High Performance Computing for Space & Astrophysical Sciences

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HPC USER FORUM
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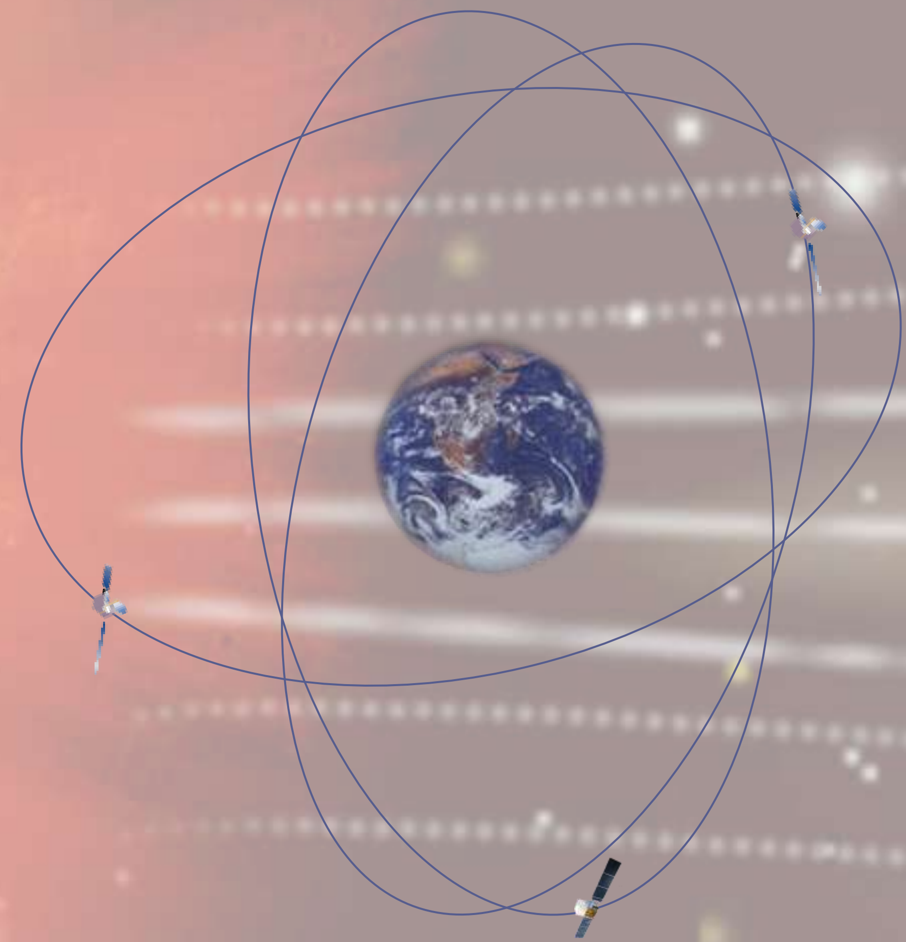
The Sun-Earth System
our home in space

Earth is habitable because the Sun shines, radiating energy throughout the entire heliosphere.

Electromagnetic energy traveling radially outward from the Sun illuminates the heliosphere with a flux of photons.



HELIOSPACE

The Sun-Earth System our home in space

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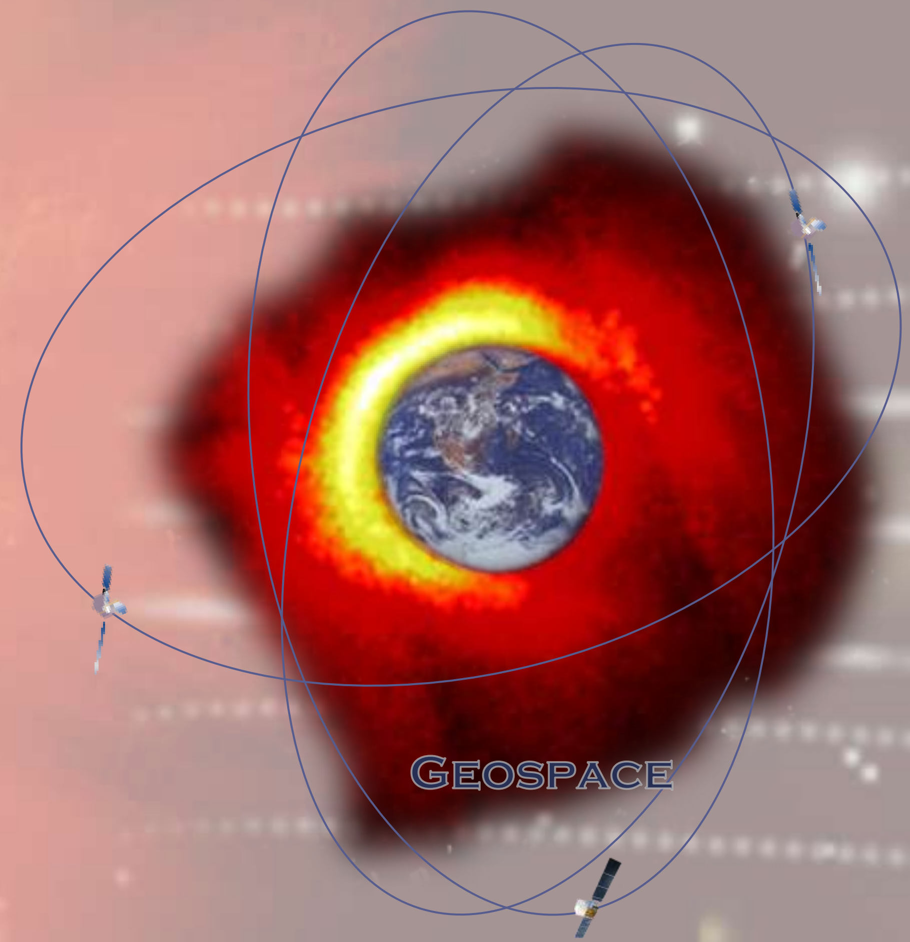
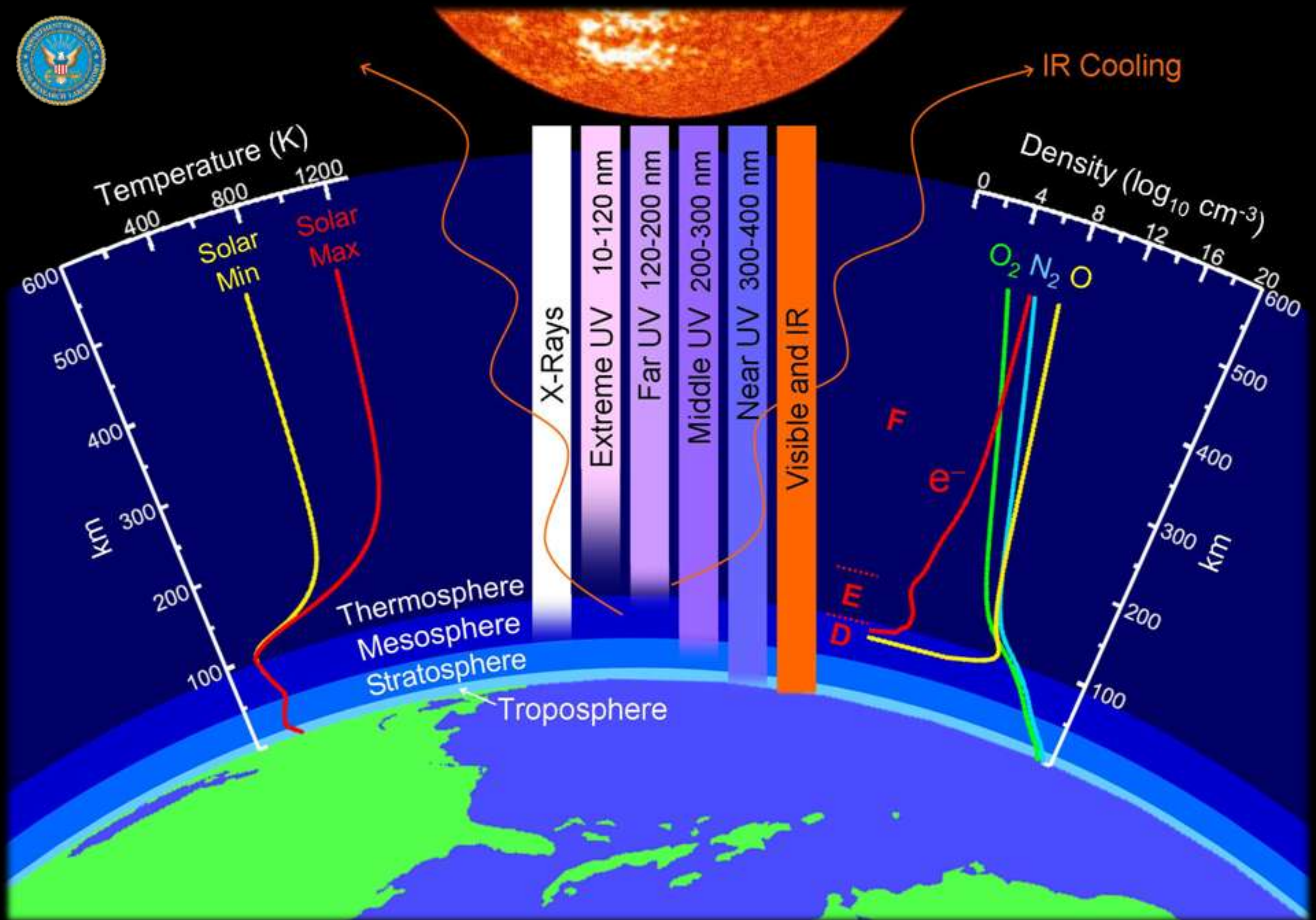
Electromagnetic energy traveling radially outward from the Sun illuminates the heliosphere with a flux of photons.

Earth, which has no primary energy source of its own, intercepts the Sun's energy, collecting photons emitted from all locations of the solar disc to its various domains of ocean, land, and atmosphere.

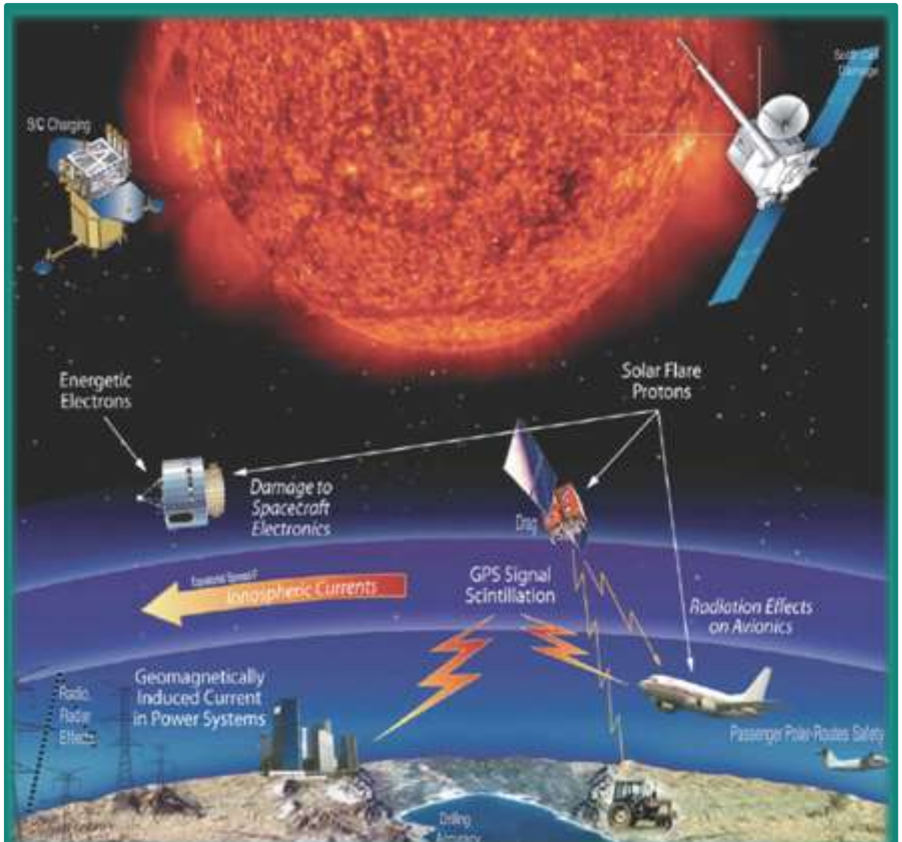


HELIOSPACE



The Sun effects the variable, dynamic atmosphere of geospace

Space environmental dynamics ...



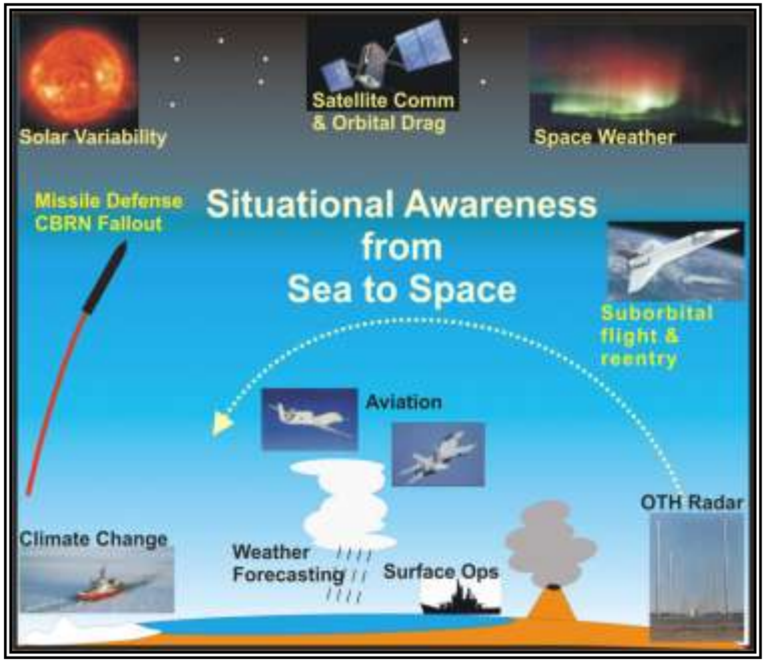
Comms on the Move; ISR; Missile Detection, Tracking, Intercept; Precision Engagement; Intell; S/C Anomaly Assessment; Attack Assessment; Power Grid Failures

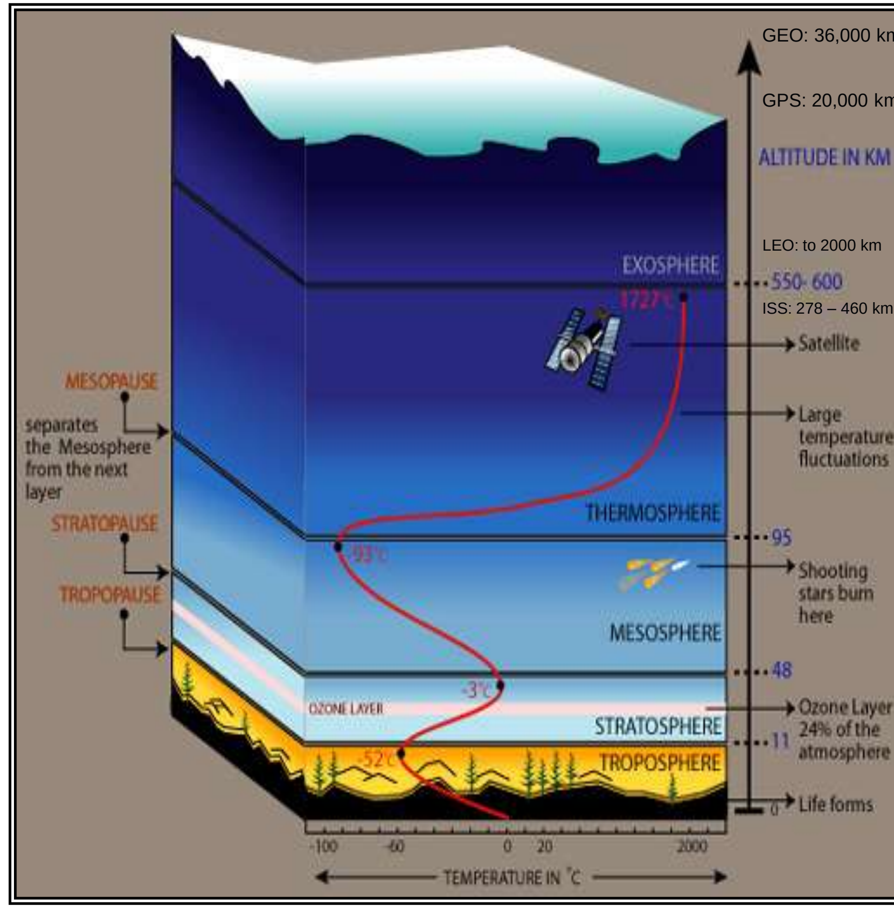
... affect orbital tracking, space situational awareness, C²ISR, precision navigation and timing, the fundamental understanding of geophysical phenomena, and effects of natural and artificial radiation sources

'Space weather includes any and all conditions and events on the Sun, in the solar wind, in near-Earth space and in our upper atmosphere that can affect space-borne and ground-based technology systems and through these, human life & endeavor. .. Today the [prediction] batting average is about 0.5, which is about the same as was the case with .. severe meteorological storms - then a more mature field of study - in the 1960s.'

[From: *A Guide to the Sun-Earth System*, Jack Eddy, NASA, 2010]

Geospace



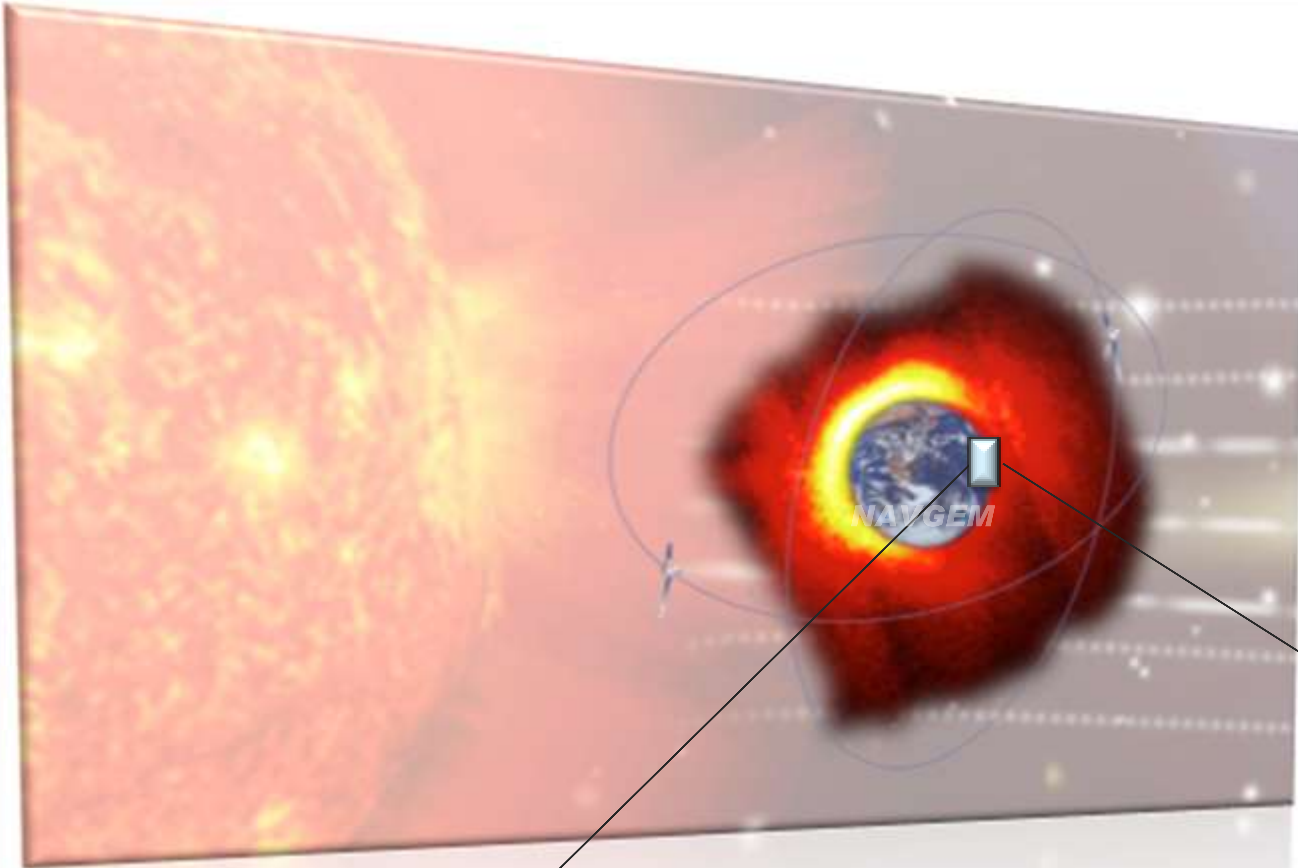


Ionosphere

[2daysscience.blogspot.com; http://dsc.discovery.com/space/my-take/space-junk-debris-cleanup.html]

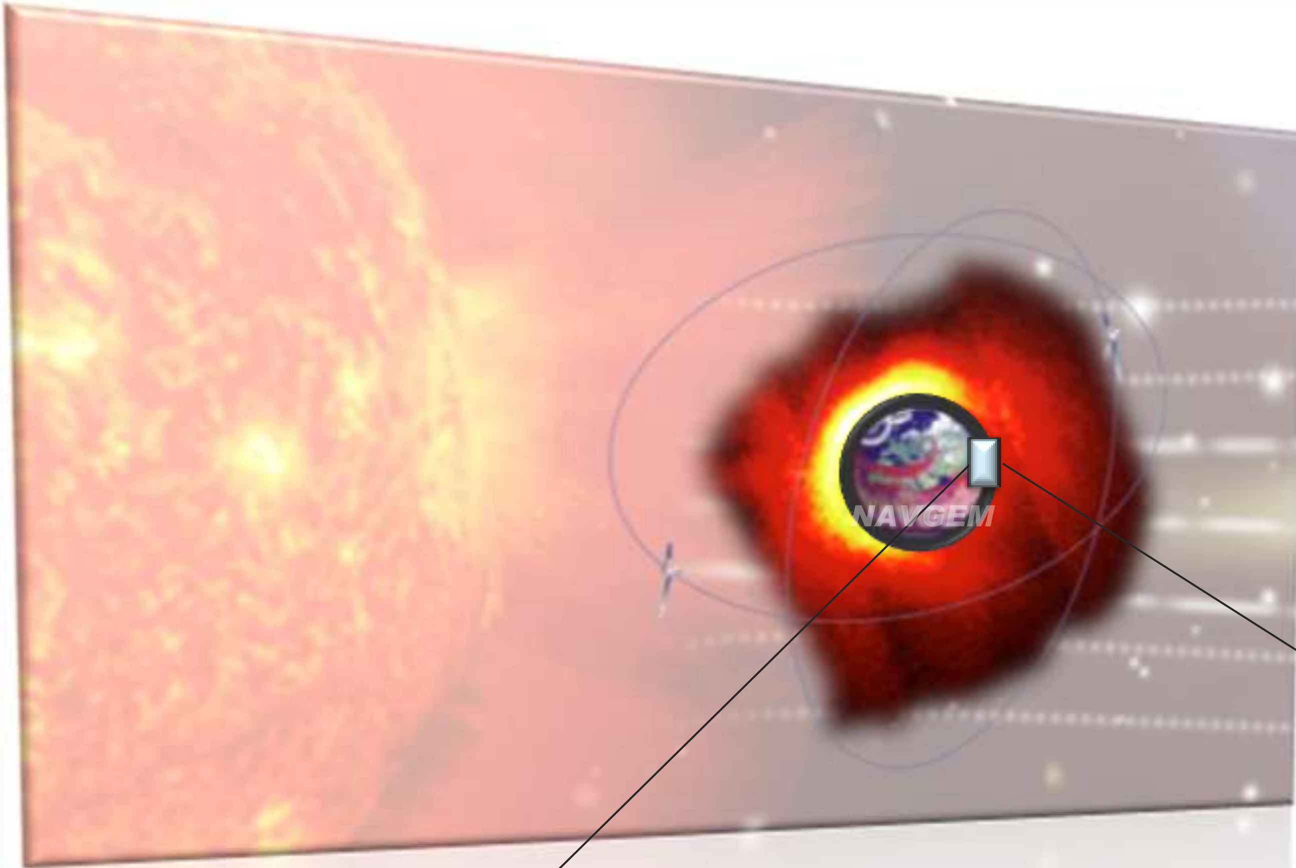
<u>S&T Status:</u> Research in the development and deployment of space-based sensors that measure the thermosphere and ionosphere; in application of theoretical, experimental, and HPC computational techniques to understand near-Earth dynamics to gain a predictive capability and mitigate environmental effects; and, in problem-centric tasking and fusion processing systems and analysis architectures for increased situational awareness

