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Arcus: The X-ray Grating Spectrometer Explorer

R. K. Smith[*a], M. H. Abraham[b], R. Allured[a], M. Bautz[c], J. Bookbinder[d], J. N. Bregman[e], L. Brenneman[a], N. S. Brickhouse[a], D. N. Burrows[f], V. Burwitz[g], R. Carvalho[d], P. N. Cheimets[a], E. Costantini[h], S. Dawson[d], C. DeRoo[a], A. Falcone[f], A. R. Foster[a], C. E. Grant[c], R. K. Heilmann[c], E. Hertz[a], B. Hine[d], D. Huenemoerder[c], J. S. Kaastra[h], K. K. Madsen[i], R. L. McEntaffer[f], E. D. Miller[c], J. Miller[e], E. Morse[j], R. Mushotzky[k], K. Nandra[g], M. Nowak[c], F. Paerels[l], R. Petre[m], L. Plice[d], K. Poppenhaeger[n], A. Ptak[m], P. Reid[a], J. Sanders[g], M. L. Schattenburg[c], N. Schulz[c], A. Smale[m], P. Temi[d], L. Valencic[o], S. Walker[d], R. Willingale[p], J. Wilms[q], S. J. Wolk[a]

[a]Smithsonian Astrophysical Observatory, 60 Garden St, Cambridge, MA, US; [b]The Aerospace Corp, El Segundo, CA, US, [c]Massachusetts Institute of Technology, Cambridge, MA, US; [d]NASA Ames Research Center, Moffet Field, CA US; [e]University of Michigan, Ann Arbor, MI, US; [f]The Pennsylvania State University, State College, PA, US; [g]Max-Planck-Institut für extraterrestrische Physik, Garching, DE; [h]SRON Netherlands Institute for Space Research, Utrecht, NL; [i]California Institute of Technology, Pasadena, CA, US; [j]Orbital ATK, Dulles, VA, US; [k]University of Maryland, College Park, MD, US; [l]Columbia University, New York, NY, US; [m]NASA Goddard Space Flight Center, Greenbelt, MD, US; [n]Queen's University, Belfast, UK; [o]Johns Hopkins University, Baltimore, MD, US; [p]University of Leicester, Leicester, UK; [q]Friedrich-Alexander-Universitaet, Erlangen-Nürnberg, DE

1. ABSTRACT

Arcus will be proposed to the NASA Explorer program as a free-flying satellite mission that will enable high-resolution soft X-ray spectroscopy (8-50Å) with unprecedented sensitivity – effective areas of >500 sq cm and spectral resolution >2500. The Arcus key science goals are (1) to determine how baryons cycle in and out of galaxies by measuring the effects of structure formation imprinted upon the hot gas that is predicted to lie in extended halos around galaxies, groups, and clusters, (2) to determine how black holes influence their surroundings by tracing the propagation of outflowing mass, energy and momentum from the vicinity of the black hole out to large scales and (3) to understand how accretion forms and evolves stars and circumstellar disks by observing hot infalling and outflowing gas in these systems. Arcus relies upon grazing-incidence silicon pore X-ray optics with the same 12m focal length (achieved using an extendable optical bench) that will be used for the ESA Athena mission. The focused X-rays from these optics will then be diffracted by high-efficiency off-plane reflection gratings that have already been demonstrated on sub-orbital rocket flights, imaging the results with flight-proven CCD detectors and electronics. The power and telemetry requirements on the spacecraft are modest. The majority of mission operations will not be complex, as most observations will be long (~100 ksec), uninterrupted, and pre-planned, although there will be limited capabilities to observe targets of opportunity, such as tidal disruption events or supernovae with a 3-5 day turnaround. After the end of prime science, we plan to allow guest observations to maximize the science return of Arcus to the community.

