

CALIBRATION AND LINE-OF-SIGHT CHARACTERIZATION OF A SPACBORNE OPTICAL PAYLOAD

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ABSTRACT

This paper presents a detailed characterization and geometric mapping of the Line-of-Sight (LOS) for the spaceborne optical payload which is composed of dual cameras to increase field-of-view of the system. The primary objective of this study is to establish a precise mathematical relationship between the instrument's detector pixels and their corresponding directional vectors in space, thereby ensuring accurate geolocating for the target surface mapping. The method combines two measurement levels that were originally performed in different coordinate frames. At unit level, two optical reference cubes provide an internal instrument frame and an external spacecraft-accessible frame. The relative orientation of the cubes is reconstructed from theodolite measurements and co-collimation data. At system level, a collimator, a hexapod, autocollimators, and theodolites are used to map illuminated detector pixels to LOS angles. Linear regressions show that the azimuth response of both 2048-pixel cameras is essentially linear, while the elevation response reveals small detector-line tilts. Representative LOS vectors are generated for pixels 0, 1024, and 2047, interpolated across each focal-plane line, and transformed from the Cube1 frame into the Cube2 frame for spacecraft-level use. The analysis also identifies the principal limitations of the dataset: only one face of each cube was measured in the inter-cube campaign, and the exact transformation between the Cube1 and rear-autocollimator frames was not directly measured. Three explicit assumptions are therefore required. The reported vectors should be interpreted as the best estimate supported by the available measurements, with dominant alignment uncertainties expected to be on the order of 50 microradians.

Keywords: Line-of-sight, Dual-camera payload, Geometric mapping

1. INTRODUCTION

Accurate knowledge of an imaging payload's line of sight is required to relate detector samples to spacecraft attitude and, ultimately, to surface coordinates. For a push-broom or line-scanning instrument, the calibration problem is not limited to a single boresight vector. It also includes the direction of the detector line, the angular sampling per pixel, the relative alignment of multiple cameras, and the transfer of all instrument-level measurements into a coordinate frame that remains observable after payload integration. These requirements become especially important for space exploration imaging, where navigation and image geolocation depend on a consistent chain from detector coordinates to the spacecraft reference frame.

The Dual Camera Payload (DCP) introduced in this paper is for the Korean space exploration mission. Each camera contains 2048 detector pixels numbered from 0 to 2047. The available flight-model measurement record contains two complementary datasets. The first is a unit-level measurement of the relative orientation between two optical reference cubes. Cube1 represents the internal DCP measurement frame, whereas Cube2 is arranged so that at least two cube faces remain visible at spacecraft level. The second dataset is a DCP-level geometric mapping campaign in which selected detector pixels were illuminated by a collimator while instrument angular motion was monitored by autocollimators and theodolites.

The central challenge is that neither dataset alone provides the final spacecraft-usable LOS. Geometric mapping produces LOS information in, or approximately in, the Cube1 frame. Spacecraft integration, however, requires the LOS in the Cube2 frame because Cube1 becomes only partially visible after integration. The analysis must therefore establish a transformation from Cube1 to Cube2 and then apply that transformation consistently to all pixel LOS vectors.

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The source measurement report also records important incompleteness in the metrology chain. Only the +Z face of each cube was measured during the inter-cube campaign, although two nonparallel faces are normally required to define a complete three-dimensional cube frame. In addition, the geometric mapping campaign did not directly determine the small rotation between Cube1 and the rear-autocollimator frame. The original analysis resolves these gaps with three explicit assumptions. Rather than concealing these assumptions, the present paper treats them as part of the measurement model and discusses how they affect interpretation of the results.

The remainder of this paper is organized as follows. Section 2 describes the reference-cube architecture and the unit-level transfer measurement. Section 3 presents the system-level geometric mapping setup and the construction of pixel LOS vectors. Section 4 summarizes the measured relationships, the Cube1 and Cube2 vector results, the detector-line interpretation, and the expected uncertainty. Section 5 concludes with recommendations for use of the dataset and for future calibration campaigns.

2. UNIT-LEVEL REFERENCE CUBE MEASUREMENT

2.1 Reference-cube architecture

DCP includes two optical reference cubes that serve different stages of alignment verification. Cube1 is defined by the orthogonal axes $[X_{c1}, Y_{c1}, Z_{c1}]$ and is used for instrument-level measurements. Cube2 is defined by $[X_{c2}, Y_{c2}, Z_{c2}]$ and is the external reference intended for spacecraft-level alignment. The mechanical arrangement is driven by visibility after integration. The +Z_{c2} and -X_{c2} faces remain accessible at spacecraft level, whereas only one Cube1 face remains visible. Consequently, Cube1 is suitable for laboratory geometric mapping, but Cube2 is the required delivery frame for the final LOS vectors.

