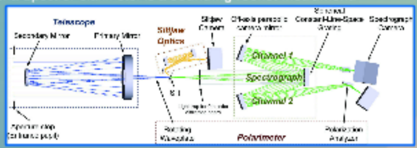
CLASP: Polarization calibration to reach the 0.1% polarization sensitivity in the VUV range

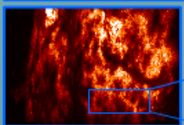
Giono, G.[1], Ishikawa, R.[1], Narukage, N.[1], Kano, R.[1], Katsukawa, Y.[1], Kubo, M.[1], Ishikawa, S.[2], Bando, T.[1], Hara, H.[1], Suematsu, Y.[1], Winebarger, A.[3], Kobayashi, K.[3], Auchère, F.[4], Trujillo Bueno, J.[5]
1: National Astronomical Observatory of Japan (NAOJ) 2: Japanese Aerospace Exploration Agency (JAXA) 3: NASA Marshall Space Flight Center (MSFC) 4: Institut d'Astrophysique Spatiale (IAS) 5: Instituto de Astrofisica de Canarias (IAC)

1) Scientific motivation

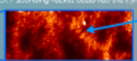
The Chromospheric Lyman-Alpha SpectroPolarimeter is a **sounding rocket instrument**,



designed to measured the linear polarization of the Lyman-alpha line emitted in the **solar upper-chromosphere and lower transition region**.

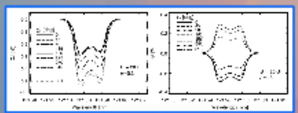


VAULT sounding rocket observed the Lyman-Alpha line from the chromosphere with a 0.33 arcsecond resolution in 2002.



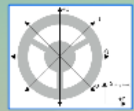
Thread structure of ~10" length and ~1" width

The polarization created bu scattering processes and atomic population imbalance is expected to be sensitive to the magnetic field strength and orientation via the **Hanle effect**.



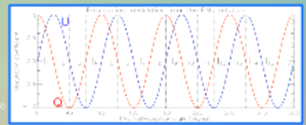
Simulated polarization profiles (Stokes Q/I and U/I) for different azimuth angle of the magnetic field vector, close to the limb. (Trujillo Bueno 2011)

2) Polarimetry



Stokes parameters definition as seen from the entrance aperture.

CLASP performs polarimetric measurement using a **rotating half-waveplate** located in the Polarization Modulation Unit (PMU). The PMU triggers the CCDs for exposure every **300ms** (**22.5°** continuous rotation of the half-waveplate).



Modulation of Stokes parameters for one full PMU rotation (channel 2)

The polarization signal can be **demodulated** by combining consecutive exposures:

$$\frac{Q'}{I'} = \frac{\pi}{2}\left(\frac{I_1 - I_2 - I_3 + I_4}{I_1 + I_2 + I_3 + I_4}\right) \quad \frac{U'}{I'} = \frac{\pi}{2}\left(\frac{I_1 + I_2 - I_3 - I_4}{I_1 + I_2 + I_3 + I_4}\right)$$

However, deviation from such ideal case have to be represented with the instrument **response matrix**:

$$\begin{pmatrix} I' \\ Q' \\ U' \\ V' \end{pmatrix} = \begin{pmatrix} 1 & x_{10} & x_{20} & x_{30} \\ x_{01} & x_{11} & x_{21} & x_{31} \\ x_{02} & x_{12} & x_{22} & x_{32} \\ x_{03} & x_{13} & x_{23} & x_{33} \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

Checked to be negligible

Stokes V not important for CLASP

Checked to be <1%

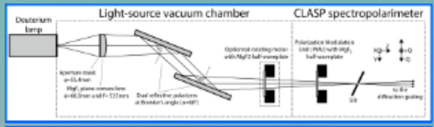
reduced to

$$\begin{pmatrix} Q'/I' \\ U'/I' \end{pmatrix} = \begin{pmatrix} q' \\ u' \end{pmatrix} = \begin{pmatrix} x_{01} & x_{11} & x_{21} \\ x_{02} & x_{12} & x_{22} \end{pmatrix} \begin{pmatrix} 1 \\ q \\ u \end{pmatrix}$$

Core **response matrix** is composed of the **spurious polarization**, **scale errors** and **azimuth errors**.

3) Light-source for polarization calibration

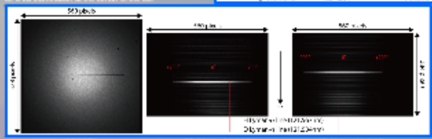
A **Lyman-alpha light-source** is required to input the Stokes parameters needed to determine the **response matrix**.



Light-source conceptual design.

Light-source inside and outside as attached to CLASP Spectro-Polarimeter.

Typical image recorded by the three CCDs for a LS illumination at the center of the slit.



SJ CCD SP Channel 1 CCD SP Channel 2 CCD

This **light-source** can produce a almost perfectly linearly polarized beam (**>99%**) at the center of the spot, with similar F# as CLASP telescope.

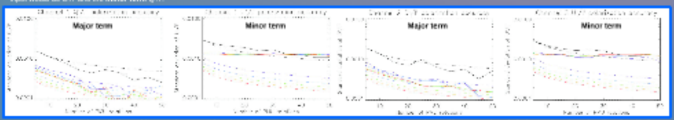
4) Polarization calibration: Tolerance and accuracy

$$\begin{pmatrix} Q'/I' \\ U'/I' \end{pmatrix} = \begin{pmatrix} q' \\ u' \end{pmatrix} = \begin{pmatrix} x_{01} & x_{11} & x_{21} \\ x_{02} & x_{12} & x_{22} \end{pmatrix} \begin{pmatrix} 1 \\ q \\ u \end{pmatrix}$$

Matrix Element	Spurious Polarization	Scale Error	Azimuth Error
Tolerance	1.7x10^{-4}	2x10^{-2}	1x10^{-2}

The **spurious polarization** needs a **10^{-4} accuracy**, and since it is determined from the polarization measurement, the same accuracy is needed on the demodulated Q'/I' and U'/I'.

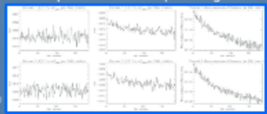
The **major term** is defined as the measured Q'/I' for a +Q or -Q input, whereas the **minor term** would be the measured U'/I' for the same input. Consecutively, the **major term** for a +U or -U input would be U'/I' and the **minor term** Q'/I'.