Geospace HPC Research Examples



High Altitude Numerical Weather Prediction

Geospace HPC Research Examples



High Altitude Numerical Weather Prediction

NAVGEM: Towards a Ground-to-Space Navy Global Earth System Prediction Capability (ESPC)

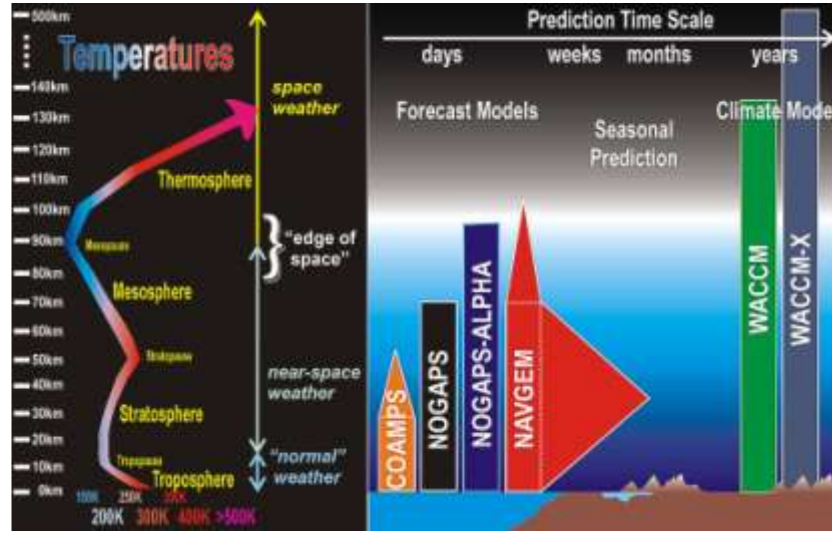
Stephen Eckermann

Objective

- To extend the **Navy Global Environmental Model (NAVGEM)**, as the DoD's bridge strategy to a future ESPC, from its current upper boundary at ~65 km altitude, to altitudes of ~100 km
- Use the system to improve the skill and range of atmospheric forecasts, with an emphasis on deep coupling pathways affecting seasonal prediction (e.g. Arctic sea ice)
- Transition new capabilities to the operational NAVGEM at Fleet Numerical Meteorology & Oceanography Center (FNMOC) if/where they yield improved skill or new Navy-relevant capabilities

Approach

- Extend HPC global semi-Lagrangian forecast model to ~100 km
- Add new HPC physics packages to the model that are important at these new high-altitude atmospheric regions
- Extend HPC Data Assimilation System (NAVDAS-AR) to ~100 km
- Fully couple the forecast model and DAS to provide forecast-assimilation capabilities over the 0-100 km height range
- Assimilate new high-altitude observations into the system
- Validate new high-altitude forecasts against independent stratospheric and mesospheric observations
- Quantify the impacts on prediction skill at all altitudes
- Transition new developmental (NOGAPS-ALPHA) components with promising skill impacts into NAVGEM, and objectively quantify impacts using standard Navy forecast skill metrics
- Close continuous collaboration among the NRL Space Science, Marine Meteorology and Remote Sensing Divisions



(Image: Naval Research Laboratory)

Schematic depiction of the prediction ranges of various atmospheric models relevant for this work, plotted versus altitude (y) and predictive time scale (x). Prediction over this entire space is the long-term goal of the collaborative Earth System Prediction Capability (ESPC).

Deliverable/Value/Accomplishment

- Successful (world first) development and demonstration of a prototype global numerical weather prediction system extending from the ground to the edge of space at ~90 km, known as NOGAPS-ALPHA, which is now informing NAVGEM.
- 2010 transition of NOGAPS from ~35 km to ~65 km altitude using NOGAPS-ALPHA components, which led to large increases in tropospheric forecast skill (~3-6 hours at +5 days)
- Completed inaugural operational transition of NAVGEM to FNMOC on 13 February 2013
- Further, NOGAPS-ALPHA fast ozone photochemistry schemes transitioned to Navy and National Weather Service models

Spatial Heterodyne Imager for Mesospheric Radicals (SHIMMER)

Christoph Englert

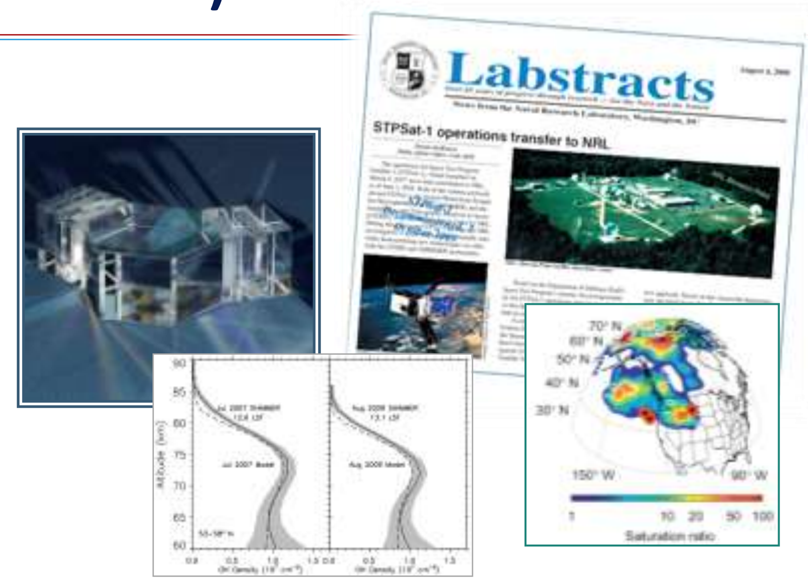
Objective

SHIMMER, the primary payload of STPSat-1 from March 2007 thru Oct 2009, had four main objectives:

1) Fly in space, for the first time, a monolithic Spatial Heterodyne Spectrometer (SHS) to increase the technical readiness level for this innovative optical technique
2) Observe mesospheric OH (hydroxyl) on a global scale at all (daytime) local times to investigate atmos. photochemistry
3) Observe Polar Mesospheric Clouds (PMCs) at the edge of their polar occurrence region
4) **Validate NOGAPS-ALPHA/ NAVGEM saturation modeling**

Approach

- SHIMMER uses the first monolithic Spatial Heterodyne Spectroscopy (SHS) interferometer, which allowed the design of a high resolution UV spectrometer that was a factor of 7 smaller and lighter than a comparable, conventional grating spectrometer
- OH density profiles were derived from OH resonance fluorescence signal superimposed on the bright "blue sky" scattered background
- PMC occurrences and brightnesses were inferred from enhanced scattered UV at PMC altitudes
- STPSat-1 was operated for 1 year by the DoD Space Test program and for an additional 1.5 years by NRL from Blossom Point MD
- SHIMMER data is being used to advance understanding and near-predictive capability of the space domain, towards exploiting the geospace environment and its impact on Navy/ Marine Corps systems



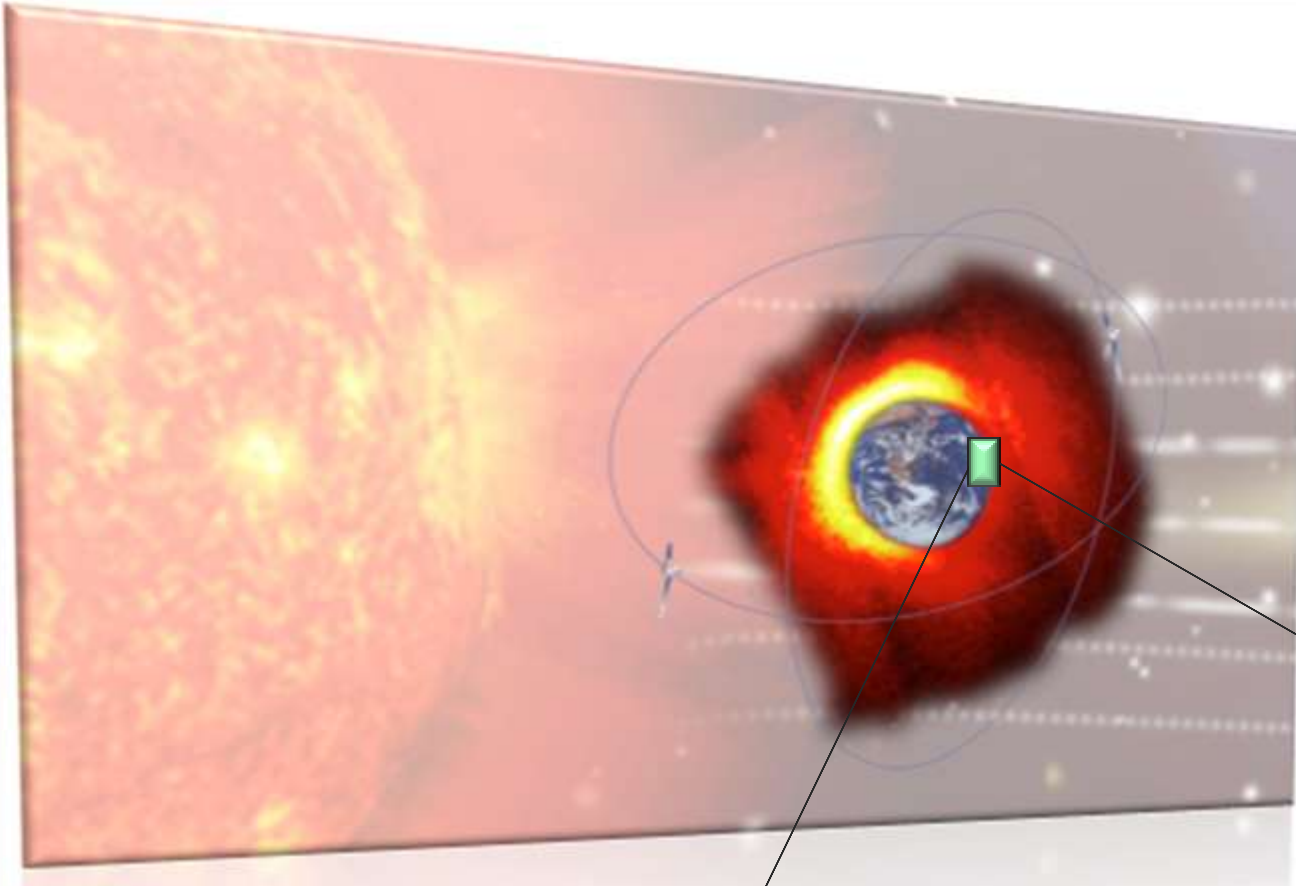
Top left: Image of monolithic interferometer; top right: STPSat-1 on orbit & Blossom Point; bottom left: OH model/data comparison; bottom right: NOGAPS-ALPHA saturation map and mid-latitude PMC observations.

(TL & TR: NRL; BL: Englert et al., JGR, 2010; BR: Eckermann et al., JASTP 2009)

Deliverable/Value/Accomplishment

- Successful demonstration of SHS technique on orbit
- First global mesospheric OH data set covering all daytime local times
- Multi year PMC data set at the edge of the PMC regions
- OH data solved long standing HO_x dilemma (a fundamental question about the atmospheric HO_x photochemistry)
- PMC data allowed validation of high altitude extension of Navy operational weather prediction system
- SHS is now a new, demonstrated space sensing tool

Geospace HPC Research Examples



Infrasound Calibration Experiment Signal Modeling

Empirical Modeling of the Upper Atmosphere: NRLMSISE-00, HWM07, and G2S

Douglas Drob

Objectives

Measurement-based specification of the upper atmosphere system and its response to solar and lower atmospheric drivers. The upper atmosphere is operationally important because of the drag it exerts on low Earth orbit satellites, and because of its fundamental influence on the ionosphere.

These empirical models are a key components of upper atmospheric research and operations, for:

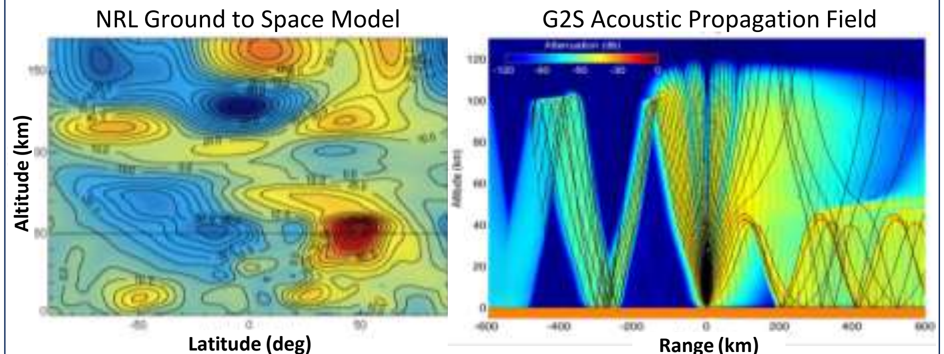
- Specification and prediction of the environment;
- Benchmark for calibrating and validating new measurements and measurement techniques;
- Interpolation and extrapolation of data; and,
- Initial and/or boundary condition for general circulation models.

Approach

- Collect all available contemporary and historical upper atmospheric data (most extensively from DoD, NASA, NSF).
- Rigorous statistical analysis of the systematic response of the data to key drivers and variables.
- Encapsulate the behavior of the data in a user-friendly model with important physical constraints.
- Model validation; identification of biases among data sets and measurement techniques.
- Ground-to-Space HPC real-time atmospheric specification merges operational lower atmospheric meteorology with NRL's upper atmospheric empirical models.

<u>MSIS</u>: Mass Spectrometer & Incoherent Scatter Radar Exosphere;
<u>HWM</u>: Horizontal Wild Model;
<u>G2S</u>: Ground to Space

A G2S objective is to improve understanding of effects of atmospheric dynamics on observable infrasound propagation characteristics.



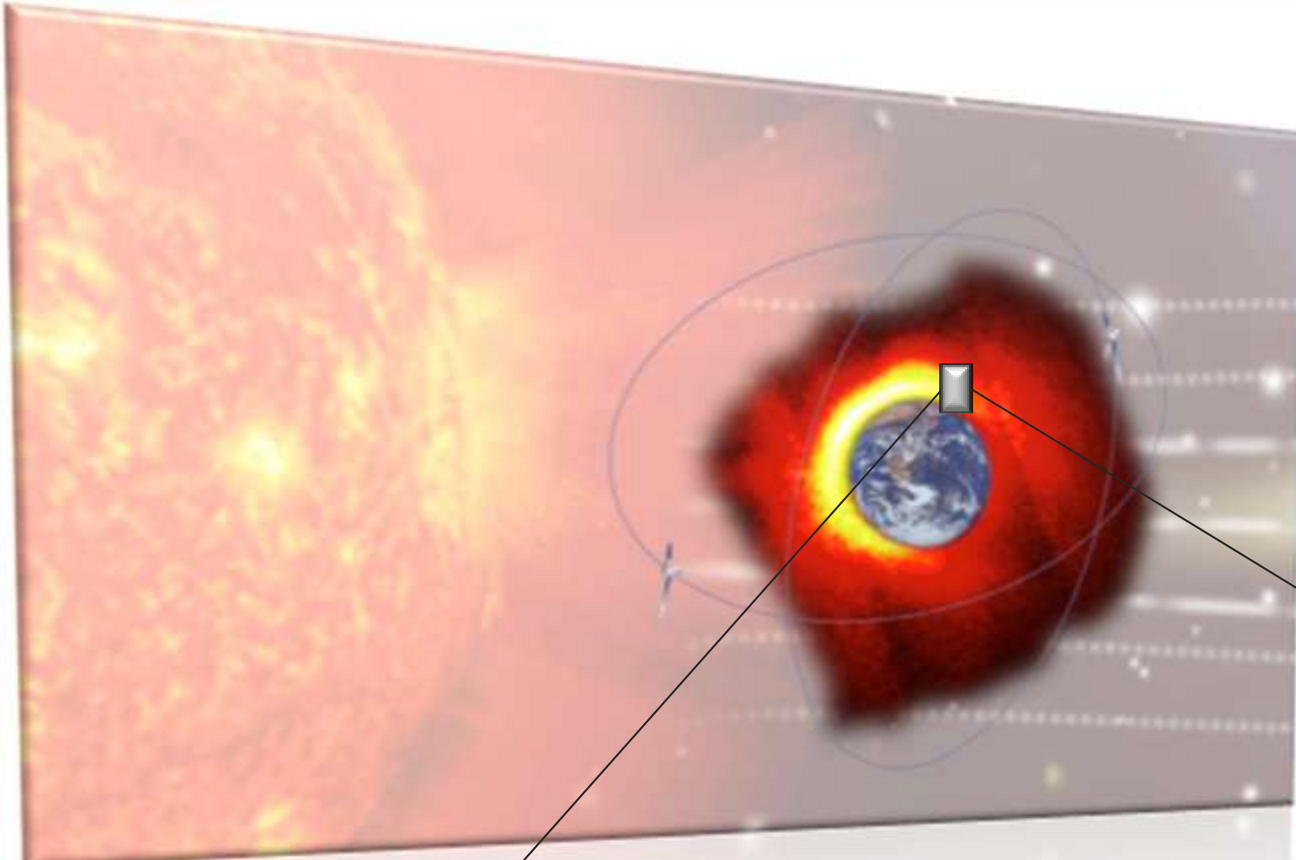
G2S merges meteorological data with NRLMSISE-00 and HWM07; the left panel shows an example of G2S east-west winds. One application of G2S is the propagation of infrasound signals, as shown in the example in the right panel.

(Image: Naval Research Laboratory)

Deliverable/Value/Accomplishment

- Delivered whole-atmosphere models: NRLMSISE-00 model of total density, temperature and composition; HWM07 model of winds, 0-500 km altitude; G2S real-time atmospheric specification
- These models are used operationally by AFWA, DMSP, SMDC, AFTAC, NNSA, and MDA
- G2S used for infrasound propagation in CTBTO monitoring research; demonstrated improvement in source location
- The models are used extensively by space weather research communities, including NRL, AFRL, NASA, and NOAA
- NRLMSISE-00 and HWM07 are the COSPAR international Standard Reference Atmosphere (CIRA)

Geospace HPC Research Examples



Bottomside Ionosphere Weather Modeling

The ionosphere acts as the boundary between Earth's neutral atmospheres and space, containing weakly ionized plasmas that are strongly coupled to the neutral atmosphere. It experiences a constant tug-of-war between terrestrial drivers from below and solar drivers from above.

Bottomside Ionosphere Weather Modeling

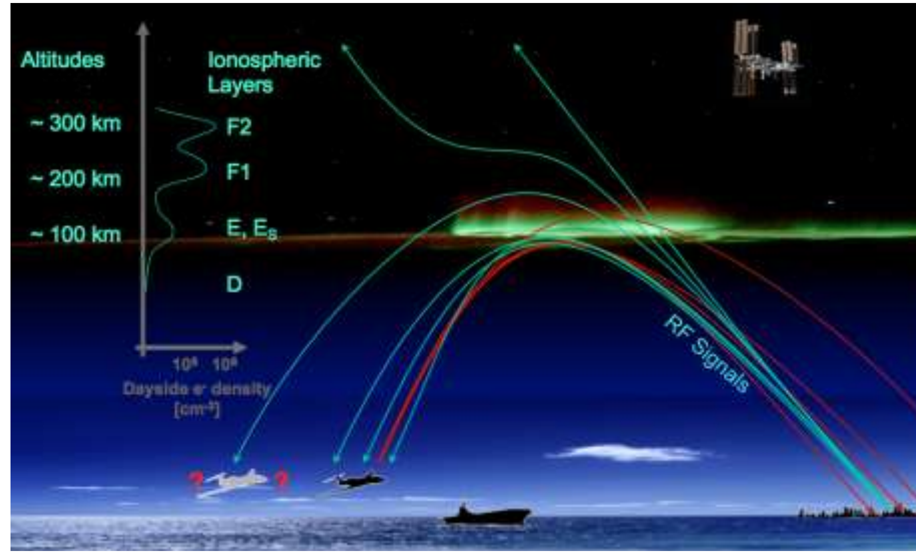
Christoph Englert

Objective

Demonstrate and validate a high-performance computing atmospheric simulation capability that includes sufficient atmospheric modeling of the variability of the bottom-side ionosphere (BSI) at low to mid latitudes, for accurate numerical forecast of HF radio wave propagation through Earth's atmosphere and ionosphere

Approach

- Develop a coupled atmospheric model, combining existing components WACCM-X (Whole Atmosphere Community Climate Model) and SAMI3 (NRL comprehensive, physics-based model of the ionosphere)
- Constrain the lower atmosphere with lower atmosphere meteorology information from NAVGEM
- Include D/E region chemistry and metal ions
- Quantitatively assess model performance with data -- ground-based and satellite observations -- using modern HF propagation codes
- Address science questions: How does the ion composition in the BSI (metal, molecular, proton hydrates) affect RF propagation? What are the roles of atmospheric waves (e.g., tides and gravity waves) in the BSI, especially for the initiation of sporadic-E events?

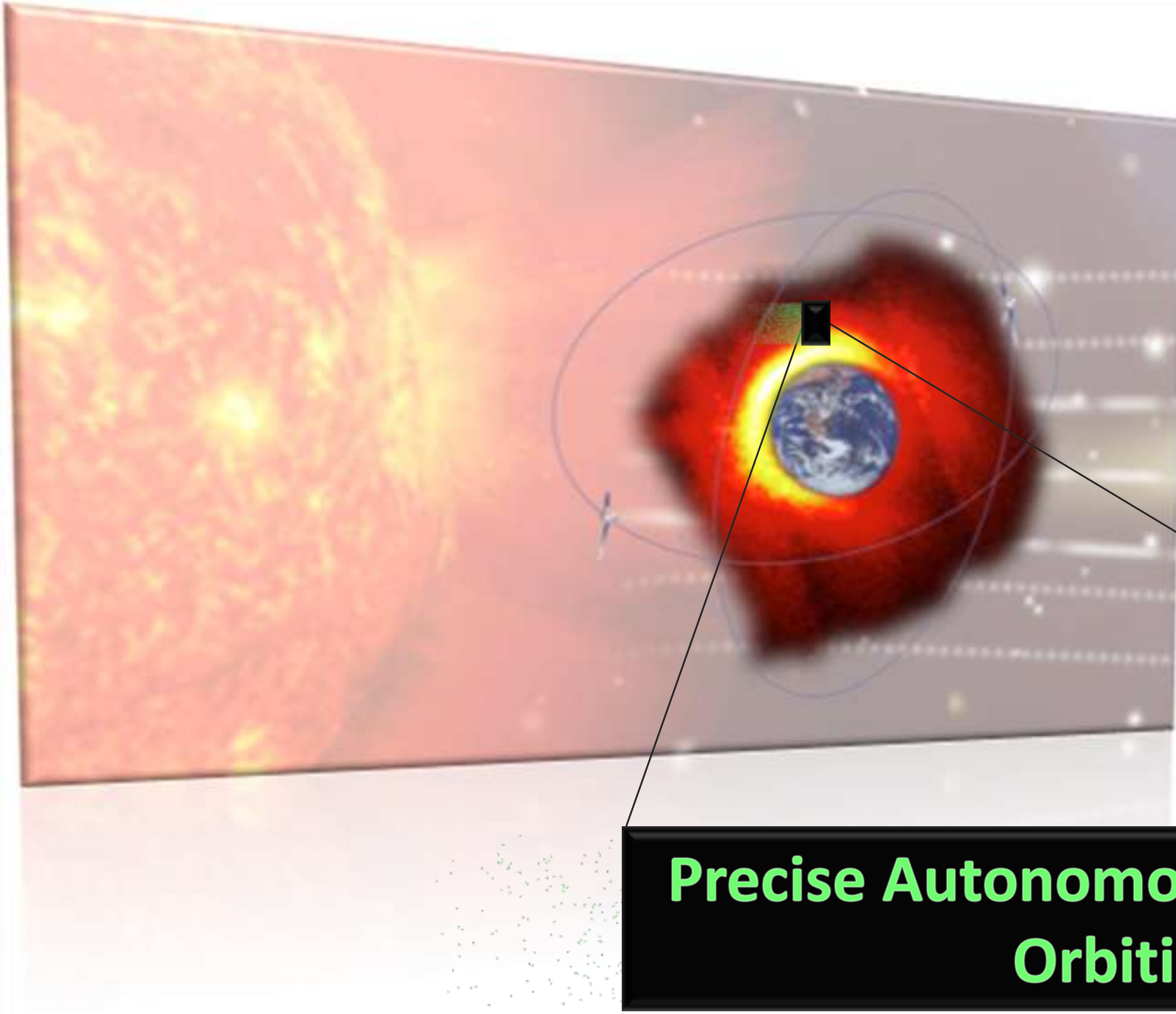


The BSI reflects radio signals, useful for applications like medium and long range wavelength comms and radar. This highly variable layer depends on external drivers such as solar forcing and lower atmospheric dynamics. Combining several atmospheric models that cover the various regions from ground thru the BSI enables better specification and forecasting.