Figure 1 illustrates the relative placement and axis conventions of the two cubes. The geometry is not a simple relabeling of axes; the Cube2 frame is substantially rotated with respect to Cube1. A measured three-dimensional rotation is therefore required before instrument LOS vectors can be used by spacecraft alignment and attitude-reconstruction processes.

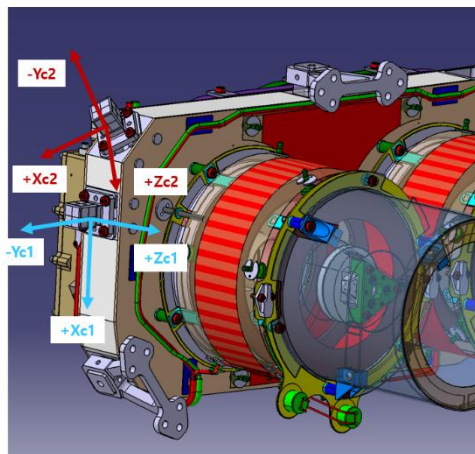


Figure 1. Reference cubes and coordinate directions

2.2 Inter-cube measurement configuration

The relative cube directions were measured with two theodolites. One instrument observed a face of Cube1 and the other observed a face of Cube2. A co-collimation operation established the relative orientation between the two theodolite frames, allowing an observation made by one instrument to be expressed in the frame of the other. This approach forms a transformation chain from Cube1 to the first theodolite, from the first to the second theodolite, and from the second theodolite to Cube2.

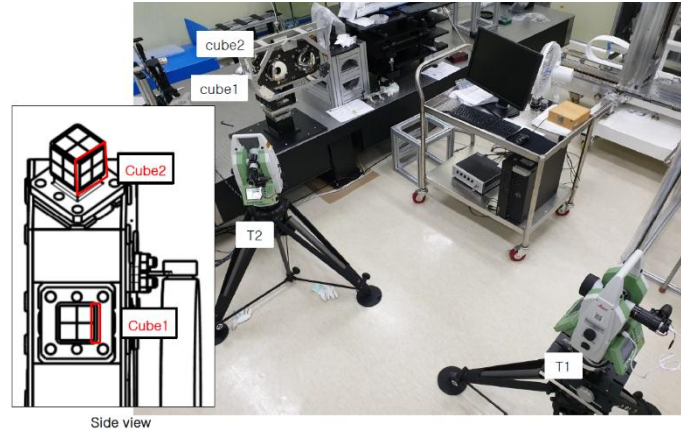


Figure 2. Between cube measurement setup

2.3 Coordinate transformation model

For any vector v expressed in Cube1, the corresponding Cube2 vector is written as

$$\begin{aligned}\{v\}_{c2} &= [RT_c2_c1] \cdot \{v\}_{c1} \\ &= [RT_c2_t2] \cdot [RT_t2_t1] \cdot [RT_t1_c1] \cdot \{v\}_{c1}\end{aligned}$$

where, $[RT_c2_c1]$: transformation matrix from Cube1 frame to Cube2 frame

$\{v\}_{c1}$: vector expressed in Cube1 frame

$\{v\}_{c2}$: vector expressed in Cube2 frame

Here, $[RT_t1_c1]$ maps Cube1 into the first-theodolite frame, $[RT_t2_t1]$ is obtained from co-collimation, and $[RT_c2_t2]$ maps the second-theodolite frame into Cube2. The product $[RT_c2_c1]$ is a proper rotation matrix when the constructed axes are normalized and orthogonalized. Applying one common matrix to every LOS vector preserves the internal angular relationships among pixels and between the two cameras.

A useful feature of this representation is separation of unit-level optical mapping from spacecraft-level frame transfer. The detector model can be updated independently in Cube1, while the inter-cube rotation can be updated if improved metrology becomes available. The final Cube2 products are then regenerated by matrix multiplication without repeating the full geometric mapping campaign.

3. SYSTEM-LEVEL GEOMETRIC MAPPING

3.1 Test setup and measurement sequence

The DCP-level geometric mapping setup combines a front collimator, a hexapod carrying or steering the instrument, a rear autocollimator, a side autocollimator, and two theodolites. The rear theodolite observes the -Zc1 face of Cube1, while the side theodolite observes the -Yc1 face. Co-collimation between theodolites provides a relationship between their frames. The collimator generates a target at optical infinity and is positioned so that a selected detector pixel is illuminated. As the hexapod changes the instrument pointing, the rear autocollimator records angular motion.

