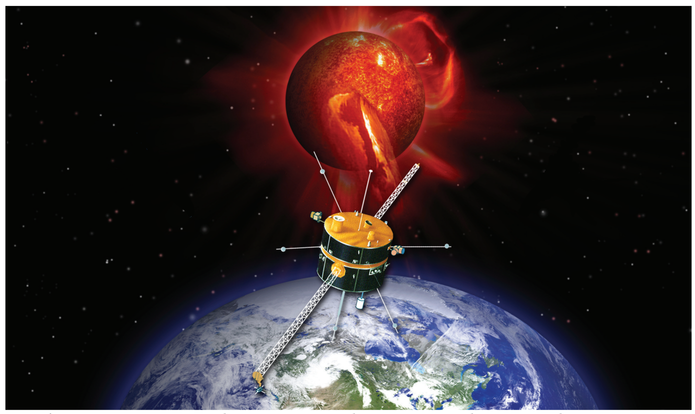

Figure 1: *Wind, a comprehensive solar wind monitor.*

Wind has contributed to numerous independent discoveries since the last Senior Review, from kinetic effects of solar wind reconnection and plasmas to solar cycle seasonal variations. These new results span all three heliophysics research objectives described in the *2014 Science Plan for NASA's Science Mission Directorate*. Interest in *Wind* data remains very high, even though it's >28 years old, as evidenced by the **over 1397 refereed publications** between Jan. 1, 2020 and Dec. 31, 2022. *Wind* has **over 6789 refereed publications since launch** listed on the *Wind* project Web page: https://wind.nasa.gov. As of Apr. 26, 2023 (from NASA ADS), these publications have amassed **over 202,685** citations, **over 1,251,940** reads, **an h-index of 166**, and **an i10-index of 3872**. The *Wind* science data products are publicly served directly from the instrument team sites and CDAWeb, with a single project webpage containing links to and descriptions of the large number of *Wind* data products. SPDF CDAWeb has registered **>26,835,199 data access requests and file downloads** for *Wind* alone between Jan. 1, 2020 and Jan. 1, 2023 (not including OMNI of which *Wind* is a critical component). There have also been 11 doctoral and 4 Masters degrees (171 total graduate degrees since 1994) completed using *Wind* data, and 28 PhDs are currently in progress. Finally, *Wind* continues to remain a relevant mission as evidenced by recent press releases and high impact publications (i.e., **28** in *Nature*, **1** in *Science*, **1** in *Rev. Geophys.*, and **4** in *Phys. Rev. Lett.* since 2020), for instance at:
Exceptional Cosmic Blast;
Giant Flare in Nearby Galaxy;
Fast Radio Bursts.

Because of its longevity, *Wind* observations have allowed researchers to compare long-term variations in solar wind properties, solar wind transients, micron-sized dust fluxes, and solar radio emissions from the end of solar cycle 22 through all of cycle 24 without needing to compensate for changing instrumentation and calibration.

Wind has also contributed critically to multi-mission studies, as part of the Heliophysics System Observatory (HSO). With its ample fuel reserves, sufficient for >65 years, *Wind* will continue to provide accurate solar wind input for magnetospheric studies (supporting MMS and THEMIS) and serve as the 1 AU reference point for outer heliospheric (e.g., *Voyager*, MAVEN, JUNO) investigations, in addition to providing critical support for other missions (e.g., STEREO, ACE, DSCOVR, etc.) as well as *Parker Solar Probe* and *Solar Orbiter* in the inner heliosphere. Moreover, new *Wind* results will continue to improve theories of solar wind heating and acceleration, and energetic particle acceleration and transport processes. ***Wind* will continue to provide critical measurements to complement the observations made by *Parker Solar Probe* and *Solar Orbiter* which will enable researchers to relate the solar wind at 1 AU to its coronal source and compare radio burst power with source locations.**

Rationale for Continuing the *Wind* Mission

- *Wind* continues to provide unique, robust, and high resolution solar wind measurements
- *Wind* serves as the 1 AU reference for *Parker Solar Probe* and *Solar Orbiter*
- *Wind* also serves as the 1 AU reference for outer heliospheric missions
- *Wind* aids in cross-calibration efforts for multiple NASA and non-NASA missions
- *Wind* still has redundant systems, instruments, and enough fuel for >65 years
- *Wind* remains very scientifically productive as evidenced by publication rate

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1 The *Wind* Spacecraft

1.1 Historical Background

The *Wind* spacecraft was launched on November 1, 1994 with a Delta II rocket. *Wind* and *Polar* were the stand-alone components of the Global Geospace Science (GGS) Program, a subset of the International Solar Terrestrial Physics (ISTP) Program which included the additional missions *Geotail*, SOHO, and *Cluster*. *Wind*'s original name was *Interplanetary Physics Laboratory* while its GGS partner *Polar* was short for *Polar Plasma Laboratory*. This is, in part, why the name for the *Wind* spacecraft is sometimes written in all capital letters though it was never an acronym. *Wind*'s original purpose was (1) to make accurate in-situ measurements of interplanetary conditions upstream of the magnetosphere to complement measurements made in the magnetosphere by *Polar* and *Geotail* and (2) to remotely sense interplanetary disturbances for possible future predictive purposes. The instruments were therefore designed to make highly accurate solar wind measurements.

Prior to May 2004, *Wind* performed a series of orbital maneuvers (see Figure 2) that led to: ∼67 petal orbits through the magnetosphere; out of the ecliptic plane lunar rolls in April and May of 1999; four east-west prograde 1:3–Lissajous orbits reaching ≳300 R_E along the ±Y-GSE direction between August 2000 and June 2002; and an excursion to the L2 Lagrange point from November 2003 to February 2004 (i.e., >220 R_E downstream of Earth and ∼500 R_E downstream of ACE). In May 2004, *Wind* made its final major orbital maneuver and was inserted into an L1 orbit, where it has remained and will continue to remain for the foreseeable future. Note that *Wind*'s L1 orbit has a ±Y-GSE displacement about the sun-Earth line of ∼100 R_E, much larger than ACE or DSCOVR.

