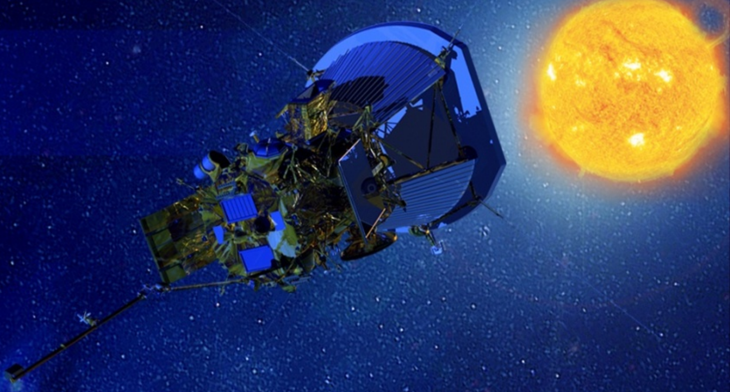
Solar Probe Plus

A NASA Mission to Touch the Sun



Solar Probe Plus Introduction (payload focus)

Jim Kinnison
SPP Mission System Engineer

Jim.Kinnison@jhuapl.edu

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Science Questions Addressed by Solar Probe Plus

Overarching Science Objective

- To determine the structure and dynamics of the Sun’s coronal magnetic field, understand how the solar corona and wind are heated and accelerated, and determine what mechanisms accelerate and transport energetic particles.

Detailed Science Objectives

- Trace the flow of energy that heats and accelerates the solar corona and solar wind.
- Determine the structure and dynamics of the plasma and magnetic fields at the sources of the solar wind.
- Explore mechanisms that accelerate and transport energetic particles.

Level 1 Objectives & Processes require high quality, integrated measurements

L1 Science Objectives	Sample Processes	Needed Measurements	Instruments
1. Trace the flow of energy that heats and accelerates the solar corona and solar wind. 2. Determine the structure and dynamics of the plasma and magnetic fields at the sources of the solar wind. 3. Explore mechanisms that accelerate and transport energetic particles.	- heating mechanisms of the corona and the solar wind; - environmental control of plasma and fields; - connection of the solar corona to the inner heliosphere. - particle energization and transport across the corona	- electric & magnetic fields and waves, Poynting flux, absolute plasma density & electron temperature, spacecraft floating potential & density fluctuations, & radio emissions - energetic electrons, protons and heavy ions - velocity, density, and temperature of solar wind e-, H+, He++ - solar wind structures and shocks	FIELDS - Magnetic Field - Electric Field - Electric/Mag Wave ISIS - Energetic electrons - Energetic protons and heavy ions - (10s of keV to ~100 MeV) SWEAP - Plasma e-, H+, He++ - SW velocity & temperature WISPR - White light measurements of solar wind structures

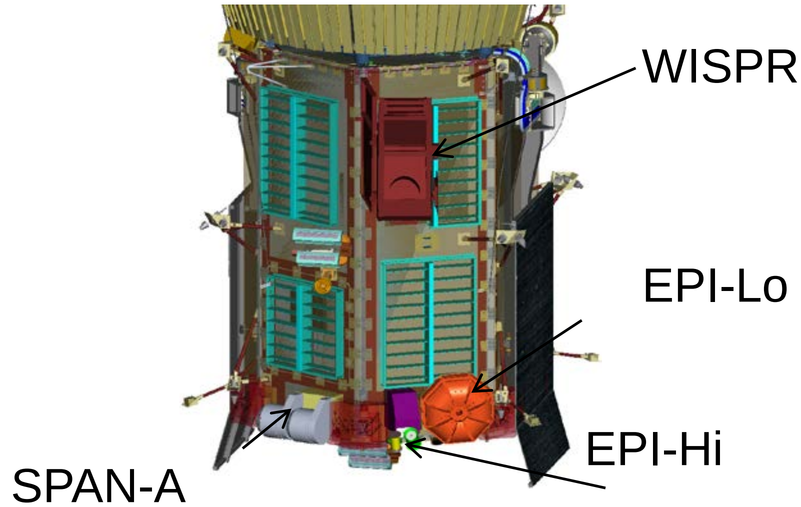
SPP Investigations to Answer the Science Questions

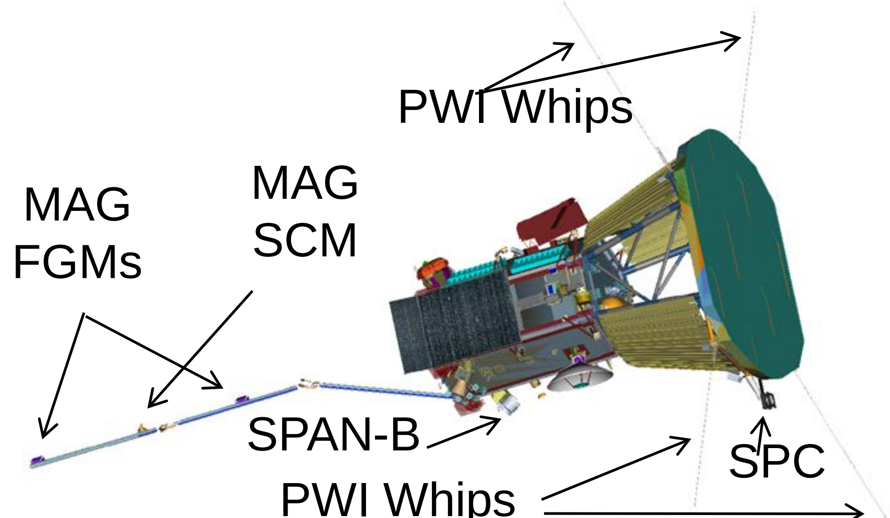
Investigation	Instruments	Measurements
Fields Experiment (FIELDS) – S. Bale, Univ. of California, Berkeley	4 x Electric Antennas 2 x Fluxgate Magnetometers (MAG) 1 x Search Coil Magnetometer (SCM)	electric & magnetic fields and waves, Poynting flux, absolute plasma density & electron temperature, spacecraft floating potential & density fluctuations, & radio emissions
Integrated Science Investigation of the Sun (ISIS) – D. McComas, Southwest Research Institute	High energy Energetic Particle Instrument (EPI-Hi) Low energy Energetic Particle Instrument (EPI-Lo)	energetic electrons, protons and heavy ions (10s of keV to ~100 MeV)
Solar Wind Electrons Alphas and Protons (SWEAP) - J. Kasper, Smithsonian Astrophysical Observatory	Solar Probe Cup (SPC) 2 Solar Probe ANalyzers (SPAN)	velocity, density, and temperature of solar wind electrons, protons and helium ions
Wide-field Imager for Solar PRobe (WISPR) – R. Howard, Naval Research Laboratiry	White light imager	images the solar wind, shocks and other structures in the solar corona and inner heliosphere
Heliospheric Origins with Solar Probe Plus (HeliOSPP) – M. Velli, Jet Propulsion Laborar	Observatory Scientist	addresses SPP science objectives via multi-instrument data analysis and provides independent advice to optimize the scientific productivity of the mission

