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Geopositioning and precision validation of landing locations on the Moon using LRO NAC images and LRRRs

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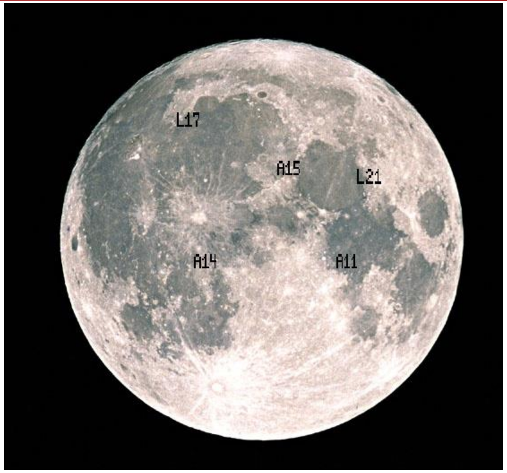
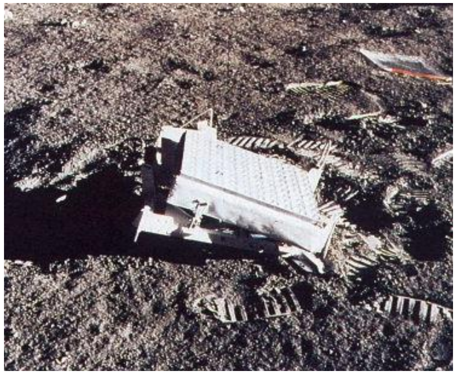
Contents

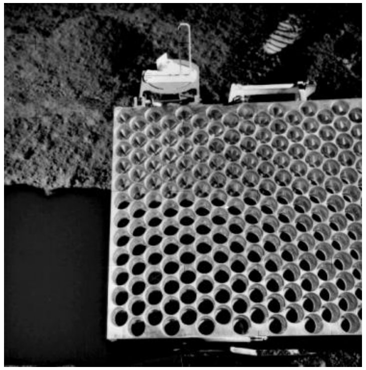
Introduction – Lunar Laser Ranging

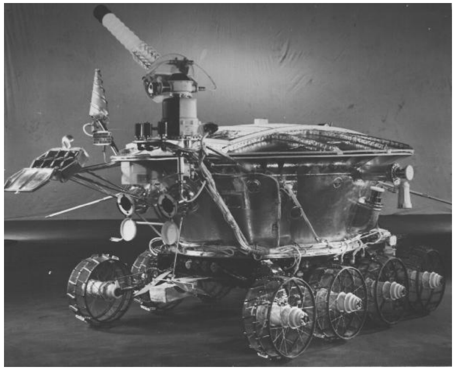
- Lunar Laser Ranging (LLR) provides the most accurate position information, with retroreflector coordinates known to ±27 cm in the X/Y/Z principal axis (PA) frame (Williams et al., 2013), on the Moon.
- LLR plays critical role on deriving reference frame, calibrating Lunar observation equipment, verifying the position accuracy etc..
- But only for the 5 existing LLR targets. It will be necessary to ***tie the other datasets*** into an LLR frame or one based on it.
- How to determine coordinates of other sites?




Apollo 11 retroreflector array


Apollo 14 retroreflector array

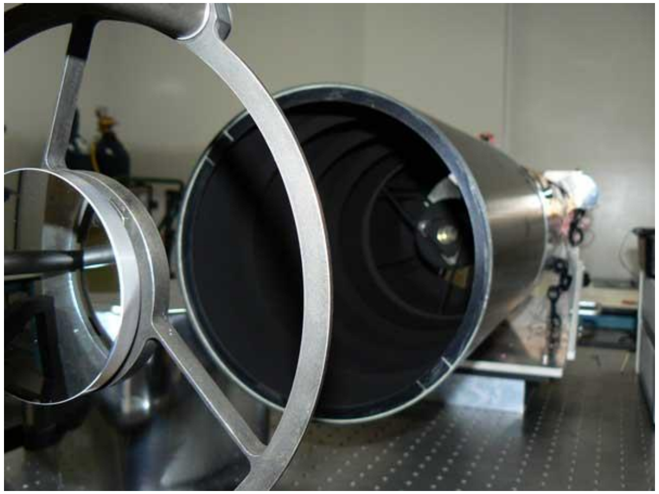

Apollo 15 retroreflector array


Lunokhod

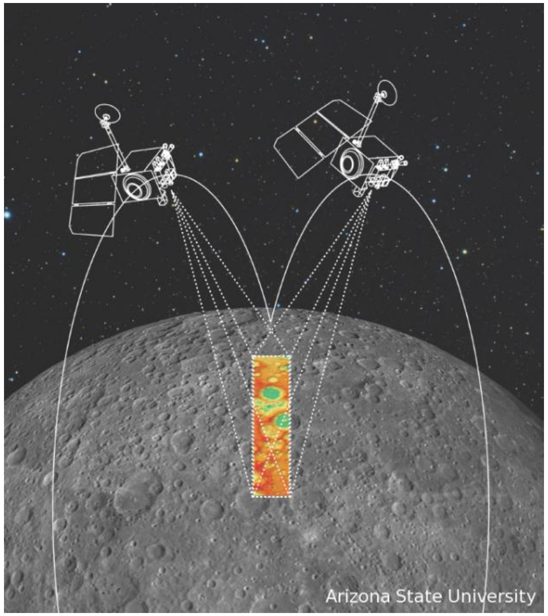
Introduction – Lunar Reconnaissance Orbiter

NASA Lunar Reconnaissance Orbiter (LRO) mission carries seven instruments.
•Sent to the Moon on 18 June 2009, 7 years in lunar orbit.
•LROC consists of one Wide Angle Camera (WAC) and two Narrow Angle Cameras (NACs).
•NAC images have the highest resolution of up to 0.5 m.
•LRO Camaras (LROC) geometric stereo coverage from different orbits (off-nadir slews).

