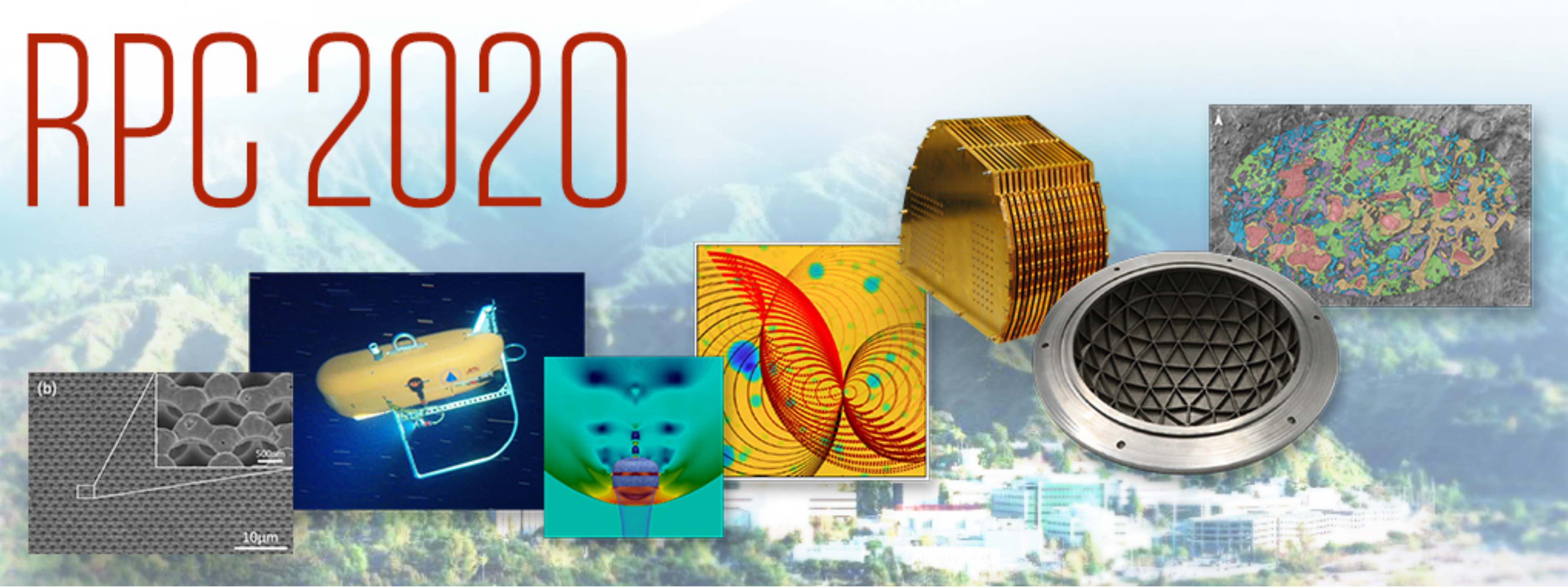

Virtual Research Presentation Conference

Application of High-Dynamic-Range (HDR) Imaging to Optical Navigation and Body Mapping

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Program: Innovative Spontaneous Concepts

Assigned Presentation RPC-192

Jet Propulsion Laboratory
California Institute of Technology

Tutorial Introduction

Abstract:

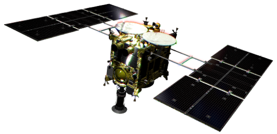
Optical Navigation (OpNav) is necessary for missions to small bodies and whenever highly-accurate spacecraft-target relative knowledge is crucial to success. It utilizes an onboard camera to improve the accuracy of spacecraft navigation, enables mapping and modeling of a target body via stereophotoclinometry (SPC), and makes autonomous operations possible. To date, most OpNav images are limited in their information content due to the large illuminance variations encountered in space. Each individual exposure of the camera is limited in its dynamic range and thus only capable of imaging either dim *or* bright targets well, but not both. High dynamic range (HDR) imaging, currently used in commercial image processing and seen in modern smartphones, can be accomplished with recent advances in detector technology, or by algorithmically combining the best exposed parts of both faint and bright images. We proposed a study of its use in a space application where the ability to simultaneously resolve all the aspects of a scene including the relatively bright sunlit surfaces, shadowed regions, potential small moons, and faint background stars could have a profound mission impact.