Solar Probe: Science Payload

Solar Probe Plus
A NASA Mission to Touch the Sun

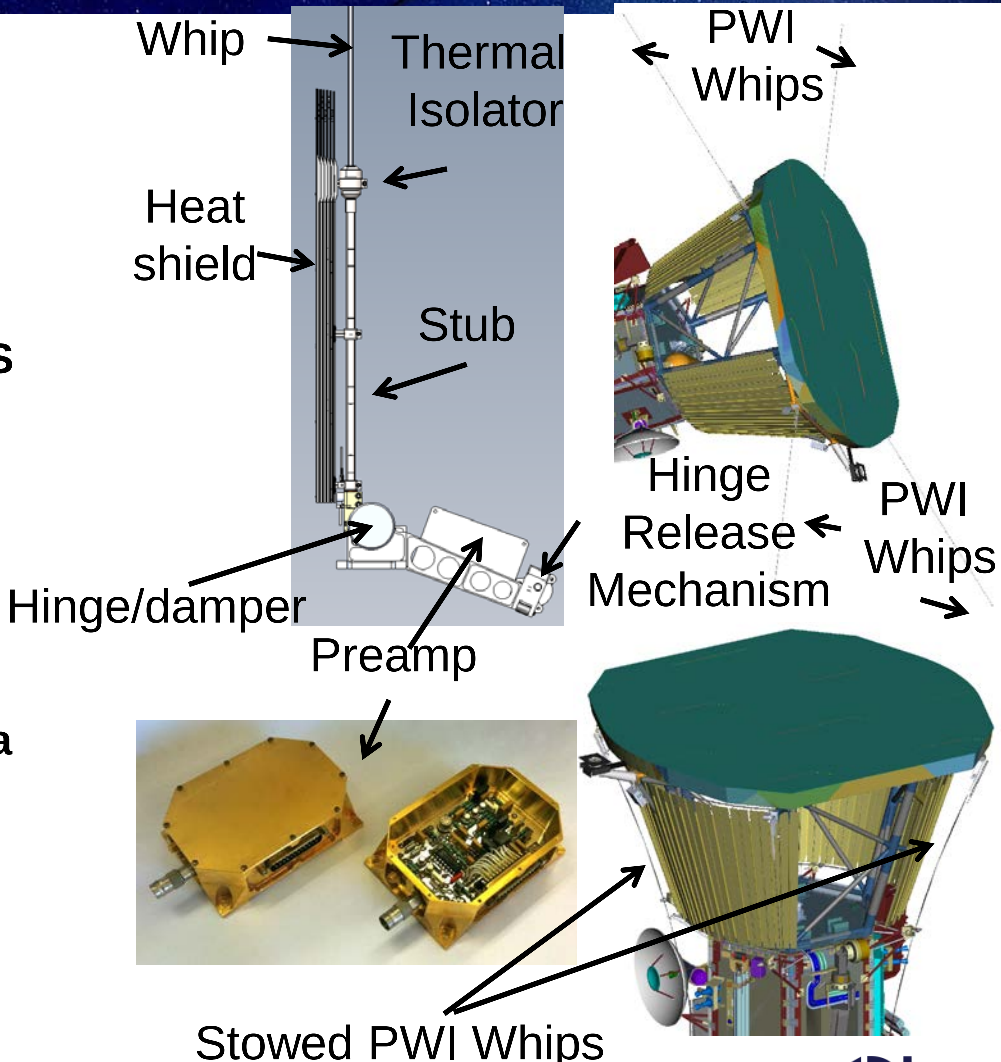
- **FIELDS:**
  - **PI: Stuart Bale, UC Berkeley SSL**
  - **PWI (Plasma Waves Instrument)**
  - **MAG (Magnetometer)**
- **SWEAP (Solar Winds Electrons Alphas and Protons):**
  - **PI: Justin Kasper, Smithsonian CFA**
  - **SPC (Solar Probe Cup)**
  - **SPAN (A & B)**
- **ISIS (Integrated Science Investigation of the Sun)**
  - **PI: Dave McComas, SWRI**
  - **EPI-Hi**
  - **EPI-Lo**
- **WISPR (Wide-field Imager for Solar Probe)**
  - **PI, Russell Howard, NRL**





FIELDS PWI (Plasma Waves Instrument)

- Measures DC & AC electric fields
- 2.3 m electric field antennas:
  - 4 whips (2 co-linear pairs) exposed beyond umbra: Niobium C-103 tube
  - Canted 5º from orthogonal (for WISPR FOV reasons)
  - Mounted on TSA (coplanar) behind TPS
  - Heat shield: layers of Niobium sheet
  - Whips stowed back along S/C
  - P5 Pin-puller actuators (two per antenna: whip cage & hinge)
  - Dampers control deployment speed
- FIELDS Instrument Control Unit (ICU) provides internal processing, buffers data & controls both PWI and MAG
- Institutions: UC Berkeley, Univ. of Minnesota, LASP (CU, Boulder), LESIA (Obs de Meudon, France)

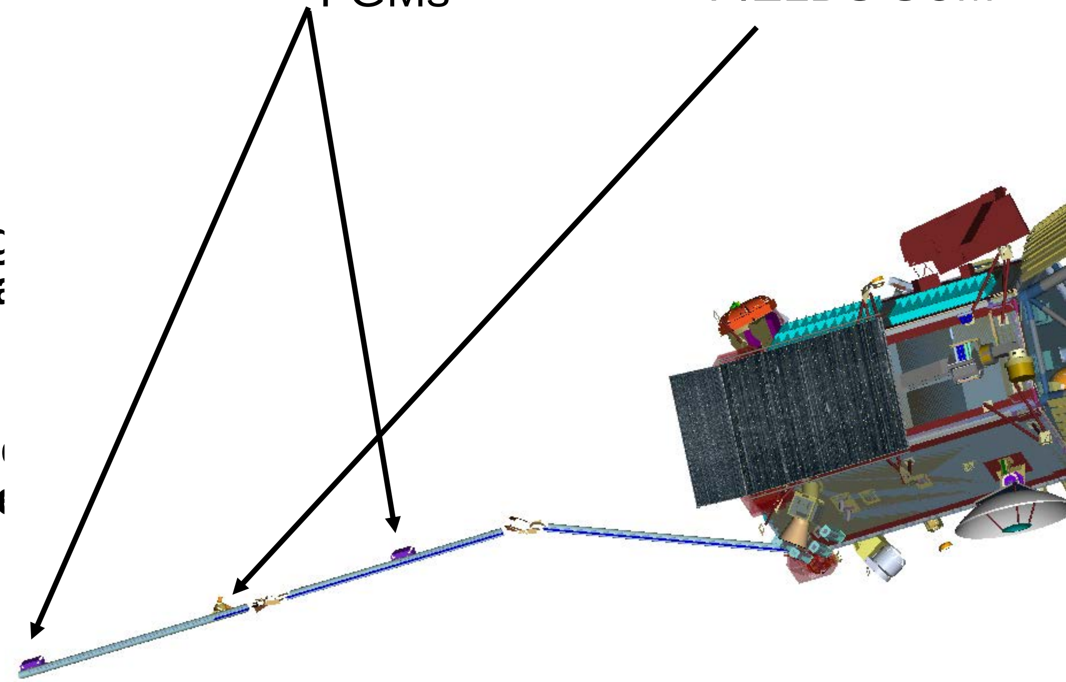


FIELDS MAG (Magnetometer)

- **2 fluxgate magnetometers (FGMs, inboard and outboard) for DC magnetic field**
- **1 vector search-coil magnetometer (SCM) for AC magnetic fluctuations**
- **SCM and FGMs aligned on centerline (z-axis) of S/C**
- **Mounted on a ~4-m boom (APL-provided)**
- **FIELDS Instrument Control Unit (ICU) provides internal processin buffers data & controls both PWI a MAG**
- **Institutions: UC Berkeley, NASA/Goddard Space Flight Cent Laboratoire de Physique et Chimi de l'Environnment et de l'Espace (LPC2E, France)**

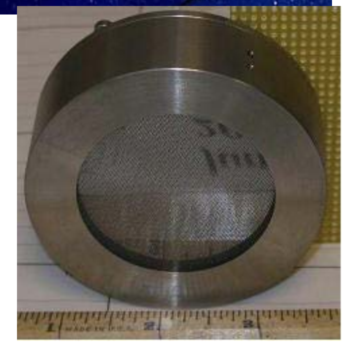
FIELDS FGMs

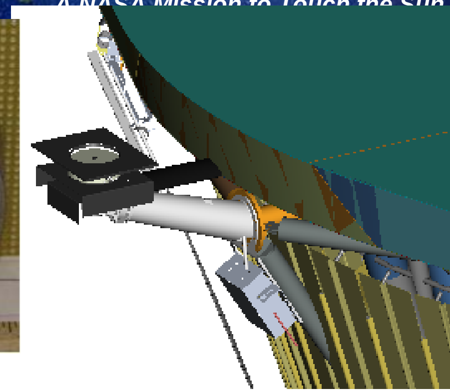
FIELDS SCM



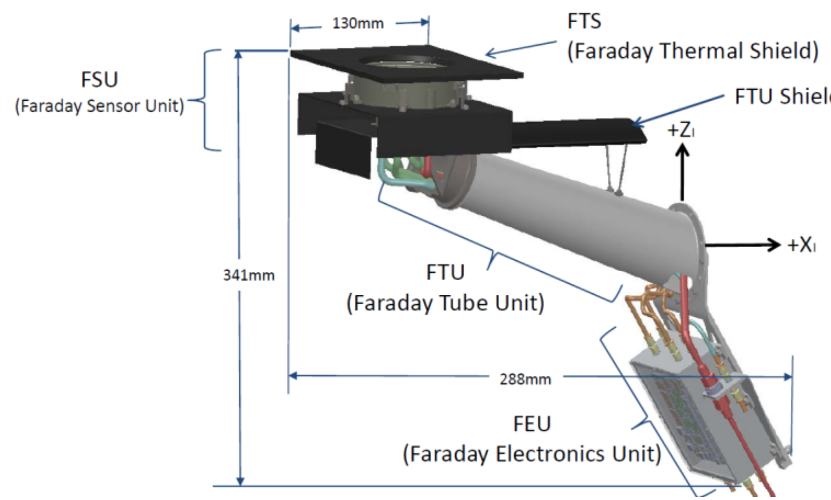
SWEAP SPC (Solar Probe Cup)