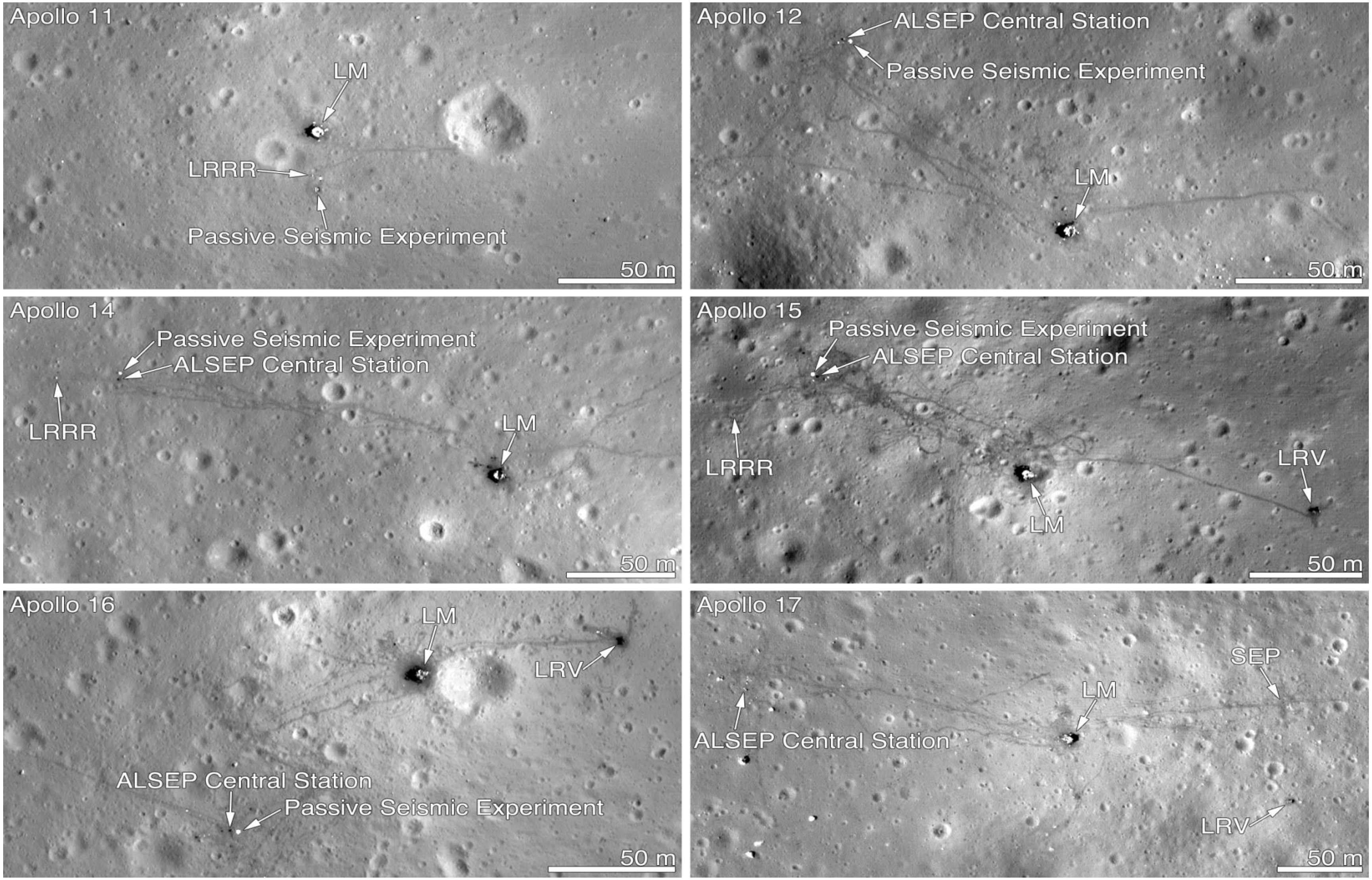
- **TU Berlin**: member of LOLA (Lunar Orbiter Laser Altimeter) & LROC science teams
    - DTM processing (LOLA & LRO NAC)
        → historic & future landing sites
    - co-registration, block adjustment
    - Apollo cartography



