アストロダイナミクスシンポジウム
2023.7.24

A robust method against Solar condition to generate Initial Template Image for Optical Navigation in Planetary Exploration

惑星探査での画像航法における太陽条件にロバストな初回マッチング用テンプレート作成手法

MMX
Martian Moons eXploration

〇Yosuke Takeo, Naoki Okada, Shinji Matani, Yuki Matsumoto, and Go Ono (JAXA)

Background

- Image navigation for Small body landing in Planetary Exploration[1-5]

Image navigation classification

- OpNav Horizon-based — Ex).Rosseta, (like Star-tracker)
- Monocular — Ex).OSIRIS-Rex(3D) /SLIM, **MMX(2D)**
  - **TRN:Terrain Relative Navigation**
- Stereo — triangulation

GN&C architecture

- classic — Ground-based
- autonomous

High gravity (On-board navigation)
On-board = low computational cost required

MMX : on-board navigation and control

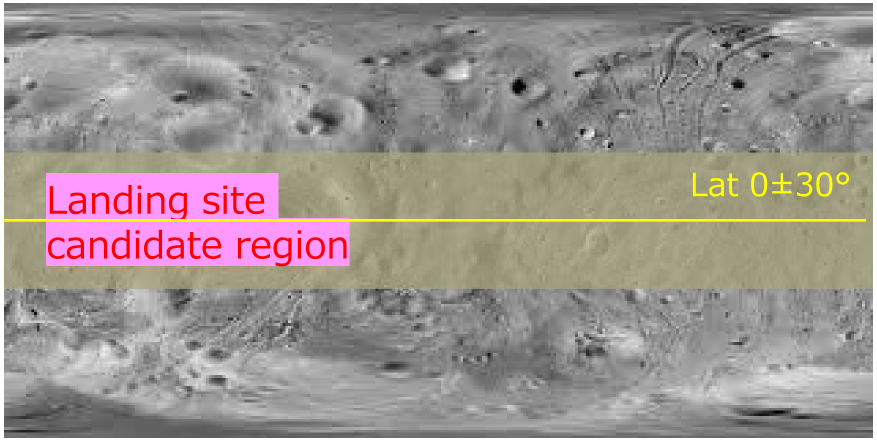
- Crater-based navigation (alt > 300m)
  - Ex) SLIM, 2023
- **Template matching navigation (alt < 300m)**
  - EX) Mars Exploration Rover(MER), 2004

- Template matching is **primitive (classical)** method for image navigation
- Computational cost : **small(good)**
- Resource : **small(good)**
- Solar condition change : **weak**

In this study, we propose the robust method against solar condition

MMX mission

- MMX is world's first sample return mission from a Mars satellite[6][7]
- Decent operation
  - Rehearsal#1, Landing #1
    - Unti-Mars side
  - Rehearsal#2, Landing #2
    - Mars side (“blue” area)



(landing image)

- Launch : 2024
- Mass : About 4000kg
- Mission duration : About 5yr
- Mission Instruments
  - Sampler
  - Gamma-ray, neutron spectrometer
  - Near-infrared spectrometer
  - Wide FOV camera
  - Narrow FOV camera

Image navigation and decent sequence in MMX mission

- Template matching will be performed from 300m to 10m altitude after crater matching navigation(CB).
- Due to residual error of CB, error reset is required by initial template which is uploaded from the ground, and its source is captured image by CAM-T(telescopic) in QSO-L.
- Templates of 2nd matching and later are generated by cropping from the previously taken image.
- The accuracy of **initial template matching** is very important because it directly affects landing accuracy.

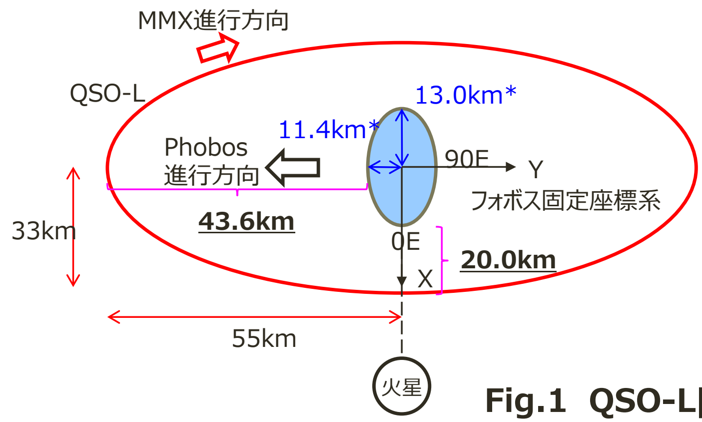


Fig.1 QSO-L[6]