Deliverable/Value/Accomplishment

- Provides necessary, quantitative understanding of the drivers that dominate the neutral upper atmosphere and the corresponding ionized bottom-side ionosphere
- Coupling of mature individual models for BSI specification capability for development of validated regional and global scale model, towards transition
- Contribution towards ESPC (Earth System Predictive Capability): an interagency collaboration between DoD, NOAA, DOE, NASA and NSF for coordination of research to operations for an Earth system analysis and extended range prediction capability

Geospace HPC Research Examples



Precise Autonomous Monitoring of Orbiting Space Objects

PRESAGE: Quantifying and Reducing Space Collision Risk w/ Sun-Earth System Forecasting & Probabilistic Dynamics

John Emmert

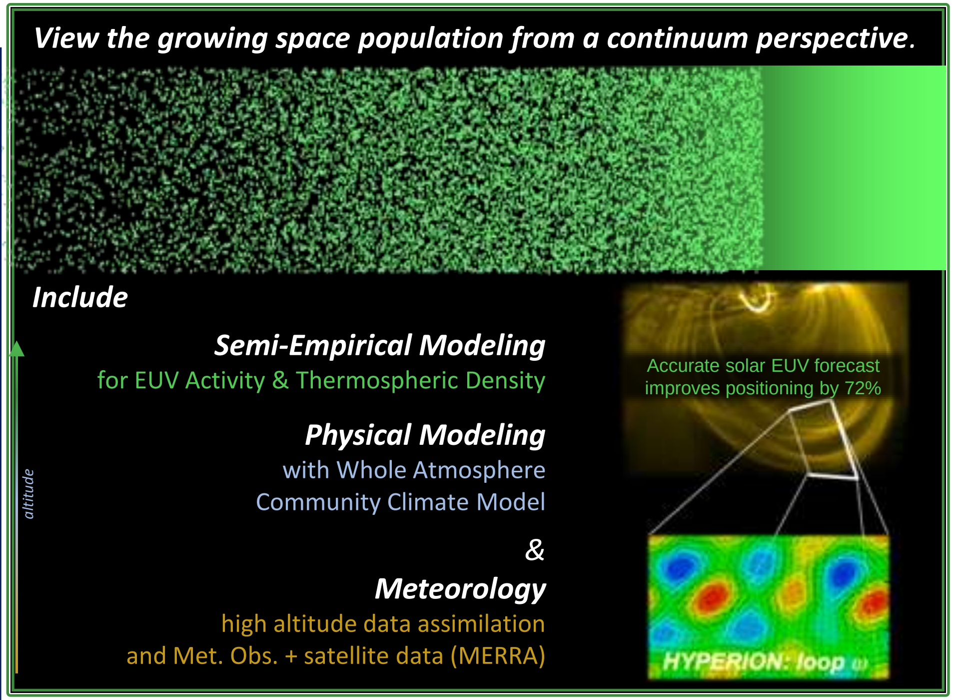
Objective

Quickly assimilate tracking data of new orbiting space objects, while simultaneously shrinking the error ellipsoids, in order to create more room to operate in space. To do this we need to know where all satellites and debris are and where they will be for the next seven days.

Current capabilities are inadequate to monitor the space objects population to avoid collisions. E.g., current practice did not prevent the Iridium-Cosmos collision that increased space debris by 10%. (False alarms are also bad; and, avoidance maneuvers are both costly and risky.) The biggest obstacles to achieving effective collision avoidance are inaccurate prediction of Sun-Earth system dynamics and atmospheric drag, and current manually intensive techniques for assimilating tracking data.

Approach

- Probabilistic SSA / cataloging using Bayesian learning, for monitoring of a much bigger population and faster handling of rapid changes in population, i.e., better inference and statistics
- Thermospheric density forecast modeling improvements to eliminate major source of density uncertainty from the lower atmosphere, using NRLMSISE-00, WACCM-X (0-500km), NRL-HDAS (high-alt data assimilation; 0-100km), MERRA (0-50km): new physics, better modeling, HPC performance
- Key solar extreme ultraviolet (EUV) irradiance forecasts to eliminate major source of density uncertainty from above, using NRLSSI, NRLEUV, GONG and HYPERION, for new data and – for the first time – incorporation of physics beyond empirical modeling

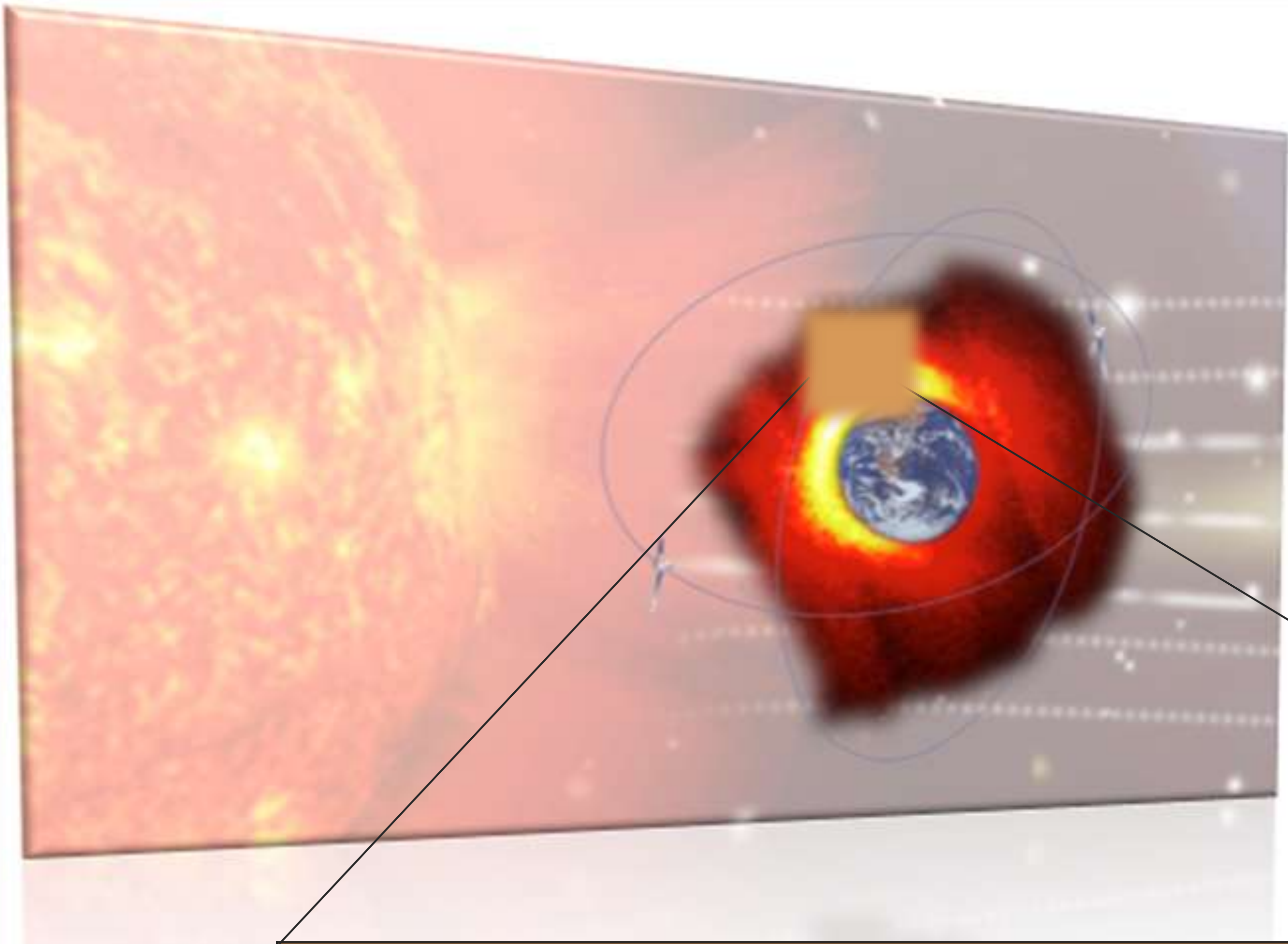


(Image: NRL)

Deliverable/Value/Accomplishment

- Validation against observations and comparison with current capabilities
- Proof-of-Principle capability ready for prototyping
- Enhancements to the NRLMSIS-E empirical thermosphere model which has significant commercial, military and academic demand.
- Anticipated payoff: 85% reduction in 7-day position uncertainty volumes; and, capability to handle 10x increase in space catalog

Geospace HPC Research Examples



Software for Optimization of Radiation Detectors

SoftWare for Optimization of Radiation Detectors (SWORD)

Bernard Phlips

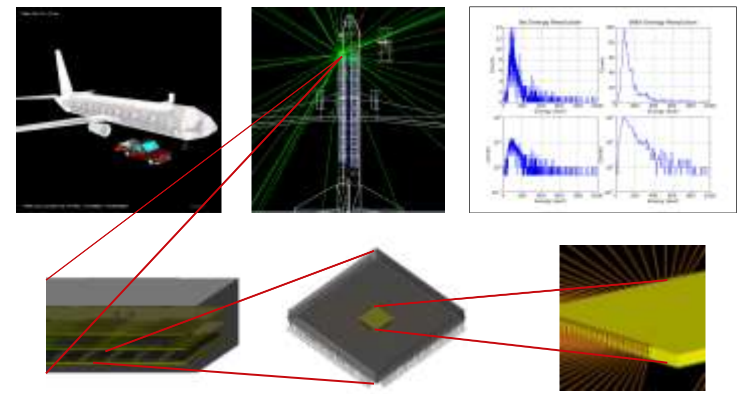
Objective

Provide a vertically integrated radiation transport software tool for graphically setting up, running, and analyzing results from numerical simulation of high energy radiation detection systems and other systems that operate in a high energy radiation environment. Realistic radiation transport simulations provide a cost-effective means to investigate and optimize instruments and systems for defense, homeland security, and space science applications. SWORD enables developers and technical evaluators to assess instruments and systems in relevant radiation environments, without actual hardware, using a single software package that does not have a steep learning curve to implement.

Approach

- NRL is SWORD PI institution for the DHS Domestic Nuclear Detection Office (DNDO) and the Defense Threat Reduction Agency (DTRA)
- SWORD provides an integrated package that includes:
  - A graphical CAD system for designing the simulated scenario, including geometries, radiation and detector properties
  - A standard library of pre-defined objects of interest (e.g., vehicles, containers), radiation spectra, and COTS detectors; and, ability to ingest GIS and CTDB data to automatically generate scenes or cities for use in the simulations
  - Handling of very complex geometries (> 100,000 objects), and seamlessly integrated spectrum and image analysis tools
  - Support for two of the most commonly used radiation transport engines: GEANT4 (CERN) and MCNPX (LANL)
  - Increasingly expanding support for additional simulation engines: ADVANTG/Denovo (ORNL), GADRAS (SNL)
- SWORD is made available to users through the Radiation Safety Information Computational Center (RSICC) at ORNL

Design **Simulate** **Analyze**



SWORD *can model from detonation spectrum to input spectrum into silicon die*

Deliverable/Value/Accomplishment

- SWORD, an NRL-developed package to enable radiation transport modeling of complex scenes and geometries, is the primary tool for simulating radiological/ nuclear environments for DNDO, the ONR Maritime Weapons of Mass Destruction Detection Program (M-WMD-D), and the DTRA Operations Research, Modeling & Analysis Office (J91SM)
- The SWORD Team was recognized with the FY12 DoD Value Engineering Achievement Award for their efforts to reduce cost to the government through the use of simulation
- SWORD builds on years of NRL Space Science simulation experience for development of orbiting gamma-ray detectors
- NRL releases new versions of SWORD annually to RSICC (v5.0beta in FY13), and has more than 120 current users

Miniature Array of Radiation Sensors (MARS)

Andrew Nicholas

Objective

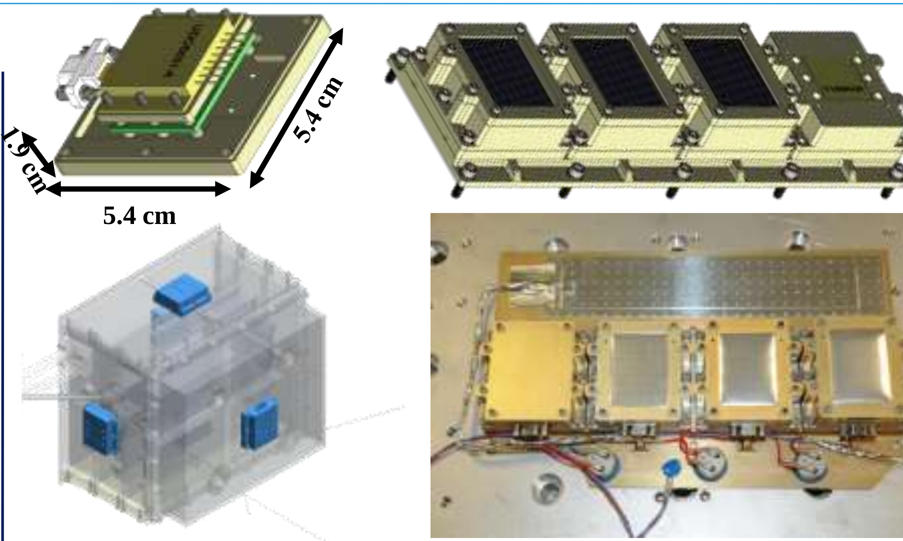
Provide an array of persistent, ubiquitous sensors that monitor the total dose radiation on the host spacecraft for 3-D rad modeling. The concept is to provide a radiation state-of-health measurement like that of a of a thermistor. **Validate SWORD modeling.**

Approach

- Hybrid microcircuit which directly measures accumulated total ionizing dose in a silicon test mass since power-up, technology developed by Aerospace and transitions to Teledyne.
- Persistent sensor – 100% duty cycle
- Low Size, Weight, and Power (SWAP) small telemetry requirement
  - 5.4 x 5.4 x 1.9 cm, 110g, 30 mW avg., 66 bits/sample/sensor
- An array of micro-dosimeters is flown on the STP-H4 host experiment (GLADIS), several nodes on the exterior and one on the interior. First flight of technology post industry transition.
- A co-located array of four dosimeters with varying amount of shielding to look at different energy levels
- Nodes connect to a simple central data collector that collates data for distribution to host platform data handling system.

DAC Analog Output Conversions

DACx	Dose Conversion	Range
low	5 uRad/4.9 mV	0-5.1 mRads
med	1.3 mRad/4.9 mV	0-1.3 Rads
high	326 mRads/4.9 mV	0-334 Rads
log	custom log scale	0-86 kRads



(Images: Naval Research Laboratory)

Figure. Clockwise from upper left, MARS node configuration, array of 4 nodes with varying shielding thickness, flight hardware, location of single nodes on GLADIS box.

Deliverable/Value/Accomplishment

- Flight of an array of micro-dosimeters placed on the interior and exterior of a host spacecraft will provide radiation depth-dose profile in the vehicle, which can be directly compared with SWORD calculations using rad. transfer and mass modeling
- Spacecraft Design Aid
  - Enables verification of space vehicle radiation design models *(e.g.. SWORD, SPENVIS)*
  - Critical for highly exposed applications
  - Deep dielectric discharges
  - Determine amount of shielding
- Launch Plans: MARS delivered to STP-H4 payload complement for launch on HTV-4 (Tanegashima, Japan) in Aug 2013 for flight on International Space Station

SWORD, applied to MARS data on the International Space Station (ISS)

Bernard Phlips

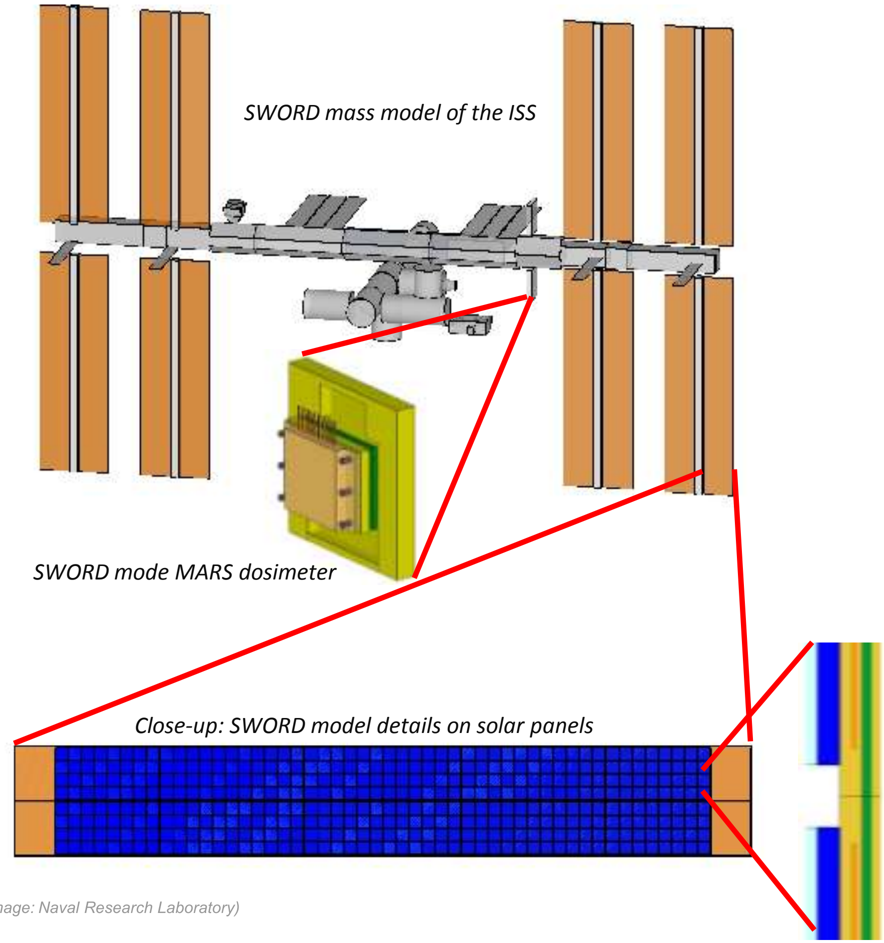
Objective

SWORD (SoftWare for Optimization of Radiation Detectors) is a widely-used and trusted software capability that applies 3-D Monte Carlo methods to simulate the passage of high energy radiation through matter. The simulations provide an effective means to study radiation environments in maritime, urban, and space scenarios of interest. HPC systems are an efficient mechanism for performing the computationally-extensive SWORD studies in a timely manner.

SWORD as applied to space situations

- Can make complex mass models of spacecraft for accurate radiation transport calculations
- Have made mass models with > 100,000 objects
- Can expose mass model to any high energy radiation:
  - Cosmic rays
  - Trapped particles
  - Solar X-rays and gamma ray flares
  - Albedo gamma rays and neutrons

"The effects of radiation are part of the price of doing business in space. There are solar flares, random magnetic distortions, and what some NASA scientists call the 'killer electrons' of the Van Allen radiation belts. The place where S/C are most vulnerable, though is the … South Atlantic Anomaly (SAA), centered 300 km off the coast of Brazil. To avoid exposing astronauts to intense radiation, spacewalks are not scheduled on the ISS when its passing through the Anomaly – which happens two to five times a day." The Bermuda Triangle of Space: the high-energy SAA threatens satellites; 12 Mar 2013, Jim Hodges, C4ISR Digital Edition, Defense News [http://www.defensenews.com/article/20130312/C4ISR01/303120028/The-Bermuda-Tr].

