Performance Characterization of a Landmark Measurement System for ARRM Terrain Relative Navigation

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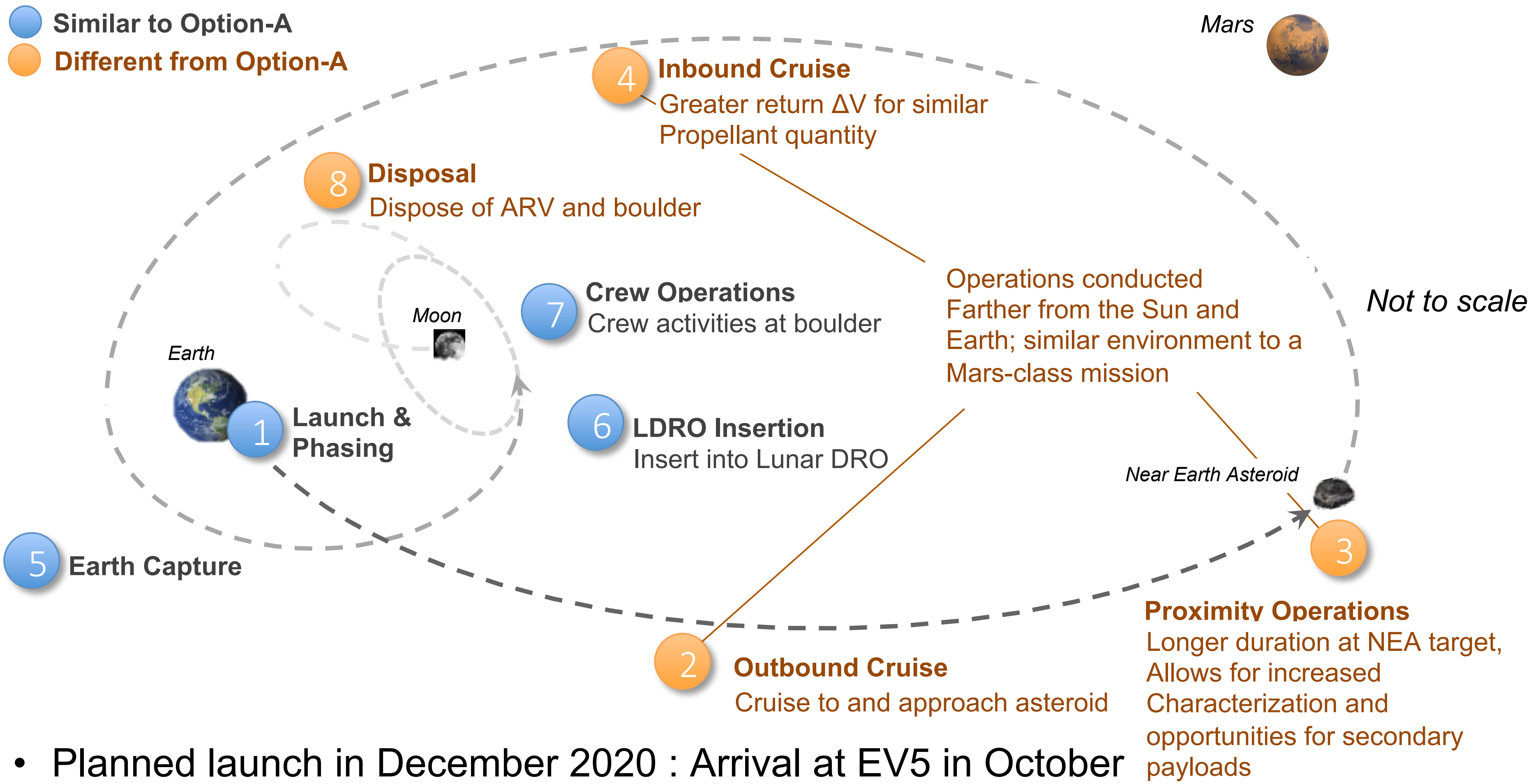
ARRM and ARM Overviews

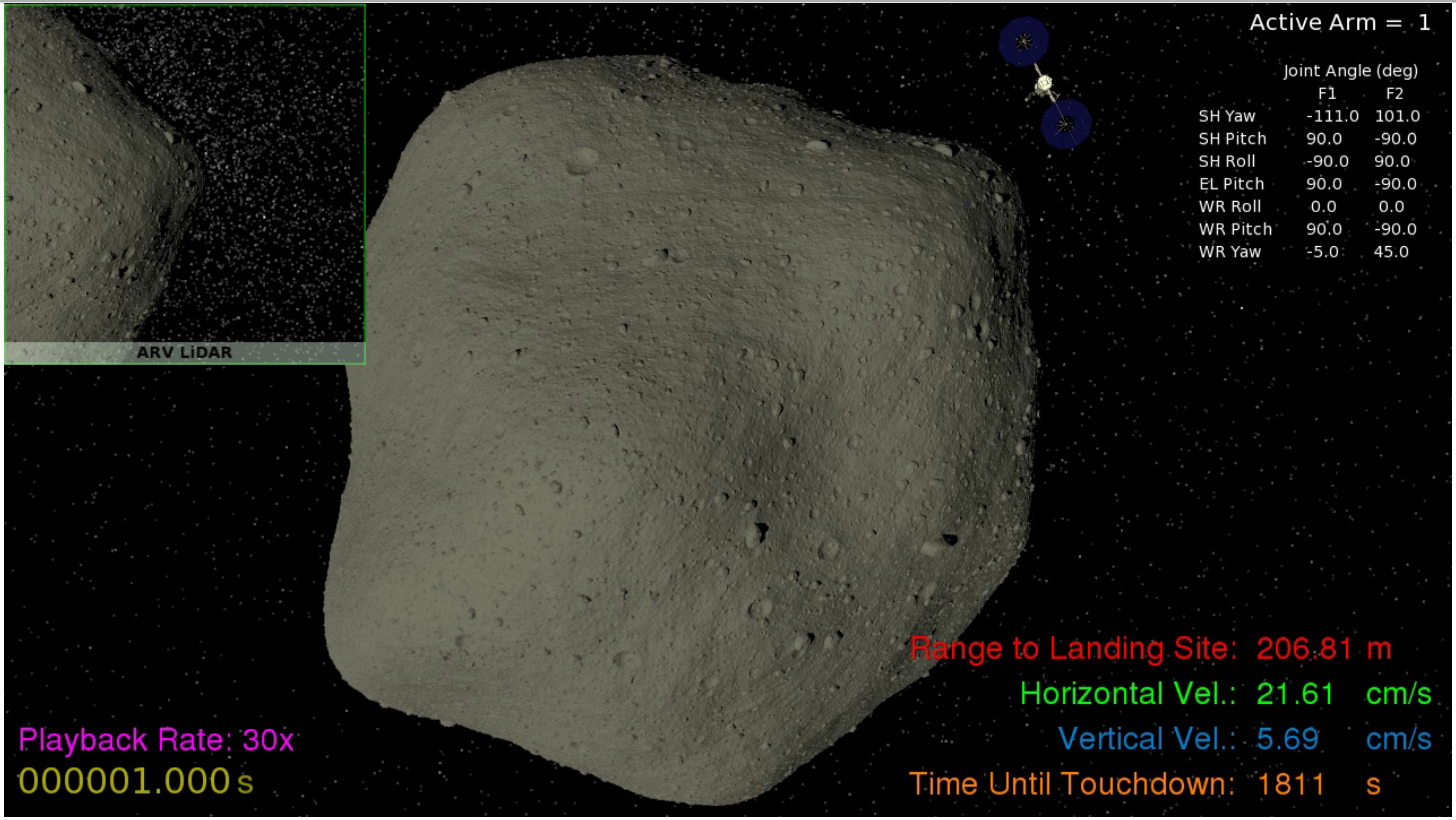


- Planned launch in December 2020 : Arrival at EV5 in October 2022 : Return to Earth (with boulder) in late 2025
- Light times necessitate autonomous landing, boulder retrieval and ascent

