Wallops Arc-Second Pointing (WASP) System

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The United States National Aeronautics and Space Administration's (NASA) Wallops Flight Facility (WFF), as part of the Goddard Space Flight Center (GSFC), has developed and demonstrated a scientific balloon pointing control system capable of stable sub-arc-second accuracy. Since the initial 2011 test flight, the Wallops Arc-Second Pointing (WASP) system has been utilized to provide precision control of directional scientific instruments across multiple balloon-borne flights, both within the continental United States and Antarctica. While the WASP system has proven itself capable, the team at WFF continues to improve its capabilities. Efforts are underway to improve the control software, integrate more capable tracking and pointing hardware, as well as lightening and optimizing the center control gimble. With two successful flights in 2019, the WASP team is currently preparing for a flight from Esrange, Sweden, in the spring of 2022.

I.Introduction

The WASP system provides a two-axis stabilized platform for scientific instruments operating while suspended beneath a high-altitude balloon. The WASP system consistently provides pointing accuracy and stability performance within the arcsecond to sub-arcsecond regime. The WASP system uses a standard NASA rotator located above the gondola to provide coarse azimuth positioning of the balloon payload. A pitch-yaw articulated gimbal system located on the main gondola is utilized to provide fine two-axis pointing of the instrument support structure.

The NASA Balloon Program Office (BPO) sponsored the engineering development of WASP in the late 2000s to provide a flexible fine-pointing infrastructure capability to science groups possessing novel instruments but not necessarily having (or desiring) an in-house instrument pointing control expertise. There is a significant degree of adaptability in how the WASP system integrates with the main gondola and the instrument support structure, allowing for the accommodation of a large variety of instrument and gondola geometries.

Since its inaugural flight in 2011, the WASP system has been used to provide fine pointing of five unique scientific instruments during the conduct of seven balloon flights. WASP flight operations have been conducted from Ft. Sumner, NM, and McMurdo Station, Antarctica. Flight preparations are currently underway for the XL-Calibur payload to be launched from Esrange, Sweden. Recent developments and improvements in the rotator electronics, in-flight alignment techniques, control-law tuning, and assembly have resulted in the achievement of sub-arcsecond performance on the two most recent flights.

II.System Description and Updates

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The WASP system has been described in detail in previous papers.[1,2] Figure 1 provides an overview of most of the WASP system components as configured for a typical balloon flight.

