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# Advanced Space-based Solar Observatory (ASO-S): an overview

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**Abstract** The Advanced Space-based Solar Observatory (ASO-S) is a mission proposed for the 25th solar maximum by the Chinese solar community. The scientific objectives are to study the relationships between the solar magnetic field, solar flares and coronal mass ejections (CMEs). Three payloads are deployed: the Full-disk vector MagnetoGraph (FMG), the Lyman-$\alpha$ Solar Telescope (LST) and the Hard X-ray Imager (HXI). ASO-S will perform the first simultaneous observations of the photospheric vector magnetic field, non-thermal imaging of solar flares, and the initiation and early propagation of CMEs on a single platform. ASO-S is scheduled to be launched into a 720 km Sun-synchronous orbit in 2022. This paper presents an overview of the mission till the end of Phase-B and the beginning of Phase-C.

**Key words:** space vehicles: instruments — Sun: magnetic fields — Sun:flares — Sun: CMEs — Sun: UV radiation — Sun: X-ray, gamma-rays

## 1 INTRODUCTION

In the last two decades, research on solar physics in China has developed rapidly. According to Schrijver (2016), among the total number of refereed publications in 2015, the percentage of papers with a leading author from China took 12%, ranking second in the world, just after the USA. This demonstrates that, in addition to having more young researchers, the recently established ground facilities in China, such as NVST (Liu et al. 2014), ONSET (Fang et al. 2013), MUSER (Yan et al. 2016), etc., are beginning to play a role. On the other hand, the open data policy of international space missions (like RHESSI, Hinode, STEREO, SDO, IRIS and so on) plays a special role. Although it is now an important member of the international solar physics community, China has not yet had any dedicated solar satellite. Developing space-based solar missions has become an outstanding task confronted by the Chinese solar community.

As a matter of fact, it has already been a long trek to develop space missions to study the Sun in China. The earliest effort could be dated back to 1976, when the first solar mission proposal, named ASTRON-1, was proposed and implemented (see Gan et al. 2012). Then in the 1990s, some solar payloads on the "Shenzhou" series of manned spacecraft were implemented (Zhang et al. 2003; Ma et al. 2005). The Space Solar Observatory (SST) was also proposed in the 1990s (Ai 1996). In the 2000s, the SMall Explorer for Solar Eruptions (SMESE, a joint Chinese-French mission, Vial et al. 2007), Kuafu (Schwenn et al. 2008) and others were proposed and promoted. However, none of these reached either the engineering stage or the launch stage, except the X-ray and Gamma-ray spectrometer as a payload on the "Shenzhou-2" spacecraft which worked in orbit for about half a year in 2001. In order to better organize space science missions, in 2011, the Chinese Academy of Sciences (CAS) opened a new domain named the "Strategic Priority Research Program of Space Science". It particularly emphasizes supporting the development of scientific satellites at three different levels: concept studies (Phase-0/A), background studies (Phase-A/B) and mission engineering studies (Phase-B/C/D). This new program provides us an excellent opportunity to develop solar missions.

The idea of Advanced Space-based Solar Observatory (ASO-S) was proposed in 2010, based partially on SMESE, with more attention paid to both the science and technology merits, as well as the frontiers of modern solar physics. ASO-S then underwent a cycle of mission life beginning in Phase-0/A (2011-2013) and continuing to Phase-A/B (2014-2016). At the end of 2017, after a serious competition with other candidates, ASO-S was formally accepted by CAS and it has been undergoing engineering studies in an official Phase-B/C/D. This paper presents an overview of the mission at the end of Phase-B and the beginning of Phase-C, i.e., until May 2019. Since most designs and key techniques have been finished, the changes in the following Phase-C and D should be, in principle, small. In Section 2, we present the scientific objectives. Payload deployments and spacecraft designs are given in Sections 3 and 4 respectively. In the last two sections, we describe the mission operations briefly and present a summary. More details about each topic can be found in the individual papers of this special issue.

