National Aeronautics and Space Administration

Relative Terrain Imaging Navigation for the Asteroid Redirect Robotic Mission (ARRM)

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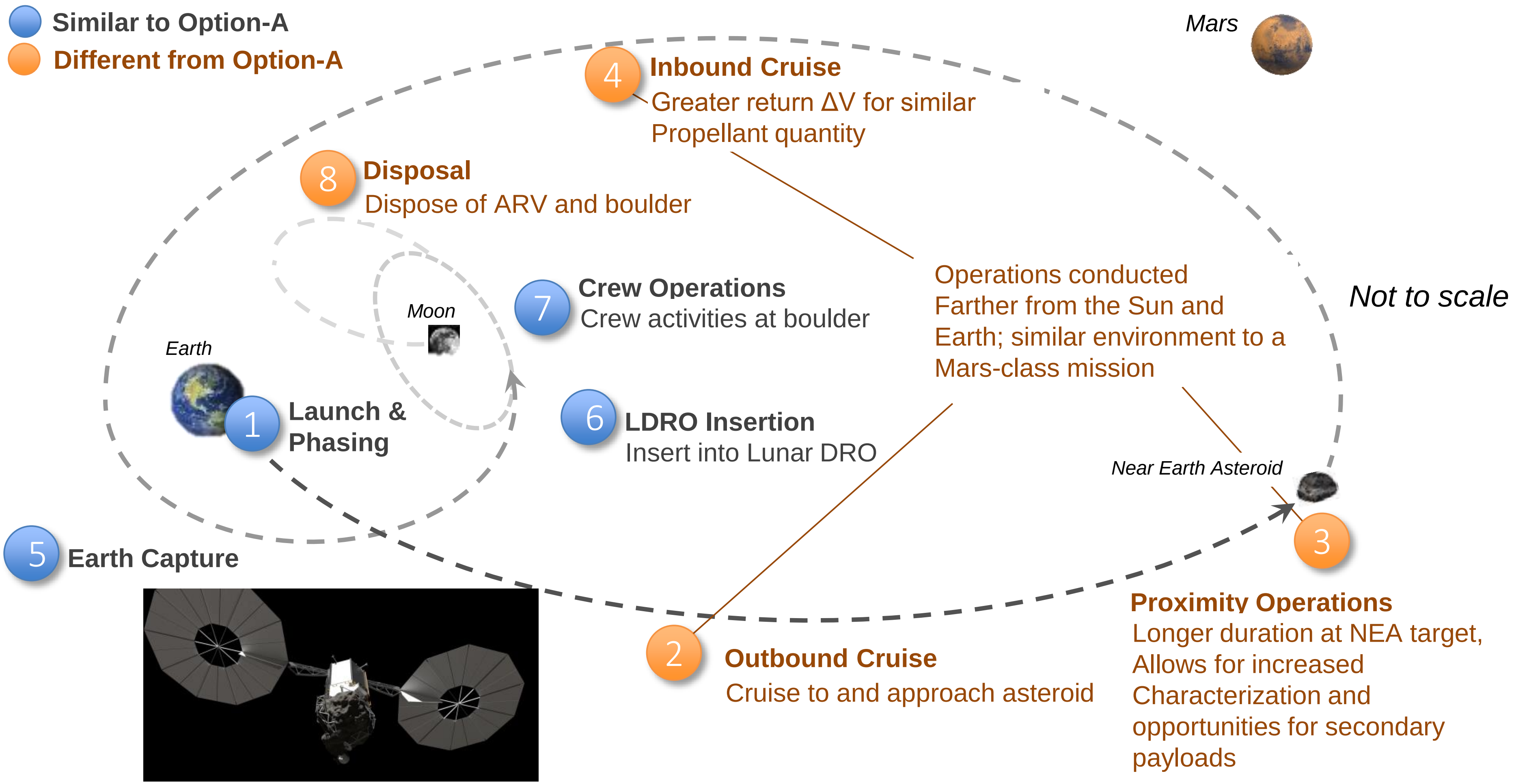
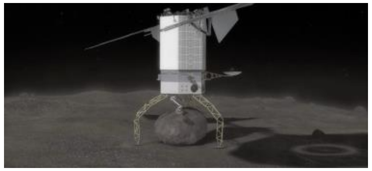
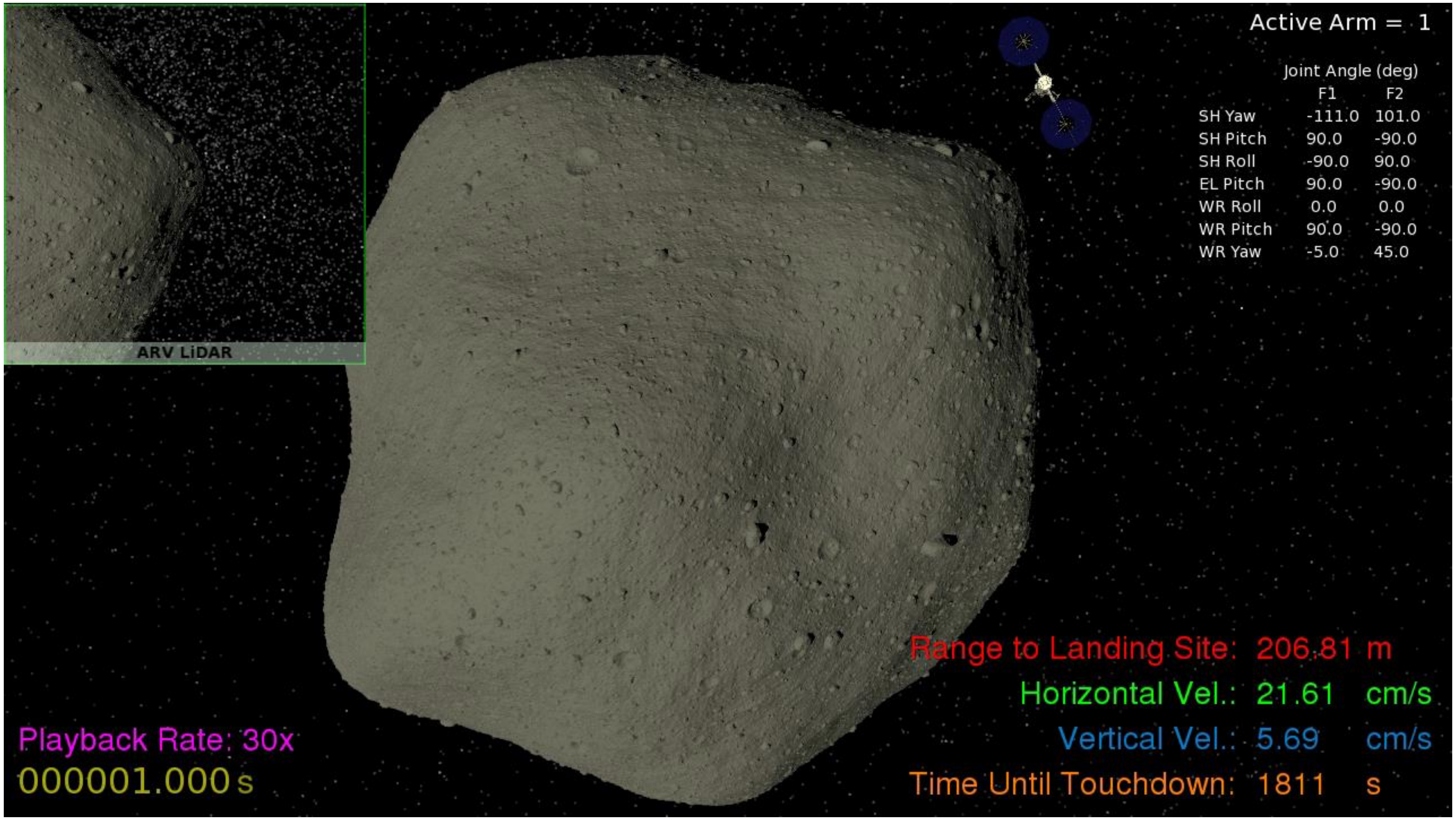
Asteroid Redirect Mission (ARM) Concept