Measured Q'/I' and U'/I' for both channel for a +Q input, as a function of PMU rotation (16 exposures) stacking. Solid line shows different number of pixel summing along the slit: 1 (black), 7 (purple), 13 (blue), 19 (green), 25 (orange), 31 (red). Dash line shows the theoretical curve when considering only photon noise. +/- 4 pixels were summed in spectral direction around the D line.

The accuracy on the **major term** decreased to the **10^{-4} level**, with spatial/temporal summation (reducing photon noise) but the accuracy on the **minor term** is limited to 10^{-3}. This is due to a small decrease of the exposure time, affecting the **minor terms**.

The **minor terms** cannot be used to determine the **spurious polarization**.



Example with major term, minor term and exposure difference for both channel

5) Polarization calibration: Method and results

To avoid the contamination of the minor term accuracy to the **spurious polarization** accuracy, two independent least square fitting were used to retrieve the matrix elements.

First fitting: Combining measurement to remove the effect of the spurious polarization.

$$\begin{aligned} q'_{+Q} - q'_{-Q} &= x_{11}(q_{+Q} - q_{-Q}) + x_{21}(u_{+Q} - u_{-Q}) \\ q'_{+U} - q'_{-U} &= x_{11}(q_{+U} - q_{-U}) + x_{21}(u_{+U} - u_{-U}) \\ u'_{+Q} - u'_{-Q} &= x_{12}(q_{+Q} - q_{-Q}) + x_{22}(u_{+Q} - u_{-Q}) \\ u'_{+U} - u'_{-U} &= x_{12}(q_{+U} - q_{-U}) + x_{22}(u_{+U} - u_{-U}) \end{aligned}$$

Major term / Minor terms / Major term

Measured Stokes parameters Ex: Measured U'/I' for a +U input

Known input Stokes parameters Ex: Input U/I for a +U input

Use the fixed **scale error** and **azimuth error** terms

Second fitting: Determine the spurious polarization, using only the **major terms**.

$$\begin{aligned} q'_{+Q} &= x_{01} + x_{11}q_{+Q} + x_{21}u_{+Q} \\ q'_{-Q} &= x_{01} + x_{11}q_{-Q} + x_{21}u_{-Q} \\ u'_{+U} &= x_{02} + x_{12}q_{+U} + x_{22}u_{+U} \\ u'_{-U} &= x_{02} + x_{12}q_{-U} + x_{22}u_{-U} \end{aligned}$$

With this method, the limited accuracy of the **minor term** only affect the accuracy of the **scale** and **azimuth** terms.

Measurements were performed for **four orientations** of the light-source and a **half-waveplate** was also used after the LS polarizer to change the polarization input of the LS. For each LS position, a **15 minutes** measurement was recorded for each of the 16 positions of the half-waveplate, resulting in **4x(+Q,+U,-Q.-U)** input per LS position.

Channel 1	x_{01}	x_{11}	x_{21}	x_{02}	x_{12}	x_{22}
+Q LS input	0.00198	0.97639	0.01238	-0.00046	-0.01182	0.97618
+U LS input	0.00219	0.97640	0.00890	-0.00037	-0.00646	0.97620
-Q LS input	0.00223	0.97736	0.00836	-0.00030	-0.00812	0.97708
-U LS input	0.00204	0.97573	0.00599	-0.00040	-0.00667	0.97566
Mean	0.00211	0.97649	0.00891	-0.00038	-0.00877	0.97625
Error (+/-)	0.00013	0.00086	0.00347	0.00008	0.00305	0.00082
Tolerance	0.00017	0.02000	0.01000	0.00017	0.01000	0.02000

Each line is obtained with the fitting method on the 16 measure-ments recorded for the given LS position.

Channel 2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

As a result, the unprecedented accuracy at the 0.01% level on the **spurious polarizations terms** was achieved. The tolerance required on the **scale error** and **azimuth error terms** was also successfully achieved.

This poster presentation only scratched the surface of CLASP polarization calibration: many other measurements were also performed (without half-waveplate for comparison, with quarter waveplate to check cross-talks from Stokes V, etc...) during the extensive experiment. The reader is invited to read the detailed article for more information, which will be submitted soon (G.Giono et al, 2015)

Hinode 9 meeting, Belfast 17/09/15

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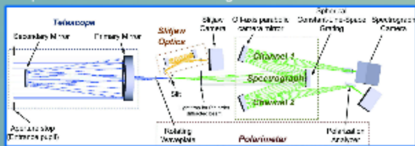

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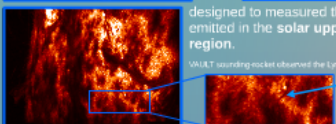

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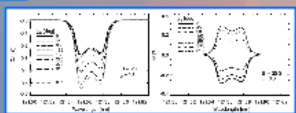

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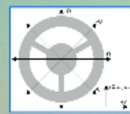

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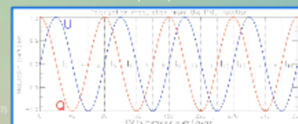

Modulation of Stokes parameters for one full PMU rotation (channel 1)

The polarization signal can be **demodulated** by combining consecutive exposures:

$$\frac{Q'}{I'} = \frac{\pi}{2}\left(\frac{I_1 - I_2 - I_3 + I_4}{I_1 + I_2 + I_3 + I_4}\right) \quad \frac{U'}{I'} = \frac{\pi}{2}\left(\frac{I_1 - I_2 - I_3 - I_4}{I_1 - I_2 - I_3 + I_4}\right)$$

However, deviation from such ideal case have to be represented with the instrument **response matrix**:

$$\begin{pmatrix} I' \\ Q' \\ U' \\ V' \end{pmatrix} = \begin{pmatrix} 1 & x_{10} & x_{20} & x_{30} \\ x_{01} & x_{11} & x_{21} & x_{31} \\ x_{02} & x_{12} & x_{22} & x_{32} \\ x_{03} & x_{13} & x_{23} & x_{33} \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

Checked to be negligible

Stokes V not important for CLASP

Checked to be <1%

reduced to

$$\begin{pmatrix} Q'/I' \\ U'/I' \end{pmatrix} = \begin{pmatrix} q' \\ u' \end{pmatrix} = \begin{pmatrix} x_{01} & x_{11} & x_{21} \\ x_{02} & x_{12} & x_{22} \end{pmatrix} \begin{pmatrix} 1 \\ q \\ u \end{pmatrix}$$

Core **response matrix** is composed of the **spurious polarization**, **scale errors** and **azimuth errors**.