## 2 SCIENTIFIC OBJECTIVES

Solar flares and coronal mass ejections (CMEs) are the two most powerful types of eruptions on the Sun. They release huge amounts of energy in a short time, which are manifested as radiation covering the full spectral waveband from radio to gamma-rays, as high energy particles and as high speed material flow. They may have disastrous consequences on the environment, which can affect human survival. The energies of solar flares and CMEs are now believed to come originally from the solar magnetic field. Therefore, simultaneous observations of the solar magnetic field, solar flares and CMEs, and research on the relationships between them, are of particular importance. The key scientific questions addressed by the ASO-S will focus on the following three relationships:

1) Relationship between the solar magnetic field and solar flares:

Observations and simulations have proven that flares are powered by the release of free magnetic energy due to magnetic reconnection, which reconfigures the magnetic field topology and converts magnetic energy to thermal and non-thermal energies. In this scenario, the primary question is what kind of magnetic configuration and evolution is favorable for the occurrence of a flare. More specifically, the following questions need to be addressed: What roles do magnetic field shearing and magnetic flux emergence play in storing pre-flare energy and triggering flares? Where does magnetic reconnection occur and what is the threshold for triggering reconnection? How does the flare-related current sheet form during the magnetic field evolution? Which magnetic topology is favorable to magnetic reconnection? What characteristics does magnetic reconnection have during its evolution? How does the magnetic field evolve before, during and after flares? What is the relationship between the flare energy and released magnetic energy, and how is the flare energy partitioned among different forms of thermal orientation, non-thermal domains, waves, etc.? What determines the scale and proportion of the released flare energy? What are the particle acceleration mechanisms during flares?

Precise measurements of the photospheric vector magnetic fields and thermal and non-thermal imaging observations of solar flares will help us to find solutions to the aforementioned questions, deepen our understanding of the solar magnetic field and solar flares, especially their possible cause-effect relationship, and provide the physical foundations for prediction of flare occurrence.

2) Relationship between the solar magnetic field and CMEs:

With respect to the local energy release of solar flares, CMEs are large-scale eruption phenomena on the Sun, which can even cover the whole solar disk. Up to now, reliable magnetic field measurements can only be made in the photosphere, but CMEs are often observed in the corona. Such a spatial gap brings difficulties in understanding their relationship. Therefore, we need both a more accurate measurement of the photospheric magnetic field and a more reliable method to extrapolate the photospheric magnetic field into the corona. The primary question on the relationship between the solar magnetic field and CMEs is what kind of magnetic configuration and evolution can lead to CMEs. Extended questions include the following concerns: What are the precursors of CMEs, especially in terms of the characteristics of the initial magnetic field? What quantitative relationship can we find between the magnetic field complexity and the productivity of CMEs? Do all CMEs contain a flux rope/flux ropes? Do flux ropes exist before CMEs or do they form during eruptions? Are CMEs triggered locally (e.g., by magnetic reconnection) or unitarily on a large scale (e.g., by ideal MHD instabilities or loss of equilibrium)? Is there any large-scale magnetic reconnection in CMEs? How are small-scale active regions and global magnetic fields coupled with each other? What role does large-scale magnetic connectivity play in CMEs? What are the propagation properties of CMEs (including acceleration and deceleration) and how are they related to the magnetic field? Can the direction of CMEs be solely determined by the magnetic field? Can we use the accumulation of magnetic helicity to predict CMEs? What are the consequences of interactions of CMEs?

Precise measurements of full-disk photospheric vector magnetic fields and observations of full-disk extreme ultraviolet (EUV) images, as well as those of the inner corona, will help us find solutions to the aforementioned questions, deepen our understanding of solar magnetic fields and CMEs, especially their possible cause-effect relationship, and ultimately provide the physical foundations for the prediction of CME occurrence.

3) Relationship between solar flares and CMEs:

Nowadays, solar physicists tend to believe that the solar magnetic field is the major engine driving solar flares and CMEs. The energies released during solar flares and CMEs originate from the non-potential magnetic field. Nevertheless, some very important questions in solar physics remain: what kind of magnetic field can produce solar flares, what kind of magnetic field can produce CMEs, and what kind of magnetic field can produce both flares and CMEs almost simultaneously? The relationship between flares and CMEs also reflects the relationship between the evolution of small-scale magnetic fields and the consequence of large-scale magnetic fields. The detailed questions can be listed as follows. Is there any cause-effect relationship between flares and CMEs? Does a flare trigger a CME or vice versa, or is there no link between them? Why does small-scale magnetic field change sometimes lead to a large-scale eruption? How are free magnetic energies partitioned between a flare and its related CME? Why are some flares accompanied by CMEs and others are not, and how is this behavior determined? What are the special properties of flares accompanied by CMEs? Do pure CMEs exist? What are the differences between the properties of particles accelerated by flares and by CME-driven shocks? What is the relationship between CMEs and other eruptive events, e.g., filament eruptions, EUV waves, etc.?

