Tracking Particles Ejected from Active Asteroid Bennu with Event-Based Vision

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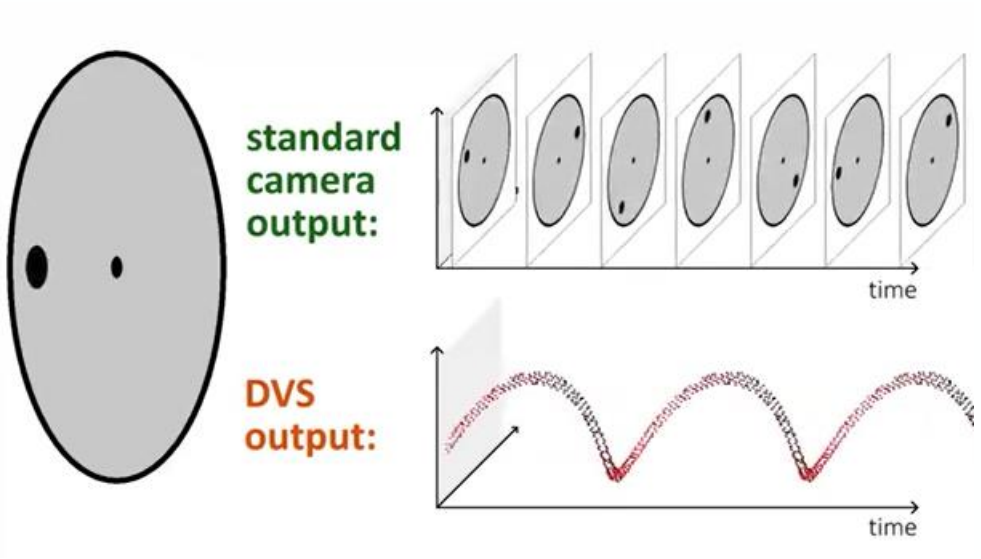
Outline

- Background:
  - Event-Based Vision
  - Towards Event-Based Cameras for Space Applications
  - Application: Tracking Particles around Active Asteroids
- Data Pipeline:
  - Rendering Particle Ejection Episodes
  - Synthetic Event-Stream Processing
  - Multi-Object Tracking
- Conclusion
- Outlook

Event-Based Vision

- Event-based cameras, or dynamic vision sensor (DVS), are inspired by the **retina**
- Unlike standard cameras, event-based cameras only capture changes in scene brightness



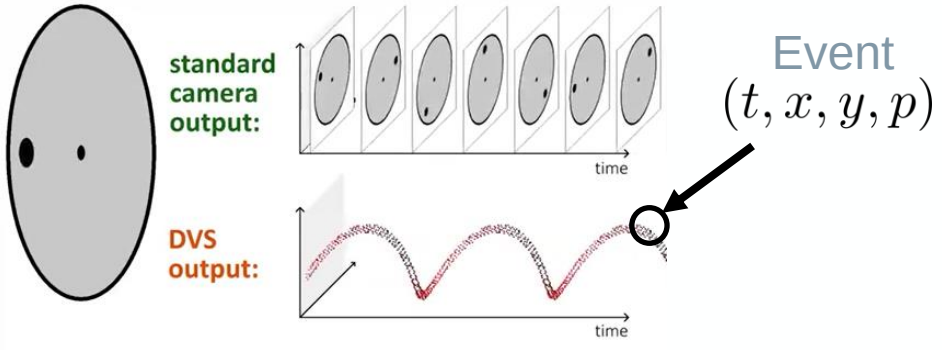
Frames vs event-streams [1]
(DVS = dynamic vision sensor)

PROPHESEE EVK4 event-based camera [2]