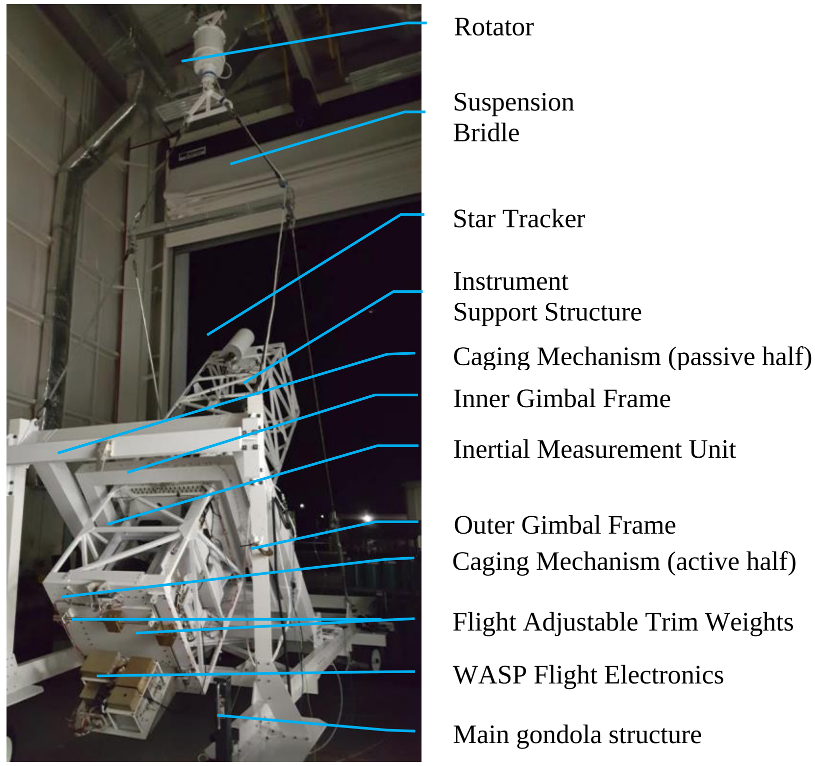

Figure 1
WASP PICTURE-C Gondola During Nighttime Alignment Verification Test

The NASA Rotator is shown at the top of Figure 1. This system provides coarse azimuth pointing of the main gondola structure below. The rotator was developed in the mid-1990s; however, in 2017, the electronics package was revamped. Modifications included porting the flight software to a single-board computer running an embedded Linux O/S, allowing the rotator flight software to share much of the WASP code base and integrate more tightly. Improvements in the isolation of the rotator rate sensor from motor-induced chassis voltages have resulted in significant tightening of the rotator pointing performance. The rotator can now achieve ~10-arcmin stability, reducing disturbance torques transmitted through the yaw gimbal.

The main gondola is suspended below the rotator, typically using a bridle system, as is shown in Figure 1, to accommodate desired elevations of longer payloads. The main gondola holds the balloon bus elements (e.g., transmitters, receivers, antennae, power systems, instrumentation, crush-pads, and ballast hoppers). From a pointing system perspective, the gondola provides the structural foundation for the WASP gimbal frame system. WASP has flown with several gondola structures – some designed and fabricated by the science team, most designed and fabricated by the WASP team.

WASP two-axis pointing is achieved through a pitch-yaw gimbal system. Figure 2 shows a schematic of the gimbals and hubs. The outer gimbal frame (mounted to the main gondola structure) connects to the gimbal inner frame via two pitch-axis hubs. The inner gimbal frame connects to the instrument structure via two yaw-axis hubs. The starboard pitch-axis hub and top-side yaw-axis hub each house a brushless DC torque motor to provide the pitch-yaw actuation of the instrument structure relative to the main gondola. The port-side pitch-axis hub and bottom-side yaw-axis hub each house a resolver which provides gimbal frame and motor position information for actuator motor commutation and gondola-relative navigation.

The WASP hub and gimbal systems tend to drive mission formulation on several fronts. The size of the inner frame limits the diameter of telescopes using them. The current design of the inner gimbal has maximum inside dimensions of 1.0 meters both vertically and horizontally. Instruments can side-step the gimbal size limitation by mounting on a cantilevered structure in front of the inner frame, but this approach comes at a significant weight penalty. The hubs are currently sized to accommodate a 680kg inner pointed structure.

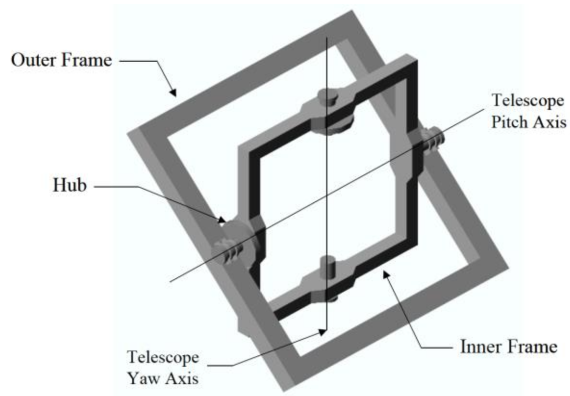

Figure 2
WASP Pitch/Yaw Gimbal System

The designs of the outer and inner gimbal frames have remained essentially unchanged since WASP was first developed. The only significant change to the outer frame assembly has been the addition of internal doubler plates at the hub interfaces to mitigate damage from hard landings. The sole upgrade to the inner frame assembly has been changing from a square frame to a rectangular frame, larger in the vertical dimension, allowing science teams to integrate stiffer structures in the pitch plane. A redesign of the inner gimbal frame is currently underway that is intended to improve manufacturability, eliminate counterweights, reduce cost, and reduce mass.

The WASP control law makes use of an attitude solution that is developed from an Extended Kalman Filter which merges the attitude integrated from the onboard three-axis inertial rate sensor with quaternion and unit vector data measured by a star-tracker or sun sensor. The WASP attitude solution is capable of accommodating data from multiple sources at once. Reference [1] detailed a degradation in performance experienced during the X-CALIBUR flight, which was in part attributed to a misalignment between the IMU and the star-tracker. Prior to this flight, the WASP team had attempted several approaches for determining the alignment between the rate sensor and the star tracker. Most required the two sensors to be co-located on a rigid plate to maintain the alignment between the ground measurement and flight operations. A means of accurately determining the misalignment offsets between an inertial rate sensor and a star-tracker (or sun sensor) was devised using the X-CALIBUR flight data. Ground support software has been developed to permit segments of raw integrated quaternions from the rate sensor and data from a star tracker or sun sensor to be batch processed in such a way to determine the orientation of the rate sensor relative to the star tracker. Alignment offsets can be determined to ~1-minute accuracy by processing a 5-minute-long segment of sensor data. This is sufficient to eliminate the attitude solution degradation from the sensor misalignment. The technique was applied during pre-flight hang-tests to determine misalignment offsets for both the BITSE and PICTURE-C missions. In both cases, the ground-determined offsets were sufficient for flight operations.