Nominally, the rear-autocollimator azimuth corresponds to across-track LOS variation and its elevation corresponds to along-track variation. The mapping therefore converts pixel number into two angular coordinates. Because the LOS is near +Zc1, the azimuth and elevation angles can be converted into a unit vector with dominant Z component and small X and Y components.

The test record does not include a direct measurement of the complete transformation between Cube1 and the rear-autocollimator frame. The original interpretation therefore uses assumption: there is no misalignment between these frames, such that autocollimator azimuth is assigned to the Yc1 LOS component and autocollimator elevation to the Xc1 component. The most likely residual mismatch is a small rotation about Zc1, which would mix the derived X and Y components and rotate the detector-line direction in the focal plane.

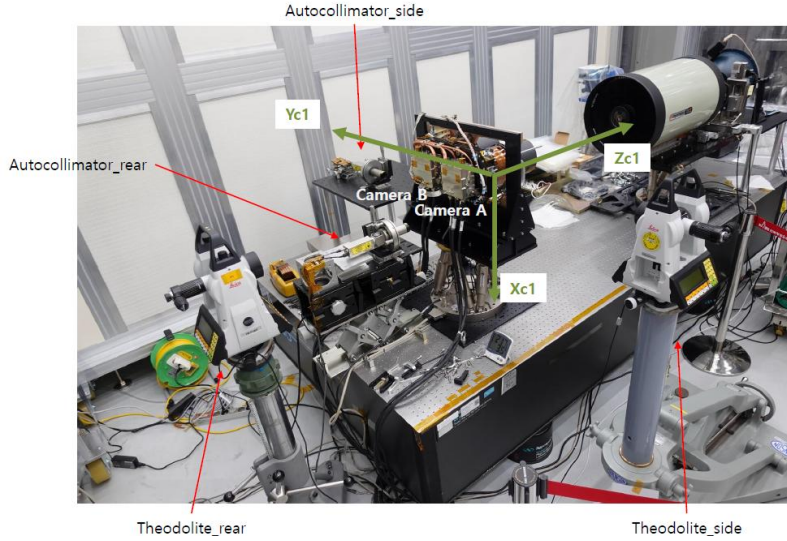


Figure 3. Geometric mapping configuration

3.2 Pixel-to-angle regression

For each camera, the measured azimuth and elevation angles were fitted as linear functions of pixel index p . The azimuth relationships are exceptionally linear, with reported coefficients of determination equal to 1.0000 for both cameras. Camera A follows $\text{azimuth} = 1.4254 \times 10^{-3} p - 0.96161 \text{ deg}$, and Camera B follows $\text{azimuth} = 1.4282 \times 10^{-3} p - 3.6672 \text{ deg}$. The similar slopes indicate nearly identical angular sampling scales for the two cameras.

The elevation relationships have much smaller slopes. Camera A follows $\text{elevation} = 3.6493 \times 10^{-6} p + 0.17357 \text{ deg}$ with $R^2 = 0.99353$. Camera B follows $\text{elevation} = -1.5290 \times 10^{-6} p + 0.085132 \text{ deg}$ with $R^2 = 0.95333$. The elevation slope is not interpreted as a separate imaging dimension; instead, it indicates that the physical detector line is slightly tilted relative to the nominal across-track direction of the autocollimator frame.

The observed linearity supports a compact LOS model. The source report tabulates vectors at pixels 0, 1024, and 2047, and states that intermediate vectors may be obtained by linear interpolation. For high-accuracy downstream processing, interpolation should preferably be followed by normalization so that every LOS remains a unit vector.