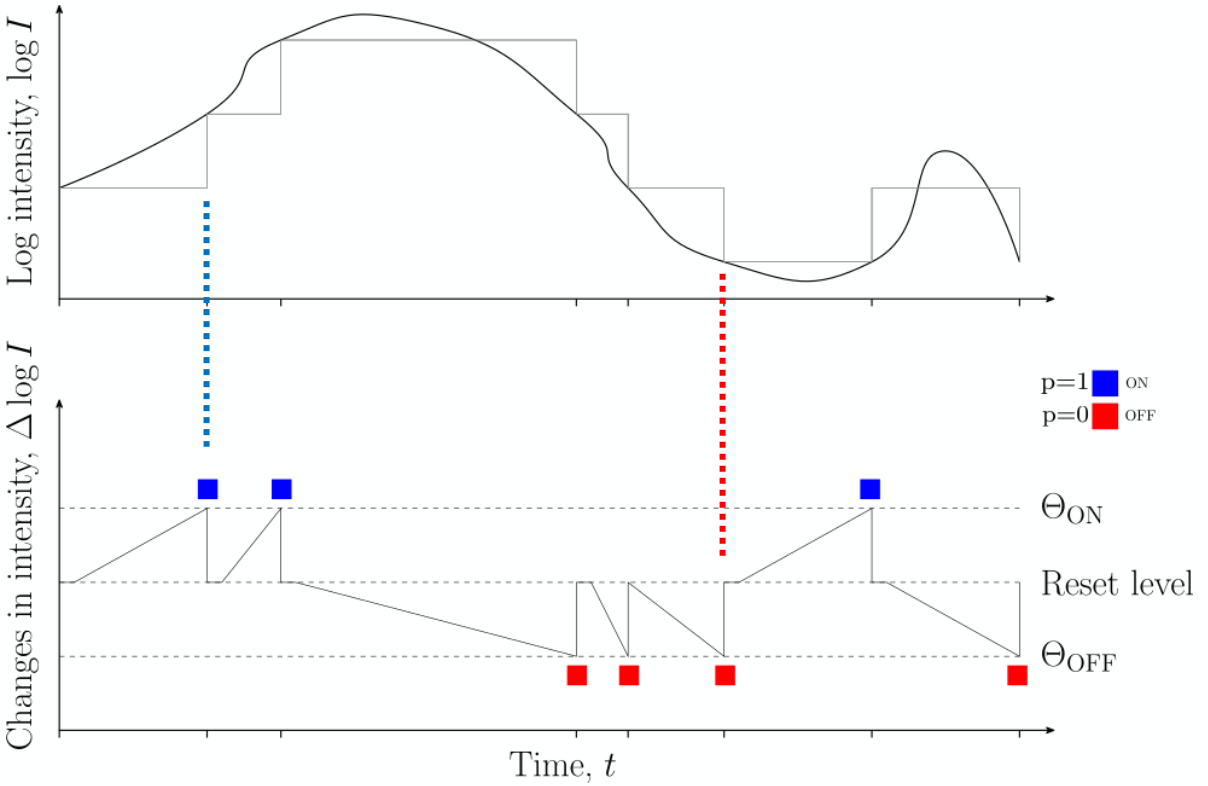
Sand hourglass captured by an event-based camera [3]

Event-Based Vision

- The pixels of a dynamic vision sensor output events **independently** and **asynchronously**



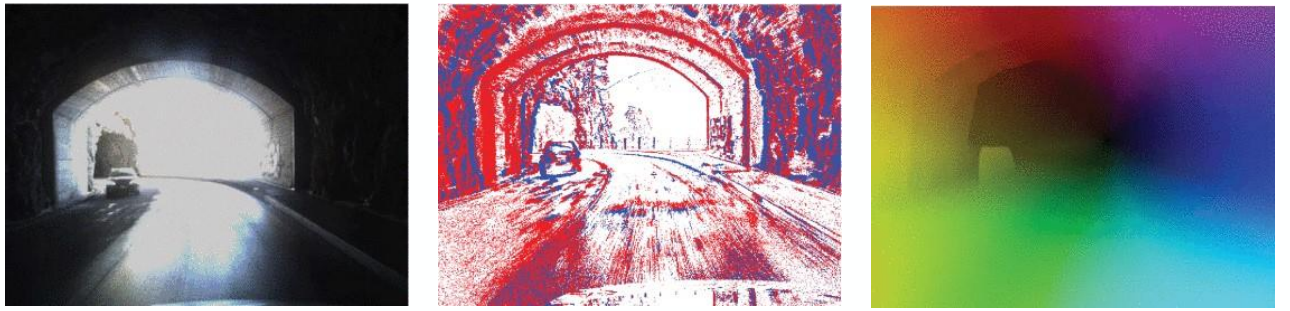
Property	Value	Unit
Motion dependent		
High dynamic range	> 120	dB
High readout rates	$2 - 120$	MHz
Low temporal resolution	$20 - 150$	μs
Low power consumption	$32 - 84$	mW