LRO NAC



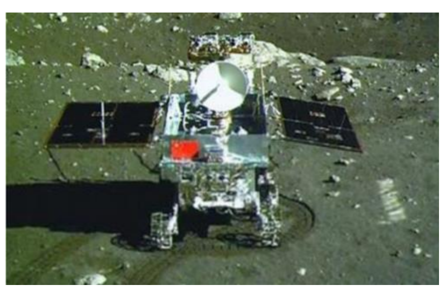
stereo coverage from different orbits

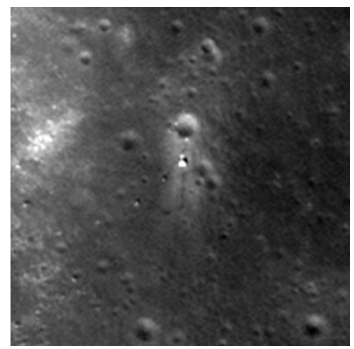


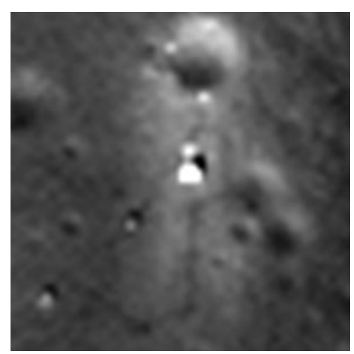
LROC images of the Apollo landing sites showing the locations of the LM descent stages, LRVs, and instruments. Note also the rover and astronaut tracks. LROC frames M175124932R, M175428601R, M175388134R, M175252641L/R, M175179080L, and M168000580R (Apollo 11-17, respectively) (Wagner et al., 2016)

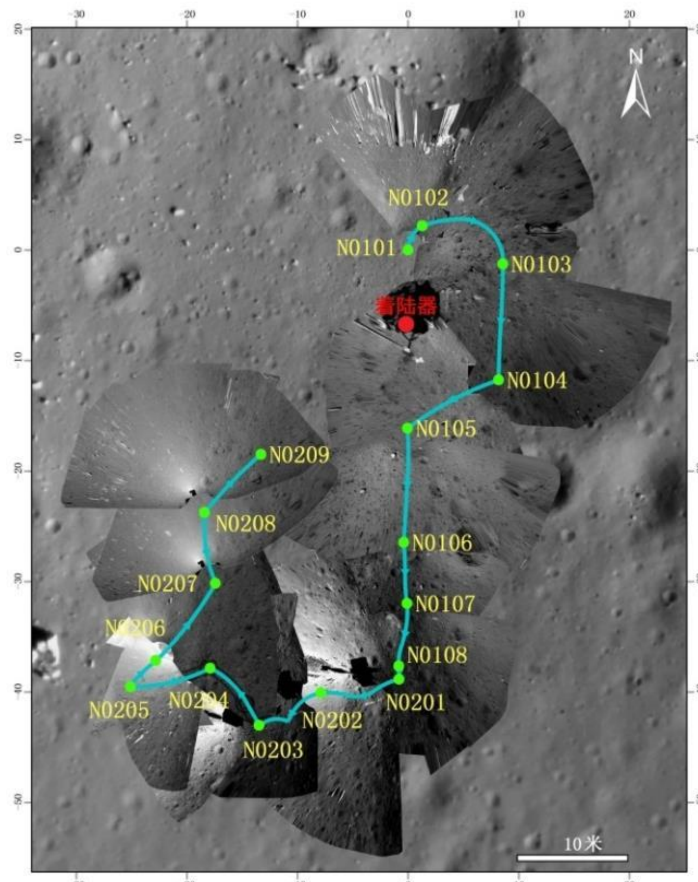
Introduction - Chang’E-3 (CE-3)

CE-3 is the first lander and rover mission of China after the success of Chang’E-1 and Chang’E-2 orbiter missions. It was launched on 2 December 2013 and successfully landed at (44.12 °N, 19.51 °W) (radio-tracking solution) at northern Mare Imbrium of the Moon on 14 December 2013.









