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A Multi-Faceted Approach to Enabling Large-Scale Science in a Microsat Constellation

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ABSTRACT

The Polarimeter to UNify the Corona and Heliosphere (PUNCH) mission is a constellation of microsatellites that combines advances in several areas of technology enabling the use of simple imaging instrumentation to measure, to-date, inaccessible aspects of the outer corona and solar wind. The primary PUNCH measurement is brightness and polarization state of light scattered by electrons entrained in solar wind features. This measurement is made possible in the context of a small explorer budget by leveraging a combination of three key elements: (a) a constellation of four small satellites conducting synchronized observations, (b) availability of low-cost off-the-shelf components, and (c) advanced and rigorous science data processing that enables the four microsats to produce 3D images as a single virtual observatory. This paper will discuss the contribution of each of these key enablers, and present the overall status of this NASA Small Explorer mission scheduled for launch in 2025.

MISSION OVERVIEW

The Polarimeter to UNify the Corona and Heliosphere (PUNCH) mission[1] is a constellation of microsatellites that combines advances in several areas of technology enabling the use of simple imaging instrumentation to measure, to-date, inaccessible aspects of the outer corona and solar wind. PUNCH is a Class D Small Explorer (SMEX) mission funded under the 2016 Heliophysics SMEX announcement of opportunity (AO)[2].

The PUNCH space segment is composed of four suitcase-sized microsatellites with a mass of approximately 60 kg each, developed by the Southwest Research Institute (SwRI). Each microsatellite hosts a single primary science instrument: three of the observatories host a Wide Field Imager (WFI) instrument, and one hosts a Narrow Field Imager (NFI). The NFI observatory is also slated to host a Student Collaboration instrument called STEAM, for STudent Energetic Activity Module. STEAM is an x-ray spectrometer instrument being developed and managed by students under the direction of the Colorado Space Grant Consortium[3]. PUNCH is currently integrating the flight observatories and preparing for environmental testing.

The WFI and NFI instruments both comprise two common elements and instrument-specific baffles and optics. The two common elements include a charge-coupled device (CCD) camera developed by the Rutherford Appleton Laboratory (RAL), and a Polarizing Filter Wheel (PFW) developed by the Naval Research Laboratory (NRL). The NFI instrument, also developed by NRL, is a compact coronograph[4] and has a solar occulter and a circular geometry, and will image the solar corona. The three WFI instruments, developed by SwRI, are heliospheric imagers with a solar/lunar baffle and a linear geometry, and will image the inner heliosphere. Figure 1 shows artists concepts of the fully integrated NFI and WFI observatories.

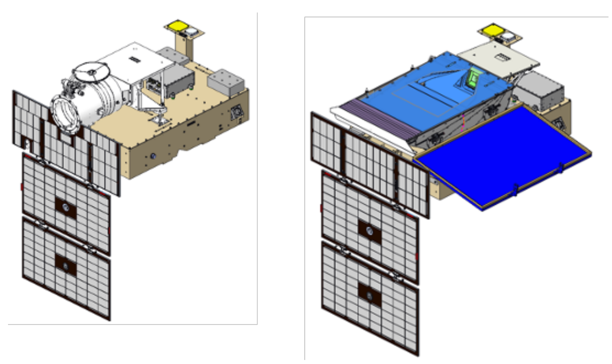


Figure 1. NFI (left) and WFI (right) Observatories

PUNCH is slated for launch in 2025 as a secondary payload aboard a Falcon 9 launch vehicle into a polar, sun-synchronous, low-Earth orbit at an altitude of approximately 620km. After launch and deployment, the three WFI observatories will drift into position 120° apart in the orbit plane, and then the drift will arrested by the on-board propulsion system. The position of the NFI observatory is not constrained. The four observatories then take a continuous set of Global Positioning System (GPS)-synchronized images every eight minutes, each set comprising images with seven polarizer settings. This approach allows PUNCH to operate as a single virtual observatory. The images are stored on-board and downlinked to the ground during regular ground contact passes via the Swedish Space Corporation (SSC Space) ground data network.