- 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

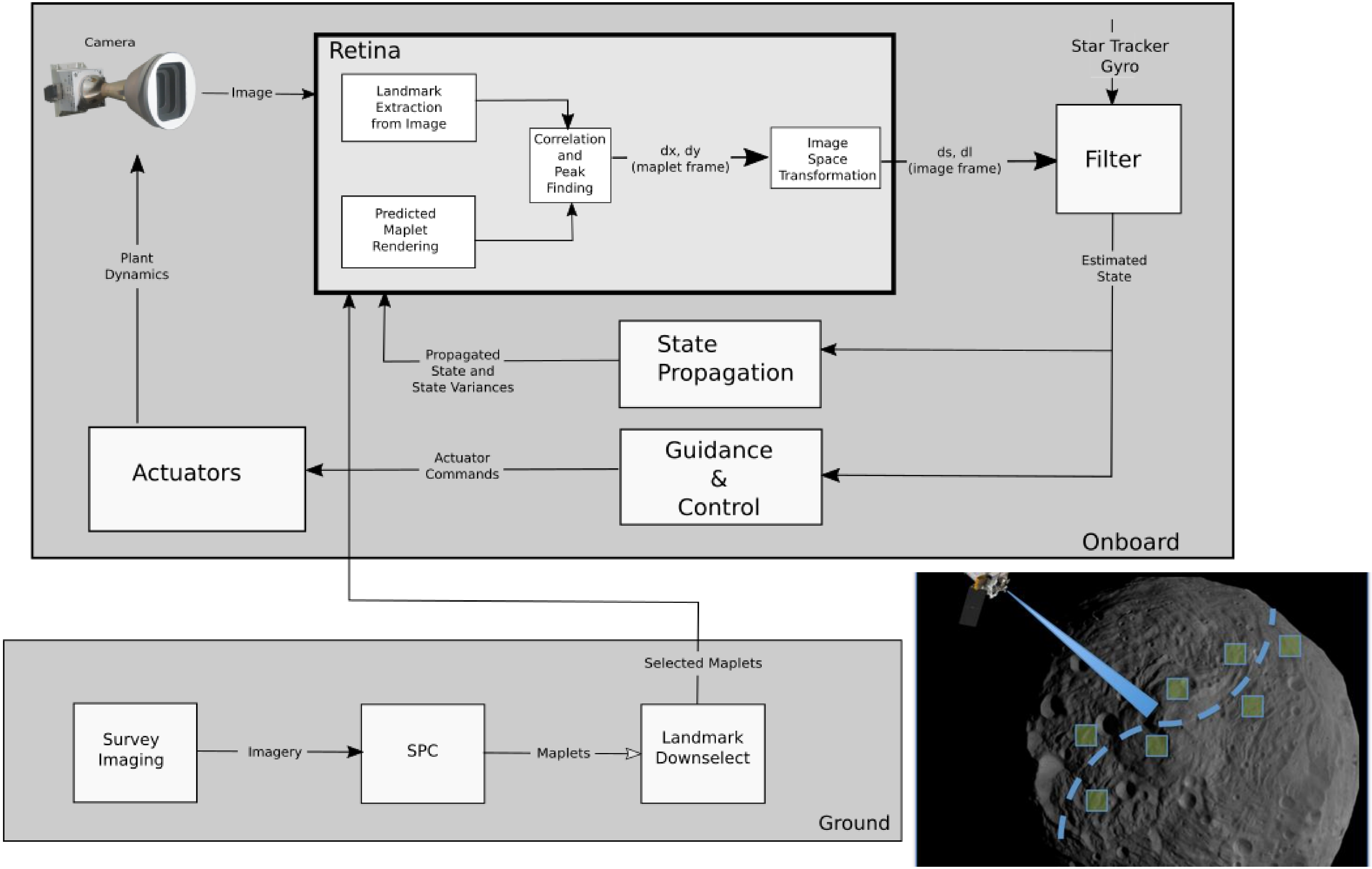


ARRM Proximity Operations



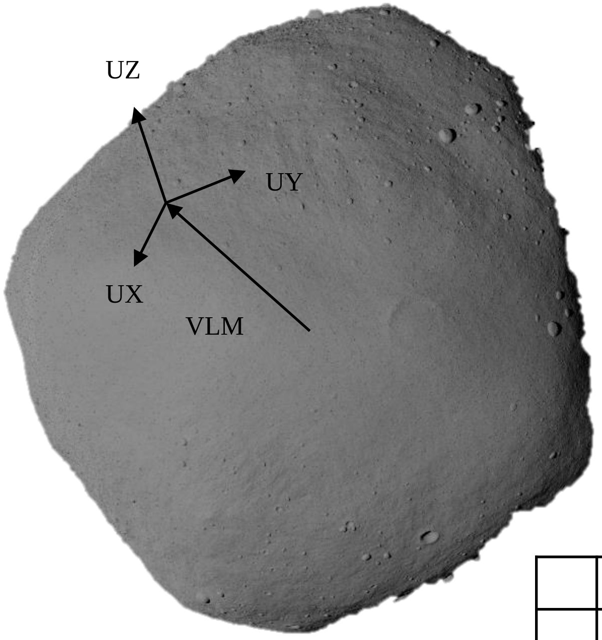
- Key Events in Proximity Operations
  - Transition from the 5 km hold point to 200 m waypoint on pre-defined burn
  - 200 m waypoint to 50 m also performed on a pre-defined burn
  - 50 m to 20 m descent and asteroid spin rate matching performed with closed loop control
  - No thrusting towards surface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