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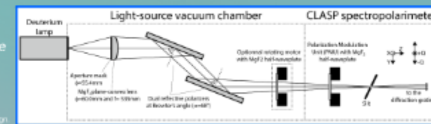
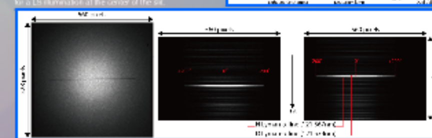
A **Lyman-alpha light-source** is required to input the Stokes parameters needed to determine the **response matrix**.



Light-source conceptual design

Light-source inside and outside as attached to CLASP Spectro-Polarimeter

Typical image recorded by the three CCDs for a LS illumination at the center of the slit



SJ CCD SP Channel 1 CCD SP Channel 2 CCD

This **light-source** can produce a almost perfectly linearly polarized beam (**>99%**) at the center of the spot, with similar F# as CLASP telescope.

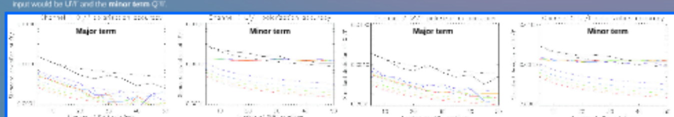
4) Polarization calibration: Tolerance and accuracy

$$\begin{pmatrix} Q'/I' \\ U'/I' \end{pmatrix} = \begin{pmatrix} q' \\ u' \end{pmatrix} - \begin{pmatrix} x_{01} & x_{11} & x_{21} \\ x_{02} & x_{12} & x_{22} \end{pmatrix} \begin{pmatrix} 1 \\ q \\ u \end{pmatrix}$$

Matrix Element	Spurious Polarization	Scale Error	Azimuth Error
Tolerance	1.7×10^{-4}	2×10^{-2}	1×10^{-2}

The **spurious polarization** needs a **10^{-4} accuracy**, and since it is determined from the polarization measurement, the same accuracy is needed on the demodulated Q'/I' and U'/I'.

The **major term** is defined as the measured Q'/I' for a +Q or -Q input, whereas the **minor term** would be the measured U'/I' for the same input. Consecutively, the **major term** for a +U or -U input would be U'/I' and the **minor term** Q'/I'.



Measured Q'/I' and U'/I' for both channel for a +Q input, as a function of PMU rotation (16 exposures) stacking. Solid line shows different number of pixel summing along the slit: 1 (black), 7 (purple), 13 (blue), 19 (green), 25 (orange), 31 (red). Dash line shows the theoretical curve when considering only photon noise. +/- 4 pixels were summed in spectral direction around the 0 line.

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Example with major term, minor term and exposure difference for both channel

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To avoid the contamination of the minor term accuracy to the **spurious polarization** accuracy, two independent least square fitting were used to retrieve the matrix elements.

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Major term / Minor terms / Major term

Measured Stokes parameters Ex: Measured U/I' for a +U input

Known input Stokes parameters Ex: Input U/I for a +U input

Use the fitted **scale error** and **azimuth error** terms

Second fitting: Determine the spurious polarization, using only the **major terms**.

$$\begin{aligned} q'_{+Q} &= x_{01} + x_{11}q_{+Q} + x_{21}u_{+Q} \\ q'_{-Q} &= x_{01} + x_{11}q_{-Q} + x_{21}u_{-Q} \\ u'_{+U} &= x_{02} + x_{12}q_{+U} + x_{22}u_{+U} \\ u'_{-U} &= x_{02} + x_{12}q_{-U} + x_{22}u_{-U} \end{aligned}$$

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Mean	0.00211	0.97649	0.00891	-0.00038	-0.00877	0.97625
Error (+/-)	0.00013	0.00066	0.00247	0.00006	0.00365	0.00062
Tolerance	0.00017	0.02000	0.01000	0.00017	0.01000	0.02000

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-Q LS input	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
-U LS input	[illegible]	0.97075	[illegible]	0.00235	-0.00115	0.97037
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NAOJ

Prezi

1. National Astronomical Observatory of Japan (NAOJ) 2. Japanese

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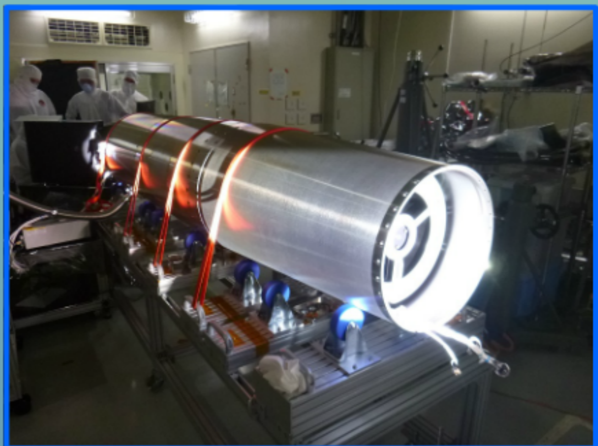