M. Shoemaker et al., AAS/AIAA Space Flight Mechanics Meeting, Napa, CA, 2016

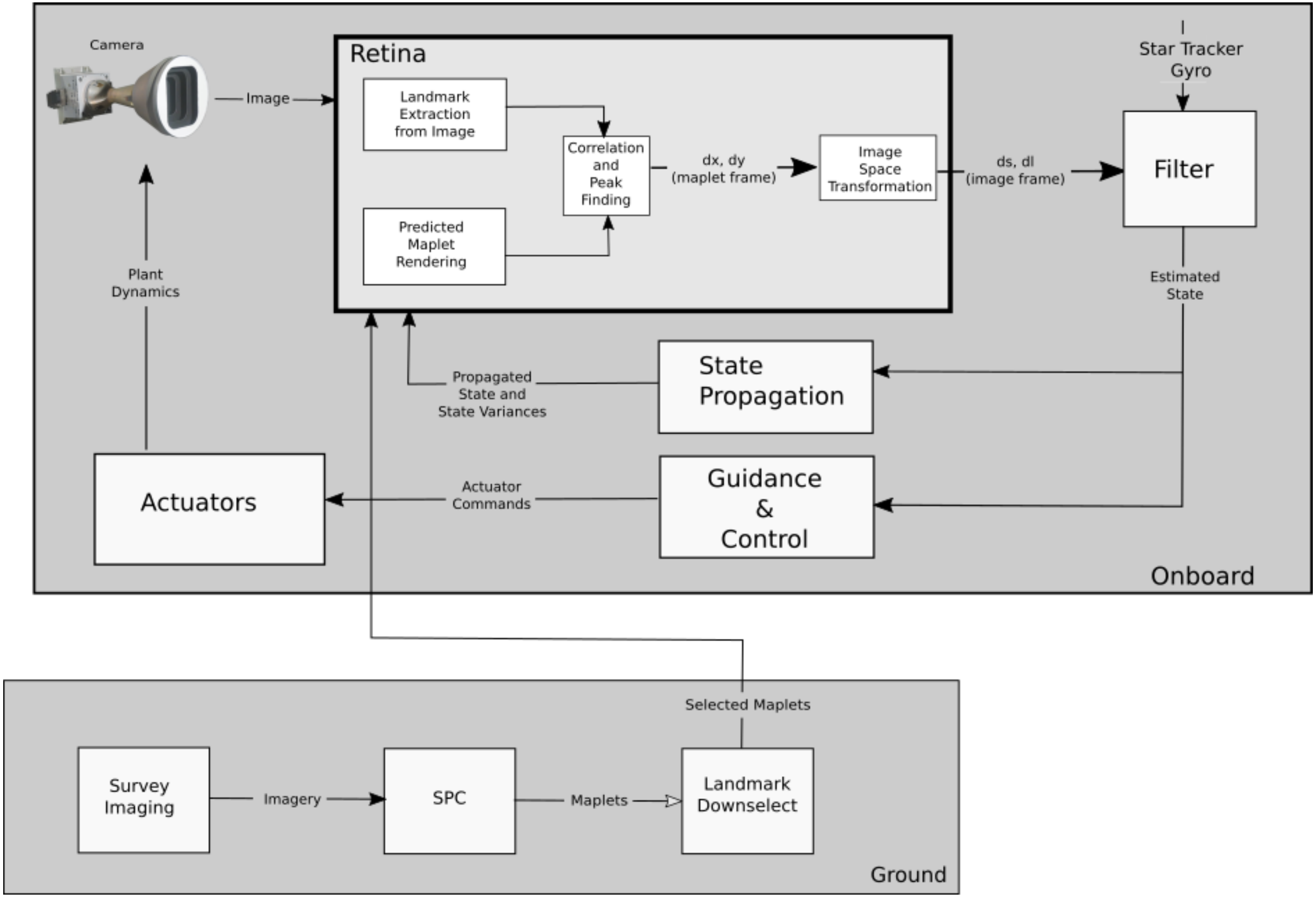
ARRM Overview

Credit: Alex Pini and Marcelo Gonzalez



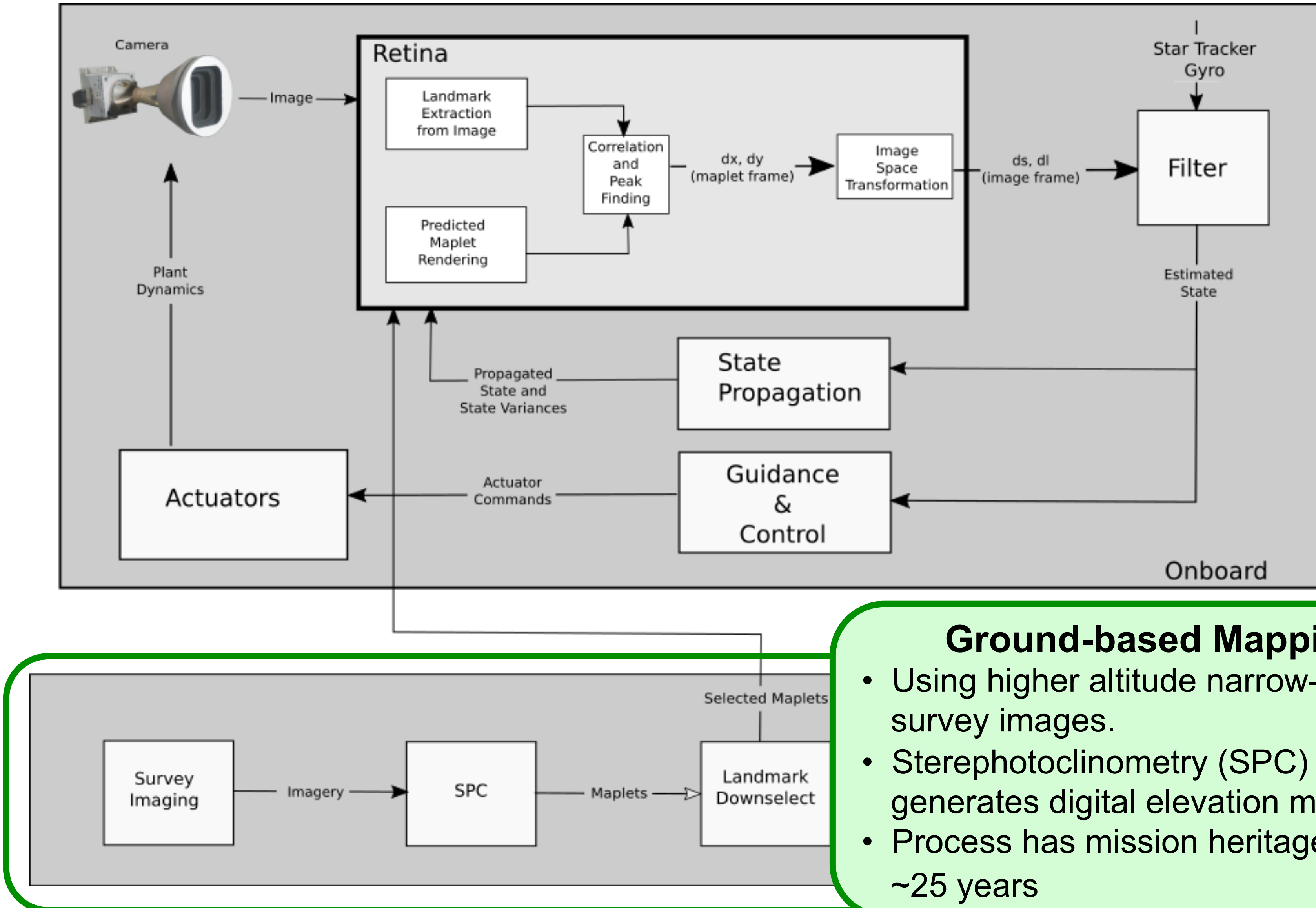
- Transition from the 5 km hold point to 200 m waypoint on pre-defined burn
- 200 m waypoint to 50 m also performed on a pre-defined burn
- 50 m to 20 m descent and asteroid spin rate matching performed with closed loop control
- No thrusting towards surface after 20 m

Overview



Camera
Image
Retina
Landmark Extraction from Image
Correlation and Peak Finding
Predicted Maplet Rendering
dx, dy (maplet frame)
Image Space Transformation
ds, dl (image frame)
Star Tracker
Gyro
Filter
Estimated State
Plant Dynamics
Propagated State and State Variances
State Propagation
Actuators
Actuator Commands
Guidance & Control
Onboard
Selected Maplets
Survey Imaging
Imagery
SPC
Maplets
Landmark Downselect
Ground