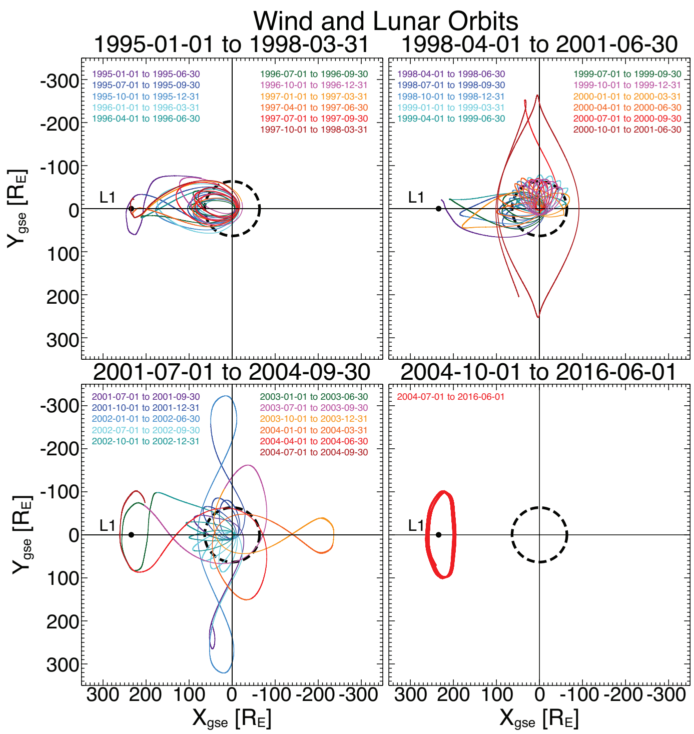

Figure 2: *Orbital trajectories of the* Wind *spacecraft in the GSE XY plane from 1 November 1994 to 1 June 2016. Colors denote time ranges as indicated. The dashed black circle indicates the Moon's orbit. Note that the XY projection of the orbit has not noticeably changed since 31 December 2015. Figure taken from Wilson III et al. [2021].*

The *Wind* team successfully performed three halo orbit insertion maneuvers between June 26, 2020 and November 9, 2020 and an additional attitude correction maneuver on October 20, 2022. The first three were necessary to avoid the solar exclusion zone – around the solar disk where solar radio emissions cause sufficient interference with spacecraft communications to prevent telemetry signal locks. The latter maneuver was necessary to correct the spacecraft spin axis so it never deviates by more than 1° from south ecliptic pole.

The project scientist led the effort of publishing an extensive review [Wilson III et al., 2021] of the entire mission that provides detailed discussions about instruments, spacecraft, and publications. Much of the following sections are a summarization of several of these details.

1.2 Current Status

The *Wind* spacecraft continues to operate in good health. In 2000, the communications system was successfully reconfigured to enhance the telemetry margin. Reliance on a single digital tape recorder (with two tape units, TUA and TUB) since 1997 has never hampered operations, and measures have been taken to minimize its use in order to extend tape recorder life as long as possible. For more details about the spacecraft health/status, see Section 1.4.

Seven of the eight *Wind* instruments, including all of the particles and fields instruments, remain largely or fully operational. The EPACT, high energy particle, and SMS solar wind composition instruments have suffered some degradation, but both continue to provide valuable measurements. The SWE electron instrument required some reconfiguration to maintain its capabilities. The TGRS γ-ray detector has been turned off, as planned, due to having insufficient coolant to operate. For technical details about instrument capabilities see Table 1 and for details about status/health see Section 1.5.

In conclusion, *Wind* is operationally healthy and continues to maintain a large fuel reserve, capable of sustaining the spacecraft at L1 for >65 years.

1.3 *Wind*'s Unique Capabilities

Wind's complement of instruments was optimized for studies of solar wind plasma, interplanetary magnetic field, radio and plasma waves, and of low energy particles.

The instrument suite is not equivalent to that of ACE; rather the two missions complement each other. ACE – launched ∼3 years after *Wind* – focuses on the detailed investigation of high energy particles for which *Wind* has more limited capabilities. Several of *Wind*'s solar wind, particle, radio, and plasma wave instruments are unique. *Wind*'s instrument capabilities are summarized in Table 1. ***Wind* makes unparalleled observations of low energy particles, radio waves, and the solar wind near the Earth.** More details about *Wind*'s unique capabilities are discussed in the following paragraphs.

Wind is unparalleled in its capacity for making high time resolution (HTR) measurements of quasi-static magnetic fields (with MFI) and thermal solar wind electrons (with 3DP). Though STEREO/SWEA has a higher cadence in burst mode, the low energy ($\lesssim$60 eV) electrons cannot be measured by this instrument. The MMS spacecraft's FPI detectors can also measure much faster than *Wind*/3DP, but FPI was not designed for the solar wind causing it to over(under) estimate the temperature(density) [e.g., see detailed discussion in Wilson III et al., 2022]. *Parker Solar Probe* also has the capacity to measure the electrons at a faster absolute cadence, but near its closest approach to the sun the cadence normalized to physical time scales will be comparable to or slower than *Wind*/3DP at 1 AU. Thus, *Wind*/3DP still retains the highest relative time resolution for accurate measurements of thermal electrons in the solar wind.

Wind/MFI offers continuous coverage of the quasi-static magnetic fields at ∼11 samples per second (sps) over the entire mission (∼22 sps when *Wind* was within $\lesssim$100 R_E of Earth). Although the DSCOVR magnetometer has a ∼50 sps rate data product, it only covers ∼8 years of solar wind observations, it's not publicly available on SPDF/CDAWeb, and it's less accurate than *Wind* data. The highest cadence of the ACE magnetometer data on SPDF/CDAWeb is ∼1 sps, a factor of ∼11 slower than *Wind*/MFI. Thus, *Wind*/MFI has the highest sample rate of science-quality magnetic fields for the longest continuous solar wind measurements.