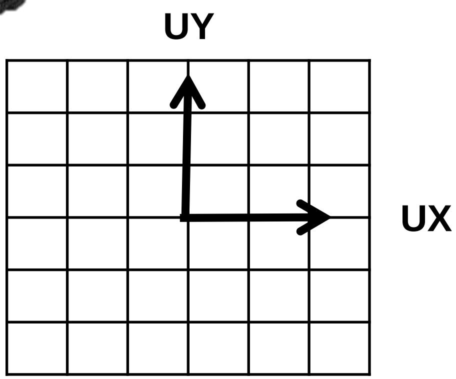
ARRM Proximity Operations GNC Architecture

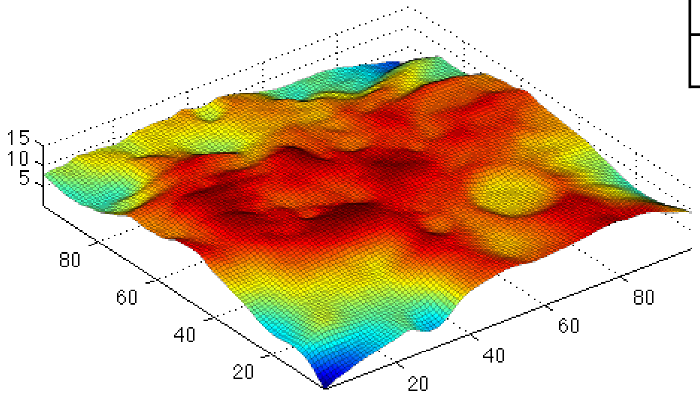


Retina Algorithms: Maplet Preprocessing

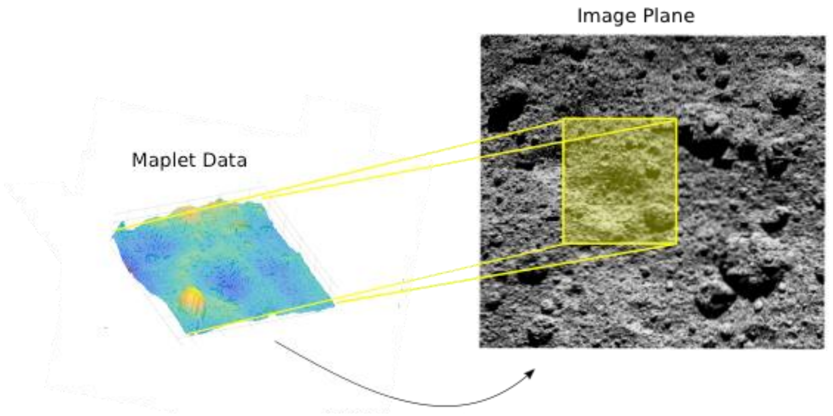
- Landmark
  - Body-fixed surface location
- Maplet
  - Local coordinate system and *n x n* grid centered on a landmark
  - Contains height and albedo data
  - Also called a digital elevation map (DEM)
- Tesselation
  - Process of converting maplet into triangles in an efficient manner for intersection testing
  - Surface normal data also computed
  - Albedo data also preserved