- **Solar Probe Cup (SPC)**
  - **Sensor in direct sunlight**
  - **Faraday Cup faces Sun for high cadence bulk ion & electron measurements**
- **Uses same SWEM (SWEAP Electronics Module) as SPAN-A and –B (UC, Berkeley)**
  - **Electrical interface to spacecraft**
  - **Controls SPC & SPAN, formats data products, buffers data**
  - **Includes SAO boards:**
    - **Analog Processing Board (APB): analyzes analog signals from SPC**
    - **High Voltage Modulator Board (HMB): produces high voltage signal for SPC's modulator grid**
- **Smithsonian Astrophysical Observatory (SAO)**





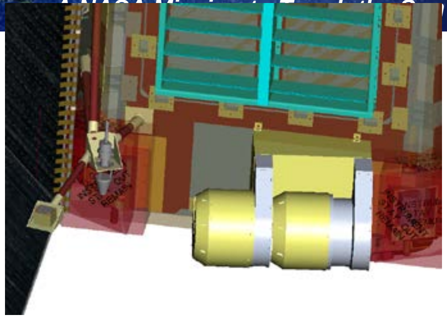
Above right: SPC mounted on TSA
Above left: SPC prototype



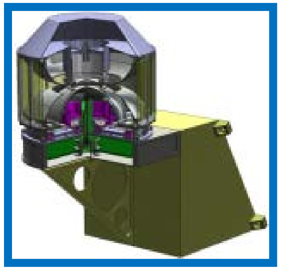
Above: SPC details

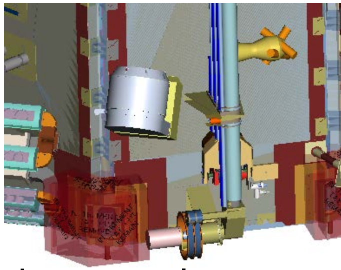
SWEAP: SPAN-A and –B (Solar Probe Analyzers)

- Solar Probe Analyzers (SPAN)
  - Electrostatic analyzers (ESAs) in shadow at back of spacecraft on RAM (SPAN-A) & anti-RAM (SPAN-B) sides
  - Detailed measurements of 3D ion & electron velocity distribution functions
  - SPAN-A Plus enhancement:
    - Added time of flight (TOF) section to provide mass per charge resolution.
      - Separates minor ion species, enabling distinct proton & alpha velocity distribution functions.
- Uses SWEM (SWEAP Electronics Module) interface, along with SPC
  - Electrical interface to spacecraft
  - Controls SPC & SPAN, formats data products, buffers data
- UC, Berkeley, Space Sciences Lab (SSL), as part of SAO SWEAP Investigation

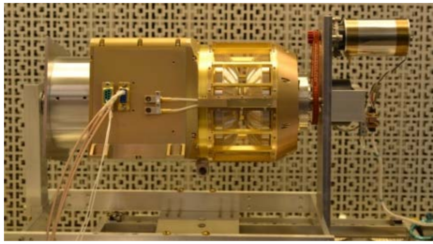


Above: SPAN-A-Plus on Ram-side



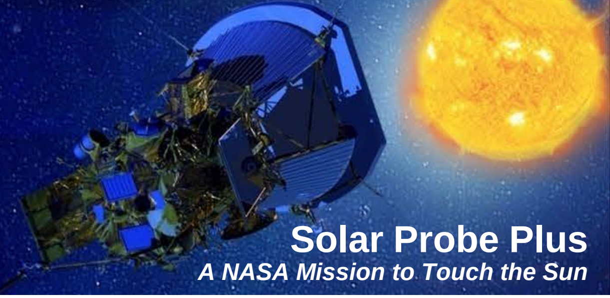


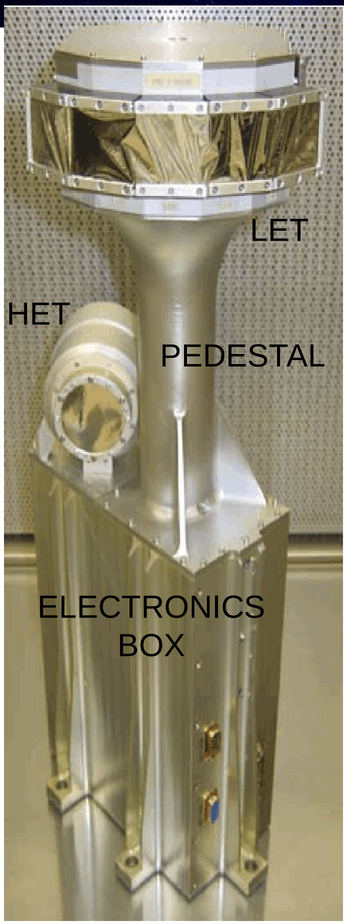
Above: SPAN-B: Anti-ram: observes electrons



Above left: THEMIS ESA (heritage)
Above right: MAVEN Solar Wind Ion Analyzer (SWIA)

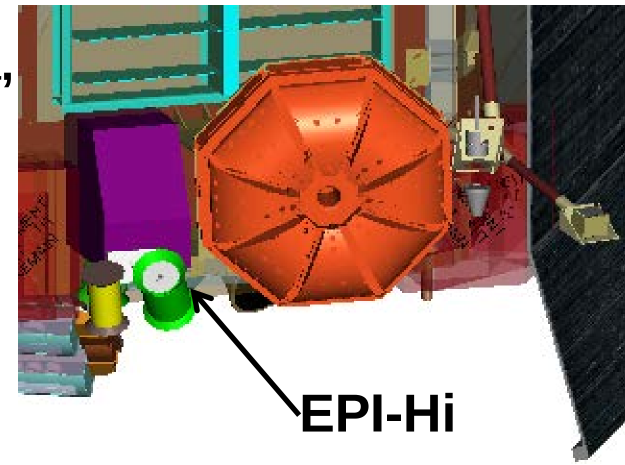
ISIS-EPI-Hi Summary

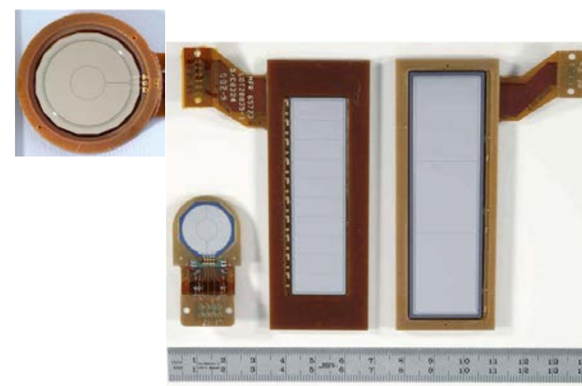




Above: STEREO/IMPACT LET & HET (EPI-Hi heritage)

- **Measures energetic particle spectra, composition, and angular distributions using the dE/dx vs. E technique in a sensor system consisting of:**
  - **Double-ended High Energy Telescope (HET)**
  - **Two Low Energy Telescopes (LETs), one of which is double-ended (LET1) and one of which is single-ended (LET2)**
- **Together they cover ~1 to >100 MeV/nuc for protons and heavy elements and ~0.5 to 6 MeV for electrons**
- **EPI-Hi has its own internal data buffering and processing capability**
  - **Caltech/JPL/SWRI**