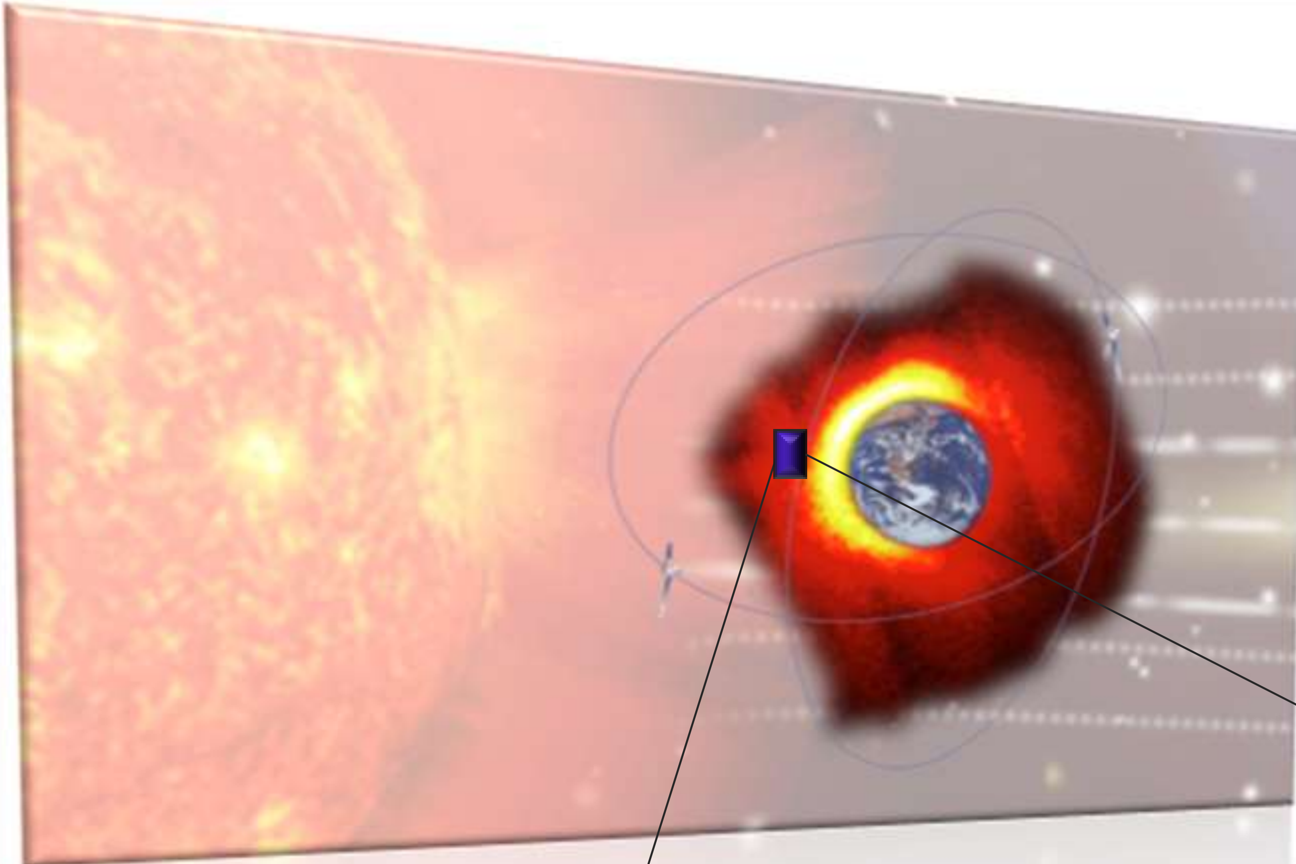


(Image: Naval Research Laboratory)

SWORD as applied to MARS

- Model dose to MARS dosimeters and include effects of material nearby and from entire International Space Station (ISS)
- Model dose to solar cells
- Establish correlation between dose to MARS and solar cells

Geospace HPC Research Examples



Integrating the Sun-Earth System for the Operational Environment

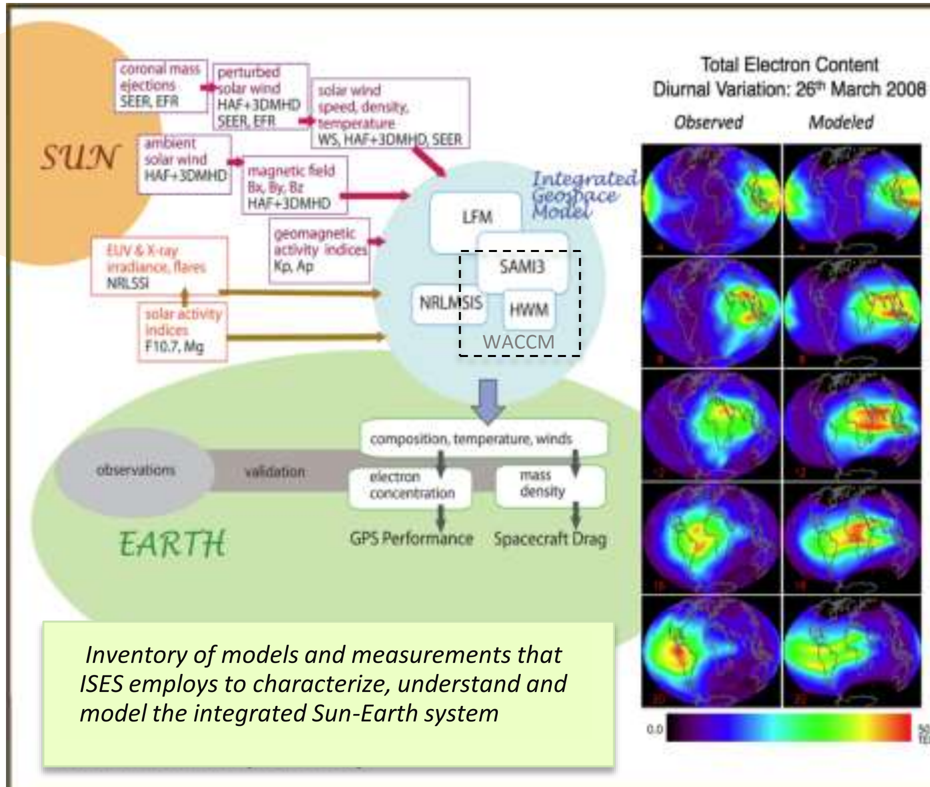
Integrating the Sun-Earth System (ISES) for the Operational Environment

Judith Lean

Objective

Characterize and simulate multiple chains of physical processes that link the Sun-Earth system, to advance space science and enable Naval/ Marine Corps and wider DoD operations to better account for, adapt to, and exploit operational impacts of the space environment due to electrons, ions and neutrals. *Investigate:*

1) Climatology, weather resulting from cycles: solar, seasonal, etc
2) Disturbances following solar-driven geomagnetic storms
3) Data products utilized in current DoD environmental sensing
4) Effects on space environment applications due to the non-uniform ionosphere and plasmasphere



Inventory of models and measurements that ISES employs to characterize, understand and model the integrated Sun-Earth system

Approach

Conduct data analyses, model simulations and validation in these conceptual time frames:

- Intervals of days-to-weeks: *Whole Heliosphere Interval 2008*
- Comparative solar minima epochs: *2008 vs 1996*
- Episodes of geomagnetic disturbances: *e.g. 3-5 April 2010*
- Solar Cycle 23: 1996-2010

In each case:

- Comprehensive specification of Sun & heliosphere from surface magnetic fields to source surface, with heliospheric propagation to L1 and magnetopause (boundary of geospace)
- Multiple geospace simulations with different scenarios for EUV irradiance, heliospheric inputs, thermospheric density, winds, electrodynamic coupling, lower boundary conditions
- Detailed comparisons with observations eg TEC, ionosondes, IRI, UV-remote sensing, GAIM, drag-derived neutral densities
- Simulations made with forecast inputs

Deliverable/Value/Accomplishment

An in-house, first-principles, validated DoD HPC simulation model and suite of specification runs to….

- Provide new knowledge of geophysical “targets” (SAO, winds, electrodynamics, storms, solar rotation and solar cycle)
- Quantify limitations in current operational capabilities
- Investigate future emerging science and DoD space weather issues
- Improve platforms to assimilate observations for ops and forecasting
- Specify requirements for future DoD space weather instruments

Special Sensor Ultraviolet Limb Imager (SSULI)

Andrew Nicholas

Objective

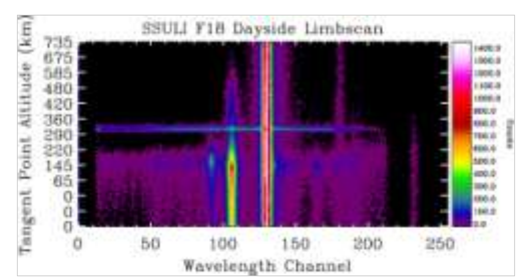
- Measurements provide scientific data supporting military and civil systems
- Assists in predicting atmospheric drag effects on Satellites and Reentry Vehicles
- Ionospheric data products ingested by DoD state-of-the-art assimilative space weather model, GAIM *(see chart following)*
- New models of global electron density variation
- First operational instrument of its kind
- Provides new technique for remote sensing of Ionosphere and Thermosphere from space

Approach

- Passively measures vertical profiles of natural airglow radiation from gases and ions in upper atmosphere and ionosphere from LEO
- Exploits Extreme-UltraViolet (EUV) to Far-UltraViolet (FUV) emissions
  - Wavelength Range of 80 nm to 170 nm, at 1.5 nm Resolution
- Uses a spectrograph with a mirror which scans from 27 to 10 degrees below the satellite horizon every 90s
  - Scans a vertical slice of the atmosphere from 50 - 750 km altitude
- Produces electron density profiles, neutral density profiles, atmospheric composition, and temperatures of upper atmosphere
- Leverages the NRL previous high resolution airglow/aurora Spectroscopy (HIRAAS) Experiment, flown onboard the DoD Space Test Program (STP) Advanced Research and Global Observations Satellite (ARGOS)
- Next-generation follow-on sensor SSULI+ provides improved capabilities in more compact design.

Deliverable/Value/Accomplishment

- Third of five SSULI remote sensing instruments was launched on October 18, 2009 onboard the DMSP F-18 satellite
- In August 2012, SSULI on F-18 transitioned from Cal/Val to Operations at the Air Force Weather Agency.
- Independent analysis of SSULI data in GAIM has determined strong operational impacts:
  a) 1st most significant impact on peak heights
  b) 2nd most significant impact on total electron content
  c) 2nd most significant impact on peak electron density



*highlighted on 2 April 2013

Doppler Asymmetric Spatial Heterodyne (DASH) Spectroscopy

Christoph Englert

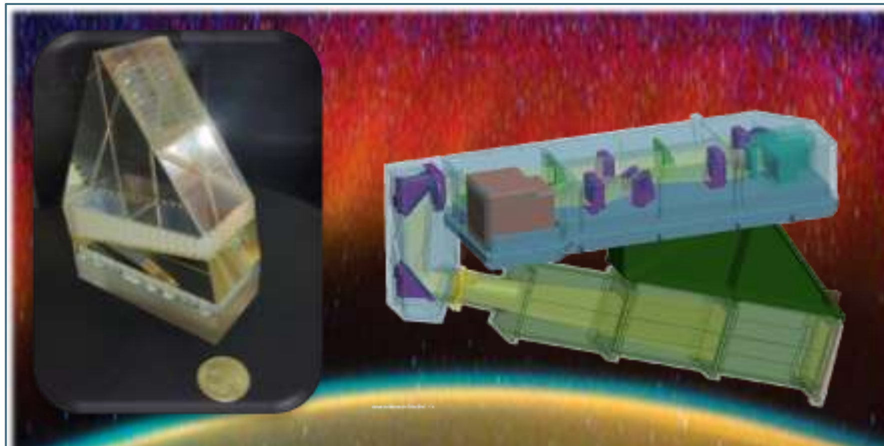
Objective

The objective of the DASH development effort is to increase the TRL of the innovative DASH spatial heterodyne spectroscopy (SHS) technique for future space based thermospheric wind observations. (NRL Patent 7,773,229)

High quality global thermospheric wind observations are currently not available, but are essential for improving orbit determination and comms, geopositioning, via ingest into models such as ISES.

Approach

- A DASH interferometer passively measures the Doppler shift of atmospheric emissions to derive the wind velocity and temperature
- The interferometer is similar to conventional SHS, but it has an additional optical path difference built in to optimize the Doppler shift measurement
- The TRL increase is accomplished via the design and fabrication of a monolithic DASH interferometer, laboratory testing and a ground based demonstration. For the ground based demonstration, thermospheric winds are measured at night by observing the atomic oxygen airglow ("red line" at 630nm wavelength). Verification and validation is achieved with a co-located Fabry-Perot interferometer
- On 12 April 2013, NASA selected the Ionospheric Connection Explorer (ICON) to proceed to Phase B. NRL participation in ICON includes providing the thermospheric wind instrument as one of the four Mission science payloads, and also scientific data analysis and interpretation. ICON will study the extreme variability of the ionosphere, to understand the way space weather events grow to envelop regions of Earth with dense ionospheric plasma



Left: *Image of monolithic DASH interferometer;* ***Right:*** *Conceptual design of a DASH space flight instrument.*

(Instrument Images: NRL)

Deliverable/Value/Accomplishment

- Interferometer has been designed, fabricated, tested in the laboratory, and integrated in a ground based breadboard instrument
- Ground based DASH instrument performed successfully, and validated field measurements of thermospheric winds
- Launch Plans: A DASH spaceflight instrument, the Michelson Interferometer for Global High-resolution Thermospheric Imaging (MIGHTI), is included in NASA ICON Explorer Mission proposal led by UC Berkeley that is now at the start of Phase B
- DASH TRL is significantly increased, shortening the time until space based wind observations will be operationally available for DoD Space Situational Awareness, upper atmospheric analysis

Small Wind And Temperature Spectrometer (SWATS)

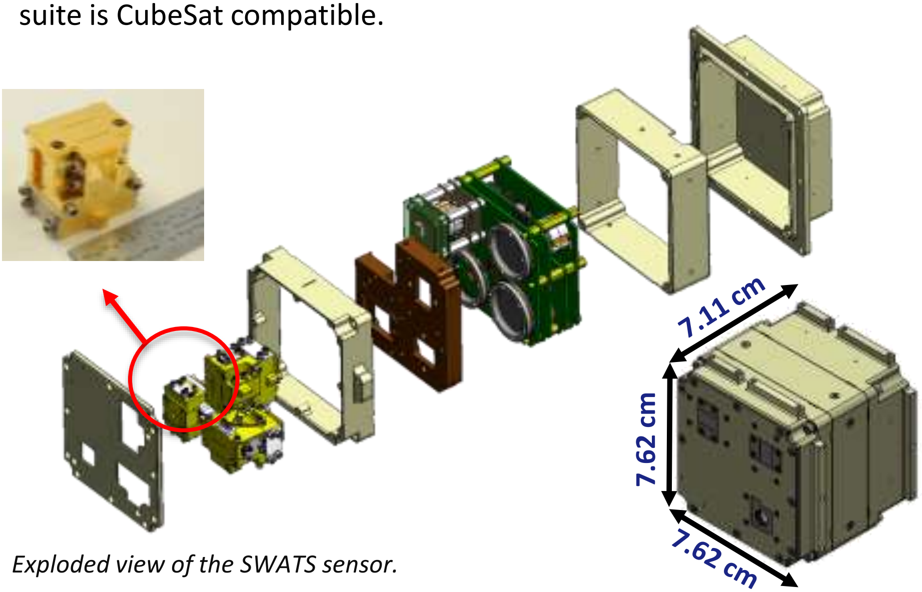
Andrew Nicholas

Objective

Develop low size, weight and power (SWaP) in-situ instrument suite capable of measuring neutral winds, neutral temperature, neutral composition, ion drifts, ion temperature and ion composition. The sensor suite is also known as the Winds Ions Neutrals Composition Suite (WINCS).

Approach

NRL is the PI institution on a collaborative effort with NASA Goddard Space Flight Center to develop a low SWaP in-situ sensor sponsored by the the National Reconnaissance Office (NRO), Air Force Space and Missile Command (SMC), the Office of Naval Research (ONR), and the National Science Foundation. The sensor suite is CubeSat compatible.



Exploded view of the SWATS sensor.

Flight Hardware for the SWATS instrument, from left to right: spectrometer body, flight electronics, focal plane array, anodes and HV power supply

Measurements Capabilities

Instrument	Parameter	Range	Resolution	
WTS	Density	10^3-10^{10} cm^{-3}	<3%	Neutrals
WTS	Temperature	1000-4000 K	<1%	
WTS	Wind	+/- 2000 m/s	16 m/s	
NMS	Composition	10^3-10^{10} cm^{-3}	<3%	
IDTS	Density	10^3-10^7 cm^{-3}	<3%	Ions
IDTS	Temperature	1000 - 4000 K	<1%	
IDTS	Drift	+/- 2000 m/s	16 m/s	
IMS	Composition	10^3-10^7 cm^{-3}	<3%	

Deliverable/Value/Accomplishment

- NRL has developed a low SWaP in-situ sensor:

  Volume: 7.62 x 7.62 x 7.11 cm

  Mass: 635 g

  Power: 1.3 W

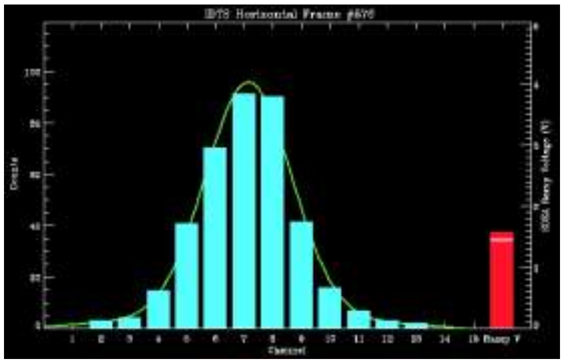
- Intent is to demonstrate operational utility of data set from CubeSat and other small satellite busses
- Ideal for an operational constellation of 30-50 sensors, as secondary payloads to larger satellites or primary instrument on CubeSats

SWATS *continued*: ground testing validation and launch plans

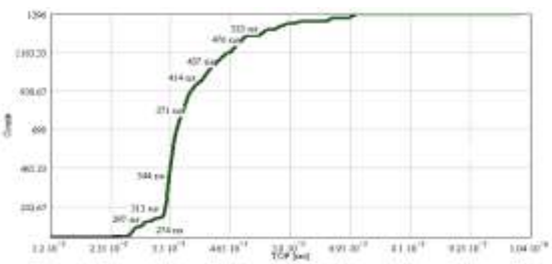
Andrew Nicholas

SWATS Sensors Ground Testing Results

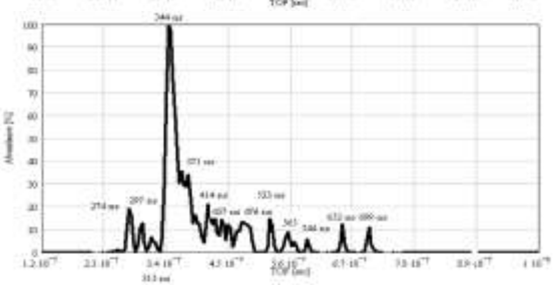
Laboratory testing at GSFC and NRL show good performance of spectrometer suite. Cathode testing has shown cathode to be robust and long-lived. The cathode performance testing showed no degradation after two months of humidity exposure.



IDTS Lab Data
- Source N^+ and N_2^+
- Energy = 5 eV



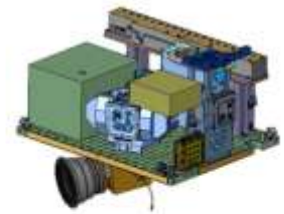
GEMS Lab Raw Data
- Source N2+
- With ambient chamber gasses



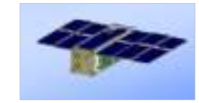
GEMS Processed Lab Data
- Mass Spectrum

SWATS Host Platforms

International Space Station



STP-Sat3



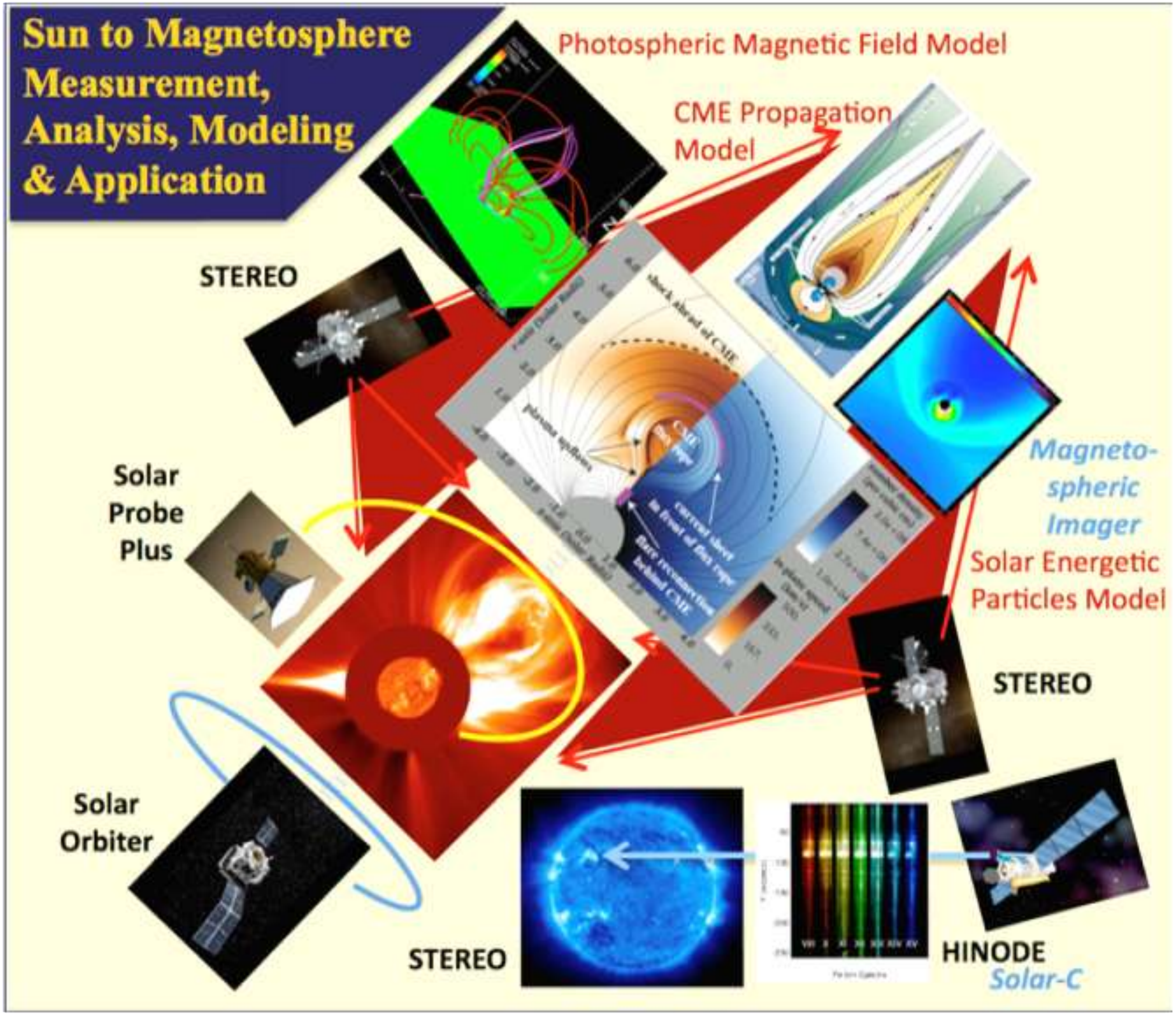
SENSE CubeSat

Launch Plans, sponsored by the DoD Space Test Program

- Aug 2013: STP-H4 on Express Logistics Carrier-1 (ELC) on the International Space Station, 400 km circular orbit, 51.6° inclination, Launch Vehicle: HTV-4 from Tanegashima, Japan

  *Dual Use Sensor demonstration
- NET 30 Sep 2013: STP-Sat3, 500 km circular orbit, 51.6° inclination, Launch Vehicle: Minotaur-1 on ORS-3 mission out of Wallops Island, VA
- NET 30 Sep 2013: Space Environmental NanoSat Experiment (SENSE) an USAF SMC CubeSat, 500 km circular orbit, 51.6° inclination, Launch Vehicle: Minotaur-1 on ORS-3 mission out of Wallops Island, VA
- CY 2014: CubeSat investigating Atmospheric Density Response to Extreme driving (CADRE) a Univ. of Michigan NSF CubeSat. *Orbit and LV TBD.*

Heliospace

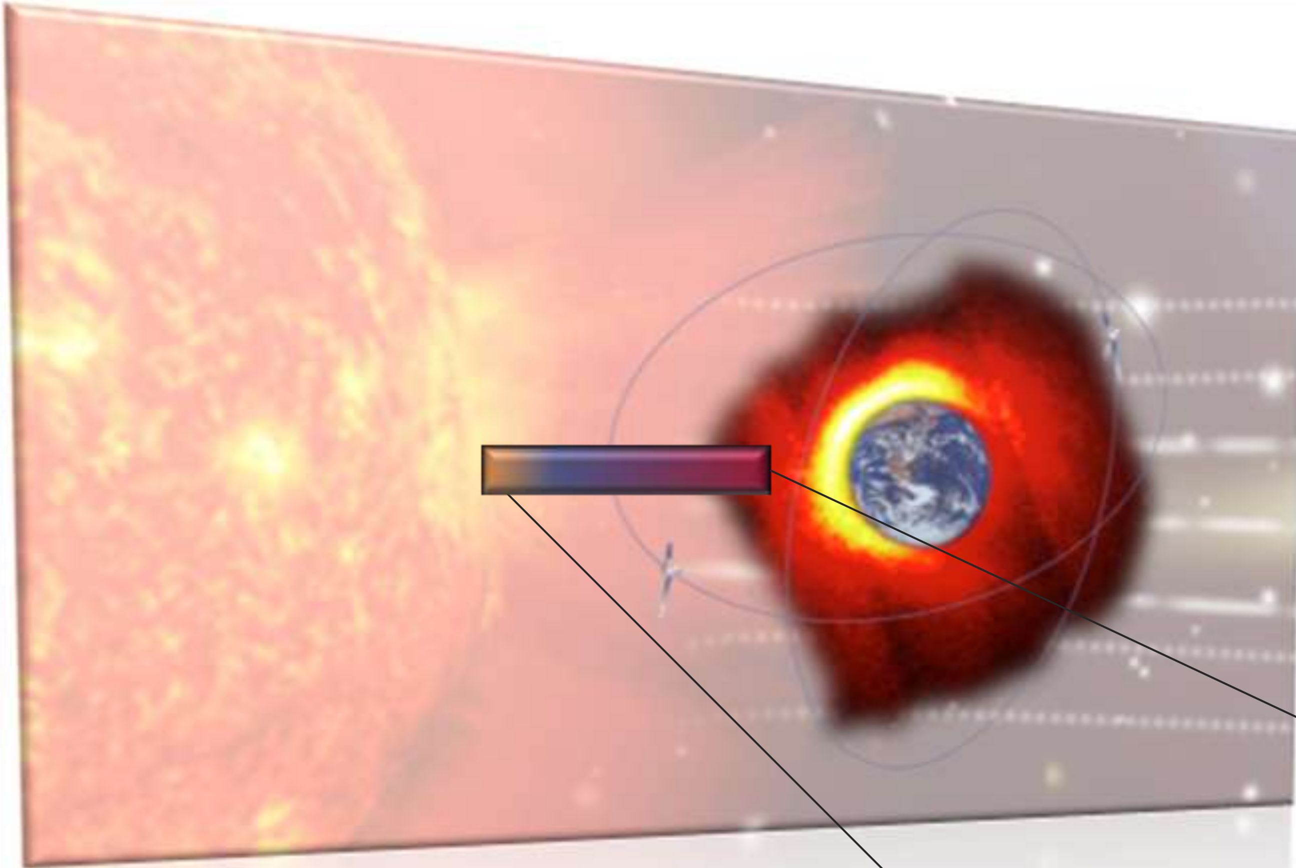


S&T Status:

Research in solar and heliophysics space-based sensors -- most notably coronagraphs, heliospheric imagers, and solar spectrometers -- and a steady stream of fundamental discoveries and insights driven by the data that this world-leading instrumentation provides.