Pixel operation principle [4]

Towards Event-Based Cameras for Space Applications

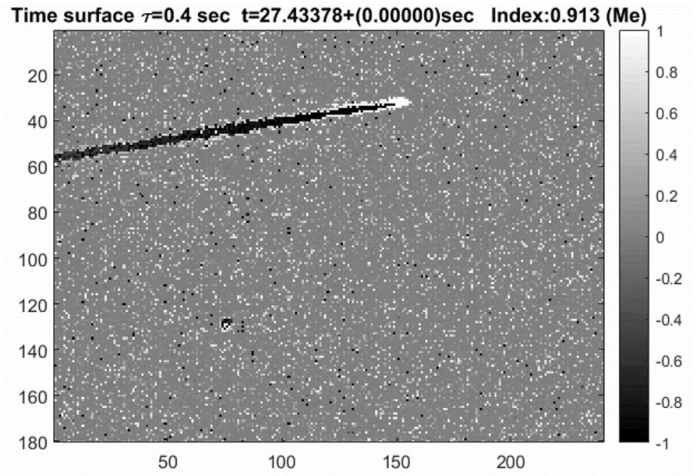
- Other fields (e.g., robotics):
  - High-speed dynamics
  - Challenging lighting conditions
  - Optical flow-based navigation



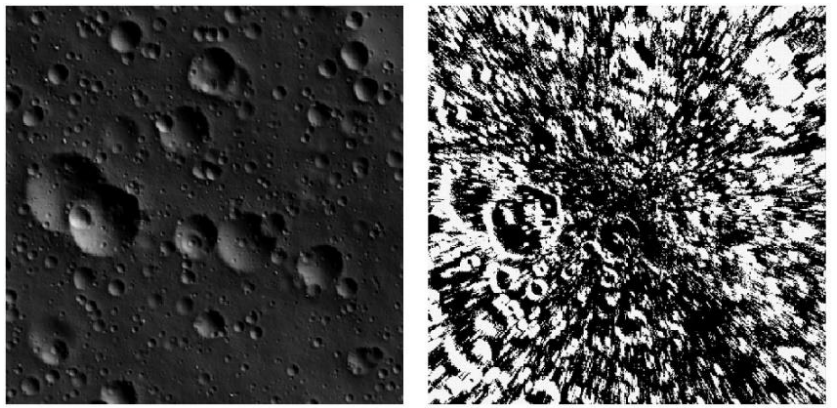
(a) (b) (c)

Driving scene with high dynamic range: (a) image frame, (b) event-frame, (c) optical flow [5]

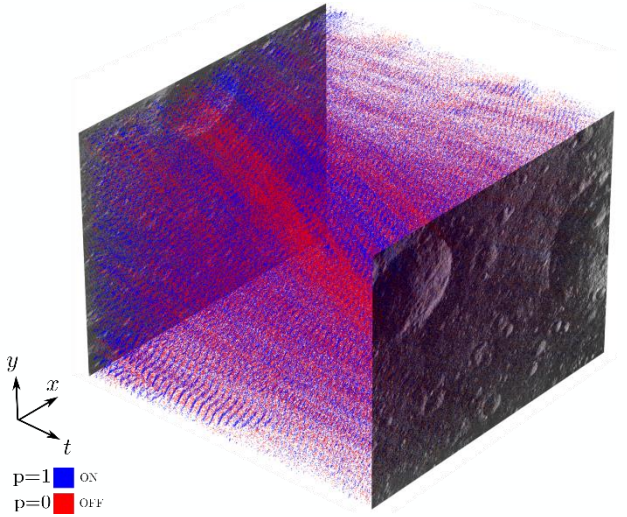
- Space applications:



Event-based recordings of **resident space objects** (from the ground) [6]



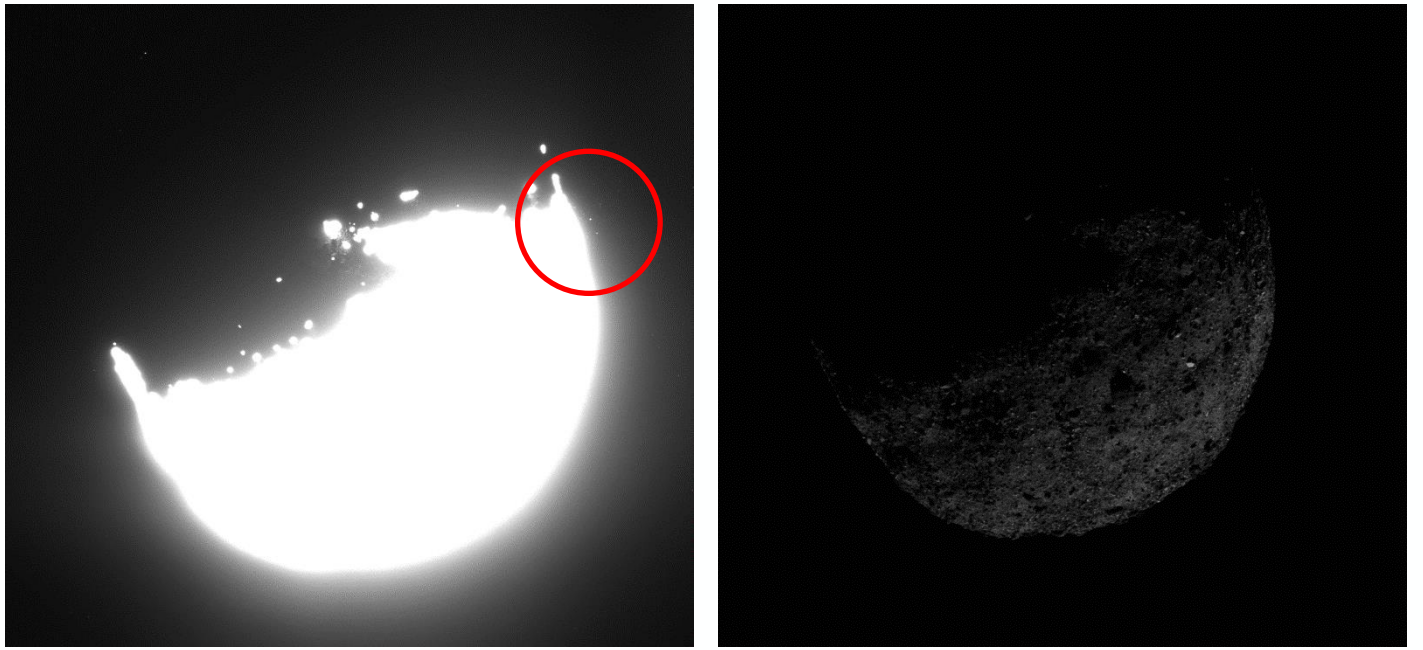
Simulating event-based **ventral landings** for divergence estimation [7]



Simulating event-based **nonventral landings** for motion estimation [8]

Particle Ejection Episodes at Bennu

- OSIRIS-REx reported particle ejection episodes around asteroid Bennu
- NavCam images were used to track the centimeter-size particles
- Notable episodes:
  - January 6th, 2019 (Orbital A)
  - January 19th, 2019 (Orbital A)
  - September 13th, 2019 (Orbital C)
- Current solutions:
  - Offline image processing
  - Offline automated tracking (frame-by-frame)



Original NavCam 1 images of the particle ejection episode from January 19th 2019 (long and short exposure)[9]

