In-flight performance of the polarization modulator in the CLASP rocket experiment

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ABSTRACT

We developed a polarization modulation unit (PMU), a motor system to rotate a waveplate continuously. In polarization measurements, the continuous rotating waveplate is an important element as well as a polarization analyzer to record the incident polarization in a time series of camera exposures. The control logic of PMU was originally developed for the next Japanese solar observation satellite SOLAR-C by the SOLAR-C working group. We applied this PMU for the Chromospheric Lyman - alpha SpectroPolarimeter (CLASP). CLASP is a sounding rocket experiment to observe the linear polarization of the Lyman - alpha emission (121.6 nm vacuum ultraviolet) from the upper chromosphere and transition region of the Sun with a high polarization sensitivity of 0.1 % for the first time and investigate their vector magnetic field by the Hanle effect. The driver circuit was developed to optimize the rotation for the CLASP waveplate (12.5 rotations per minute). Rotation non - uniformity of the waveplate causes error in the polarization degree (i.e. scale error) and crosstalk between Stokes components. We confirmed that PMU has superior rotation uniformity in the ground test and the scale error and crosstalk of Stokes Q and U are less than 0.01 %. After PMU was attached to the CLASP instrument, we performed vibration tests and confirmed all PMU functions performance including rotation uniformity did not change. CLASP was successfully launched on September 3, 2015, and PMU functioned well as designed. PMU achieved a good rotation uniformity, and the high precision polarization measurement of CLASP was successfully achieved.

Keywords: Sun, Vacuum ultraviolet, Magnetic fields, Polarization measurement

1. INTRODUCTION

It is known that magnetic fields are the energy source of many phenomena in the universe. It is also same in the Sun, and magnetic fields measurements are important to investigate energy release and transfer phenomena. The solar magnetic field can be measured by polarimetric observation using the quantum mechanical effects such as the Zeeman effect. The magnetic field on the solar surface (photosphere) has been measured with good resolution solar far (e.g., the Solar Optical Telescope[1] onboard the Hinode[2] satellite). However, it is technically difficult to measure the magnetic fields of upper layers of solar atmosphere such as upper chromosphere, transition region or corona using the Zeeman effect. One way to overcome this difficulty and measure the magnetic fields in these layers is the Hanle effect. Several emission lines from the Sun are linearly polarized by atomic scattering, and the polarization degree becomes smaller if the magnetic fields presents. By measuring the linear polarization precisely, it is possible to estimate the magnetic fields.

We perfomoed the Chromospheric Lyman-dalpha Spectropolarimeter (CLASP) sounding rocket experiment to observe the linear polarization of the Lyman-alpha light (Vacuum Ultraviolet, $\lambda = 121.6$ nm) from the Sun with a

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high sensitivity and estimate magnetic fields of the upper chromosphere and transition region[3] by the Hanle effect. We used the continuously rotating waveplate to measure the polarization by CLASP. The waveplate rotator is an important element to measure the polarization precisely. A Polarization Modulation Unit (PMU), a motor system to rotate a waveplate continuously for the next Japanese solar observation satellite SOLAR-C[4] by the SOLAR-C working group at Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, and National Astronomical Observatory of Japan in collaboration with the Mitsubishi Precision company.[5] For CLASP, we used the rotator part of PMU (PMU-ROT) and control logic developed for SOLAR-C, and newly developed the driver circuit (PMU-DRV) to optimize the rotation to the CLASP flight rotation speed of 4.8 s per rotation. In this article, we describe the overview of the polarization measurement method by CLASP, and report the performance during the flight.

2. POLARIZATION MEASUREMENT BY CLASP

Determining the magnetic fields of the upper chromosphere and transition region by the Lyman-alpha spectropolarimetry was difficult because of the technical difficulties of the precise polarization measurements. CLASP rotates the angle of polarization continuously by a rotating half waveplate mounted on PMU, and extracts polarization component with a certain angle by a reflective polarization analyzers. By the amplitude and phase of modulated time profile (polarization modulation) synchronized to the PMU rotation, CLASP obtains polarization degree and angle (Fig. 1). CCD cameras take data 16 times per single waveplate rotation. By combining those 16 values from a single rotation, we can calculate the Stokes vectors I, Q and U.[6] CCD images should be taken with the certain timing synchronized to the CCD rotation (one exposure per 22.5 °). This is realized by a exposure synchronization signal sent by the PMU-DRV. The CCD cameras end the current exposure and start the next exposure when they receive the signal.