This research is producing space environmental weather and climatology measurements and models in use by operational forecasting agencies and by inter-governmental scientific assessment bodies.

Heliospace HPC Research Examples



Solar Wind Modeling

Solar Wind Modeling

Chin-Chun Wu

Objective

Model the evolution of the solar wind from the Sun to the Earth an beyond, using both semi-empirical and advanced 3D MHD numerical modeling techniques.

Predict key solar wind plasma and magnetic field parameters throughout the inner heliosphere during both quiet and disturbed solar wind conditions, including disturbances due to coronal mass ejections (CMEs) and co-rotating interaction regions (CIRs) at the boundary between slow and fast wind streams.

CMEs and CIRs are the drivers of major geomagnetic storms and solar energetic particle (SEP) space weather events.

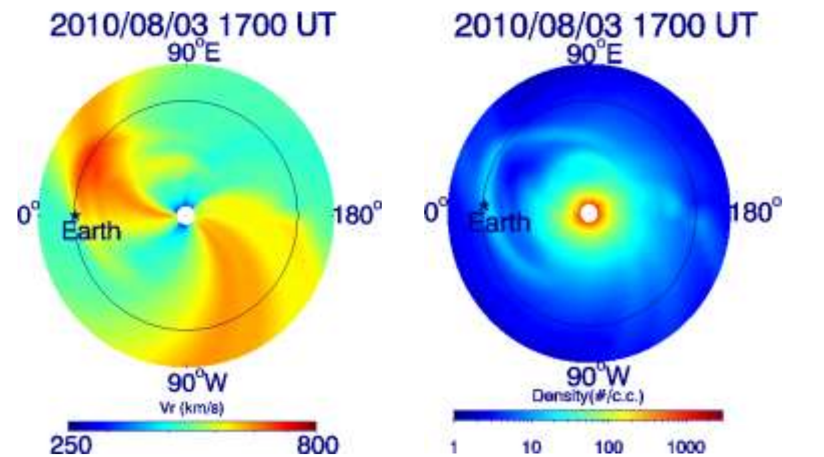
Approach

Wang-Sheeley (WS) Model:

- The WS model uses magnetograph measurements of the solar photospheric field to predict the current daily-averaged solar wind speed and magnetic field polarity at Earth (or anywhere else in the heliosphere)

3DMHD Model:

- The model is capable of simulating realistic background solar wind profiles as well as solar disturbances (e.g., CMEs/CIRs) from the surface of the Sun to the Earth and beyond
- The numerical simulation uses the observed line-of-sight (LOS) magnetic field at the solar photosphere extrapolated to 2.5 Rs by the WS model
- This model combines two simulation codes: the Hakamada-Akasofu-Fry kinematic code (HAFv.2) + a fully 3-D, time-dependent magneto-hydrodynamic (MHD) simulation code



Solar wind speed and density, respectively, in the solar equatorial plane at 1700UT on August 3, 2010, following a series of Earth-directed CMEs in the preceding three days.

(Image: Naval Research Laboratory)

Deliverable/Value/Accomplishment

- NRL delivered the WS model to NOAA and to the Air Force Weather Agency, where the model is used operationally to provide space weather forecast products and to provide key boundary conditions for detailed numerical simulations
- 3DMHD model has been used to successfully model the major space weather events of the last solar cycle, including the intense Halloween storm events of 2003
- NRL is currently using the 3DMHD model to support analysis of observations from the NRL-led SOHO/LASCO and STEREO/SECCHI experiments

Sun-Earth Connection Coronal and Heliospheric Investigation (SECCHI)

Russell Howard

Objective

Advance the understanding of the 3-D structure of the Sun's corona, the origin of Coronal Mass Ejections (CMEs), CME propagation through the heliosphere, and the dynamic coupling between CMEs and Earth.

CMEs, the most energetic phenomena in the solar system, are major drivers of geomagnetic space weather storms that adversely affect ISR, precision engagement, missile detection and intercept, Comms on the Move, spacecraft anomaly assessment, orbital tracking, polar flight activities, the power grid. CMEs were discovered by NRL, with an NRL-built solar coronagraph, in 1971.

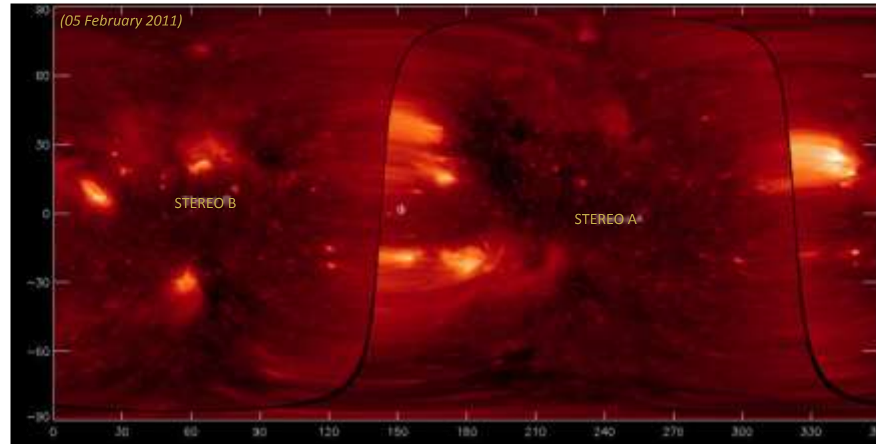
Approach

SECCHI: the solar and heliospheric imaging instrument suite on the NASA STEREO Mission

- NRL is SECCHI PI institution for NASA; consortium of US and international partners
- NRL led development of the 10 telescopes SECCHI suite
- Builds on successful NRL LASCO coronagraph on NASA/SOHO, led to NASA award to NRL for NRL as PI institution for WISPR (NASA Solar Probe Plus coronagraph)

STEREO Mission: October 2006 Launch - *present*

- Two identical satellites (STEREO A/Ahead-of-the-Earth & STEREO B/Behind-the-Earth) in ecliptic plane solar orbit
- Earth-centered stereographic angle between STEREO satellites increases 45 degrees/year



http://science.dodlive.mil/2011/02/08/researchers-view-the-sun-in-3d/

Cartesian projection of the entire solar atmosphere as observed by the NRL SECCHI twin Extreme Ultraviolet Imagers at a temperature of 1.6 million degrees. SECCHI acquires full maps of the Sun every 10-20 min.

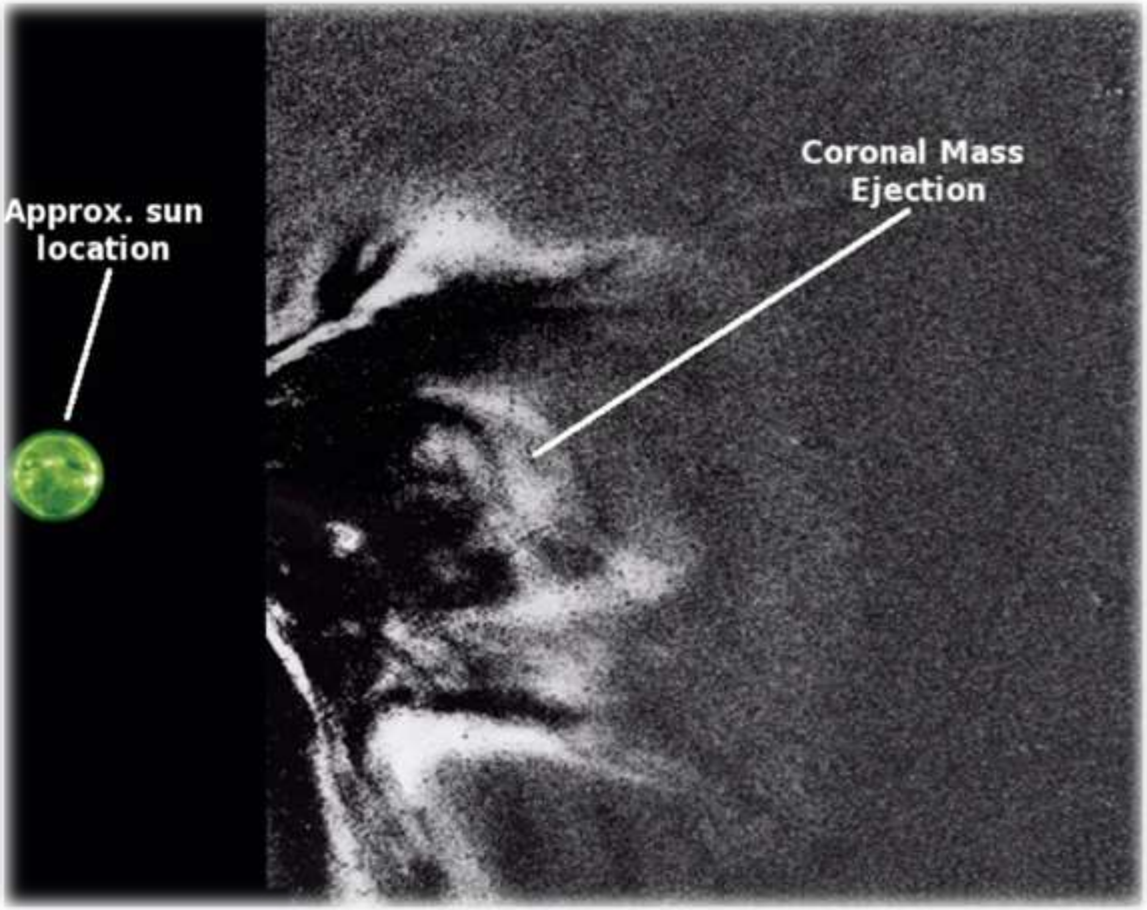
(Image: Naval Research Laboratory)

Deliverable/Value/Accomplishment

- NRL delivered the two SECCHI instrument suites to NASA; this included NRL in-house conception and optical design of the SECCHI COR2 coronagraph and the SECCHI Heliospheric Imager, leading the Goddard Space Flight Center in completion of the SECCHI COR1 coronagraph, and leading Lockheed-Martin (partner/sub to NRL) in completion of the SECCHI Extreme Ultraviolet Imager (EUVI)
- NRL currently delivering to NASA the SECCHI Mission operations and data analysis from on site at NRL-DC
- SECCHI results demonstrate improved accuracy (from 30 hours down to 8 hours) predicting CME impacts at Earth

Sun-Earth Connection Coronal and Heliospheric Investigation (SECCHI) Heliospheric Imager

Russell Howard



Conceived, developed, and operated at NRL, SECCHI's Heliospheric Imager (HI) instrument on NASA's STEREO spacecraft is a new remote sensing tool that tracks, for the first time, Coronal Mass Ejections (CMEs) as they pass through the volume of space between the Sun and the Earth. Images from HI show continuous solar wind outflow from the Sun, and are applied to detect significant changes in solar outflow (often resulting from CMEs that are headed to Earth, and arrive within 24 to 72 hours). Data from HI is useful towards validating HPC models of heliospace dynamics.

Solar Orbiter Heliospheric Imager (SoloHI)

Russell Howard

Objective

Advance the understanding of the solar wind and the propagation to Earth of Coronal Mass Ejections (CMEs) and Corotating Interacting Regions (CIRs) Sun by imaging the solar wind.

CMEs, the most energetic phenomena in the solar system, and CIRs are major drivers of geomagnetic space weather storms that adversely affect ISR, precision engagement, missile detection and intercept, Comms on the Move, spacecraft anomaly assessment, orbital tracking, polar flight activities, the power grid. CMEs were discovered by NRL, with an NRL-built solar coronagraph, in 1971.

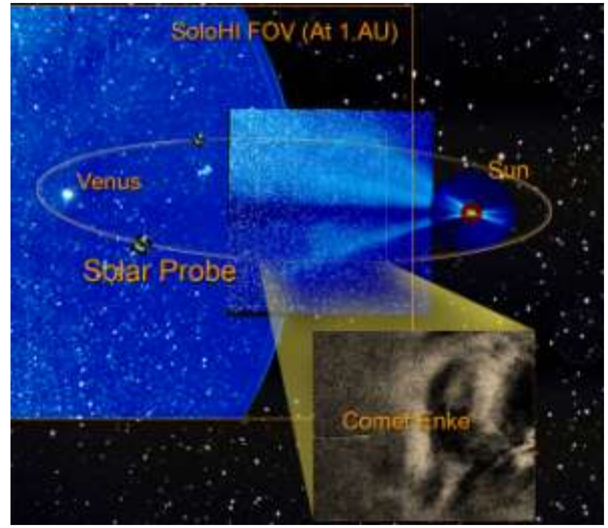
Approach

SoloHI: The heliospheric imager for the ESA/ NASA Solar Orbiter Mission

- NRL is PI institution for NASA
- NRL is leading development of the telescope
- Builds on successful NRL SECCHI heliospheric imager on NASA/STEREO

Solar Orbiter Mission: July 2017 Launch

- Orbits the Sun from 0.3 to 0.7 AU
- Inclination of orbital plane relative to the ecliptic plane increases to 35º
- First mission with imaging and in-situ instruments to go so close to the Sun and the first mission to image the Sun and heliosphere from above the ecliptic plane



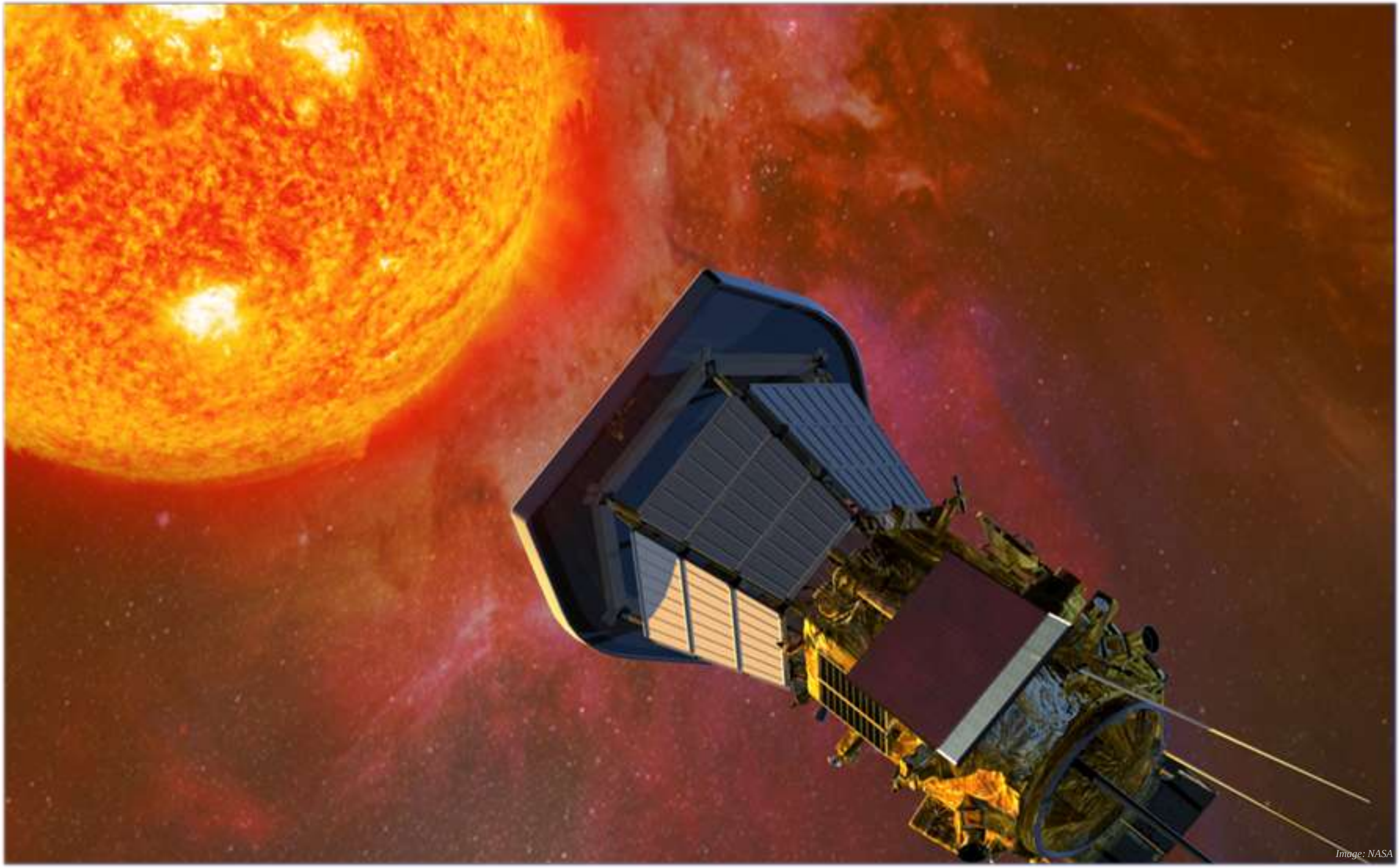
A composite image showing the expanded field of view of SoloHI compared to the field of SECCHI on the STEREO mission. The Sun is the small light circle inside a red circle. The black and white inset is an example of a CME propagating outward and blowing off the ion tail of Comet Encke.

(Image: Naval Research Laboratory)

Deliverable/Value/Accomplishment

- NRL will deliver the SoloHI instrument to NASA in January 2015; this includes NRL in-house conception and optical design of SoloHI and development of a new Advanced Pixel Sensor which was completed in March 2013, and the instrument electronics control system and software
- NRL will deliver to NASA and ESA the SoloHI Mission operations and data analysis from on site at NRL-DC. The Solar Orbiter (SO) mission control will be in Europe
- Oct 2011: ESA selected SO as 1st Cosmic Vision Program mission;
  Sep 2012: SoloHI successfully passed preliminary design review, is currently in Phase C
- SoloHI will provide unique observations of heliospheric plasmas, determining the 3D electron density and velocity structure of the inner heliosphere and how it propagates to 1 AU

NASA Solar Probe Plus (SPP); July 2018 launch



On 2 Sept 2010 the Wide-field Imager with NRL researcher Russell Howard as PI was chosen as one of the proposals selected by NASA for financial award. As instrument PI institution, NRL will design and develop the NASA-sponsored Wide-field Imager for the new NASA mission Solar Probe Plus that will plunge directly into the Sun's atmosphere ~4 million miles from our star's surface.

Wide-Field Imager for Solar Probe Plus (WISPR)

Russell Howard

Objective

Understand the morphology, velocity, acceleration and density of evolving solar wind structures when they are close to the Sun.

Derive the 3D structure of the solar corona through which in-situ measurements are made to determine the sources of the solar wind.

Determine the roles of turbulence, waves, and pressure-balanced structures in the solar wind.

Measure the physical properties of SEP-producing shocks and their CME drivers as they evolve in the corona and inner heliosphere.

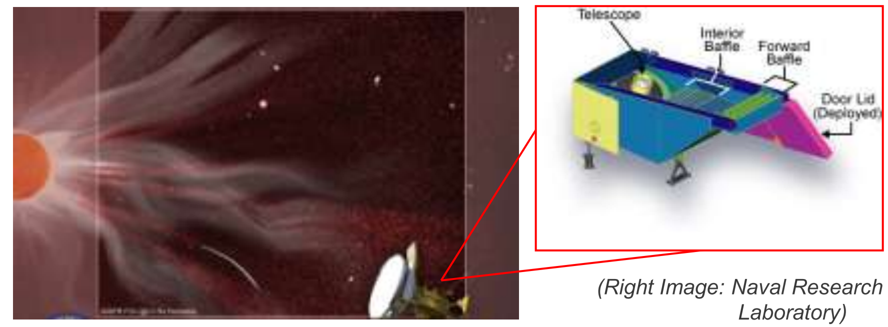
Approach

WISPR: Wide-field visible light heliospheric imager for the NASA Solar Probe Plus mission

- NRL is WISPR PI institution for NASA; consortium of US and international science partners
- NRL will develop the WISPR instrument and will operate it after launch
- Builds on successful NRL SECCHI heliospheric imagers on the NASA STEREO mission

Solar Probe Plus (SPP) Mission: July 2018 Launch

- SPP will explore one of the last regions of the inner solar system to be visited by a spacecraft, the Sun's outer atmosphere (or corona) where it extends into space
- SPP will complete 24 orbits about the Sun over 7 years, coming as close as 3.7 million miles (8.5 Rs) above the solar photosphere



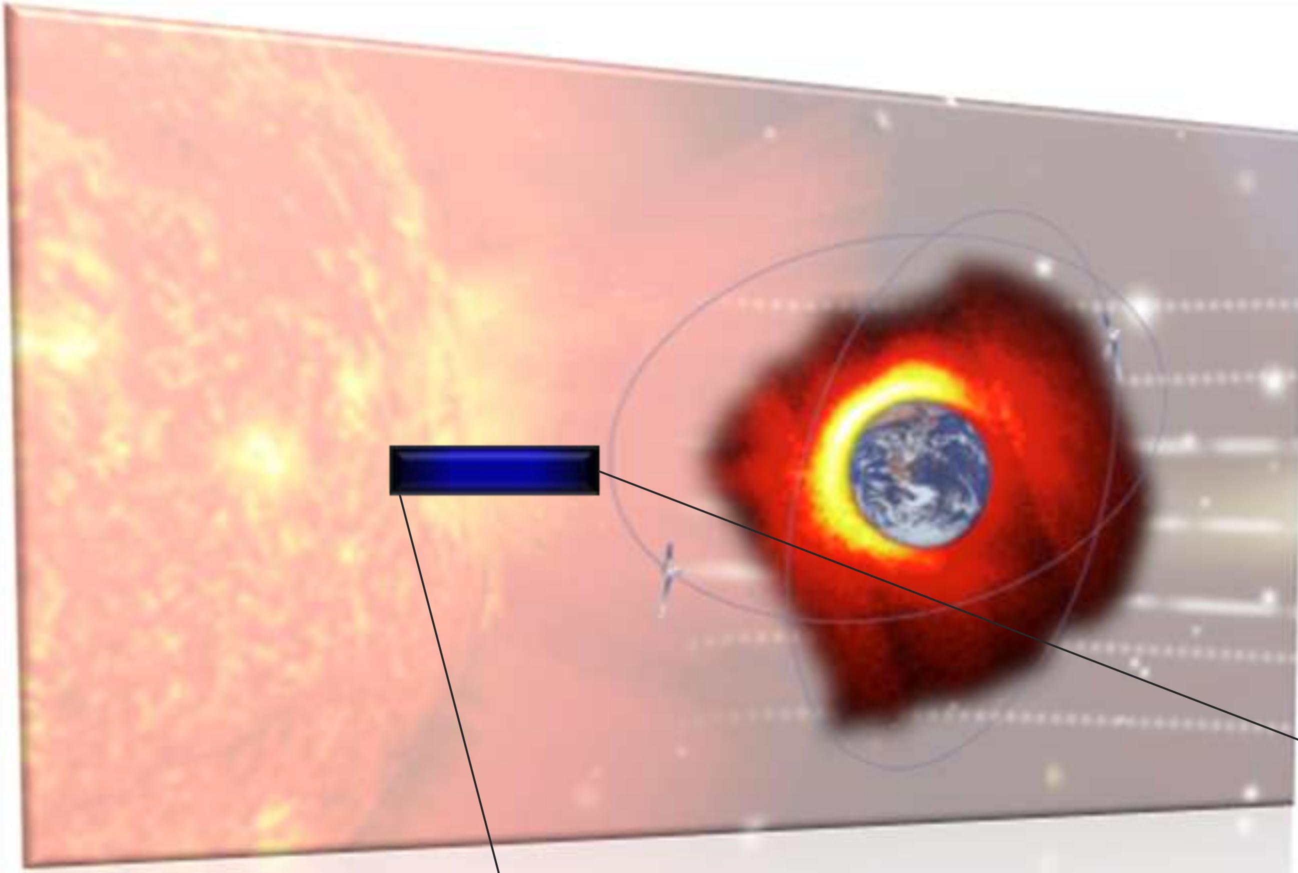
(Right Image: Naval Research Laboratory)

Artist's impression of the SPP spacecraft at closest approach to the Sun with the WISPR field of view superimposed. The opto-mechanical layout of NRL's WISPR is shown on the right.