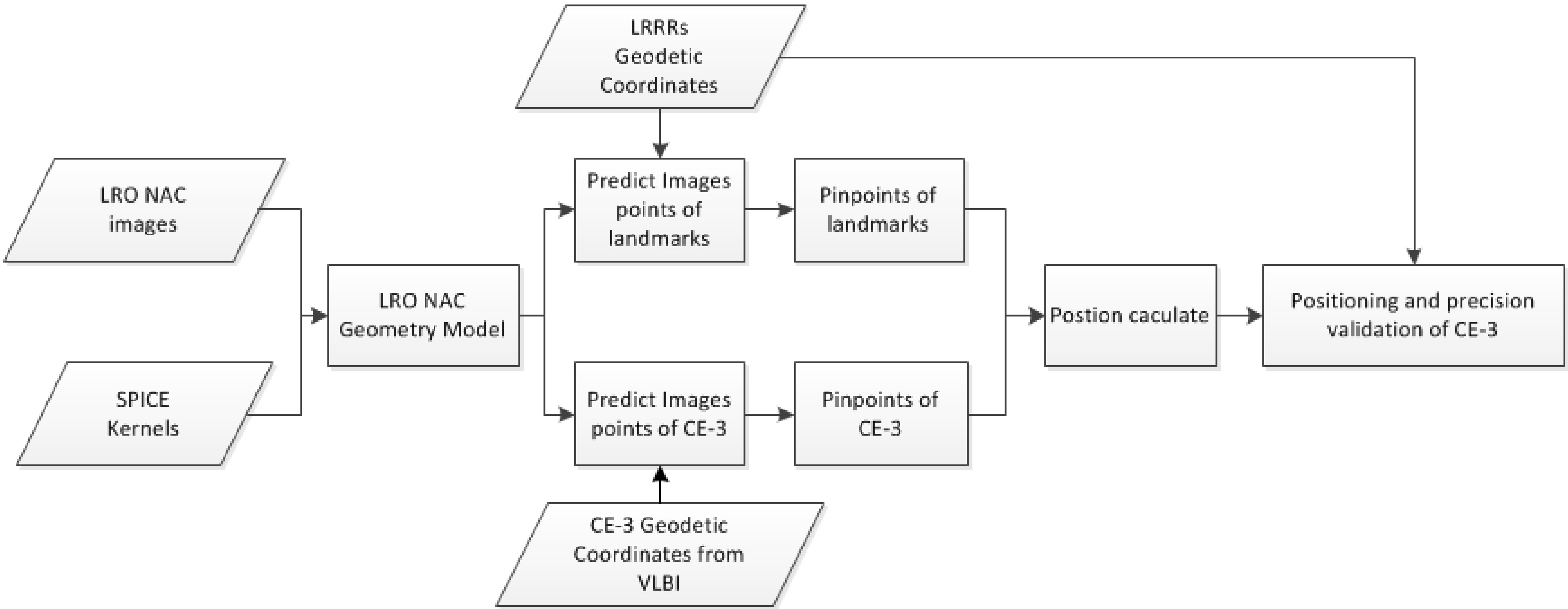
Introduction - Objectives

Location of CE-3 lander was derived from multiple LRO NAC images.

The method was validated by coordinate analysis of other landing sites, where accurate coordinates are available with the Lunar Ranging Retro Reflectors (LRRRs).

With continual data acquisition, these areas of the lunar surface have been covered many times. How to achieve the best geopositioning and mapping precision in those areas with multi-image coverages?

Methodology



Methodology

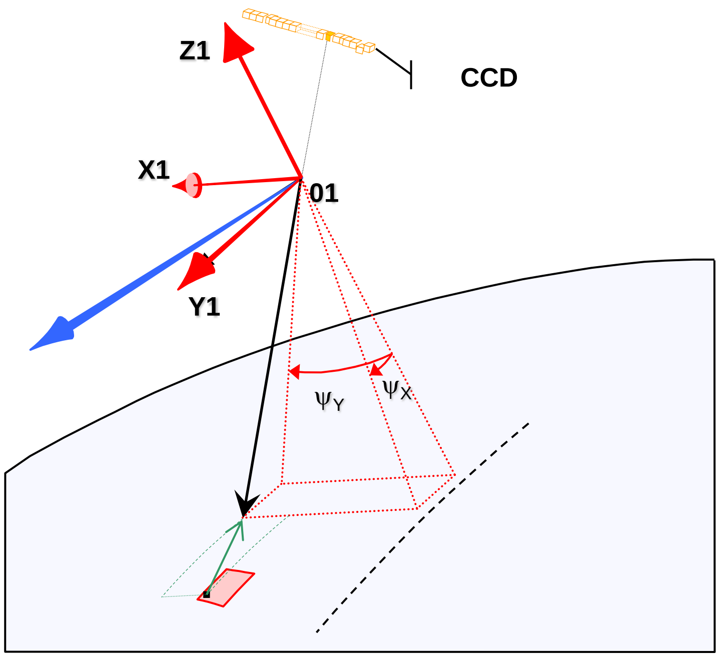
Rigorous sensor model (RSM)

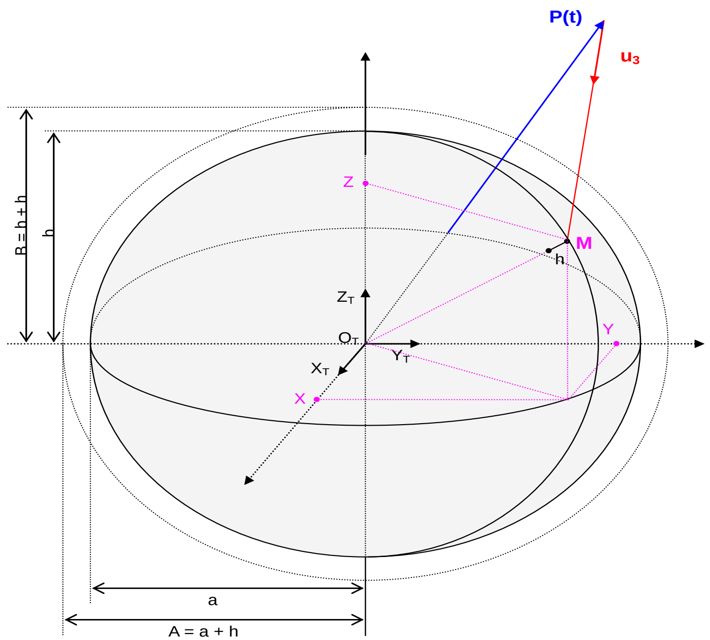
The RSM connects the image coordinates of a LROC NAC image with the corresponding Moon body fixed coordinates. It is represented by collinearity equations with interior and exterior orientation elements retrieved from the corresponding SPICE kernels.

$$\begin{bmatrix} X - X_s \\ Y - Y_s \\ Z - Z_s \end{bmatrix} = \lambda R_{ol} R_{bo} R_{ib} \begin{bmatrix} x \\ y \\ -f \end{bmatrix} = \lambda R \begin{bmatrix} x \\ y \\ -f \end{bmatrix}$$