Imaging observations of CMEs, especially in the inner corona, and non-thermal imaging and spectral observations of flares, together with accurate measurements of full-disk photospheric vector magnetic fields, will be very helpful in resolving the above questions, deepening our understanding of the relationship between solar magnetic fields, solar flares and CMEs, and providing important physical bases for the predictions of space weather.

In short, the key scientific questions addressed by the ASO-S can be summarized as "1M2B," namely, the solar magnetic field, solar flares and CMEs, focusing on their physical formation, intrinsic interactions and mutual consequences. Explicitly, the four major scientific objectives can be described as follows:

1) To simultaneously acquire non-thermal images of solar flares in hard X-rays and the initiations of CMEs in the Ly$\alpha$ waveband, in order to understand the relationships between flares and CMEs;

2) To simultaneously observe the full-disk vector magnetic field, the energy build-up and release of solar flares, and the formation of CMEs, in order to understand the causality among them;

3) To record the response of the solar atmosphere to eruptions, in order to understand the mechanisms of energy release and transport;

4) To observe solar eruptions and evolution of the magnetic field, in order to provide clues for forecasting space weather.

Some extended discussions on the above four objectives can be found in Gan et al. (2015).

## 3 PAYLOAD DEPLOYMENT

To fulfill the scientific objectives, ASO-S deploys three instruments: the Full-disk vector MagnetoGraph (FMG), Ly$\alpha$ Solar Telescope (LST) and Hard X-ray Imager (HXI). Table 1 lists the main parameters of these three instruments.

The FMG consists of six subsystems: optical imaging, polarization, electronics, thermal control, imaging stability and data processing. One of the key parts is the polarization subsystem, where a birefringent Lyot filter with 7-level adjustment ensures the working wavelength remains at 532.42 nm with a bandwidth less than 0.011 nm. Another key part is the imaging stability subsystem which ensures an image stability better than $0.25''$/30 s, so as to satisfy the requirement for time resolution of the FMG. Figure 1 illustrates the optical and mechanical design of FMG. The detailed design of FMG is described by Deng et al. (2019).

The LST in fact consists of three instruments: the Solar Disk Imager (SDI), Solar Corona Imager (SCI) and White-light Solar Telescope (WST). The SDI and SCI are proposed to observe CMEs continuously from the solar disk (initiation) to a few solar radii (early propagation), and to record flares and other activity as well, while the WST, besides its purpose for calibration, can also be used to observe white-light flares. The most critical technology incorporated in SCI is the suppression of stray light. As of this writing, the prototype model of the LST can attain $< 10^{-6}\,\mathrm{B_\odot}$@$1.1\,\mathrm{R_\odot}$ and $< 5\times10^{-8}\,\mathrm{B_\odot}$@$2.5\,\mathrm{R_\odot}$ ($\mathrm{B_\odot}$ is the mean solar disk brightness). Figure 2 displays the optical and mechanical layouts of LST. For details on LST, we refer readers to Chen et al. (2019) and Li et al. (2019b).

The HXI aims to image the full solar disk in the high energy range of $\sim$30 keV to 200 keV, with a high angular resolution and a high time cadence. The principle of HXI is the same as that of the Hard X-ray Telescope (HXT) aboard Yohkoh (Kosugi et al. 1991) using indirect imaging of spatial modulation. HXI comprises a collimator and solar aspect subsystem, a calorimeter subsystem and an electronics subsystem. There are in total 91 pairs of grids (in the form of 44 pairs of sin-cos subcollimators and one single set of three subcollimators) with different pitches and orientations on both front and rear plates, providing $u$-$v$ Fourier components for image reconstruction. Accurate alignment between front and rear grids is one of the key technologies incorporated in HXI. In addition, HXI also measures the total flux and charged particle background by using remaining eight detectors. Figure 3 shows the design of the HXI (Zhang et al. 2019).