Since its formulation, the WASP system has incorporated independently operating Proportional-Integral-Derivative (PID) control laws in the pitch and yaw fine pointing channels. Over the years, gain setting approaches have varied. Typically, a rule of thumb approach was utilized to set the proportional gain, the derivative gain was set to achieve damping objectives, and the integral gain was set sufficient to achieve bias correction within the desired time response. Gain settings were checked for stability in a linear analysis. Iteration between time response and stability was nonintuitive. Recently, the WASP team has taken to computing the gains using a closed-form pole-placement approach for a simplified single-axis dynamic model of the pointed mass. With this approach, the designer specifies the desired closed-loop natural frequency and damping ratio for the oscillating poles; the gains are computed based on these specified parameters and the moment of inertial of the center body. The time response of the hardware has been found to closely match the simplified third-order model. The stability of the system is still verified against the linear model. This approach has been useful for making in-flight gain adjustments. In order to tighten the pointing system performance, a higher natural frequency is specified. In cases where it appears that the control system is interacting with the flight bridle or center structure, a lower control response frequency is selected, and gains are automatically computed and sent. The pole placement procedure has taken the guesswork out of trying to individually tune the PID gains.

In addition to the PID control laws, two Neural Network control law methodologies (detailed in Reference [3]) have been added to the WASP Flight Software. The so-called Sub-arcsecond Neural Network Attitude Reference Controller (SNNARC) and the Modified State Observer (MSO) techniques have been demonstrated in simulation and ground testing to improve the station-keeping pointing stability performance of WASP. SNNARC utilizes a two-layer network to estimate nonlinear system dynamics with a baseline reference tracking control law. MSO uses a single-layer network to estimate the state in an input-output feedback linearization controller. Both controllers were tested on PICTURE-C during its integration and test flow for the 2021 campaign. The WASP team had plans and procedures for placing each control law into service in turn during that flight.

The Wallops-developed Celestial Attitude Reference Determination System (CARDS) (see Reference [1]) has been the mainstay for daytime (and nighttime) star, sun, planet, and moon sensing during six of the seven science flights, and the WASP team plans to continue using CARDS for future flights. The utility and flexibility of having an in-house star tracker have been exceedingly valuable for meeting unique mission requirements posed by various science groups. However, one of the biggest challenges to maintaining this capability has been keeping up with the shifting landscape of commercial camera and lens hardware. The XL-Calibur flight will debut the Wallops Integrated Star Tracker (WaIST). WaIST uses the Vision Components VCSBC nano 0252 "board camera" – a camera integrated with a Dual-Core ARM computer running the Linux operating system. The CARDS flight software has been ported to the VCSBC board, making use of the VC API for accessing image data. The WaIST was introduced into the XL-Calibur sensor stable in order to add needed wide-field sun-sensing capability without taxing the CARDS computer, which was already managing three star-tracker cameras to support various mission modes.

III.Recent and Upcoming Flights

Two missions flown during the 2019 Fort Sumner balloon launch campaign utilized the WASP system for attitude control – BITSE and PICTURE-C. The WASP and University of Massachusetts teams attempted to re-fly the PICTURE-C mission during the 2021 Fort Sumner campaign but did not get a flight opportunity. In 2022, the WASP team is working with the XL-CALIBUR team to fly from Esrange, Sweden, in the spring/summer launch campaign. The PICTURE-C mission is set for another re-fly attempt in the fall Ft. Sumner campaign.

A. Balloon-Borne Investigation of Temperature and Speed of Electrons in the Corona (BITSE)

The BITSE mission used WASP to point a coronagraph instrument at the sun. This instrument was the first to measure temperature and electron speed simultaneously in the 3 – 8 solar radius coronal region. The BITSE payload made use of the WASP test-flight gondola (from the 2012 test flight) to mount its instrument (see Figure 3).