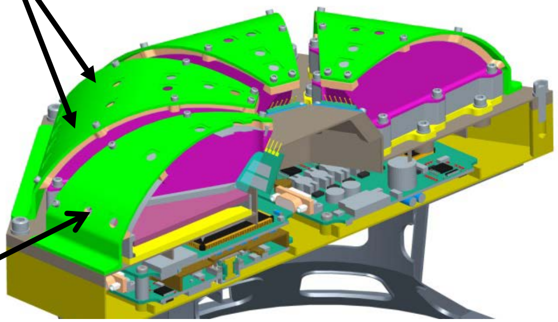


Above: STEREO LET & HET Si Detectors

ISIS-EPI-Lo Summary

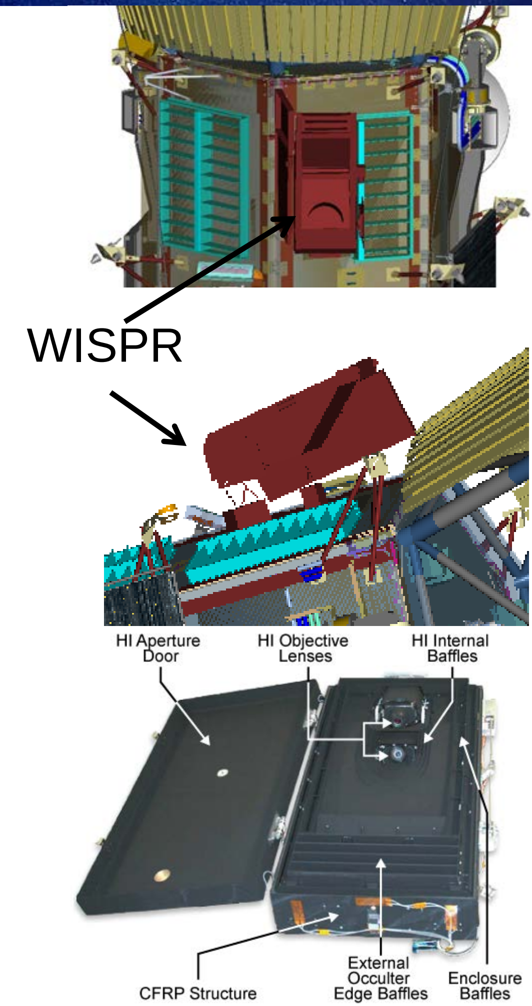
- **High-heritage TOF-based mass spectrometer that measures:**
  - **energetic electron (25-500 keV)**
  - **ion spectra (~0.02-7 MeV protons & 0.02-2 MeV/nuc heavier ions)**
  - **Resolves all major heavy ion species and ^{3}He and ^{4}He over much of this energy range in multiple directions.**
  - **^{3}He measured as a key indicator of impulsive events.**
- **Covers the critical energy range from suprathermal energies (~20 keV/nuc) up to the lower portion of EPI-Hi energy range with a single instrument**
- **EPI-Lo has its own internal data buffering and processing capability**
  - **APL/SWRI**

Above: EPI-Lo PIDDP single-wedge prototype



WISPR (Wide field Imager for Solar Probe)

- **Wide-Field Imager of the Heliosphere**
- **Visible light observations (500-700 nm)**
- **Only mechanism is a one-shot door (Starsys paraffin actuator with LED/photodiode encoders)**
- **2 telescope design, with 2 next-generation 2K x 2K APS sensors**
- **Heritage from SECCHI/HI (STEREO)**
- **Images of coronal structures when they are close to the Sun, as they approach, and as they pass over the spacecraft**
- **Varying viewpoint supports fine-scale 3D reconstructions**
- **Image slow and fast solar wind structures and fluctuations directly**
- **Image CMEs and Shocks**
- **Provides the links between the solar wind structure and SPP *in-situ* instruments.**
- **APL provides WISPR DPU (Data Processing Unit)**
- **Naval Research Lab (NRL)**



SECCHI/HI Heritage

Reference Mission: Launch and Mission Design Overview

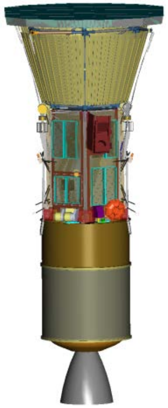
Solar Probe Plus
A NASA Mission to Touch the Sun

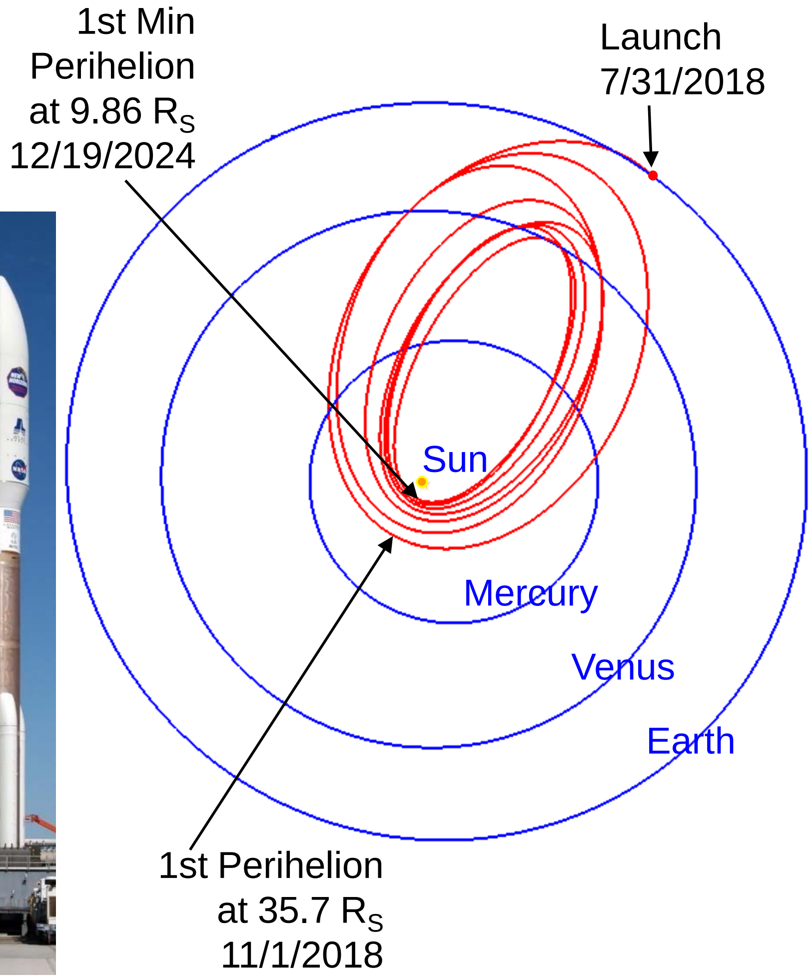
Launch
- **Dates: Jul 31 – Aug 19, 2018 (20 days)**
- **Max. Launch C3: 154 km²/s²**
- **Requires Atlas V 551 class with Upper Stage**