## 4 MISSION PROFILES

ASO-S has a Sun-synchronous orbit at an altitude of 720 km with an inclination angle of 98.275°. This choice of position takes into account the balance between a lower particle background along the orbit for HXI and a lower stray light level for LST (see also Vial et al. 2007). This orbital design causes the spacecraft to undergo some eclipsing in each orbit for a few months, and the maximum eclipsing time is 18 minutes. The attitude control uses a three-axis stability technology. The platform attitude pointing accuracy is designed to be $\leqslant 0.01°$ with a stabilization accuracy $\leqslant 0.0005°\,\mathrm{s}^{-1}$. The payload attitude pointing accuracy is designed to be better than $10''$, and the stabilization accuracy $\leqslant 0.25''$/30 s for FMG, $0.45''$/120 s for SCI and $0.12''$/60 s for SDI. All these higher pointing requirements are provided by the stability subsystems of the payload itself. The launch vehicle is a CZ-2D rocket, which has the capability to carry a 1000 kg mass into an orbit with altitude of 720 km. The ASO-S mission is scheduled to finish the flight model by the end of 2021 and the spacecraft will be launched into orbit in 2022. The major parameters of the spacecraft are listed in Table 2. The current design of ASO-S as a whole is displayed in Figure 4 and the exploded view is depicted in Figure 5.

The ASO-S spacecraft bus is designed and manufactured by the Innovation Academy for Microsatellites, Chinese Academy of Sciences. The whole spacecraft, besides the three instruments, comprises seven subsystems: Mechanical, Thermal Control, AOCS, Electrical Power, OBDH, TT&C and Data Transmission. One of the key techniques is how to ensure the three instruments point to the Sun along a common axis with an accuracy less than $30''$ during its full lifetime. This issue has been resolved in the prototype model of ASO-S.

## 5 OPERATION AND DATA ANALYSIS

There are two organizations working together to manage the spacecraft in orbit. One is the Mission Operation Center (MOC), the other is the Science Operation and Data Center (SODC) (Huang et al. 2019). The National Space Science Center of the Chinese Academy of Sciences is responsible for MOC. The main function of MOC is to receive the data via three satellite ground stations at Sanya, Kashi and Miyun. After a simple processing at MOC, all of

**Table 1** The Main Parameters of the Three Instruments aboard ASO-S

| | | | |
|---|---|---|---|
| FMG | | | |
| Diameter | 140 mm | | |
| Field of View | $34'$ | | |
| Spatial Resolution | $\leqslant 1.5''$ | | |
| Spectral line | Fe I 532.4 nm | | |
| FWHM | 0.011 nm | | |
| Time Resolution | Normal mode: 2 min; Fast mode: 40 s | | |
| Accuracy of Polarization | 0.0015 for normal mode | | |
| HXI | | | |
| Field of View | $40'$ | | |
| Energy Range | $\sim$30 – 200 keV | | |
| Energy Resolution | 27%@32 keV | | |
| Time Resolution | 0.5 s | | |
| Spatial Resolution | $< 3''$@32 keV | | |
| Number of Grid Collimators | 91 | | |
| LST | SCI | SDI | WST |
| Diameter | 60 mm | 60 mm | 130 mm |
| FOV | 1.1 – 2.5 $R_\odot$ | 0 – 1.2 $R_\odot$ | 0 – 1.2 $R_\odot$ |
| Wavelength | 121.6$\pm$10.0 nm<br>700$\pm$40.0 nm | 121.6$\pm$7.5 nm | 360$\pm$2.0 nm |
| Spatial Resolution | $4.8''$ | $1.2''$ | $1.2''$ |
| Time Cadence | 15 – 60 s | 4 – 40 s | 1 – 120 s |