PUNCH ground operations are handled by the Mission Operations Center (MOC) and Science Operations Center (SOC), both located at SwRI's Boulder, Colorado facility. The MOC schedules and manages ground contacts, generates and uploads command sequences to the microsatellites, and receives science and engineering telemetry received from the ground stations. The SOC processes the science data from the four observatories into a single image set, such that the final science product is a PSF-corrected and background-subtracted integrated movie produced by the single PUNCH "virtual observatory".

The primary PUNCH measurement is brightness and polarization state of light scattered by electrons entrained in solar wind features. This measurement is made possible in the context of a SMEX budget by leveraging a combination of three key elements: (a) a constellation of four small satellites conducting synchronized observations, (b) availability of low-cost off-the-shelf components, and (c) advanced and rigorous science data processing that enables the four microsats to produce 3D images as a single virtual observatory. Each of these elements will be further discussed in this paper.

LARGE-SCALE SCIENCE FROM SMALL-SCALE SATELLITES

PUNCH seeks to obtain large-scale science in the context of a small explorer mission[5] by deploying a constellation of four microsatellites combining the smaller field of view (FOV) of a coronagraph with the much larger FOV of three heliospheric imagers. The mission is guided by a single science goal: to understand the cross-scale processes that unify the solar corona and heliosphere. That goal leads to two major science objectives: determining how the solar corona becomes the ambient solar wind that fills the solar system; and understanding the dynamic evolution of transient structures, such as CMEs and shocks. Both major objectives are addressed through sensitive deep-field imaging, in visible light, of sunlight scattered by free electrons in the inner solar system.

The rarefied plasma (solar "K corona" and solar wind) being studied is visible against far brighter foreground and background objects: the solar "F corona" (Zodiacal light) and the starfield itself. This drives a mission with moderate light-gathering ability and highly precise photometry. The scientific FOV extends from the outer solar corona, starting about 1° away from the Sun, to a full 45° away from the star. This drove the need for at least two separate instruments: an inner-field imager and an outer-field imager, to capture the wide optical dynamic range: over four orders of magnitude in brightness across the FOV.

The solar wind evolves rapidly as it expands into interplanetary space, and coronal mass ejections (CMEs) can travel upwards of 1 Mm/sec, driving a high image cadence of roughly one per minute (two full 3-exposure polarization sequences per 8-minute observing interval, plus one unpolarized clear exposure for calibration).

The combination of wide field of view, high imaging cadence, and continuous observation drove data rate for the mission to nearly 10 Gb per day per spacecraft. Collecting the science data required either heroic downlink measures or low Earth orbit. A LEO mission implied that the planet itself would obscure half the FOV from the point of view of a single spacecraft.

The specific accommodation requirements for PUNCH were driven by the apertures and stray light characteristics needed for the imagers. The sizes of coronagraphs (such as PUNCH/NFI) and heliospheric imagers (such as PUNCH/WFI) are driven by the physics of Fresnel diffraction[4,6]. Both instruments have limiting lengths under 1 meter long. Therefore, physical accommodation was possible on a constellation of four small satellites to look in all directions at once, relative to Earth.

Launching PUNCH on four satellites rather than one exacerbated several challenges of conventional imaging instrumentation. In particular, it forced careful specification of the instrument requirements to ensure the images were as intercomparable as possible despite being collected by different instruments built by different teams at different institutions (SwRI and NRL); it elevated the importance of cross-constellation coordination, as the four spacecraft are synchronized to within 1 second; and it required extremely careful alignment and photometric calibration in ground processing. Because the starfield, in particular, is both much brighter than the solar wind and also challenging to remove via conventional techniques[7] the multiple-smallsat approach required extreme rigor in PUNCH instrument calibration, the PUNCH ground system, and the data processing pipeline to merge images seamlessly from the four different instruments.

THE SCIENCE CRAFT: TAILORED STRUCTURES AND COTS COMPONENTS

Two key enablers for development of a constellation-based mission within a SMEX budget include recent advances in the small satellite component market, and the ability to customize the small bus structure and electrical interfaces around the needs of the instrument.