Trajectory Design
- **7 Venus gravity assist flybys**

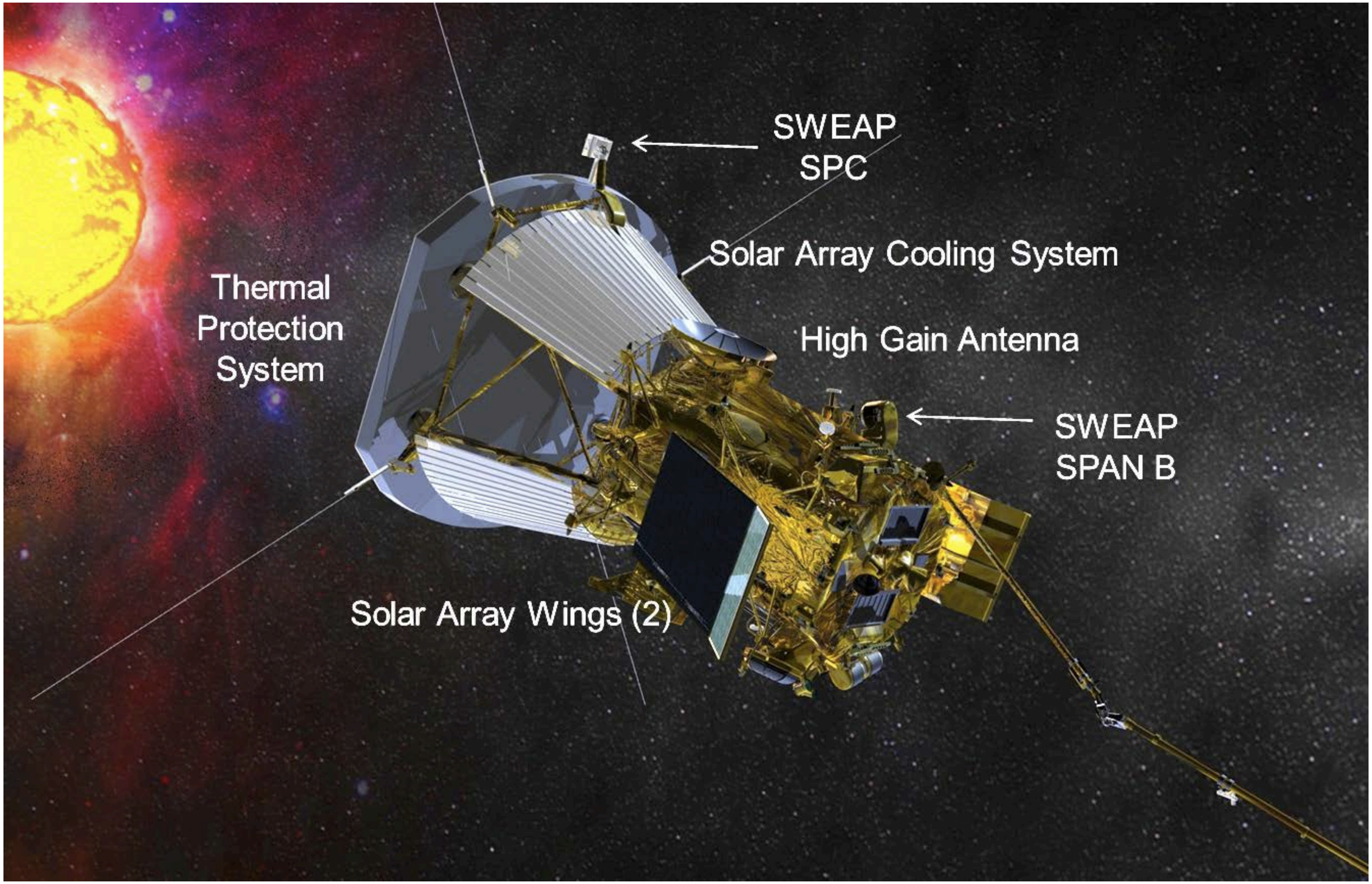
Final Solar Orbits
- **Perihelion: 9.86 R_S**
- **Aphelion: 0.73 AU**
- **Inclination: 3.4 deg from ecliptic**
- **Orbit period: 88 days**