Problem Description (1/3)

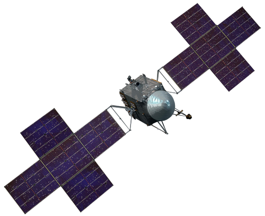
Context (Why this problem and why now):

1) Small Body missions to moons/asteroids/comets to help us better understand planetary/solar system formation and dynamics are becoming more common. Cubesat innovations and availability may further increase the rate at which these bodies/systems can be explored.

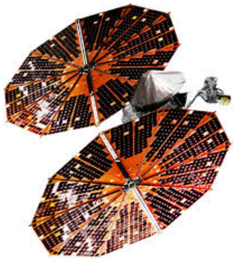
OSIRIS-REx - ops
(Bennu)



Hayabusa2 – ops
(Ryugu)



Psyche - prelaunch
(Psyche)



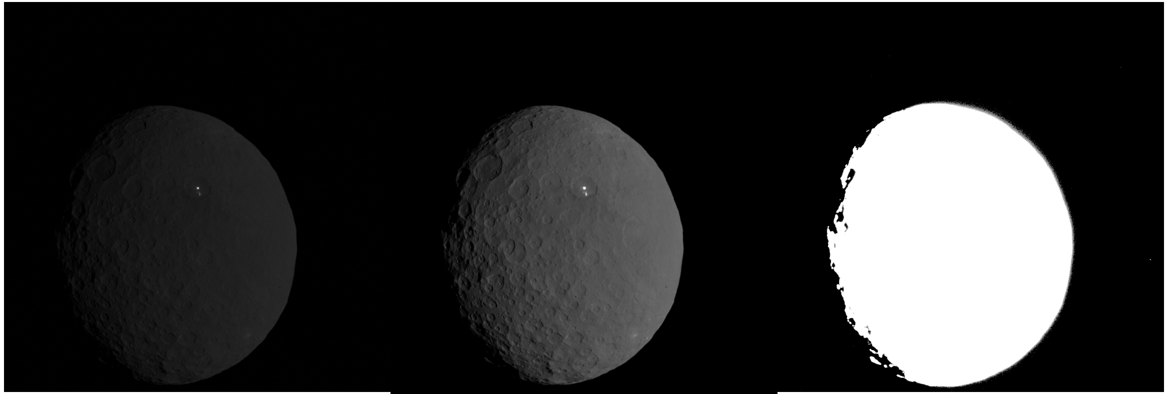
LUCY - planned
(Trojan Asteroid Tour)

2) The future is autonomous. All these spacecraft are or will be performing proximity operations such as low-orbiting for body-mapping or touch-and-go landings for sample returns. Enabling these operations to be carried more autonomously could drastically reduce expense and potential risks/delays in mission operations. The more information a spacecraft "knows" about its environment/target the better for autonomy, and higher dynamic range imaging could potentially provide additional information.

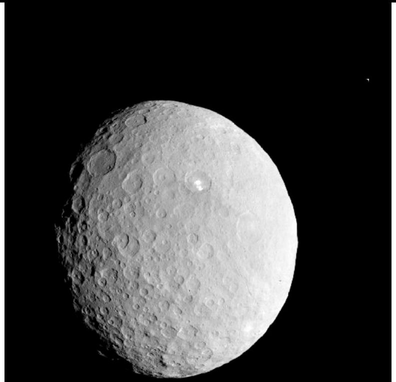
Problem Description (2/3)

SOA (Comparison or advancement over current state-of-the-art):