Overview



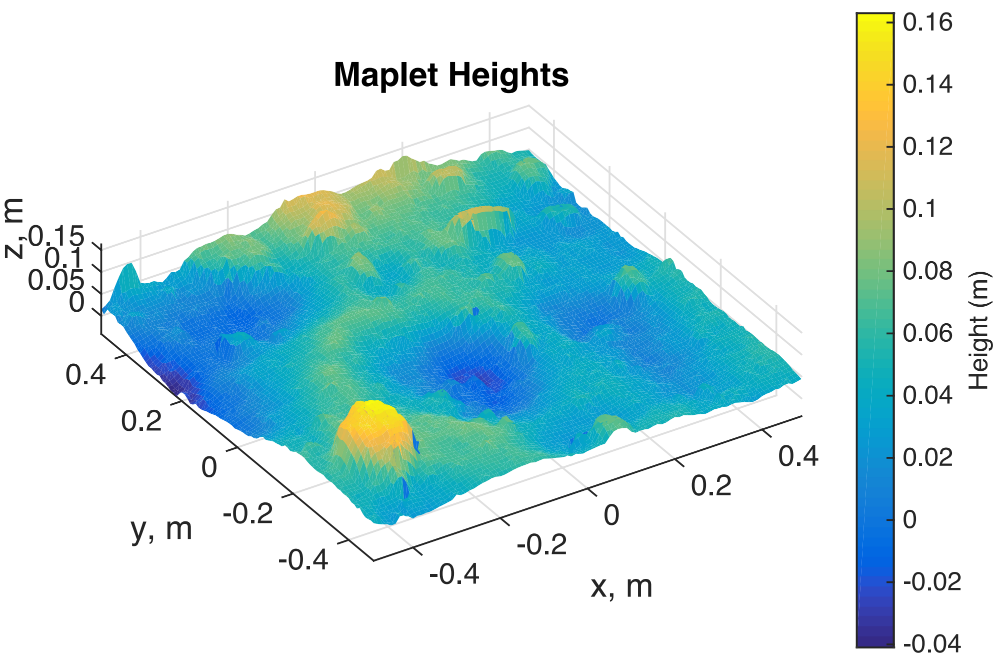
Ground-based Mapping

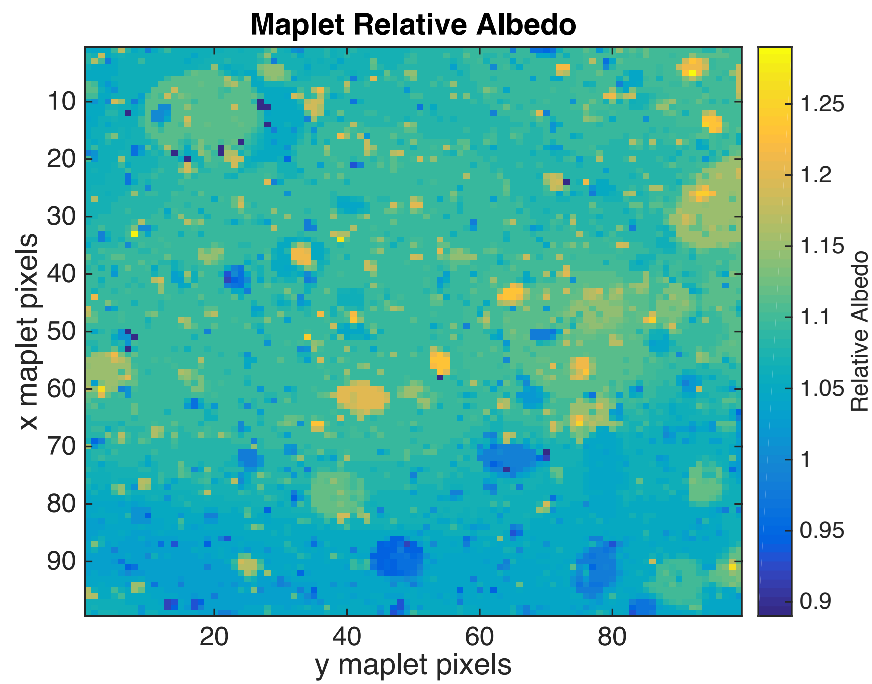
- Using higher altitude narrow-FOV survey images.
- Sterephotoclinometry (SPC) generates digital elevation maps.
- Process has mission heritage over ~25 years

Landmark and Maplet Definitions

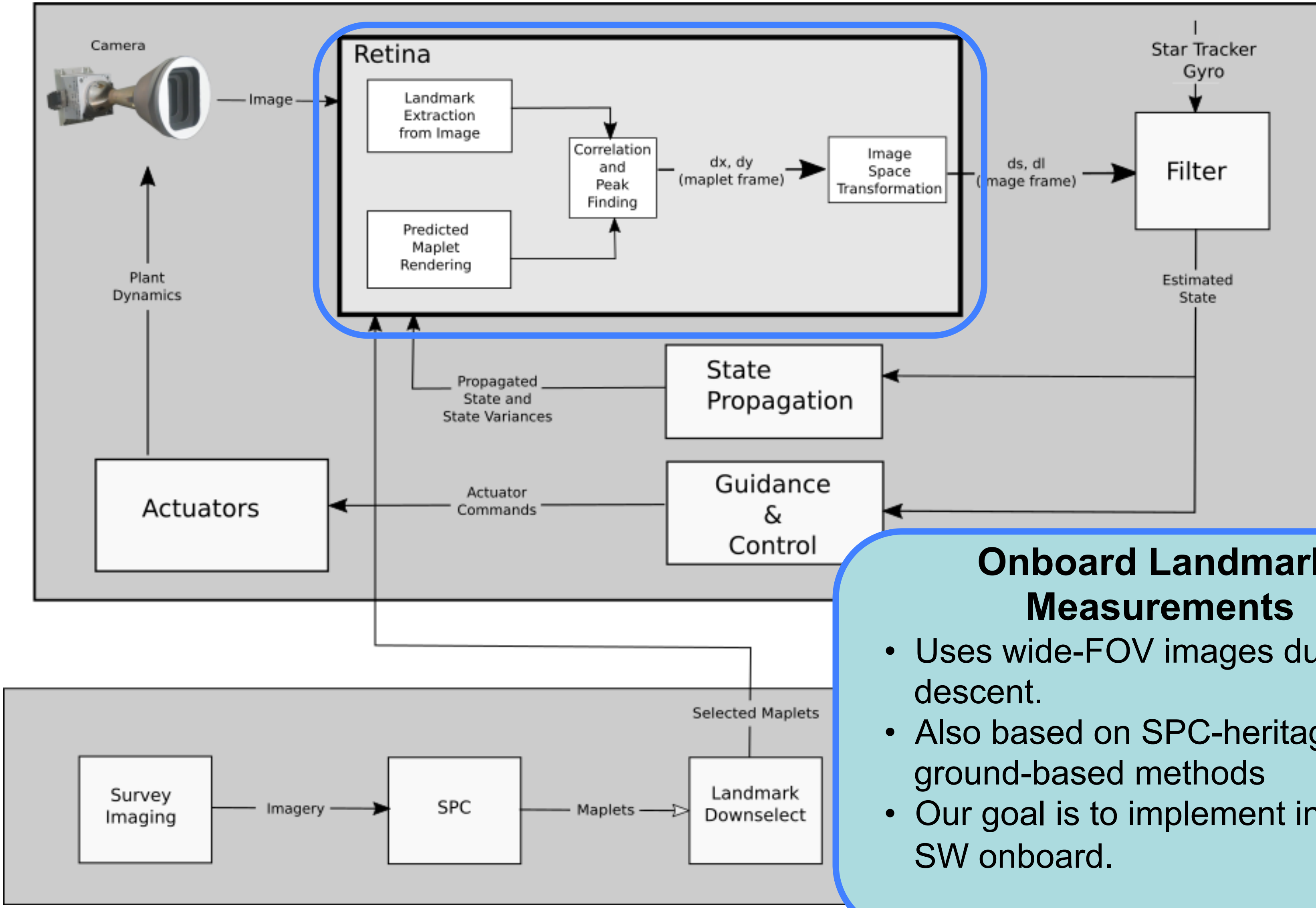
Terminology:

- Maplets – small maps that tile the surface
- Landmark – origin of a maplet





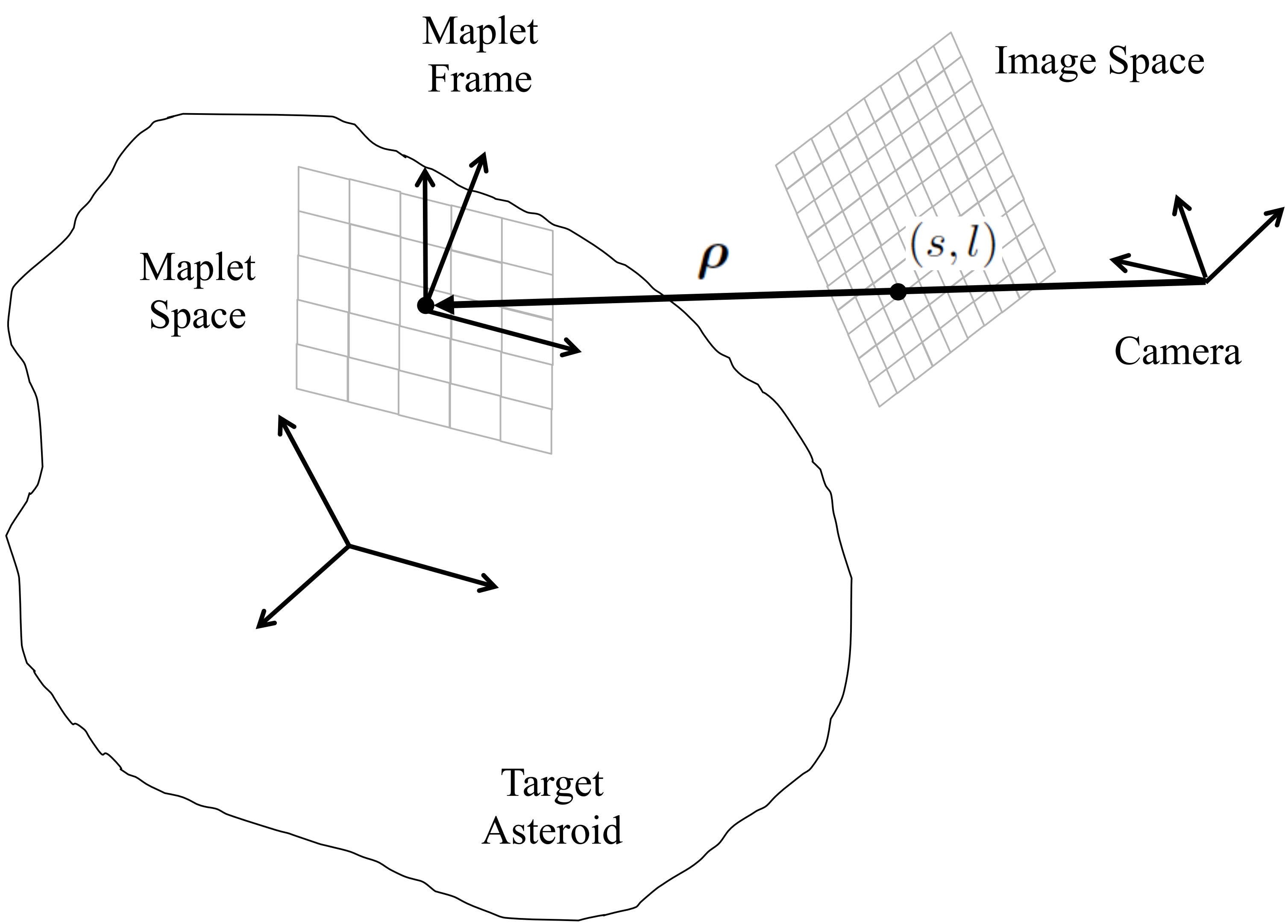
Overview



Onboard Landmark Measurements

- Uses wide-FOV images during descent.
- Also based on SPC-heritage ground-based methods
- Our goal is to implement in flight SW onboard.

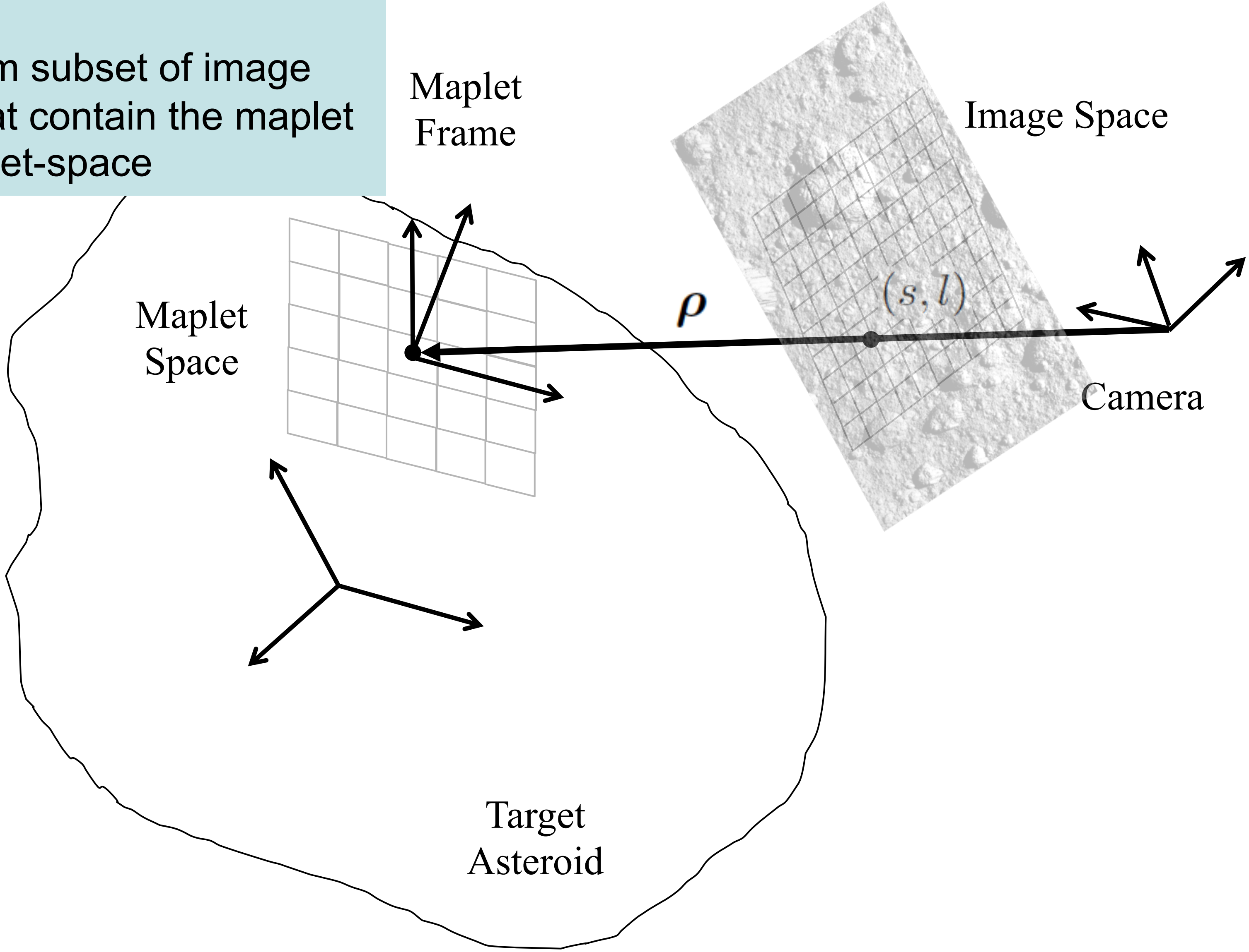
Landmark Measurement Process



M. Shoemaker et al., AAS/AIAA Space Flight Mechanics Meeting, Napa, CA, 2016

Step 1:

- Transform subset of image pixels that contain the maplet into maplet-space



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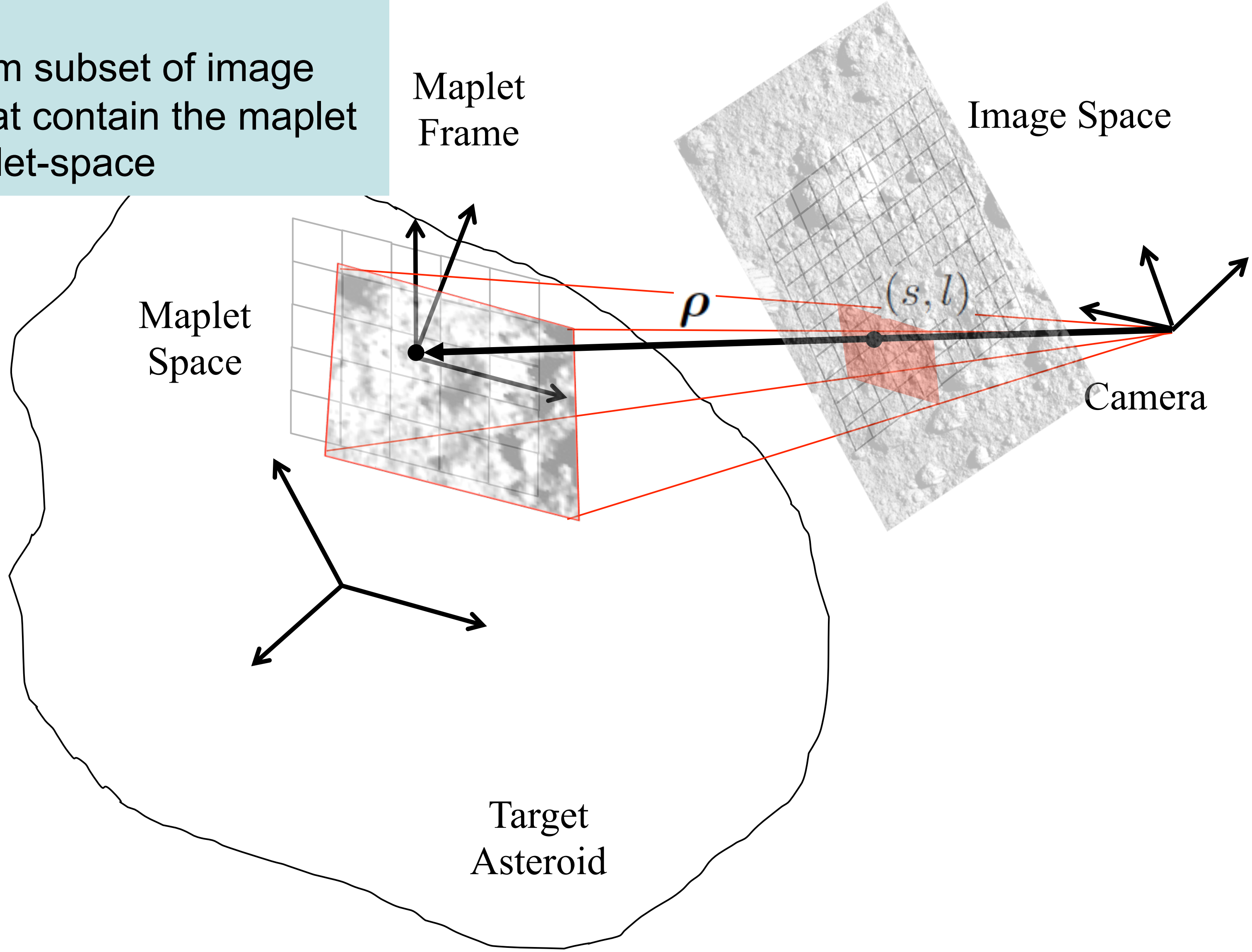
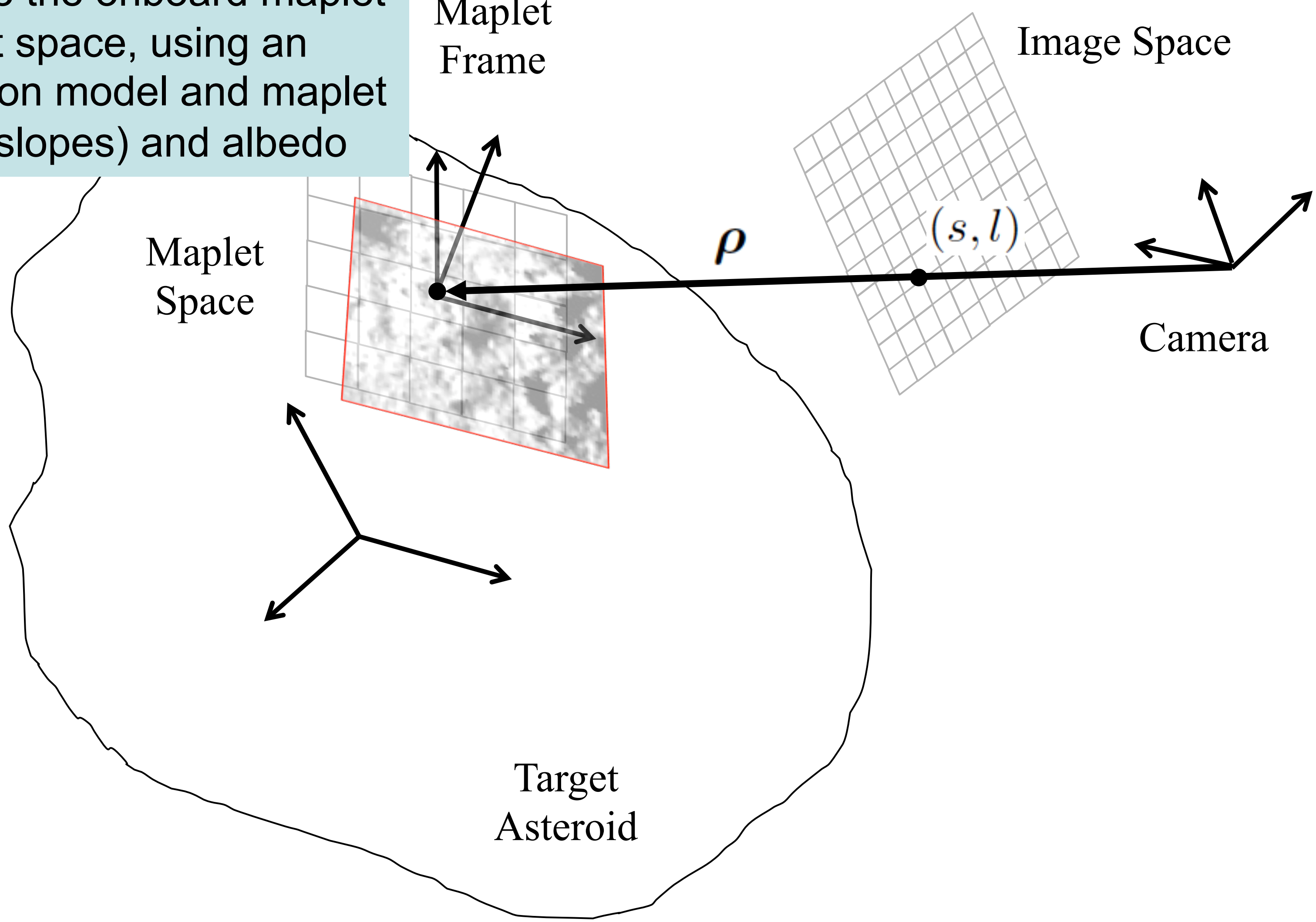


Landmark Measurement Process

Step 2:

- Illuminate the onboard maplet in maplet space, using an illumination model and maplet heights (slopes) and albedo