The SMEX Class D Observatory design process leverages Commercial Off The Shelf (COTS) components and previously flown subsystem designs wherever possible. Like the game of Tetris®, a collection of required components (identified during mission design) are mechanically tucked into place, accommodating the needs each instrument, and electrically unified by heritage deep space avionics tailored by interface.

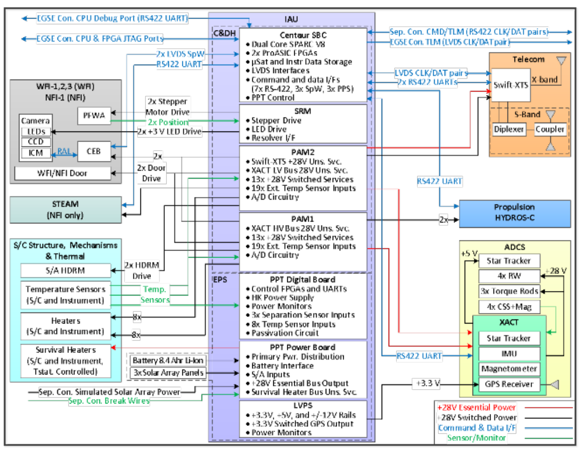


Figure 2. PUNCH Block Diagram

COTS Subsystems

PUNCH builds upon successful design strategies from SwRI's Cyclone Global Navigation Satellite System (CYGNSS) mission, for a constellation of SMEX *microsats or µSats*—assembling a COTS component-based architecture, with key mission-specific updates:

- An integrated Attitude Determination and Control (ADCS) subsystem (all sensors and actuators pre-validated as assembly).
- Addition of an electrolysis-based propulsion subsystem to support initial arrest of post-drift orbit position.
- Addition of an X-band software-defined radio, for improved 25 Mbps data downlink to support the increase science data production.
- A monolithic primary bus structure to reduce fastener count and simplify component integration (at the expense of some change accommodation)

The ADCS, Propulsion and Telecom subsystems all leverage recent advances in the CubeSat marketplace for low-cost components. For ADCS, the PUNCH µSats will be flying the Blue Canyon XACT-100 Subsystem (Control Module, integrated with Nano Star Trackers, RWP-100 Reaction Wheels, 6 Am^2 Torque Rods & Coarse Sun Sensors. The propulsion subsystem and radios are both from Tethers Unlimited: a HYDROS-C H_2-O_2 Propulsion Module and SWIFT-XTS S-/X-band Radio.

Component development activity targeted at spacecraft in the 1-50kg mass range has significantly exceeded that of larger weight classes in recent years, and µSat budgets can rarely afford the cost and/or size/weight/ power (SWaP) of components built for larger spacecraft (>100kg). It follows that a significant challenge in µSat component selection is that this particular class of spacecraft is identifying components that meet the cost and SWaP restrictions of this class of mission while also having a level of reliability that exceeds that of most CubeSat missions. It is a nascent marketplace, which can result in a veritable "no man's land" when it comes to component selection.

Because CubeSat and TechDemo missions rarely have the Safety & Mission Assurance demands of NASA primary missions, PUNCH has been challenged to bridge reliability analyses gaps for this Class D Small Explorer. For example, radiation performance and qualification data for many new components is either considered proprietary/competition sensitive, or is simply not yet available due to some of the new technologies in use. A detailed risk management process, informed by reviews of inherited items (i.e., pre-existing data from COTS product development cycles), has been used to identify specific gaps for mitigation. A key beneficial outcome of this process has been improvements in component designs at the EEE-INST-002 part level, as well as mission Concept of Operations, to mitigate potential PUNCH radiation performance issues.

Tailored Heritage Avionics

High-heritage absolute and relative time command sequence capabilities from the CYGNSS flight software were combined with single-string avionics from a pair of defense smallsat missions to compile the Integrated Avionics Unit (IAU) for PUNCH.

The IAU interfaces with the Solar Array to efficiently couple energy within the power system, and provides for charging/discharging of the battery.