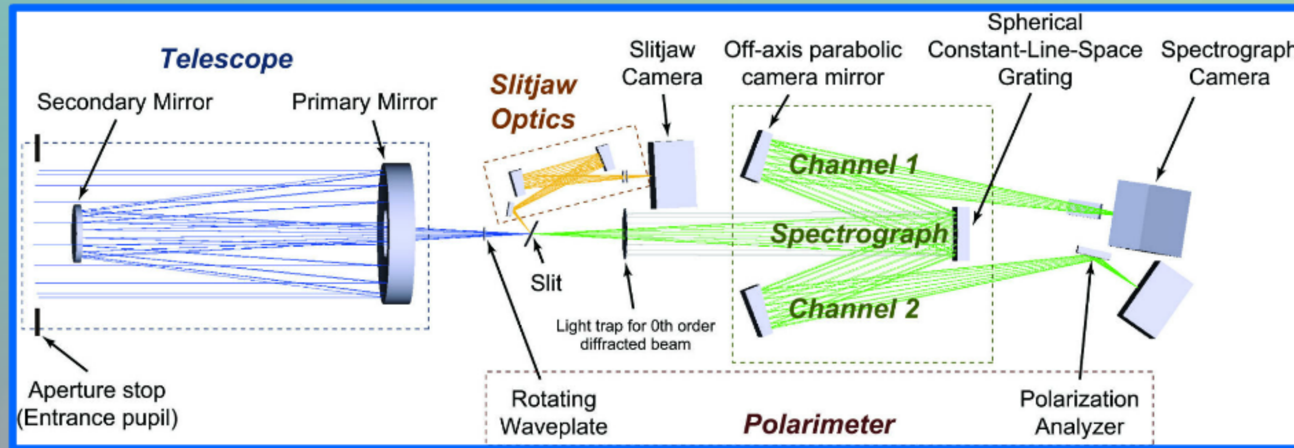

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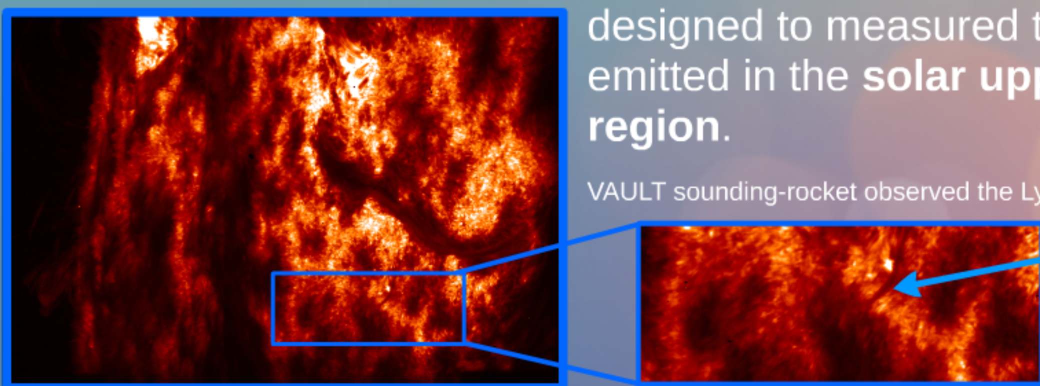

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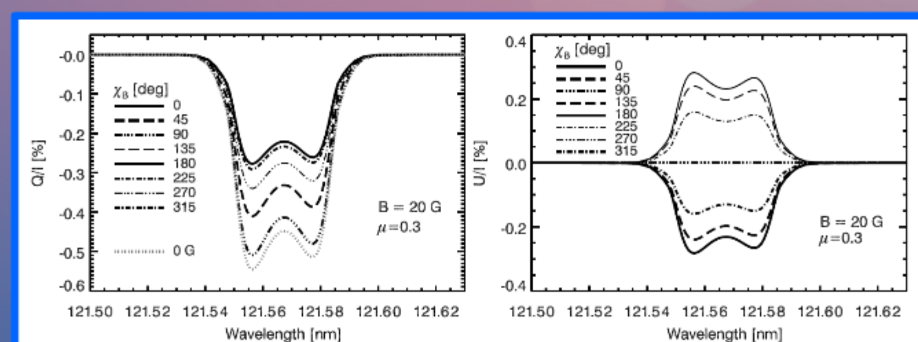
The polarization created bu scattering processes and atomic population imbalance is expected to be sensitive to the magnetic field strength and orientation via the **Hanle effect**.

Simulated polarization profiles (Stokes Q/I and U/I) for different azimuth angle of the magnetic field vector, close to the limb. (Trujillo Bueno 2011)



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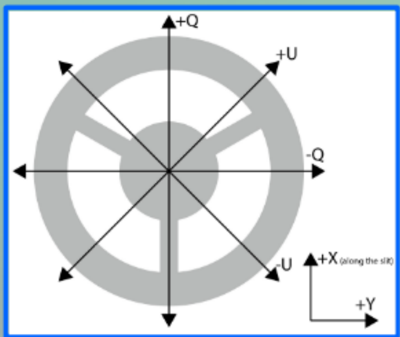
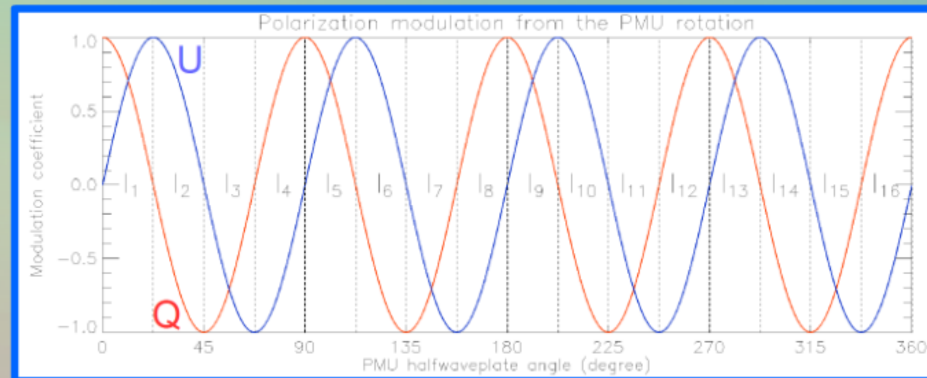
2) Polarimetry



Stokes parameters definition as seen from the entrance aperture.

CLASP performs polarimetric measurement using a **rotating half-waveplate** located in the Polarization Modulation Unit (PMU). The PMU triggers the CCDs for exposure every **300ms** (**22.5°** continuous rotation of the half-waveplate).



Modulation of Stokes parameters for one full PMU rotation (channel 2)

The polarization signal can be **demodulated** by combining consecutive exposures:

$$\frac{Q'}{I'} = \frac{\pi}{2}\left(\frac{I_1 - I_2 - I_3 + I_4}{I_1 + I_2 + I_3 + I_4}\right) \quad \frac{U'}{I'} = \frac{\pi}{2}\left(\frac{I_1 + I_2 - I_3 - I_4}{I_1 + I_2 + I_3 + I_4}\right)$$

However, deviation from such ideal case have to be represented with the instrument **response matrix**:

$$\begin{pmatrix} I' \\ Q' \\ U' \\ V' \end{pmatrix} = \begin{pmatrix} 1 & x_{10} & x_{20} & x_{30} \\ x_{01} & x_{11} & x_{21} & x_{31} \\ x_{02} & x_{12} & x_{22} & x_{32} \\ x_{03} & x_{13} & x_{23} & x_{33} \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

Checked to be negligible (x_{10}, x_{20}, x_{30})

Stokes V not important for CLASP (x_{03}, x_{13}, x_{23}, x_{33})