Keywords: Gratings, X-rays: spectroscopy, Instrumentation

2. INTRODUCTION

With sufficient resolution and sensitivity, an X-ray spectrometer can determine the physical properties of not only every abundant atomic species but also each ionic state, enabling study of every relevant aspect of a plasma. Astrophysical high-resolution X-ray spectroscopy has made major discoveries[1,2,3,4,5], but potential progress has been limited both because the effective areas are typically <10% of X-ray imaging missions and the available resolutions are $\lambda/\Delta\lambda < 1000$. As a result, neither the *Chandra* nor *XMM-Newton* gratings can effectively survey the hot low density gas at and beyond the outskirts of galaxies and clusters, despite the fact that most of the baryons in the Universe are found in these regions.

[*]rsmith@cfa.harvard.edu; phone 1 617 495-7143; http://hea-www.harvard.edu/~rsmith

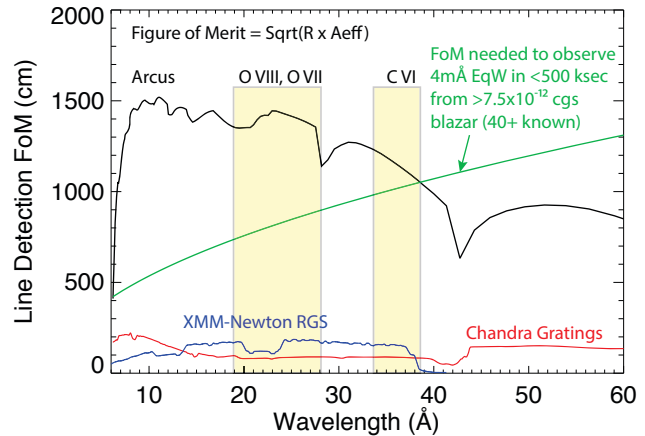| GOALS	METHOD	SELECTED INSTRUMENT REQUIREMENTS	
Determine how baryons cycle in and out of galaxies	Measure the radial profiles of hot gas at and beyond the virial radii of galaxies and clusters, and all phases of gas in our Galaxy	Spectral Resolution (21.6-28Å)	2500
		A_{eff}(21.6-28Å) (avg)	500 cm²
		Background @ 24Å	0.006 cts/s
		A_{eff}(16-21.6Å) (avg)	500 cm²
		Spectral Resolution (16-21.6Å)	2000
		Relative A_{eff} cal per resol. element	±10%
		Bandpass	8-50Å
		CCD energy resolution	150 eV
Determine how black holes influence their surroundings	Measure the mass, energy, and composition of outflowing winds from the inner regions of black holes	Wavelength calibration	0.4mÅ
		Absolute A_{eff} calibration	±20%
		Time Resolution	10 s
Understand how accretion forms and evolves stars and circumstellar disks	Observe material accreting onto young stars along with stellar coronae from young and main sequence stars	Bandpass	8-50Å
		Min Spectral Res. (8-50Å)	1000
		A_{eff}(8-50Å) (avg)	300 cm²
		A_{eff}(19Å)	300 cm²

Figure 1 – [Left] A brief review of the Arcus science goals, methods, and requirement. [Right] The figure of merit to detect absorption features from ions at an unknown redshift. The green curve shows the value required for a 5σ detection of a 4 mÅ feature in 500 ksec or less, using any of 40 blazars with known flux. Bands where C VI, O VII, and O VIII lines at modest (z<0.2) redshift could be found are highlighted in yellow.

