IAA 1.9: Atmosphere aerosol remote sensing: Aerosol-UA experiment

Status report for Bremen September IAA meeting 2018

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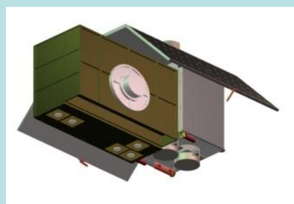
Ukrainian satellite mission Aerosol-UA: polarimetric investigation atmospheric aerosol

Three segments:

Satellite:



ScanPol + MSIP

Data processing:

Mission products

AERONET:

Validation

Idea for Aerosol-UA project come from Glory experiment and APS instrument

The advantages of ScanPol polarimetry

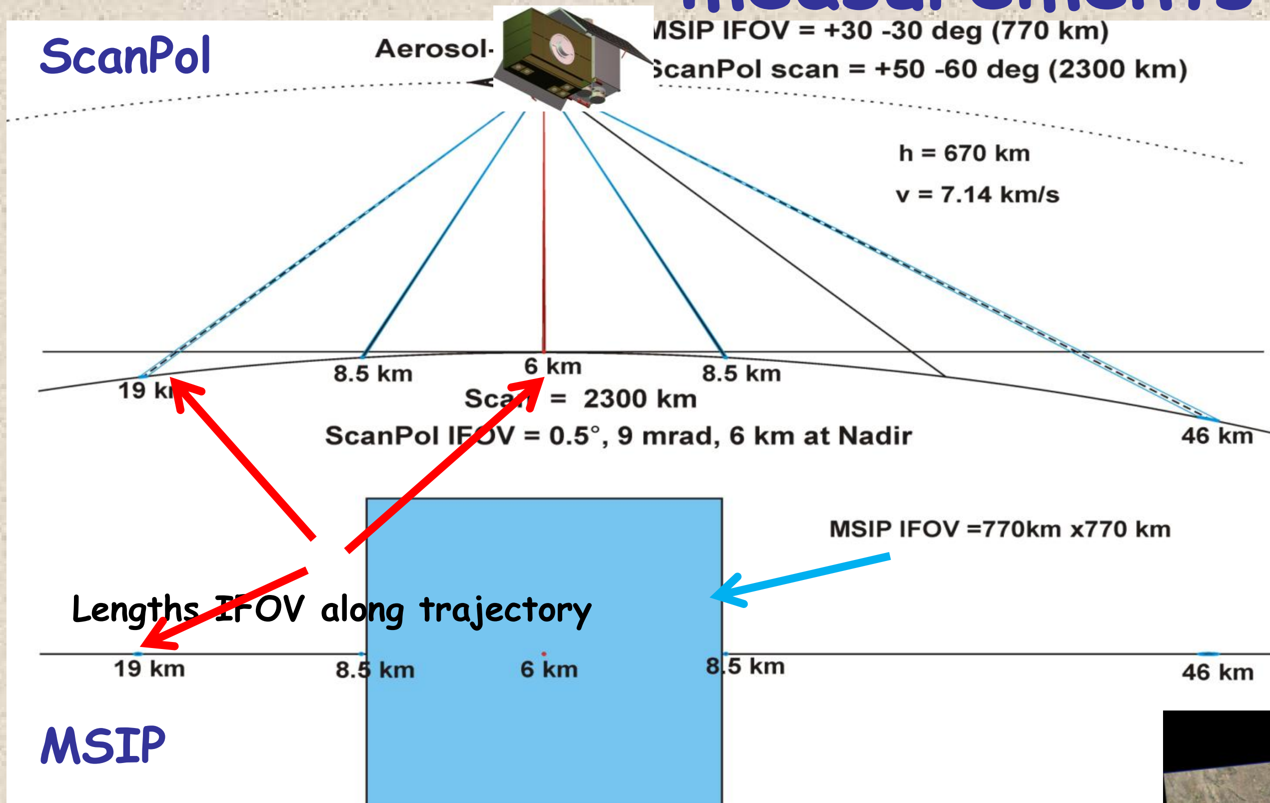
- Polarization is a relative measurement that can be made accurately + many scattering angles.

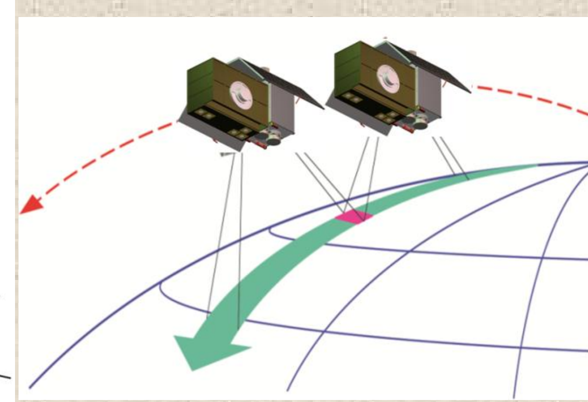
- Polarimetric ScanPol measurements will be calibrated on the orbit.

- Polarization change with scattering angle and wavelength gives microphyscs: size, refractive index and shape of aerosol.

- Synergy of scanner and imager will produce new quality of data, hopefully different from similar aerosol missions.

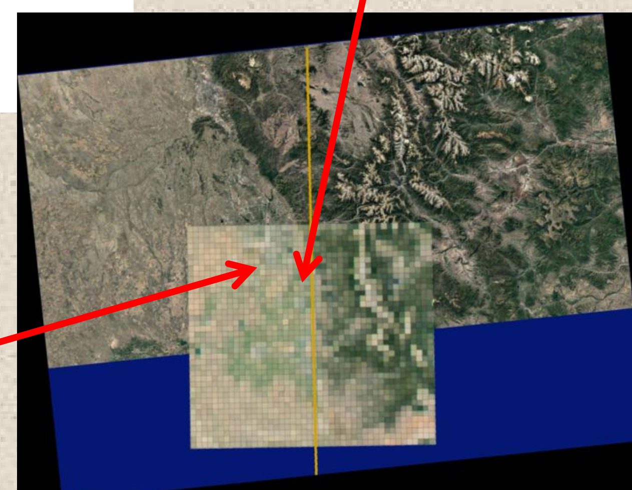
Geometry ScanPol and MSIP measurements





ScanPol track

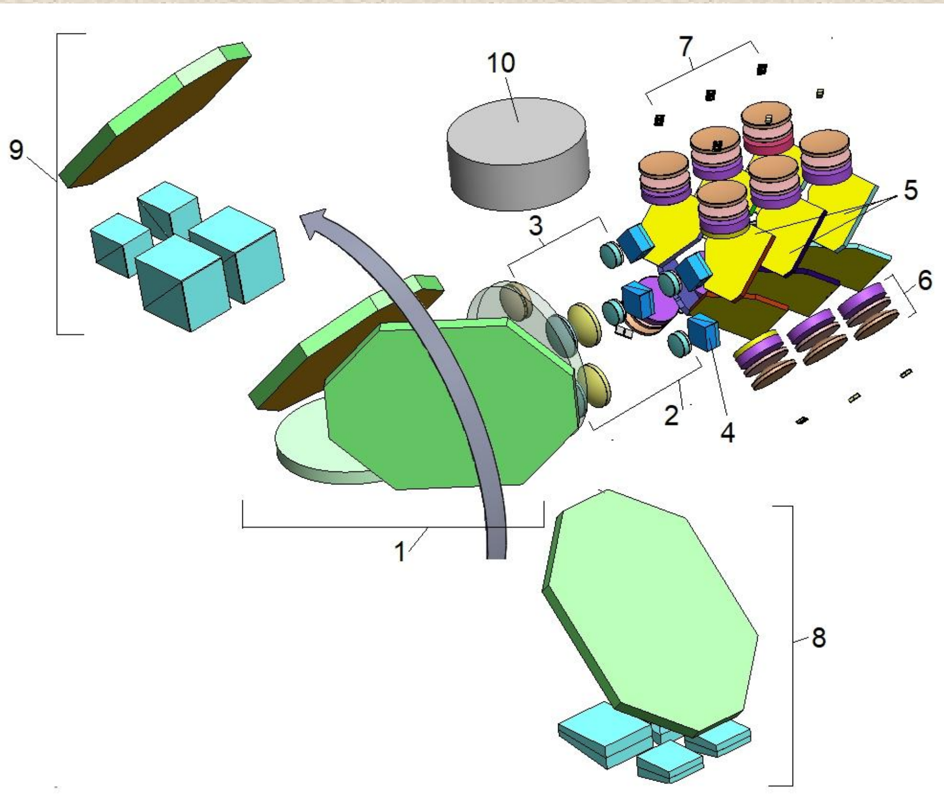
Field-Of-View MSIP and ScanPol



MSIP

ScanPol polarimeter optical design, updated in 2018

Spectral band: 370-1610 nm, six spectral channels:

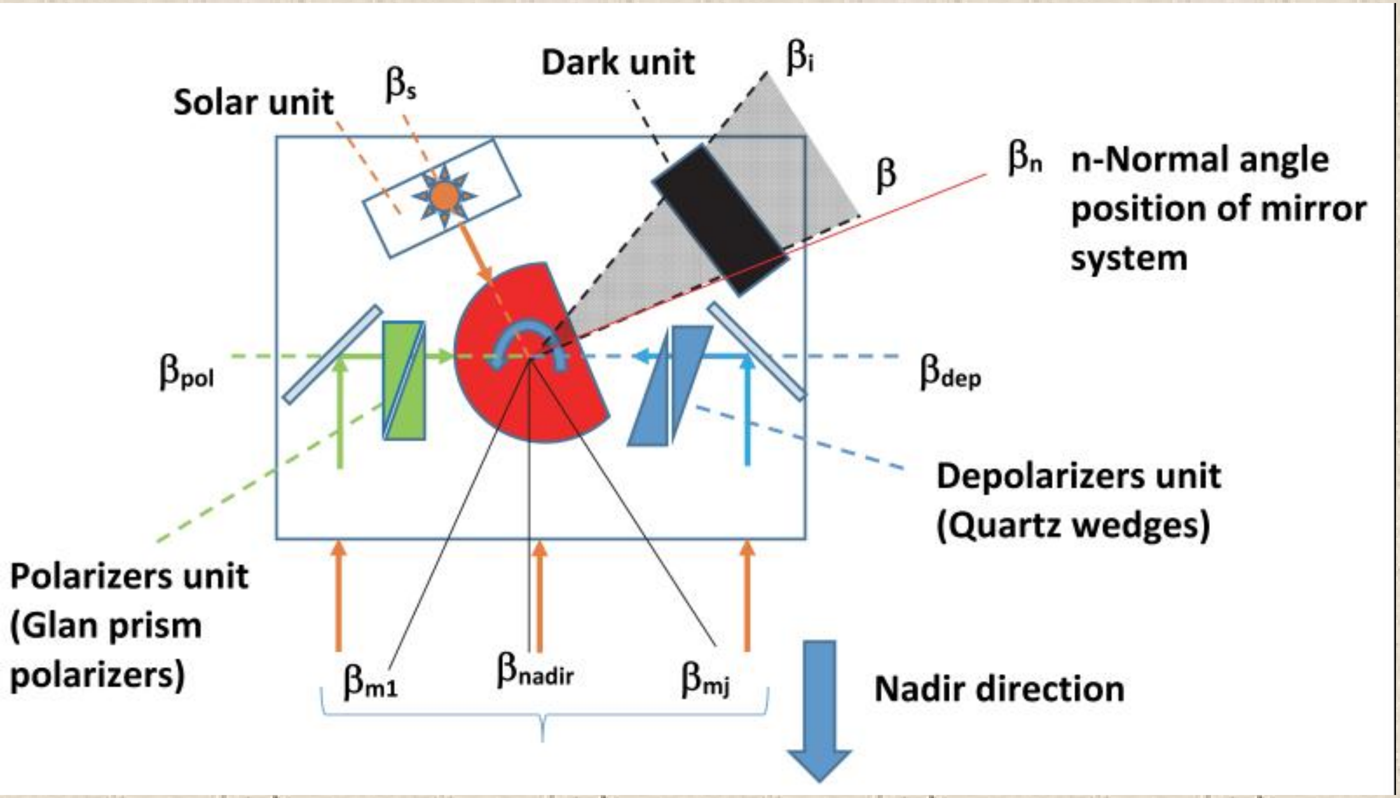


370 nm – tropospheric aerosol and top of clouds
410 nm – aerosol over ocean and surface
555 нм – aerosol over ocean and surface, ocean color
865 nm – aerosol over ocean and surface
1378 nm – separate cirrus clouds, stratosphere aerosol, separation of troposphere and stratosphere aerosol in case of volcanic eruption
1610 nm – separation surface signal from aerosol over Earth' surface
Filter ½ width 20 - 60 nm