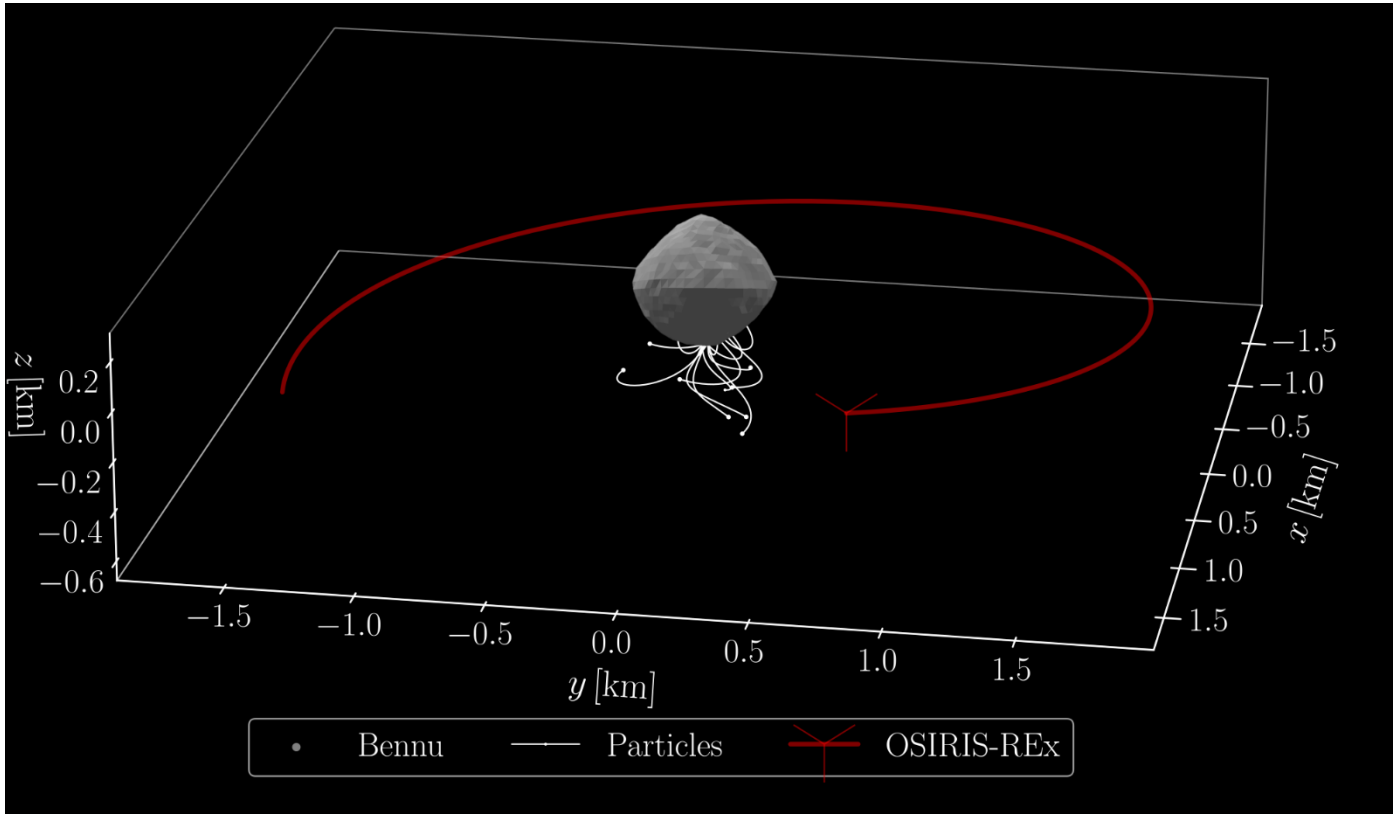
Tracking Ejecta with an Event-Based Science Camera

Objective:

- Demonstrate the use case of an event-based science camera for tracking ejecta in the vicinity of active bodies

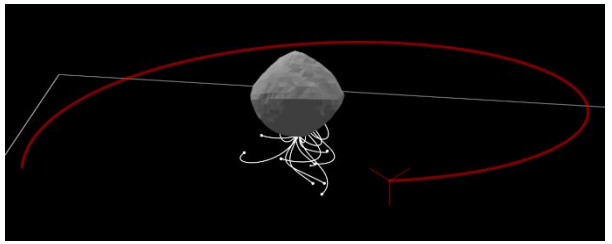
Simulation assumptions:

- Pinhole camera model
- Simplified viewpoint
- Known number of particles



Bennu-fixed particle ejection visualization based on the interpolation of SPICE kernels from 2019-09-13T21:00:00 to 2019-09-14T00:00:00 [10]

Simulation Pipeline

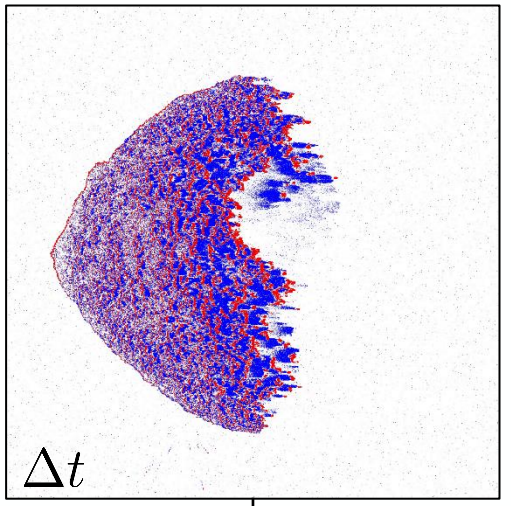


SPICE kernels:
- Particles
- OSIRIS-REx
- Sun

0

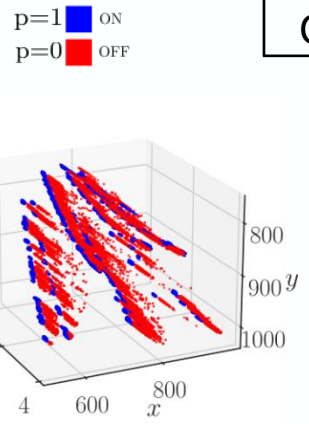
1

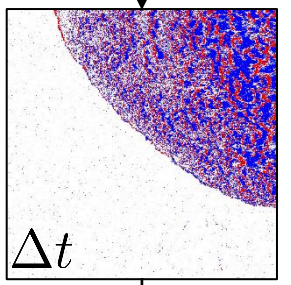
- Bennu model
- Rubble-pile texture
- Pinhole camera ($\mathbf{K}\,[\mathbf{R}|\mathbf{T}]$)