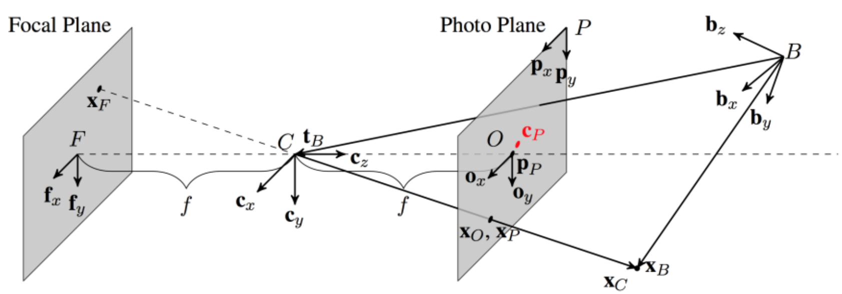


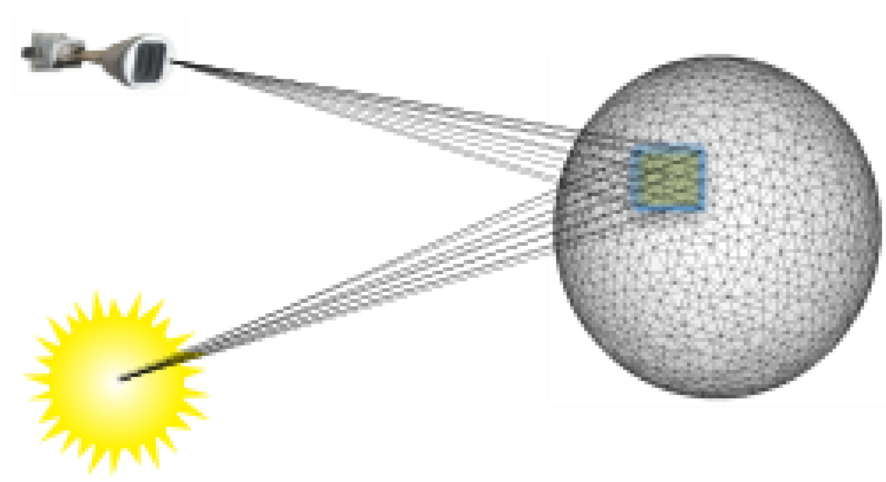




Retina Algorithms: Predicted Image Generation

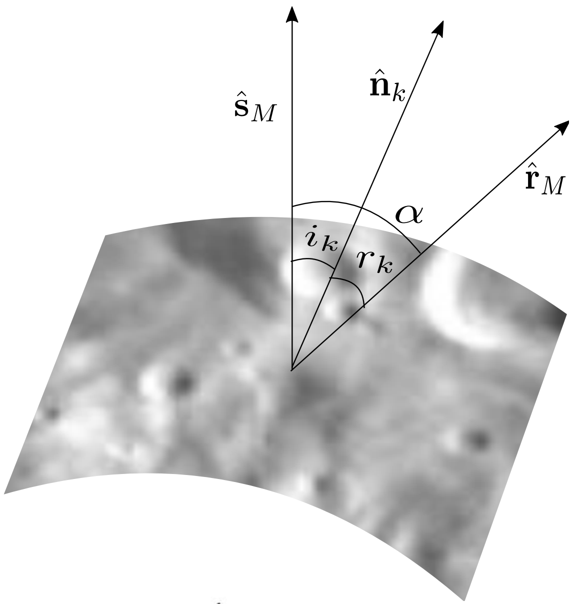






- Camera Model used to project maplet data onto image plane
  – First done to determine range of pixels to render
  – Second to project rays from camera focal plane to the maplet surface
- Rays that intersect surface geometry are then tested for a path to the Sun
- Use of several acceleration techniques used in ray tracing make the implementation tractable for an embedded system

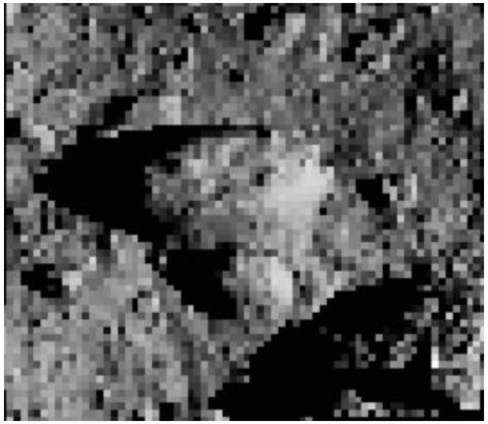
Retina Algorithms: Illumination Model



- Definitions
  - $\hat{\mathbf{n}}_k$ - surface normal
  - $\hat{\mathbf{s}}_M$ - vector to the Sun
  - i_k - angle to the Sun
  - $\hat{\mathbf{r}}_M$ - vector to vehicle
  - r_k - reflectance angle
  - α - phase angle

Synthetic Image

Predicted Image



$$I_k = a_k \left((1-\beta)\cos(i_k) + \beta \frac{\cos(i_k)}{\cos(i_k) + \cos(r_k)} \right)$$