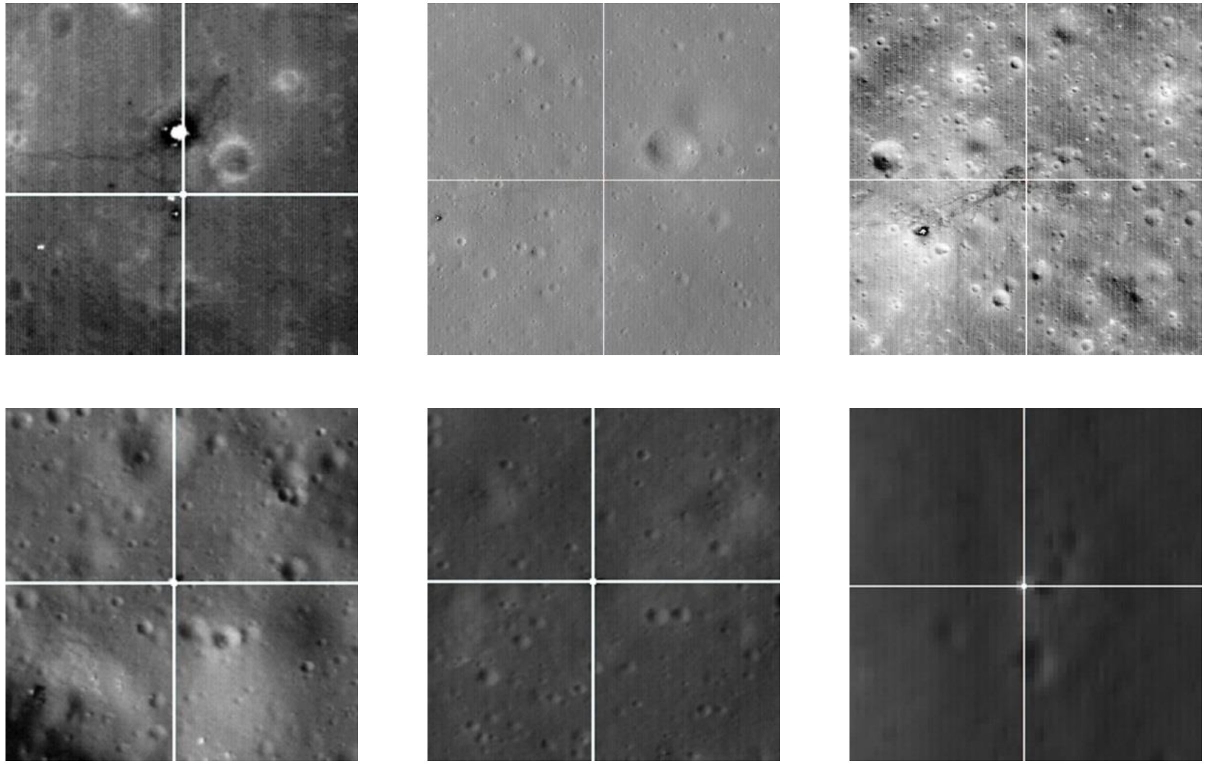
The 3D coordinates of a ground point can be calculated through space intersection using the image coordinates of corresponding points from a stereo image pair.

The ground location can also be calculated from a single image if the elevation of the point is known.





Experimental results



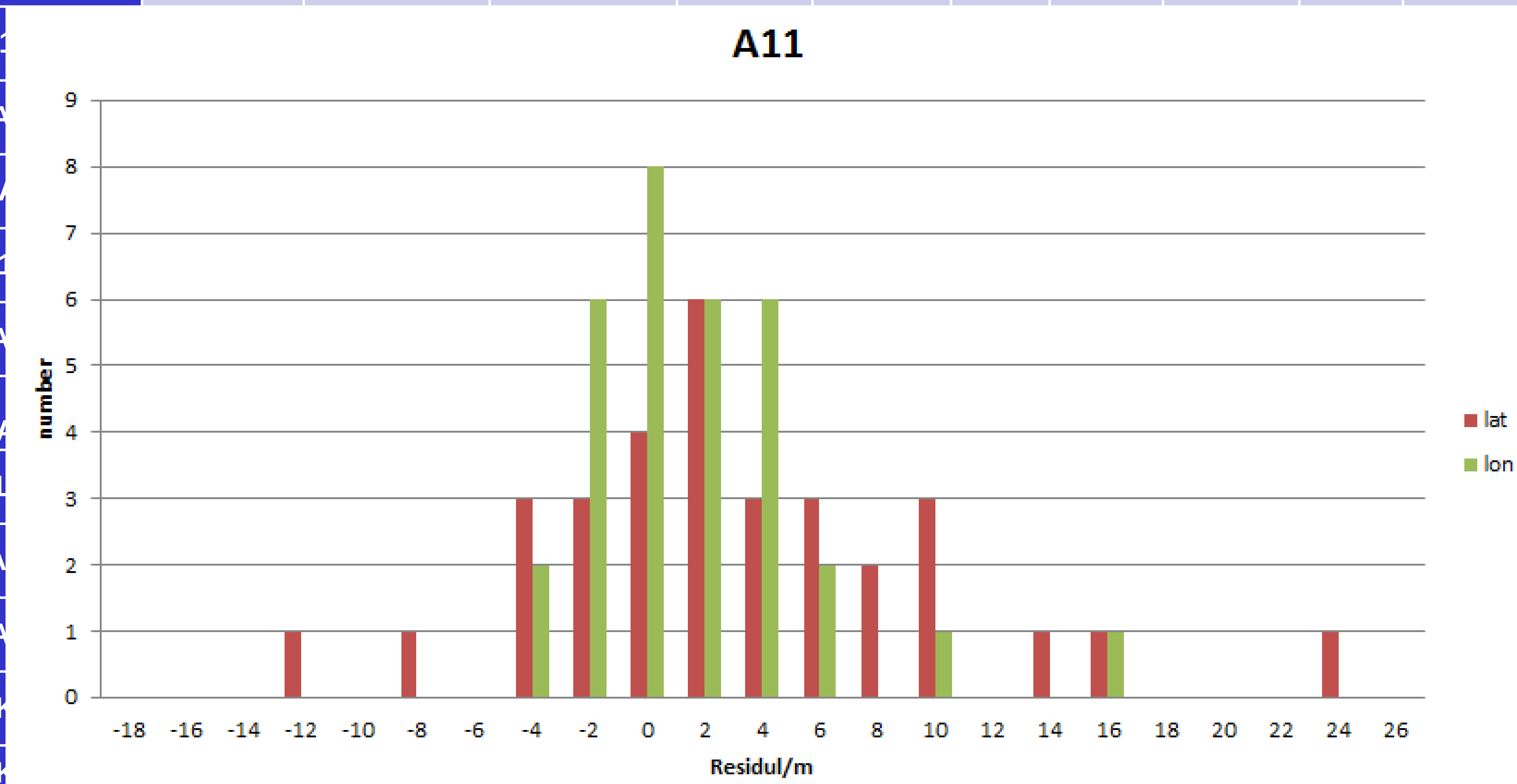
Locations of the landmarks on images
(Clockwise from top left: A11 LRRR、A14 LRRR、A15 PSE*、
CE-3 Lander、LK2 LRRR、LK1 LRRR)