Crop

2





Mask

0. Ground truth data source
1. Scene rendering
2. Synthetic event processing
3. Multi-object tracking (MOT)

3

Observations $\mathbf{Z}$

Track Maintenance

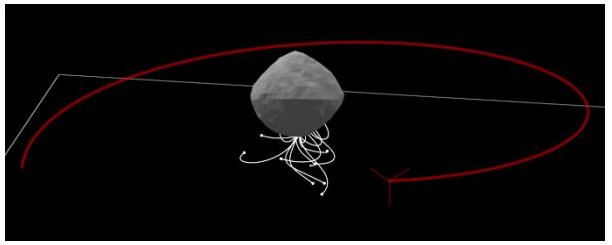
Data Association

Estimation

Gating

$\hat{\mathbf{x}}, \hat{\mathbf{P}}$

1. Reconstructing Particle Ejections

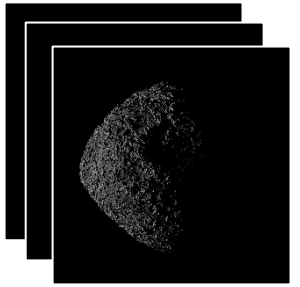


SPICE kernels:
- Particles
- OSIRIS-REx
- Sun

0

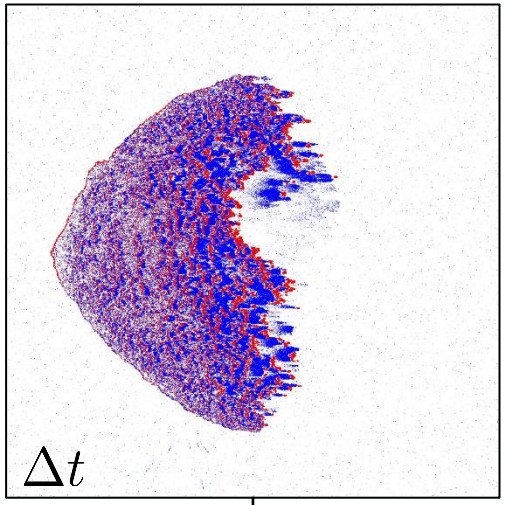
NAIF

blender



1

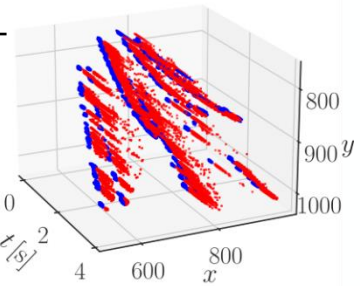
- Bennu model
- Rubble-pile texture
- Pinhole camera ($\mathbf{K}\,[\mathbf{R}|\mathbf{T}]$)