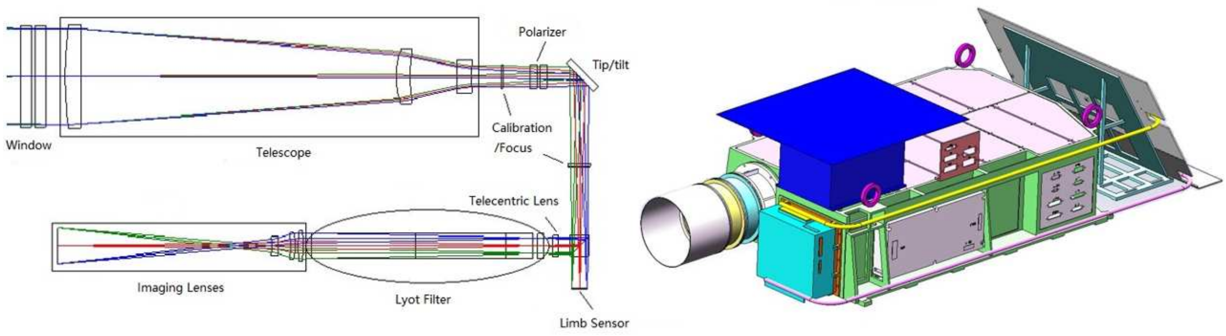


**Fig. 1** The optical and mechanical design of FMG.

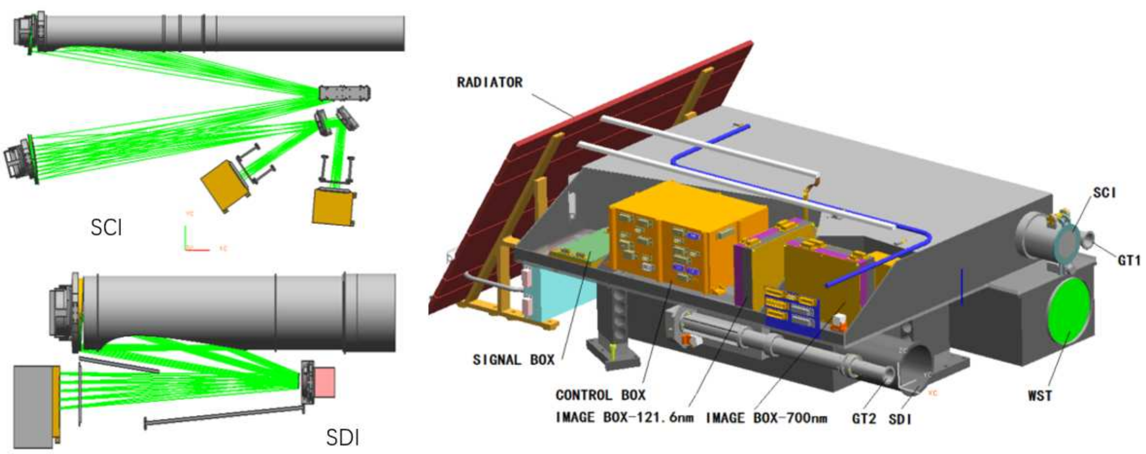


**Fig. 2** The optical and mechanical layouts of LST.

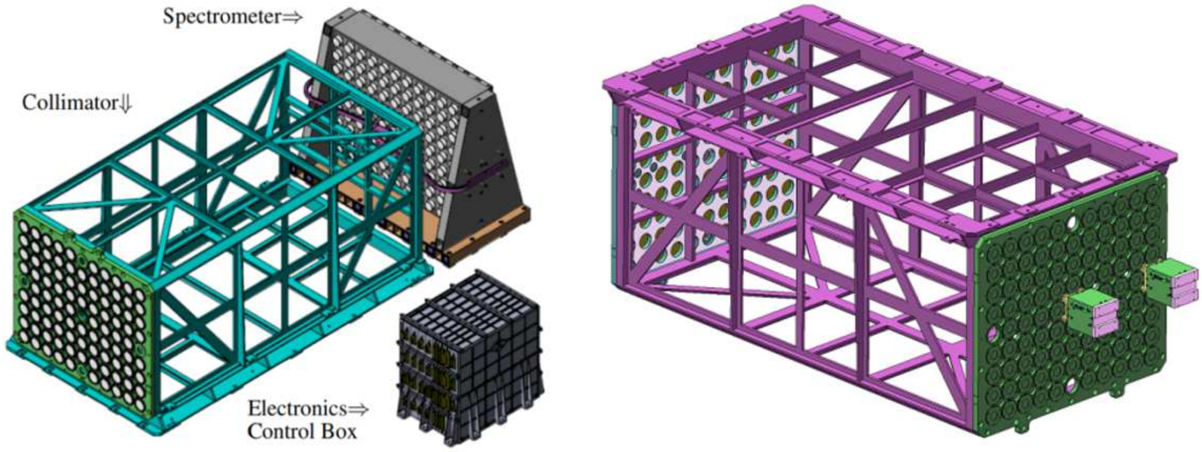


**Fig. 3** The configuration of HXI.

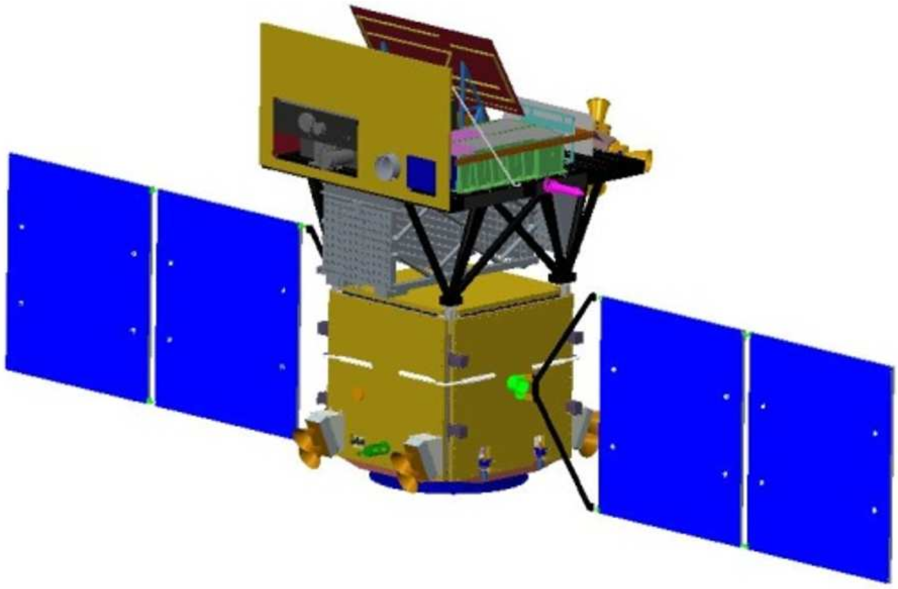

**Fig. 4** The design of the ASO-S spacecraft.

**Table 2** The Major Parameters of the ASO-S Spacecraft

| | |
|---|---|
| Orbit | |
| Altitude | 720 km |
| Inclination | 98.275° |
| Descending node | 6:00 AM |
| Attitude control | |
| Pointing accuracy | 0.01° $(3\sigma)$ |
| Stability | 0.0005° $\mathrm{s}^{-1}$ $(3\sigma)$ |
| Weight | ∼888 kg (payloads ∼366 kg) |
| Power | ∼898 W (mean); ∼1235 W (peak) |
| Size | $<$ Φ2385 mm×2442 mm (at launch) |
| Data transmission | S band: 2000 bps uplink, 8192 bps downlink;<br>X band: 1000 Mbps downlink |
| Onboard data storage | 4 Tbits |
| Launch site | Jiuquan, Gansu Province |
| Launch date | 2022 (planned) |
| Lifetime | $>$ 4 years (expected) |

the data will be immediately transferred to SODC at Purple Mountain Observatory of Chinese Academy of Sciences, where the data will be processed into high-level data which will be finally provided to users all over the world. Details on data processing for the FMG, LST and HXI are given by Su et al. (2019a), Feng et al. (2019) and Su et al. (2019b), respectively.

There are four divisions in the SODC: scientific operation, data management, data analysis center and user services. The key part is the data analysis center, which will be the same as the data center for the previous mission and will provide a user-friendly interface and powerful software, so that users can easily access the data and conduct corresponding analyses according to their own purposes. The data policy of ASO-S will soon be drafted by the