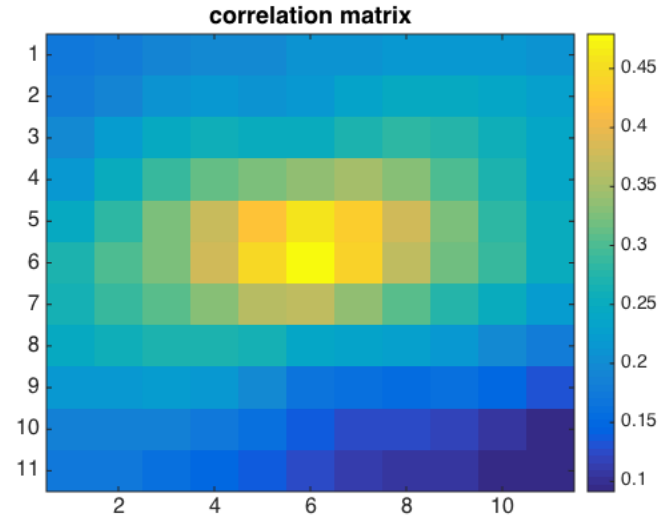
$$\beta = \exp^{(-\alpha/\alpha_0)}$$

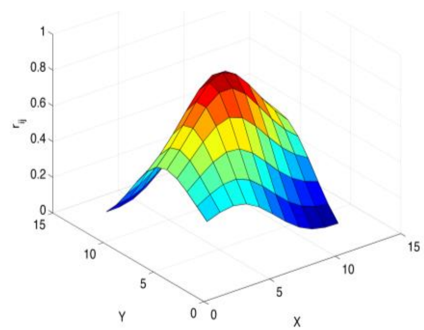
- The illumination model above is from McEwen 1991
- Beta is a weighting term to mix the Lambertian and Lommel-Seeliger components of the model
  - The weighting factor, α_0 is chosen from experience.
- The images at right show good agreement between a synthetic image and one rendered with Retina

Retina Algorithms: Cross Correlation

$$C = \frac{\frac{1}{N}\sum_{i=1}^{k}\sum_{j=1}^{l}\left(\mathbf{I}_p(i,j)\mathbf{I}_e(i,j)\right) - \mu_p\mu_e}{\left(\mu_{p_2} - \mu_p^2\right)\left(\mu_{e_2} - \mu_e^2\right)}$$

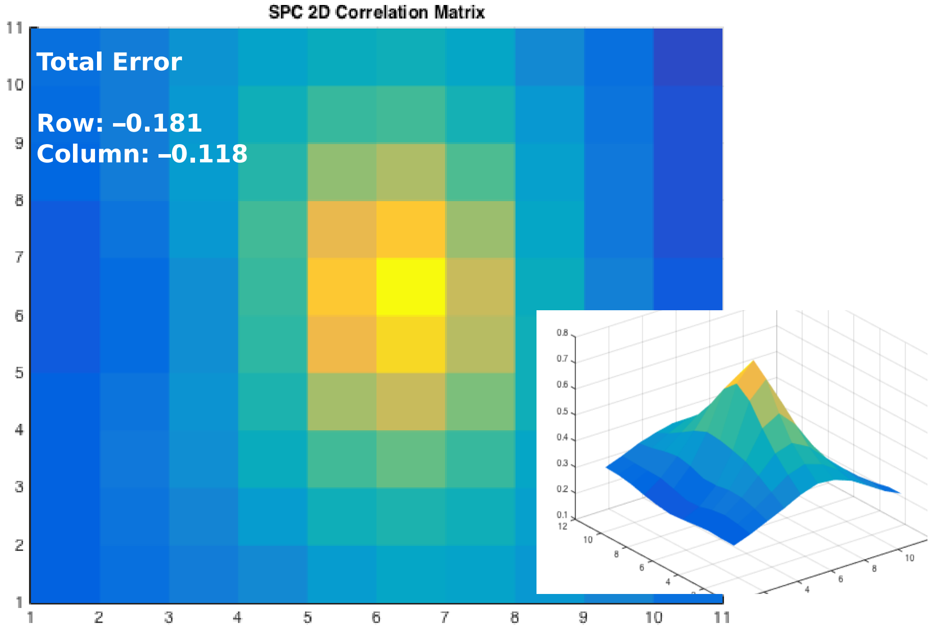
- *i* is the row in the image, *j* is the column
- $\mathbf{I}_p$ is the predicted image pixel at row *i*, col *j*
- $\mathbf{I}_e$ is the pixel value in the real image
- μ_p is the mean of pixels in the predicted image
- μ_e is the mean of pixels in the real image
- μ_{p_2} is the variance of pixels in the predicted image
- μ_{e_2} is the variance of pixels in the real image