*Willner et al., Phobos shape and topography models, 2014

Initial Template

Target Matching Navigation (Template matching)

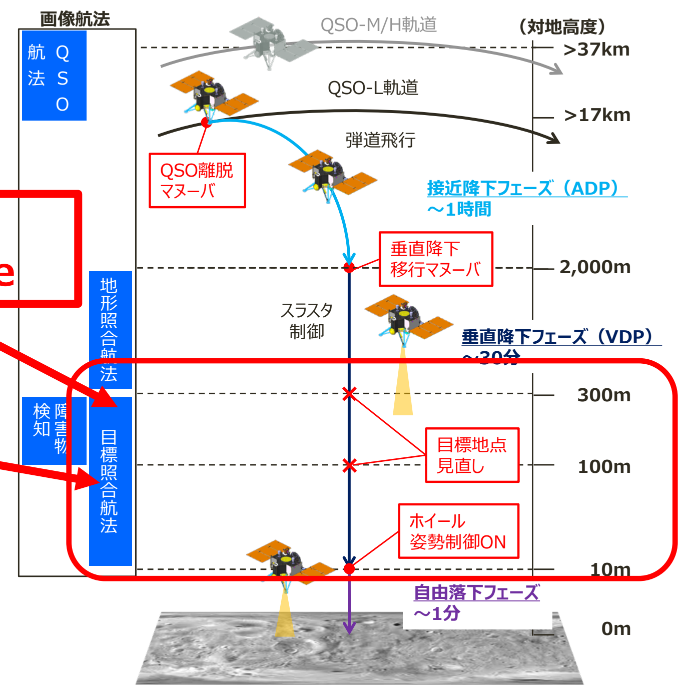


Fig.2 Image navigation and decent sequence[7]

Image	Camera
Target image	Wide FOV (CAM-W)
Initial template	Telescopic (CAM-T)

Problem and proposed method

- Initial template matching is generated by using the image captured from QSO-L by CAM-T before decent operation.
- Decent operation will be performed at daybreak. However, observation chances of such a solar condition in QSO-L are limited.
- Thus, robust matching can facilitate observation operations in QSO.

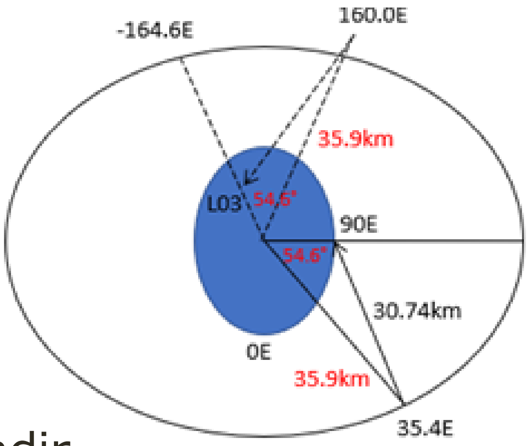
Proposed method(pre-processing):

- Histogram equalization for initial template to enhance contrast and to be robust for matching

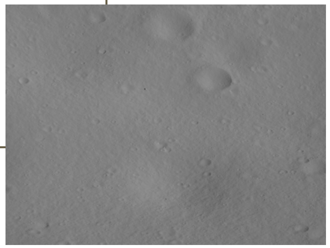
Other operational innovations:

- Increase exposure time
- Oblique viewing to gain resolution in the case of far side (leading / trailing side)