Observable Stokes parameters: I, Q, U (0,90,45,135°)
Photometric accuracy: 4%
Polarimetric accuracy: 0.15%
On-board calibration: all three Stokes parameters

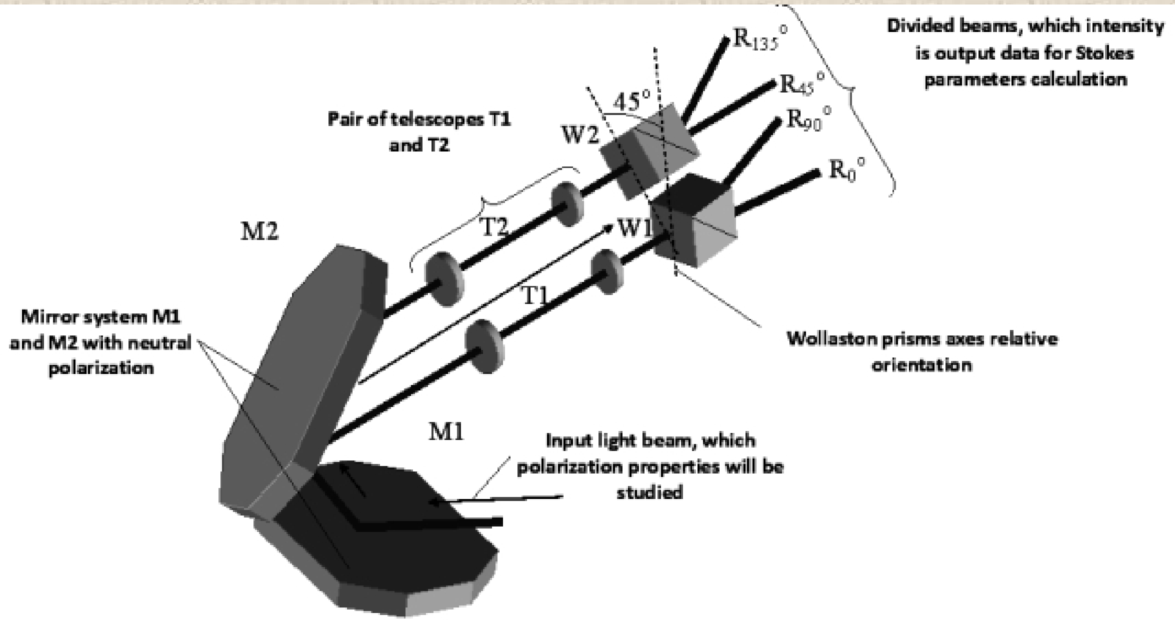
ScanPol is similar to APS Glory

ScanPol polarimeter calibration model



The scan mirrors and calibration units layout of the ScanPol instrument: red segment is scan mirrors with rotation direction shown; blue element is quarts wedges of the depolarization unit seen at β_{dep} angle; green element is the Glan prism polarizer unit seen at β_{pol} angle, black element is the dark unit seen between β_0 and β_i angles; solar calibration unit seen at β_s angle. Scanning directions along-track between scan angle β_{m1} = +50° and β_{m2} = –60° from nadir (β_{nadir}).

ScanPol polarimeter laboratory test

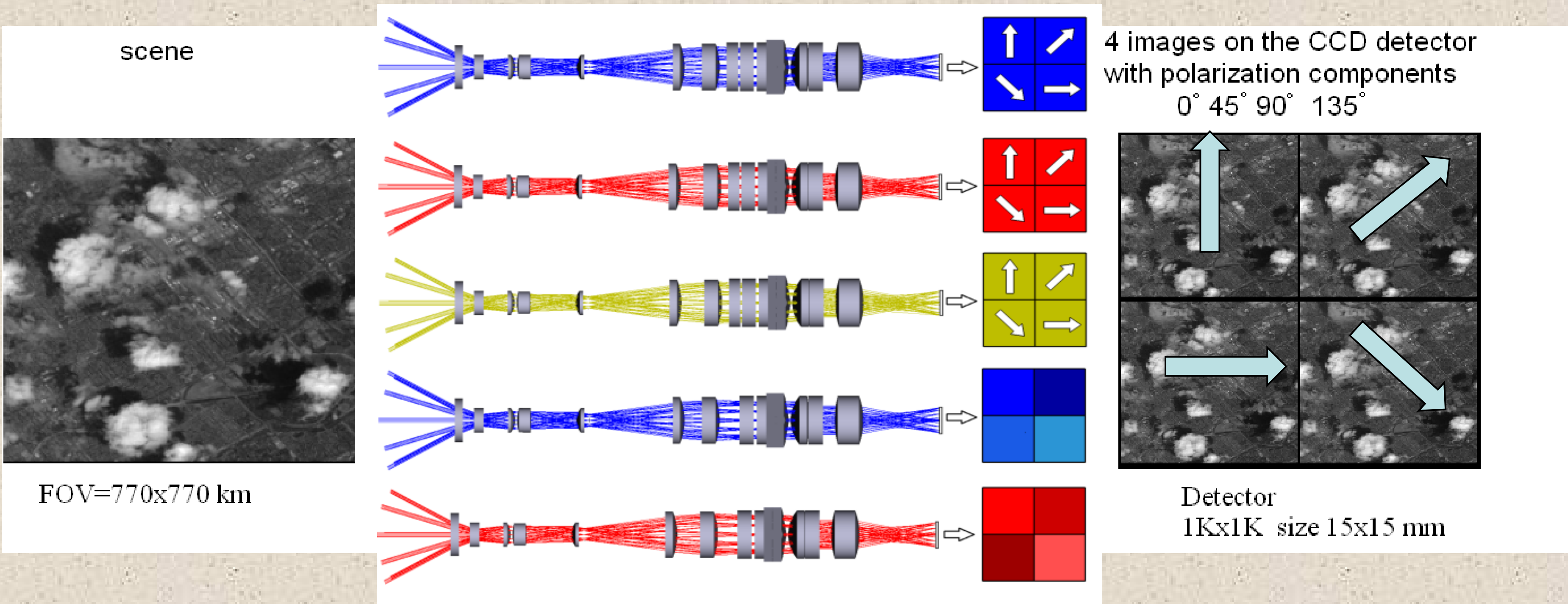


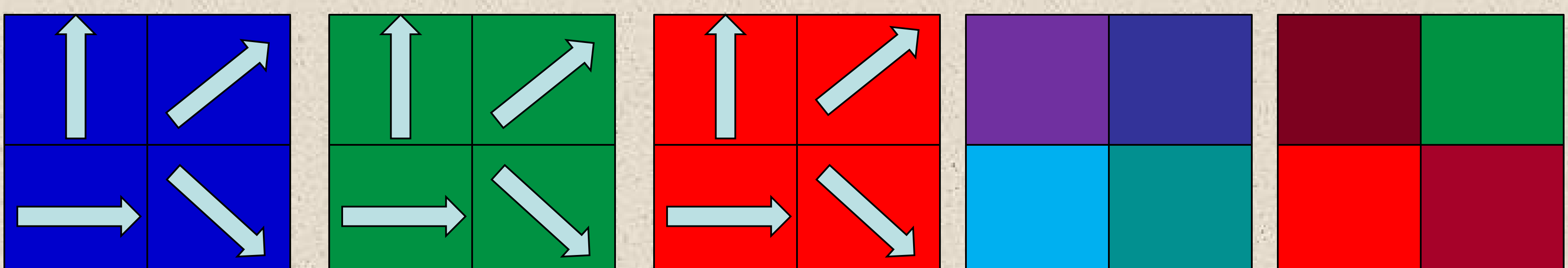
Equivalent polarization scheme of the ScanPol polarimeter single spectral channel: scan mirrors M1 and M2, telescopes T1 and T2, Wollaston prisms W1 and W2, intensity signals $R_{0°}$, $R_{45°}$, $R_{90°}$, and $R_{135°}$.

Multi-Spectral Imager-Polarimeter (MSIP)

- MSIP main purposes: aerosol/clouds parameters measurements and aerosol - clouds separation
- Three spectral polarimetric channels: 410, 555, 865 nm 0°, 45°, 90°, 135° polarization each
- Two intensity channels: (1) 410, 443, 470, 490; (2) 555, 670, 865, 910 nm
- Wide FOV: 60°x60°, 770x770 km, resolution 3-6 km
- Images rate 1.5 s^{-1} ÷ 6.0 s^{-1} (dependent on data rate transmission), exposure <0.5 s
- Intercalibration of the MSIP using ScanPol scans, <1% accuracy