Wind/STICS is unique among currently operational spacecraft as it is the only sensor in the solar wind fully dedicated to providing measurements of heavy ions for an energy range spanning ∼6.2–223.1 keV/amu. STICS is a time-of-flight mass spectrometer, it can differentiate many minor ionic species and look at their characteristics in the suprathermal energy range to better understand their origin. In addition, *Wind*/LEMT provides high energy particle data over a range of energies

Table 1: Operational Instruments on *Wind*

Name	Type	Cadence	Range	Status & Notes
MFI				**Nominal**
	3 $B_{o,j}$[a]	∼11–22 sps[b]	±4 – ±65,536 nT	±0.001 – ±16 nT
WAVES				**Nominal**
TDS Fast	2 δE_j	1.8–120 ksps	∼0.1–300 mV/m	∼80 μV rms
TDS Slow	1 or 3 δE_j	0.1–7.5 ksps	∼0.5–300 mV/m	∼300 μV rms
	1 or 3 δB_j	0.1–7.5 ksps	∼0.25 – $\gtrsim$30 nT	∼10^{-9} nT^2 Hz^{-1} @ 100 Hz
TNR	1 δE_j	∼1 min	∼4–256 kHz	∼7 nV $Hz^{-1/2}$
RAD1	2 δE_j	∼1 min	∼20–1040 kHz	∼7 nV $Hz^{-1/2}$
RAD2	2 δE_j	∼1 min	∼1.1–14 MHz	∼7 nV $Hz^{-1/2}$
3DP				**Nominal**
EESA	e^-	∼3–22 s	∼0.003–30 keV	∼20% $\Delta E/E$[c], ∼5.6–22.5°
PESA	H^+, He^{2+}	∼3–75 s	∼0.003–30 keV	∼20% $\Delta E/E$, ∼5.6–22.5°
SST Foil	e^-	∼12 s	∼25–400 keV	∼30% $\Delta E/E$, $\gtrsim$22.5°
SST Open	H^+	∼12 s	∼25–6000 keV	∼30% $\Delta E/E$, $\gtrsim$22.5°
SWE				**VEIS Off,**
				Strahl Reconf.
FCs	H^+, He^{2+}	∼92 s	∼0.15–8 keV	∼6.5% $\Delta E/E$
Strahl	e^-	∼12 s	∼0.005–5 keV	∼3% $\Delta E/E$
				∼3° × 30°
SMS				**SWICS Off,**
				MASS Reduced
STICS	H – Fe	$\gtrsim$3 min	∼8–226 keV/e	∼5% $\Delta E/E$, ∼4° × 150°
			1–60 amu/e	∼12% $\Delta M/M$[d]
EPACT				**IT off,**
				APE Reduced
LEMT	He – Fe	$\gtrsim$5–60 min	∼2–12 MeV/n	$\gtrsim$20% $\Delta E/E$
			∼2–90 Z	$\gtrsim$2% $\Delta Q/Q$[e]
STEP	H – Fe	$\gtrsim$10 min	∼0.02–2.56 MeV/n	$\gtrsim$30% $\Delta E/E$
				∼17° × 44°
				Nominal
KONUS	photons	$\gtrsim$2 ms	∼0.02–15 MeV	$\gtrsim$5% $\Delta E/E$
		$\gtrsim$3 s	∼0.02–1.5 MeV	Background Mode
				Off (out of coolant)
TGRS	photons	$\gtrsim$62 μs	∼0.025–8.2 MeV	∼3 keV @ 1 MeV
				eff. ∼43% @ 511 keV

[a] three magnetic field vector components [b] samples per second [c] normalized energy resolution
[d] normalized mass resolution [e] normalized charge resolution

not covered by ACE (i.e., ∼1–10 MeV/amu).

The *Wind*/WAVES instrument provides unique radio observations from near the Earth in the 4 kHz to 14 MHz frequency range. *Wind* is the only spacecraft at L1 that consistently observes the upper hybrid line (or plasma line), which provides the most accurate and only unambiguous measurement of the total electron density in the solar wind. Thus, the density - normally obtained as a moment of or fit to the velocity distribution function from particle instruments like SWE and 3DP - can be accurately and independently verified using the WAVES instrument. **The WAVES instrument provides the only method for an independent, in-flight, and ab-**

solute calibration for particle instruments near Earth. Combined with radio observations from STEREO and *Parker Solar Probe*, *Wind*/WAVES provides an essential third vantage point for unambiguously localizing inner heliospheric radio sources in addition to their beam patterns.

The *Wind*/WAVES instrument can also be used for solar energetic particle (SEP) studies and interplanetary and interstellar dust [e.g., see detailed discussions in Wilson III et al., 2021]. *Wind* is still the only near-Earth spacecraft which can measure both the electromagnetic and particle signatures of SEP events.

Finally, *Wind* and ACE are the primary data sources for the widely-used near-Earth OMNI dataset found on SPDF/CDAWeb. In fact, when *Wind* data is available and it's within the ellipse of ACE's L1 orbit, it is chosen as the primary spacecraft for solar wind plasma and field data [e.g., see Alterman, 2022]. **Thus, *Wind*'s distinct capabilities make it an essential asset to the Heliophysics community and a critical component of the HSO.**

1.4 Spacecraft Health

Wind continues to operate in good health. The communication system was successfully reconfigured in 2000 to enhance the telemetry margins and reliance on a single digital tape recorder (with two tape units) since 1997 has never hindered operations. The flight operations team (FOT) took steps to minimize wear and extend the lifespan of the two tape units. Since the last Senior Review, the spacecraft has experienced the usual instrument latch-ups and single-event upsets (SEUs) that are likely caused by high energy particles. As in the past, the FOT was able to restore all instruments to fully operational within a day or two depending on Deep Space Network (DSN) scheduling. The automation of the recovery process for the WAVES instrument after latch-ups (i.e., due to SEUs) was successfully completed in October 2016 and the spacecraft command tables now include automated tests of the SWE electron instrument. Thus, *Wind* continues to maintain a fully operational status.