Mission duration: 7 years

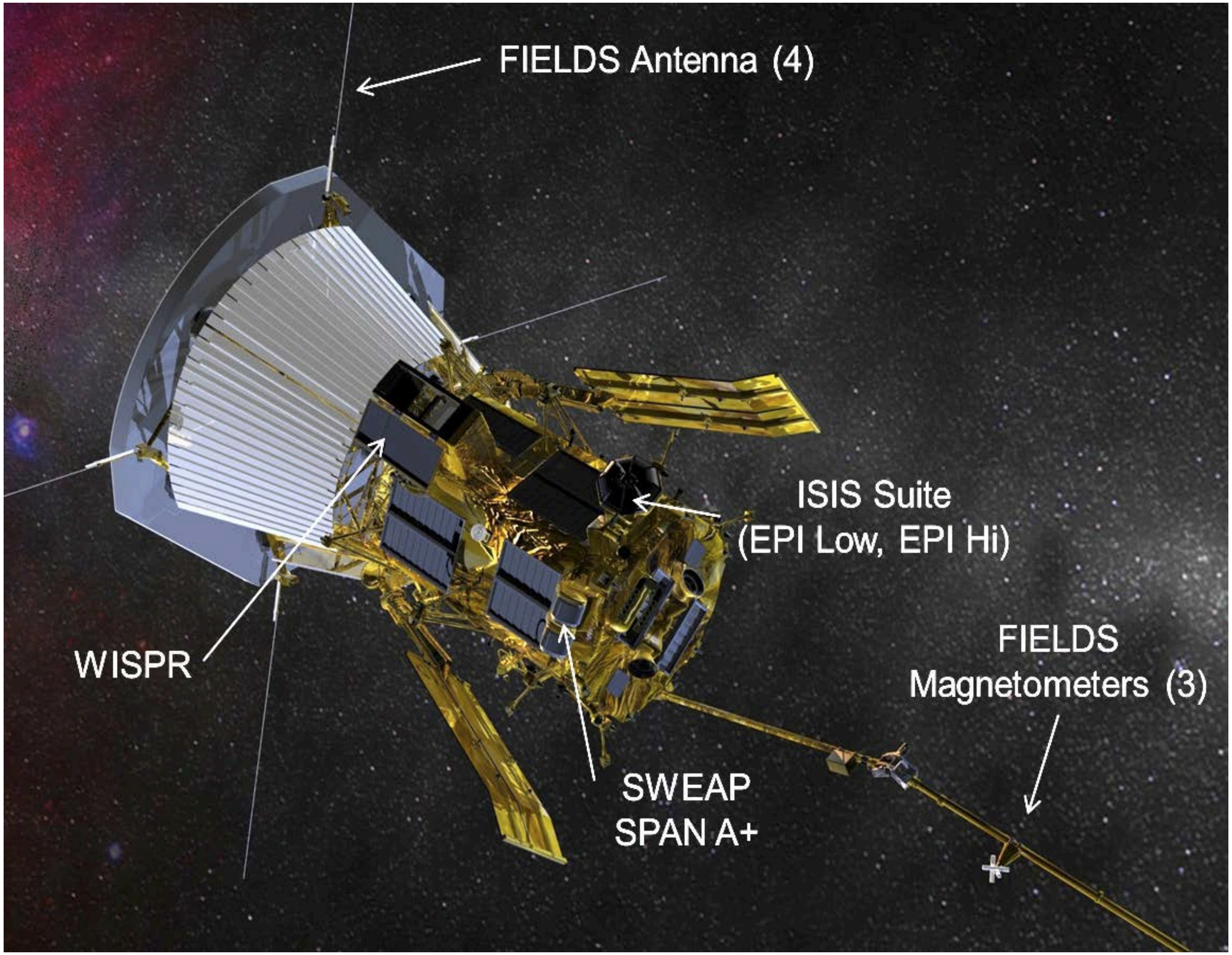




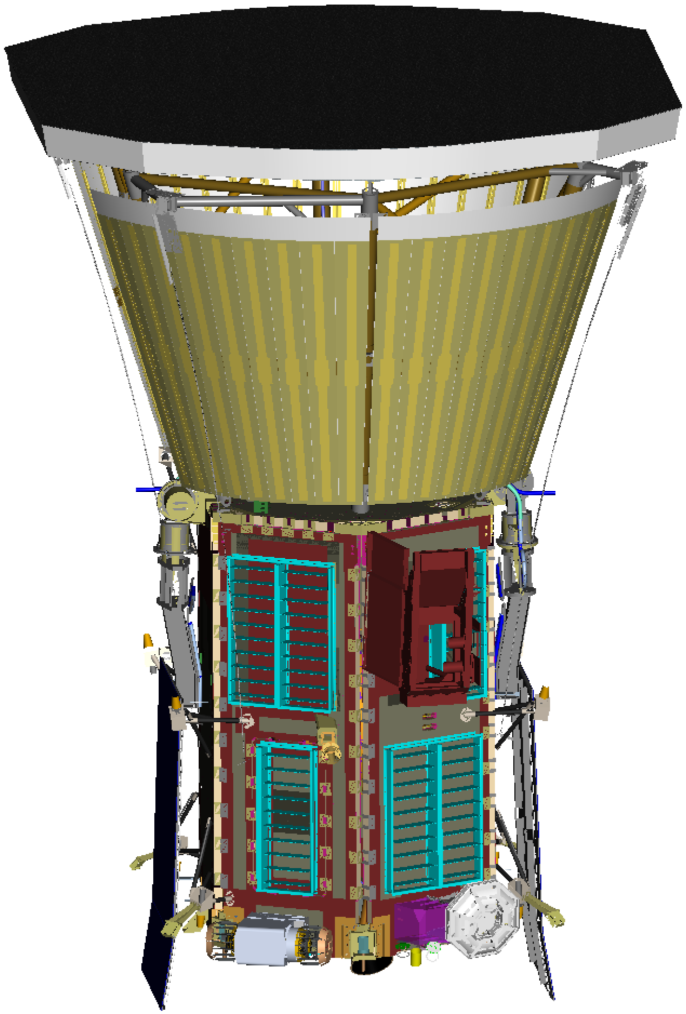
Reference Vehicle: Anti-Ram Facing View



Reference Vehicle: Ram Facing View

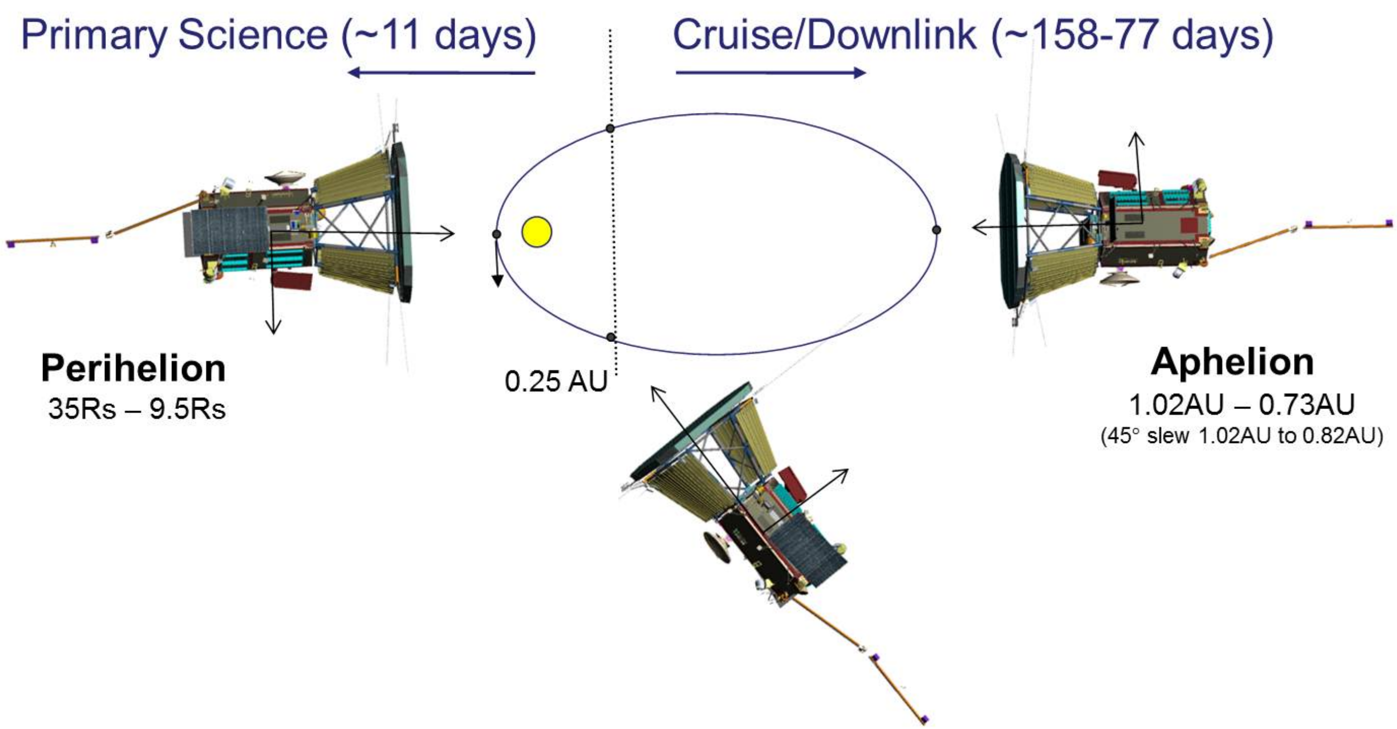


Spacecraft Overview



- NASA selected instrument suites
- 665 kg max launch wet mass
- Reference Dimensions:
  - S/C height: 3m (TBR)
  - TPS max diameter:2.3m (TBR)
  - S/C bus diameter: 1m (TBR)
- C-C Thermal protection system
- Hexagonal prism s/c bus configuration
- Actively cooled solar arrays
  - 364W (TBR) electrical power at encounter
  - Solar array total area: 1.54m^2 (TBR)
  - Radiator area under TPS: 4.4m^2 (TBR)
- 0.6m HGA, 34W TWTA Ka-band science DL
- Science downlink rate: 163kb/s (TBR) at 1AU
- Blowdown monoprop hydrazine propulsion
- Wheels for attitude control

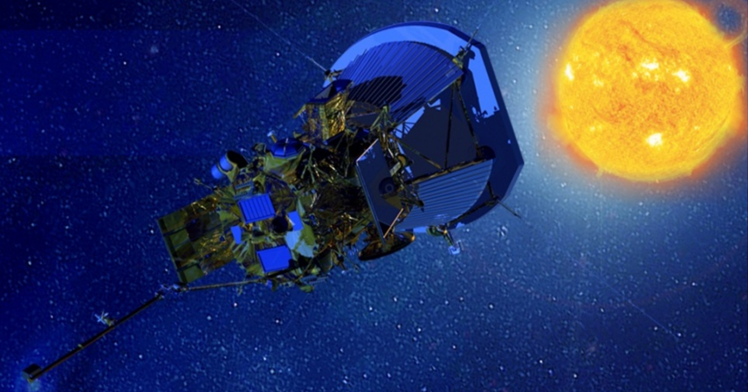
Reference Vehicle:
Concept of Operations