MultiSpectral Imaging Polarimeter MSIP





Polarization 0°, 45°, 90°, 135°

410 nm 555 nm 865 nm

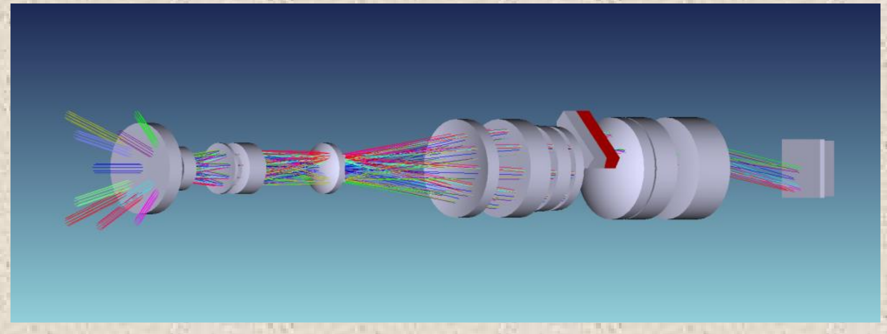
Overall 20 Sp/Pol channels

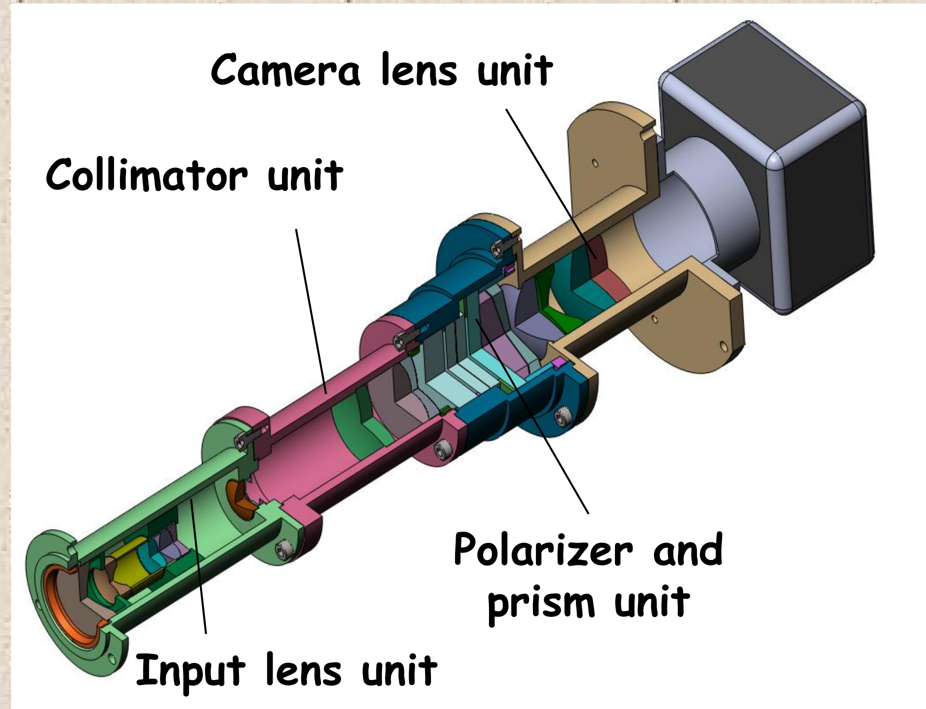
Intensity

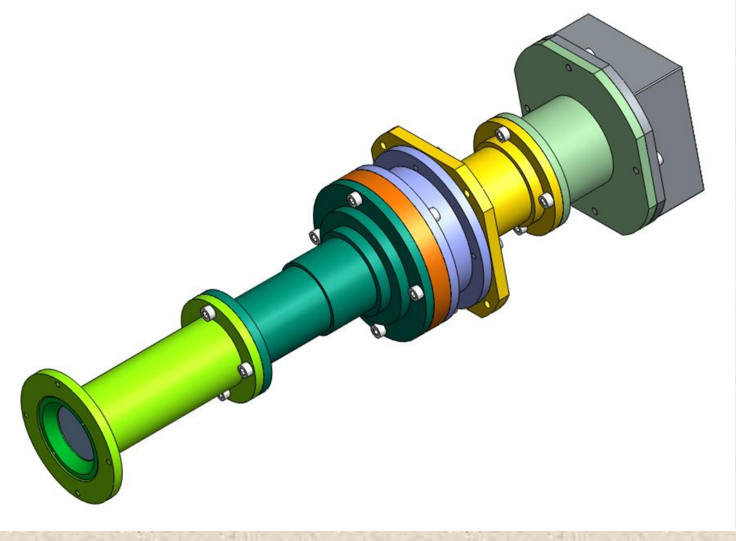
410+443+470+490 nm

555+670+865+936 nm

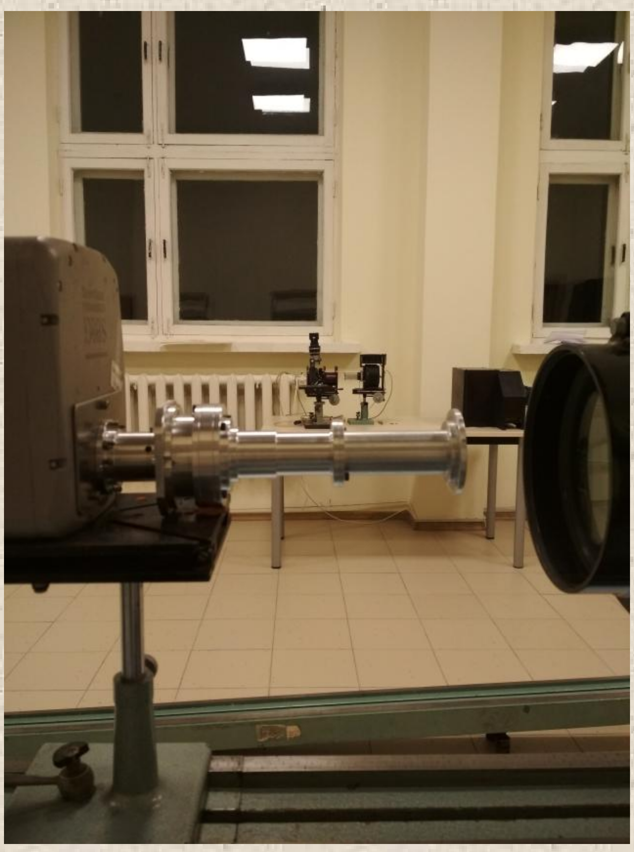
MSIP optical channel

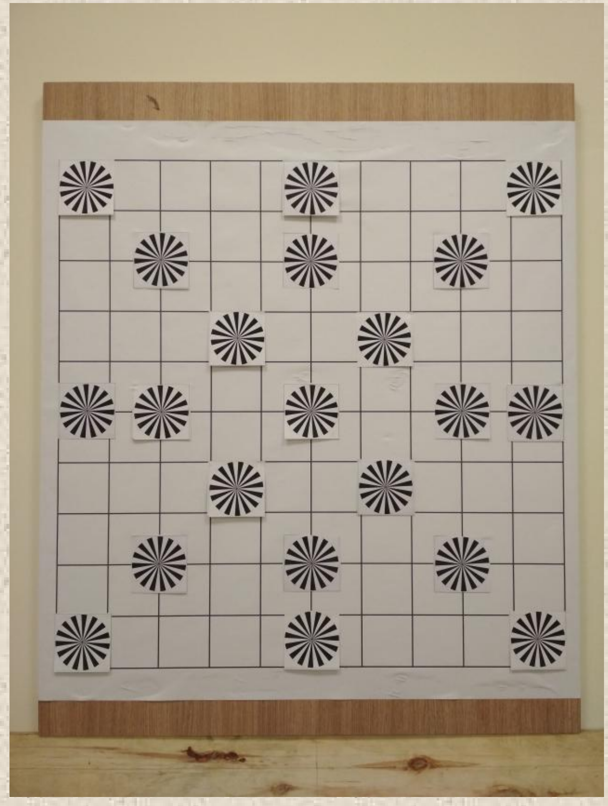


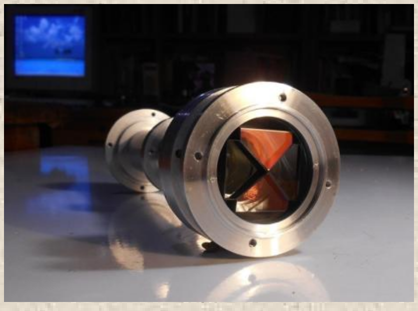




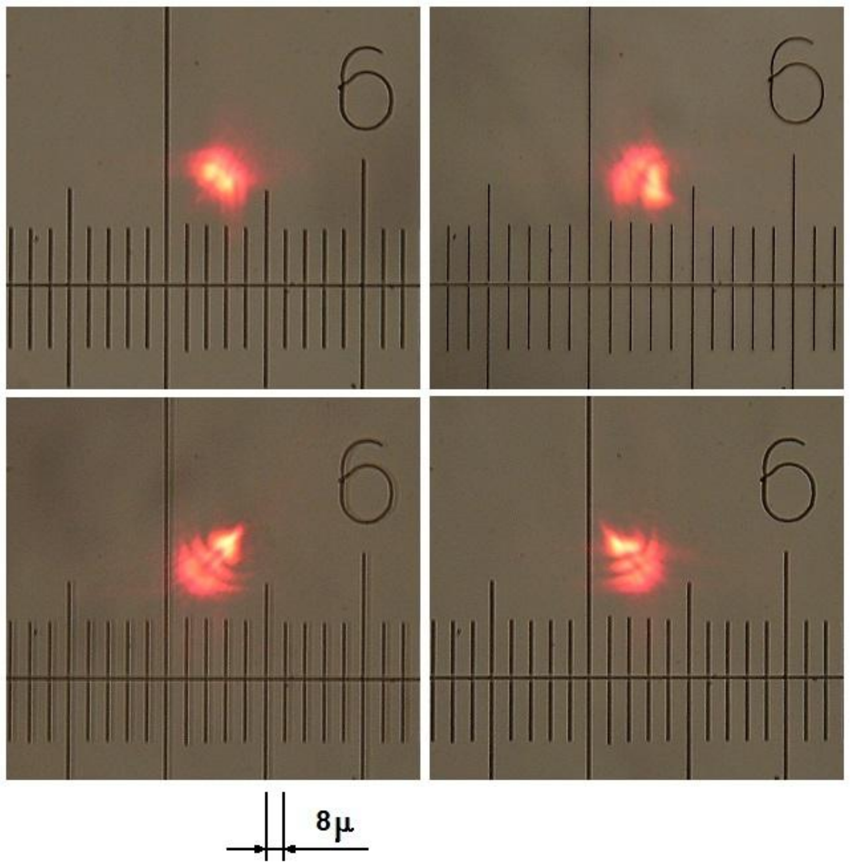
MultiSpectral Imaging Polarimeter test measurements