To anchor the integrated attitude solution, WASP used a CARDS unit that was converted into a sun-sensor via two MidOpt neutral density filters with an optical density of 4.0 stacked in front of the String Ray lens. An additional reflective bandpass filter was placed on the front so that the science team could use images taken by the sun sensor to gauge relative background levels throughout the flight.

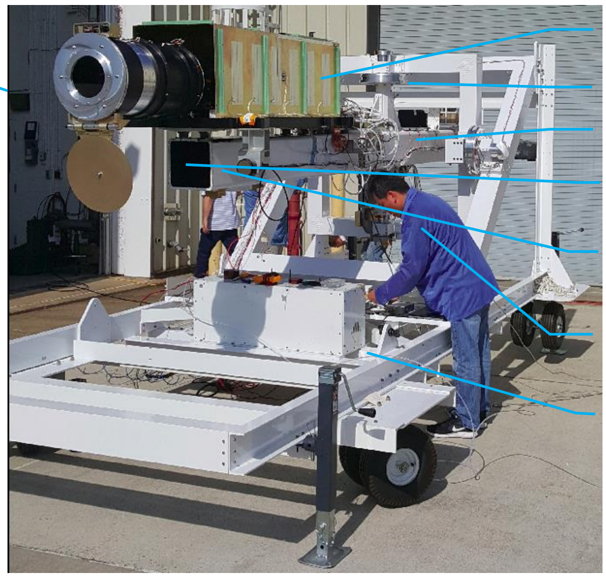

Figure 3
BITSE Gondola During Integration at Wallops Flight Facility

The BITSE flight was launched on September 18, 2019. After acquiring the sun and aligning the WASP sun sensor to the instrument, the WASP system spent 4 hours and 4 minutes staring at the sun. During that time, the pointing system was able to hold the pointing error within 1-arcsecond 99.4% of the time. Figures 4 and 5 show the WASP pointing performance over the science data taking time. While the overall performance was the best demonstrated by WASP to date, the team did note several 2 – 5 arcsecond poke-outs. These were caused by periodic data corruption between the serial resolver interface and the flight computer affecting the actuator motor commutation. The data corruption was found to be due to a software timing change introduced in a new computer build. The timing issue was addressed, and additional filtering has been added to the resolver data stream.