Detecting this hot diffuse gas is the primary *Arcus* science, together with studying warm absorbers from supermassive black holes and the physics of stellar coronae, as listed in Figure 1 [Left]. The details of the science case can be found in Brenneman et al (2016, this volume). Figure 1 [Right] shows the relevant figure of merit (the square root of the product of the resolution and effective area) needed to detect absorption features from ions of oxygen and carbon over a range of redshifts z<0.3. Curves are shown for *Arcus* as well as the *Chandra* and *XMM-Newton* gratings. Long observations of well-known bright featureless background sources such as blazars are needed to find the diffuse hot gas in the halos of galaxies and the general intergalactic medium. The expected equivalent widths, however, of this gas are < 10 mÅ. Figure 1 [Right] shows that only *Arcus* has the required parameters to measure the dozens of sightlines required for a realistic survey. While extremely long observations of the very brightest sources with *Chandra* or *XMM-Newton* might provide one or two measurements of O VII or C VI absorption features, the paucity of sufficiently bright sources makes the broad survey needed to obtain the physical condition in the gas impossible without a mission like *Arcus*.

3.   INSTRUMENTATION

The baseline *Arcus* science case relies upon long (typically ~1 day) observations of ~250 moderately bright point X-ray sources that that are distributed approximately evenly across the sky. Observations may be done in any order, and can be interrupted without issue. There is only one science observing mode, limiting complexity and reducing the requirements on mission operations (see §5.2).

The science case places a few key requirements on the instrument, including a bandpass from 8-50Å and an average effective area and spectral resolution in the O VII bandpass (21.6-28Å) of >500 sq. cm and R>2500, respectively. These requirements are achieved using a design that combines grazing incidence 12m focal length X-ray optics with off-plane reflection gratings that disperse incoming photons onto an array of CCD detectors in the focal plane, held 12m apart by an Extendable Optical Bench (EOB), itself covered by a 'sock' to eliminate stray optical light. The design is highly modular, with the optics and gratings arranged into four distinct 'petals.' A single optic
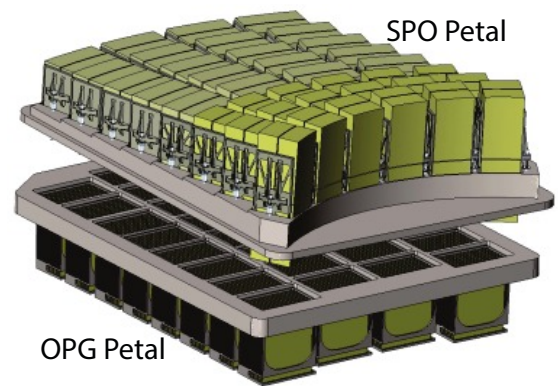
Figure 2: An Arcus channel, showing the optics petal on top with the grating petal below. Alignment and mounting hardware that connects the two petals to each other and to the optical bench are not shown for clarity.

petal and grating petal are aligned to form a 'channel' which disperses X-rays into an arc in the focal plane. The channels are aligned in pairs so that a single detector array receives dispersed photons from two channels. As a result, two detector

arrays in the focal plane are sufficient to detect light from four channels.

3.1 Silicon Pore Optics

Arcus will use Silicon Pore Optics (SPO) (Collon, 2016, this volume) that are being planned for ESA's *Athena* mission. SPOs provide a highly modular system with a largely automated production system, combining high efficiency with modest expense. As part of preparing for the Athena mission, SPOs have undergone environmental testing[10], and an alignment method has been developed as well. To maximize the potential for reuse of mandrels and manufacturing experience, Arcus has selected the same focal length as Athena (12m), and uses SPO modules with the same radii of curvature as are planned for *Athena* (348 – 784mm). The size of each SPO Mirror Module (MM) varies slightly with radius, but ranges from 76-168mm in length, with a geometric area facing the sky of 55.8mm by 50 – 90mm.

Figure 3: Highly asymmetric SPO PSF measured at PANTER.