Checked to be <1% (x_{31}, x_{32})

reduced to

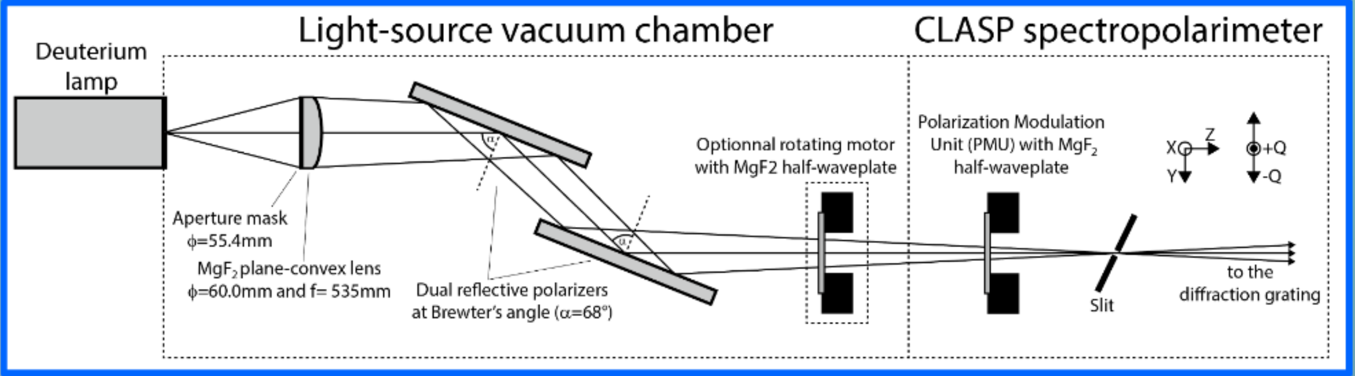
$$\begin{pmatrix} Q'/I' \\ U'/I' \end{pmatrix} \equiv \begin{pmatrix} q' \\ u' \end{pmatrix} = \begin{pmatrix} x_{01} & x_{11} & x_{21} \\ x_{02} & x_{12} & x_{22} \end{pmatrix} \begin{pmatrix} 1 \\ q \\ u \end{pmatrix}$$

Core **response matrix** is composed of the **spurious polarization**, **scale errors** and **azimuth errors**.

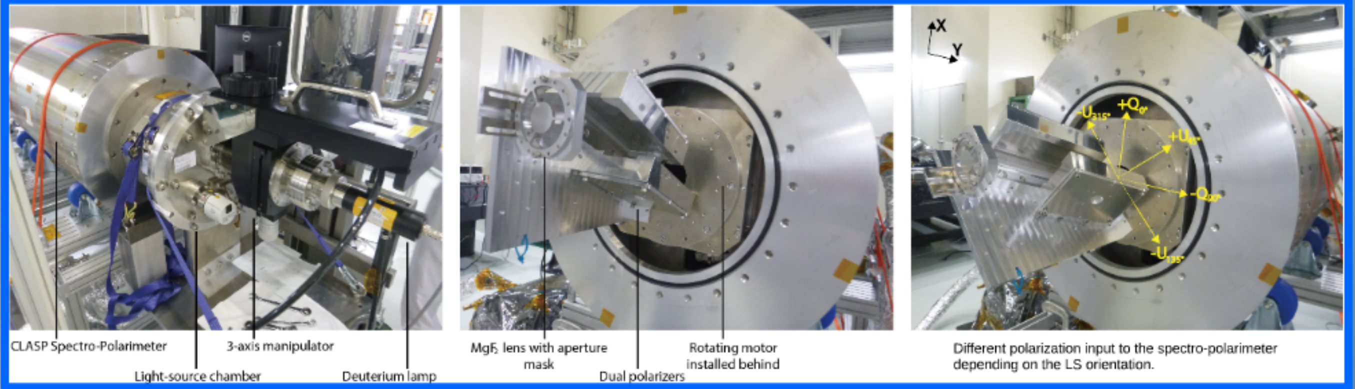
ysique Spatiale (IAS) 5. Instituto de Astrofísica de Canarias (IAC)

3) Light-source for polarization calibration

A **Lyman-alpha light-source** is required to input the Stokes parameters needed to determine the **response matrix**.

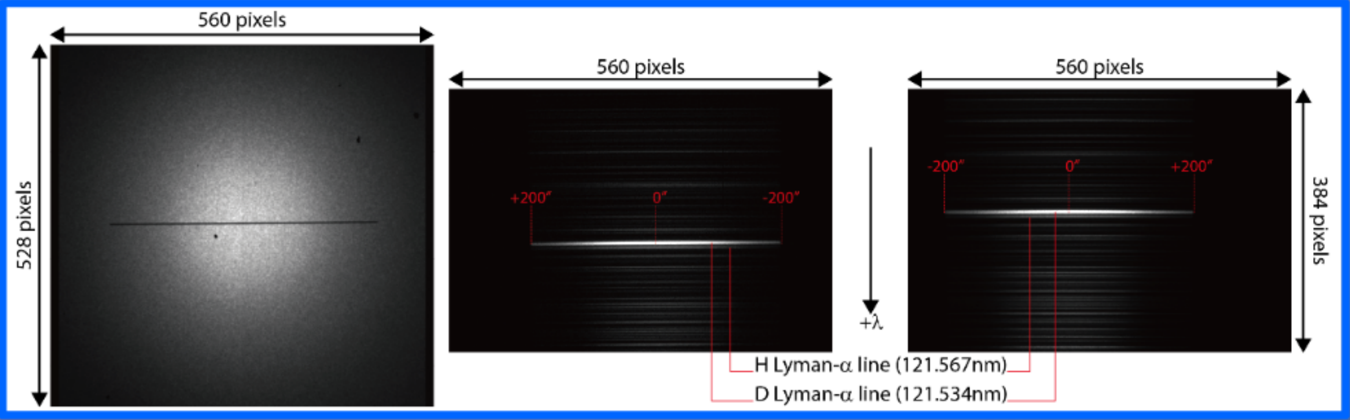


Light-source conceptual design.



Light-source inside and outside as attached to CLASP Spectro-Polarimeter.

Typical image recorded by the three CCDs for a LS illumination at the center of the slit.



SJ CCD SP Channel 1 CCD SP Channel 2 CCD

This **light-source** can produce a almost perfectly linearly polarized beam (**>99%**) at the center of the spot, with similar F# as CLASP telescope.