LDR Images



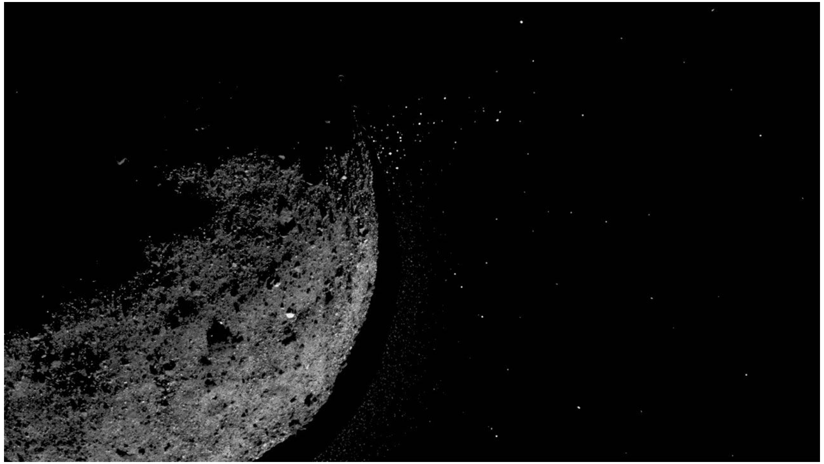
Synthesized HDR image



Problem Description (3/3)

Relevance to NASA and JPL (Impact on current or future programs):

The situation at Bennu (OSIRIS-REx)



Methodology (1/3)

Theory:

The real world is high dynamic range. We'd need millions of values to store all the actual brightnesses, but an 8-bit photo for example can only store 256 values. High dynamic range image synthesis is essentially done in 3 steps:

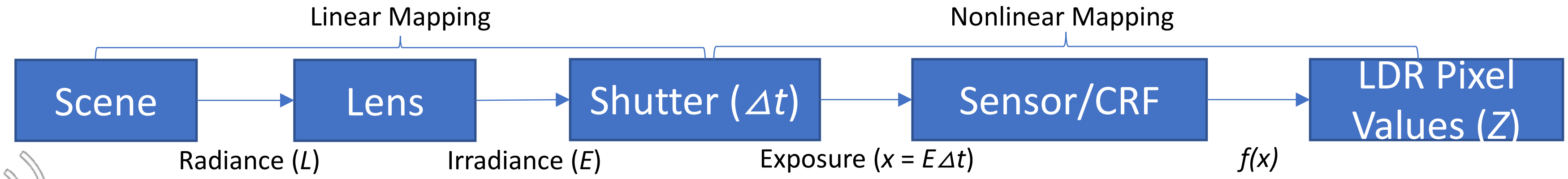
1. Take multiple low dynamic range images at different exposure settings
2. Apply calibration to each image according to camera's nonlinear response function (CRF)
3. Combine the calibrated images according to some weighting scheme.

$$Z_{ij} = f(E_i \cdot \Delta t_j)$$

$$g(Z_{ij}) = ln(E_i) + ln(\Delta t_j)$$

Solve for g via Debevec and Malik [3]

$$ln(E_i) = \frac{\sum_{j=1}^{p} w(Z_{ij}) \cdot [g(Z_{ij}) - ln(\Delta t_j)]}{\sum_{j=1}^{p} w(Z_{ij})}$$



Methodology (2/3)

Formulation, theory or experiment description:

An image pair from the OSIRIS-REx dataset

The LDR image set simulation was as follows:

- A real image of Ceres was used as the starting point, and the background dark current/noise was zeroed out

- In order to maintain a reasonable number in the set, the full bit-depth of the scene was set to 11 bits, or 2048 maximum pixel value.

- The adjusted dynamic range was divided into overlapping sections, allowing for each image in the collection to only cover a subset of the overall range. This is consistent with real world imaging, in which the exposure time is varied to capture different scene characteristics.

- These pixel values were then altered according to a realistic non-linearity function, which degrades performance of the imager towards the extremes of the dynamic range.

- The exposure time associated with each image was tuned specifically for the dynamic covered in that image.

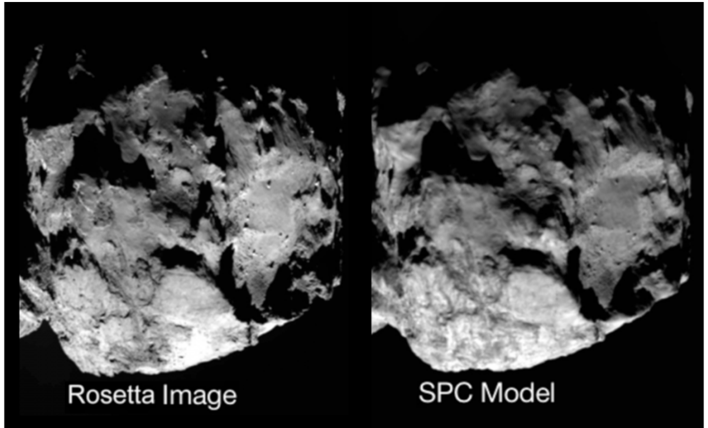
- Both a zero-noise set, and a set with added white noise in the images were produced for testing.