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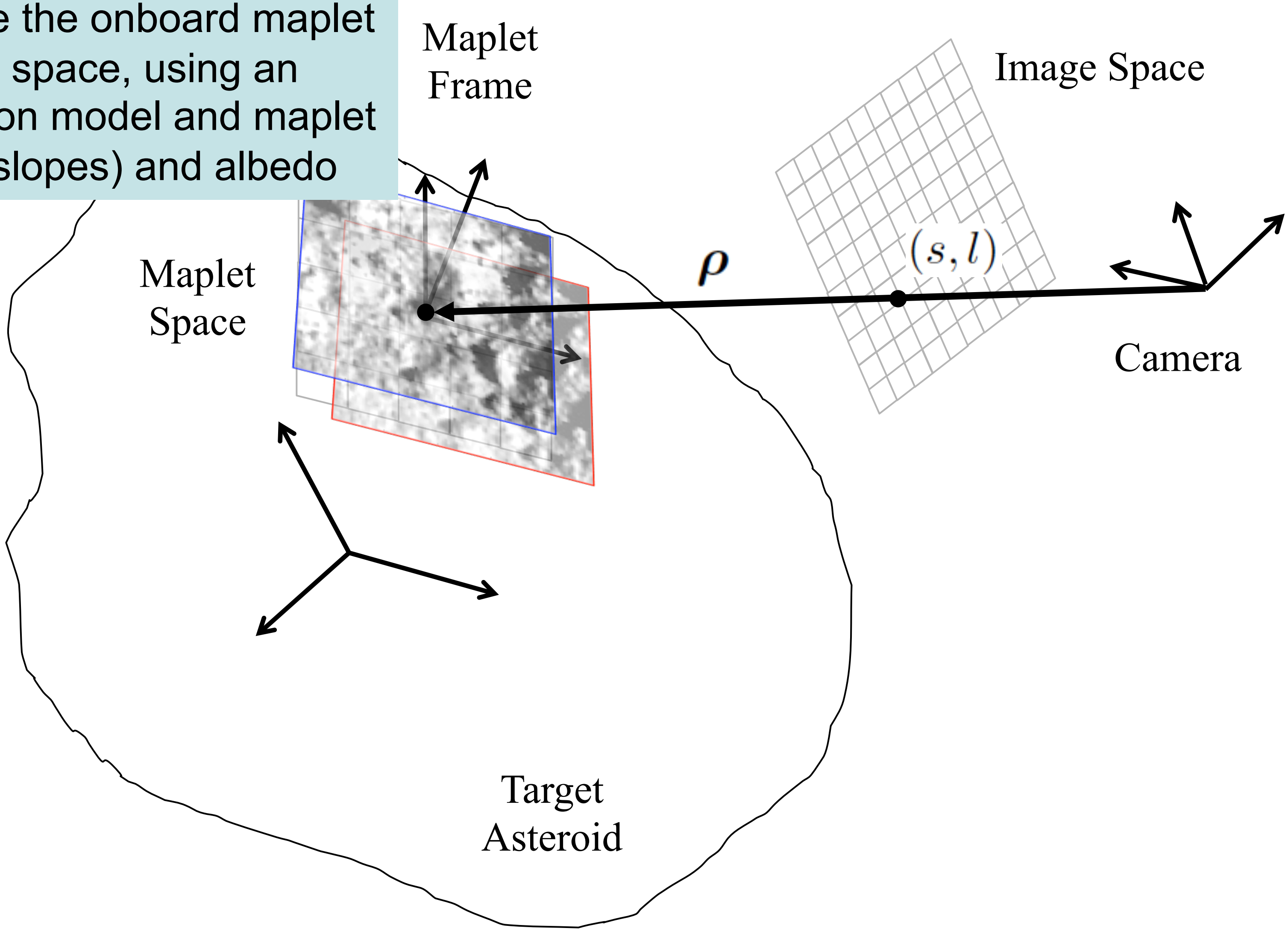
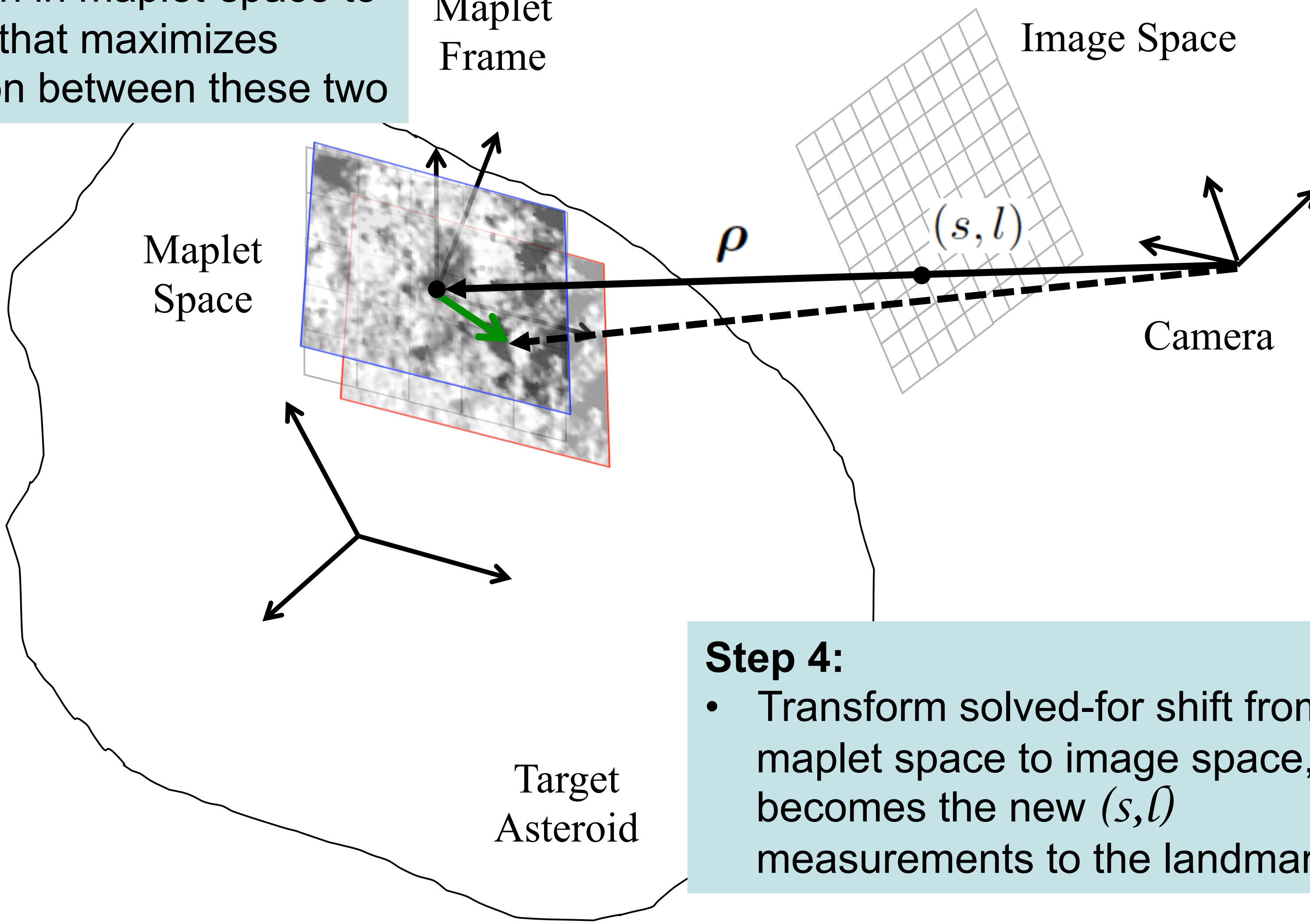


Landmark Measurement Process

Step 3:
- 2D search in maplet-space to find shift that maximizes correlation between these two



Step 4:
- Transform solved-for shift from maplet space to image space, becomes the new *(s,l)* measurements to the landmark