Prezi

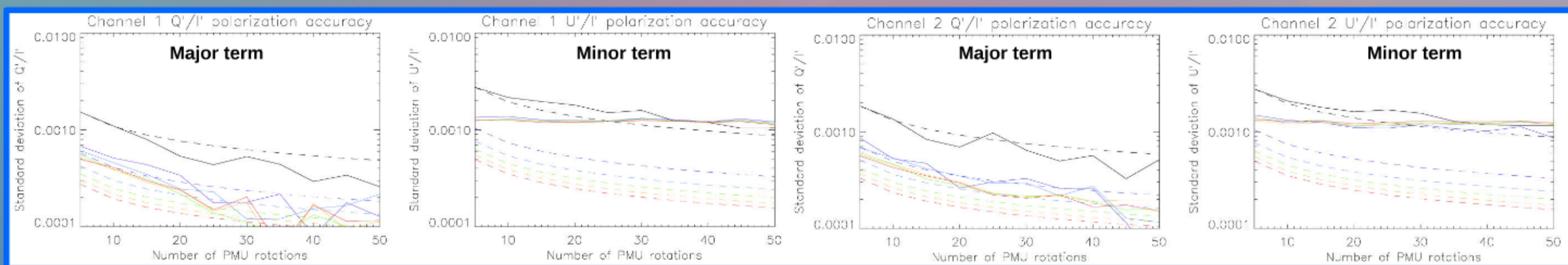
4) Polarization calibration: Tolerance and accuracy

$$\begin{pmatrix}Q'/I'\\U'/I'\end{pmatrix} \equiv \begin{pmatrix}q'\\u'\end{pmatrix} = \begin{pmatrix}x_{01} & x_{11} & x_{21}\\x_{02} & x_{12} & x_{22}\end{pmatrix}\begin{pmatrix}1\\q\\u\end{pmatrix}$$

Matrix Element	Spurious Polarization	Scale Error	Azimuth Error
Tolerance	1.7×10^{-4}	2×10^{-2}	1×10^{-2}

The spurious polarization needs a **10^{-4} accuracy**, and since it is determined from the polarization measurement, the same accuracy is needed on the demodulated Q'/I' and U'/I'.

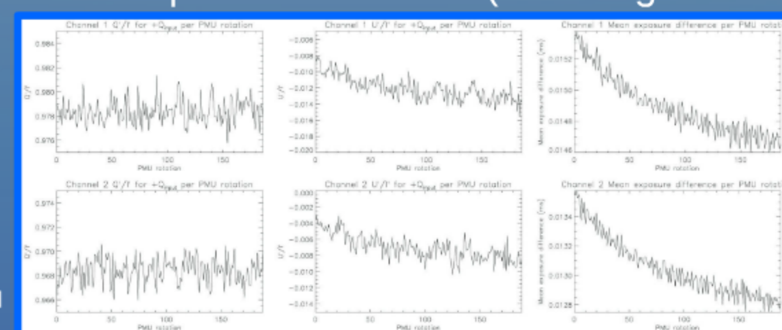
The **major term** is defined as the measured Q'/I' for a +Q or -Q input, whereas the **minor term** would be the measured U'/I' for the same input. Consecutively, the **major term** for a +U or -U input would be U'/I' and the **minor term** Q'/I'.



Measured Q'/I' and U'/I' for both channel for a +Q input, as a function of PMU rotation (16 exposures) stacking. Solid line shows different number of pixel summing along the slit: 1 (black), 7 (purple), 13 (blue), 19 (green), 25 (orange), 31 (red). Dash line shows the theoretical curve when considering only photon noise. +/- 4 pixels were summed in spectral direction around the D line.

The accuracy on the **major term** decreased to the **10^{-4} level**, with spatial/temporal summation (reducing photon noise) but the accuracy on the **minor term** is limited to 10^{-3}. This is due to a small decrease of the exposure time, affecting the **minor terms**.

The **minor terms** cannot be used to determine the spurious polarization.



Example with major term, minor term and exposure difference for both channel

SJ CCD SP Channel 1 CCD SP Channel 2 CCD

5) Polarization calibration: Method and results

To avoid the contamination of the minor term accuracy to the spurious polarization accuracy, two independent least square fitting were used to retrieve the matrix elements.

First fitting: Combining measurement to remove the effect of the spurious polarization.

Major term:
$$q'_{+Q} - q'_{-Q} = x_{11}(q_{+Q} - q_{-Q}) + x_{21}(u_{+Q} - u_{-Q})$$

Minor terms:
$$q'_{+U} - q'_{-U} = x_{11}(q_{+U} - q_{-U}) + x_{21}(u_{+U} - u_{-U})$$
$$u'_{+Q} - u'_{-Q} = x_{12}(q_{+Q} - q_{-Q}) + x_{22}(u_{+Q} - u_{-Q})$$

Major term:
$$u'_{+U} - u'_{-U} = x_{12}(q_{+U} - q_{-U}) + x_{22}(u_{+U} - u_{-U})$$

Measured Stokes parameters
Ex: Measured U'/I' for a +U input

Known input Stokes parameters
Ex: Input U/I for a +U input

Use the fitted scale error and azimuth error terms

Second fitting: Determine the spurious polarization. using only the **major terms**.

$$q'_{+Q} = x_{01} + x_{11}q_{+Q} + x_{21}u_{+Q}$$
$$q'_{-Q} = x_{01} + x_{11}q_{-Q} + x_{21}u_{-Q}$$
$$u'_{+U} = x_{02} + x_{12}q_{+U} + x_{22}u_{+U}$$
$$u'_{-U} = x_{02} + x_{12}q_{-U} + x_{22}u_{-U}$$

With this method, the limited accuracy of the **minor term** only affect the accuracy of the scale and azimuth terms.

Measurements were performed for **four orientations** of the light-source and a **half-waveplate** was also used after the LS polarizer to change the polarization input of the LS. For each LS position, a **15 minutes** measurement was recorded for each of the 16 positions of the half-waveplate, resulting in **4x(+Q,+U,-Q.-U)** input per LS position.