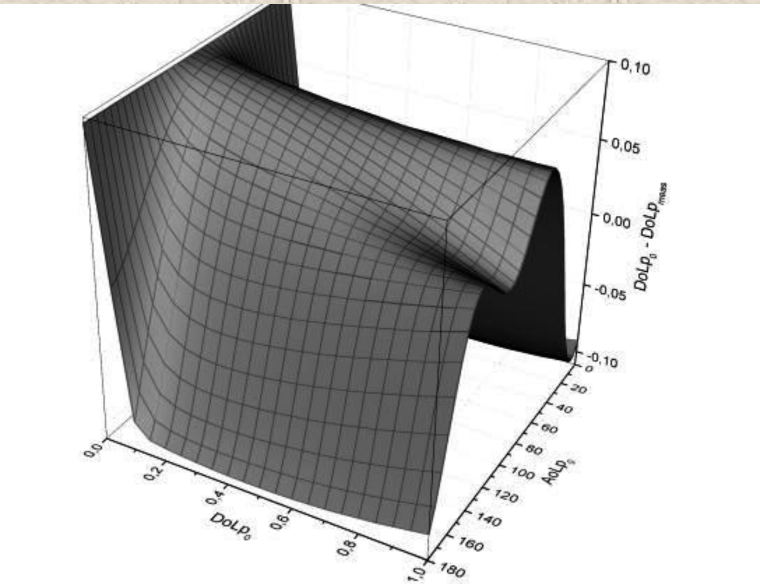




MultiSpectral Imaging Polarimeter test measurements

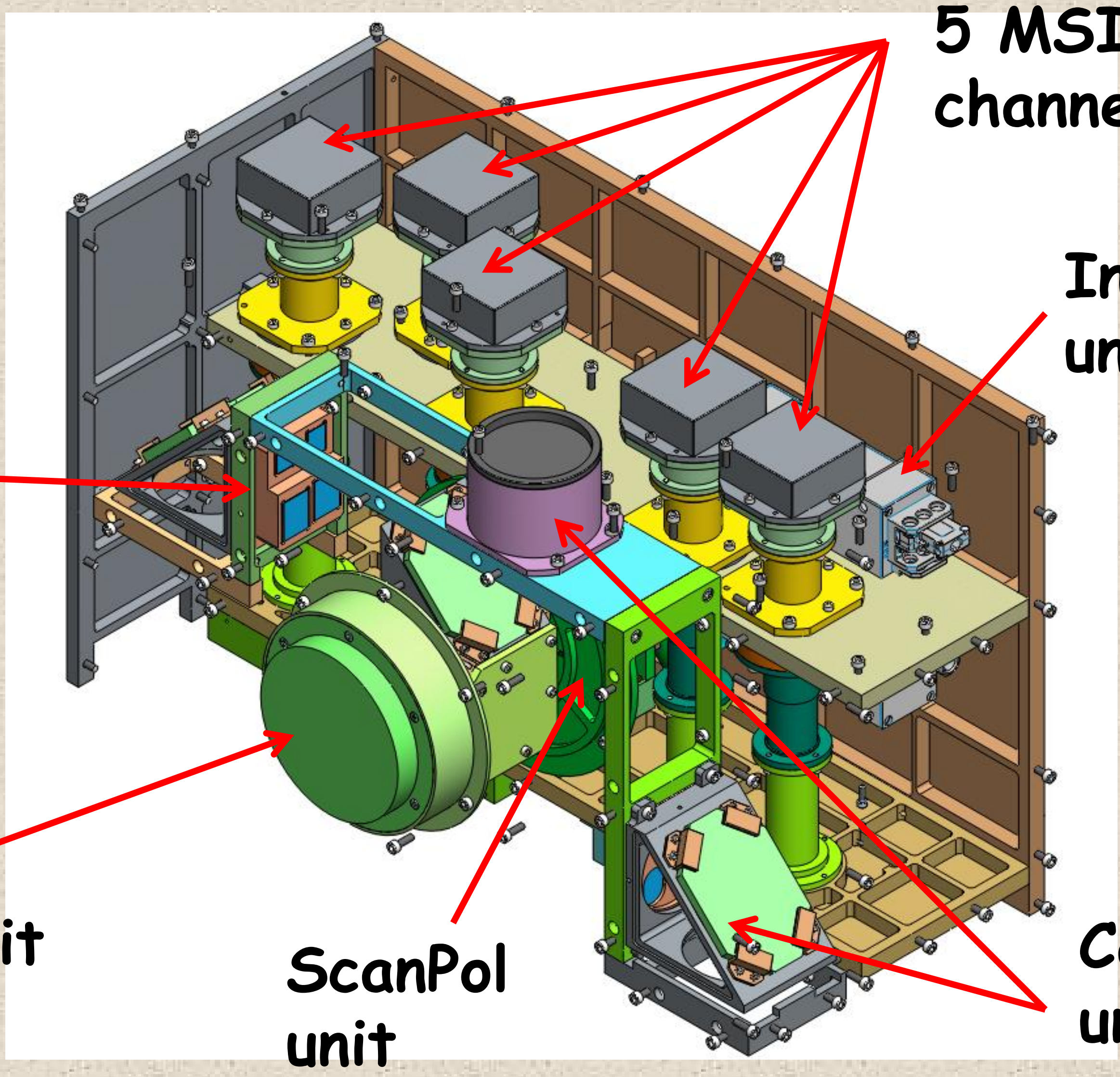


Four images size in MSIP from the dot source

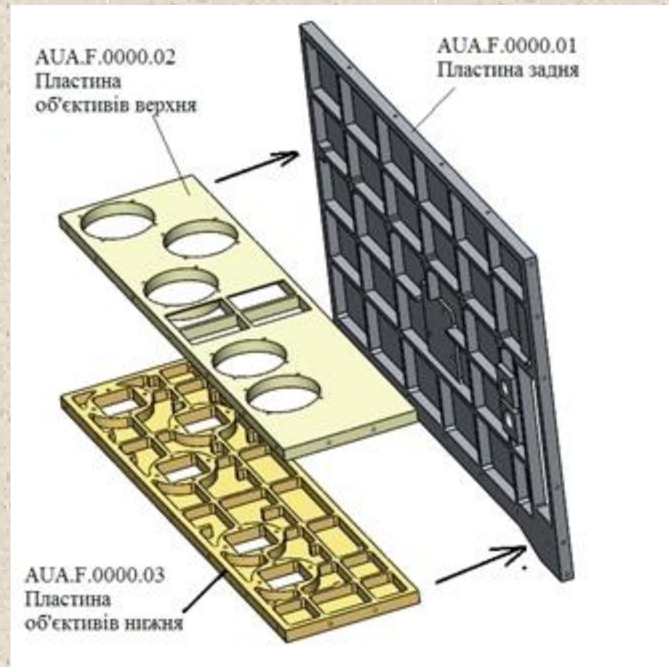


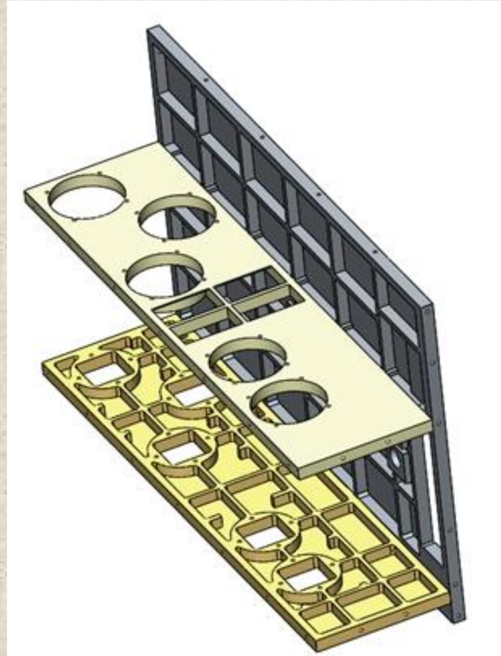
DoLP errors for MSIP test field registration

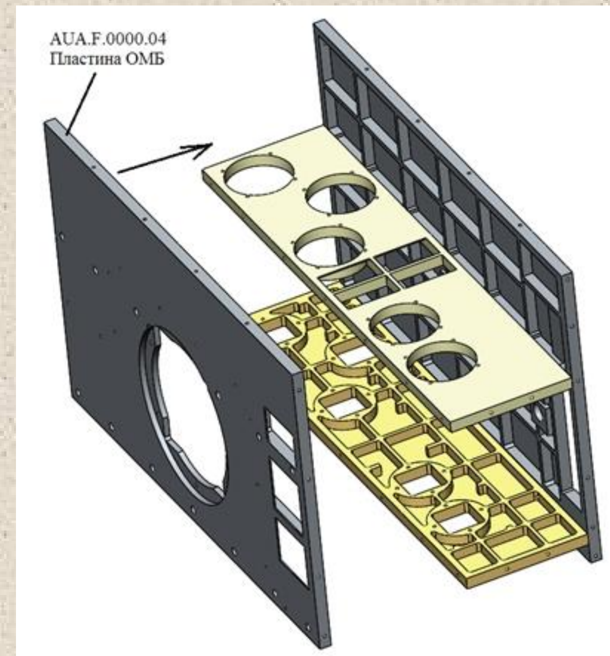
ScanPol and MSIP polarimeters: adaptation to YuzhSat platform

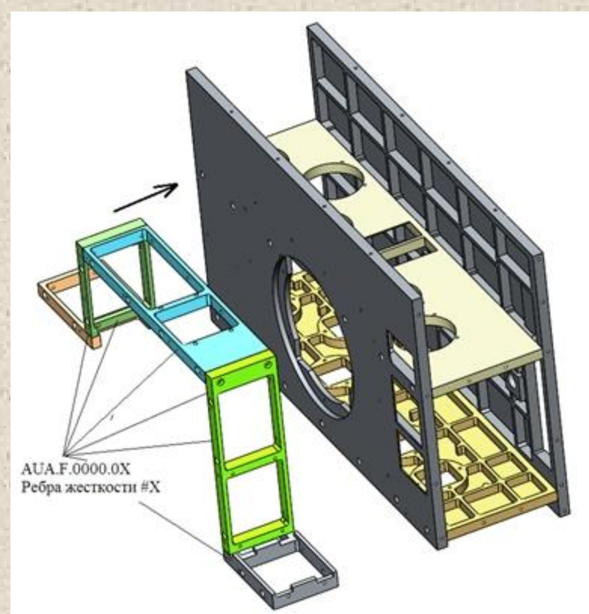


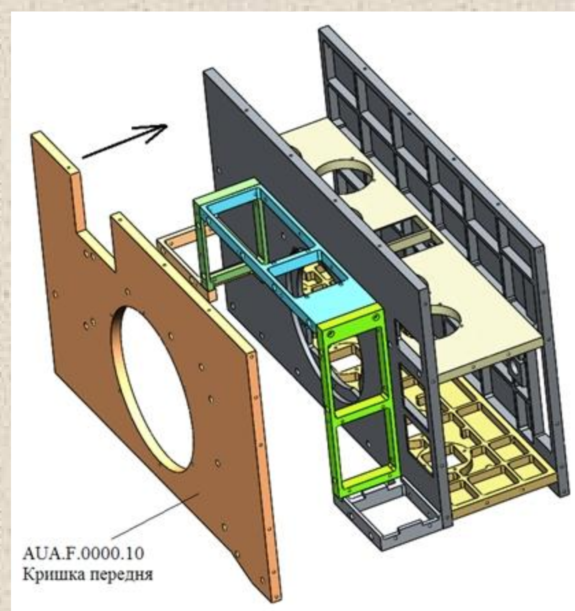
Assembling of ScanPol and MSIP details - 1