An examination of the spacecraft power systems (see Figure 3) shows that the batteries can maintain average bias voltages high enough to exceed the current load shed setting of 19.1 V until at least 2070 based on an extrapolation beyond the date range of the lower right panel. To cause a spacecraft reset, all three batteries must simultaneously fall below this load shedding voltage level which is commandable from the ground and will be changed when necessary to avoid a spacecraft reset. The load shedding can be safely reduced to at least 18.2 V (reached well after 2100 based on present trends). The current trend shows that the battery temperatures will not exceed the critical threshold of ∼17°C until well after the year 2100.

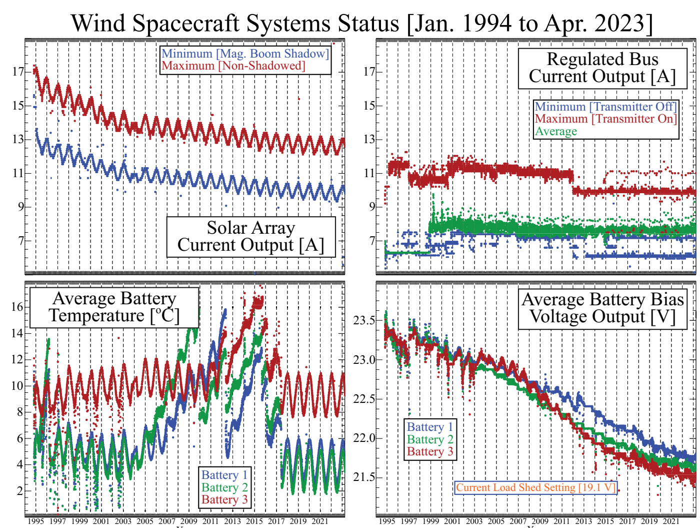

Figure 3: ***Status of* Wind*'s Power System:*** *Daily averages from Jan. 1, 1994 to Apr. 1, 2023.*

The solar array output is producing more than enough current for spacecraft operations and will continue to do into late ∼2059, assuming that the maximum current drawn from the batteries (i.e., red line in upper right in Figure 3) does not exceed the average solar array output (not shown). The maximum solar array output (i.e., red line in upper left-hand panel) will not drop to the maximum regulated bus output until mid ∼2088, assuming current trends hold. Therefore, *Wind* can operate at current capacity for the next several decades.

Wind continues to maintain a large fuel reserve showing ∼35.4 kg remaining, which is equivalent to ∼71 m/s of radial delta-V assuming normal thruster operations. Typically only four station keeping maneuvers are performed each year, each requiring only ∼0.13 kg of fuel. Thus, *Wind* has enough fuel for >65 years.

Table 2: Wind Instrument and Spacecraft Anomalies

Date	Part Affected	Impact
January 19, 1995	GTM1[a]	failure
October 1995	APE-A/APE-B/IT HVPS[b]	suffered a loss of gain
April 30, 1997	CAP1[c]	Reed-Solomon encoder failure
December 13, 1997	DTR2[d]	power supply failure
January 2000	TGRS	γ-ray instrument turned off (planned coolant outage)
May 2000	SMS-SWICS	solar wind composition sensor turned off
June 2001	SWE-VEIS	thermal electron detectors HVPS failure
August 2002	SWE-Strahl	reconfigured to recover VEIS functionality
June 2009	SMS DPU	experienced a latch-up reset – MASS acceleration/deceleration power supply in fixed voltage mode
2010	SMS-MASS	experienced a small degradation in the acceleration/deceleration power supply
May 19, 2014	3DP-PESA Low	suffered an anomaly that affected only the telemetry HK[e] data
October 27, 2014	CAP1	anomaly at ∼21:59:38 GMT
November 7, 2014	CAP2	set to primary while recovery starts on CAP1
November 26, 2014	SWE	full reset due to CAP1 anomaly
January 30, 2015	CAP1	fully recovered
April 11, 2016	DTR1 TUA	began experiencing read/write errors (∼1% bit errors)
May 6, 2016	DTR1 TUB	FOT sets as primary recorder

[a] two GGS telemetry modules, GTM1 and GTM2 [b] high voltage power supply
[c] two command and attitude processors, CAP1 and CAP2 [d] two digital tape recorders, DTR1 and DTR2, each with independent tape units, TUA and TUB [e] house keeping

1.5 Instrument Status

Seven of the eight *Wind* instruments, including all of the fields and particles suites, remain largely or fully functional. The only instrument fully turned off is the TGRS γ-ray instrument that was designed for only a few years of operations (instrument off prior to ∼January 2000). The general status of all instruments is summarized in Table 3. The specific degradations in instrument capabilities are described in the following discussion.

The EPACT APE-A/APE-B/IT high voltage power supply (HVPS) suffered a loss of gain in October 1995. The EPACT-APE detector only returns two energy channels of ∼5 and ∼20 MeV protons during enhanced periods. The EPACT-LEMT and -STEP telescopes continue to operate normally, providing crucial and unique observations of solar energetic particles up to 10 MeV in energy. The SMS-SWICS solar wind composition sensor had to be turned off in May 2000. The SMS DPU experienced a latch-up reset on 26 June 2009 causing the MASS acceleration/deceleration power supply to stay in a fixed voltage mode, rather than stepping through a set of voltages. The moderate risk of power cycling of the SMS DPU required to fix this issue was declined to protect the unique and fully functional SMS-STICS sensor. In 2010, MASS experienced a small degradation in the acceleration/deceleration power supply further reducing the instrument efficiency. However, the SMS-MASS sensor still returns science quality data.