Solar Array Position

Solar Probe Plus

A NASA Mission to Touch the Sun

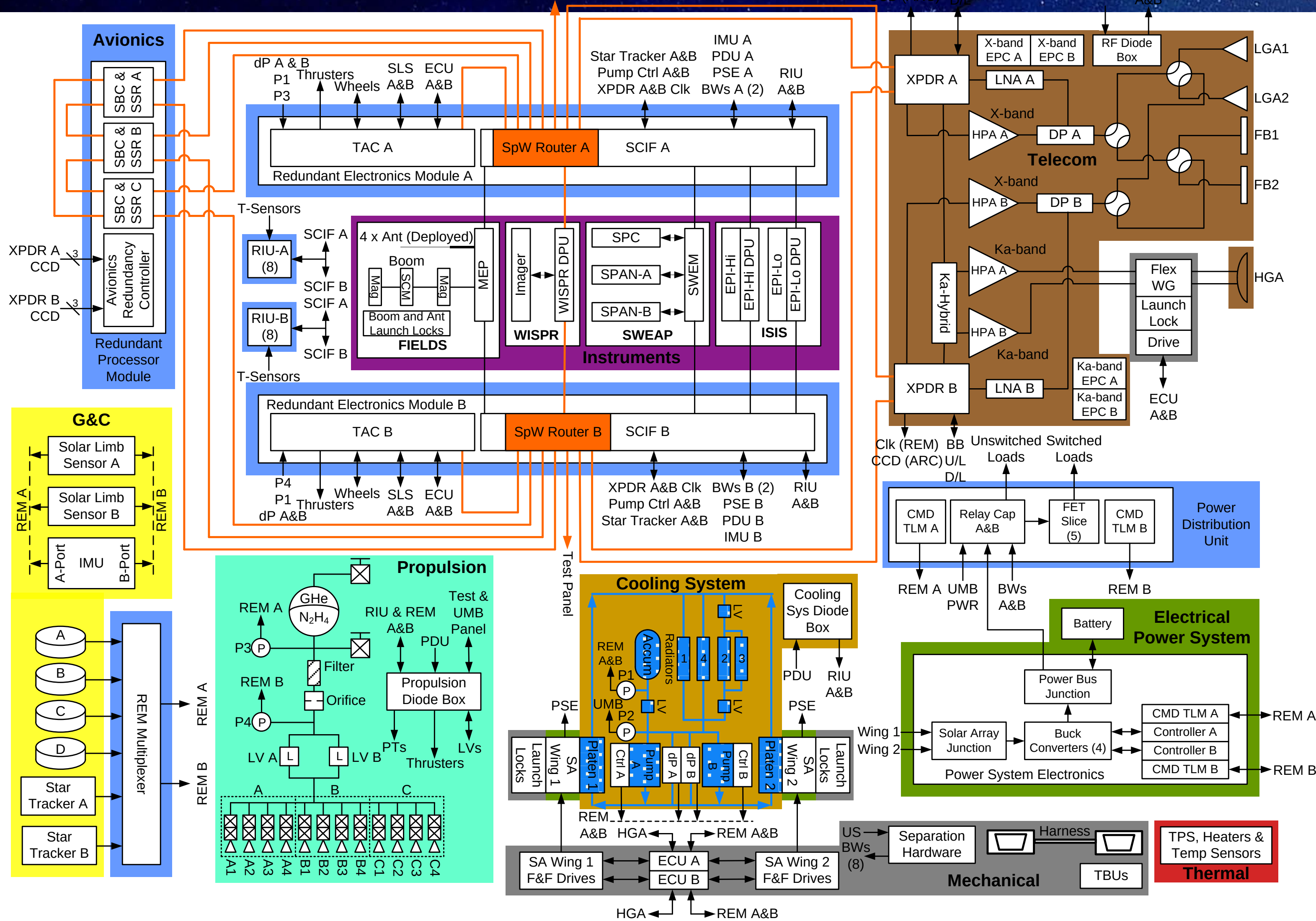


Backup

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Block Diagram
February Baseline

Solar Probe Plus
A NASA Mission to Touch the Sun



Solar Probe Plus Organizational Chart

NASA
Science Mission Directorate
Heliophysics Division
Acting Director: V. Elsbernd
Program Scientist: M. Guhathakurta
Program Executive: J. Lee

GSFC LWS Program Office
Program Manager: N. Chrissotimos
PM for APL Projects: M. Goans
Mission Scientist: A. Szabo

SD Management

Project SAM: L. Becker

Planning Manager: C. Battista
Financial Manager: J. Rodgers

EPO
TBD

Solar Probe Plus Project Office
Project Manager: A. Driesman
Deputy Project Manager: E. Reynolds
Deputy PM for Instruments: P. Hill

Obs Scientist – JPL
M. Velli*

WISPR – NRL*
PI: R. Howard
PM: S. Plunkett

SWEAP – SAO
PI: J. Kasper
PM: J. Bookbinder

ISIS – SwRI
PI: D. McComas
PM: S. Weidner

FIELDS – UCB
PI: S. Bale
PM: P. Harvey

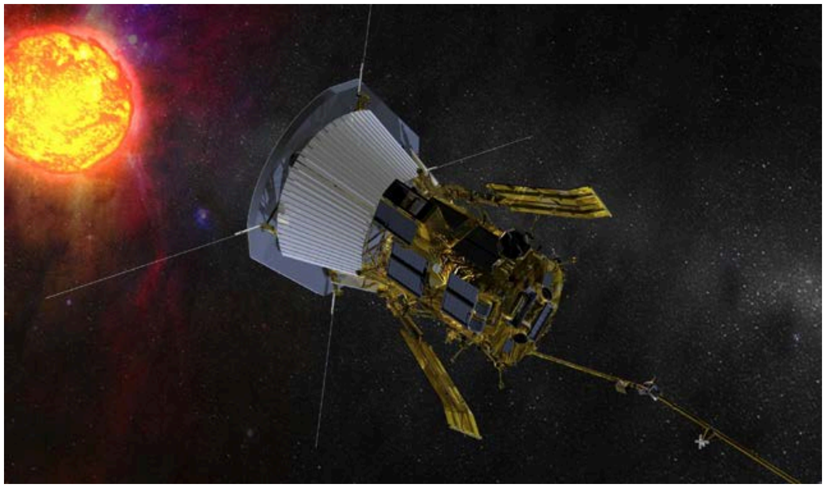
Mission System Engineer
MSE: J. Kinnison
DMSE: M. Lockwood

Project Scientist
N. Fox

Upper Stage Project
PjM: C. Engelbrecht

* Funded directly by NASA

Solar Probe Plus Quad Chart



Overview

Using in-situ measurements made closer to the Sun than by any previous spacecraft, SPP will determine the mechanisms that produce the fast and slow solar winds, coronal heating, and the transport of energetic particles.

Solar Probe Plus will fly to less than 10 solar radii (Rs) of the Sun, having “walked in” from 35 Rs over 24 orbits.

Sponsor: NASA SMD/Heliophysics Div

- Program Office – GSFC/LWS
- Project Scientist - APL
- Project Management - APL
- S/C Development & Operations – APL
- Science Investigations selected by AO:
  - SWEAP - Smithsonian Astrophysical Observatory
  - FIELDS - UC Berkeley
  - WISPR - Naval Research Laboratory
  - ISIS – Southwest Research Institute
  - HelioOrigins – Jet Propulsion Laboratory

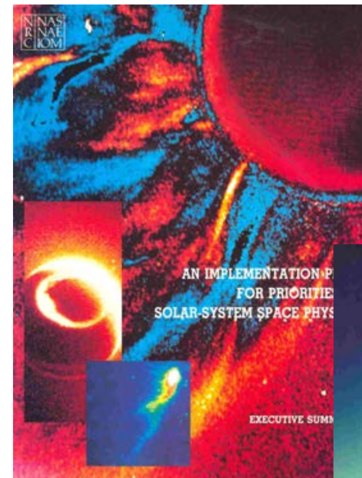
Preliminary Mission Milestones (Assuming 2018 Launch)

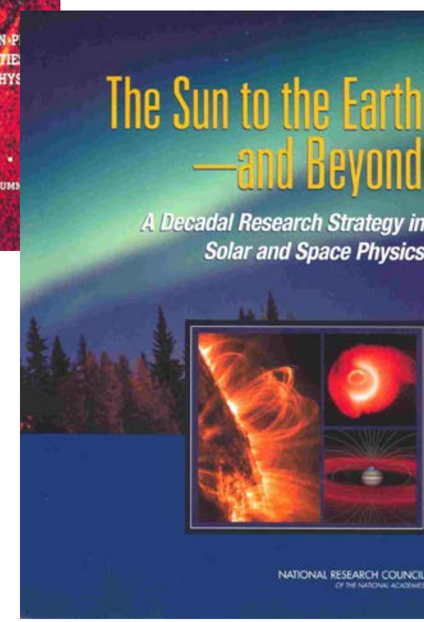
Pre-Phase A:	07/2008 – 11/2009
Phase A:	12/2009 – 01/2012
Phase B:	02/2012 – 03/2014
Phase C/D:	03/2014 – 08/2018
Phase E:	09/2018 – 09/2025

Solar Probe History (1958 - present)

Solar Probe Plus
A NASA Mission to Touch the Sun

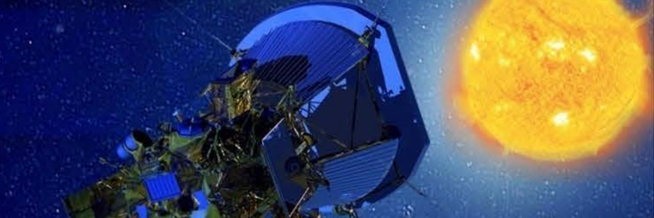
New STDT in line of studies dating back to "Simpson's Committee" of the Space Science Board (National Academy of Sciences) (24 October 1958)