Current SPO technology is already sufficient for *Arcus*, although ESA is continuing development for *Athena*. The Arcus optical design takes advantage of the highly asymmetric nature of the point spread function of modular X-ray optics (see Figure 3) via a method known as 'subaperturing'[6]. Only a limited azimuthal range of the potential full shell is used for the telescope. This creates a telescope PSF that resembles the full shell PSF in one dimension but is significantly reduced in width in the orthogonal dimension. Currently, the smallest measured SPO PSF is ~10 arcseconds HEW in total (Collon, 2016, this volume), but in the narrow axis the PSF is only 1.4 arc seconds FWHM. A grating spectrometer reproduces the telescope PSF as the line spread function (LSF) in the spectrum. Therefore, if the gratings are aligned to the optics so that the photons will be dispersed along the narrow PSF direction, the spectral resolving power can be optimized without necessitating *Chandra*-quality optics.

3.2 Off-Plane Gratings

Off-plane reflection (OPGs) gratings allow dense packing geometries compared to the more standard in-plane design, providing high throughput and resolving power for soft X-rays. "Off-plane" refers to the fact that the dispersion direction is out of (or 'off') the plane of incidence, as shown in Figure 4, while in-plane dispersion, which is for example used by the *XMM-Newton* RGS, is in the plane of incidence. Aligning the gratings this way increases their efficiency over standard gratings by up to a factor of two[12] and enables them to be stacked into modules.

The *Arcus* gratings will be commercially fabricated on fused silica wafers; see McEntaffer (2016, this volume) for details. Briefly, the process begins by creating a master grating via e-beam lithography on a silicon plate with an average ruling density of 6275 gr/mm. A series of dry and wet etch processes are used to transfer the pattern to a crys-

Figure 4: Schematic of off-plane grating diffraction

talline plane of the silicon that is oriented at a specific angle relative to the wafer surface. This etched wafer is then used as a mold to transfer the blazed profile onto a flat fused silica wafer using nanoimprint lithography. The resulting blazed grating surface is coated with gold or B4C to optimize its X-ray reflectivity. Recent testing at PANTER demonstrated that the replicated gratings retain the blaze and line shape of the master[11], as well as testing at the Advanced Light Source at LBNL synchrotron facility confirmed that the blazed grating efficiency is >35%, more than meeting the Arcus system requirements (McEntaffer 2016, this volume).

Continuing with the modular design used throughout the *Arcus* instrument, grating plates will be mounted into a Grating Module (GM). Unlike the SPO MMs, however, the *Arcus* GMs are all identical, each with an open aperture of 52.4mm x 70mm, and a length of 100mm, containing 15 aligned grating plates. The grating plate alignment method
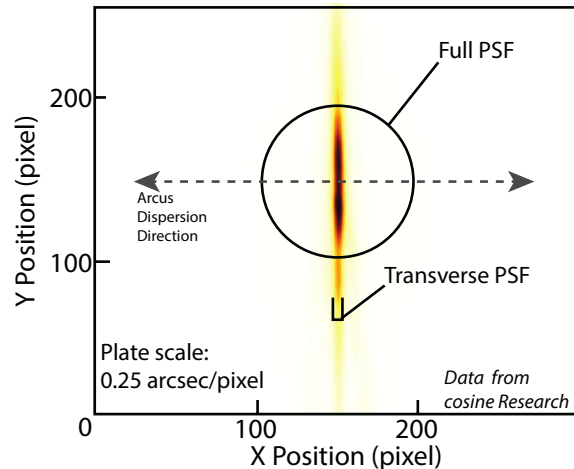
is described in [8], with one enhancement. As the grating master plate can now be created via e-beam lithography, the grating design includes a small (~25 mm^2) optical grating that is aligned to the X-ray grating. This enables measurement of yaw directly using an optical laser, rather than requiring the use of a UV laser.

3.3 Mounting and Aligning the SPO and OPG modules

The SPO and GM alignment sensitivities were derived using the methods described in [7]. The tightest tolerances are the 6 micron translations of the SPO modules. To align the SPO modules into a petal structure, a large diameter collimated laser beam will be used to simultaneously illuminate multiple modules. By tracking the pupil diffraction pattern's central peak, we have demonstrated that the SPO focal spot translation can be measured to <5 microns. The collimated beam will be translated as modules are added in order to maintain alignment across the entire petal. A removable reference flat between the petal and the laser will be used to maintain alignment of the collimated beam as it is translated.