The VEIS thermal electron detectors on the SWE instrument suffered high voltage power supply problems in June 2001. In August 2002 the SWE Strahl sensor was reconfigured to recover most of the original functions. Moreover, the 3DP instrument also covers the impacted electron measurements making these observations still redundant and hence robust. The entire SWE instrument suite required a full reset due to the CAP anomaly (see Section 1.4 for details), which resulted in a complete loss of data from late Oct. 27, 2014 to Nov. 26, 2014, and partial loss until Dec. 1, 2014 when the instrument was returned to nominal operations.

On May 2014 the 3DP instrument (specifically PESA Low) suffered an anomaly that only affected the telemetry house keeping (HK) data. A quick investigation showed that while the telemetry information (e.g., micro-channel plate grid voltage) showed unreliable instrument operations information, the science data remained unaffected (i.e., no noticeable change in flux was observed during and after event). All the other detectors within the 3DP instrument suite continue to operate nominally. Thus, the anomaly resulted in no loss of scientific data.

Aside from the complete or partial data losses due to the 2014 CAP and 2016 tape unit anomalies (see Section 1.4 for details), all of the instruments continue to be fully functional. The dates of significant instrumental issues are listed in chronological order in Table 2.

1.6 Science Team

The *Wind* instrument/science team is a small but dedicated group of scientists. Due to the longevity of the mission, a number of the original instrument PIs have retired or passed away. The SWE instrument suite is currently headed by **Bennett A. Maruca (University of Delaware)** with Michael L. Stevens (Harvard Smithsonian) leading the SWE Faraday Cup team. **Stuart D. Bale (University of California, Berkeley SSL)** is the PI of 3DP. **Andriy Koval (University of Maryland, Baltimore County/Code 672)** took over as PI of the MFI instrument replacing Adam Szabo (GSFC), who moved on to other missions. **Susan T. Lepri (University of Michigan, Ann Arbor)** is the PI for SMS. **Keith Goetz (University of Minnesota, Twin Cities)** is the PI for WAVES. The original WAVES PI was Jean Louis Bougeret of France, so our French colleagues also maintain a PI who is **Karine Issautier (Observatoire de Paris-Meudon)**. Both the original and previous acting EPACT PIs, Tycho von Rosenvinge and Allen Tylka, respectively, retired so **Ian G. Richardson (University of Maryland, College Park/Code 672)** took over as the EPACT PI in late 2019. Finally, unfortunately Rafail Aptekar passed away in late December 2020 so **Dmitry Frederiks (Ioffe Institute, Laboratory for Experimental Astrophysics, St. Petersburg, Russia)** has taken over as the KONUS PI. Lynn B. Wilson III (GSFC, Code 672) has been Project Scientist for *Wind* since June 2016. A summary of the instrument leads can be found in Table 3.

The *Wind* instrument/science team brings a great deal of experience and enthusiasm for new discoveries, and looks forward to continuing to support the wide exploitation of *Wind* data in the community as evidenced by the long and increasing list of *Wind* scientific publications (i.e., **over 1397 refereed publications** between Jan. 1, 2020-Dec. 31, 2022, i.e., since the last Senior Review). Efforts by the new team members have resulted in the release of several new data sets since the last Senior Review, with additional data sets planned to be released before the next Senior Review.

***Wind* Students:** *Wind* observations remain a popular source of material for solar wind, magnetospheric, atmospheric, radio, and astrophysical measurements and a rich source of material for Masters, PhD, and postdoctoral work. Since the last Senior Review, **11 students earned PhDs, at least 4 student earned a Masters degree, and 8 postdocs** benefited from *Wind* observations. At present, there are at least 9 Masters and 28 PhD students using *Wind* observations.

1.7 Ground Operations

Table 3: The status of the *Wind* instruments

Instrument	Principal Investigator	Institution	Status
SWE	B.A. Maruca	Electrons: GSFC, UNH Ions: SAO	Strahl detector reconfigured Faraday Cup fully operational
3DP	S.D. Bale	UC Berkeley	Fully operational
MFI	A. Koval	GSFC/UMBC	Fully operational
SMS	S. Lepri	U. Michigan	SWICS turned off MASS reduced coverage STICS fully operational
EPACT	I. Richardson	GSFC/UMCP	IT turned off APE – only 5 and 20 MeV protons LEMT and STEP operational
WAVES	K. Goetz	U Minnesota	Fully operational
KONUS	D. Frederiks	Ioffe Institute, Russia	Fully operational
TGRS	B. Teegarden	GSFC	Intentionally turned off (ran out of coolant)

Wind ground operations take place at Goddard and have fully transitioned from the legacy *Polar*-*Wind*-*Geotail* system to Multi-Mission Operations Center (MMOC) that consolidates *Wind* operations with that of ACE. The automated distribution and archiving of level zero files and production of key parameter (KP) files takes place at Goddard in the Science Directorate under the control of the project scientist. The two server (plus backup) system are periodically upgraded and maintained at modest cost.

The data recovery rate for *Wind* for the years 2020 up to 2023 averaged ∼98.5% with a median of ∼99.8%. Most data losses have resulted from Deep Space Network (DSN) errors (i.e., hardware and software issues) or due to schedule conflicts with other spacecraft launches and/or emergencies.

The current operation of *Wind* requires one ∼2 hour DSN support every other day, though contacts occur more frequently sometimes. This allows the up-linking of the Stored Command Table load and the playback of the Digital Tape Recorder (DTR). *Wind* also maintains real-time solar wind monitoring during these 2 hour contacts. *Wind* can store only three days worth of commands, thus this is the longest *Wind* can go without ground contact or the spacecraft performs an emergency load shed. Currently about half of the contacts are completely automated allowing the operations staff to keep day schedules. It should be noted that all DSN and communication costs are reported as "in-kind" costs so they are not considered part of *Wind*'s operational budget.