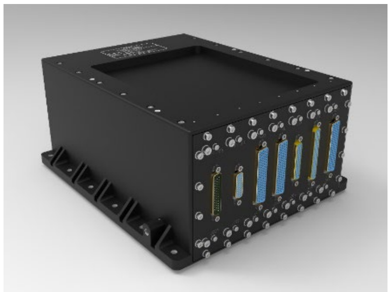


Figure 3. PUNCH Integrated Avionics Unit

It also provides power switching and distribution for spacecraft sensors, actuators and communication devices, as well as for internal power regulation for its electronics and spacecraft sensor network. It hosts processing for command and data handling and compression of instrument data. It houses both volatile and non-volatile data storage, and processes engineering and science data into Consultative Committee for Space Data Systems (CCSDS) packets for storage and downlink.

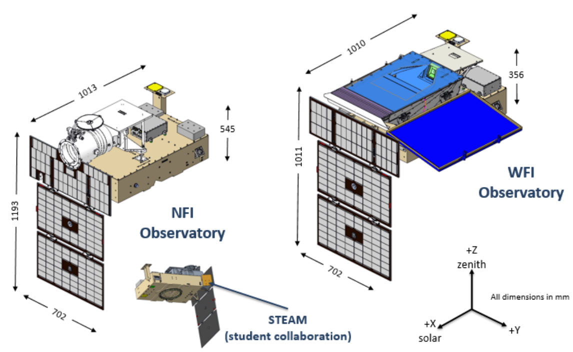
A Class D parts program with reduced screening demands was implemented for the IAU. Previous board-level designs were tailored to meet the PUNCH-unique component interfaces and instrument needs, including:

- Chassis with custom Backplane: 7 slots (scalable), providing shielding to radiation exposure and thermal mitigation
- Centaur: primary command/control electronics with dual-core SPARC V-8 GR712RC processor and 2 RTProAsic FPGAs (subsystem & instrument data processing)
- Peak Power Tracker: high efficiency 2-board interface between solar array, battery and essential power bus for the spacecraft (with switched power)
- Power and Analog Module: 2 copies provide power distribution and signal conditioning
- Stepper and Resolver Module: implements redundant set of stepper motor drivers for the instrument polarizing filter wheel, and readout of resolver interface for positional feedback
- Low Voltage Power Supply: accepts +28V nominal power and produces secondary voltages (and voltage/current monitors) for components.

Structure & Thermal Control

Large spacecraft (100s or 1000s of kilograms [kg]) from traditional aerospace contractors typically have significant heritage and reuse in the mechanical structure, avionics and software. As such, a science mission can capitalize on the existing bus design from a heritage perspective, but in exchange must adapt the instrument design to the target spacecraft bus accommodations (mechanical mounting, electrical interface, field of view, etc.).

A microsatellite sits between a traditional (>100 kg) large bus and a tiny (<10 kg) CubeSat, with mass of the order of 50 kg. For both PUNCH and the CYGNSS mission that immediately preceded it, the overarching strategy is to customize the mechanical bus to the science to produce a 'sciencecraft'. This customizable attribute of μSat design was an enabler for the PUNCH mission to be able to accommodate three very different instruments (two primary and one student instrument) across four observatories without having to design two different spacecraft. The two PUNCH observatories are nearly identical mechanically, in spite of hosting three instruments with significant differences, using common electrical interfaces and instrument-specific mechanical mounts. Three spacecraft host a heliospheric imaging instrument with a flat geometry, and the fourth hosts a coronograph instrument with a tubular geometry and a dual-Xray spectrometer.



After all components were selected for PUNCH, they were positioned first to accommodate the needs of each instrument, and then to minimize balance mass needed for center-of-gravity tuning in support of requirements for both launch vehicle separation, and the propulsion thrust vector. Finally, second-order configuration impacts (e.g., torque rod proximity to magnetometer) were resolved.

After that, the Solar Array (S/A) was sized for both stowed and deployed configurations and power demand. It is important to note here that while the S/A is assembled from heritage COTS products (i.e., ZTJ cells, EX-1515 substrates, E250 hold-down/release mechanism), it must also be tailored along with the structure to a form factor governed by the hosted instruments.