Once the SPO modules are aligned, flexures on the module – a triangle of three on one side and one on the other – will be bonded in place. The triangle of flexures isolates the module from differential CTE issues between it and the petal. The grating modules are then aligned into the system in a similar fashion, this time co-aligning the zero-order reflections. The yaw angle of the gratings cannot be constrained by reflection of visible light and will be monitored by fiducials on each grating module.

3.4 Focal Plane and Electronics

The Arcus detector subsystem consists of two identical X-ray CCD detector arrays (DA), each with low-noise detector electronics (DE), controlled by the instrument control unit (ICU). The two DAs operate in parallel, providing redundancy. The detector subsystem architecture and its major components have heritage from *Chandra*, *Swift*, and *Suzaku*, and all critical elements in the detector string (DA, DE) have been prototyped and tested. Key aspects of the detector subsystem are listed in Table 1.

The FP array in each of the DAs comprises eight 2048x1024 CCDs to record two dispersed spectra from two different channels. This is achieved by using opposite blaze angles on the two OPG petals, so that each throws the spectra in the correct direction. The focal plane layout is shown in Figure 5.

Table 1: Focal plane overview

Characteristic	Value
Detectors	Back-illuminated frame transfer X-ray CCDs
CCD format	2048x1024, 24 um pixels, 8 parallel outputs
Focal plane array	8 CCDs
CCD Spectral Resolution (order sorting)	CCD FWHM < 130 eV
System read noise	<4 electrons RMS @ 625 kpixels s^{-1}
CCD Frame rate	0.5 Hz
Focal plane temperature	-90±0.5 °C (passively cooled)
Blocking filters (UV/optical and molecular contamination)	On chip: 50nm Al (UV/optical) Freestanding: 45 nm polyimide + 20nm Al

The CCDs will be produced by MIT Lincoln Laboratory, leveraging designs with extensive flight heritage. Analog signal processing electronics prepared by the MIT Kavli Institute will capitalize on designs for *TESS* (expected launch 2017), informed by flight experience with *Chandra* and *Suzaku*.

Each focal plane module is fitted with a filter and door assembly. Primary UV/optical blocking will be provided by an on-chip 50nm Al deposition (see Bautz 2016, this volume). Additional protection will be provided by a 45 nm polyimide filter, supported by a silicon strongback, that will be maintained at room temperature to protect the focal plane from external contamination. This filter will include a 20nm Al layer for charge control and additional UV optical blocking. The strongback exploits technology developed for sounding rocket instruments by the University of Wisconsin, which was also used in the *Hitomi* mission[9]. The door is designed to be opened once upon deployment.

The *Arcus* Instrument Control Unit (ICU) supplies regulated and unregulated switched power to the instrument, pro-
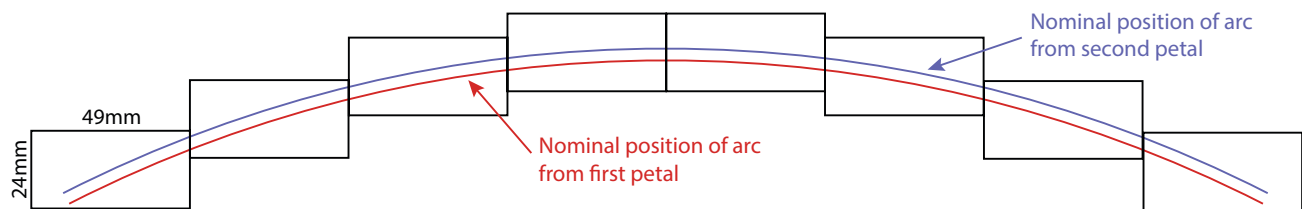

Figure 5: One Arcus focal plane array, using 8 CCDs. Nominal positions of the diffracted spectra for an on-axis source are shown from two channels.

cessing instrument commands, recording instrument housekeeping, extracting X-ray events from the CCD camera data stream, and formatting telemetry.