1.8 End of Mission Plan

Under the current plan, standard station-keeping maneuvers are made every ∼3 months to maintain *Wind*'s orbit about the first Earth-sun Lagrange point, L1. The flight operations team (FOT) successfully completed three halo orbit insertion maneuvers between June 26, 2020 and November 9, 2020 to prevent the spacecraft from extended trajectories through the solar exclusion zone – around the solar disk where solar radio emissions cause sufficient interference with spacecraft communications to prevent telemetry signal locks. On October 20, 2022 the FOT performed an attitude maneuver to reorient the spin axis so it's maximum annual deviation from the south ecliptic pole never exceeds 1°. Finally, the FOT is investigating performing another attitude maneuver to increase the spacecraft spin rate as each station-keeping maneuver and the halo orbit insertion maneuvers have had a net slowing of the spin rate over the past decade or more. The spin rate is still >19.1 rpm but the nominal rate for the mission was intended to be ∼20 rpm.

There is currently ∼71 m/s of fuel remaining or >65 years in the current orbit. The current orbit keeping maneuvers necessary to maintain the halo orbit are not any more significant, fuel-wise, than the previous Lissajous orbit maneuvers. Thus, the spacecraft will very likely suffer a single-point hardware or physical failure long before it runs out of fuel.

Due to the orbit regime and heritage of *Wind*, it does not currently have a requirement for an End of Mission Plan (EOMP).

2 Science Value of *Wind*

Wind is one of the most productive and active missions in the Heliophysics System Observatory (HSO) as evidenced by the **over 6789 refereed publications since launch**, **over 1397** being published since the last senior review. It's not merely a supporting mission used for small works either, given that there were at least **29** papers published in either *Nature* or *Science* since 2020 (see full list at https://wind.nasa.gov). A comprehensive review of *Wind*'s accomplishments over its first quarter century of activity was published by Wilson III et al. [2021]. The article was awarded the *Top Cited Article 2021–2022* in *Reviews of Geophysics*.

Wind has played a pivotal role in the determination of the source of Fast Radio Bursts and the measurement of one of the strongest gamma-ray bursts (GRBs) ever detected (e.g., see Exceptional Cosmic Blast). Thus, not only is *Wind* critical for Heliophysics missions, it plays an important role for Astrophysics missions as well.

3 *Wind*'s Support for Other Missions

As part of the Heliophysics System Observatory (HSO), *Wind* has been contributing to numerous science investigations that rely on multi-spacecraft observations. Some of these have been mentioned in the preceding sections. In addition, *Wind* observations are critical to the interpretation of observations from many other spacecraft. This is evidenced by the **over 1397 refereed publications and the >26,835,199 *Wind* data access requests on CDAWeb since the last Senior Review.** This section outlines some of the functions of *Wind* in the HSO.

3.1 Inner Heliospheric Missions

ACE: *Wind* and ACE have been working under mutual calibration support for several years in order to increase the scientific value of each mission. *Wind*'s capacity to measure the total electron density using the WAVES radio receivers to observe the upper hybrid line or plasma line (e.g., Section 1.3), coupled with two independent thermal ion plasma measurements (3DP and SWE), gives *Wind* three separate measurements for cross-calibration, resulting in highly accurate thermal plasma observations which can be used to calibrate with ACE. Further, the SWE instrument can operate even during intense high energy particle events associated with solar flares and CMEs, which can disrupt the ACE plasma instrument. The robustness of *Wind*'s instrumentation and measurements makes it a invaluable asset for near-Earth solar wind monitoring.

The spin axes of *Wind* and ACE are orthogonal to each other, which provides an opportunity for magnetic field cross-calibration. The spin plane components measured by a fluxgate magnetometer are most accurate, so the orthogonality of the spacecraft spin planes allows the out-of-the-spin-plane components to be calibrated when the two spacecraft are in near proximity to each other.

The EPACT-LEMT telescope on *Wind* can observe particles in the ∼1–10 MeV/nuc range, which falls between the energy ranges of the ULEIS and SIS instruments on ACE. The ecliptic south spin axis of *Wind* allows the LEMT telescope to measure flux anisotropies better than the sun-pointing spin axis of ACE. In addition, the larger geometric factor of EPACT allows it to observe lower intensity solar energetic particle events than the ACE instrumentation. ***Wind* provides significant and unique calibration information for ACE and makes complementary measurements that facilitate collaborative studies.**

DSCOVR: The Deep Space Climate Observatory (DSCOVR) was launched on Feb. 11, 2015. DSCOVR is tasked to provide solar wind proton and magnetic field measurements from L1 (the same region where *Wind*, ACE and SOHO operate) for NOAA space weather prediction purposes. *Wind* has been an essential calibration tool for DSCOVR and is the primary reference for DSCOVR plasma data trending and anomaly tracking. NOAA requested a combination of ACE and *Wind* data to be used as a back up in case of issues with DSCOVR (e.g., similar to the 2019 anomaly that affected DSCOVR's attitude control systems), in addition to planning for operations following on from DSCOVR.

STEREO: The STEREO-Behind spacecraft suffered a loss of contact in October 2014, leaving only STEREO-Ahead. It is currently close to Earth and will be so for the near future but will continue it's angular separation providing an additional ∼1 AU reference point but well separated from Earth. Combined *Wind*-STEREO observations provide insight into the evolution of solar wind structures near the ecliptic at 1 AU in space and time, and on the variation of solar particle events with heliolongitude. The spacecraft also both make radio observations that can be combined to track solar radio emissions in the inner heliosphere.

MAVEN: The Mars Atmosphere and Volatile EvolutioN Mission (MAVEN), designed to study the Martian atmosphere, arrived at Mars (∼1.5 AU) on September 22, 2014. Mars remained on the far side of the sun, relative to Earth, until early 2016 and moved toward ∼90° relative to the sun-Earth line in early 2017. It is currently ∼90° behind Earth and also STEREO-Ahead.