- The figures were saved in the common .fits format.

Methodology (3/3)

Innovation, advancement:

One of our biggest hopes for the application of HDR in optical navigation was to test improvement in the landmark/feature tracking of celestial bodies. Improved dynamic resolution of a body from investigative imaging techniques such as HDR was thought to potentially enable refined shape modeling, as well as safer proximity and landing operations done autonomously. Full testing of the effects of HDR images throughout the process of shape model generation and feature tracking development with JPL's stereo-photoclinometry (SPC) software would have required time beyond the scope of this initial R&TD. Fortunately, we were aware of relevant research performed by a colleague, Jacopo Villa [6], whose analysis framework could test feature tracking performance using the SURF and ORB feature tracking algorithms. He was generous enough to use this analysis setup and compare the number of features identified when using an LDR image (8-bit in this case) and an HDR image (16-bit) .



Results (1/5)

Project Objectives:

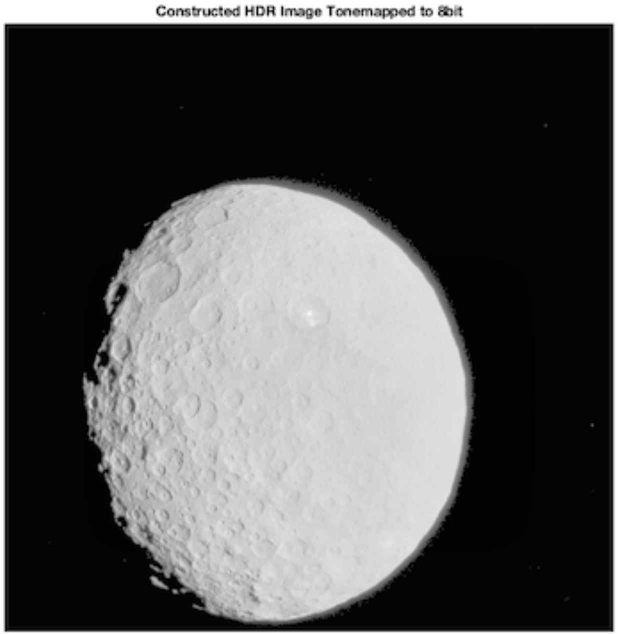
The objective of this research was to characterize the potential benefits of applying high dynamic range (HDR) imaging techniques to optical navigation imagery. This meant:

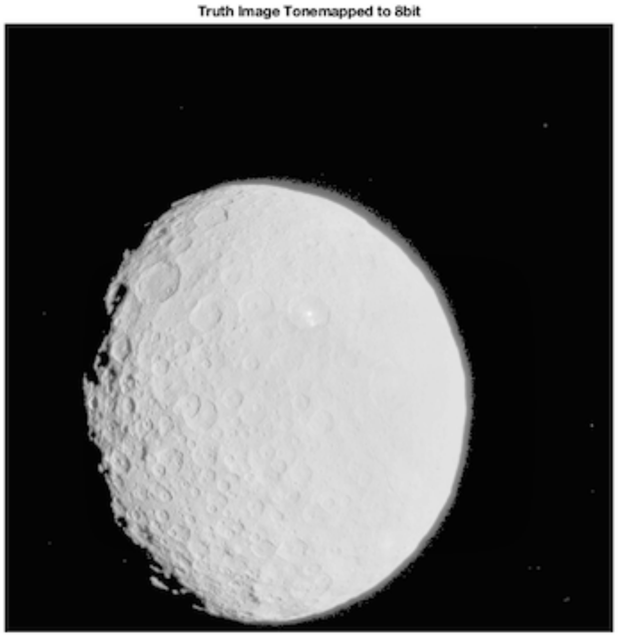
1) implementing an algorithmic method of creating HDR images and applying them to existing optical navigation image sets,