Event recognition processing will be done via a high-speed FPGA. CCD bias frames will be stored on-board for each CCD in the instrument. The Event Recognition Processing (ERP) board will perform bias subtraction on the incoming CCD data stream and will then compare each 3x3 group of pixel values to commandable thresholds, grading the pixels according to lookup tables to distinguish between X-ray events and background (charged particle) events. Valid X-ray events will be formatted and sent to the spacecraft for telemetry to the ground.

4. MISSION DESIGN

4.1 Overview

The Arcus science case (Figure 1 [Left]) places a few critical requirements on the overall mission. The key Arcus requirements are:

   a)   High effective area
   b)   High spectral resolution
   c)   High efficiency observation of targets dispersed around the sky
   d)   Low background radiation environment

Requirement (a) is met largely within the grating instrument itself, using four optical channels with high-throughput SPOs and OPGs, combined with high-efficiency CCDs covered by thin contamination and UV/optical blocking filters. Requirement (b), maintaining high resolution places requirements on the observatory. Ultimately, the error in the absolute pointing knowledge reconstructed on the ground for each event must be no greater than 1 arcsec per axis (1σ). An additional, but less crucial, pointing requirement is placed on the actual

Figure 6: Arcus orbit with command & telemetry links as well as science downlink noted.

pointing of 30 arcsec (3σ), purely to maintain the dispersed arcs on the detector array itself (see Figure 5). To ensure high efficiency observing, the observatory is capable of slewing at >1 deg/min.

Requirements (c) and (d) are attained by placing the Arcus observatory in a 4:1 lunar resonant (80,000 km x 225,000 km) orbit, as shown in Figure 6. This provides 6.85 days of science data collection, with 5 hours of science data downlink that can be obtained using a Ka-band or medium-gain S-band antenna during perigee passes. This stable orbit provides a low radiation environment as it remains above the Van Allen belts at all times, and also has low disturbance torques from either the Earth or Moon. It provides over 90% availability for science observations, and can be arranged such that eclipses are rare, and limited to durations shorter than 5 hours.

4.2 Arcus Observatory

Figure 7 shows an overview of the Arcus satellite. The four front optics channels (two shown in Figure 7) will be maintained at room temperature via a combination of a heaters plus a thermal pre-collimator, and protected by a door that opens once after deployment. The 3-sided coilable extendable boom includes a light-blocking 'sock' and will deploy a single time after Arcus reaches its desired orbit. The instrumental radiator will maintain the detectors at -90±0.5C, which can be achieved in high Earth orbit (see §4) with a modest sized radiator without the use of active cooling. The Arcus observatory total mass is well within the capabilities of the launch vehicles in consideration for the 2016 MIDEX AO.

The spacecraft is provided by Orbital ATK and is based on designs with substantial flight heritage. It is designed for a two year baseline science mission, with a goal of 5 years. Spacecraft consumables and wear out items are designed for 10 years of on-orbit life. The spacecraft is thermally isolated from the instrument and connected to the instrument focal plane support structure

5. OPERATIONS

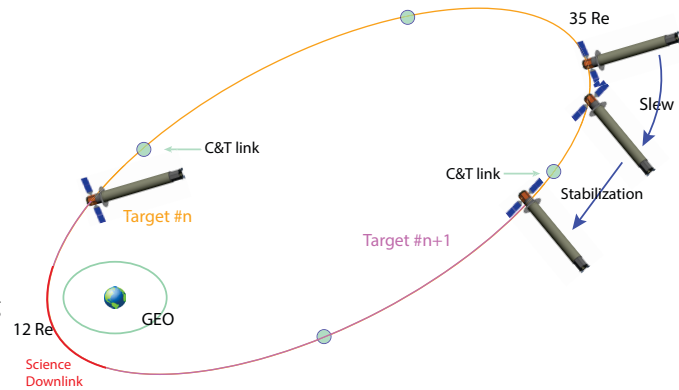## 5.1 Overview

As previously depicted in Figure 6, Arcus operates in a 4:1 lunar resonant (80,000 km x 225,000 km) orbit, providing provides 6.85 days of science data collection and 5 hours of science data downlink during perigee passes. Instrument