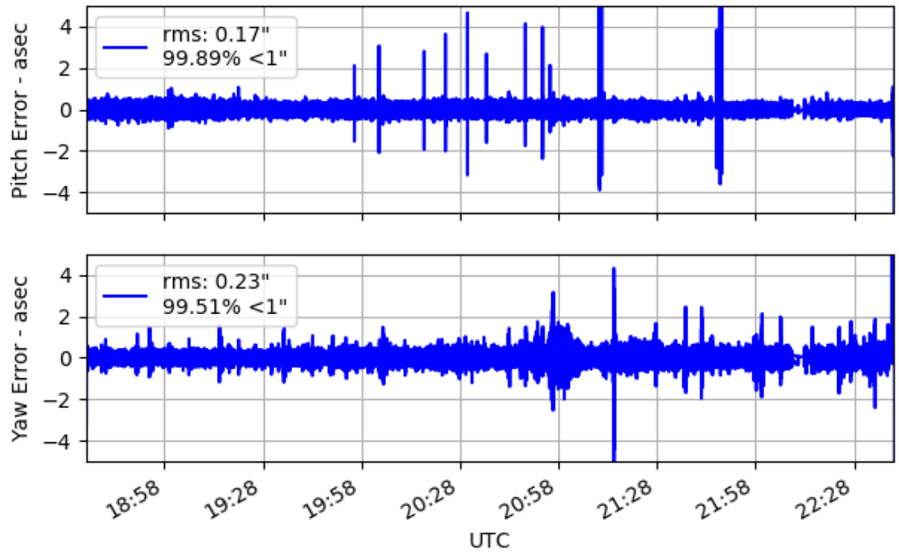

Figure 4
WASP Pointing Performance During BITSE Flight

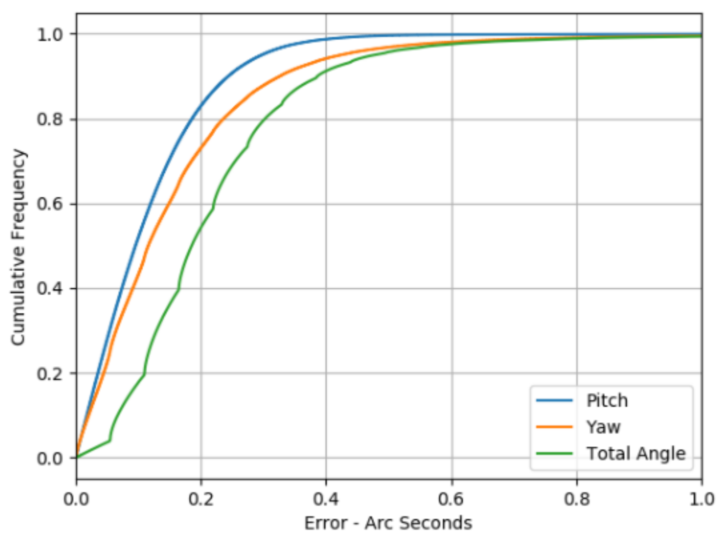

Figure 5
WASP Pointing Performance During BITSE Flight

B. Planetary Imaging Concept Testbed Using a Recoverable Experiment – Coronagraph (PICTURE-C)

The PICTURE-C mission was launched from Fort Sumner on September 28, 2019. During this flight, WASP was used to point a stellar coronagraph at four calibration stars and four stars of scientific interest during a 9-hour, 7-minute period at float. PICTURE-C used a novel deformable mirror approach to provide sub-milli-arcsecond stabilization of their instrument, which was to directly image debris disks around stars. The pointing requirements levied on WASP included a frequency envelope that could not be directly verified in ground testing. Much time was spent during the flight adjusting the WASP control gain settings in an attempt to enhance the performance of the PICTURE-C mirror control loop. Throughout the flight, the WASP RMS pointing error varied between 0.15 – 0.8 arcseconds depending on the control gain settings. Figures 6 and 7 show the WASP pointing performance while on a representative target.

Throughout the flight, the PICTURE-C science team had limited success getting their control loops to maintain lock for extended periods. Flight data from the instrument revealed a high-frequency noise floor that exceeded the threshold established during mission design. Improvements in the instrument allowed limited ground testing to occur prior to the 2021 re-fly attempt in which the WASP hub shaft rotation motors were identified as potential sources of the noise.

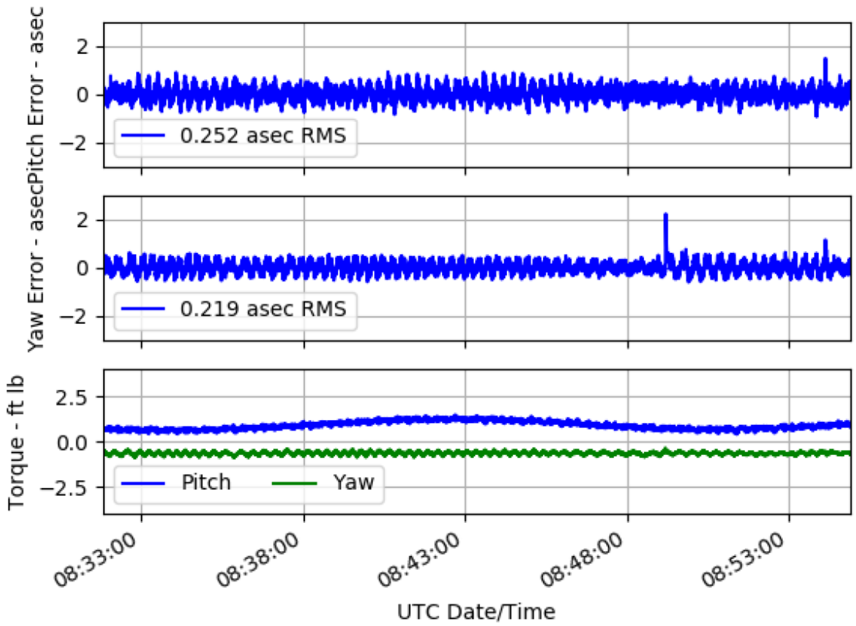

Figure 6
WASP Pointing Performance during PICTURE-C Flight (While on b-Ori)