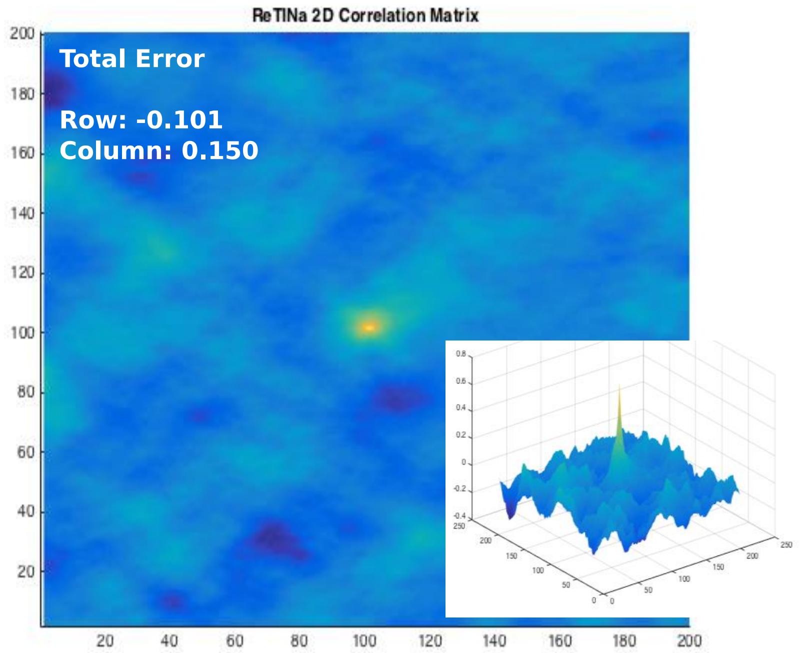




- Uses Pearson moment correlation
  - Other correlation methods are being explored to ensure robust performance.
- Correlation matrix created by shifting predicted image
  - Magnitudes of shift determined by filter covariance

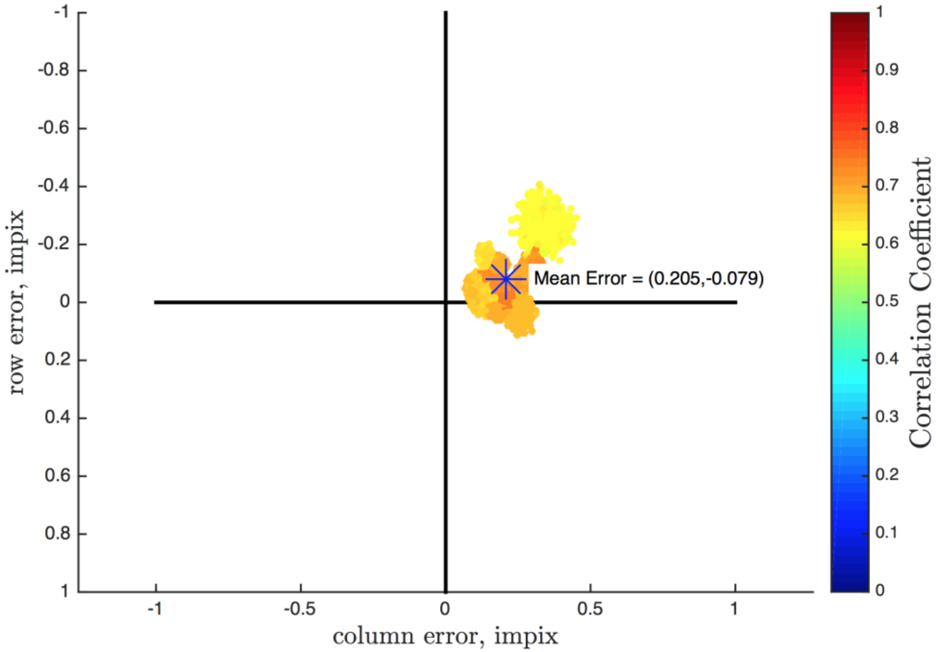
Retina Algorithms: Sub-Pixel Peak Finding