APL

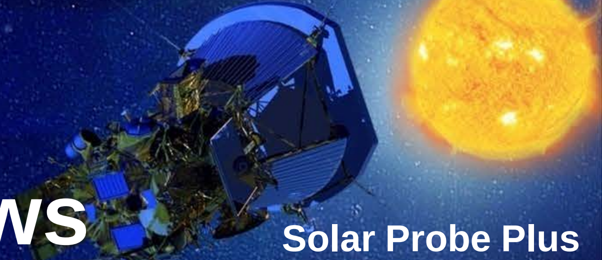
System Engineering Organization



Solar Probe Plus
A NASA Mission to Touch the Sun

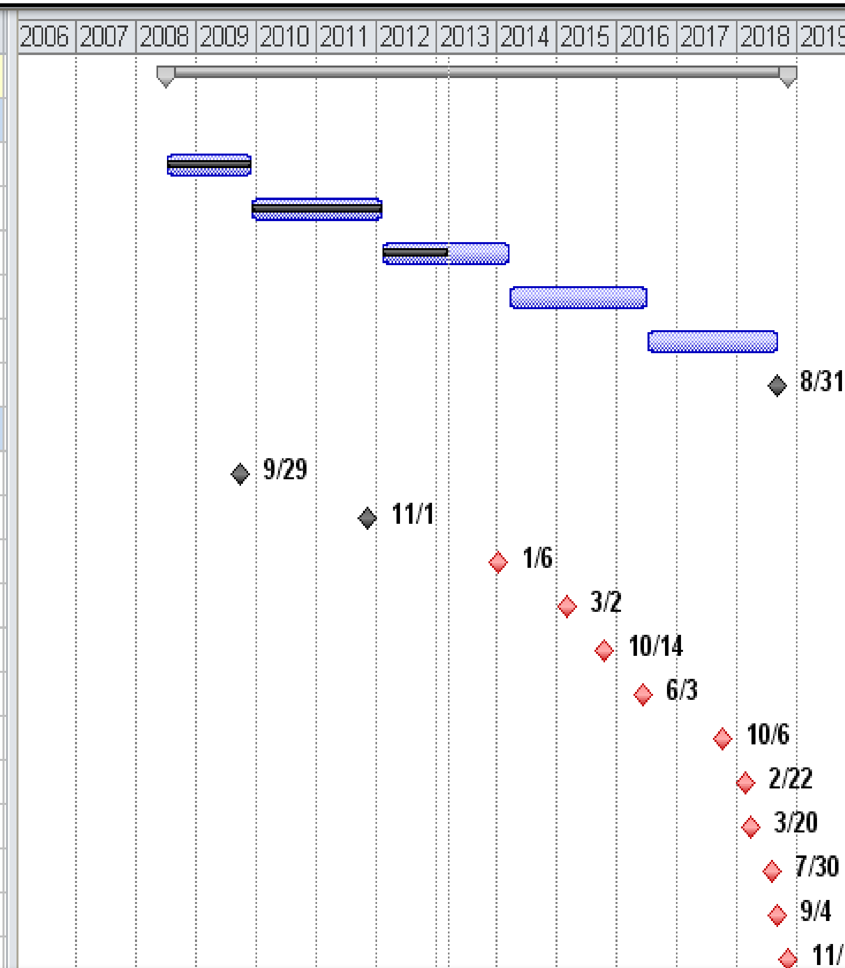
- **Mission System Engineer**
  Jim Kinnison
  Mary Kae Lockwood (Deputy)
  - Fault Management — Sanae Kubota
  - EMI/EMC — Carl Herrmann
  - Parts — David Bonner
  - Requirements — Dan Kelly
  - Contamination Control — John Nichols
  - Materials and Processes — Tyler Langley
  - Reliability — Clay Smith
  - Radiation — Dave Roth
  - Data System Engineer — Alan Mick
  - Charging — Michelle Donegan
  - Mission Design/Navigation — Yanping Guo
  - Integration & Test — Mike Colby
  - Spacecraft SE — Mary Kae Lockwood, Rich Conde (Deputy)
  - Payload SE — John Boynton
  - Ground System HW — Walter Mitnick
  - Upper Stage SE — Rich Anderson
  - Mission Software SE — Mike Furrow
  - Mission Operations — Nick Pinkine
  - Launch Vehicle Integration Manager — Steve Vernon

Phase Duration and Key Reviews



Solar Probe Plus
A NASA Mission to Touch the Sun

Task Name	Start	Finish
Solar Probe Plus Mission Schedule	**7/2/08**	**11/1/18**
Mission Phases	**7/2/08**	**8/31/18**
Pre-Phase A	7/2/08	12/1/09
Phase A	12/2/09	1/31/12
Phase B	2/1/12	3/14/14
Phase C	3/15/14	6/23/16
Phase D	6/24/16	8/30/18
Phase E Start (Ends 9/1/25)	8/31/18	8/31/18
Mission-Level Milestones	**9/29/09**	**11/1/18**
MCR	9/29/09	9/30/09
MDR	11/1/11	11/3/11
PDR	1/6/14	1/8/14
CDR	3/2/15	3/4/15
MOR	10/14/15	10/14/15
SIR	6/3/16	6/3/16
PER	10/6/17	10/6/17
PSR	2/22/18	2/22/18
ORR	3/20/18	3/20/18
LRR/LRD	7/30/18	7/30/18
Orbital Checkout Complete	9/4/18	9/4/18
First Perihelion	11/1/18	11/1/18



APL

Spacecraft Technology Development

Solar Probe Plus

A NASA Mission to Touch the Sun

Subsystem	Description	Development Plan
Thermal Protection System (TPS)	Lightweight, non-ablative insulating layer. Provides umbra to protect spacecraft from near-Sun environment. Shaped to provide “knife edges” for solar array wings and “chamfers” for Solar Limb Sensors.	Significant materials and coatings testing. Full-scale mechanical prototype tested in the launch environment. Subscale prototype used in thermal testing in perihelion environment.
Solar Array Cooling System	Pumped-water cooling system for thermal control of the solar cell wings. Dissipates ~6000 W of heat at perihelion and is designed and operated to prevent freezing at aphelion.	Additional wing and radiator fabricated and structurally tested for launch environment. Full-scale “1/2” cooling system prototype in fabrication to include one wing, two radiators and pump. Testing includes thermal and hydraulic performance.
Solar cells	Primary and secondary sections with fixed cant angle between sections. Secondary section uses a thermally optimized cell stack illuminated to about 25 Suns at perihelion.	Full size secondary section in fabrication, including water-cooled substrate and flight-like cell assemblies to be tested at high solar irradiance, high temperature conditions.
Solar Limb Sensor	Positioned in umbra so that sensors are illuminated before any other item in the umbra. Provides early warning of umbra violation.	Prototype sensor fabrication and testing in penumbra environment.

Payload Technology Development

Instrument	Description	Development Plan
FIELDS	Four niobium whip antennas extend beyond TPS for electric field measurements. Each mounted to TSA through thermal choke to prevent heat transfer into structure.	Significant materials testing in realistic solar environment. Fabrication and test of thermal choke prototype to validate thermal modeling.
SWEAP Solar Probe Cup	Faraday cup using a series of high voltage and ground grids to measure energy of incoming solar wind ions. Mounted on arm that extends beyond TPS for direct observation of radial solar wind flow.	Significant materials and coatings tests performed to develop characteristics over temperature. Mechanical and thermal tests of grid prototypes have been done Prototypes will be used in thermal and mechanical tests to prove concept and validate modeling.

Protecting Solar Probe Plus

SPP Design
TPS coating, foam thickness provides standard spacecraft thermal environment.
All spacecraft components are packaged within an 8° packaging umbra, from nominal TPS, providing at least 2° margin against 6° umbra at 9.5Rs. Spacecraft pointing accuracy is 6 arcmin (0.1deg), well within umbra margin.
Solar cell laydown designed for higher thermal conductivity, higher temperature tolerance. Solar array angle autonomously controlled, meets power load with minimum thermal load. Solar array cooling system sized for additional margin above margined power loads.
Designed to meet radiation environments.
Dust environment, impact analysis, design guidelines – s/c and instruments. Solar arrays oriented parallel to ram to minimize dust environment on arrays.
Spacecraft is designed to be single fault tolerant and to minimize fault management response time. Fault management designed for autonomous safing and recovery.
Solar Limb Sensors provide an additional sensor to warn of a nearing umbra violation. Solar array current and voltage sensors provide additional sensors to warn of high irradiance or over-temperature on the wings.
Mission design "walk-in" provides calibration opportunity in less severe environment

Launch System Overview

- Launch System is the Launch Vehicle and Upper Stage
- Mission performance is determined by combined LV and US performance
  - SC separated mass: 665 kg
  - C3 requirement: 154 km^2/sec^2
- Significant Phase B effort to define launch vehicle performance

Note: Mechanical interfaces designed to be compatible with all EELV Class vehicles