Oblique viewing



Nadir

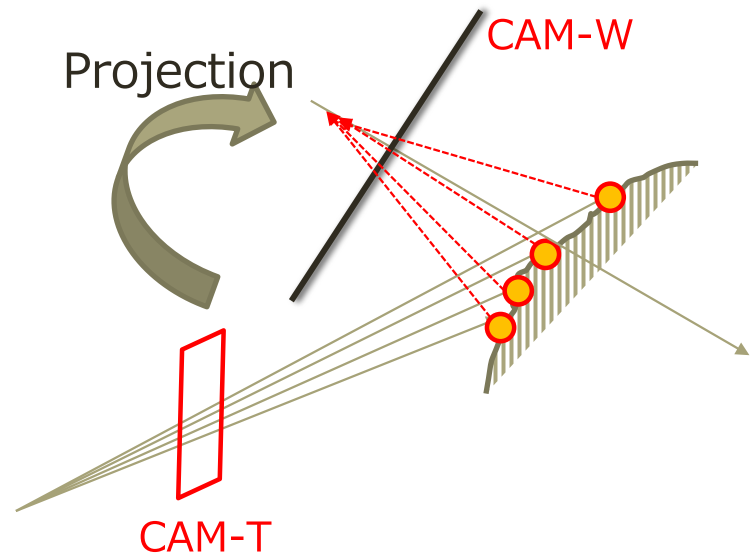


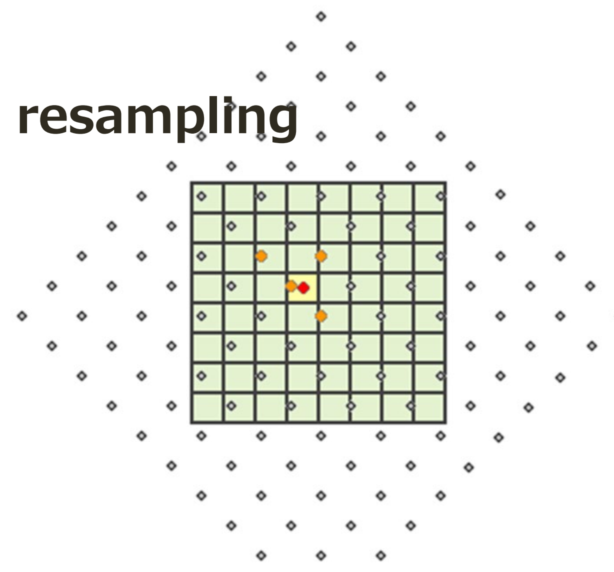
Procedure for generating template

- Obtain intersections with Phobos surface by each pixel of CAM-T image captured from QSO-L using DEM
- Project intersections 3D coordinates with respect to Phobos fixed coordinate onto CAM-W attitude and position by following equation:

$$\begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = P \begin{pmatrix} X \\ Y \\ Z \\ 1 \end{pmatrix}$$

  - Where P is the perspective projection matrix, which can be calculated from K[R | t], assuming K is internal camera matrix, R is rotational(attitude) matrix, and t is spacecraft position, respectively.
- Because the image coordinates x, y are the real-number, resampling is required (i.e., bi-linear interpolation)
- Finally, pre-processing and trimming by template-size



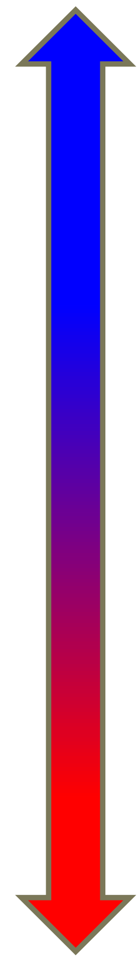


https://www.esrij.com/gis-guide/imagery/resampling/

Template matching

- finding small parts which match a template image with maximum similarity

Low Cost



Robust

Sum of Abusolute Difference(SAD)

$$S = \sum\sum |g(d_x + i, d_y + j) - f(i,j)|$$

In this study, utilize SAD/NCC considering computational cost

Normalized Cross-Correlation(NCC)

$$S = \frac{\sum\sum\{g(d_x + i, d_y + j) - f(i,j)\}}{\sqrt{\sum\sum(g(d_x + i, d_y + j))^2}\sqrt{\sum\sum(f(i,j))^2}}$$

Zero-means Normalized Cross-Correlation(ZNCC)

$$S = \frac{\sum\sum\{(g(d_x + i, d_y + j) - \mu_g) - (f(i,j) - \mu_f)\}}{\sqrt{\sum\sum(g(d_x + i, d_y + j) - \mu_g)^2}\sqrt{\sum\sum(f(i,j) - \mu_f)^2}}$$