Prior to launch vehicle selection, spacecraft structural sizing is then governed by quasi-static interface acceleration, equivalent sine, random vibration, shock and acoustic loads from representative environmental test campaigns (e.g., GEVS). After launch vehicle selection, requirements are refined at a stack level with (transient) coupled loads analyses and anticipated acoustically-driven dynamics.

Thermal design begins with hot operational cases to size radiators, and cold safe-mode cases to size heaters, followed by special operational states and configurations such as thermal modes defined by specific combinations of power states and orbit/beta angles. These efforts bound the coatings, sensors & heaters needed for a successful mission.

THE SINGLE VIRTUAL OBSERVATORY: ADVANCED SCIENCE PROCESSING

PUNCH requires substantially more complex ground science data processing than even larger mission classes, in order to extract an incredibly small signal (light reflected off free electroncs in the solar wind) from a very noisy foreground and background.

In order to generate data products for scientific analysis, it is necessary to carefully calibrate each image produced by the individual observatories, resolve the polarization measurements—which are initially made in the instrument reference frame—into a common framework, combine each observatory's observations into a single image, and remove stray light, the bright F-corona and background stars, to finally reveal the faint coronal and heliospheric features that are the focus of the mission's scientific objectives. Achieving all these steps requires uncommon measurement sensitivity (better than $1\text{x}10^{-17}$ of the mean solar photospheric radiance at 80 solar radii), and pointing knowledge (better than 0.1 pixels), which means the requirements for data calibration and processing are considerably stricter than is typical for a mission of this scale. The ultimate result of this careful processing is a set of images that reveal the complete polarization state of the corona across the PUNCH's full FOV. These images are stored in Flexible Image Transport System (FITS) files that are fully compliant with the FITS version 4.0 standards and requirements for analysis using standard community tools like SunPy and AstroPy[8,9,10].

The calibration pipeline lives within and is maintained by the PUNCH SOC, and is written in Python, following the HelioPy's standards for software development, which govern open-source development practices, coding style, and testing requirements. Once completed, the calibration package, *PunchBowl*, will be released as a SunPy-affiliated open-source package for community use. PunchBowl is a standalone package, fully capable of executing all processing steps required to generate calibrated PUNCH data products, but it can be managed by a second package, *PunchPipe*, that governs the execution of the software within the SOC's automated pipeline. PunchPipe is built using the *Prefect* Python-based workflow management package, which allows the SOC to integrate PunchBowl software into the automated data processing pipeline in a straightforward manner, while still maintaining compatibility for end users to carry out manual processing in their own local software environments (without the automated processing).

PunchBowl further leverages several other software packages, several of which have been developed within the PUNCH project and released as standalone tools, as well as many community-based software tools, particularly those in AstroPy and SunPy. Within the processing software, data is stored and transported in a self-contained PUNCH Data Object (PDO), which uses the *ndcube* Python package, a powerful tool for storage and manipulation of astronomical image data and metadata. The PDO moves data between modules, receives updated data arrays and metadata from modules following processing steps, and contains methods for constructing, saving, and displaying files. The use of the PDO significantly reduces the software overhead required to manage data within each individual module from that of older data processing pipelines, and provides key functionality to move and manipulate data for analysis tasks as well. Below we describe the PUNCH data products, the data processing steps, and the specific software packages that execute key steps in the data pipeline.

Figure 4 provides an overview of the PUNCH data products, processing pipeline steps, and overall end-to-end data flow. All PUNCH data are stored in FITS format. There are four data product levels:

- Level-0: Raw camera frames in instrument units with instrument/observatory metadata required for initial calibration.
- Level-1: Calibrated camera frames in units of solar radiance, updated metadata and pointing information in the World Coordinate System (WCS) standard; a secondary data structure provides uncertainty information.
- Level-2: Calibrated images, resolved into standard polarization, and projected into an appropriate coordinate system. Level-2 images include NFI frames and mosaic trefoil images from the three WFIs that merge data from all

four PUNCH observatories for each set observation time. A multidimensional data array provides complete polarization information; a secondary array provides uncertainty.