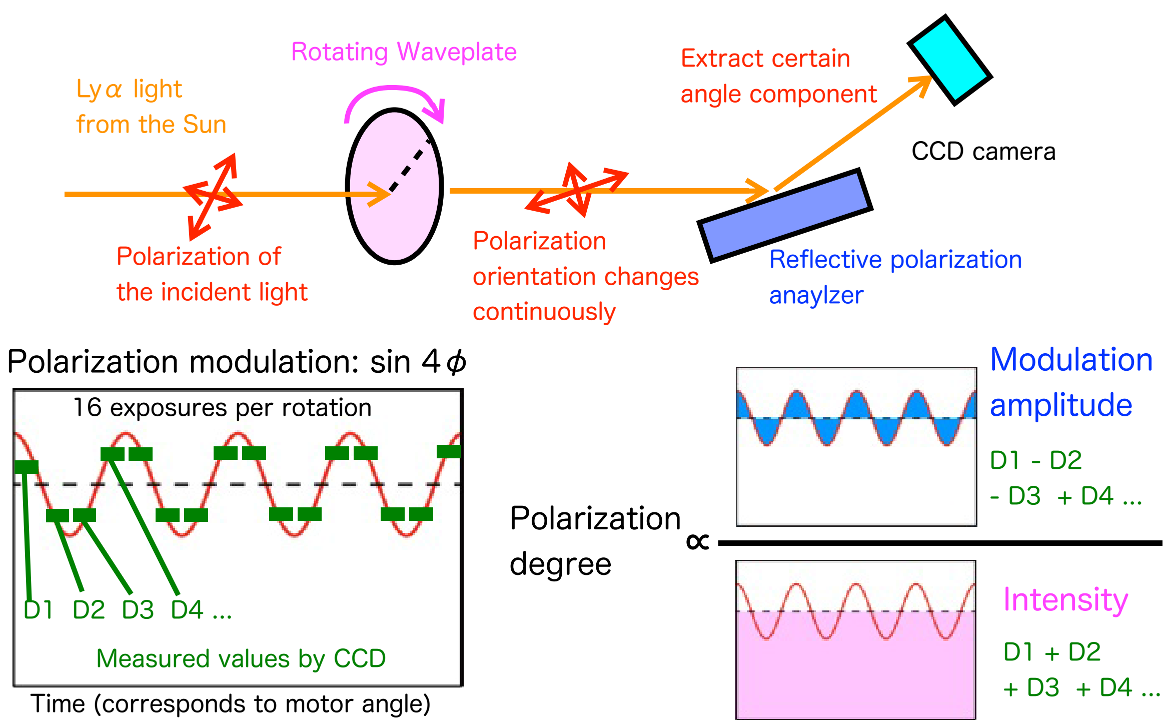

Figure 1. Method to measure the linear polarization by CLASP. (Top) Schematic diagram of the CLASP polarization measurement. (Bottom Left) Example of polarization modulation curve and expected CCD observation data. (Bottom right) Schematic to show the polarization degree (Stokes Q/I) is proportional to the modulation amplitude divided by the intensity.

If the rotation is not uniform, polarization degree and angle are not correctly estimated (scale error and crosstalk between Q and U of the Stokes vector). These causes the errors in magnetic field estimation, and high rotation uniformity is required. In the ground test, it was confirmed that scale error and crosstalk are as low enough as $<0.01\%$.[7] Four status signals of PMU, motor current, current rotation angle, angle deviation and temperature, are sent from PMU-DRV to the ground as the part of the telemetry. By checking the angle deviation signal, we can confirm how uniform PMU rotates during both of ground tests and the flight.

3. GROUND TESTS AND INSTALLATION

We confirmed the interfaces between PMU and the other instruments. The CCD cameras and data acquisition system were developed by NASA, and we confirmed that CCD exposures are successfully triggered by the exposure synchronization signal by PMU-DRV. It was also confirmed that the PMU status signals are successfully received by the data acquisition system.