science data collection rates are modest (4 Gb/day) which allows for the use of a Ka or medium-gain S-band antenna to downlink science and observatory state-of-health data. *Arcus* also has four S-band command & telemetry, ranging/ tracking contacts per orbit via the observatory's low-gain S-band antennae, which may also allow some science data downlink.

Mission operations during the baseline mission will benefit from a well-defined and modest target list (~200 sources in 2 years) that have no timing or continuity requirements. Similarly, science operations will benefit from strong heritage in science data software algorithms as well as team members from the *Chandra* and *XMM-Newton*. An overview of the operational concept is shown in Figure 8.

Figure 7: Cutaway image of Arcus satellite, showing optical bench, extendable boom, focal plane array, and spacecraft.

5.2 Mission Operations

NASA Ames Research Center (ARC) will host the *Arcus* Mission Operations Center (MOC). After commissioning, the spacecraft will have one primary contact per orbit to downlink science data and upload a 2-week long observation schedule. Four other brief contacts with the spacecraft will be used to monitor the health and performance. Prior to contacts, command sequences will be verified with ground software, and as needed, validated by simulation on the engineering model.

The MOC ground data system will automatically initiate Level 0 processing after data downlinks, creating reconstructed, time-ordered, unprocessed data with communications artifacts (e.g. sync frames, communications headers, duplicate data) removed. Pertinent data will then be routed as appropriate (e.g., instrument data to the Science Operations Center).

For staffing purposes, a flight controller will be on call at all times in case of issues with the spacecraft, and will respond according to a previously defined issue type. Along with interfacing with the *Arcus* SOC, the ARC MOC supports local archive of spacecraft telemetry for the duration of *Arcus*' full and extended mission (5 years; estimated <1 Tb).

5.3 Science Operations

The Science Operations Center (SOC), located at the Smithsonian Astrophysical Observatory (SAO) with components at MIT, GSFC, and Friedrich-Alexander-Universitaet (FAU), ensures the scientific success of the mission: selecting targets along with their observing times and modes, and then processing and calibrating the data returned to enable analysis by the full science team. The SOC develops the long and medium-term observation plan. The initial targets are selected as part of the proposal itself. However, the team plans to take into account early data analysis results to ensure baseline science requirements are addressed.

Raw telemetry data received from the MOC will be processed at the SOC to create basic X-ray Level 1 event files as well as instrument housekeeping files, using software developed at FAU with heritage from the eRosita instrument on *Spectrum-X Gamma*. These files are then processed to attach grating information to each event (Level 1.5), requiring the identification of dispersed arcs, event orders, and exact wavelengths to tag each event. The algorithms required are created by the same MIT team that developed the *Chandra* High-Energy Transmission Grating, using similar approaches as that software. Finally, fully-processed Level 2 event files including identification of background events, bad pixels, and calibrated responses will be generated, using algorithms and approaches originally developed for *Chandra*, *XMM-Newton*, and *Suzaku*. The SOC will be responsible for ensuring delivery of these products to the science team and that they are archived in the HEASARC. This includes the raw telemetry, the processed events, as well as the pipeline software itself and all necessary calibration files, tools, and documentation.