- Level-3: Background- and starfield-subtracted calibrated images resolved into total and polarized brightness components. A variety of products are available including NFI-only, WFI trefoils and complete mosaics, as well as several derived products, including quicklook images and solar wind flow maps.

Level-0 to Level-1 Processing

Level-0 products are generated from raw CCSDS packets received from the MOC, and are passed into the Level-1 processing pipeline (Figure 4, top row). The pipeline uses a quartic flat field map to correct for nonlinearity in the instrument CCD response, as well as to correct for instrumental vignetting and any instrumental anisotropies, as well as the instrumental offset due to bias and dark current. Once this initial step is completed, images are now in linear instrumental units (DN).

The next processing step scrubs cosmic ray spikes from the calibrated CCD images. Individual PUNCH images contain vertical (in the detector coordinate system) streaks due to the shutterless frame-transfer operating mode: the CCD continues to expose as the image is migrated to the storage portion of the CCD[11]. Cosmic rays are single events and do not generate column-aligned streaks, while stars are stationary and do produce streaks. Despiking uses convolution with a custom "spike detection" mask tuned to the camera readout mode. The spike detection mask is directly convolved with the photometric intermediate image to produce a spike-detection image, which in turn is thresholded to produce a spike mask. The spike mask identifies spike pixels, which are replaced with a median of nearby non-spiked pixels prior to destreaking.

Destreaking then accounts for the smearing effects from PUNCH's shutterless frame transfer mode. Each detector continues exposing during readout as the science image is moved off of the active detector area and onto the storage area. This convolves the resulting image with a causal "effective Point-Spread Function (PSF)" that comprises a spike and a long, constant-value streak. The value of the streak depends on the ratio between the camera exposure time and the per-row transfer time. Each photometrically calibrated, despiked image is convolved with the calculated inverse PSF to remove streaks, leveraging essentially the same technique that has been successfully applied on heliospheric imager data from the STEREO mission for years, leaving only the desired image of the sky[12].

Next, a known stray light pattern is subtracted from the destreaked image, before the image undergoes a (PSF) deconvolution. PSF deconvolution is critically important to obtaining uniform, merged data because the PSF varies across the instrument FOV, particularly in the WFI images. This PSF deconvolution is achieved with a purpose-built Python package called *regularizePSF*, which is available within the HelioPy and SunPy software ecosystems. An extensive discussion of the theory, approach and implementation of the regularizePSF package is available for PUNCH data users[13].

The final step in generating Level-1 data files is to use the background stars visible in the image to determine the pointing to extreme precision required for subsequent processing. An initial concept for this step leveraged the method of Astrometry.net, which uses a computed catalog of hashes of star quadrangles to find likely matches in an image[14]. Although this method is extremely effective at blind identification of pointing for unknown starfields, it lacked the required precision for PUNCH, so we instead implemented a stellar *point set registration* algorithm.

Point set registration is a classic computer vision problem that determines the spatial transformation between two point clouds. For PUNCH, one point cloud corresponds to a known stellar catalog and the other to the extracted stellar pixel positions in an image. PUNCH data processing uses known satellite pointing information to transform the stellar catalog from astrophysical world coordinates into camera coordinates. By finding the transformation between the resulting two point sets, one can determine the error in the original pointing estimate and subsequently work backwards to correct it. This step uses a simple implementation of the iterative closest point algorithm that alternates between estimating the transformation and assigning which points correspond to each other to determine the instrument pointing to within the required precision[15].

This task is complicated by the optical distortion of the lens assembly in PUNCH. Stars far from the image center do not appear where they would with a perfectly undistorted optical system. We correct for distortion in our point set registration by implementing a distortion model, determined by iteratively characterizing the pointing error in many sub-regions of PUNCH images. Because Level-1 images are stored in camera coordinates, this distortion model must be included in the Level-1 metadata to retain pointing knowledge across the entire FOV.