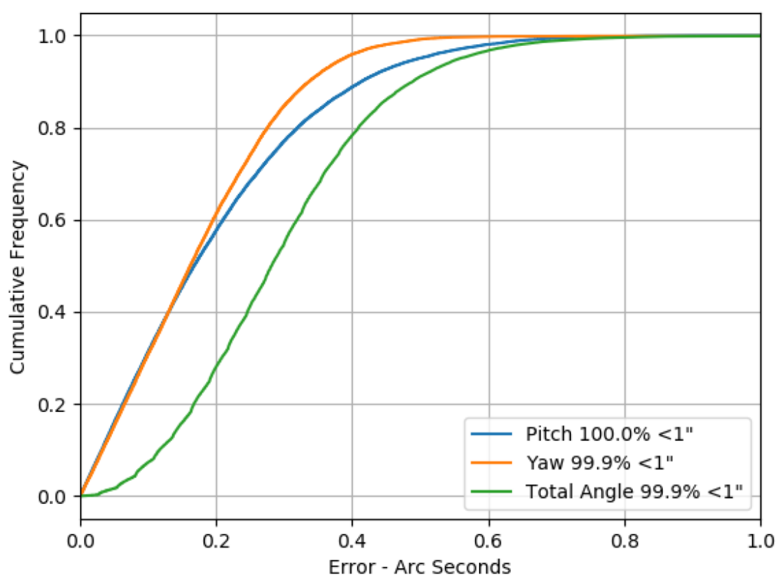

Figure 7
WASP Pointing Performance during PICTURE-C Flight (While on b-Ori)

C. XL-CALIBUR

XL-CALIBUR is a balloon-borne X-ray telescope experiment set to fly from Esrange Space Center, Sweden, in the late spring of 2022. The experiment utilizes the spare X-ray mirror from the Hitomi mission with a 12-m focal length, requiring a 12-m carbon-fiber truss to hold the mirror and polarimeter instrument. The XL-CALIBUR experiment uses a specialized gondola design (Figure 8 right) to permit up to 75º elevation angles. WASP is interfacing with three star-trackers and one WaIST configured as a wide-field sun sensor to permit pointing at targets close to the sun and high elevations (Figure 8 left).

Figure 8
XL-Calibur During Integration Testing at Wallops Flight Facility
(Left: front view during nighttime startracker testing. Right: side view during daytime sun-sensor testing)

IV.Conclusions

Wallops Island Flight Facility personnel have worked to develop the stable, balloon-borne pointing system since the initiative's inception in the late 1990s. With nearly two decades of successful flights, the WASP has proven to be a capable and beneficial technology. Not wanting to sit on past successes, the program continues to develop advancements in the systems technology. Efforts like integrating a linear control system and optimizing the gimbal design based on operational lessons will further increase pointing accuracy. Looking forward to the next few years, re-flights of Picture-C and XL-Calibur, as well as the initial flight of CORSAIR, will provide continued opportunities to the WASP program as well as our scientific partners for successful balloon-born science.

Acknowledgments

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References

[1] Stuchlik, D. W. and Lanzi, R. J., "The NASA Wallops Arc Second Pointer (WASP) System for Precision Pointing of Scientific Balloon Instruments and Telescopes," *AIAA Balloon Systems Conference*, AIAA 2017-3609, June 2017.

[2]Stuchlik, D. W, "The Wallops Arc Second Pointer – A Balloon Borne Fine Pointing System," *AIAA Balloon Systems Conference*, AIAA 2015-3039, June 2015.

[3] Galchenko, P. and Pernicka, H. "Neural Network Attitude Control System Design for the Wallops Arc-Second Pointer," *AIAA Journal of Guidance, Control, and Dynamics*, February 2022.

[4] Gopalswamy N., Newmark J., Yashiro S., Mäkelä P., Reginald N., Thakur N., Gong Q., Kim Y. H., Cho K. S., Choi S. H., Baek J. H., Bong S. C., Yang H. S., Park J. Y., Kim J. H., Park Y. D., Lee J. O., Kim R. S. and Lim E. K., "The Balloon-Borne Investigation of Temperature and Speed of Electrons in the Corona (BITSE): Mission Description and Preliminary Results," *Solar Physics*, Vol. 296, Jan. 2021, pp. 1–32.

[5] Mendillo C. B., Hewawasam K., Martel J., Potter T., Cook T. A. and Chakrabarti S., "The PICTURE-C Exoplanetary Imaging Balloon Mission: First Flight Preparation," *Techniques and Instrumentation for Detection of Exoplanets IX, Proceedings of the 2021 International Society for Optics and Photonics Conference*, Vol. 11823, Soc. of Photo-Optical Instrumentation Engineers, Bellingham, WA, Aug. 2021, pp. 125–133.