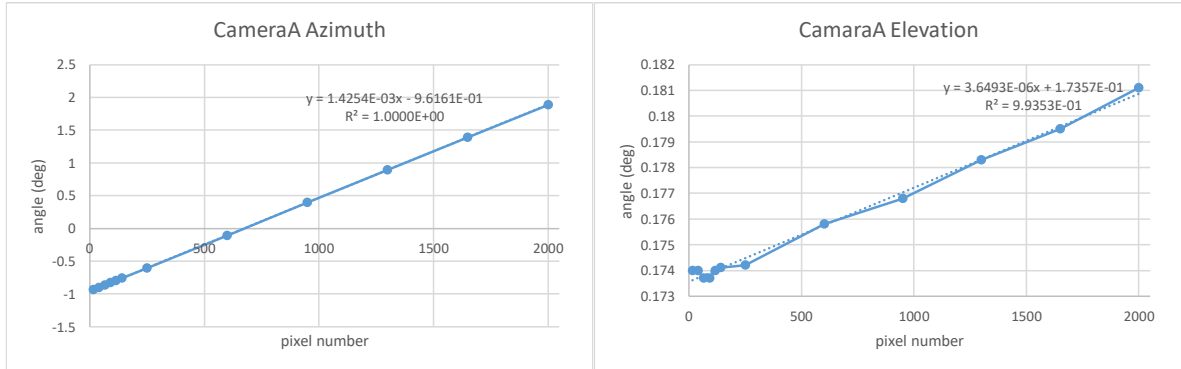


Figure 4. Camera A azimuth and elevation measurements versus detector pixel

3.3 LOS vector construction and center LOS

The measured elevation and azimuth are associated with the X_{c1} and Y_{c1} components, respectively. For small angles, X and Y are approximately proportional to the corresponding angular offsets in radians, while Z is obtained from unit-vector normalization. The exact sign convention follows the orientation adopted in the measurement report. The resulting vector tables show that both camera lines point close to $+Z_{c1}$ but occupy different Y_{c1} ranges.

The center line of sight (CLOS) is defined as the average of six representative vectors: pixels 0, 1024, and 2047 from Camera A and the same three pixels from Camera B. Averaging these samples gives a practical overall instrument boresight. Because the average of unit vectors is not automatically unit length, normalization may be applied when the vector is used as a direction; the tabulated CLOS is already very close to unit magnitude.

4. MEASUREMENT RESULTS AND INTERPRETATION

4.1 Regression results and detector-line orientation

The azimuth slopes differ by only about 0.2%, confirming that the two detector lines have nearly the same angular pitch. Over 2047 pixel intervals, the nominal angular spans are approximately 2.918 deg for Camera A and 2.923 deg for Camera B. The intercept difference places Camera B at a more negative azimuth than Camera A, producing adjacent or partially separated fields that together form the observation geometry.

Table 1. Linear pixel-to-angle models for the DCP geometric mapping.

Camera	Angle	Slope (deg/pixel)	Intercept (deg)	R ²
A	Azimuth	1.4254E-03	-9.6161E-01	1.0000
A	Elevation	3.6493E-06	1.7357E-01	0.99353
B	Azimuth	1.4282E-03	-3.6672E+00	1.0000
B	Elevation	-1.5290E-06	8.5132E-02	0.95333

The ratio between elevation and azimuth slope provides the detector-line tilt in the autocollimator frame. The reported values are approximately +0.15 deg for Camera A and -0.06 deg for Camera B. A positive sign indicates that azimuth and elevation increase with pixel number in the same sense, whereas a negative sign indicates opposite senses. These small tilts are visible in the target-surface projected footprint as a slight along-track displacement from one end of each detector line to the other.

4.2 LOS vectors in the Cube1 frame

Camera A traverses from positive to negative Yc1 as pixel number increases, while its Xc1 component increases slightly. Camera B remains at positive Yc1 across the sampled detector positions and has a small decreasing Xc1 component. The dominant Zc1 values confirm that the optical axes are close to the nominal +Zc1 direction.

Table 2. Representative LOS vectors in the Cube1 frame.

Camera	Pixel	Xc1	Yc1	Zc1
A	0	0.0030294069	0.0167824159	0.9998545760
A	1024	0.0030946284	-0.0086917420	0.9999574375
A	2047	0.0031597861	-0.0341353855	0.9994122229
B	0	0.0014858303	0.0639614257	0.9979512655
B	1024	0.0014585034	0.0384711620	0.9992586464
B	2047	0.0014312032	0.0129807578	0.9999147222

The CLOS in Cube1 is [0.002277687, 0.014902148, 0.999886363]. At a notional altitude of 100 km above a locally flat target surface, the small Xc1 and Yc1 offsets correspond to kilometer-scale displacement from a +Zc1 nadir reference. The original footprint plot assumes the spacecraft boresight is coincident with +Zc1 and the velocity direction with +Xc1; target surface curvature is neglected. Under those simplifying assumptions, the plot is intended for physical interpretation rather than precise geolocation.