Level-1 to Level-2 Processing

Because PUNCH polarization measurements are made in the individual instrument frame, and instruments change orientation as they orbit, polarization observations must be resolved from this instrument frame to a common one prior to being combined into Level-2 mosaic images (Figure 4, second row left). This is achieved by another purpose-built package, called *SolPolPy*. PUNCH polarization observations use a triplet strategy, in which individual polarization images are taken with polarizer angles spaced 60° apart. PUNCH uses a triplet framework we refer to as MZP (for –60°, 0°, and +60°; i.e., Minus, Zero, Plus). There is a straightforward set of transformations that can be implemented to convert from an arbitrary reference angle to a common one (and further to total and polarized brightness measurements for Level-3 files)[16]. SolPolPy receives images with the MZP triplet referenced to the instrument's orientation and converts to the solar reference frame. As a side note, SolPolPy will also be able to work on data using other polarization strategies, such as quartets of polarizers spaced at 45° increments; and will be available for community use as a SunPy-affiliated package.

Following this step, the images are marked to identify diffuse bright structures over and above the background F-corona. Data marking uses a variant of the ZSPIKE temporal despiking algorithm to identify auroral transients. ZSPIKE relies only on the temporal structure (and not the spatial structure) of spikes to determine whether a region is a transient brightening; it identifies both small moving bright features (such as other satellites) and also aurorae. The variation from direct ZSPIKE includes some spatial structure by lowering the threshold for detection in large regions, via convolution of the heuristic mask image with a diffuse-feature kernel.

Once observations from each PUNCH observatory are resolved into a common polarization framework and all anomalous features are marked, they can be resampled into the appropriate projection (azimuthal equidistant projection for mosaic images) and combined. This is straightforwardly achieved by defining the destination WCS parameters, which are fixed to the Sun, and using the input files WCS information and AstroPy's *Reproject* package to resample the image into the desired projection. Each individual reprojected image is then merged into a single mosaic via a weighted average that leverages the data uncertainties carried in the secondary Header Data Unit (HDU) of each file. The resulting Level-2 files combine all four observatories' observations into a single, unified trefoil at four-minute intervals. Over time, the trefoil pattern rotates to generate several trefoils that can be combined at Level-3 to fill in the complete unified observatory FOV.

Level-2 to Level-3 Processing

The key Level-3 processing steps are to remove unwanted signal from the F-corona and background stars (Figure 4, second row right). The SOC maintains separate MZP models of the F-corona, which are updated using the data stream itself at regular intervals. The process is based on the techniques developed through the SOHO LASCO and STEREO SECCHI instrument suites[17]. A circularly symmetric 3D F-corona model is constrained by L2 images over a rolling period of one month, and is used to generate a time-dependent rendered image using the known parameters of Earth's orbit. The rendered model is subtracted from each L2 mosaic to yield an image containing the K-corona and starfield.

The starfield model is also generated on-the-fly from the data themselves. The mosaics are resampled from the observing frame to absolute celestial coordinates and resolved into an MZP polarization referenced to the celestial sphere. In this coordinate system, the starfield is fixed, enabling separation of the moving Thomson-scattered signal from the stationary starfield signal. After starfield subtraction, the data are resampled back to the observing coordinate system. This process has been extensively demonstrated and makes use of locally optimized spatial filters to carry out the resampling. The resulting background-subtracted MZP images are combined and resolved into total and polarized brightness.

The final processing step computes weighted averages of multiple carefully processed Level-3 trefoils to generate low-noise, full-frame mosaics and low-noise NFI images for scientific analysis. These products are subsequently used to generate solar wind maps, derived from flow-tracking algorithms, and compressed quicklook images. JPEG2000 images are delivered to the *jHelioviewer* archive, which provides simple image display and analysis capabilities[18]. jHelioviewer is a powerful tool for combining data from multiple perspectives, enabling straightforward inter-analysis with remote sensing observations from *Solar Orbiter* and *Parker Solar Probe*, as well as other instruments that view the Sun from the Earth's perspective.

Additional planned Level-3 products support space weather forecasting activities and emphasize identification of CME onsets in the inner FOV, and CME progress tracking in the outer FOV. Currently, only unpolarized measurements are planned, serving as a backup data stream in the event that an anomaly on-board operational space weather missions disrupts this critical data stream.