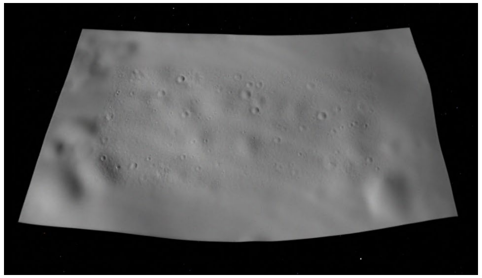
Simulation

Simulation condition

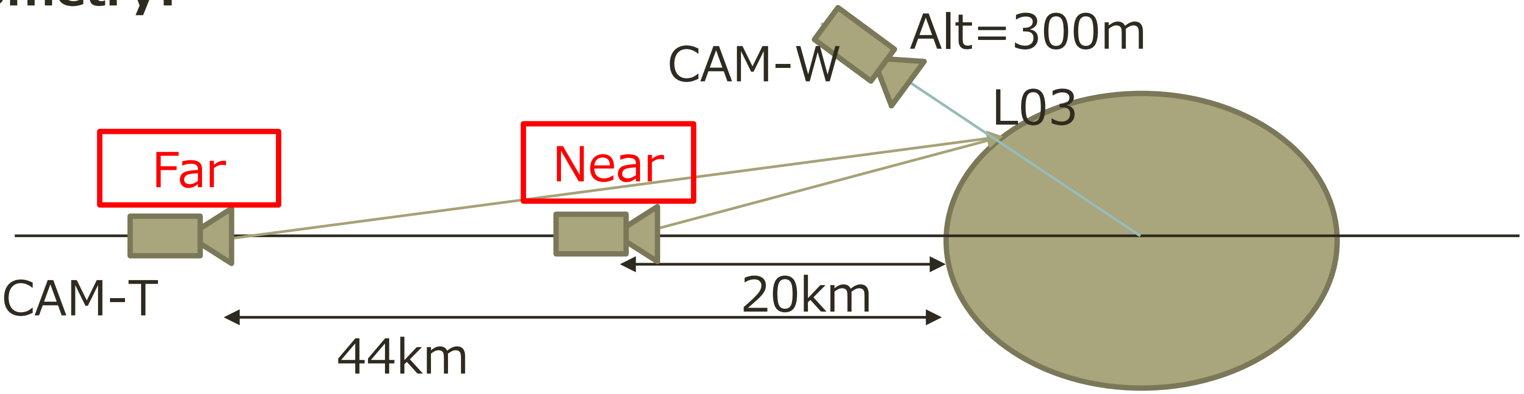
- Template size (px) : 128 x 128
- Target image size (px) : 1024 x 1024
- Landing point : L03 (Candidate site)
- Solar conditions:
  - Target image
    - EL= 145°, AZ= 40° (FIX)
  - Template
    - EL, AZ = Variables
- Model : Hapke reflectance

L03 Landing candidate site

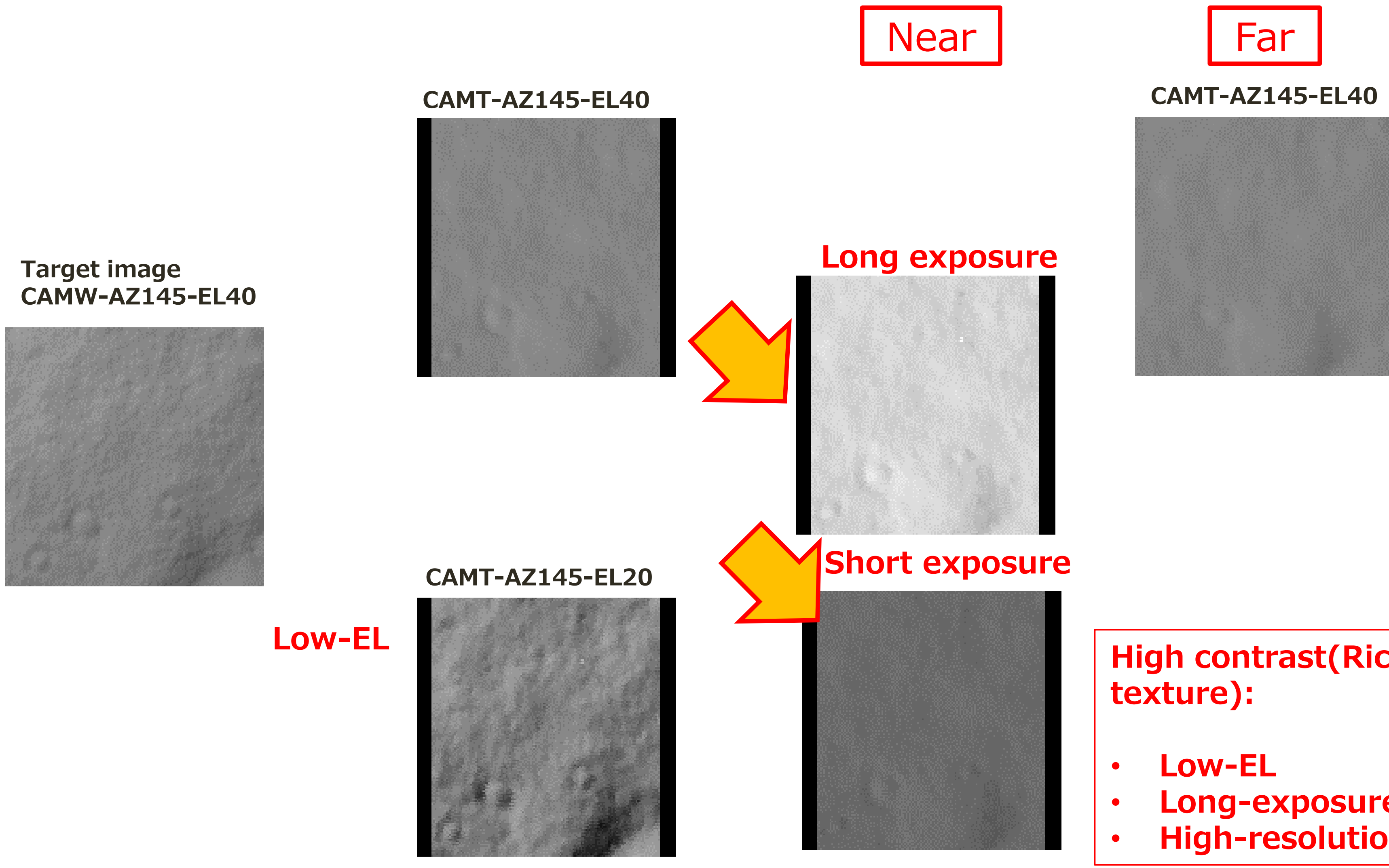
(Lat, Lon = 25.8°, −164.6°)



