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The Science Operations and Data Center (SODC) of the ASO-S mission

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Abstract A ground data analysis center is very important to the success of a mission. We introduce the Science Operations and Data Center (SODC) for the ASO-S mission, which consists of a scientific operation subcenter, a data management subcenter, a data analysis subcenter and a user service subcenter. The mission planning process, instrument observation modes and the data volume are presented. We describe the data flow and processing procedures from spacecraft telemetry to high-level science data, and the long-term archival as well. The data policy and distributions are also briefly introduced.

Key words: space vehicles: instruments — methods: data analysis — techniques: image processing

1 INTRODUCTION

The Advanced Space-based Solar Observatory (ASO-S) is the first solar mission to be launched under the strategic pioneer program on space science of the Chinese Academy of Sciences (CAS). The main purpose of ASO-S is to understand the relationships between solar magnetic fields, solar flares and coronal mass ejections (CMEs) (Gan et al. 2015, 2019a,b). ASO-S is scheduled to be launched using a Long March-2D rocket at the end of 2021 or early 2022 from the Jiuquan Satellite Launch Center in Gansu province to a Sun-synchronous orbit at an altitude of about 720 km.

The observatory contains three payloads. They are:

The **Full-disk vector MagnetoGraph** (FMG), which conducts full-disk, high-cadence measurements of the solar photospheric magnetic field with a resolution of $\sim$1.5 arcsecond (4096×4096 pixel images).

The **Lyman-alpha Solar Telescope** (LST), which consists of a set of three telescopes. Two of them, named Solar Disk Imager (SDI) and White-light Solar Telescope (WST), provide full-disk images in the Lyman-alpha (121.6 nm) line and white light waveband (360 nm), respectively, with $\sim$1.2 arcsecond resolution (4608×4608 pixel images), while the other one, called Solar Corona Imager (SCI), images the solar corona from 1.1 to 2.5 solar radii in both the Lyman-alpha line and white light (700 nm) waveband with $\sim$ 4.8 arcsecond resolution (2048×2048 pixel images).

The **Hard X-ray Imager** (HXI) takes imaging spectroscopy of solar non-thermal X-ray emission from $\sim$30 to 200 keV. The HXI is based on a Fourier-transform imaging technique identical to that of the Hard X-ray Telescope (HXT) on the Yohkoh mission (Kosugi et al. 1991). The HXI implements a set of 91 subcollimators to record the energy spectra in 2048 channels.

Such combination of the above-mentioned payloads enables observing solar magnetic fields, solar flares and CMEs with high temporo-spatial resolution.

Data flow in the orbit of the ASO-S spacecraft is similar to that of other solar spacecraft, such as the Solar TErrestrial RElations Observatory (STEREO) (Eichstedt et al. 2008) mission. After the successful launch of ASO-S, the onboard instruments will produce scientific and engineering data according to the uploaded observing plans. The scientific data will be sent to the spacecraft data system in the form of telemetry packets. Similarly, engineering data from the payloads and spacecraft will also be formatted into telemetry packets. These packets transferred to the spacecraft data system are compressed and stored on a shared solid state mass memory, which is about 4 Tbits in size. These packets are transmitted to the ground Mission Operation Center (MOC) whenever possible.

The MOC, located at the National Space Science Center, CAS, is responsible for operations of the ASO-S mission. The MOC provides the scheduling of multi-mission operations, conducts preliminary processing of telemetry data to level 0 data, distributes the generated level 0 data and so on.

The other ground system working with the MOC to support the ASO-S science mission is the Science Operations and Data Center (SODC) located at Purple Mountain Observatory, CAS. The telemetry data of ASO-S received by the MOC will be unpacked, verified and re-organized according to the standard agreed upon by both MOC and SODC. Then the level 0 data products will be transferred to SODC. The main mission of the SODC is to create high level data from the received level 0 data, and to develop software for both data processing and analysis. Both high level data products and analysis software will be available to users. The main function of SODC is described in Section 2. The high-level data products, brief definitions and processing of data products are presented in Section 3. The method of data distribution is described in Section 4, followed by a summary in Section 5.