Channel 1	x_{01}	x_{11}	x_{21}	x_{02}	x_{12}	x_{22}
+Q LS input	0.00198	0.97639	0.01238	-0.00046	-0.01182	0.97618
+U LS input	0.00219	0.97649	0.00890	-0.00037	-0.00846	0.97620
-Q LS input	0.00223	0.97735	0.00836	-0.00030	-0.00812	0.97708
-U LS input	0.00204	0.97573	0.00599	-0.00040	-0.00667	0.97555
Mean	0.00211	0.97649	0.00891	-0.00038	-0.00877	0.97625
Error (+/–)	0.00013	0.00086	0.00347	0.00008	0.00305	0.00082
Tolerance	0.00017	0.02000	0.01000	0.00017	0.01000	0.02000

Each line is obtained with the fitting method on the 16 measure- -ments recorded for the given LS position.

Channel 2	x_{01}	x_{11}	x_{21}	x_{02}	x_{12}	x_{22}
+Q LS input	-0.00203	0.97123	0.00757	0.00042	-0.00707	0.97103
+U LS input	-0.00232	0.97027	0.00534	0.00051	-0.00496	0.96998
-Q LS input	-0.00198	0.97103	0.00807	0.00037	-0.00777	0.97091
-U LS input	-0.00211	0.97073	0.00059	0.00055	-0.00115	0.97037
Mean	-0.00211	0.97081	0.00539	0.00046	-0.00524	0.97057
Error (+/–)	0.00021	0.00055	0.00480	0.00009	0.00409	0.00059
Tolerance	0.00017	0.02000	0.01000	0.00017	0.01000	0.02000

As a result, the unprecedented accuracy at the 0.01% level on the spurious polarizations **terms** was achieved. The tolerance required on the scale error and azimuth error **terms** was also successfully achieved.

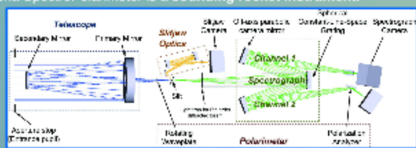
This poster presentation only scratched the surface of CLASP polarization calibration: many other measurements were also performed (without half-waveplate for comparison, with quarter waveplate to check cross-talks from Stokes V, etc...) during the extensive experiment. The reader is invited to read the detailed article for more information, which will be submitted soon (G.Giono et al, 2015)

CLASP: Polarization calibration to reach the 0.1% polarization sensitivity in the VUV range

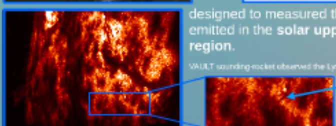
Giono, G.[1], Ishikawa, R.[1], Narukage, N.[1], Kano, R.[1], Katsukawa, Y.[1], Kubo, M.[1], Ishikawa, S.[2], Bando, T.[1], Hara, H.[1], Suematsu, Y.[1], Winebarger, A.[3], Kobayashi, K.[3], Auchère, F.[4], Trujillo Bueno, J.[5]
1: National Astronomical Observatory of Japan (NAOJ) 2: Japanese Aerospace Exploration Agency (JAXA) 3: NASA Marshall Space Flight Center (MSFC) 4: Institut d'Astrophysique Spatiale (IAS) 5: Instituto de Astrofisica de Canarias (IAC)

1) Scientific motivation

The Chromospheric Lyman-Alpha SpectroPolarimeter is a **sounding rocket instrument**,



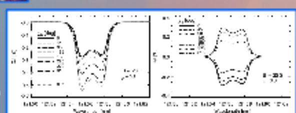
designed to measured the linear polarization of the Lyman-alpha line emitted in the **solar upper-chromosphere and lower transition region**.



VAULT sounding-rocket observed the Lyman-Alpha line from the chromosphere with a 0.33 arcsecond resolution in 2002.

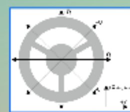
Thread structure of ~10" length and ~1" width

The polarization created bu scattering processes and atomic population imbalance is expected to be sensitive to the magnetic field strength and orientation via the **Hanle effect**.



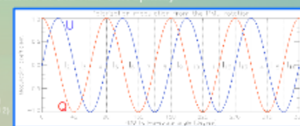
Simulated polarization profiles (Stokes Q/I and U/I) for different azimuth angle of the magnetic field vector, close to the limb. (Trujillo Bueno 2011)

2) Polarimetry



Stokes parameters definition as seen from the entrance aperture

CLASP performs polarimetric measurement using a **rotating half-waveplate** located in the Polarization Modulation Unit (PMU). The PMU triggers the CCDs for exposure every **300ms** (**22.5°** continuous rotation of the half-waveplate).



Modulation of Stokes parameters for one full PMU rotation (channel 1)

The polarization signal can be **demodulated** by combining consecutive exposures:

$$\frac{Q'}{I'} = \frac{\pi}{2}\left(\frac{I_1 - I_2 - I_3 + I_4}{I_1 + I_2 + I_3 + I_4}\right) \quad \frac{U'}{I'} = \frac{\pi}{2}\left(\frac{I_1 - I_2 - I_3 - I_4}{I_1 - I_2 - I_3 + I_4}\right)$$

However, deviation from such ideal case have to be represented with the instrument **response matrix**:

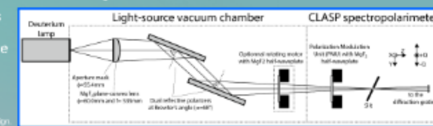
$$\begin{pmatrix} I' \\ Q' \\ U' \\ V' \end{pmatrix} = \begin{pmatrix} 1 & x_{10} & x_{20} & x_{30} \\ x_{01} & x_{11} & x_{21} & x_{31} \\ x_{02} & x_{12} & x_{22} & x_{32} \\ x_{03} & x_{13} & x_{23} & x_{33} \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} \xrightarrow{\text{reduced to}} \begin{pmatrix} Q'/I' \\ U'/I' \end{pmatrix} = \begin{pmatrix} q' \\ u' \end{pmatrix} = \begin{pmatrix} x_{01} & x_{11} & x_{21} \\ x_{02} & x_{12} & x_{22} \end{pmatrix} \begin{pmatrix} 1 \\ q \\ u \end{pmatrix}$$

Checked to be negligible — Stokes V not important for CLASP — Checked to be <1%

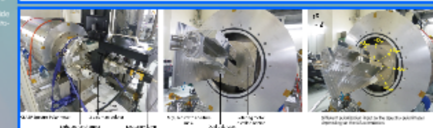
Core **response matrix** is composed of the **spurious polarization**, **scale errors** and **azimuth errors**.