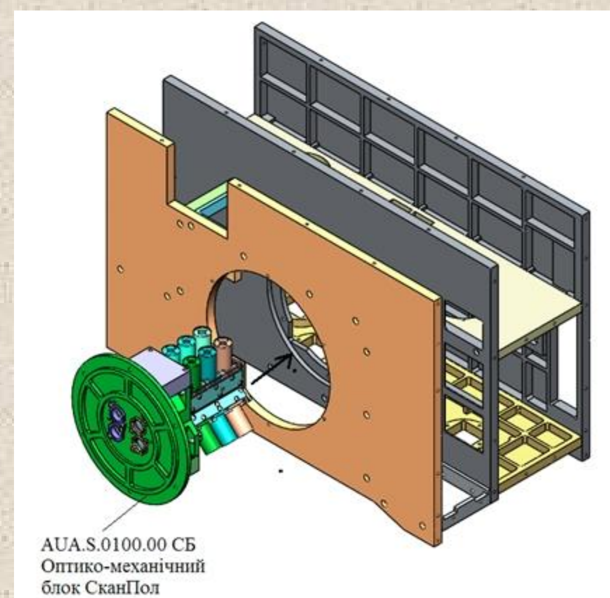




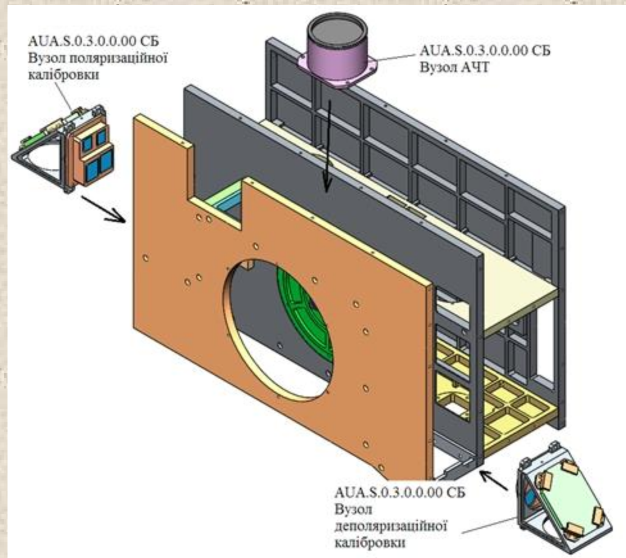


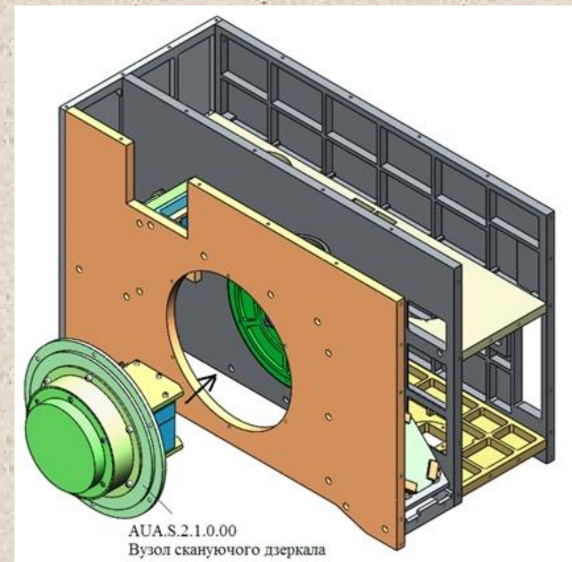


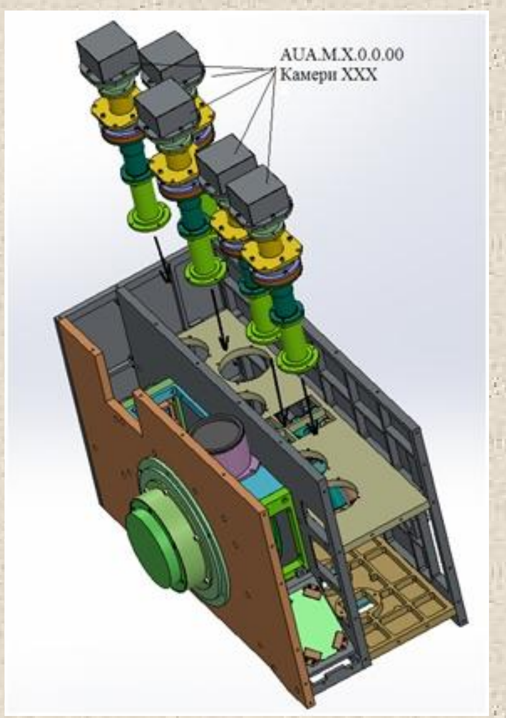


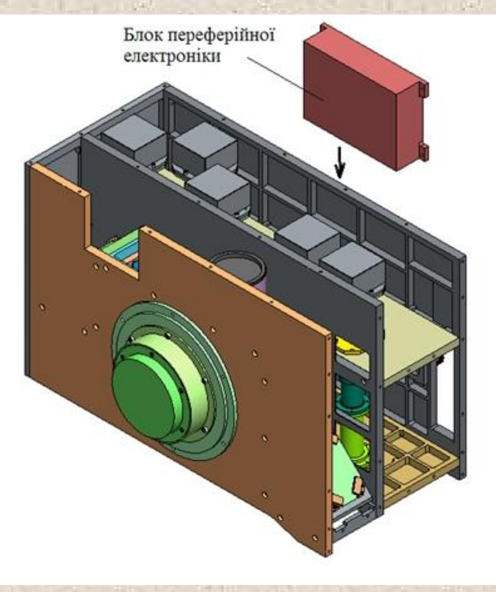


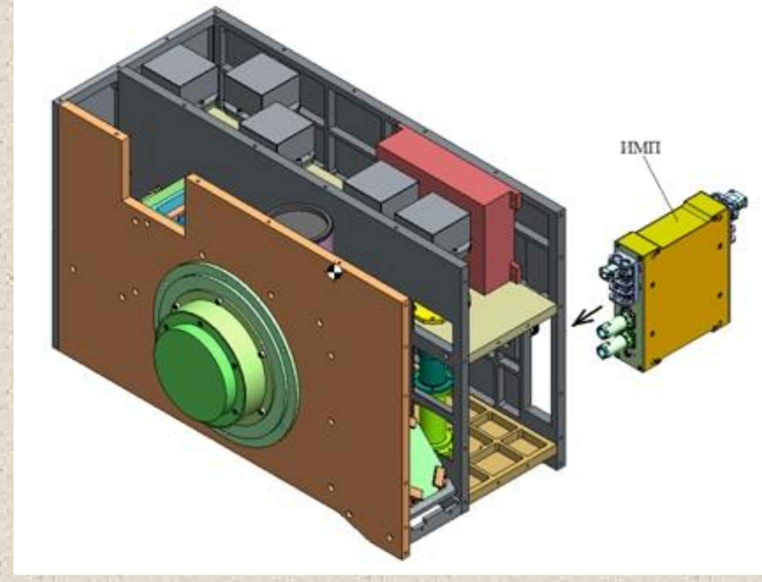
Assembling of ScanPol and MSIP details - 2

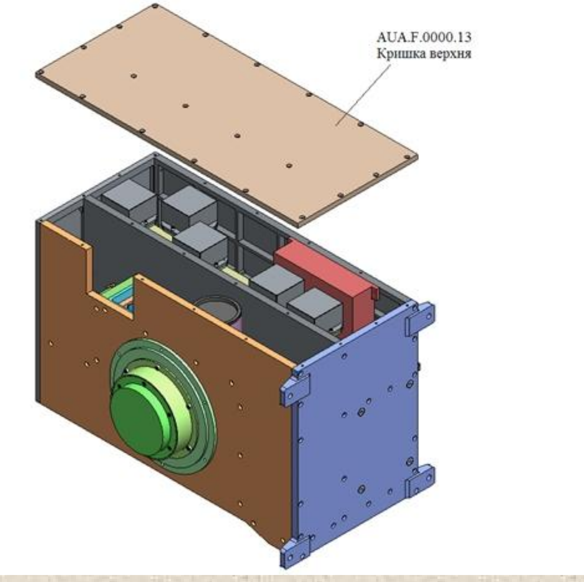




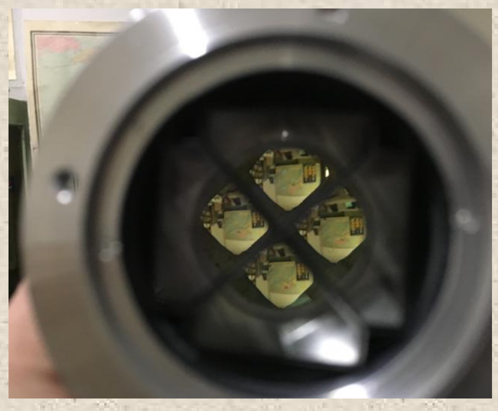








Aerosol-UA dimension-dynamical model and channel of MSIP polarimeter, 2018



MSIP polarimeter channel test, and splitted image

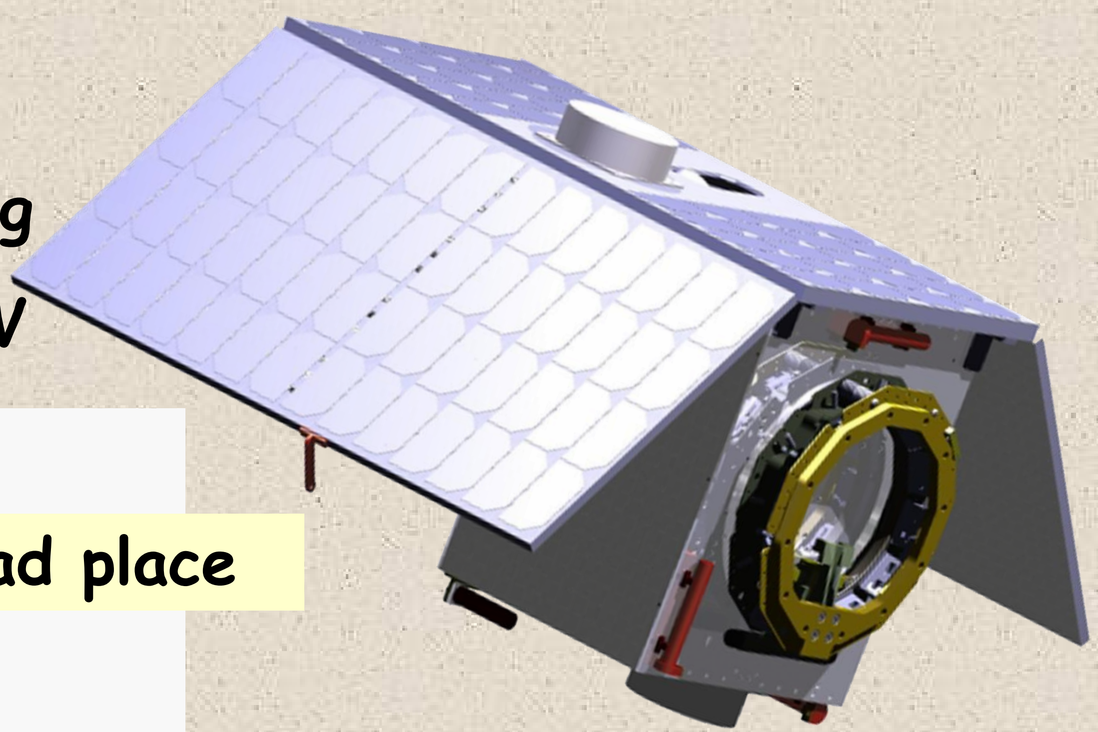
Dimension-dynamical model

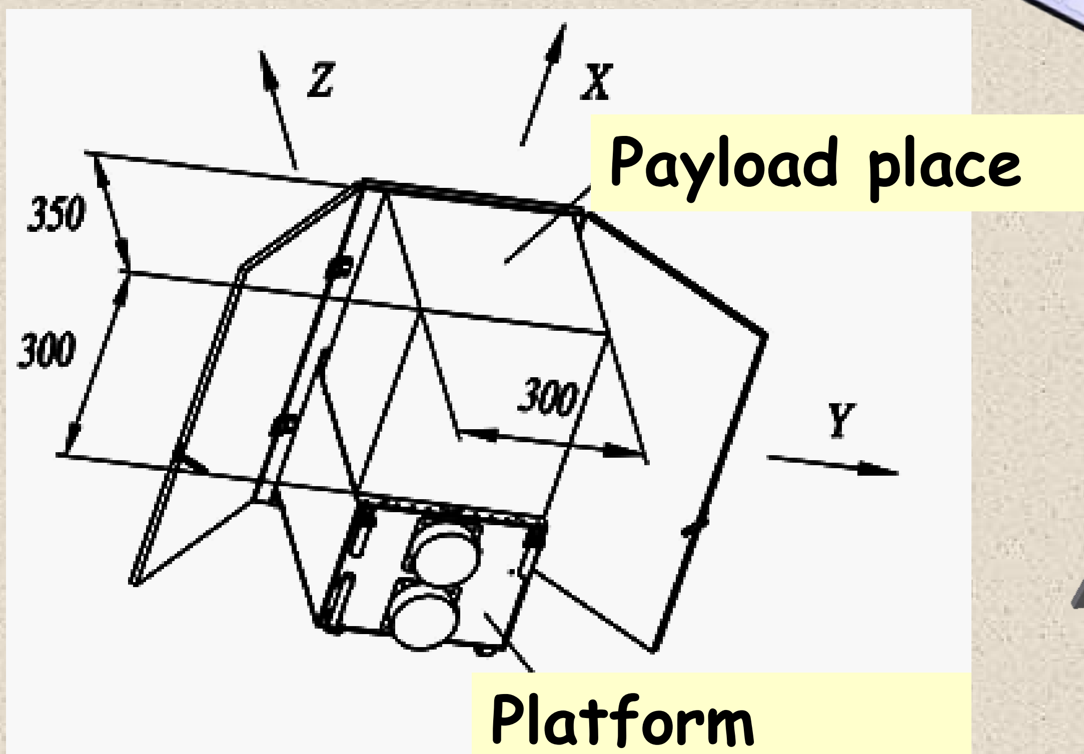
YuzhSat orbital platform for research payload DB "Yuzhnoe"