PSP and SolO: *Parker Solar Probe* (PSP) [Fox et al., 2016] launched on August 12, 2018 and *Solar Orbiter* (SolO) [Müller et al., 2013] launched on February 9, 2020. The primary scientific goal of PSP is to determine the processes responsible for heating and acceleration of the solar corona and solar wind. SolO has similar goals but is also tasked with imaging the solar poles. *Wind* has played a critical role in several PSP and SolO studies already [e.g., see discussion in Wilson III et al., 2021]. These three missions all heavily rely upon their radio frequency measurements for local and remote information of the solar wind and solar corona. The short ∼88 day orbit of PSP and the ∼0.3–0.76 AU orbit of SolO will provide frequent radial and magnetic field alignments with *Wind* allowing for multi-spacecraft studies that will significantly enhance the science return of both PSP and SolO. **Thus, *Wind* will continue to help identify and investigate temporal vs. spatial variations and local vs. large scale phenomena in conjunction with STEREO-A, PSP and SolO.**

3.2 Magnetospheric Missions

Nearly all magnetospheric investigations utilize, in some way, data from an upstream solar wind monitors such as *Wind* either directly or indirectly via the OMNI database. This is partly evidenced by the **>26,835,199 data and FTPS access requests** registered by SPDF/CDAWeb for *Wind* alone (i.e., not including OMNI) between Jan. 1, 2020 and Jan. 1, 2023. Missions relying on *Wind* for solar wind data include *Cluster*, THEMIS, ARTEMIS, *Van Allen Probes* (decommissioned, but community is still publishing papers using its data), and MMS. In addition, the long duration dust impact database obtained from WAVES observations [Malaspina & Wilson III, 2016] offers a unique baseline of comparison against the AIM SOFIE experiment, which measures meteoric smoke. This led to a unique study that estimated the total precipitation rate of rocky objects from space that generate meteoric smoke [Hervig et al., 2022].

Both MMS and THEMIS/ARTEMIS rely heavily upon upstream monitors including *Wind* for various reasons (e.g., determining the distance to the magnetopause from MMS). However, neither spacecraft can fully resolve the solar wind electron and ion core populations [Wilson III et al., 2022]. *Wind* data was used to directly calibrate the THEMIS thermal plasma instruments [McFadden et al., 2008a,b], since the THEMIS electric field receivers do not consistently observe the upper hybrid line. **Thus, *Wind* will continue to provide high quality solar wind observations in support of magnetospheric and solar wind studies by the MMS mission.**

3.3 Solar and Astrophysics

Wind was originally equipped with two gamma-ray instruments, TGRS and KONUS. TGRS ran out of coolant (known event) early in the mission but the KONUS instrument is still actively producing data and remains a very active partner in the Gamma-ray Burst Coordinates Network or GCN (GSFC GCN) and Interplanetary Network (IPN, GSFC IPN). The primary missions involved in the GCN are *Swift*, *Fermi*, LIGO/Virgo/KAGRA, IceCube, HAWC, ISS/CALET, MAXI, INTEGRAL, AGILE, *Wind*, MOA, SNEWS, Super-Kamiokande, and GECAM. *Wind* is the oldest mission in the IPN [e.g., Svinkin et al., 2022], which determines the source directions of transients by triangulation. The primary missions involved in the IPN are *Wind*, INTEGRAL, *Swift*, *Fermi*, AGILE, Suzaku, Insight-HXMT, RHESSI, ISS/CALET, GECAM-B, *Mars Odyssey*, and MESSENGER. In late 2023, NASA's Psyche mission will be added.

Wind has also accumulated an extensive list of solar flares from our own Sun during its more than 28 year-long history (http://www.ioffe.ru/LEA/kwsun/). This database (named KW-Sun) provides light curves with high temporal resolution (up to 16 ms) and energy spectra over a wide energy range (now ∼20 keV to ∼15 MeV). The list of KONUS triggered-mode solar flares from 1994 to the present, along with their GOES classification, is automatically updated and available at http://www.ioffe.ru/LEA/Solar/.

Wind/KONUS played a key role in several recent discoveries including: the identification of the source of a Fast Radio Burst (FRB), the first observed within our galaxy, coming from a magnetar (Fast Radio Bursts); discovery of a giant flare (GF) in a nearby galaxy originating from another magnetar (Giant Flare in Nearby Galaxy); and the detection of one of the strongest gamma-ray bursts (GRBs) ever recorded with total energy output of upwards of 10^{54} ergs or 10^{47} J (Exceptional Cosmic Blast). All of these phenomena are rare, transient events. That is, there are only about a dozen known magnetars (also called soft gamma repeaters or SRGs), GFs only occur once every decade or so, and FRBs are a relatively new phenomena that was only recently explained to result from processes involving magnetars. **Due to the rarity of these astrophysical events, an additional three years of *Wind* KONUS observations will significantly enhance the events collected by the IPN and the GCN.**

3.4 *Wind*, CCMC, and CDAW

The Coordinated Community Modeling Center (CCMC) is tasked to validate heliospheric and terrestrial magnetospheric models. Proper evaluation of the magnetospheric models depends critically on accurate solar wind measurements which drive these models. Historically, *Wind* measurements have been used as the standard. As future models become more complex and increasingly sensitive to uncertainties in the driving conditions, ***Wind* measurements will continue to provide an essential input for the CCMC model validation program.**

***Wind* and CDAW Data Center:** The CDAW Data Center is a repository of CMEs, solar radio bursts, and associated space weather phenomena (https://cdaw.gsfc.nasa.gov). In particular, *Wind*/WAVES data contribute to the online catalog of CMEs manually identified from SOHO/LASCO images since 1996. This includes a link to a list of CMEs associated with type II radio bursts observed by *Wind*/WAVES, and also daily movies combining SOHO/LASCO images with *Wind*/WAVES dynamic spectra that may be used to identify the connection between CMEs and Type II, III, and IV radio bursts (e.g., Dynamic Movie Creator). **Thus, *Wind* remains an active partner in the CDAW Data Center.**

4 Data and Code

Most *Wind* data products are already delivered to SPDF/CDAWeb on a regular basis following calibration and testing by the instrument teams (see the Mission Archive Plan from the 2020 *Wind* Senior Review). The project scientist has worked closely with the teams to help ensure the continuity and proper flow of data to the final archive. Despite the mission's age, *Wind* instrument teams continue to provide new and unique data products and archive them at SPDF/CDAWeb (at least 6 new data products have been added since the last Senior Review). *Wind* generates a rather large number of data types and products; **∼64 selectable data types with ∼1586 total data products (including OMNI data products) on SPDF/CDAWeb**. Note that some prefer different terms so here "data type" is synonymous with "dataset" and "data product" with "data variable".