2 SODC TASKS AND FUNCTIONALITY

2.1 Overview

The SODC is an important part of the ASO-S ground system. The major functions of SODC are to plan scientific observations of the ASO-S mission, receive level 0 data from MOC, generate high-level data with developed software, and provide users with high-level scientific data and analysis tools including software and data analysis guides. These require a high performance computing (HPC) cluster, a massive data storage system and some relevant infrastructure to be established accordingly.

The main functions of the four SODC subcenters are described below.

The **Scientific Operation** subcenter is responsible for the scientific operation of the ASO-S instruments. Its main functions include monitoring the health of the payloads by displaying playback engineering data, preparing and optimizing the observation plan that will be uploaded to the spacecraft via the MOC, operating and maintaining the SODC, and training relevant personnel.

The **Data Management** subcenter is responsible for data management. Its main functions include receiving level 0 data products from MOC, storing generated high level data products, distributing the scientific data products and developing a database. About 0.5 TB of level 0 and 2.0 TB of high-level data products need to be stored per day.

The **Data Analysis** subcenter is responsible for the generation of data products and the development of software. Its main functions include programming the data production and analysis software, synthesizing high level data products from level 0 data, assessing data quality and proposing calibration observation of payloads as needed. At about 2.5 TB per day, the data will not be easily digestible for solar physicists. In order for solar scientists to use the ASO-S data effectively, we are going to create various catalogs for different features and events detectable on the Sun. The comprehensive processing pipeline for ASO-S will be built in the data analysis subcenter.

The **User Service** subcenter is a bridge between SODC and users, providing fast browsing, retrieval and downloading services for scientific data and data analysis guides, promoting public outreach, and collecting observation proposals from users.

Figure 1 depicts the interfaces for the four operation subcenters of SODC. The data management subcenter receives the level 0 scientific data and engineering data from MOC, then stores and sends them to the data management subcenter and scientific operation subcenter respectively. The engineering data are carefully analyzed at the scientific operation subcenter. If there is anything abnormal, an alarm message will be generated and sent to the MOC. The data analysis subcenter processes the level 0 data to generate high level data products and send them to the data management subcenter for storage. Also, the data analysis subcenter analyzes high level data products and automatically detects the special features of the Sun, such as solar flares and CMEs, and indexes the retrieved parameters in the corresponding database catalog. The scientific data products, software programs, guide documents and database catalogs will be distributed by the user service subcenter via the ASO-S website. Users can browse images and videos on the ASO-S website and download the required data. Observation proposals can also be submitted via the website. The scientific operation subcenter creates observation plans according to the user proposals and status of the instruments, then sends the plans to the MOC for uploading to the spacecraft.

2.2 Observation Planning

There are three types of observational plans, namely routine observation plans, on-demand observation plans and emergency observation plans. Emergency observation plans will be installed on the spacecraft and will be exe-