Deliverable/Value/Accomplishment

- NRL will deliver WISPR to NASA in July 2015; this will include NRL in-house conception and optical design of SoloHI, including the development of an innovative radiation hard, Advanced Pixel Sensor compact camera for flight on SPP. The prototype detector performance is similar to that previously achieved only with charge coupled device detectors
- NRL will deliver to NASA the SPP Mission operations and data analysis from on site at NRL-DC
- Currently the Mission is in Phase-B
- WISPR will determine the fine-scale 3D electron density and velocity structure of the corona and the source of Solar Energetic Particles (SEP) producing shocks

Heliospace HPC Research Examples



Numerical Modeling Framework for Heliospheric Plasmas

HiFi – Numerical Modeling Framework for Laboratory and Heliospheric Plasmas

Vyacheslav Lukin

Objective

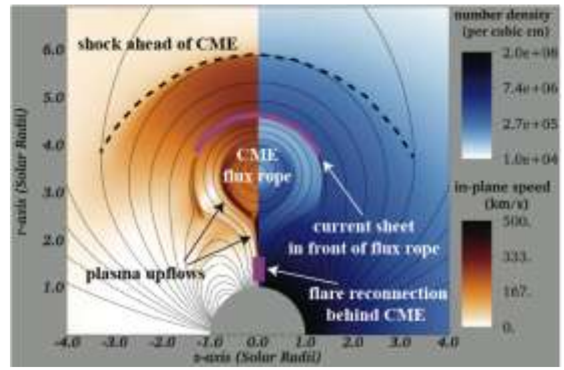
Develop, maintain, verify & validate a state-of-the-art HPC numerical framework for fluid- and particle-based predictive modeling of space weather and plasma confinement devices

To do so, build a computational plasma framework designed to maximize the combined effectiveness of its *three core features*:

1. a scalable, efficient and accurate underlying numerical algorithm;
2. an easy-to-use flexible interface for achieving basic and applied research objectives;
3. modular structure that allows to improve and upgrade the framework in-step with the latest computer science & hardware advances

Approach

- Build on the open-source HiFi multi-fluid modeling framework co-developed by NRL SSD and University of Washington for simulations of multi-scale dynamics in laboratory, solar, and heliospheric plasmas;
- Design and implement high-order implicit and scalable numerical methods for solving fluid- and kinetic-based sets of partial differential equations. Use software libraries for grid adaptation and solving associated large sparse linear systems on the latest High Performance Computing (HPC) hardware;
- Continue to pursue collaborations with computational physics and applied math communities for algorithm development, and with laboratory experiments for model validation



(Image: Naval Research Laboratory)

MHD simulations of (left) CME generation and (right) 3D magnetic reconnection performed within the HiFi modeling framework. The smallest dynamically relevant scale for reconnection is likely meters and the largest CME-relevant scale is 1000's of megameters. Both reconnection and CME-driven shocks produce non-thermal particle distribution functions that need to be modeled with kinetic simulation methods.

Deliverable/Value/Accomplishment

- To achieve predictive capability with fast turn-around, multi-scale simulations of space weather and plasma confinement devices have to make full use of the $O(10^5)$ core concurrency of the modern HPC hardware with scalable, adaptive algorithms in a validated modeling framework;
- The current fluid-based version of the HiFi framework is utilized at several research laboratories and universities in the US and around the world for simulations of solar, fusion, and basic plasma phenomena. For select applications, HiFi computations have been performed on up to 10^4 HPC cores

Large Angle Spectrometric and Coronagraphic Telescope (LASCO)

Russell Howard

Objective

Advance the understanding of the structure of the Sun's corona, the origin of Coronal Mass Ejections (CMEs), and the dynamic coupling between CMEs and Earth.

CMEs, the most energetic phenomena in the solar system, are major drivers of geomagnetic space weather storms that adversely affect ISR, precision engagement, missile detection and intercept, Comms on the Move, spacecraft anomaly assessment, orbital tracking, polar flight activities, the power grid. CMEs were discovered by NRL, with an NRL-built solar coronagraph, in 1971.

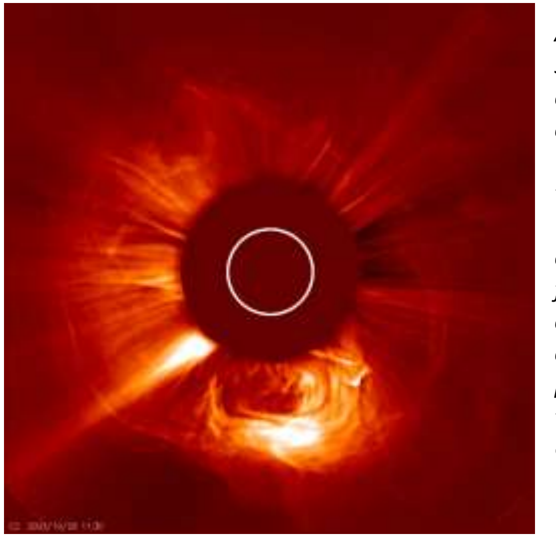
Approach

LASCO: the coronagraphic instrument on the ESA/NASA Solar and Heliospheric Observatory (SOHO) Mission

- NRL is LASCO PI institution for NASA; consortium of US and international partners
- NRL led development of the 3 telescopes of the suite
- Builds on successful NRL P78-1 (SOLWIND) coronagraph on DoD STP P78-1 Mission launched in 1979

SOHO Mission: December 1995 Launch - *present*

- The European Space Agency (ESA) was the prime in developing the SOHO payload, which was launched and operated by NASA into a halo orbit about the L1 Lagrangian Point that is 1 million miles toward the Sun
- The first solar mission to continuously view the Sun



An image of a "halo" type CME surrounding the LASCO C2 occulting disk and a prominence eruption to the South of the Sun. The white circle in the center is the size and location of the Sun, which is obscured by the occulting disk. The bright linear feather to the lower left is a coronal streamer. CMEs were observed to occur up to 6 times per day during the maximum of the solar cycle. The halo is a CME headed toward Earth.

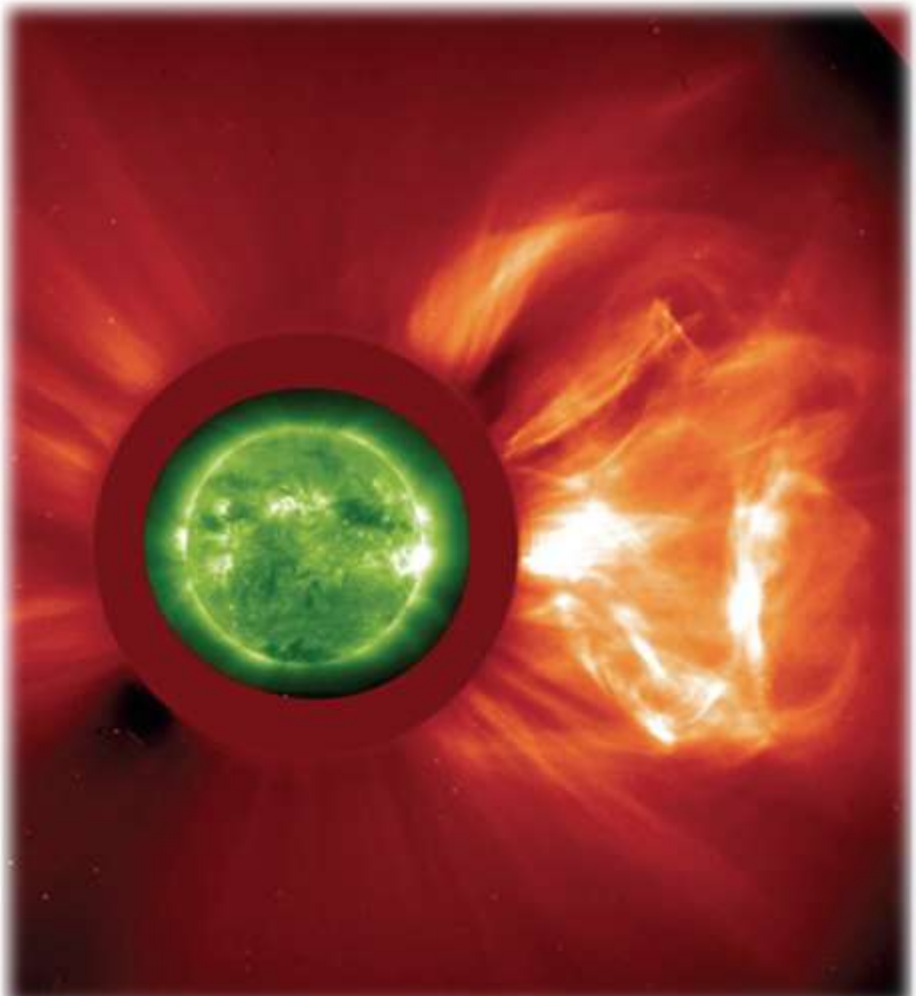
(Image: Naval Research Laboratory)

Deliverable/Value/Accomplishment

- NRL delivered the LASCO instrument suite to NASA; this included NRL in-house conception and optical design of the LASCO C3 coronagraph, the development of the CCD detectors and cameras for all the telescopes, the Fabry-Perot subsystem, the electronics control and software, leading the Max Planck Institute in the LASCO C1 coronagraph, and leading Laboratoire de Marseille in completion of the LASCO C2 coronagraph
- NRL currently delivering to NASA the LASCO Mission operations and data analysis
- LASCO results demonstrated the importance of CMEs in determining space weather impacts at Earth

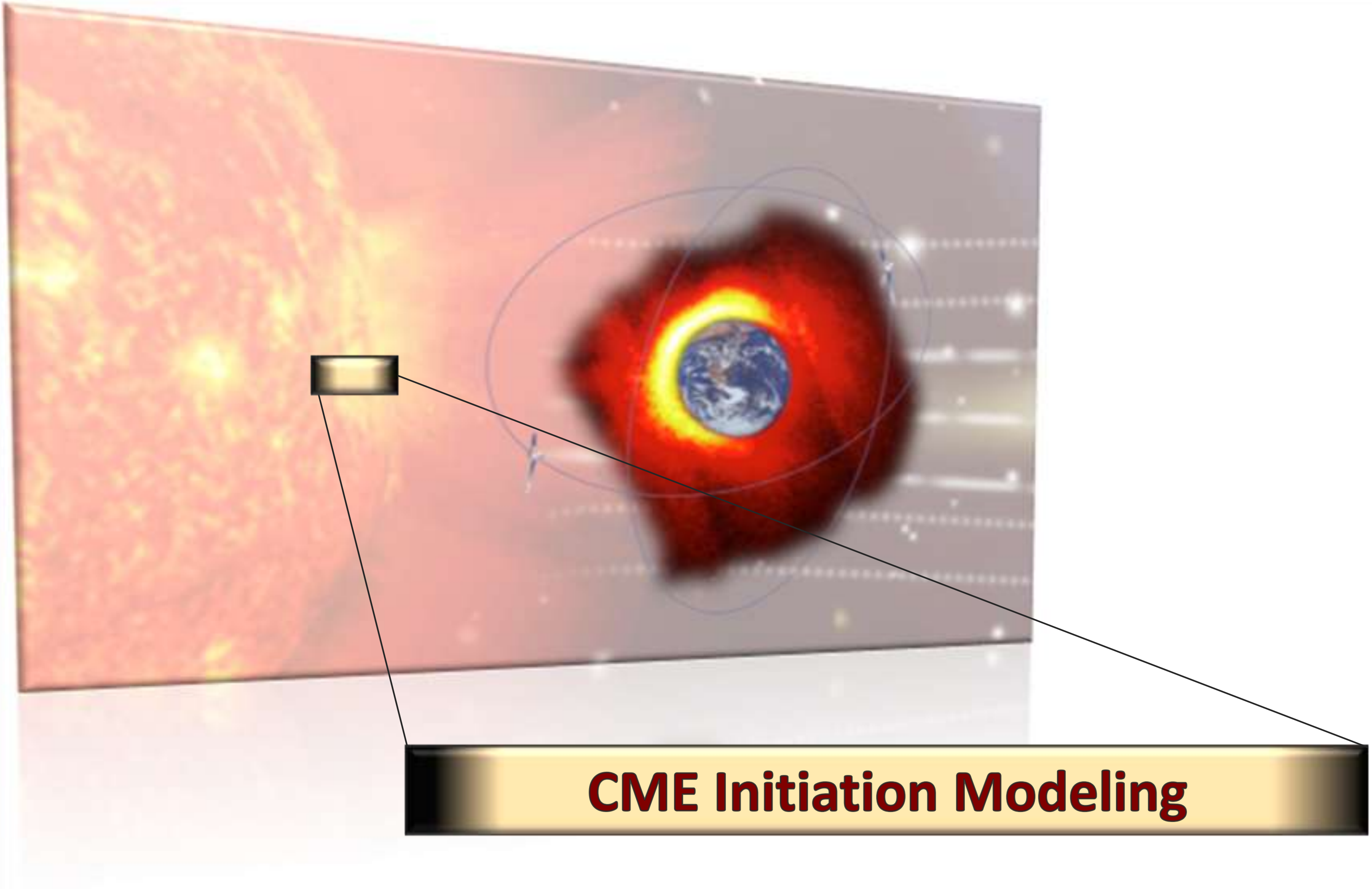
Large Angle Spectrometric and Coronagraphic Telescope (LASCO)

Russell Howard



Using a special type of telescope ("coronagraph") that blocks the blinding direct sunlight, we obtain detailed images of Coronal Mass Ejections (CMEs) – explosive ejections of solar plasma into the heliosphere. Solar coronal images such as these are taken by the NRL coronagraphs on the NASA SOHO and NASA STEREO spacecraft and relayed to Earth in near-real time. These solar storms can reach Earth within 24 to 72 hours, so immediate detection and tracking is critical to evaluate the impact on space based assets and prepare if necessary. Data from LASCO is useful towards validating HPC computer codes such as HiFi that simulate solar coronal dynamics including solar flares, coronal loops, and CMEs.

Heliospace HPC Research Examples



CME Initiation Modeling

Coronal Mass Ejection Initiation

Mark Linton

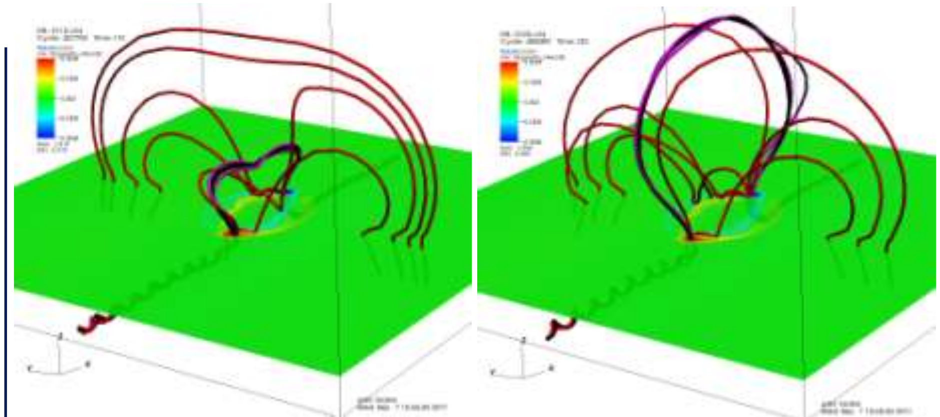
Objective

Drive Coronal Mass Ejection (CME) eruptions by self-consistently emerging convection zone magnetic field into pre-existing, coronal magnetic field configurations. Test validity of current CME models.

Improve our understanding of how CMEs are driven or destabilized. Enhance the Navy's ability to develop predictive tools for these solar eruptions and their space weather consequences, by determining how current observations of flux emergence can be incorporated into CME prediction models.

Approach

- Perform HPC simulations of the dynamic emergence from the solar convection zone into the corona of magnetic flux systems
- Use this flux emergence to test current CME models, in particular the "breakout," "torus instability" and "flux cancelation" models
- Determine the viability of these eruptions when driven by self-consistent flux emergence rather than by the kinematic lower boundary ("photospheric") motions currently used in these models
- Compare the morphology and dynamics of the resulting coronal magnetic field structures and CMEs with STEREO, Hinode, and SDO observations



(Image: Naval Research Laboratory)

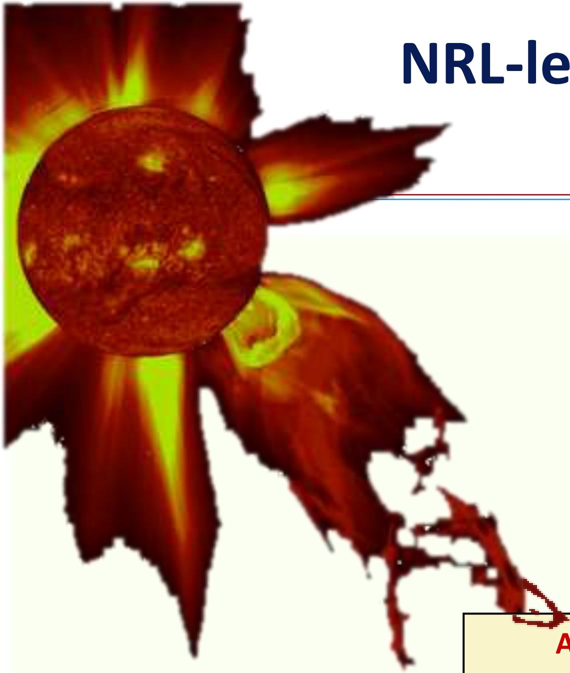
Simulation of magnetic flux rope (twisted fieldlines) emerging through solar photosphere (green plane) into an overlying coronal arcade (high, arching fieldlines). Fieldlines from the emerging rope rise into the corona and reconnect with the overlying field to form an unstable, coronal rope. Ongoing work: Can this coronal rope be made sufficiently robust and unstable that it will form an erupting CME? Leake & Linton (NRL)

Deliverable/Value/Accomplishment

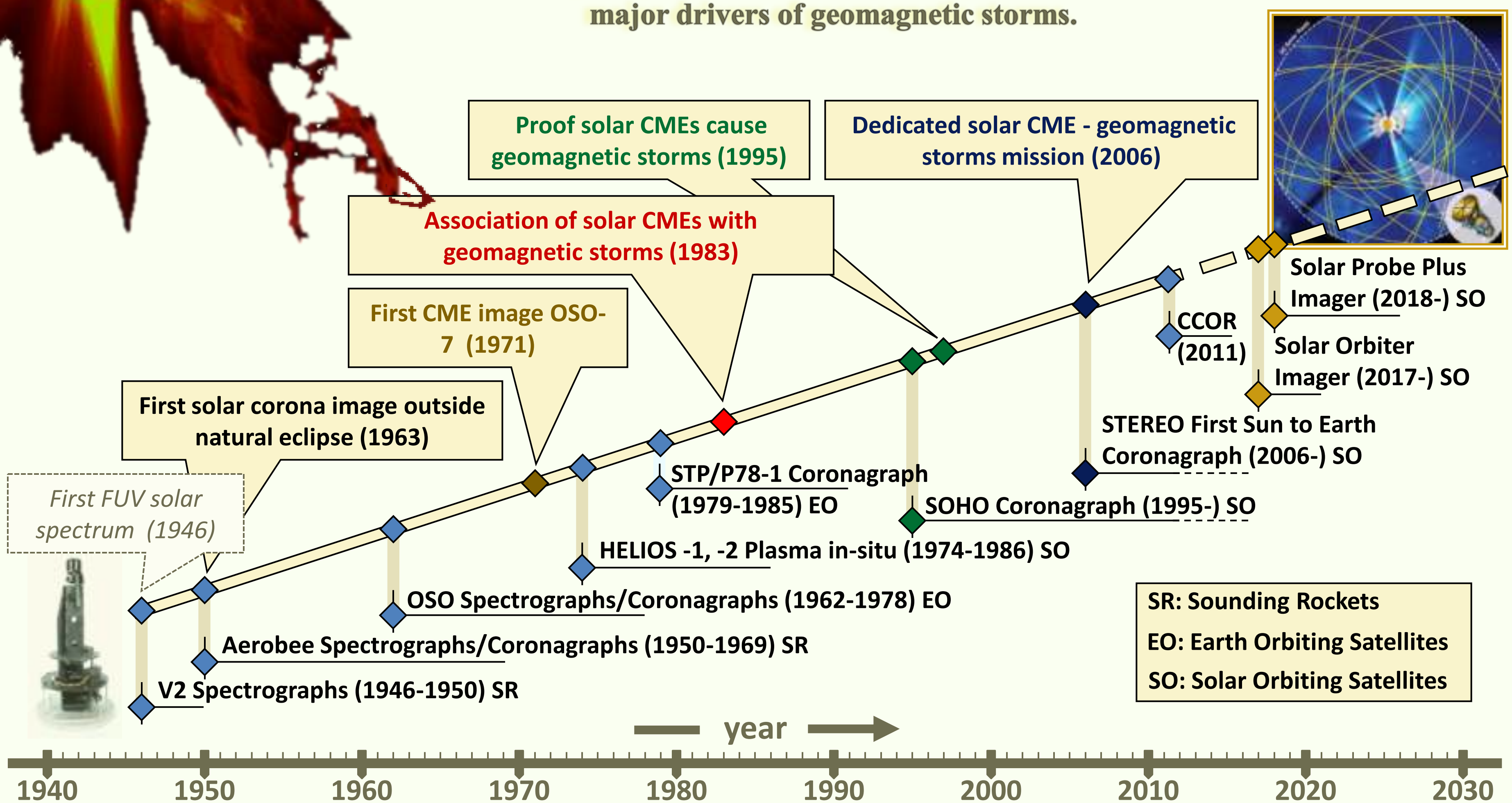
- Determined that flux emergence is not effective driver of breakout CMEs in two dimensions, as dense plasma is carried up into corona and weighs down coronal flux rope
- Showed that flux emergence is significantly more effective in three dimensions (3D), as the extra mass can drain along the emerging fieldlines
- Current work: increase flux in erupting coronal field in 3D simulations so that field can erupt as a full breakout CME
- Future work: study flux emergence mechanism for alternate CME models (torus, flux cancellation)