Mission Operations Center: *Wind* ground operations take place at Goddard and the details can be found in Section 1.7.

Software Management: There are multiple different software sources for *Wind* data including a comprehensive, standalone library created by the project scientist at:
https://github.com/lynnbwilsoniii/wind_3dp_pros;
and a standalone graphical user interface (GUI) written by B. Maruca at:
https://github.com/JanusWind
intended for fitting the reduced distribution functions of the SWE Faraday cup data. The original, open source code for decommutation of each *Wind* instrument is freely available at:
https://github.com/lynnbwilsoniii/Wind_Decom_Code.
There are several more software libraries listed/linked to on the *Wind* "Data Sources" page at:
https://wind.nasa.gov/data_sources.php.
Owing to the age of the mission and the loss of key personnel, some of the raw software code is not readily available for distribution. The team has worked to gather and freely distribute any software that is readily available and will continue to add software if it becomes available for distribution.

PDMP and CMAD Status: When *Wind* launched in November 1994, neither Project Data Management Plan (PDMP) or Calibration and Measurement Algorithms Document (CMAD) requirements existed. However, the *Wind* project has made a significant effort to make all of its science data publicly available and independently usable. The project scientist has also made the decommutation software publicly available (see above notes). Finally, the project scientist has compiled all available information and constructed both a PDMP and CMAD for the mission. Both are already readily available to the Goddard management and NASA HQ.

Due to the retirement and/or passing away of key personnel, significant augmentation of our existing data product algorithm descriptions are not possible. That is, the currently available PDMP and CMAD are in their final states with the exception of minor changes in the future to account for instrument PI changes and/or other personnel changes for the team. Additional funding will not alter this conclusion as the few key personnel that could potentially augment the existing documents do not have any time for such a task.

5 In-Guide Budget

The in-guide budget described in this section will fund the mission operations necessary to continue the safe operation of the *Wind* spacecraft along with basic data reduction and validation processes performed at the various instrument institutions. As in past Senior Reviews, nearly all of the scientific research outlined in the previous sections is expected to be or was funded through external sources, e.g., the ROSES GI and SR&T programs (or other opportunities) with each element individually proposed and peer reviewed. The only funding allocated for scientific research in *Wind*'s budget occurs indirectly as a result of funding the instrument teams to process and validate the data.

Note that *Wind* has managed to operate on a flat budget (in absolute dollars) since at least 2013 and only recently has there been plans to provide an incremental increase. A great deal of optimization and reduction in total workforce has occurred since 2013, which is the only reason such a strict budget has managed to work. The project scientist is allowed to charge up 50% of their time to the project but they have been successfully winning external proposals during their tenure allowing for extra "wiggle room" in the overall budget. This has helped prevent the project from requesting over-guide budgets in past senior reviews and annual Planning, Programming, Budgeting, and Execution (PPBE) process. Even so, the mission operates on a tight budget with multiple points of single-string personnel because it cannot afford to do otherwise. This is not uncommon in older missions (and often required), but it does present a major source of risk for continual operations.

An example is the recent and unexpected early retirement of the previous WAVES instrument PI, Robert J. MacDowall. This left the WAVES data production chain unattended and halted public release of the data for nearly a year. The issue was due to a multitude of cascading complications but ultimately the public data generation was almost entirely operated by Dr. MacDowall and required a great deal of idiosyncratic knowledge. It took the new PI, Keith Goetz, several months to get the parsed and broken code (previously only used at GSFC with numerous hard-coded file paths etc.) working for both STEREO SWAVES and even longer for *Wind* WAVES. Data has finally started flowing to public archives but note that the instrument continued to work and record data nominally during this entire interval. The only part of the chain that broke was the generation of public data products. Yet it is an important issue for older missions relying on legacy code. Most of the instruments on *Wind* rely on some form of legacy code and there is no funding or qualified personnel to update such things. Thus, although *Wind* can operate within its tight budget constraints it is important to consider the difficulties and challenges the team continues to overcome despite such limitations.

5.1 Data Production Budget

The current *Wind* project budget does not allow any directed science funding. The *Wind* science data products are publicly served directly from the instrument team sites (most are directly available from CDAWeb), with a single project webpage containing links to and descriptions of the large number of *Wind* data products; **∼64 selectable data types with ∼1586 total data products (including OMNI data products) on SPDF/CDAWeb**, which can be found at: https://wind.nasa.gov. The core data calibration and validation work carried out by the individual instrument teams does require some amount of science data analysis to verify the accuracy of the generated data products. The entire cost of these efforts varies between ∼35–45% of the total annual budget. A very conservative upper bound on pure science funding resulting from this is ∼10–15% of the total *Wind* funding or ∼20–25% of the non-mission operations funding.

5.2 Mission Operations Budget

The *Wind* mission operations budget varies between ∼40–50% of the total annual budget. It is a large fraction of the total budget, but this is mostly due to *Wind*'s small overall expense. That is, were *Wind* to have more total funding the mission operations side of the budget would not change appreciably. This is because most of the team, both mission operations and science implementation, are single-string. This is an unavoidable scenario given the limited budget and personnel resources.

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