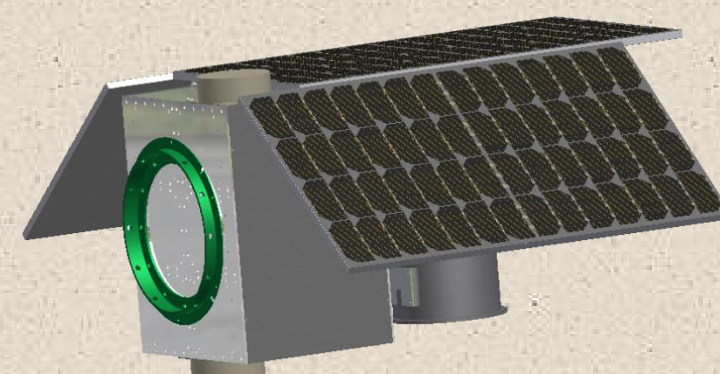
Payload mass 10-25 kg

Platform mass – 15-30 kg

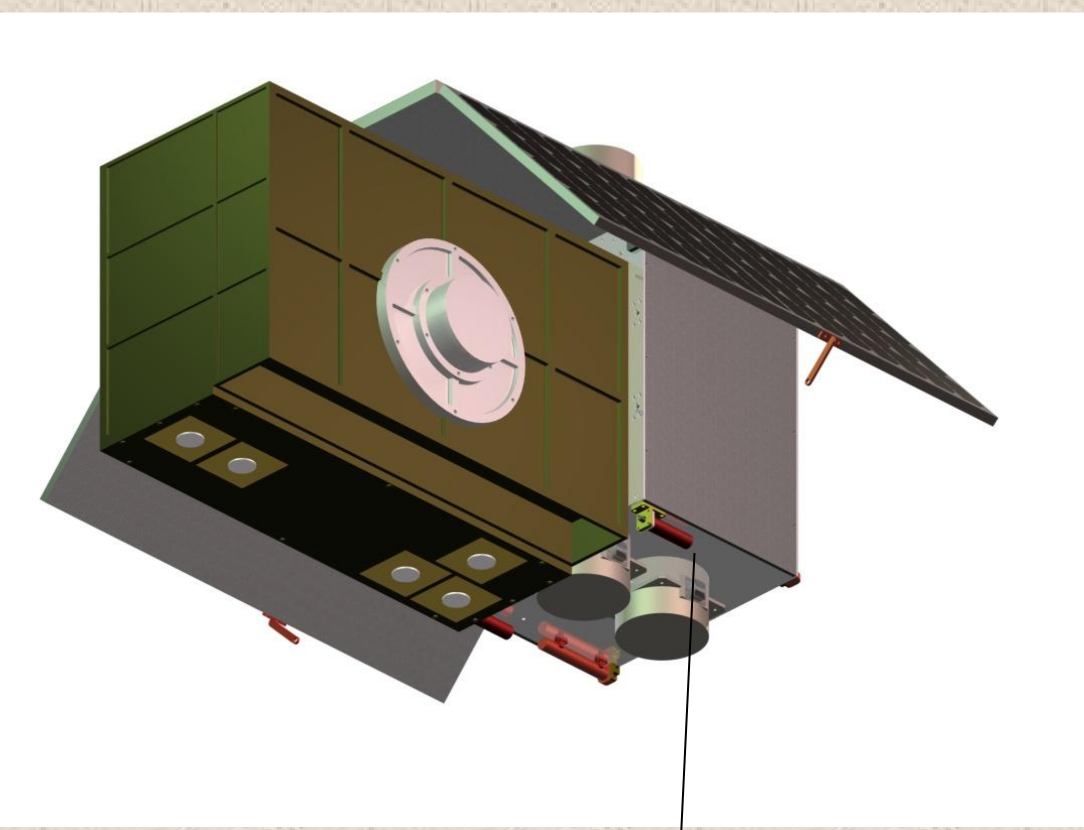
Payload power – 20-80 W







ScanPol and MSIP polarimeters onboard of YuzhSat platform



Small satellite platform YuzhSat designed by Design Bureau "Yuzhnoe"