The SOC is also be responsible for maintaining and analyzing a trend database, checking data for short- and long-term trends due to particle environment, contamination, and other effects such as boom bending. Finally, the SOC is responsible for overall Arcus calibration, including generating all necessary calibration data, offsets, and/or corrections to use in both the MOC command sequence (uplink) and the data analysis tools (downlink).
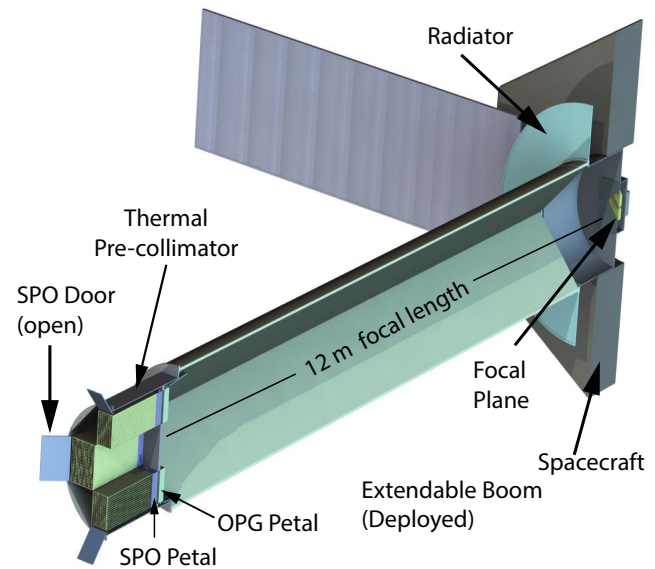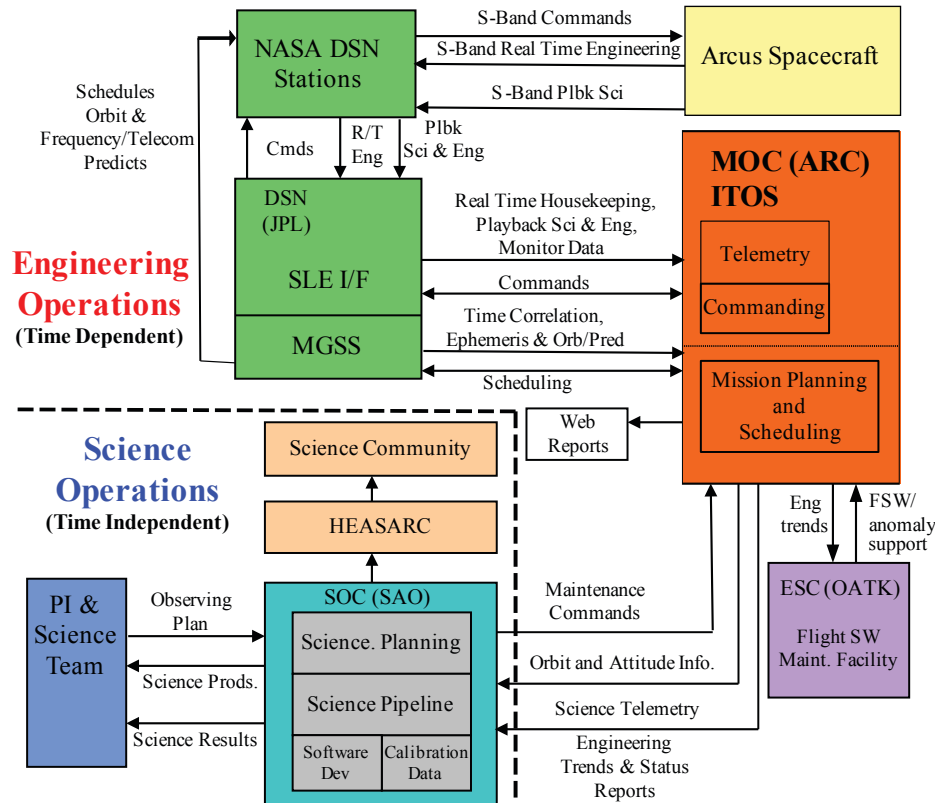
Figure 8: Arcus Operations conceptual flow diagram

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