Geometry:



- Sources of template (after resampling)



High contrast(Rich texture):

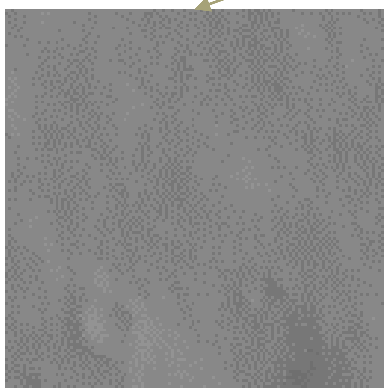
- **Low-EL**
- **Long-exposure**
- **High-resolution**

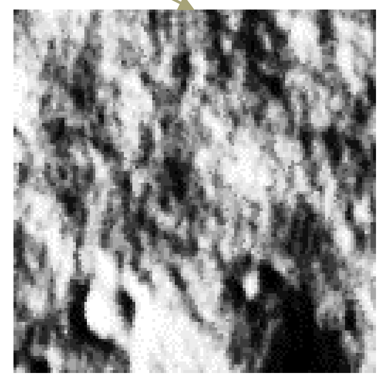
Histogram equalization

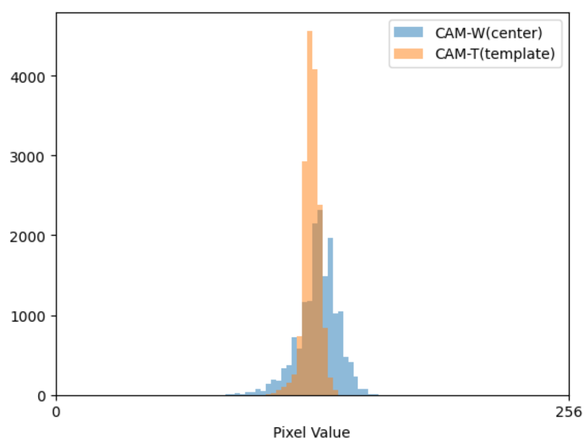
- To enhance contrast of template, histogram equalization is applicated to CAM-T image (cv2.equalizeHist)
- Average brightness should be set to 128