*Passive seismic experiment, PSE

Experimental results

Positioning and precision validation of Chang'E-3 Lander

Target	Calculated coordinate（mean）			Standard deviation			Error			Images
	Lat(°)	Lon(°)	R(m)	Lat(m)	Lon(m)	R(m)	Lat(m)	Lon(m)	R(m)	
CE-3	44.12189	19.51129	1734767.0	14.9	7.0	0.02	--	--	--	14



Coordinates of landmarks derived from multiple images and precision statistics

*Apollo lunar surface experiment package, ALSEP **Lunar modules，LM

Precision Analysis of Multiple Image Triangulation

Block adjustment based on RFM

- Rational function model (RFM)

$$r = \frac{P_1(X,Y,Z)}{P_2(X,Y,Z)} \qquad c = \frac{P_3(X,Y,Z)}{P_4(X,Y,Z)}$$

$$P_i(X,Y,Z) = a_1 + a_2X + a_3Y + a_4Z + a_5XY + a_6XZ + a_7YZ + a_8X^2 + a_9Y^2 + a_{10}Z^2 + a_{11}XYZ + a_{12}X^3 + a_{13}XY^2 + a_{14}XZ^2 + a_{15}X^2Y + a_{16}Y^3 + a_{17}YZ^2 + a_{18}X^2Z + a_{19}Y^2Z + a_{20}Z^3$$

The rational polynomial coefficients (RPCs) of each image are derived by least squares fitting using vast number of virtual control points generated by RSM of the image.

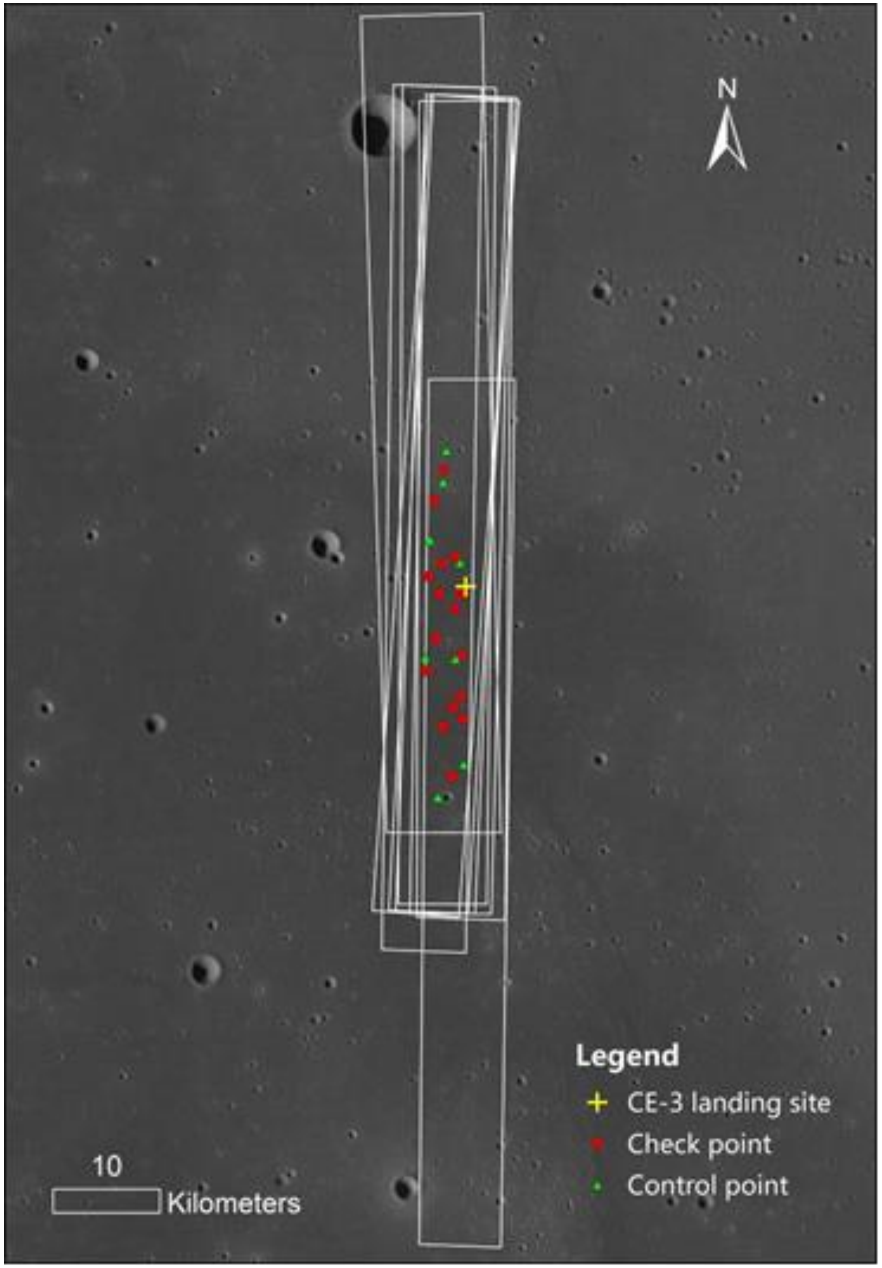
The RFM can approximate RSM with a precision of 1/100 pixel level in image space.