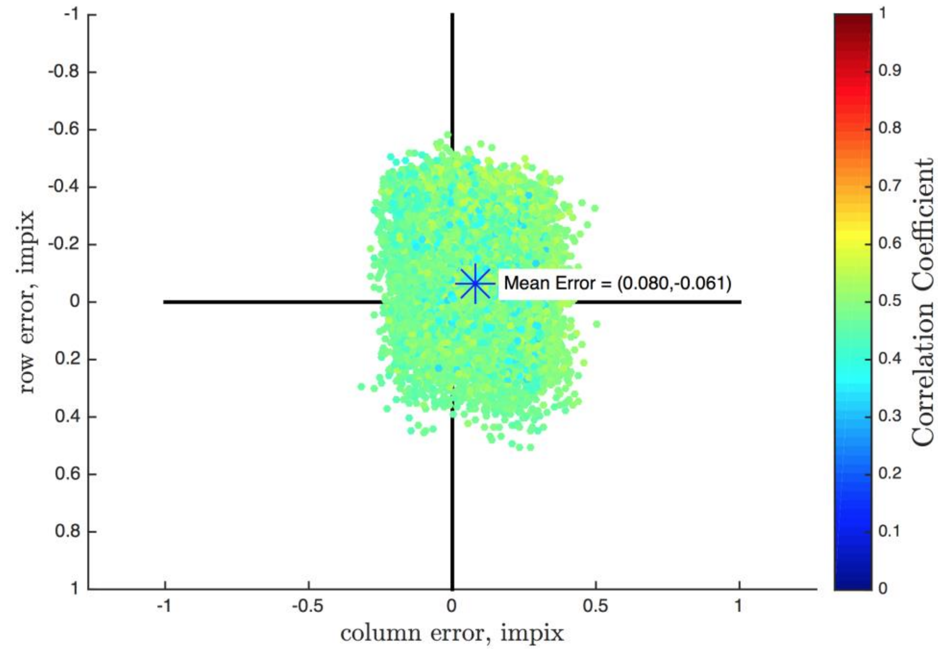




- Comparison of correlation peak finding in SPC and Retina
  - This example had no offset applied so truth is Row = 0.0, Column = 0.0
- Retina peak finding is a 3x3 grid that is linearly interpolated to find the peak to sub-pixel accuracy
  - Current SPC implementations fit a paraboloid to the correlation surface
- Results obtained in Monte Carlo analysis show lower errors with linear peak finding.

Retina Performance





- Performance between SPC and Retina obtained for the ARRM descent from 50 m to 10 m
- Perturbations applied include
  - Position, attitude, camera parameters (focal length, distortion, etc), landmark knowledge, landmark resolution, knowledge of Sun direction
- Retina more robust because
  - Registered every case while SPC did not
  - SPC shows a bias for this scenario – investigating cause

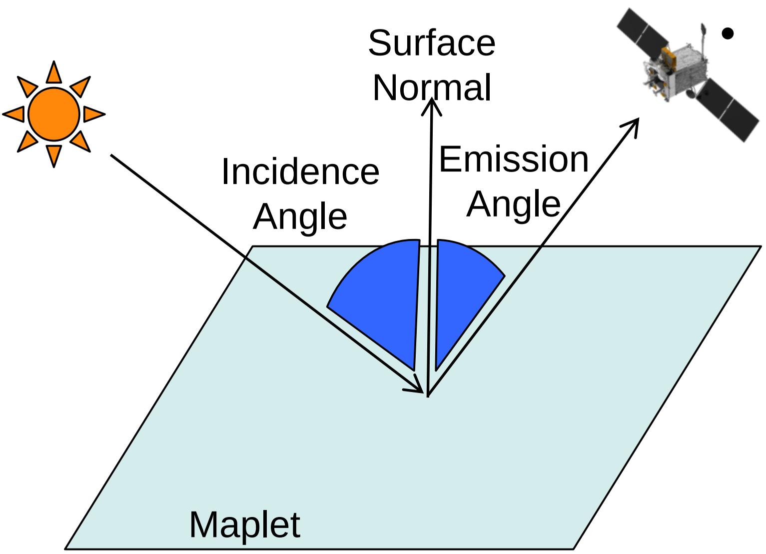
Future Work

- Further testing implementation on SpaceCube 2.0
  - Testing with 1 MP 10-bit depth images to utilize existing FlatSat
  - Will test with higher resolution imagery to compare performance to the expected performance presented here
- Refine acceleration needs for current implementation
- Exploring improved correlation algorithms
- Continue assessing performance of Retina on additional scenarios

Questions

Backup

Retina Algorithms: Illumination Model



- Definitions
  - $\hat{\mathbf{n}}_k$ is the normal to the surface
  - i_k is the angle to the Sun
  - r_k is the emission angle
  - α is the phase angle

$$I_k = a_k \left((1-\beta)\cos(i_k) + \beta \frac{\cos(i_k)}{\cos(i_k)+\cos(r_k)} \right)$$

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Synthetic Image

Retina Image