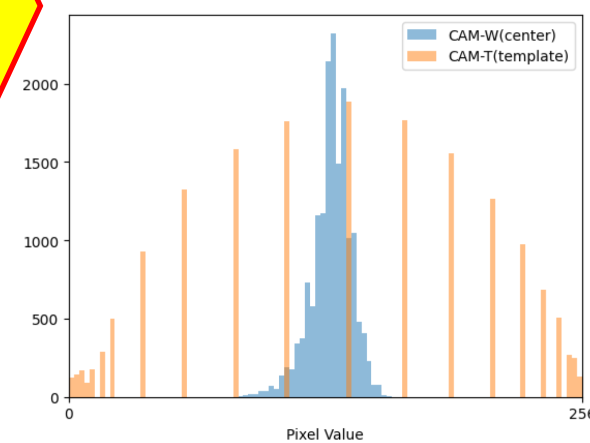
Target image
CAMW-AZ145-EL40

Source of template
AZ145-EL40







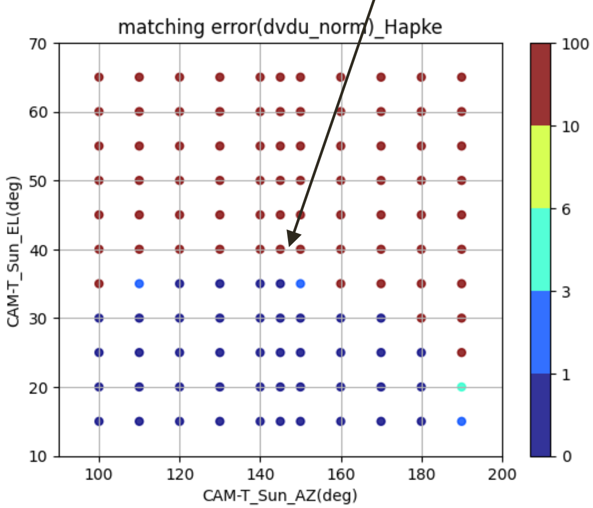


Accuracy test against solar condition

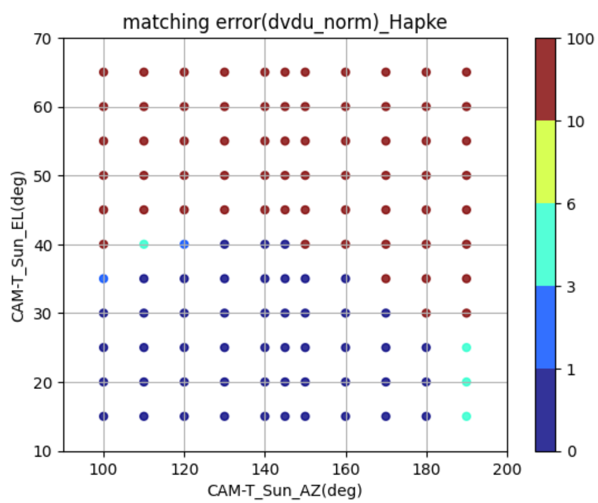
- Robustness can be increased by histogram equalization
- Matching algorithm = NCC

Near-side

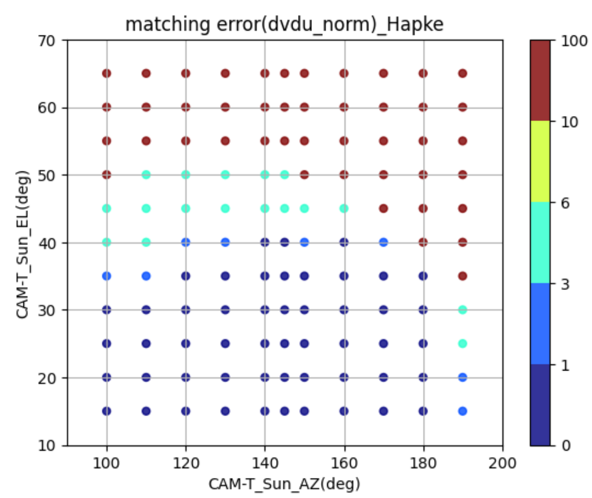
CAM-W
AZ,EL



Long exposure



Histogram equalization



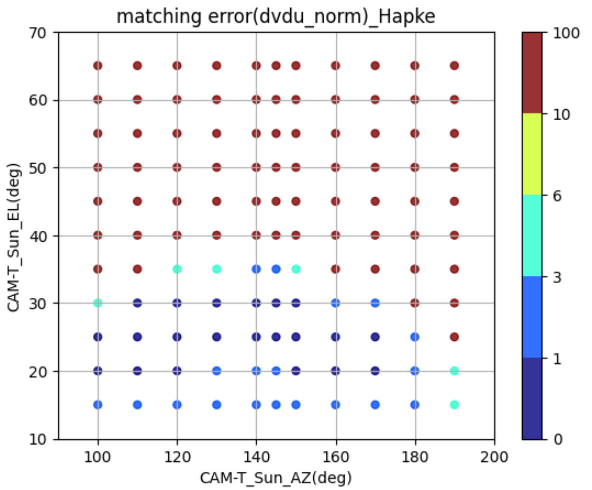
Accuracy test against solar condition

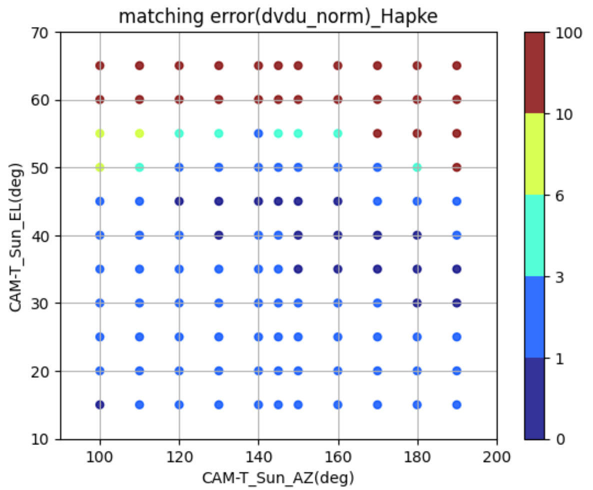
- Robustness can be increased by histogram equalization and oblique viewing
- Matching algorithm = NCC