Characteristics of payload

<u>Orbit</u>

Type: sun-synchronous

Inclination: ~98°

Altitude: ~705 km

<u>YuzhSat platform:</u>

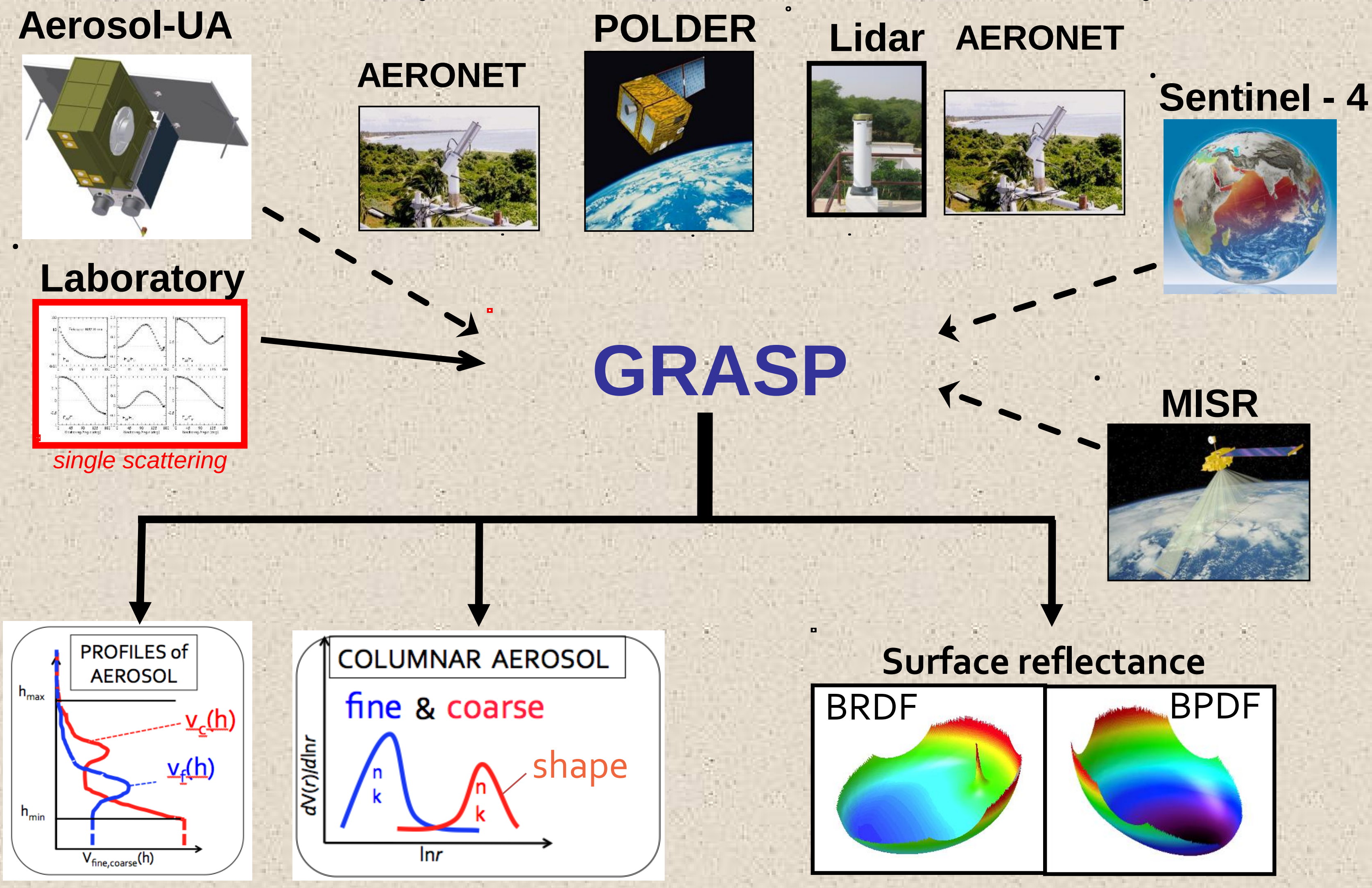
Pointing accuracy: ~0.1°

Total mass of scientific payload estimated: ~22 kg

Power for payload: ≤ 25 W

Design life: >3 years

Data processing: Generalized Retrieval of Atmosphere and Surface Properties



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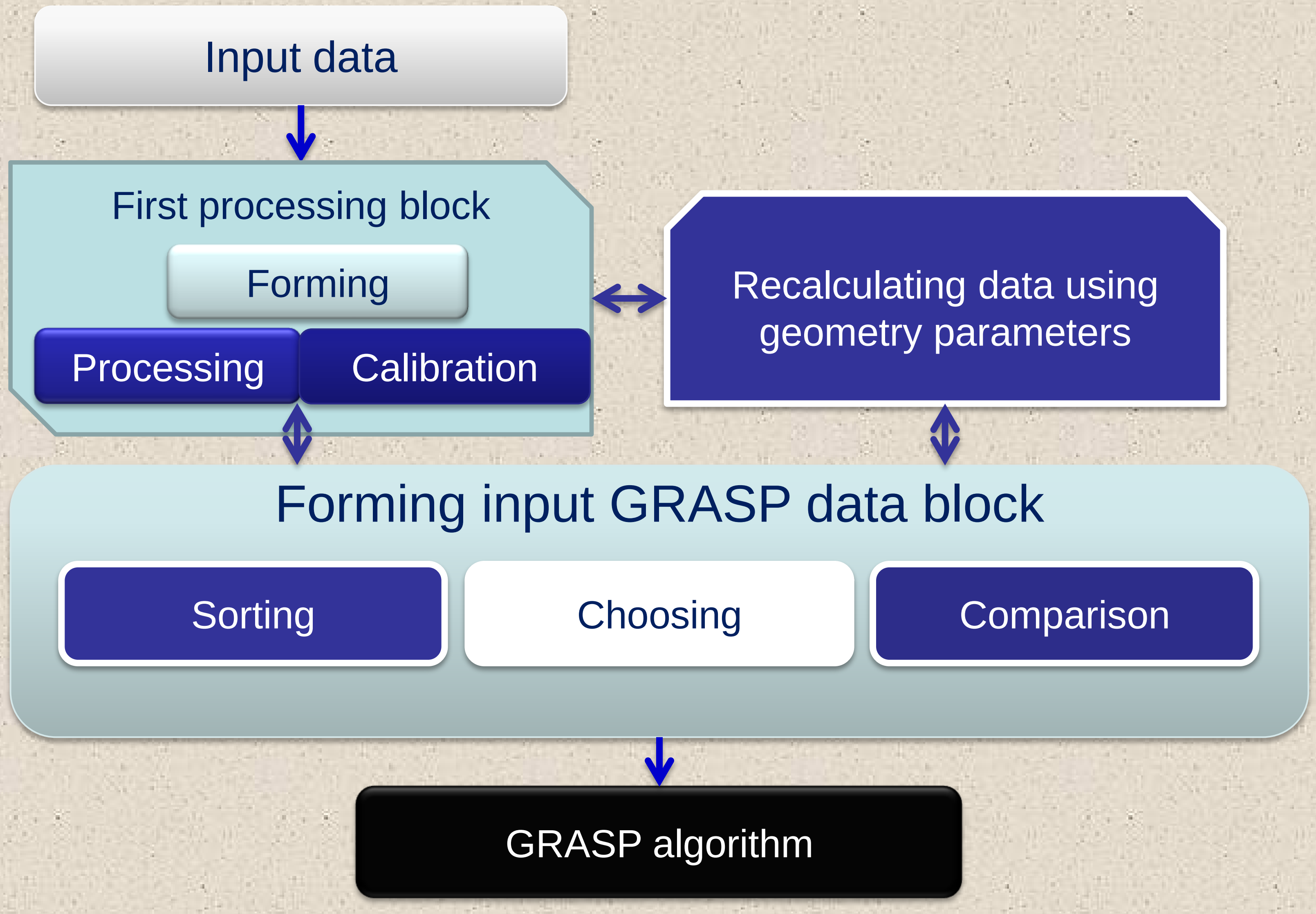
MSIP data processing scheme



Polarimetric modeling and calibration of the Aerosol-UA space mission instruments

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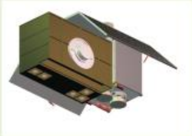


Introduction. We develop the numerical polarimetric models for the ScanPol polarimeter and the multi-spectral imager polarimeter MSIP, which are main instruments for the Aerosol-UA space mission (Milinevsky et al. 2016). Calibration of instrumental polarization under realistic parameters for elements of the ScanPol polarimetric channel is described. We use self consistent way to describe polarization systems by using the Stokes-Mueller formalism. In the model we also include possible misalignment in orientations of polarization axes of prisms, finite extinction ratios of prisms, polarization imperfections of telescopes and inequality in isotropic transmittance of intensity channels. Numerical experiment has demonstrated that proposed calibration procedure for ScanPol polarimeter can minimize influence of instrumental effects on determination of desired Degree of Linear Polarization (DOLP) and Angle of Linear Polarization (AOLP) to 0.2% and 0.1° respectively. Similar basic model has been developed for calibration of the MSIP imager polarimeter using ground-based calibration approach.

1 ScanPol polarimeter

ScanPol is the multi-channel scanning polarimeter with six solar reflectance spectral bands that measure the first three Stokes parameters. The sensor is designed to acquire spatial, temporal, and spectrapolarimetric measurements simultaneously to minimize instrumental "parasitic" effects and effects of "false" polarizations. Simultaneity is provided by separation of initial spatial field by pair conjugated telescopes and pair Wollaston prisms which polarization axis are oriented at 45 degrees. One telescope in pair provides simultaneous measurements intensities of the linear polarization components in orthogonal planes at 0° and 90° to the meridional plane of the instrument, while the other measures equivalent intensities in orthogonal planes at 45° and 135°. Polarization–intensity scanning of the ScanPol is achieved by the use of a two-mirror system with the aluminium mirrors oriented in the way when any polarization introduced at the first reflection is compensated for by the second reflection.

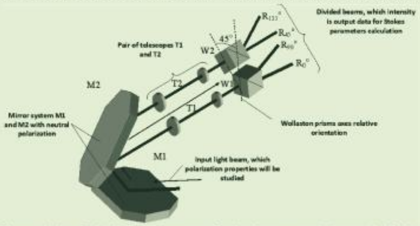


Figure 1.1 – Polarization layout of single spectral channel of the ScanPol instrument

1.1 Orbital calibration algorithm for ScanPol polarimeter data

The ScanPol instrument is the multi-channel scanning polarimeter with six solar reflectance spectral channels (Milinevsky et al. 2016) that measure the first three Stokes parameters *I*, *Q*, *U* of the scene – targeted Stokes parameters:

$S = (I; Q; U; V) = (R_{0°} + R_{90°} = R_{45°} + R_{135°}; R_{0°} - R_{90°}; R_{45°} - R_{135°}; R_R - R_L)$, where values $R_{0°}$ ...$R_{135°}$ are signal flux of the ScanPol channels (raw data from ADC), *q* and *u* are normalized Stokes parameters $q = Q/I$ and $u = U/I$.

DOLP = $p = (q^2+u^2)^{1/2}$, AOLP = θ = 1/2 atan(*u*/*q*), where p is a degree of linear polarization (DOLP), and θ is azimuth angle of the polarization (AOLP) of incoming light.

Generalized equations for connection of the measured values $R_{0°, 90°, 45°, 135°}$ (raw data – digital output from the ScanPol ADC) with the normalized targeted Stokes parameters *q* and *u* of beam light at input window of scanning system of the ScanPol instrument are:

$$\frac{RD_{0°} - K1 \cdot RD_{90°}}{RD_{0°} + K1 \cdot RD_{90°}} = \frac{a_q^{-1}\left[(-q+q_{inst})\cos(2\varepsilon_1) + (-u+u_{inst})\sin(2\varepsilon_1)\right]}{1+q_{inst}q+u_{inst}u}$$
$$\frac{RD_{45°} - K2 \cdot RD_{135°}}{RD_{45°} + K2 \cdot RD_{135°}} = \frac{a_u^{-1}\left[-(-q+q_{inst})\sin(2\varepsilon_2) + (-u+u_{inst})\cos(2\varepsilon_2)\right]}{1+q_{inst}q+u_{inst}u} \qquad (1.1)$$

, where *q* and *u* are targeted normalized Stokes parameters; *R* – raw data from ADC, *D* – black body signal, *RD*=*R*–*D* – corrected ADC data that compensated by zero, *K*1 – calibration coefficient determined by the transmissions ratio in the telescope T1 between corrected raw data from the channels 0° and 90°, *K*2 – for T2: 45° and 135° (see Fig. 1.1), ε_1 and ε_2 – the transmission axes deflection of the first and second Wollaston prisms, q_{inst}, u_{inst} – stray parameters, which are additional values to the targeted Stokes parameters *q* and *u*, appeared due to parasitic instrumental polarization of telescopes and mirrors of the ScanPol, a_q, a_u – parameters that includes the stray depolarization of light in the ScanPol channel due to polarizer imperfection and inhomogeneity of anisotropy of the telescopes and mirrors. From equations (1.1) we can calculate the targeted Stokes parameters *q* and *u*:

$$q = \frac{q_{inst}s_2(s_1+u_{inst}\Delta I_{0°,90°}) - (1+u_{inst}^2)(c_2\Delta I_{0°,90°} - s_1\Delta I_{45°,135°}) + c_1 q_{inst}(c_2+u_{inst}\Delta I_{45°,135°})}{s_1s_2 + c_2q_{inst}\Delta I_{0°,90°} + s_2u_{inst}\Delta I_{0°,90°} - q_{inst}s_1\Delta I_{45°,135°} + c_1(c_2+u_{inst}\Delta I_{45°,135°})}$$
$$u = \frac{c_1c_2u_{inst} - (s_2+q_{inst}^2s_2 - c_2q_{inst}u_{inst})\Delta I_{0°,90°} - c_1(1+q_{inst}^2)\Delta I_{45°,135°} + s_1u_{inst}(s_2 - q_{inst}\Delta I_{45°,135°})}{s_1s_2 + c_2q_{inst}\Delta I_{0°,90°} + s_2u_{inst}\Delta I_{0°,90°} - q_{inst}s_1\Delta I_{45°,135°} + c_1(c_2+u_{inst}\Delta I_{45°,135°})} \qquad (1.2)$$

$$c_{1,2} = \cos(\varepsilon_{1,2}) \quad s_{1,2} = \sin(\varepsilon_{1,2}) \quad \Delta I_{0°,90°} = \frac{RD_{0°} - K1\cdot RD_{90°}}{RD_{0°} + K1\cdot RD_{90°}}a_q \quad \Delta I_{45°,135°} = \frac{RD_{45°} - K2\cdot RD_{135°}}{RD_{45°} + K2\cdot RD_{135°}}a_u$$

Therefore, after determining calibration coefficients for measurement channel of ScanPol instrument we can retrieve the targeted polarization Stokes parameters for input light beam from equations (1.2).

1.2 Orbital calibration algorithm

The sequence of algorithm for orbital calibration of the ScanPol instrument is following. We determine the mean value of "zero" raw data *D* in the polarization channels when mirror system (MS) looks at black body (see Fig. 1.2). Then all ADC raw data obtained at other MS direction angles are corrected by that "zero" value.

Calculation radiometric coefficient A. For direction MS to angle β_s we obtain ADC intensity data from calibrated source for calculation general radiometric calibration coefficient A for in-orbit intensity calibration – that allows to transfer "zero"-compensated raw data from ADC in intensity data according NIST.

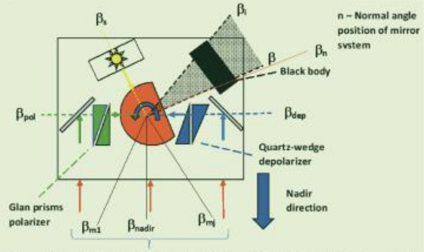


Figure 1.2 – The scanning system layout of the ScanPol instrument

Calibration *K*1 and *K*2 knowing determined previously values q_{inst}, u_{inst} and a_q, a_u. When MS looks at nadir through depolarizer (MS position in β_{dep}, see Fig. 1.2) the value *q*=0 and *u*=0, the equations (1.1) will be simplified:

$$\frac{RD_{0°} - K1 \cdot RD_{90°}}{RD_{0°} + K1 \cdot RD_{90°}} = a_q^{-1}\left[q_{inst}\cos(2\varepsilon_1) + u_{inst}\sin(2\varepsilon_1)\right]$$
$$\frac{RD_{45°} - K2 \cdot RD_{135°}}{RD_{45°} + K2 \cdot RD_{135°}} = a_u^{-1}\left[-q_{inst}\sin(2\varepsilon_2) + u_{inst}\cos(2\varepsilon_2)\right] \qquad (1.3)$$

From (1.3) we obtain refined calibration coefficients *K*1 and *K*2.