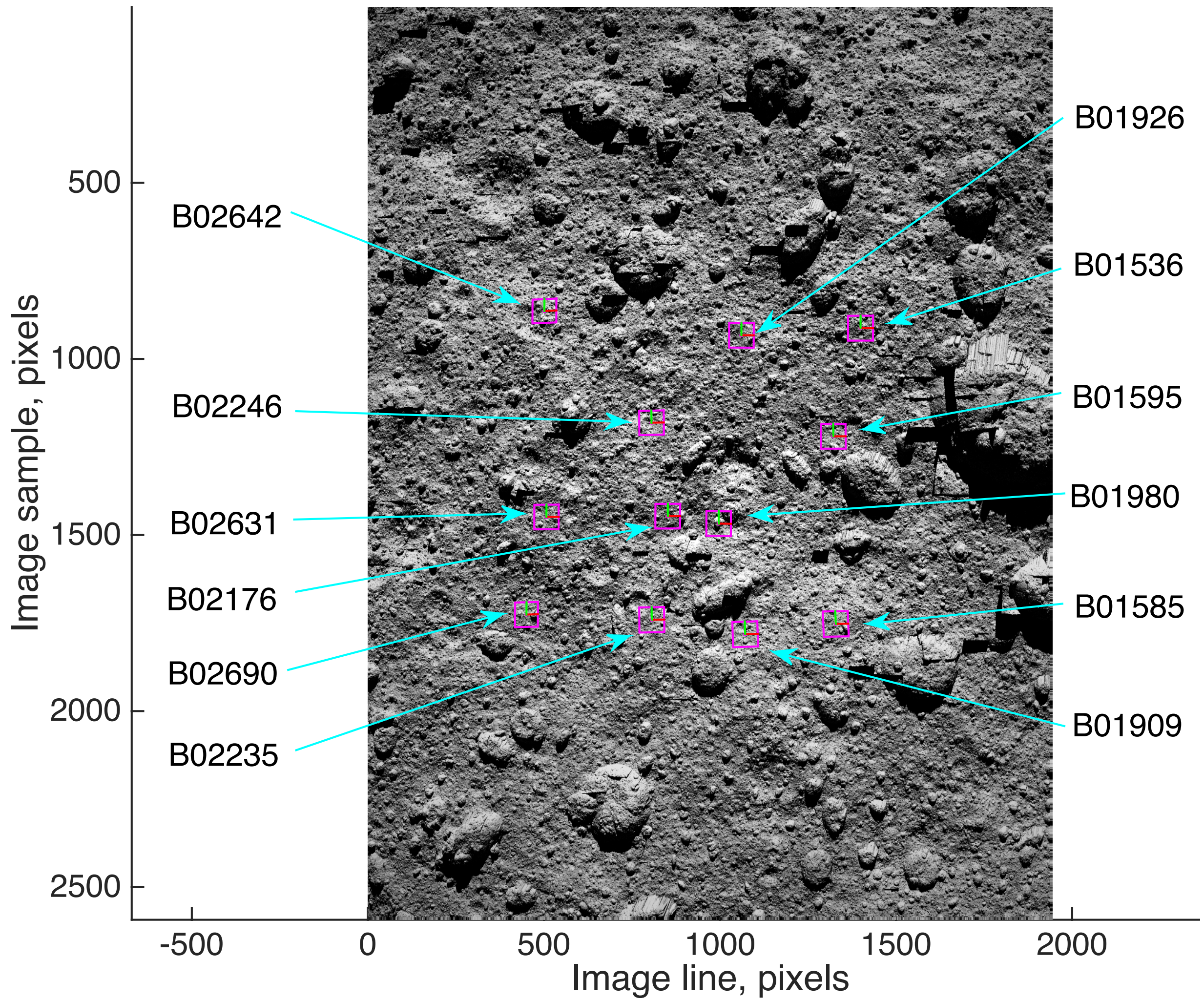
Performance Characterization

- How do errors in these parameters affect the errors in the landmark *(s,l)* measurements?
- These errors represent onboard navigation error, camera model errors, and asteroid model errors.

Parameter or state to perturb	1-σ std applied
Asteroid-relative spacecraft position $\mathbf{r}_{\mathrm{sc}}$, each component	0.1667 m
Asteroid-relative spacecraft attitude, each component	0.05 deg
Asteroid-relative landmark position $\mathbf{r}_{\mathrm{lm}}$, each component	3.33 cm
Maplet terrain height $z(x, y)$	3.33 mm
Maplet terrain albedo $a(x, y)$	0.047
Camera model pixel skew K_{yx}	1×10^{-5}
Camera model principle coordinates (s_0, l_0)	0.1667 pixels
Camera model focal length f	0.004 mm
Camera model distortion coefficients $\boldsymbol{\epsilon}$	$(1 \times 10^{-5}, 1 \times 10^{-7}, 1 \times 10^{-5}, 1 \times 10^{-5}, 0, 0)$
Asteroid-relative sun vector direction, RA and DEC	0.3 deg

Performance Characterization

- Selected 12 landmarks and tested at 50-m altitude



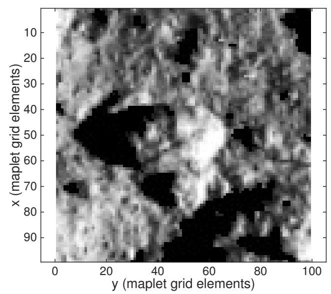
- Camera and Detector Parameters:

Parameter	Value
Detector horiz. resolution	2592 pixels
Detector vert. resolution	1944 pixels
Focal length, f	7.68 mm
Detector pixel dimensions	2.2 x 2.2 microns
Camera horiz. FOV	40.7 deg
Camera vert. FOV	31.1 deg

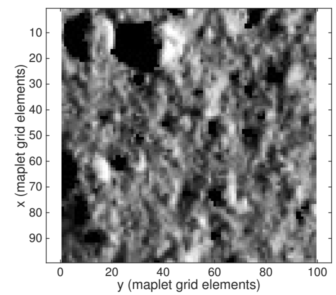
M. Shoemaker et al., AAS/AIAA Space Flight Mechanics Meeting, Napa, CA, 2016

Performance Characterization

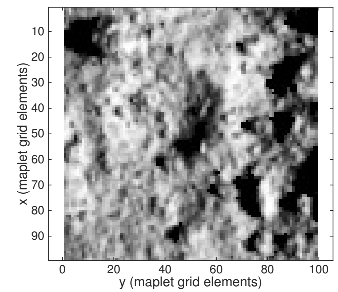
- The illuminated maplet data from these 12 landmarks at 50-m alt.:



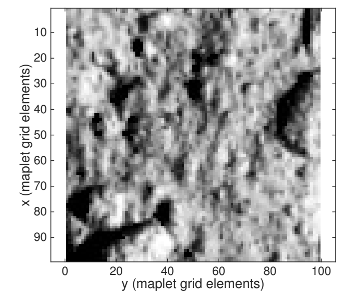
(a) B01980



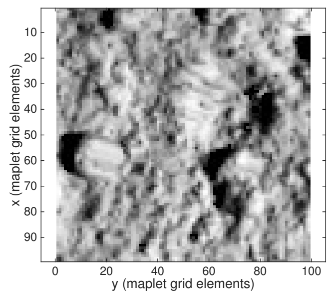
(b) B02176



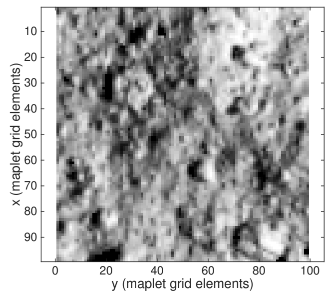
(c) B02246



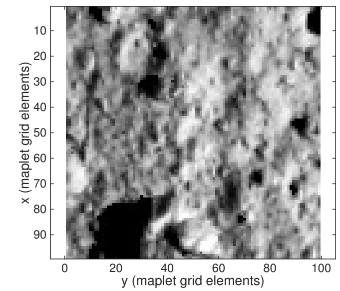
(d) B01585



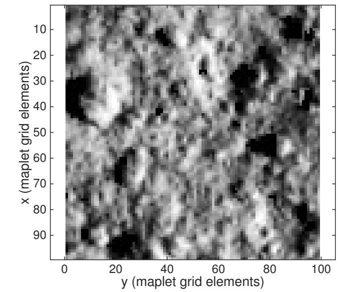
(e) B01909



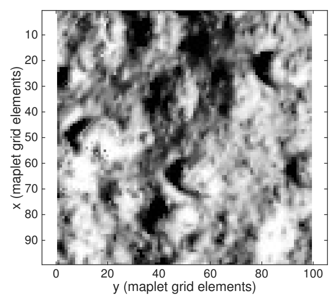
(f) B02235



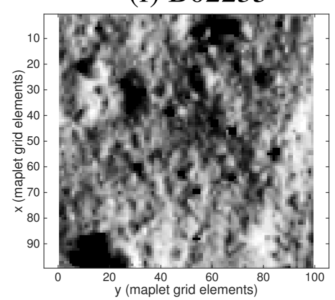
(g) B02690



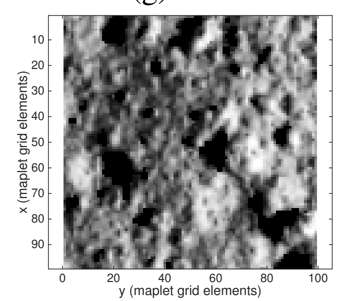
(h) B02631



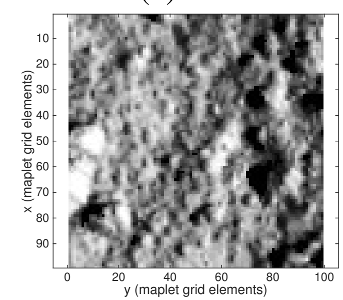
(i) B02642



(j) B01926



(k) B01536



(l) B01595

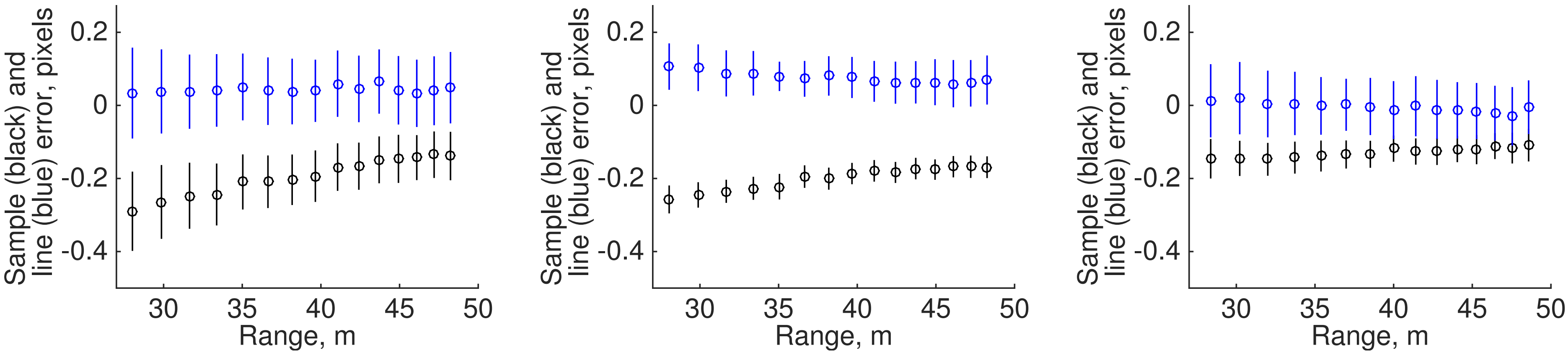
Performance Characterization

- Ran Monte Carlo sims (with Latin Hypercube Sampling) of 500 runs per landmark:

L-map ID	Sample error mean [pix]	Line error mean [pix]	Sample error std [pix]	Line error std [pix]	Num. not found	Num. below thresh.	Success Rate
B01980	-0.136	0.048	0.062	0.096	42	15	0.89
B02176	-0.163	0.053	0.028	0.066	23	25	0.90
B02246	-0.111	-0.027	0.041	0.082	31	18	0.90
B01585	-0.041	0.054	0.033	0.082	36	20	0.89
B01909	-0.049	0.081	0.043	0.085	36	15	0.90
B02235	-0.139	0.068	0.025	0.071	39	12	0.90
B02690	-0.052	-0.056	0.043	0.097	52	16	0.86
B02631	-0.107	-0.069	0.038	0.076	37	13	0.90
B02642	-0.117	0.007	0.058	0.113	46	15	0.88
B01926	-0.193	0.019	0.032	0.078	49	6	0.89
B01536	-0.208	0.118	0.037	0.083	35	19	0.89
B01595	-0.114	0.111	0.041	0.080	33	25	0.88

Performance Characterization

- Repeated Monte Carlo runs at 30-sec. time steps during part of descent for 3 landmarks:

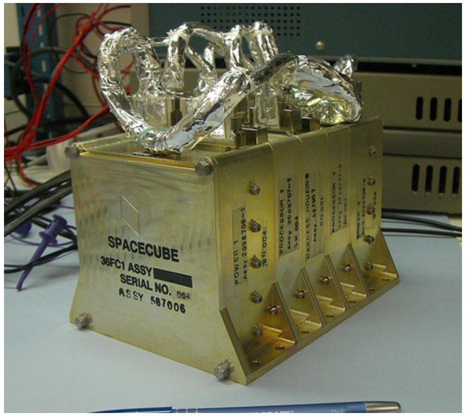


(a) L-map B01980 (b) L-map B02176 (c) L-map B02246

- Errors do not change significantly over these tests

Future Retina Development

- The ~90% success rate in these tests is caused by spacecraft position and attitude navigation errors causing the projected maplet data to only partially overlap.
- Also, the onboard rendering methods derived from SPC only approximate the surface shadows.

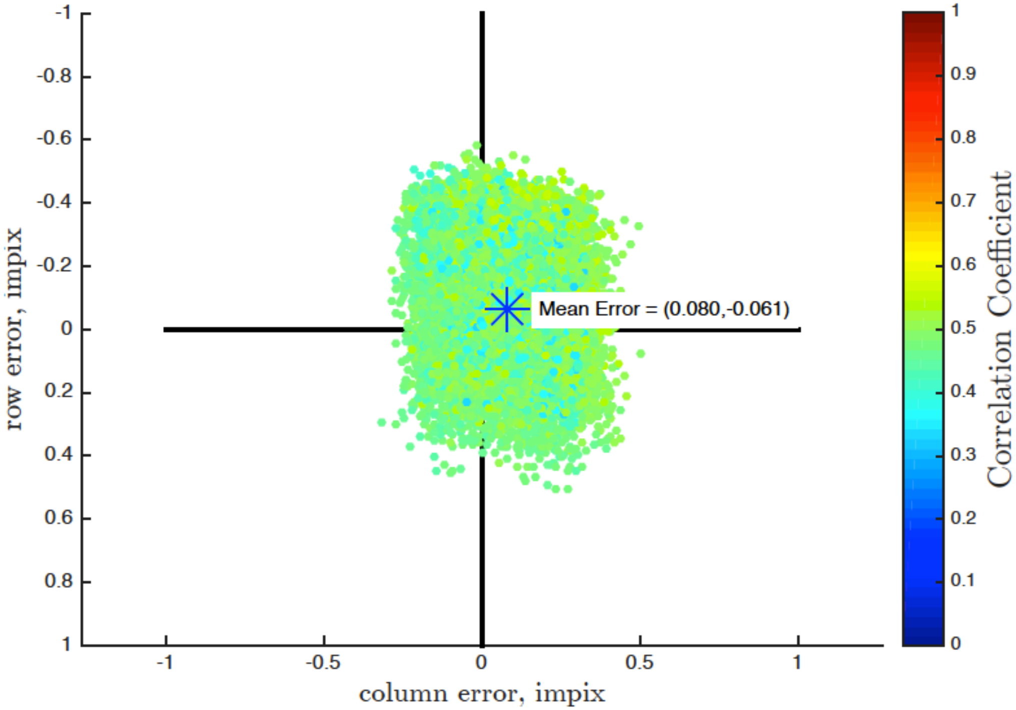


Retina (Relative Terrain Imaging Navigation) is our onboard version being developed with several modifications:

- Improved shadow predictions for onboard renderer.
- Image-space correlations (vs. maplet-space correlations) for more robust data overlaps.
- Goal is to implement on GSFC SpaceCube

Preliminary Retina results:

- Similar MC simulations resulted in 100% success rate and similar sub-pixel errors.



Summary

- Presented the SPC-derived methods for landmark measurements.
- Showed MC simulation results of perturbing the navigational and model parameters. Resulting errors in line-of-sight landmark measurements were acceptable, but more work needs to be done to improve success rate.
- Introduced Retina algorithms and ongoing work at GSFC for eventual flight SW implementation.