After the interface confirmations, PMU-ROT was installed to the CLASP structure (Fig. 2). PMU was attached to the telescope side on the baseplate between the telescope and spectropolarimeter (the detailed optical design is shown by Narukage et al.[8]). The waveplate holder mounted on PMU was blackened to reduce stray light.

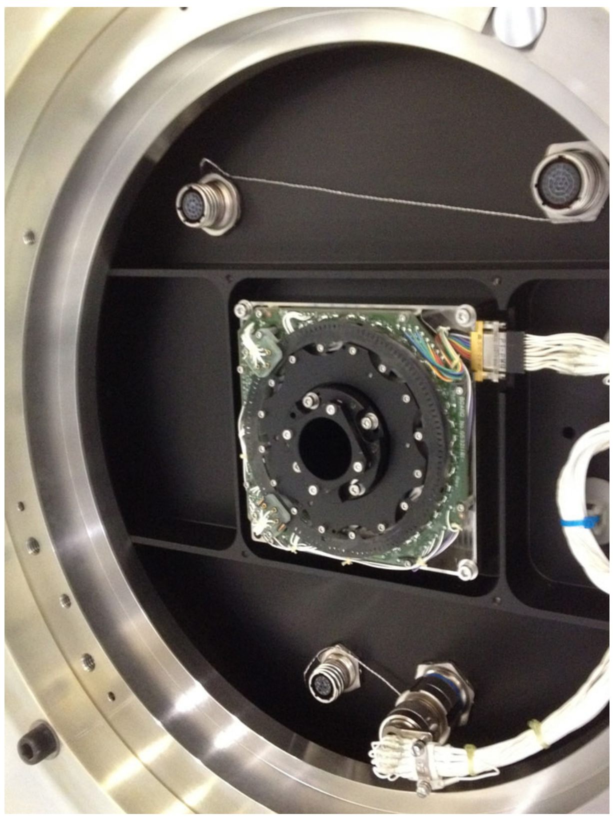

Figure 2. Photo of PMU installed on the CLASP structure.

Since PMU-ROT already have an experience of the vibration test with higher vibration level than for a sounding rocket for the future satellite application, we performed vibration tests for PMU-DRV alone and whole CLASP spectropolarimeter at ISAS. It is confirmed the performance did not change after those vibration tests by checking the angle deviation signal. After the tests, CLASP spectropolarimeter shipped to launch site, the White Sands Missile Range, New Mexico, USA.

4. IN-FLIGHT PERFORMANCE

CLASP was successfully launched on September 3, 2015, and the whole instrument including PMU worked well as expected. The summary of the observation is shown in Fig. 3. As shown in the Q/I profile at the bottom right panel in Fig. 3, the polarization signal up to ≈4 % was clearly observed. The profile is smooth and random noise component is low enough to use the profile for the magnetic field estimation at the wavelength range with the enough intensity.