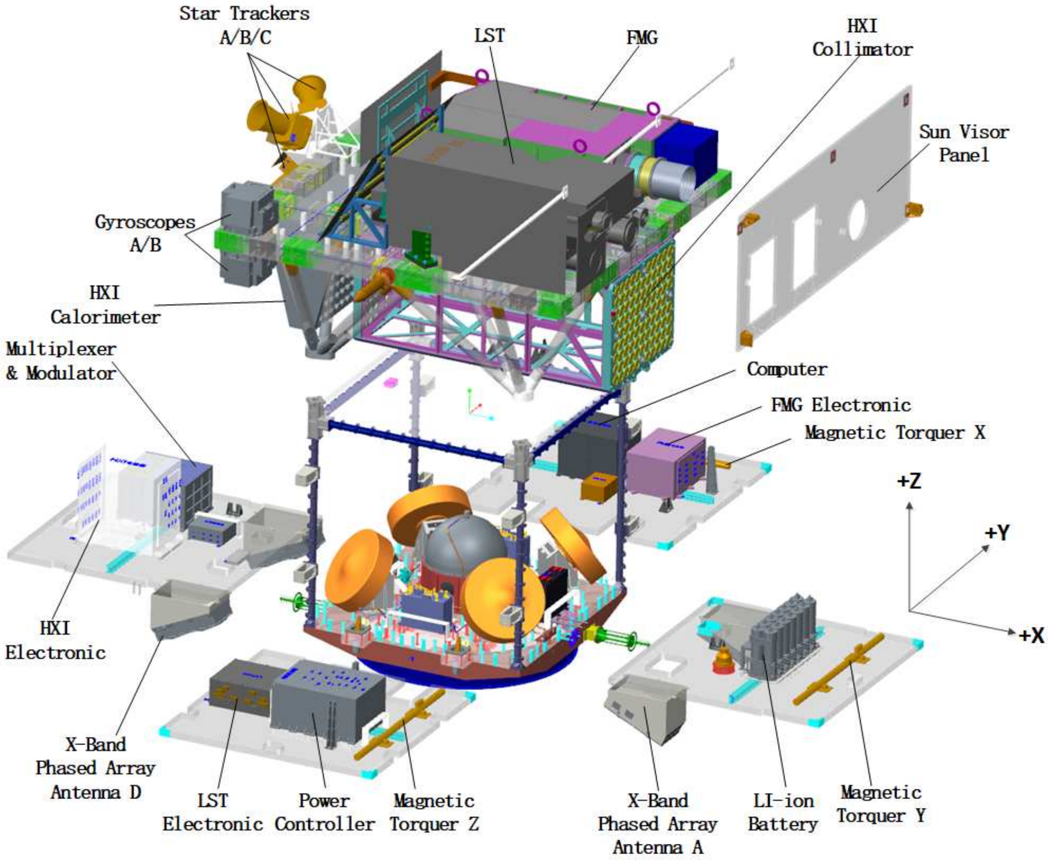


**Fig. 5** Exploded view of the ASO-S.

Science Committee led by the chief scientist of ASO-S. In principle, we will follow a completely open data policy and encourage all kinds of cooperation. Meanwhile, the ASO-S team welcomes students, post-doctoral researchers and scholars to visit and join us anytime during the manufacturing stage of the ASO-S. Cooperation at this stage is mainly focused on individual instruments, where payload scientists and payload data scientists are collaborators. After the successful launch of ASO-S, we may establish a more regular visitor program to support collaborations.

Currently, multi-waveband studies are the trend in solar physics research. ASO-S will then strengthen cooperation with other space and ground facilities available (e.g., Li et al. 2019a; Krucker et al. 2019; Vial 2019; Vourlidas 2019). The SODC will develop some software or facilitate development of joint data analysis research. The SODC also plans to play some role in space weather forecasting like predicting the arrival time of CMEs by using data from LST.

The website of ASO-S is now at: `http://aso-s.pmo.ac.cn/english`.

## 6 SUMMARY

As the first dedicated solar satellite approved in China, ASO-S is now undertaking the Phase-C study. In 2022, ASO-S will be launched into orbit by a CZ-2D rocket, so as to operate during the solar maximum of the 25th solar cycle. ASO-S deploys three instruments, the FMG, LST and HXI, observing the full disk vector magnetic field, initiation and early propagation of CMEs, and imaging of non-thermal X-ray emissions in solar flares, respectively, in order to study the relationships between solar flares, CMEs and the magnetic field. With the unique characteristic of simultaneously observing 1M2B on a single platform, the ASO-S will play an irreplaceable role in the coming years during the solar maximum.

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