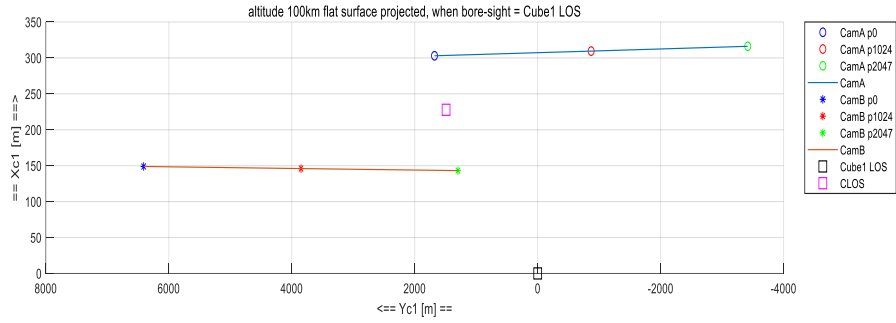


Figure 5. Illustrative projection of the measured LOS vectors onto a flat target surface at 100 km altitude

4.3 LOS vectors in the spacecraft-accessible Cube2 frame

After application of the inter-cube rotation, the LOS vectors are centered near equal-magnitude $-Xc2$ and $+Zc2$ components. This is consistent with a Cube2 orientation rotated by roughly 45 deg relative to the Cube1 boresight. The transformed CLOS is $[-0.708102106, 0.009779873, 0.706042323]$. This vector is the principal spacecraft-level result because Cube2 remains accessible for alignment measurements after DCP integration.

Table 3. Representative LOS vectors transformed into the Cube2 frame.

Camera	Pixel	Xc2	Yc2	Zc2
A	0	-0.7086482569	0.0116429132	0.7054658677
A	1024	-0.6958560420	-0.0063665740	0.7181530725
A	2047	-0.6826243949	-0.0243529301	0.7303635193
B	0	-0.7318544569	0.0439975040	0.6800391706
B	1024	-0.7199461059	0.0259084364	0.6935462187
B	2047	-0.7075805699	0.0078208442	0.7065893939

The transformation preserves the relative ordering and angular separation of detector pixels. Camera A moves toward less negative $Xc2$ and more positive $Zc2$ as pixel number increases, while $Yc2$ decreases. Camera B shows the same overall $Xc2$ - $Zc2$ trend and a decreasing positive $Yc2$. Intermediate pixel LOS vectors can be obtained from the linear model or by interpolation between tabulated points, followed by normalization.

4.4 Error sources and limits of interpretation

The numerical precision shown in the vector tables is substantially finer than the expected absolute alignment accuracy. The gravity-direction misalignment of theodolites and nonorthogonality of cube faces as principal error sources and estimates their LOS effect at approximately 50 microradians in order of magnitude.

A rotation between Cube1 and the rear-autocollimator frame, particularly about $Zc1$, would rotate the measured detector-line slopes and alter the decomposition of LOS into $Xc1$ and $Yc1$. Such a rotation would have little effect on the total angular distance of each pixel from boresight but would affect the orientation of the line of detector and the projected footprint.

The Cube2 vectors should therefore be used as a best estimate under the limited measurement environment rather than as an uncertainty-free truth set. If spacecraft-level alignment or in-orbit image correlation provides an independent boresight correction, that correction can be represented as an additional small rotation applied to the Cube2 vectors.

A stronger future campaign would measure at least two nonparallel faces of each reference cube, directly determine the Cube1-to-autocollimator transformation, repeat observations in reversed instrument orientations to separate leveling bias, and report a full covariance or Monte Carlo uncertainty for every delivered LOS vector.

5. CONCLUDING REMARKS

A unified LOS model for the Dual-camera payload has been constructed by linking unit-level reference-cube measurements with system-level geometric mapping. The geometric mapping demonstrates a highly linear relationship between detector pixel and azimuth for both 2048-pixel cameras. Small but measurable elevation slopes correspond to detector-line tilts of approximately +0.15 deg for Camera A and -0.06 deg for Camera B. Representative Cube1 LOS vectors at pixels 0, 1024, and 2047 capture the line direction and support interpolation across each detector.

The inter-cube transformation converts these results into the spacecraft-accessible Cube2 frame. Because Cube2 remains observable after integration, this vector set provides the appropriate interface for spacecraft alignment and subsequent attitude-to-image geometry processing.

The main qualification is that the available metrology did not fully observe all rotational degrees of freedom. The final transformation depends on assumptions concerning gravity alignment, the unmeasured Cube2 transverse direction, and the alignment of Cube1 with the rear autocollimator. The results are accordingly best interpreted as the most consistent estimate supported by the measurement record. Their internal linearity is strong, but their absolute orientation should be associated with an uncertainty scale of roughly 50 microradians and with the explicit assumptions documented in the analysis.

Despite these limitations, the combined approach provides a practical calibration chain from detector pixel to spacecraft-level LOS. It also establishes a modular framework in which improved cube metrology, refined instrument-level mapping, or in-orbit boresight correction can be incorporated as updated rotations without changing the basic detector model.

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