Calibration of the stray depolarization coefficients a_q and a_u using refined calibration coefficients *K*1 and *K*2. When MS looks at nadir through polarizer (MS position β_{pol}, see Fig. 1.2) the polarization of incoming beam light is linear with defined azimuth, which value is installed previously during laboratory pre-flight calibration on the ground. Therefore the Stokes parameters of incoming light are known exactly and they are used as calibration coefficients q_{cal} and u_{cal}. Inserting values q_{cal} and u_{cal} into (1.1), we can find two parasite depolarization calibration parameters a_q and a_u, knowing other calibration values:

$$a_q = \frac{q'_{cal} + q'_{inst}}{\frac{RD_{0°} - K1\cdot RD_{90°}}{RD_{0°} + K1\cdot RD_{90°}}(1+q_{cal}q_{inst}+u_{cal}u_{inst})}; \quad a_u = \frac{u'_{cal} + u'_{inst}}{\frac{RD_{45°} - K2\cdot RD_{135°}}{RD_{45°} + K2\cdot RD_{135°}}(1+q_{cal}q_{inst}+u_{cal}u_{inst})};$$

The Glan polarizer prisms will be used for calibration, which orientation at 22.5° angle in relation to Wollaston prism (see Fig. 1.2) because in that case the calibration Stokes parameters will be:

$$q_{cal} = \cos(2\cdot\pi/8) = \frac{\sqrt{2}}{2}, \quad u_{cal} = \sin(2\cdot\pi/8) = \frac{\sqrt{2}}{2}.$$

Calculation of polarization parameters of the scene are made by equation (1.3). The degree of linear polarization (DOLP) and azimuth of linear polarization (AOLP):

$$\mathrm{DOLP} = p = \sqrt{q^2+u^2} \quad \mathrm{AOLP} = \theta_{real} = \frac{1}{2}arctg\left(\frac{u}{q}\right) - \theta_{TMS}$$ where $\theta_{TMS} = 90° - \beta_{nadir}$

because the azimuth of polarization is rotated synchronously with scanning system MS.

2 MultiSpectral Imager-Polarimeter MSIP

The multispectral wide-angle imager–polarimeter MSIP will collect images on the state of the atmosphere and surface in the area, where the ScanPol polarimeter will measure. MSIP consists of five optical channels with field of view 60°x60°. Three channels are polarizing and two are photometric. Polarizing channels measure Stokes parameter *I*, *Q*, and *U* of scene image with central wavelength 410 nm, 555 nm, and 865 nm. Two photometric channels of the MSIP will serve to obtain image in eight spectral wavebands to retrieve the aerosol optical depth in wavelength 410 nm, 443, 470, 490, 555, 670, 865, and 910 nm (Fig. 2.1).

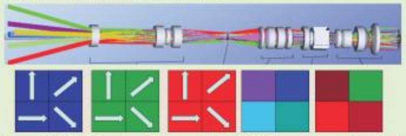


Figure 2.1 – Optical layout concept for MSIP imager-polarimeter: the light path in one optical channels (top) and fields-of-view of five MSIP polarimeter channels – three polarimetric and two intensity.

The MSIP spatial resolution is 6 km in the projection on the Earth surface, which corresponds to the instantaneous field of view of ScanPol polarimeter. The number of phase angles for measuring the single observation area is at least 15.

2.1 Multispectral imager-polarimeter MSIP layout

In the paper (Sinyavskii et al. 2013) the concept of the imager-polarimeter optical layout design has been proposed. The design allows measuring the Stokes vector components simultaneously in wide field of view without limitations by f-number of an optical system.

The optical system of MSIP (see Fig. 2.2) consists of collimator (1), composited polarizing element (2), and system of separation image to four images (4), camera lens (6) and image sensor (7).

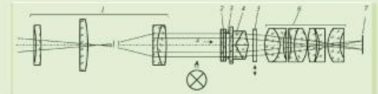


Figure 2.2 – The optical system of MSIP (one channel). A – view to input image of four polarized films with polarization angles 0°, 45°, 90°, 135°.

In Figure 2.3, the main elements of one MSIP channel which influences on quality of measuremets of polarization parameters p and θ are shown.

2.2 Telescope polarization parameters

Telescope T (collimator) is shown in Fig. 2.3, which lens could have areas with mechanical tensions that produce birefringence. We can expect that mechanical tension in telescope lens will not add the depolarization in the pixel area of the image sensor in MSIP channel. The Mueller matrix (see ex. Mishchenko et al. 1999) of the telescope in each pixel (*i*, *j*) will be:

$$\mathbf{M}_{T(i,j)} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos^2(2\alpha_{T(i,j)}) + \sin^2(2\alpha_{T(i,j)})\cos(\delta_{T(i,j)}) & \cos(2\alpha_{T(i,j)})\sin(2\alpha_{T(i,j)})(1-\cos(\delta_{T(i,j)})) & \sin(2\alpha_{T(i,j)})\sin(\delta_{T(i,j)}) \\ 0 & \cos(2\alpha_{T(i,j)})\sin(2\alpha_{T(i,j)})(1-\cos(\delta_{T(i,j)})) & \sin^2(2\alpha_{T(i,j)}) + \cos^2(2\alpha_{T(i,j)})\cos(\delta_{T(i,j)}) & -\cos(2\alpha_{T(i,j)})\sin(\delta_{T(i,j)}) \\ 0 & -\sin(2\alpha_{T(i,j)})\sin(\delta_{T(i,j)}) & \cos(2\alpha_{T(i,j)})\sin(\delta_{T(i,j)}) & \cos(\delta_{T(i,j)}) \end{pmatrix}$$

where δ is phase shift and α – birefringence axes position.

2.3 Polarization parameters of analyzers (polarizing films)

Next group of elements in Figure 2.3 that impact on quality of polarization properties of scene are four polarizing films (analyzers). Each of polarizing film described by Mueller matrix of analyzer (A):

$$\mathbf{M}_A = \frac{1+e}{2}\begin{pmatrix} 1 & \frac{1-e}{1+e}\cos(2\alpha_A) & \frac{1-e}{1+e}\sin(2\alpha_A) & 0 \\ \frac{1-e}{1+e}\cos(2\alpha_A) & \cos^2(2\alpha_A) + 2\frac{\sqrt{e}}{1+e}\sin^2(2\alpha_A) & \frac{(1-\sqrt{e})^2}{1+e}\cos(\alpha_A)\sin(\alpha_A) & 0 \\ \frac{1-e}{1+e}\sin(2\alpha_A) & \frac{(1-\sqrt{e})^2}{1+e}\cos(2\alpha_A)\sin(2\alpha_A) & 2\frac{\sqrt{e}}{1+e}\cos^2(\alpha_A) + \sin^2(\alpha_A) & 0 \\ 0 & 0 & 0 & 2\frac{\sqrt{e}}{1+e} \end{pmatrix}$$

where $e = \frac{t_\perp}{t_\parallel}$ – polarizer transmission relation. Value α_A is azimuth of transmission axes of polarizer (analyzer).

In the case, if the axes of the external coordinate system do not correspond to axes of films we should adjust α_A on four small deflection angles ε_1...ε_4 to correct misalignment of the polarizing film angle.

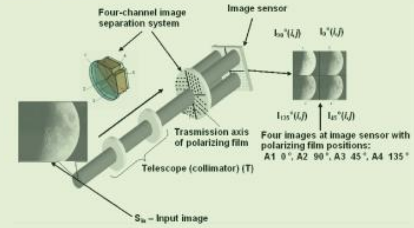
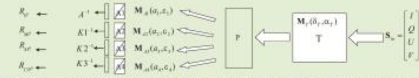


Figure 2.3 – The main elements of MSIP polarization channel.

2.4 Matrix model of MSIP polarizing channel

Considering polarization parameters of optical elements of MSIP (Fig. 2.3) we can compose the chart diagram:



According that diagram we receive equations using Mueller matrix that determine signals *R* from ADC output for input light polarization *S*:

$$R_{0°} = [\mathbf{M}_{A1}(a_1, 0° + \varepsilon_1)\cdot\mathbf{M}_T(\delta_T,\alpha_T)\cdot\mathbf{S}_{scene}]_0 + D_{0°},$$
$$R_{90°} = K1^{-1}\cdot[\mathbf{M}_{A2}(a_2, 90° + \varepsilon_2)\cdot\mathbf{M}_T(\delta_T,\alpha_T)\cdot\mathbf{S}_{scene}]_0 + D_{90°},$$
$$R_{45°} = K2^{-1}\cdot[\mathbf{M}_{A3}(a_3, 45° + \varepsilon_3)\cdot\mathbf{M}_T(\delta_T,\alpha_T)\cdot\mathbf{S}_{scene}]_0 + D_{45°},$$
$$R_{135°} = K3^{-1}\cdot[\mathbf{M}_{A4}(a_4, 135° + \varepsilon_4)\cdot\mathbf{M}_T(\delta_T,\alpha_T)\cdot\mathbf{S}_{scene}]_0 + D_{135°}.$$

Using that approach we can determine Stokes polarization parameters of scene in the pixel area removing instrumental depolarization and polarizing films axes deviation. Intensity at image sensor is $I_{\beta+\varepsilon} = K\,RD_{\beta+\varepsilon}$ and required Stokes polarization parameters of scene are:

$$\begin{bmatrix} I \\ Q \\ U \end{bmatrix} = \begin{bmatrix} 1 & a_1^{-1}\cos(2\varepsilon_1) & a_1^{-1}\sin(2\varepsilon_1) \\ 1 & -a_2^{-1}\cos(2\varepsilon_2) & -a_2^{-1}\sin(2\varepsilon_2) \\ 1 & -a_3^{-1}\sin(2\varepsilon_3) & a_3^{-1}\cos(2\varepsilon_3) \\ 1 & a_4^{-1}\sin(2\varepsilon_4) & -a_4^{-1}\cos(2\varepsilon_4) \end{bmatrix}^{-1} \begin{bmatrix} I_{0°+\varepsilon_1} \\ I_{90°+\varepsilon_2} \\ I_{45°+\varepsilon_3} \\ I_{135°+\varepsilon_4} \end{bmatrix}$$

where a_1...a_4 are scale factors compensating some instrumental depolarization effects.

Conclusions.

The numerical polarimetric models for the ScanPol polarimeter and the imager polarimeter MSIP are developed. The models allow determining the corrections for output signals to improve quality of polarization measurements and provide orbital calibration of ScanPol. The matrix approach describes optical channel polarization and depolarization properties, which can be corrected by groundbased and orbital calibration.

It is expected that the main error sources in ScanPol will be the mirrors and lenses inhomogeneity, mirror inequality, and channels' transmittance inequality. They are lead to errors in DOLP determination. The modelling demonstrates that groundbase calibration reduce the errors up to 10 times.

The main error sources in MSIP are the low extinction ratios polarizing films (partial parasitic transmission), which leads to the DOLP error, misalignment in films' orientations that leads to the AOLP error, and some images mismatches in specific pixels. All these sources can be minimized or compensated during groundbased calibration. Virtually, the orbit MSIP calibration can be partially provided by ScanPol instrument.

The modelling of MSIP calibration is not completed yet, however we expect that MSIP should provide DOLP within error <0.5% and AOLP error <1°.

References

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Conclusions and Timeline

In comparison to the several aerosol polarimetric missions planned for 2019-2021, the Aerosol-UA instrument concept at YuzhSat platform provides synergy of precision scanner-polarimeter and imager-polarimeter

1. Finalizing ScanPol calibration – end 2018
2. Construction of MSIP one channel – end 2018
3. Data processing algorithm – end 2018
4. On flight ScanPol testing – end 2019
5. MSIP construction – 2019