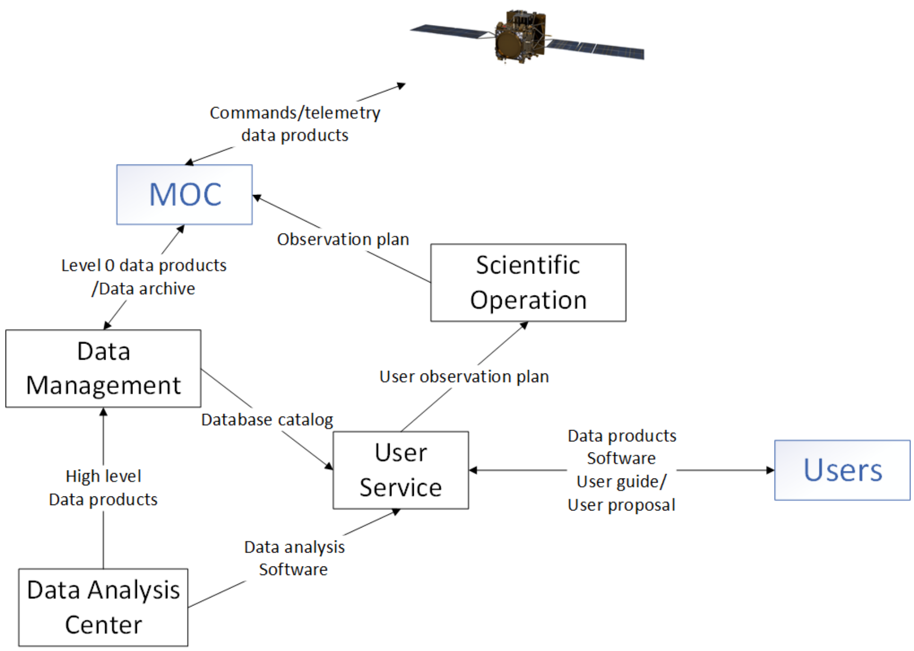

Fig. 1 The interfaces of the four operation subcenters of SODC.

cuted when an abnormal situation occurs. The purpose of the emergency observation plan is to ensure the safety of payloads and the spacecraft.

Routine and on-demand observation plans are managed by the science operation team, who will monitor the status of all the instruments, and oversee the feasibility of on-demand observation plans. On the other hand, based on the quality assessment of the observed data, calibration observations of instruments should be considered to be added to the observation plans.

After the SODC completes the observation plans, they will be sent to MOC. One day later, the observation plans will be uploaded to the spacecraft by telemetry. One week observation plans will be uploaded to the spacecraft every other day, and new observation plans will overwrite the previous one already onboard.

2.3 Observation Modes and Data Volume

The default observation mode of FMG is to measure the full-disk vector magnetic fields of the solar photosphere with a 120 s cadence. There is also a fast mode, which obtains a full-disk vector magnetogram with lower accuracy and higher cadence of ∼40 s. The field of view (FOV) and spatial resolution of FMG cannot be changed. The two modes of FMG with different cadences can be switched onboard by the observation plans or a solar flare signal detected by either LST or HXI. Details on the FMG observing mode are described by Deng et al. (2019).

The observation modes of HXI are very similar to those of FMG. The FOV of HXI is 40 arcmin, and the cadence can be set to 4 s. When the X-ray flux increases, the cadence of HXI can be switched to 0.125, 0.25, 0.5 or 1 s automatically onboard by the proposed algorithm. Zhang et al. (2019) present details on the observing modes of HXI.

The observation modes of LST are complicated: both the FOV and temporal cadence can be changed. When the HXI or LST/SDI detects a flux enhancement from the Sun, both SDI and WST increase their cadence (fast mode) and subsequently the associated temporal resolution. The cadences of SCI increase when a CME initiation is detected. Since the telescopes incorporated in the LST use CMOS detectors, it is possible to output only the data from a specified area of the detector. So, when the LST/SDI and LST/WST observe in fast mode, by default, only a partial image of 1024×1024 pixels will be recorded in order to reduce the data volume onboard. For details on the observing mode, we refer readers to Li et al. (2019).

Since the observation modes of all the payloads may switch automatically when a solar eruption or CME initiation is detected, the data volume is uncertain for ASO-S in orbit. Here, we roughly estimate the average data volume for each instrument; the observation duration of fast mode is assumed to be 3.5 hours per day. The data volume of FMG and HXI is 175 GB and 25 GB per day, respectively. Since the LST contains three telescopes, the data volume is about 300 GB per day. So, the data volume of ASO-S is about 500 GB per day, and it cannot be directly transmitted to MOC. The data need to be compressed losslessly onboard to less than 320 GB, which is the maximum data volume that can be transmitted by the spacecraft every day.

3 DATA PROCESSING AND ARCHIVING

3.1 The Data Products of ASO-S

The SODC of ASO-S produces a multitude of data products that support the ASO-S scientific investigation, with the main observables including vector magnetic fields, and imaging of solar flares and CMEs. The data products which will be released to scientific users are presented in Table 1.