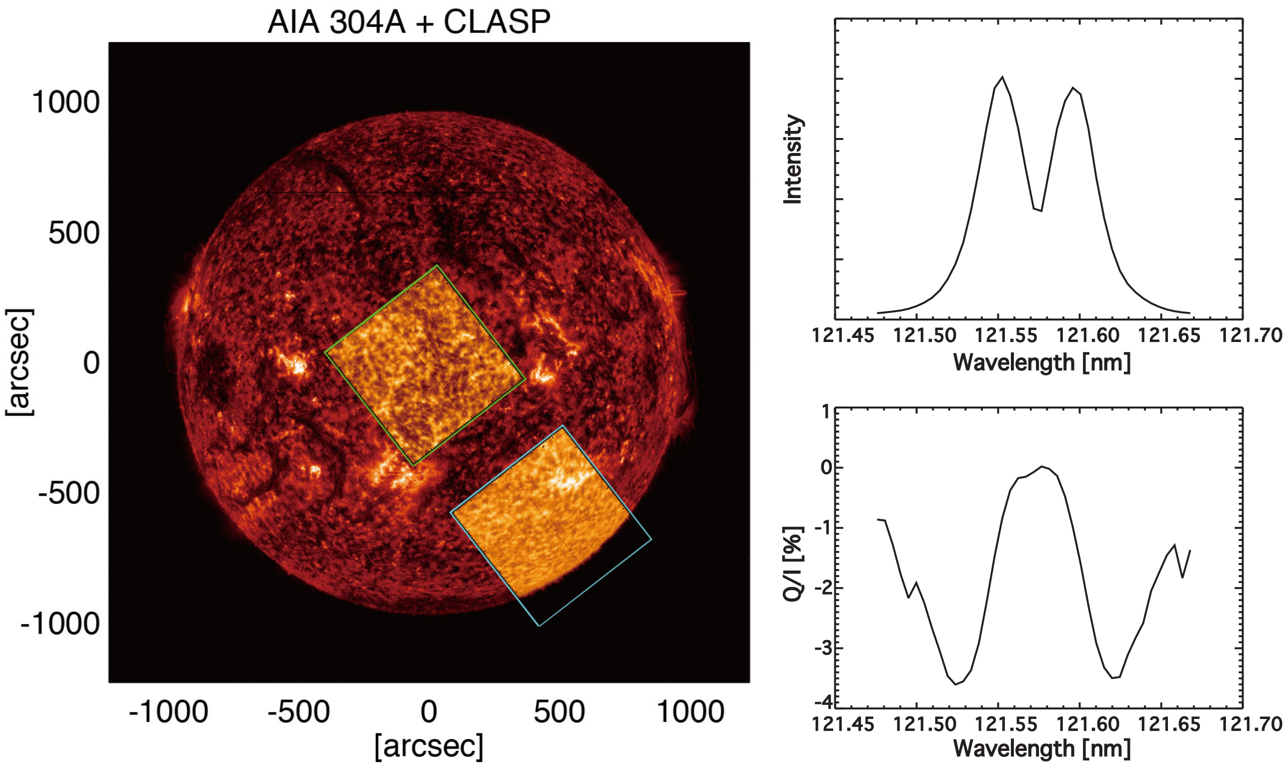

Figure 3. Summary of the CLASP observation. (Left) Lyman-alpha images obtained by the slit-jaw optics of CLASP plotted on the full Sun image taken by SDO/AIA 304 Å. (Top right) Example of an observed intensity profile. (Bottom right) Example of an observed polarization profile Q/I.

We checked the time evolution of the data obtained by the CCD cameras, and it is found that modulation curves with a 4.8 s period (16 exposure period) were successfully obtained (Fig. 4). It suggests that PMU rotated continuously with the speed of one rotation per 16 CCD exposures, and the calculated polarization is not artificial but from the Sun.

By checking the time evolution of the polarization, we found that the calculated polarization degree and angle are not constant during the observation. However, it is found that those time evolutions were not similar for the different regions. If the PMU lost the control or stopped at some moment, the polarization degrees and angles should have discontinuous time profile at the same moment. There was no such timing during the flight, and the polarization time differences during the observation are thought to be originated by the Sun.

According to the PMU status signals taken during the flight, PMU rotated continuously with no interruption during the whole observational time. The behavior of the rotation angle, motor current and temperature during the flight were quite similar as the ground tests. The angle deviation was within the same level as the ground tests, and high rotation uniformity was achieved (Fig. 5). By those status data, it is clear that PMU functioned well as on the ground and high precision polarization data were obtained.