3) Light-source for polarization calibration

A **Lyman-alpha light-source** is required to input the Stokes parameters needed to determine the **response matrix**.

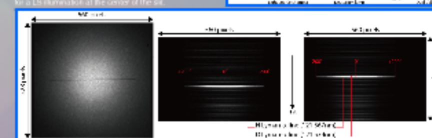


Light-source conceptual design



Light-source inside and outside as attached to CLASP Spectro-Polarimeter

Typical image recorded by the three CCDs for a LS illumination at the center of the slit



SJ CCD — SP Channel 1 CCD — SP Channel 2 CCD

This **light-source** can produce a almost perfectly linearly polarized beam (**>99%**) at the center of the spot, with similar F# as CLASP telescope.

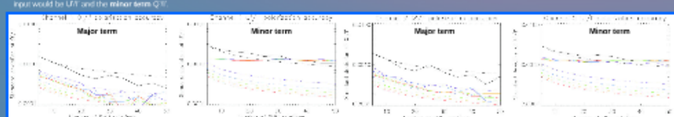
4) Polarization calibration: Tolerance and accuracy

$$\begin{pmatrix} Q'/I' \\ U'/I' \end{pmatrix} = \begin{pmatrix} q' \\ u' \end{pmatrix} = \begin{pmatrix} x_{01} & x_{11} & x_{21} \\ x_{02} & x_{12} & x_{22} \end{pmatrix} \begin{pmatrix} 1 \\ q \\ u \end{pmatrix}$$

Matrix Element	Spurious Polarization	Scale Error	Azimuth Error
Tolerance	1.7×10^{-4}	2×10^{-2}	1×10^{-2}

The **spurious polarization** needs a 10^{-4} **accuracy**, and since it is determined from the polarization measurement, the same accuracy is needed on the demodulated Q'/I' and U'/I'.

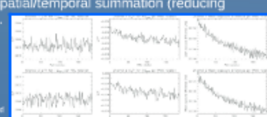
The **major term** is defined as the measured Q'/I' for a +Q or -Q input, whereas the **minor term** would be the measured U'/I' for the same input. Consecutively, the **major term** for a +U or -U input would be U'/I' and the **minor term** Q'/I'.



Measured Q'/I' and U'/I' for both channel for a +Q input, as a function of PMU rotation (16 exposures) stacking. Solid line shows different number of pixel summing along the slit: 1 (black), 7 (purple), 13 (blue), 19 (green), 25 (orange), 31 (red). Dash line shows the theorical curve when considering only photon noise. +/- 4 pixels were summed in spectral direction around the 0 line.

The accuracy on the **major term** decreased to the 10^{-4} **level**, with spatial/temporal summation (reducing photon noise) but the accuracy on the **minor term** is limited to 10^{-3}. This is due to a small decrease of the exposure time, affecting the **minor terms**.

The **minor terms** cannot be used to determine the **spurious polarization**.



Example with major term, minor term and exposure difference for both channel

5) Polarization calibration: Method and results

To avoid the contamination of the minor term accuracy to the **spurious polarization** accuracy, two independent least square fitting were used to retrieve the matrix elements.

First fitting: Combining measurement to remove the effect of the **spurious polarization**.

$$\begin{aligned} q'_{+Q} - q'_{-Q} &= x_{11}(q_{+Q} - q_{-Q}) + x_{21}(u_{+Q} - u_{-Q}) && \text{(Major term)} \\ q'_{+U} - q'_{-U} &= x_{11}(q_{+U} - q_{-U}) + x_{21}(u_{+U} - u_{-U}) && \text{(Minor terms)} \\ u'_{+Q} - u'_{-Q} &= x_{12}(q_{+Q} - q_{-Q}) + x_{22}(u_{+Q} - u_{-Q}) && \text{(Minor terms)} \\ u'_{+U} - u'_{-U} &= x_{12}(q_{+U} - q_{-U}) + x_{22}(u_{+U} - u_{-U}) && \text{(Major term)} \end{aligned}$$

Measured Stokes parameters — Ex: Measured U/I' for a +U input

Known input Stokes parameters — Ex: Input U/I for a +U input

Use the fitted **scale error** and **azimuth error** terms

Second fitting: Determine the **spurious polarization**, using only the **major terms**.

$$\begin{aligned} q'_{+Q} &= x_{01} + x_{11}q_{+Q} + x_{21}u_{+Q} \\ q'_{-Q} &= x_{01} + x_{11}q_{-Q} + x_{21}u_{-Q} \\ u'_{+U} &= x_{02} + x_{12}q_{+U} + x_{22}u_{+U} \\ u'_{-U} &= x_{02} - x_{12}q_{-U} + x_{22}u_{-U} \end{aligned}$$

With this method, the limited accuracy of the **minor term** only affect the accuracy of the **scale** and **azimuth** terms.

Measurements were performed for **four orientations** of the light-source and a **half-waveplate** was also used after the LS polarizer to change the polarization input of the LS. For each LS position, a **15 minutes** measurement was recorded for each of the 16 positions of the half-waveplate, resulting in **4x(+Q,+U,-Q.-U)** input per LS position.

Channel 1	x_{01}	x_{11}	x_{21}	x_{02}	x_{12}	x_{22}
+Q LS input	0.00198	0.97639	0.01238	-0.00046	-0.01182	0.97618
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Mean	0.00211	0.97649	0.00891	-0.00038	-0.00877	0.97625
Error (+/-)	0.00013	0.00066	0.00347	0.00006	0.00365	0.00062
Tolerance	0.00017	0.02000	0.01000	0.00017	0.01000	0.02000

Each line is obtained with the fitting method on the 16 measure-ments recorded for the given LS position.

[illegible]	x_{01}		x_{21}	x_{02}	x_{12}	x_{22}
+Q LS input	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
+U LS input	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
-Q LS input	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
-U LS input	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Mean	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Error (+/-)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Tolerance	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

As a result, the unprecedented accuracy at the 0.01% level on the **spurious polarizations terms** was achieved.
The tolerance required on the **scale error** and **azimuth error terms** was also successfully achieved.

This poster presentation only scratched the surface of CLASP polarization calibration: many other measurements were also performed (without half-waveplate for comparison, with quarter waveplate to check cross-talks from Stokes V, etc...) during the extensive experiment. The reader is invited to read the detailed article for more information, which will be submitted soon (G.Giono et al, 2015)

Hinode 9 meeting, Belfast 17/09/15

NAOJ

Prezi