Detailed definitions of the data products and processing levels of ASO-S payloads were introduced by Su et al. (2019a), Feng et al. (2019) and Su et al. (2019b) for FMG, LST and HXI, respectively. Here, we just present a summary of the data products.

All the data products except the quicklook data of the ASO-S mission are written in flexible image transport system (FITS) files. The location of the data products is managed by the SODC database catalog. The database is essentially a list of observational sequences combined with a catalog of features and events that have occurred on the Sun and are automatically recognized. Keywords and data will be combined as part of data export and stored in standard FITS format. Quicklook data derived from all three payloads will be browsable and searchable by users via the internet.

3.1.1 The data products of FMG

The main products of FMG are images of the solar photosphere near 532.419 nm and vector magnetograms. The data levels and corresponding processing for FMG are summarized as follows:

• Level 0 data are images that have been constructed from the raw telemetry stream, with processing including unpacking, verifying, reorganizing in time, splitting and splicing, and format conversion with housekeeping data and keywords.

• Level 1 data are images that have been generated from level 0, with processing including bad-pixel and spike-pixel removal, flat-fielding, dark current correction, wavelength calibration, and plate scale rotation and shift.

• Level 1.5 data are images that have been created from level 1, with processing that applies crosstalk correction. These data will be released to the public.

• Level 2 data are images of the physical observables (line-of-sight and vector magnetic field, and intensity), which have been constructed from level 1.5 data, with processing including magnetic field calibration, saturation calibration and 180° ambiguity correction. These are the main data products that will be released to the public.

3.1.2 The data products of LST

LST produces a multitude of data products that support the associated scientific investigations. LST acquires full-disk images in both the Lyα and 360 nm wavelengths, and inner corona images in both the Lyα and 700 nm wavelengths. The data levels and corresponding processing for LST are summarized as follows:

• Level 0 data are images constructed from the raw telemetry stream.

• Level 1 data are images generated from level 0 data, with processing including flat-fielding, dark current correction, spike map generation and bad pixel indexing. The images from SCI need additional stray-light subtraction and instrumental polarization correction (only for images in the 700 nm waveband).

• Level 1.5 data are images created from level 1 data, with processing of plate scaling, rotation and shift, in addition to repairing bad pixels and spike pixels.

• Level 2 data are images of physical quantities, which have been radiometrically calibrated from the level 1 data.

• Level 2.5 data are images created from level 2 data, with processing of plate scaling, rotation and shifting, and repairing bad pixels and spike pixels.

• Level 3 data are mainly derived CME parameters, which are model-dependent derivatives.

Level 1 and level 2 data from LST will be released to users.

3.1.3 The data products of HXI

HXI produces hard X-ray spectral and image data products that support the science objectives of ASO-S. The data levels and corresponding processing for HXI are summarized as follows:

• Level 0 data are count spectra constructed from the raw telemetry stream.

• Level 0.5 data are analog-to-digital conversion (ADC) spectra from all detectors. These data will be released on demand.

• Level 1 data are count spectra that have been energy calibrated from level 0.5. These are the main data products that will be released to the public.

• Level 1.5 data are two kinds of photon spectra with spectroscopic analysis and spectroscopic semi-calibration.

• Level 2 data are X-ray photon spectra and X-ray images derived from level 1.5 and are model-dependent.