NRL-led white-light coronagraph experiments

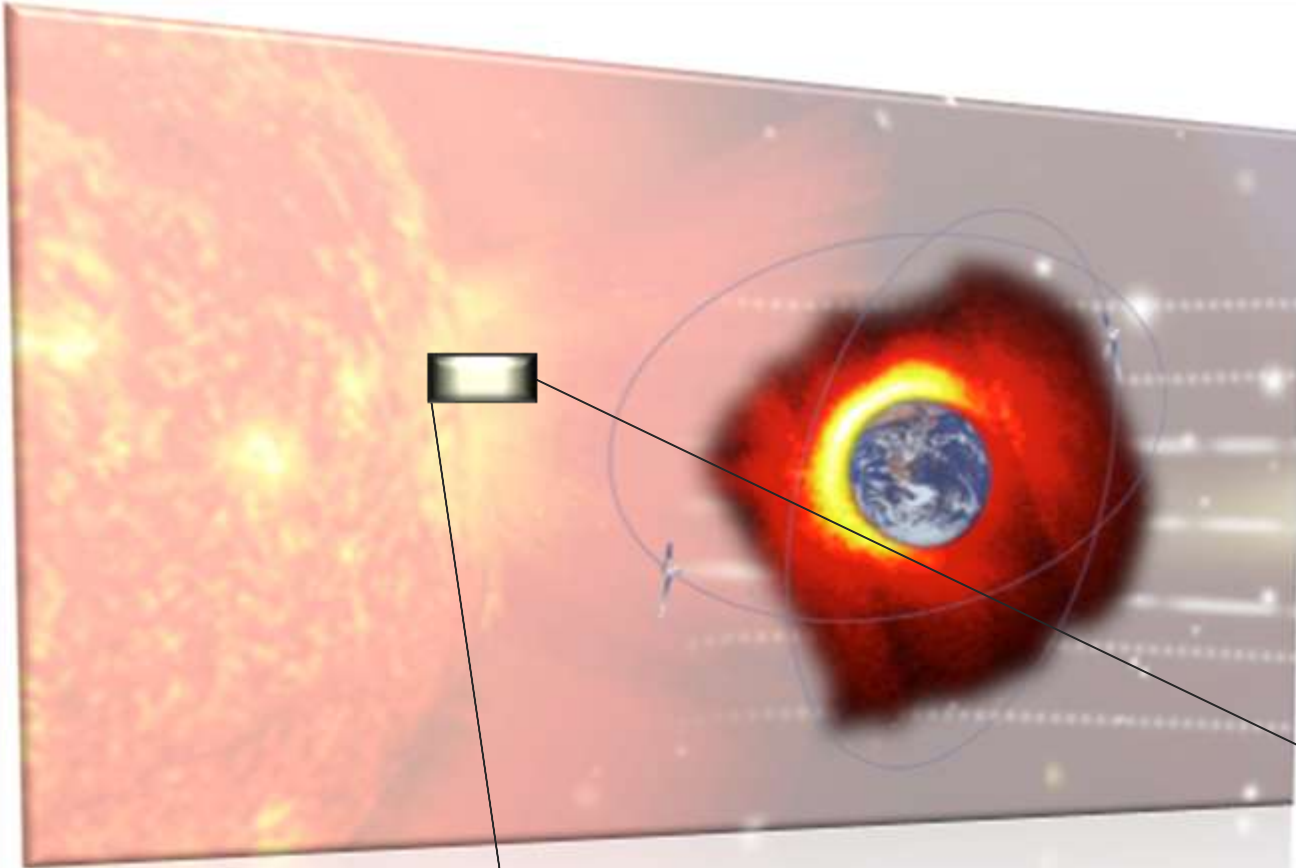
… from NRL's 1971 discovery of CMEs to our first stellar expedition



Solar Coronal Mass Ejections (CMEs) are the most energetic phenomena in the solar system and the major drivers of geomagnetic storms.



Heliospace HPC Research Examples



Coronal Dynamics Modeling

HYPERION: Modeling Solar Coronal Loops

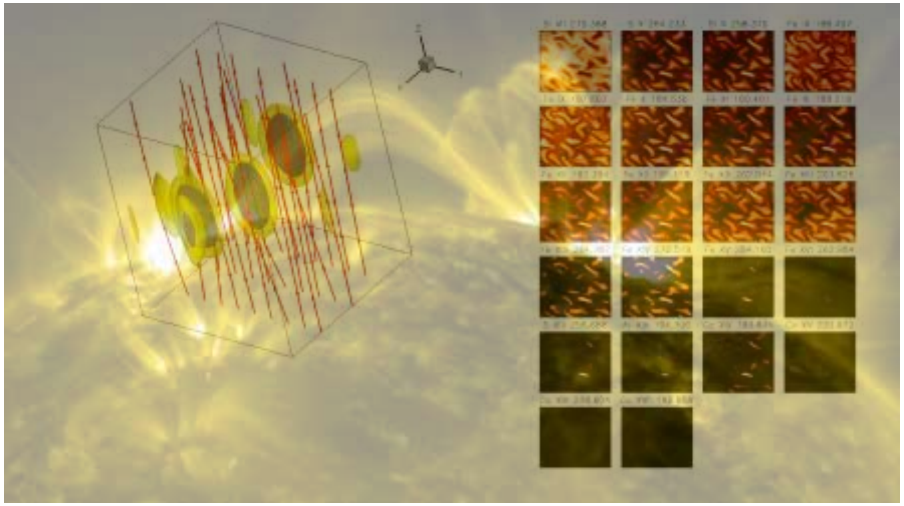
Russell Dahlburg

Objective

Magnetohydrodynamic (MHD) turbulence has long been proposed as a mechanism for the heating of coronal loops in the framework of the Parker scenario for coronal heating. So far most studies have focused on its dynamical properties without considering its thermodynamical and radiative features because of the very demanding computational requirements. We aim to extend this previous research to the compressible regime using HYPERION, a new parallelized, visco-resistive, three-dimensional compressible MHD code.

Approach

- Model solar coronal loop in Cartesian geometry
- Utilize a three-dimensional compressible MHD model with magnetic reconnection, field-wise thermal conduction, and optically thin radiation based on the CHIANTI atomic database for spectroscopic diagnostics of astrophysical plasmas which includes the wavelength range that contributes significantly to the total radiative output of the Sun
- Discretize equations with a Fourier-collocation—finite-difference scheme in space, and a time-step split third-order Runge-Kutta – forward Euler method in time. Parallelize the code for HPC with MPI
- Use data analysis techniques developed for the EUV Imaging Spectrograph on the *Hinode* satellite to post-process the HYPERION solutions and compare with solar data



HYPERION simulation results of (left) temperature isosurfaces and magnetic field lines and (right) loop summit radiation details in a coronal loop, superimposed on an SDO image of coronal loops.

Deliverable/Value/Accomplishment

- We show that the dissipative terms in the energy equation, resulting from the coronal dynamics induced by appropriate photospheric motions, represent an heating term able to balance the thermal conduction parallel to the DC magnetic field and the radiative emission
- The resulting temperature and density profiles, showing a temporal and spatial intermittency, demonstrate the efficiency of the DC heating mechanism, leading to properties that are characteristic of the Sun’s chromosphere / transition region /corona system

Extreme-ultraviolet Imaging Spectrometer (EIS) (Solar-B: *Hinode*)

George Doschek

Objective

Measure the physical conditions such as temperature, density, and dynamics in solar active regions and flares. Determine the physical mechanisms responsible for generating erupting prominences, solar flares, and coronal mass ejections (CMEs).

Solar flares and CMEs are the most energetic phenomena in the solar system and are major drivers of geomagnetic space weather storms that adversely affect ISR, precision engagement, missile detection and intercept, Comms on the Move, spacecraft anomaly assessment, orbital tracking, polar flight activities, the power grid, and ionosphere variations.

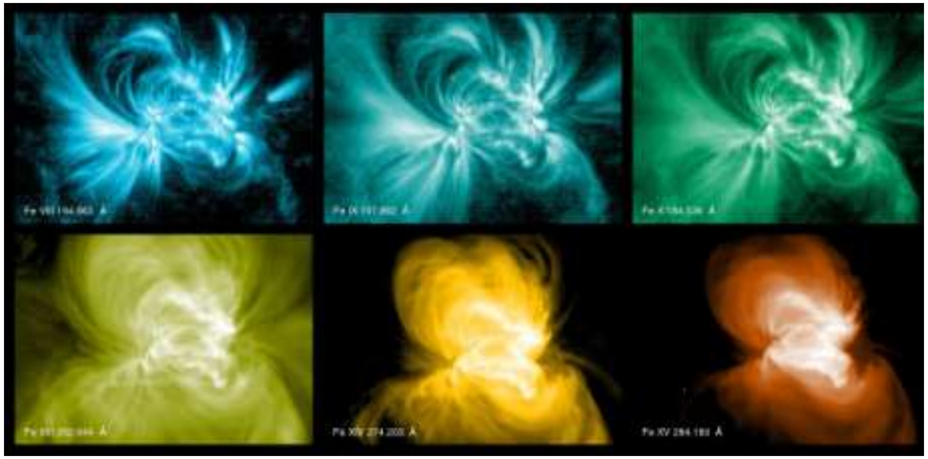
Approach

EIS: An advanced state-of-the-art extreme-ultraviolet spectrometer on the Japanese (Solar-B) *Hinode* spacecraft

- NRL is the EIS PI institution for NASA; EIS was built by an international consortium (US, UK, Japan, Norway) lead by the Mullard Space Science Laboratory in the UK
- EIS builds on the successful NRL/UK/Japan X-ray spectrometers on the Japanese *Yohkoh* (Solar-A) mission and on long-standing solar spectroscopy expertise at NRL

***Hinode* Mission:** September 2006 Launch - *present*

- *Hinode* consists of three instruments: the EIS, a white light telescope and an X-ray telescope. The goal of *Hinode* is to understand the formation and evolution of the solar atmosphere



Monochromatic images of an active region in spectral lines of iron ions formed at different temperatures. EIS can act like a remote sensing thermometer.

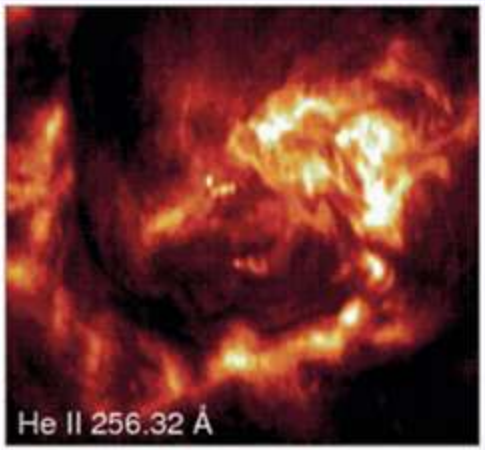
(Image: Naval Research Laboratory)

Deliverable/Value/Accomplishment

- NRL delivered to NASA the EIS optics with mounts and motor mechanisms, aluminum filters, shutter and slit assembly, and the mechanism and heater control flight electronics and software
- NRL participated in scientific design and is currently participating in mission operations, data analysis, and software development
- EIS has discovered flows from active regions that might constitute part of the solar wind impacting Earth. The measured parameters in active regions are allowing detailed tests of active region heating models

Extreme-ultraviolet Imaging Spectrometer (EIS) (Solar-B: *Hinode*)

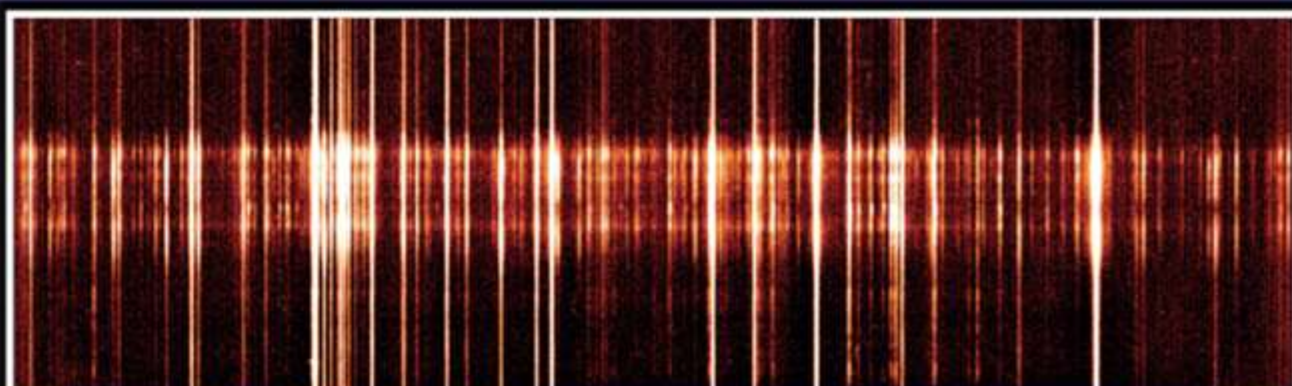
George Doschek



The NRL collaborative EIS/*Hinode* spectroscopy & imaging informs about Active Region densities, temperatures, dynamics, & atomic composition:

essential data for precision prediction algorithms.

Extreme-ultraviolet Imaging Spectrometer (EIS) image of active region



The EIS spectrum – a key to fundamental understanding; spectrum range shown is 245 - 290 A.

Solar explosions that adversely affect the Earth's environment occur in solar active regions. Measuring physical conditions in active regions, with a goal of quantitative understanding of solar explosions, is key for long range prediction. EIS data is also of great value for validating HPC computer codes such as HYPERION that simulate active regions and coronal loops.

Next Generation EUV High-Resolution Spectroscopic Telescope (for Solar-C)

Clarence Korendyke

Objective

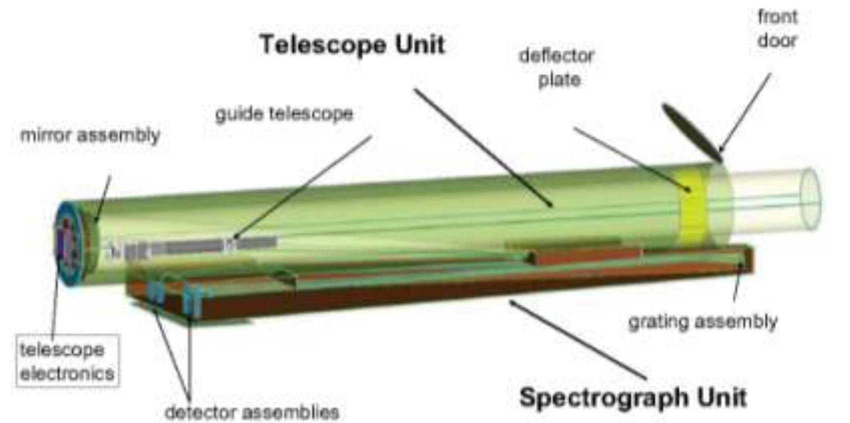
Observe the entire solar atmosphere from the chromosphere into the corona (including flares) with ultra-high spatial and spectral resolution. Determine the flow of energy and dissipation throughout the entire atmosphere. Determine the mechanisms responsible for heating the solar corona.

Understanding how the solar atmosphere is formed and maintained from first principles enables a precision space weather warning system to be developed. The ultimate goal is to predict solar phenomena that are major drivers of geomagnetic disturbances that adversely affect areas such as spacecraft anomaly assessment, orbital tracking, polar flight activities, the power grid, and ionosphere variations.

Approach

Develop an Extreme Ultraviolet (EUV) imaging spectrometer with the following properties:

- A spatial resolution of ~0.3” (240 km) and a spectral resolution sufficient to measure 3 km/s gas flows if count rates are adequate
- Observe all temperatures between 20,000 K and 20 MK with availability of suitable electron density and abundance diagnostics
- Throughput high enough to cover a large dynamical range of solar activity down to the level of a few seconds
- Current target flight opportunity: the future Japanese Solar-C Mission



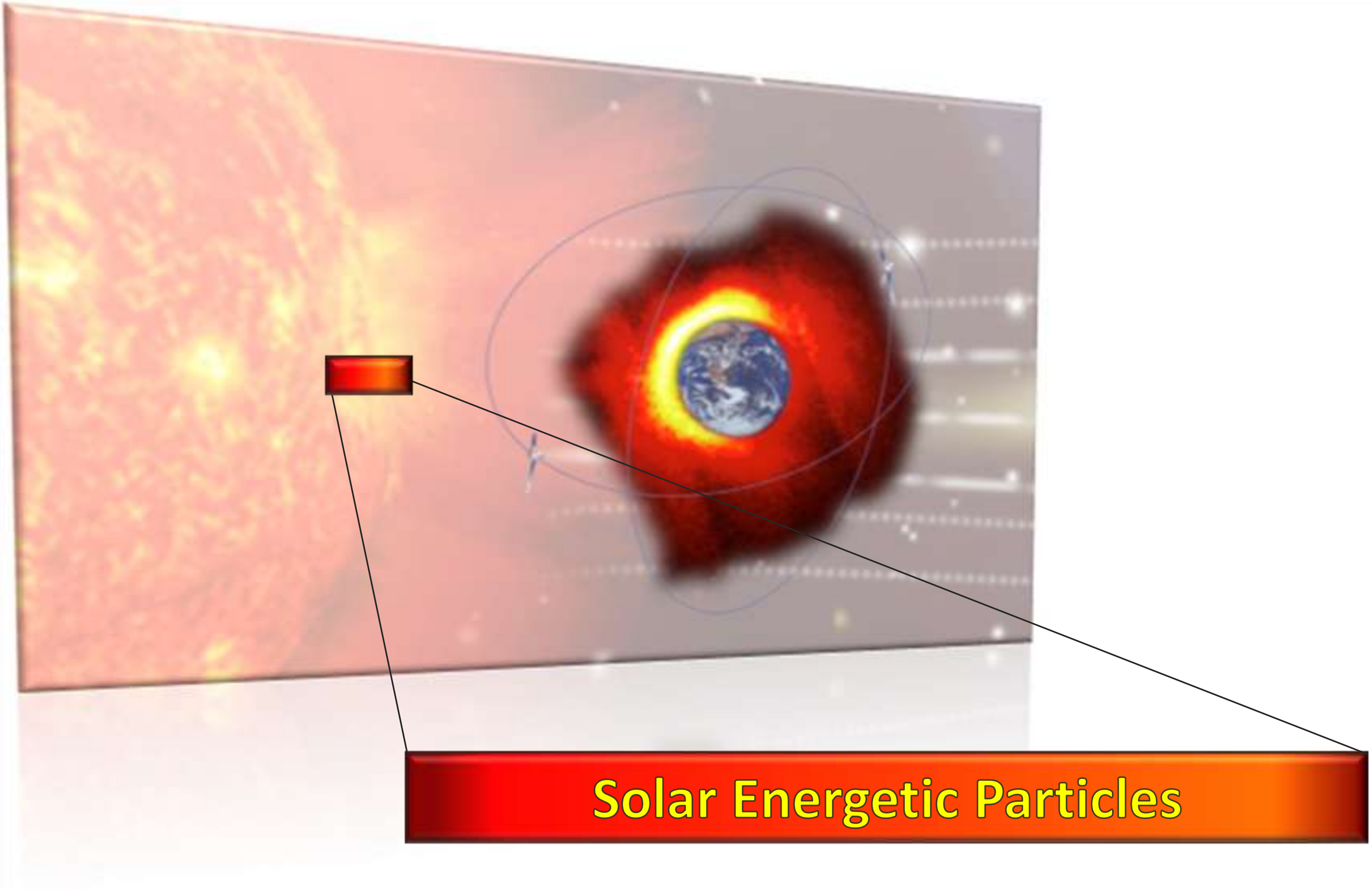
The next-generation EUV imaging telescope, proposed for the Solar-C Mission. The instrument would be built by an international consortium.

(Image: Naval Research Laboratory)

Deliverable/Value/Accomplishment

- NRL participated in the developing the scientific rationale and instrument design for a next-generation solar EUV imaging telescope. Part of the work appears in the Japanese Solar-C Interim Report, the NASA Heliophysics Roadmap, a Space Studies Board Heliophysics decadal survey white paper, and technical papers are submitted for publication to SPIE and Experimental Astronomy
- NRL scientists are participating in the worldwide community development of the Solar-C mission
- Solar-C, the next Japanese-led space solar observatory, will follow from the Solar-B *Hinode* mission

Heliospace HPC Research Examples



Seed Populations for Large Solar Energetic Particle Events

Yuan-Kuen Ko

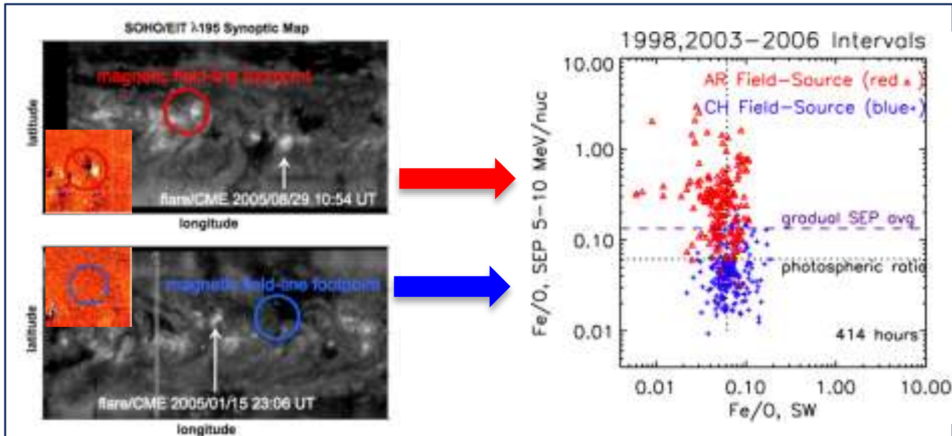
Objective

To identify sources and to quantify the characteristics of various coronal seed populations that give rise to large solar energetic particle (SEP) events produced by coronal mass ejection (CME)-driven shocks.

At high energies, relevant to spacecraft design and operation, large SEP events are highly variable in their size, duration, spectral shape, and ionic composition. These variable factors determine the nature of the radiation hazard posed to space-based systems. This project focuses on discovering the contribution of seed-particle populations to this variability, as an input for future SEP predictive capability for satellite operations.