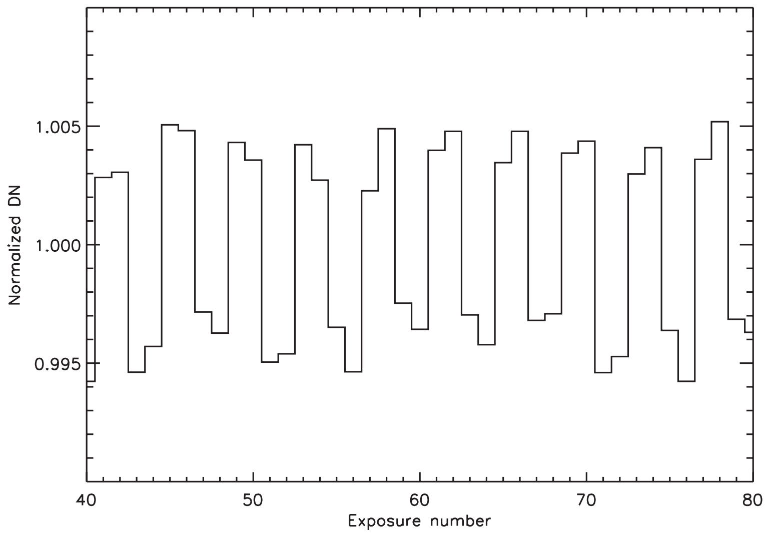

Figure 4. Example of the polarization modulation taken by CLASP during the flight. It is spatially integrated for some region, and the actual amplitudes for spatial elements are larger than shown here.

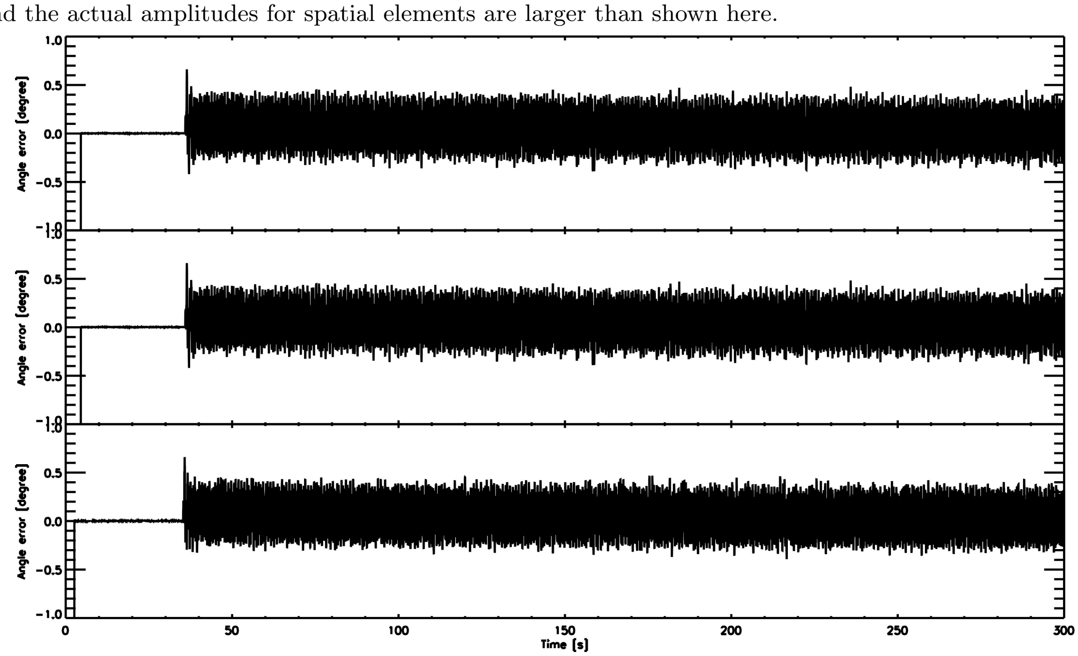

Figure 5. Angle error data taken on the ground tests before and after the vibration tests (upper and middle panels), and during the flight (lower panel).

Following to the data above, we confirmed that the PMU rotates continuously with the expected period of 4.8 s by checking the polarization modulation, and no evidence of stopping or interrupting the rotation was detected at all. Therefore, we do not have any reason to suspect the PMU status signals. Based on those result, we confirmed that CLASP successfully obtained high quality Lyman-alpha polarization data. The CLASP team works for the data analysis and the results will be published soon.

5. SUMMARY

We developed the polarization modulation unit to rotate the waveplate continuously to measure the linear polarization of the Lyman-alpha light from the Sun with the CLASP sounding rocket experiment. PMU has good rotation uniformity to meet the scientific requirement of CLASP. The PMU performance did not change before and after the vibration test, and the CLASP payload was launched. PMU functioned as expected during the flight, and the high precision polarization measurement was achieved.

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