Table 1 The Data Products of ASO-S

Data product	Instrument	Level	Format
Photosphere image (532.419 nm)	FMG	level 1.5	FITS
Line-of-sight magnetic field	FMG	level 2	FITS
Vector magnetic field	FMG	level 2	FITS
Quicklook image	FMG	level Q	JPEG
Full-Sun image (121.6±7.5 nm)	LST/SDI	level 1 and 2	FITS
Full-Sun image (360.0±2.0 nm)	LST/SDI	level 1 and 2	FITS
Inner corona image (121.6±10 nm)	LST/SCI	level 1 and 2	FITS
Inner corona polarized image (700±40 nm)	LST/SCI	level 1 and 2	FITS
Quicklook image	LST	level Q	JPEG
ADC spectra	HXI	level 0.5	FITS
Energy-del calibrated count spectra	HXI	level 1	FITS
Quicklook data	HXI	level Q	JPEG & IDL SAV
Event quicklook data	HXI	level E	JPEG & IDL SAV

- Level Q data are quicklook light curves, quicklook images and quicklook spectra based on level 0.5 data.
- Level E data are quicklook data for HXI events.

3.2 Data Flow and Pipeline Processing

The raw telemetry data will be received by three ground stations, then the data are sent to MOC for processing. After unpacking, verifying, splitting and splicing, etc., level 0 data products are produced and then transmitted to SODC over a virtual private network (VPN) for further processing and high level product creation. The processing procedures of the three payloads are not exactly the same, but ultimately the data products will be distributed through the ASO-S website. A flowchart of the data processing pipeline for the ASO-S mission at SODC is displayed in Figure 2.

3.3 Data Management and Archiving Plan

The raw telemetry data and level 0 data will be stored and archived at MOC. Level 0 data and generated high-level data products are stored at SODC. Later, the high level data products will also be archived by MOC for backup. After the ASO-S spacecraft ends its operation in orbit, the data products will continue to be stored at SODC and will be available to users for 5 years. Then all data will be transferred from SODC to MOC for permanent archiving. Users can download the data products from the MOC website after SODC is shutdown.

3.4 Software

The data processing software and data analysis software will be programmed at SODC. The languages of data processing software for the three payloads may be different. The programming languages that SODC supports are IDL, Python, C++ and Matlab. Unlike data processing software, data analysis software will be developed in the IDL language. Python is also being considered for data analysis software development, if time and human resources permit.

When the data analysis software is being developed, we will make full use of existing procedures and functions of Solar SoftWare (SSW) and will apply experience learned from previous solar spacecraft, such as Solar Dynamics Observatory (SDO) (Pesnell et al. 2012), STEREO, Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI) (Lin et al. 2002), Dark Matter Particle Explorer (Yuan & Feng 2018), etc. The framework of the data analysis software is being designed. The ASO-S software programs, both for the mission as a whole and for the individual instruments, is planned to be part of the SSW package. Within the SSW library, there will be a separate directory tree for the ASO-S mission. Under this top-level ASO-S directory, there will be separate directories for each of the three ASO-S payloads.

3.5 Hardware and Security

In order to complete the generation of high level data products within 24 hours from the time level 0 data are received by SODC, we need to establish an HPC cluster at SODC, which is currently configured with 128 high-performance CPUs.

As described in Section 2.3, the volume of level 0 data products is about 500 GB per day. The volume of all data products stored at SODC, including level 0 data and high level data, is about 2.5 TB per day. The mass storage at SODC should have a capacity of >4 PB for the 4-year lifetime of the ASO-S mission. Meanwhile, bearing in mind the possibility of extending the lifetime of the spacecraft, the mass storage needs to be expandable.

