RECONSTRUCTION OF BENNU PARTICLE EVENTS FROM SPARSE DATA. J. Y. Pelgrift[1], E. J. Lessac-Chenen[1], C. D. Adam[1], J. M. Leonard[1], D. S. Nelson[1], L. McCarthy[1], E. M. Sahr[1], A. Liounis[2], M. C. Moreau[2], B. J. Bos[2], C. W. Hergenrother[3], and D. S. Lauretta[3], [1]KinetX, Inc., Space Navigation and Flight Dynamics Practice, 21 W. Easy St., Ste 108, Simi Valley, CA 793065, USA, [2]NASA Goddard Spaceflight Center, Greenbelt, MD 20771, USA, [3]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85705, USA

Introduction: Beginning in January 2019, the OSIRIS-REx navigation camera NavCam 1 [1] imaged a number of suspected active asteroid ejection events.[2,3] For some of these events, the only observations of the ejected particles come from the first two images taken immediately after the event by NavCam 1. Without three or more observations of each particle, traditional orbit determination is not possible. However, by assuming that the particles all ejected at the same time and location for a given event, and approximating that their velocities remained constant after ejection (a reasonable approximation for fast-moving particles given Bennu's weak gravity), we show that it is possible to estimate each particles' state from only two observations. We applied this newly developed technique to reconstruct the particle ejection events observed by OSIRIS-REx during orbit about Bennu.

Method: *Overview.* Non-stellar object detections and track associations are made given sparse data from only two successive images after a suspected ejection event. Using these 2-image object tracks, the object states and ejection event locations and epochs are estimated.

Assuming linear motion of ejecta, the tracks are used to trace back to a single radiant point within the image, which is mapped to two possible Bennu surface points.

The ejection event epoch and particle 3D states are estimated using angular in-image-plane measurements. For objects with a non-zero out-of-image-plane velocity component, there is an apparent angular acceleration seen within the image. Therefore, by assuming a constant 3D metric velocity and calculating the angular or in-plane velocity of an object at different epochs, information on the epoch of the event and the 3D states can be inferred. These assumptions and approximations are needed for initial state estimation of the objects when very sparse information is available and traditional orbit determination cannot be performed.

Detections and Track Identification. For a suspected ejection event, the two NavCam images taken immediately after the event are corrected for distortion, registered on the center of Bennu, and differenced to highlight any objects moving with respect to Bennu. Some detected objects present as streaks or trails in one or more images, and therefore can be treated as multiple observations for the object at the start and end of the image exposure. If a streaked object was present in both images it could be treated as a 4-epoch track.

Associated pairs of detections (tracks) were made from identified repeated patterns and used for the radiant estimation and 3D object state determination.

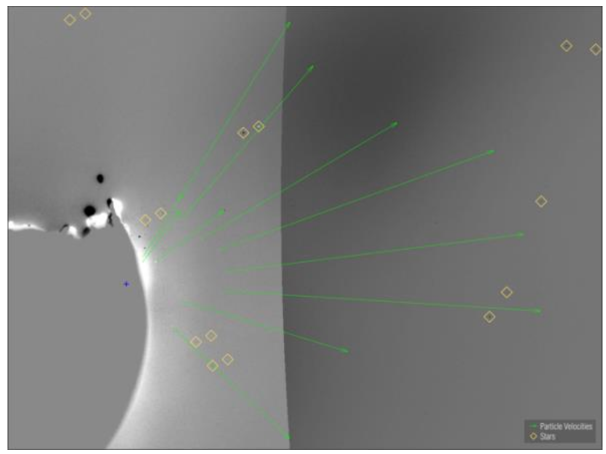

Figure 1. Ejected particle tracks for the January 19, 2019 ejection event.

Ejection Epoch Estimation. The epoch that each object left the radiant point was estimated by comparing the angular displacements of the object from the radiant at each epoch.

When only 2-epoch tracks were available, the radiant epoch is non-deterministic and coupled with an ambiguity in the 3D orientation of the ejecta cone. However, when 3- or 4-epoch tracks were available, a more robust method was used to determine the time that each object left the radiant point. This allowed for a deterministic solution of the event epoch that removed the 3D orientation ambiguity.

Ejection Location Estimation and Uncertainty. Given the radiant point within the image and the radiant epoch, two unique solutions for the ejection location on the surface of Bennu are found: a point closer to the spacecraft on the near side of Bennu and a point on the far side of Bennu, out of view of the camera. The ray tracing routines in the NAIF SPICE toolkit are used to estimate these two surface locations.

3D Object States. 3D object states are inferred by comparing the observed angular velocity to the angular velocity expected for an object that left the origin point at the estimated event time and traveled perfectly within the plane of the image (perpendicular to the camera's boresight). This assumes that the objects' velocities are constant (they are traveling in straight lines) and that every object left the origin point at the median time determined from 2D analysis. These assumptions hold up well for images that capture the particles within minutes of the event time. Objects appearing faster than expected were inferred to be moving towards the camera and objects appearing slower than expected were inferred to be moving away from the camera.

By combining this 3D information with the two solutions for the ejection location, the 3D positions of each object are found. The 3D velocities are then calculated using the position of each object at the two image times. There are two unique solutions for each object’s position and velocity that correspond to the two unique solutions for the ejection location.

Results: Ejection locations and particle velocities were estimated for 11 Bennu particle ejection events. Estimated velocities ranged from 7 cm/s to 3.3 m/s, and most events occurred at similar local solar times as seen in Figure 2.

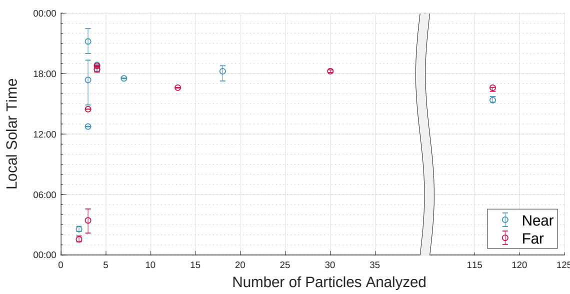

Figure 2. Estimated local solar times for 11 particle ejection events.

This presentation will present an extended description of our newly developed technique and the results from these 11 ejection events.

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References:[1] Bos B. J., et al., (2018) *Space Science Reviews*, 214 (37). [2] Hergenrother, C. W., et al. (2019). *Nature Communications*, 10 (1291). [3] Lauretta, D. S., Hergenrother, C. W., et al. (submitted). *Science.*