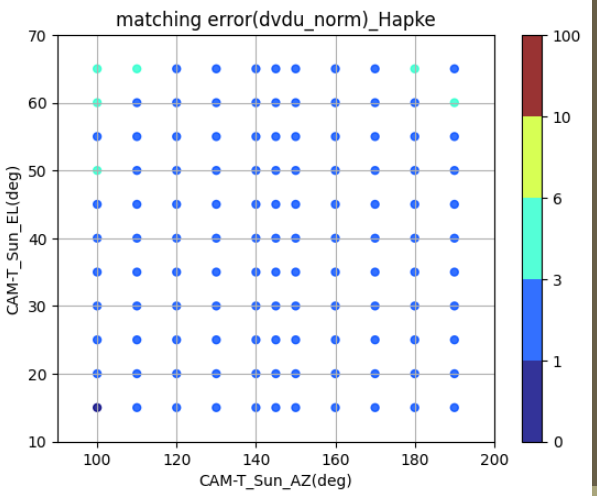
Far-side

Histogram equalization

Oblique viewing + Histogram equalization



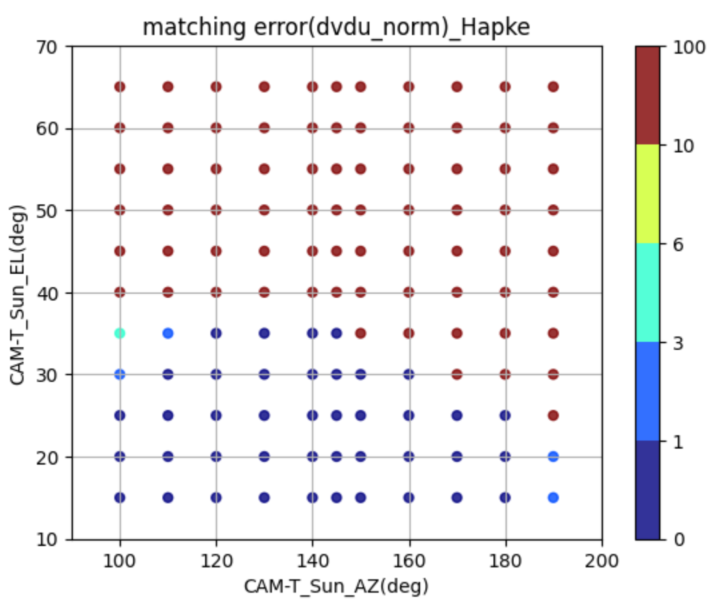




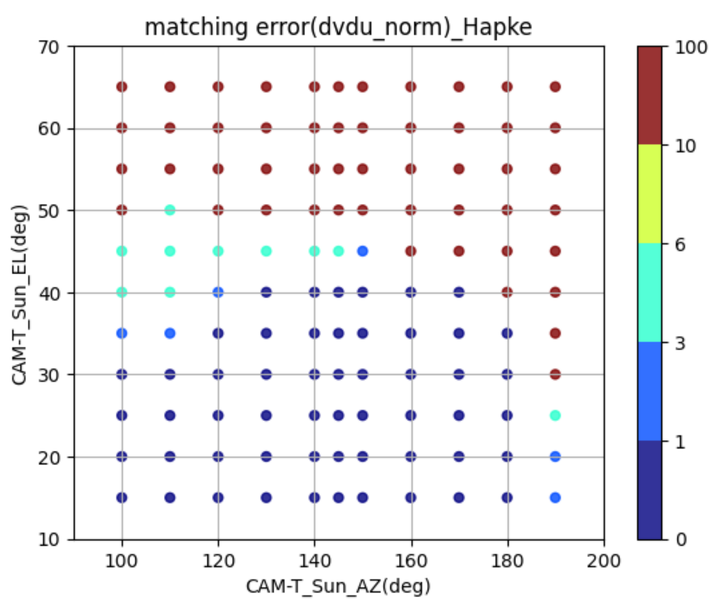
Accuracy test against solar condition

- Robustness can be increased by histogram equalization
- Matching algorithm = SAD