PUNCH data are stored in NASA's Solar Data Analysis Center (SDAC) archive and made available to the research community and public via the Virtual Solar Observatory. The bottom row of Figure 4 shows a summary of these products and the complete end-to-end data flow required to generate them.

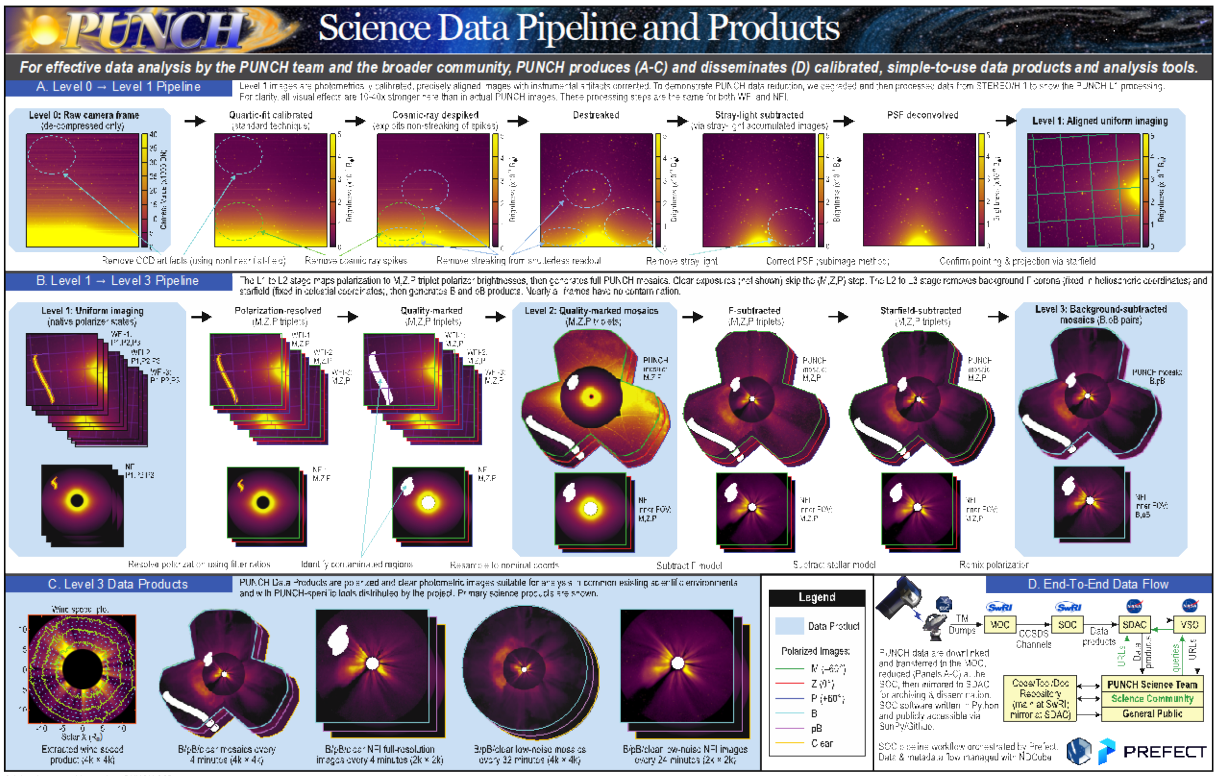


Figure 4. PUNCH Science Data Pipeline

CONCLUSION

The PUNCH mission capitalizes on several key enablers to produce continuous 3D images of the transient solar wind. Deploying two instrument types (a coronograph and three heliosphere imagers) across a constellation of four small satellites provides the wide FOV needed for PUNCH science while remaining in low Earth orbit for efficient data downlink. Combining COTS components with heritage avionics and a customized "science craft" allowed PUNCH to develop a constellation within the constraints of a SMEX budget. This also allowed PUNCH to allocate ample budget for the advanced ground science data processing required to extract the faint Thomson-scattered light reflected in the solar wind from the noisy starfield background.

ACKNOWLEDGMENTS

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