Comparing with RSM, RFM has the advantages of simplicity, and independency of sensors. It is particularly advantageous for integrated mapping using multiple images from the same orbiter or different orbiters.

- Affine transformation model in image space is used to correct image coordinates (row and column)

$$F_r = p_{r_0} + p_{r_1}c' + p_{r_2}r' + r' - r = 0$$
$$F_c = p_{c_0} + p_{c_1}c' + p_{c_2}r' + c' - c = 0$$

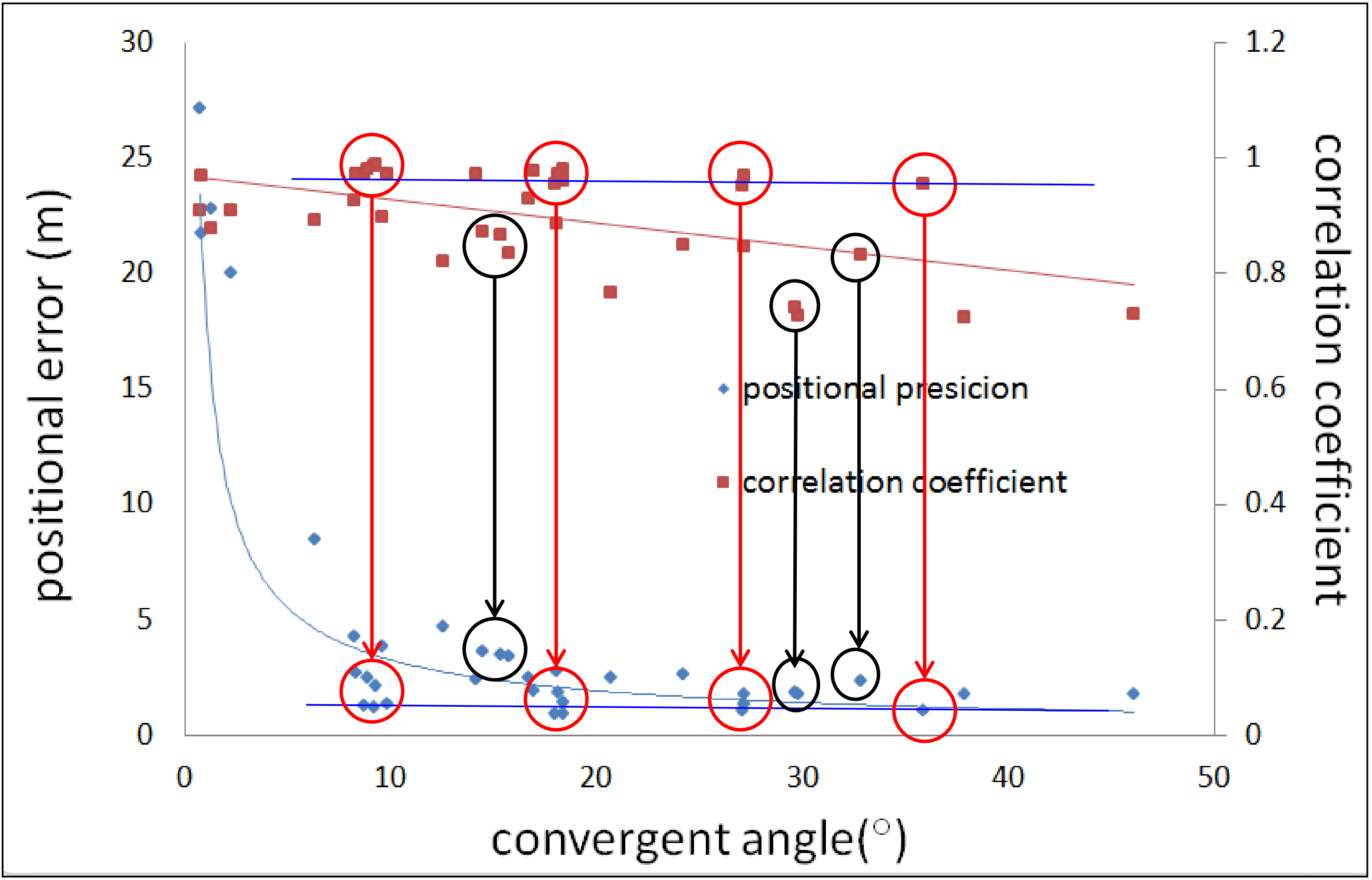
The Affine transformation parameters for each image as well as the 3D coordinates of the tie points are solved iteratively by least squares adjustments.