Near-side



Histogram equalization

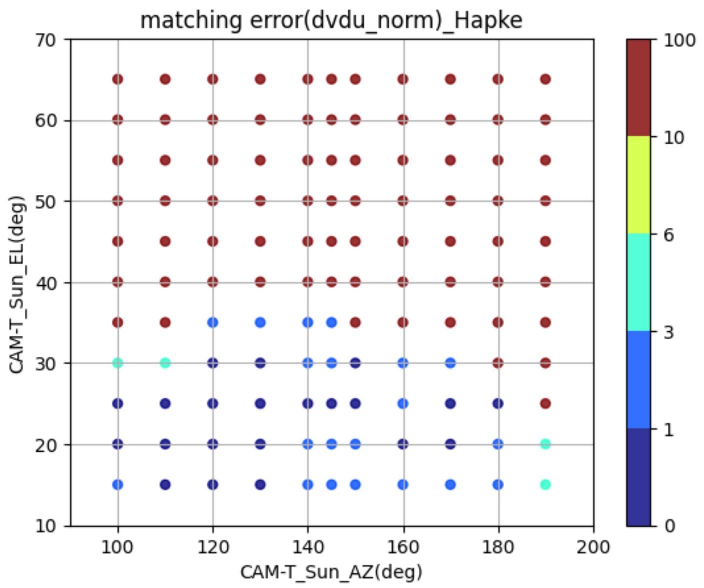


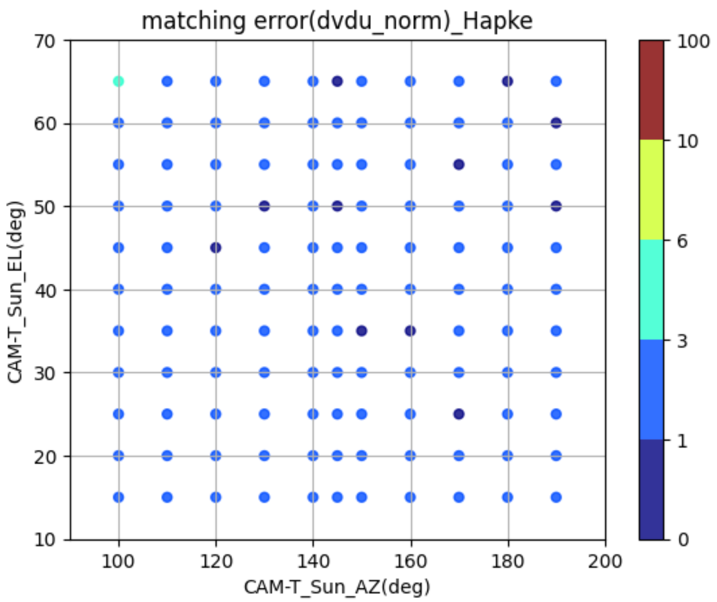
Accuracy test against solar condition

- Robustness can be increased by histogram equalization and oblique viewing
- Matching algorithm = SAD

Far-side

Oblique viewing + Histogram equalization





Conclusion & operation strategy

- Initial template matching accuracy and robustness is very important for safety landing of MMX.
- Pre-processing by Histogram equalization for template is effective for the robustness against solar condition, especially even when utilizing small cost algorithm SAD/NCC. It can keep accuracy and robustness regardless of small resource and cost navigation.
- Nevertheless, lower sun elevation than that of decent operation (CAM-W) is better (Around EL=20-40°) .
- In the case of far-side, oblique viewing is required to gain resolution.

- **Applications of this study:**
  - Not only initial template matching but also other (after 2nd) matchings (if some templates can be uploaded considering spacecraft resource).
  - Not only small body landing mission but also other navigation mission (e.g., earth satellite, docking, debris, and so on) because template matching is simple algorithm and commonly used.

ご清聴ありがとうございました

Thank you for your attention

References

- [1] High Performance Embedded Computing in Space: Evaluation of Platforms for Vision Based Navigation, George Lentaris, et al , Journal of Aerospace Information Systems, Vol . 15, No. 4, April 2018
- [2] A Survey of Vision-based Navigation Technology for Spacecraft, Ishida et al., JAXA-RM-19-005
- [3]ISAS News No.469
- [4] A NASA GN&C Viewpoint on On Board Processing Challenges to Support Optical Navigation & Other Autonomous GN&C Critical Functions, C.J.Dennehy, A.Wolf, European Workshop on On Board Data Processing (OBDP2019) 25-27 February 2019 ESA/ESTEC Noordwijk, The Netherlands
- [5] Ari Jonsson, Autonomy in Space Current Capabilities and Future Challenges AI Magazine Volume 28 Number 4 (2007)
- [6]擬周回軌道上からの画像撮影による着陸目標点の地表面傾斜角推定, 岡田, 2022
- [7]火星衛星探査計画MMX 航法誘導制御系の独立検証, 巳谷, 宇宙科学技術連合会, 2022