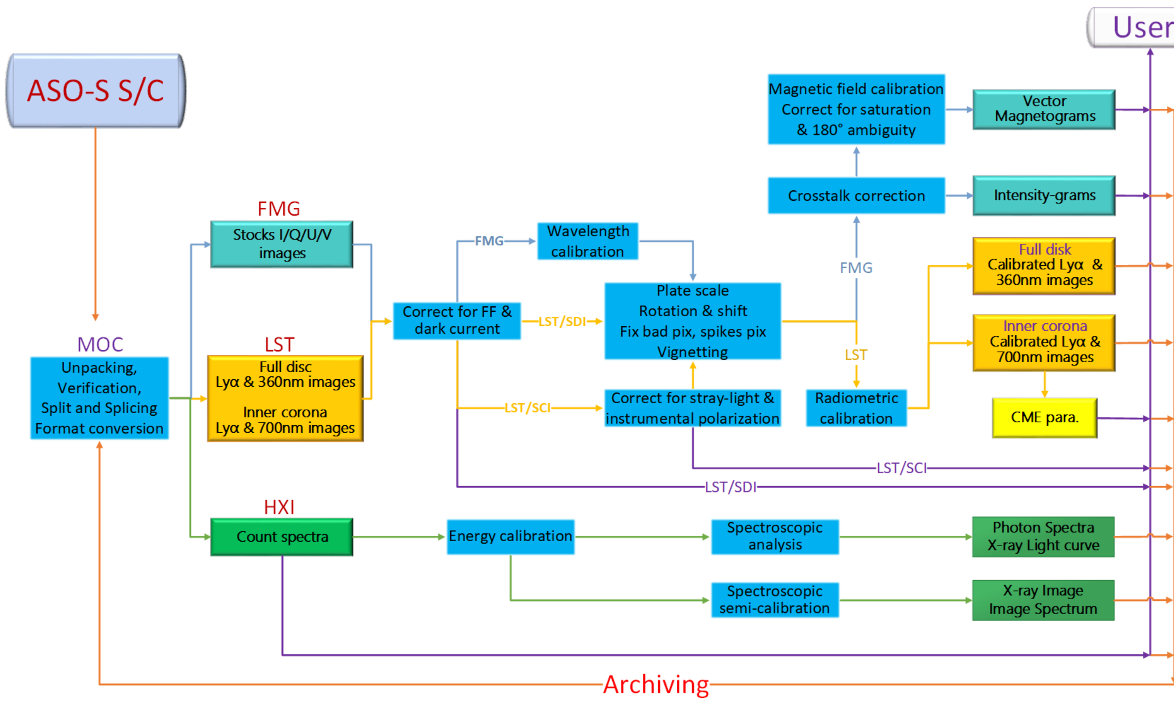

Fig. 2 The data processing pipeline of ASO-S.

SODC is responsible for data distribution and needs to configure multiple web servers and network firewalls. Users are not allowed to visit the mass storage devices directly. Instead, users should submit their data request to SODC via its website, and the servers process the user's request, prepare the requested data and temporarily store them. Once the data are ready for download, a link is sent to the user. Users should promptly download the required data, which will only be stored for one week. The necessary software and hardware firewalls will be installed between users and the web server.

4 DATA DISTRIBUTION

Although the data policy has not been drawn up at the moment, it is very likely that we will adopt a completely open data policy. After the ASO-S spacecraft is launched, all tests will be carried out in 3–4 months. After that, the instrumentation and software should be stable, and data from the ASO-S mission will be openly accessible. The high level data products are planned to be available within 24 hours after SODC receives the level 0 data. Users will be able to download the required data from the ASO-S website.

Data users can browse the quicklook data including images and videos on the ASO-S website. Also, the database catalogs can be browsed and searched with keywords, such as active regions, flares, CMEs, prominences/filaments, etc. Then users can download data of interest for research through the web server. All scientific data are in FITS format, including the full frame data, on-demand cutout data and event data. The quicklook data and event data of all three payloads can be downloaded directly from the website. The high level data products that can be downloaded directly are levels 1.5 and 2 for FMG, levels 1 and 2 for LST and levels 0.5 and 1 for HXI. If users need other high level data products, they should submit an application to SODC.

The SODC website also provides downloads of auxiliary data, such as ephemeris files, orbit data files for the spacecraft, etc.

5 SUMMARY

As of this writing, SODC of ASO-S is still in phase B, and we are gleaning insights from the experience of previous solar spacecraft data analysis centers. The ultimate purpose of SODC is to provide high quality data products for scientific data users, together with the analysis software. Receiving level 0 data, generating high level data, developing software and providing users with scientific data, software and data analysis guides are the main functions of SODC. The entire system of SODC will be fully completed in September 2021, and SODC will play an important role in the ASO-S science mission.

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