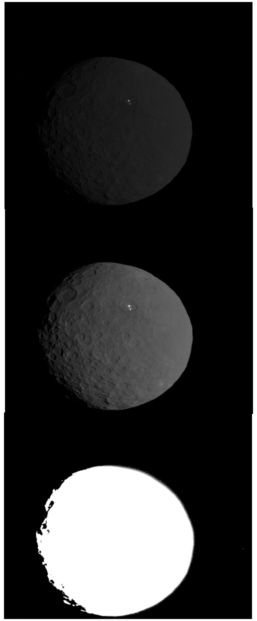
2) assessing the technique's ability to resolve background stars, particle ejecta, and increase the dynamic range and SNR of the target's surface,

3) and evaluating how this effects navigation/feature-tracking performance.

Results (2/5)



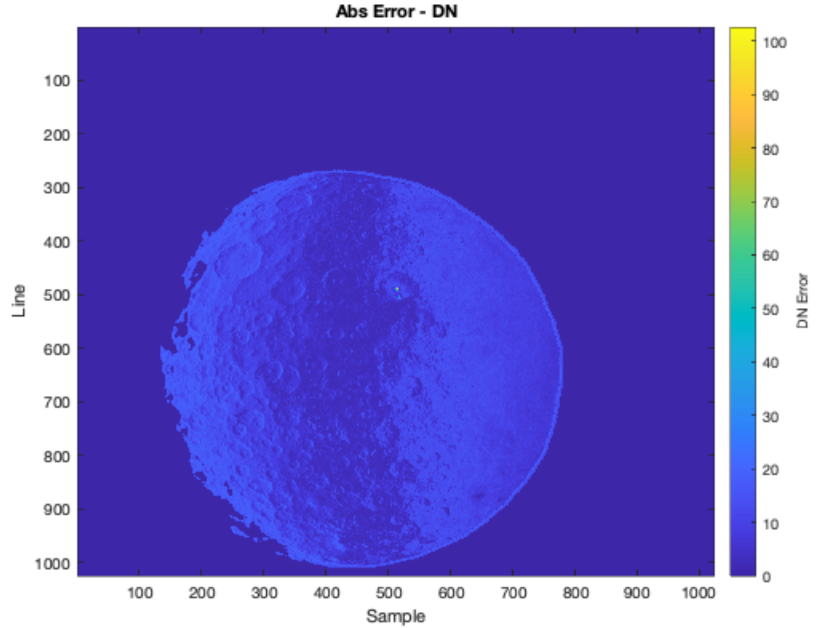


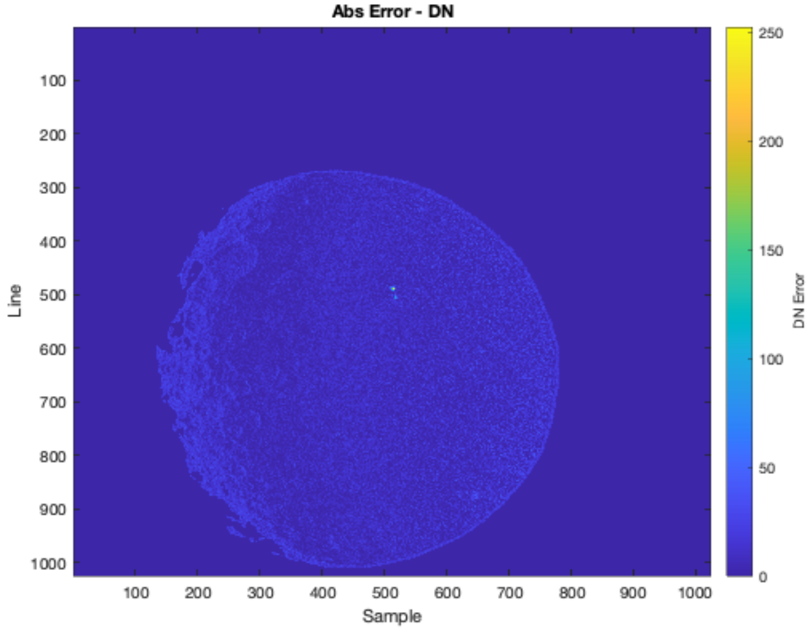


HDR noNoise reconstruction vs. truth

Results (3/5)