Nine LROC NAC images covering an area of 12 km x 75 km around the CE-3 landing site

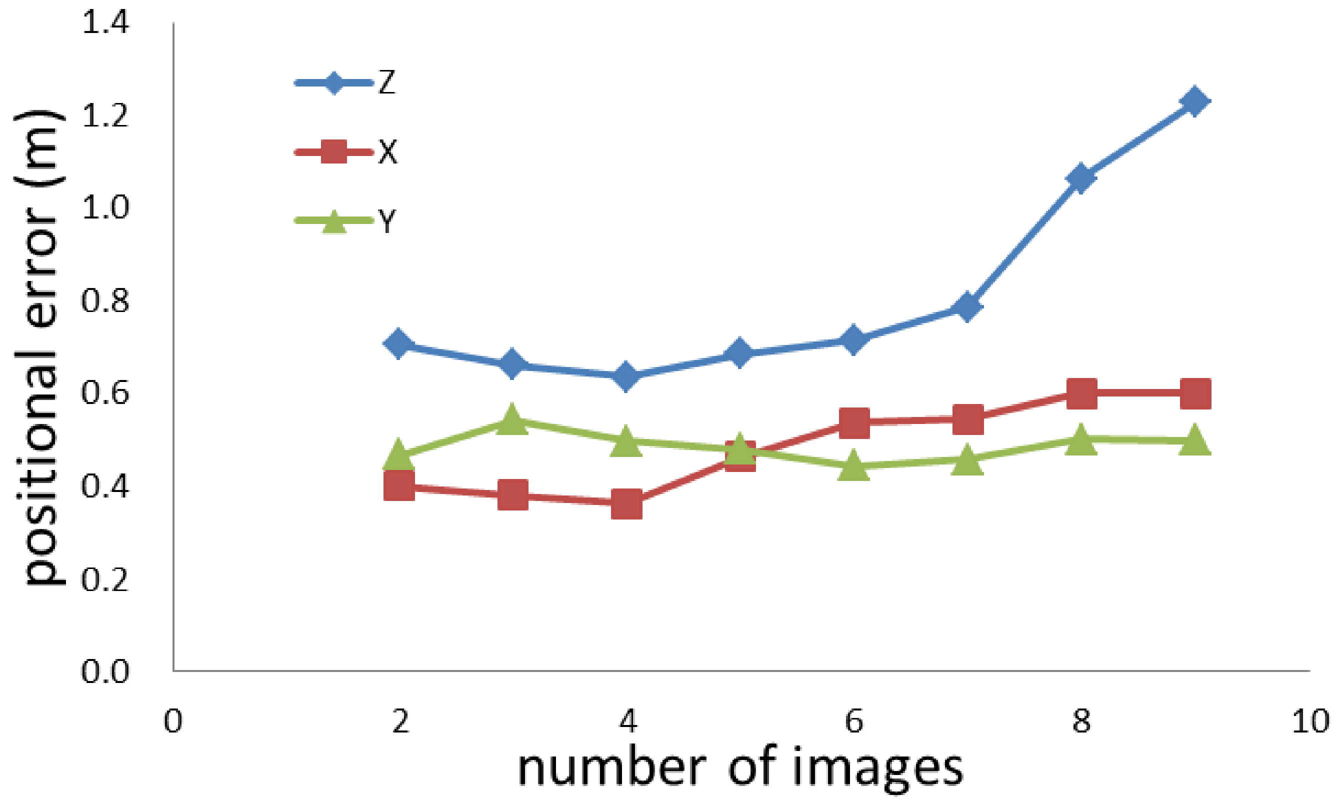
Layout of the ground coverage of 9 LROC NAC images and the distribution of control points and check points

Geopositioning precision of a stereo pair



- Least-squares correlation coefficient decreases linearly with convergent angle.
- Least-squares correlation coefficient reflects the image match error which affect positional error.
- When the convergence angle is larger than a certain value, the decisive factor of the positional error is the accuracy of the image match

Geopositioning precision of multiple images



The relationship between the number of images and the geopositioning precision in object space

Summary

A method for coordinate measurements of lunar surface landmarks from orbital imagery was refined and tested using LRRR targets (for which accurate coordinates are known). As a result, the location of CE-3 lander was determined to be (44.1219° N, 19.5113° W) using 14 LRO NAC images.

In general, the geopositioning precision (especially the height precision) is improved with the increase of the convergence angle between two images from several degrees to about 50°. However, the best precision may not come from the stereo pair with the largest convergence angle.

We suggest that to produce the best geopositioning precision, both the convergent angle and the matching error between images should be considered.

Triangulation of selected fewer images could produce better precision than that using all the images. In this research, selection of effective images for multi-image triangulation has been realized in a simple and heuristic way.

In the future, in-depth theoretical analysis will be conducted aiming to derive an automatic algorithm to select most effective images for achieving the best geopositioning precision from multiple images.

Thanks !

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