Approach

- Identify CME/flare sources and analyze SEP characteristics of large events from Solar Cycles 23 & 24
- Identify footpoint of the Sun-Earth magnetic field line; characterize its properties
- Investigate connections between footpoint characteristics and variable SEP properties
- Implement inferred seed particle distributions into SEP acceleration and transport codes
- Combine SEP (HPC) acceleration code with shock parameters from CME propagation code
- Apply NRL solar flare gamma ray and neutron production codes to quantify coronal suprathermal seed protons from neutron decay



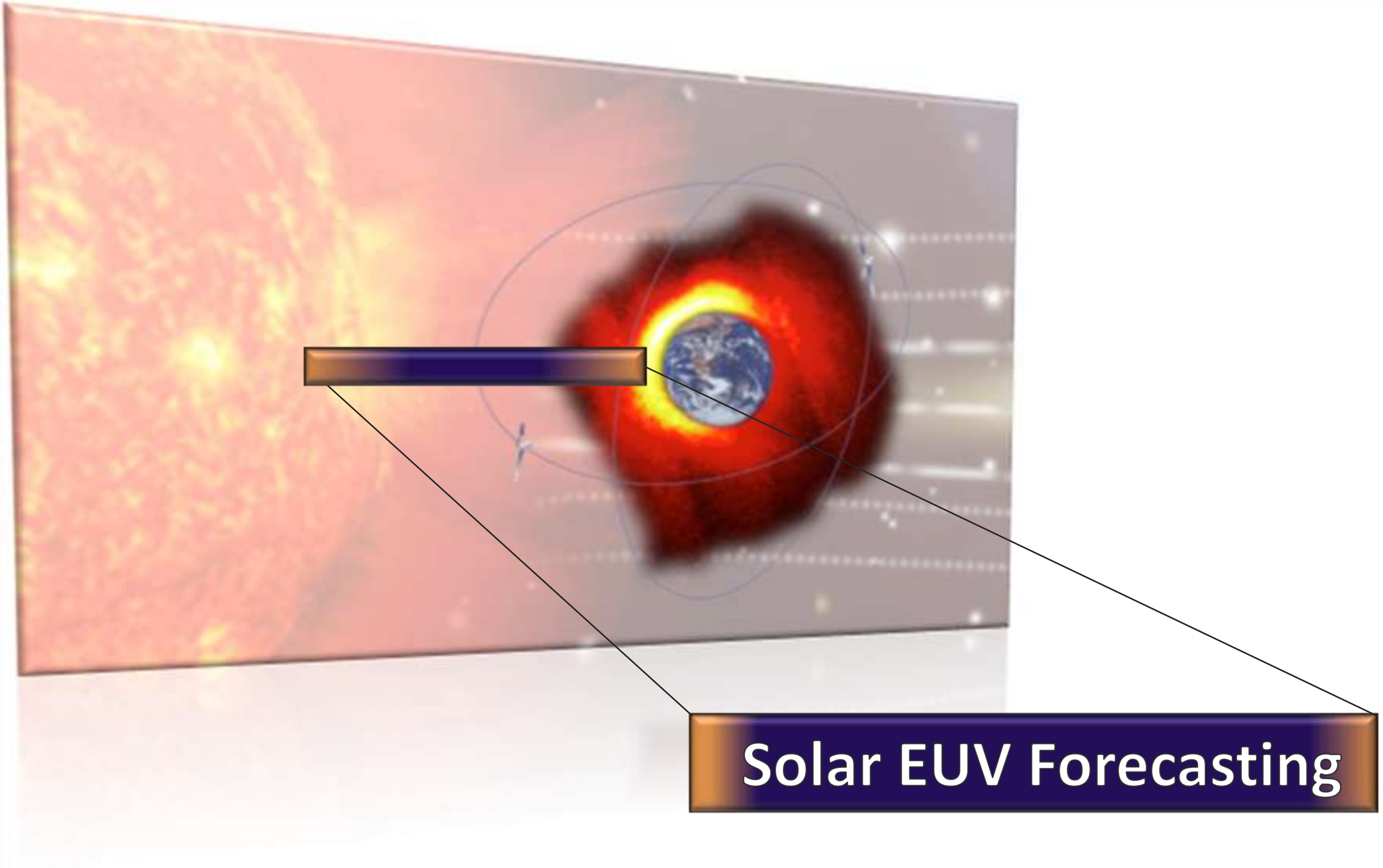
Active-region footpoints (top, red) yield enhanced SEP Fe/O; coronal-hole footpoints (bottom, blue) lead to low SEP Fe/O. NRL researchers have traced the SEP compositional variability back to the nature of the solar region that provides seed particles for shock acceleration.

(Image: Naval Research Laboratory)

Deliverable/Value/Accomplishment

- Understanding of how remotely-observed solar quantities (such as photospheric magnetic fields) govern the suprathermal seed population that gives rise to SEPs.
- Ability to identify ‘all clear’ periods when SEP radiation hazard is minimal.
- Large database of well-characterized SEP events for improvement of empirical probabilistic models (like CREME96) used by space-system designers
- Transition to operations: warnings to operators on the duration and severity of SEP events

Heliospace HPC Research Examples



Coronal Element Abundances and Enhanced Solar EUV Forecasting

Harry Warren & Martin Laming

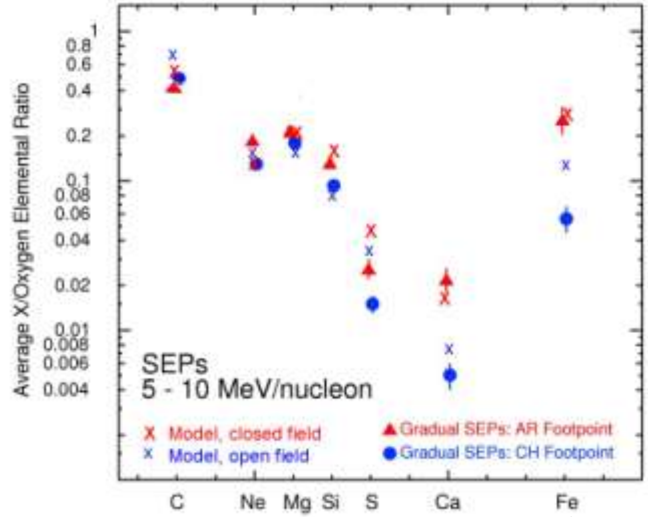
Objective

Advance the understanding of the variable elemental composition of the Sun's corona; a vital step towards the forecasting of the solar Extreme Ultraviolet (EUV) irradiance. Solar EUV radiation, mainly from ions of iron (Fe), is absorbed in the thermosphere, where it heats the ambient gas causing its scale height to lengthen, **thereby increasing the density and associated drag on satellites in the earth's upper atmosphere.** Since the potential exists for debris collisions with operating spacecraft producing further explosions, thereby increasing the debris field in a runaway fashion, mitigation strategies, including forecasting the Solar EUV irradiance are key.

Approach

Solar coronal elemental fractionation was first detected in 1963 by Pottasch. A viable explanation only recently emerged (Laming 2004, 2009, 2012). The important features are:

- Elements ionized in the chromosphere (e.g. Fe, Si, Mg, with first ionization potential less than about 10 eV) are enhanced in coronal abundance by about x 3-4. This is called the "First Ionization Potential (FIP) effect"
- The FIP effect arises as Alfvén or fast mode waves interact with chromospheric ions (but not neutrals), through a combination of wave pressure and refraction forces, known collectively as the ponderomotive force.
- If the dominant waves have a coronal origin -- as opposed to photospheric -- a number of other facets of the abundance anomaly can be theoretically explained (with resonant absorption or nanoflares as the mechanisms responsible for coronal heating)



Comparison of SEP derived abundances (adapted from Ko et al. 2012) with models for closed and open magnetic field regions. Gradual SEPs from an active region footprint (red triangles) agree very well with the closed field model (red crosses). Open field model and data are shown in blue.

(Image: Naval Research Laboratory)

Deliverable/Value/Accomplishment

- Strong chromospheric magnetic field (detectable with helioseismology) suppresses FIP fractionation. Applied to the farside of the sun, 7-day forecasts of coronal element abundances in active regions and flares appearing on the east limb of the sun become possible
- The variation of FIP effect in other coronal structures (quiet sun, coronal holes) and on other stars can be understood on the basis of this model
- The solar wind depletion of He, another longstanding puzzle in heliophysics, is also solved with this model, with implications for the origin of the slow speed solar wind

Solar-Spectral Irradiance Monitor (SUSIM)

Dennis Socker

Objective

Reduce existing major (~30%) absolute and relative 1 hr -11 year solar ultraviolet (115-440 nm) spectro-radiometric measurement discrepancies to the 0.3-3% level in order to achieve sufficient precision of irradiance data for input to models of Earth's upper atmosphere, including the ionosphere and thermosphere.

Highly variable solar ultraviolet radiation, absorbed by Earth's upper atmosphere, modulates formation of the ionosphere and heating of the thermosphere thus affecting space based radars, communications, and orbital tracking. **SUSIM (and *Hinode*) data are used to validate solar EUV forecasting models.**

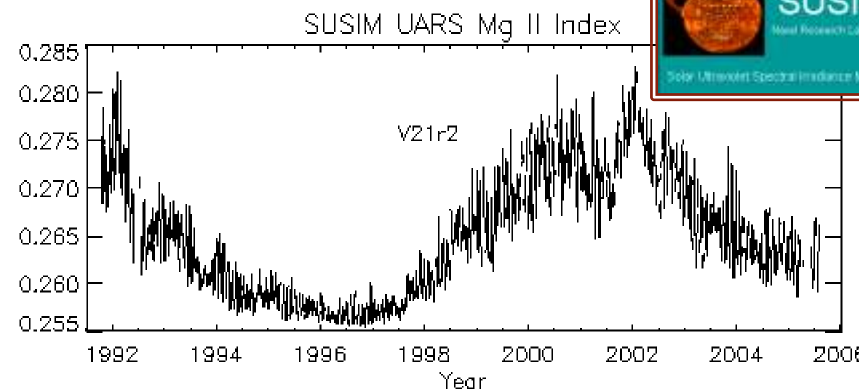
Approach

SUSIM: an advanced, high precision solar ultraviolet spectral irradiance monitor on the NASA UARS (Upper Atmosphere Research Satellite) Mission

- NRL was SUSIM PI institution for NASA
- NRL conceived and developed the SUSIM with its onboard dual precision self calibration capability
- Built on successful NRL Skylab slit spectrograph (SO82B), Calroc calibration sounding rocket, and SUSIM Spacelab-2

UARS Mission: September 1991 (Launch) – June 2005

- Provided a long term orbital platform for SUSIM to measure the solar spectral irradiance to the required precision of 0.3-3% for 14 years and for longer than a full 11 year solar cycle

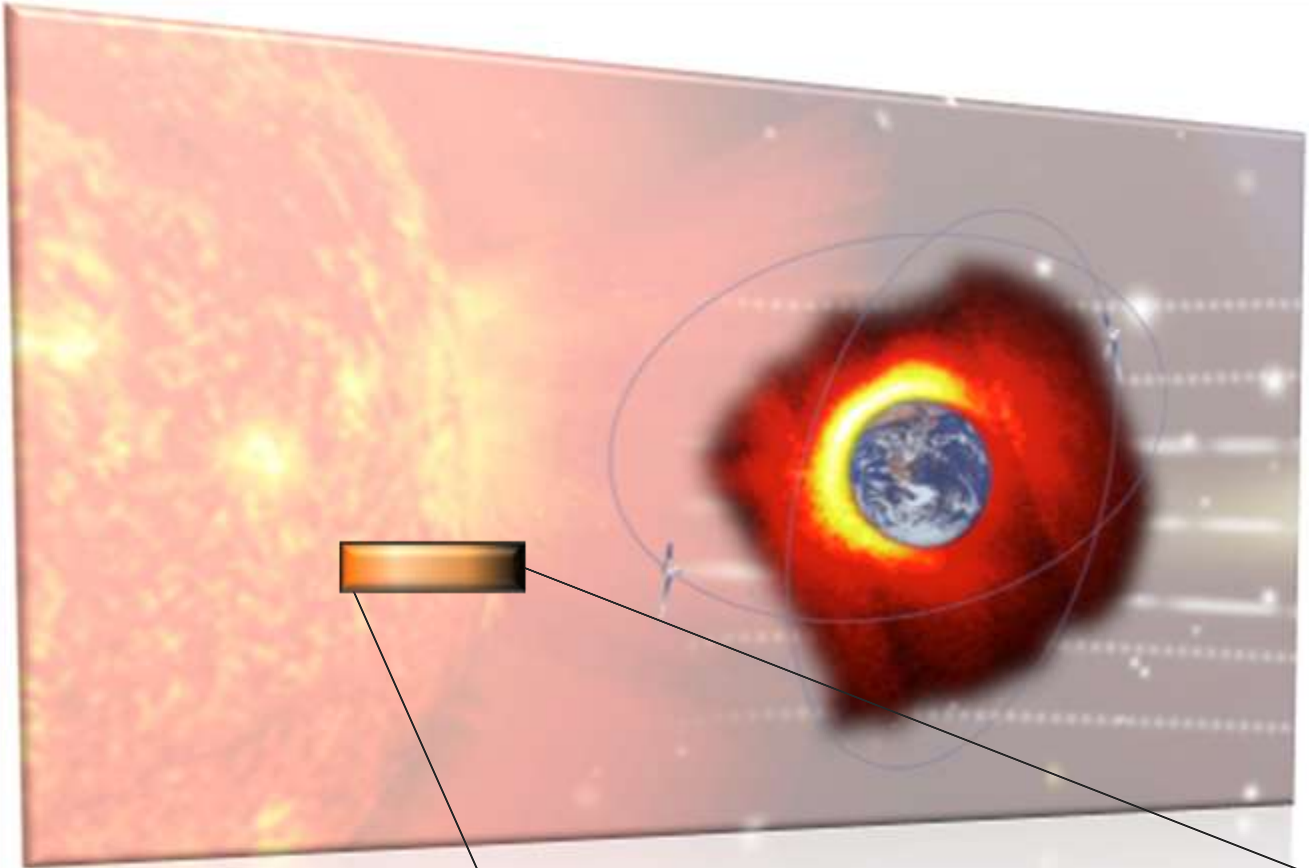


The variability of the solar Magnesium II index at 279.9 nm as measured by the NRL SUSIM aboard UARS over 14 years. The Mg II solar ultraviolet absorption line core-to-wing ratio index is one of the important metrics of solar activity and is used in connection with applied upper atmospheric models as well as basic solar and atmospheric research.

Deliverable/Value/Accomplishment

- The NRL UARS/SUSIM met the solar spectro-radiometric measurement requirements over the entirety of the UARS mission operations
- The NRL SUSIM spectral solar irradiance measurement precision has not been surpassed
- NRL is currently developing a laboratory capability to more accurately calibrate future spectro-radiometric space instruments that will be required for future climate change research

Heliospace HPC Research Examples



Helioseismology

Helioseismic Predictions of Solar Flux Emergence

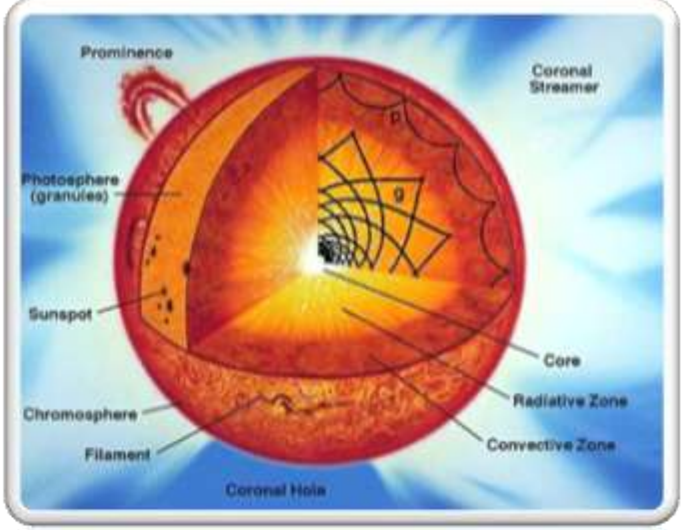
George Doschek

Objective

Give longer warning times for solar geoeffective disturbances via local, very high precision nearside helioseismology to forecast emergence of magnetic flux from below the solar surface that can coalesce into solar active regions and lead to solar geoeffective disturbances. NASA's Solar Dynamics Observatory (SDO), launched in 2010, enables this objective with high-resolution solar observations at a nearly continuous science data downlink rate of 130 Megabits/sec.

Approach

- Link NRL ocean acoustic wave propagation modeling and analysis techniques with solar physics expertise to a new frontier of solar space research: to explore local solar nearside detection of magnetic flux below the Sun's surface before it emerges, by analyzing solar surface Doppler observations
- Obtain data for this analysis from the Helioseismic & Magnetic Imager (HMI) on the LEO SDO satellite, and also from the Michelson Doppler Imager (MDI) data from the Solar & Heliospheric Observatory (SOHO) that was launched in 1996 and is providing ongoing data from L1
- Modify and apply acoustic wave HPC tools developed primarily for naval acoustics to solar flux emergence prediction, and regressive classifier approach prediction methods that are used also for ocean research acoustics topics

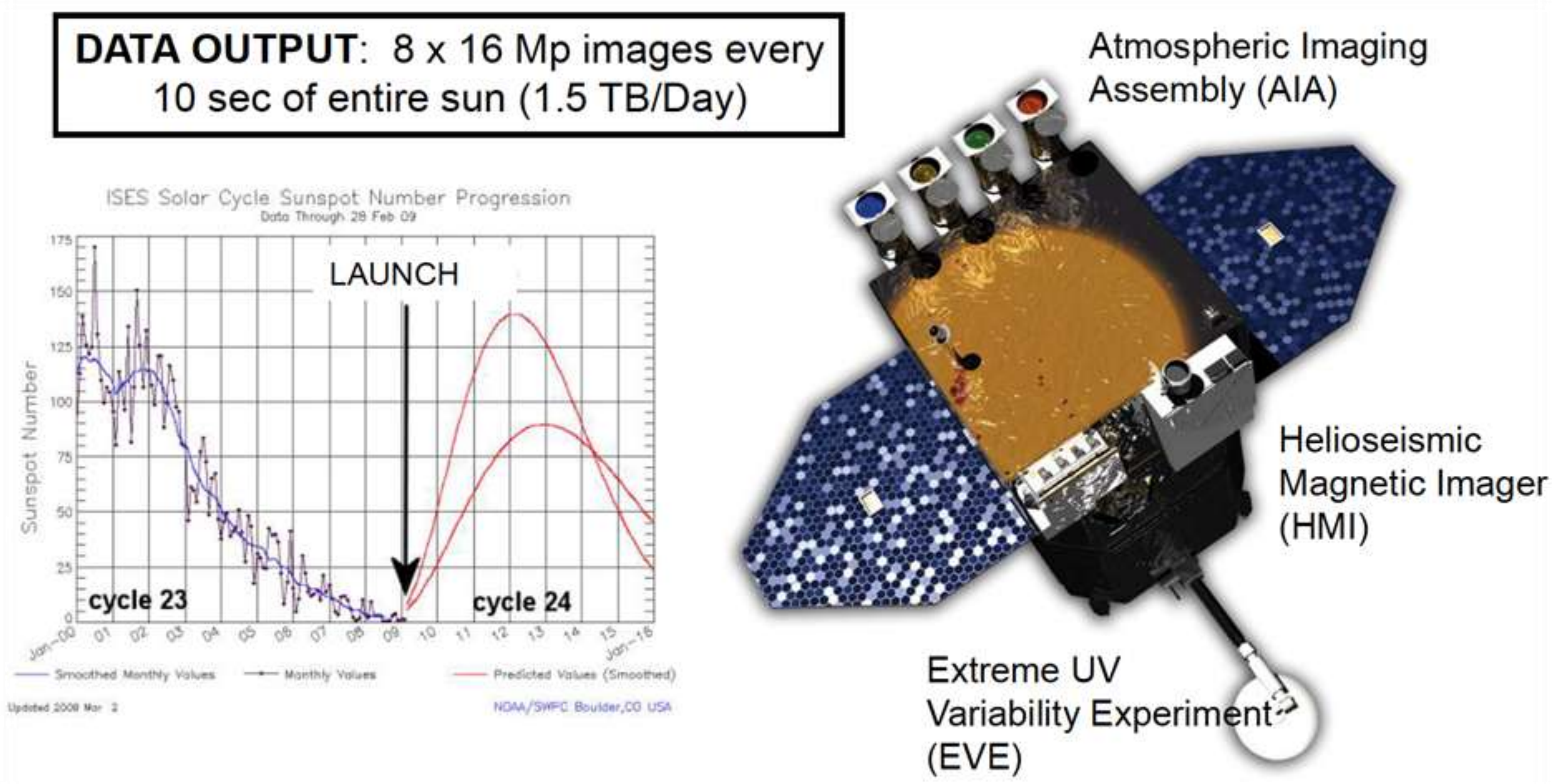


What is happening below the Sun's surface?
Need to become a 'submariner' to find out.

Deliverable/Value/Accomplishment

- Nearside helioseismology inverts acoustic wave patterns observed on the Sun's nearside due to rays that have propagated a short distance below the solar surface, and have interacted with regions of magnetic flux in the process of emerging.
- With local high-precision nearside helioseismology, solar active regions and sunspots may be detectable at very early stages in development, towards highly accurate space weather prediction

NASA Solar Dynamics Observatory



For SDO data access, see [http://sdo.gsfc.nasa.gov/data/].

The Helioseismic & Magnetic Imager (HMI) on the NASA Solar Dynamics Observatory (SDO)

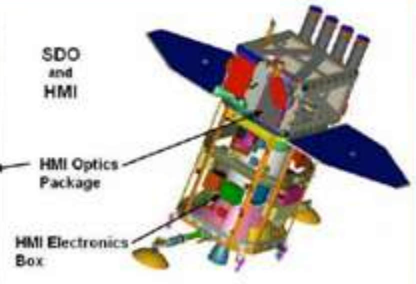
SDO was launched on 11 February 2010 into a geostationary orbit and is currently providing about 1.5 terabytes of data per day.

SDO has three instruments: HMI built by Stanford University (better than 1.5" angular resolution), the Atmospheric Imaging Assembly (AIA) EUV telescopes built by Lockheed Martin Solar & Astrophysics Laboratory (10 full-Sun images every 10s at 1.2" angular resolution), and the Extreme-ultraviolet Variability Experiment (EVE) built by the University of Colorado's Laboratory for Atmospheric and Space Physics

NRL scientists are Co-Is on EVE. All data are in the public domain and accessible via several websites.

The HMI instrument design and observing strategy are based on the highly successful MDI instrument on *SOHO*, with several important improvements. HMI observes the full solar disk in the Fe I absorption line at 6173Å with a resolution of 1 arc-second. HMI consists of a refracting telescope, a polarization selector, an image stabilization system, a narrow band tunable filter and two 4096 pixel CCD cameras with mechanical shutters and control electronics. The continuous data rate is 55Mbits/s.

Images are made in a sequence of tuning and polarizations at a 4-second cadence for each camera. One camera is dedicated to a 45s Doppler and line-of-sight field sequence while the other to a 90s vector field sequence. All of the images are downlinked for processing at the HMI/AIA Joint Science Operations Center at Stanford University.



SDO: an extraordinary observational dataset

Karl Battams

- Launched in 2010, NASA's Solar Dynamics Observatory returns approx. 1.5TB of solar imaging data **daily** !
- Data represent unprecedented spatial and temporal resolution imaging of the solar disk in Extreme Ultraviolet*
- This is the **largest open, observational space scientific data set** thus far

Project/Mission	Years active	Data volume
P78-1/Solwind	1978-1983	6GB
Solar and Heliospheric Observatory (SOHO)	1995 – present	~2TB
Solar Terrestrial Relations Observatory (STEREO)	2007 – present	~38TB
Solar Dynamics Observatory (SDO)	2010 – present	1.5TB/day

Observational scientific image analysis

New challenges: To *process*, *analyze* and *mine* new science from an observational data stream with high volume (petabytes), velocity (terabytes/sec), and variety

New insights: The SDO data offers possibility of detecting new solar physical features that were previously under-sampled or totally unresolved, in all previous data sets

New approaches: Standard 'desktop' data analysis computing approaches are insufficient and inadequate for addressing the potential offered by modern science missions. The space observational community needs new HPC-based Big Data solutions!

** and HMI observes FE I at 6173 Å*

Summary

- High Performance Computing (HPC) fundamentally advances space science
- Geospace S&T builds on HPC research to study near-Earth dynamics with coupled models, to gain a predictive capability, mitigate environmental effects, and increase situational awareness
- High Energy Space & Astrophysics S&T builds on HPC research, to simulate extreme environments and evaluate experimental concepts, and to interpret and model observed phenomena
- Heliospace S&T builds on HPC research, for observationally-driven numerical and theoretical insights, and for space environmental models and measurements
- The Sun-Earth system has tremendous observational data freely available, including now a remarkable observational dataset, SDO, which represents an opportunity for data mining experimentation with massive amounts of new physical imagery

Sincerest thanks for input from:

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Chin-Chun Wu, NRL

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DoD HPC Space & Astrophysical Sciences Computational Task Area Academic Advisor

SSD Sun-Earth System HPC Research