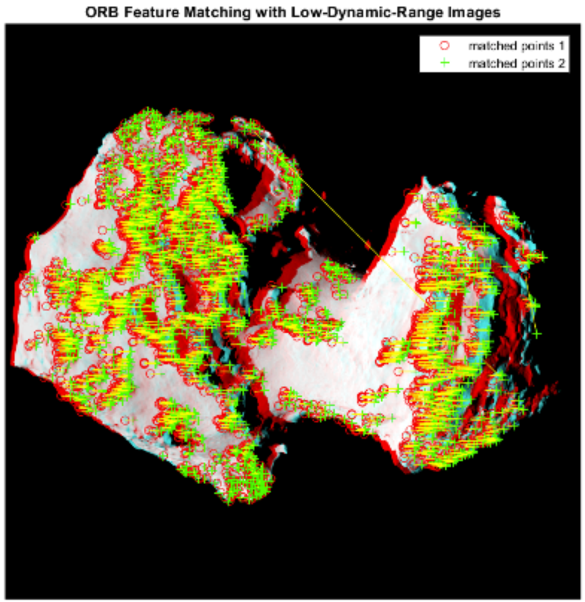
HDR reconstruction errors
(noNoise vs. noise case)



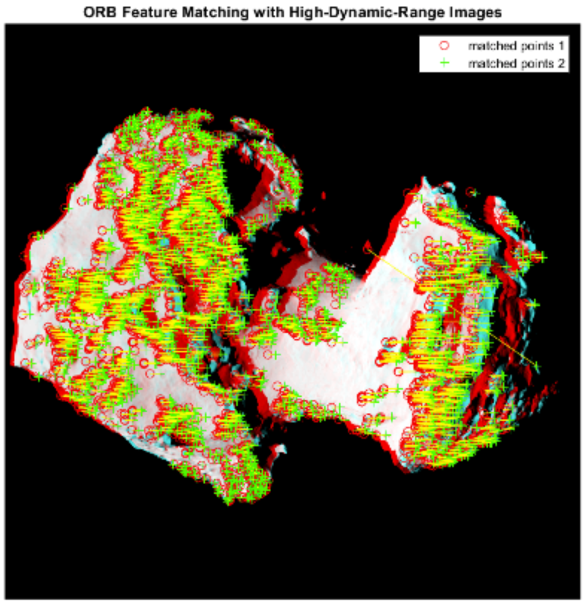


In the case with noise added, the noise reduction algorithm was able to increase the SNR by a factor of ~2.5

Results (4/5)



2938 matches



3044 matches

Feature tracking comparison

Results (5/5)

Significance and next steps

While our analysis and results did not reach the level of complexity necessary to fully endorse adoption of HDR imaging into operations as of now, we feel that it was a good first look at the concept and that it shows promise. These results could open the door for future, more advanced setups, which the timing and funding of this task simply did not allow for. The slightly improved feature matching comparison could be fully expanded into a more complex analysis in three dimensions, which not only compares the landmarks matched, but also tracks temporal visibility when using higher bit-depth photos.

The improved SNR from the HDR construction after noise suppression suggests that use cases such as the Bennu ejecta detection algorithm may benefit from ingesting HDR images.

There are also camera sensors currently being developed and brought to market which allow for advanced and rapid creation of HDR images electronically, directly at the sensor. An autonomous craft having more accurate knowledge of its environment can only improve both capabilities, and possibilities. We hope that there will be opportunities for more investigations into this topic in the future.

References

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[2] Bos, B. J., et al. "Touch and Go Camera System (TAGCAMS) for the OSIRIS-REx asteroid sample return mission." Space Science Reviews 214.1 (2018): 37.

[3] P.E. Debevec, J. Malik, Recovering high dynamic range radiance maps from photographs, in: SIGGRAPH 97 Conference Proceedings, Annual Conference Series, August 1997, pp. 369–378.

[4] Granados, Miguel, et al. "Optimal HDR reconstruction with linear digital cameras." 2010 IEEE Computer Society Conference on Computer Vision and Pattern Recognition. IEEE, 2010.

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[6] Villa, Jacopo et al. “OPTICAL NAVIGATION FOR AUTONOMOUS APPROACH OF SMALL UNKNOWN BODIES.” (2019).