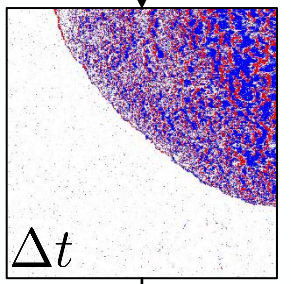


p=1 ON
p=0 OFF

Crop

2





Mask

$\mathbf{Z}$

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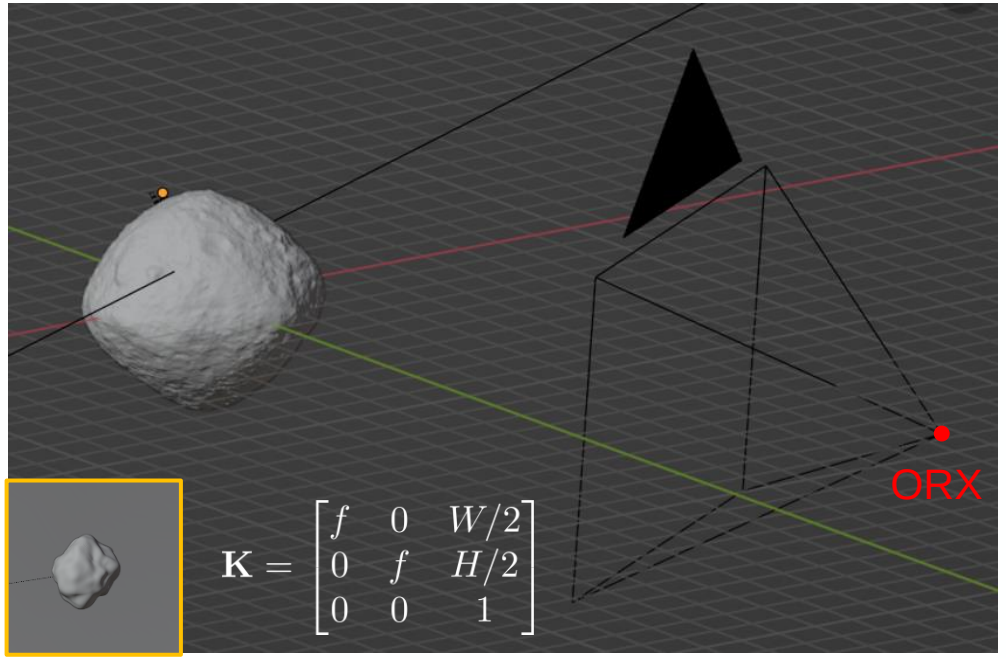
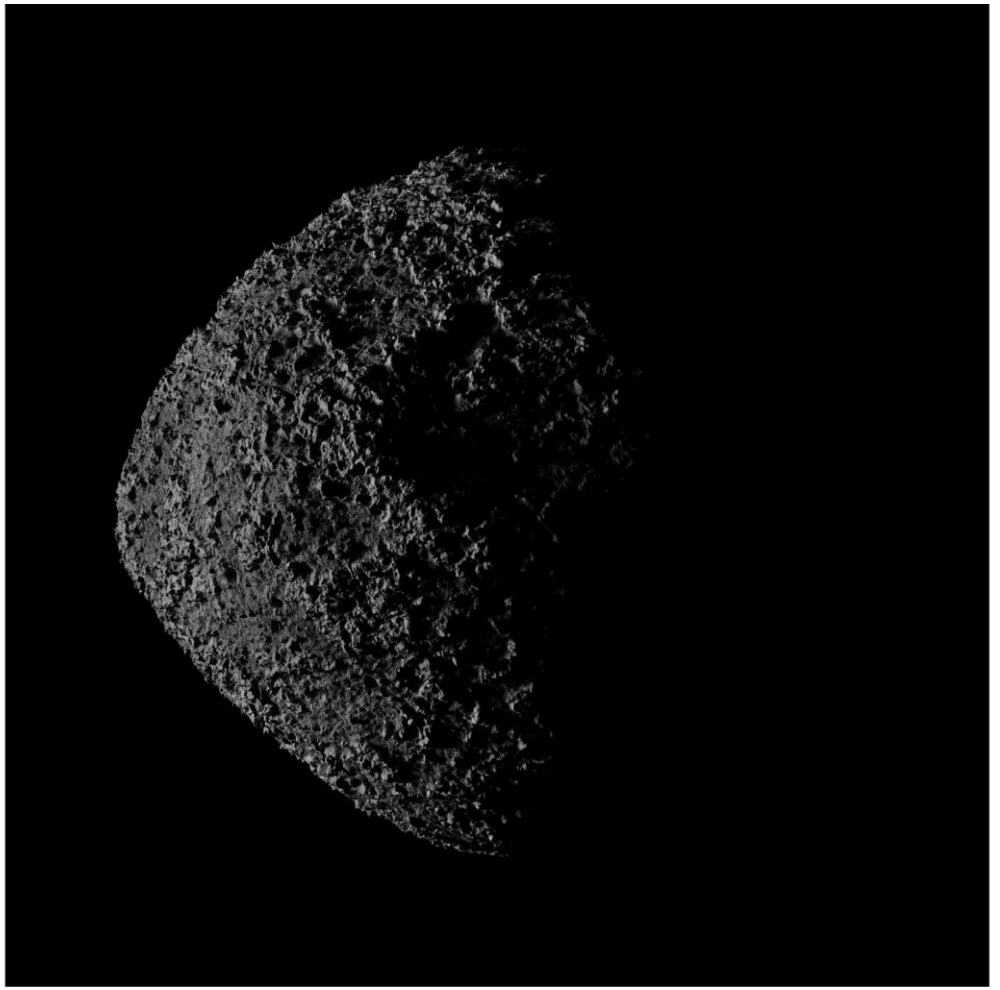
$\hat{\mathbf{x}}, \hat{\mathbf{P}}$

1. Reconstructing Particle Ejections

- Bennu model (75 cm resolution)
- Particles with diameters ~10 cm [9]
- Pinhole camera model
- Rubble-pile texture

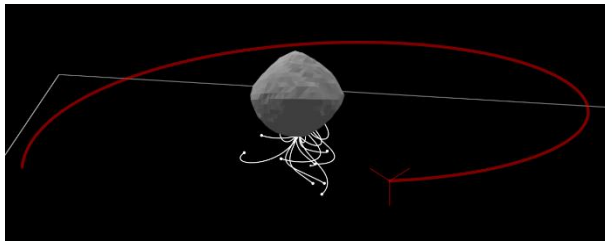


Blender scene setup: Bennu and particle models (left), pinhole camera (right)



Particle ejection simulation at 30 fps

Overview

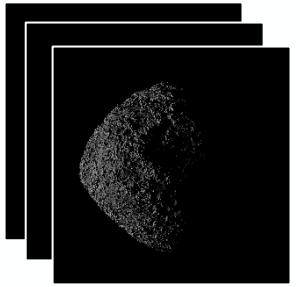


SPICE kernels:
- Particles
- OSIRIS-REx
- Sun

0

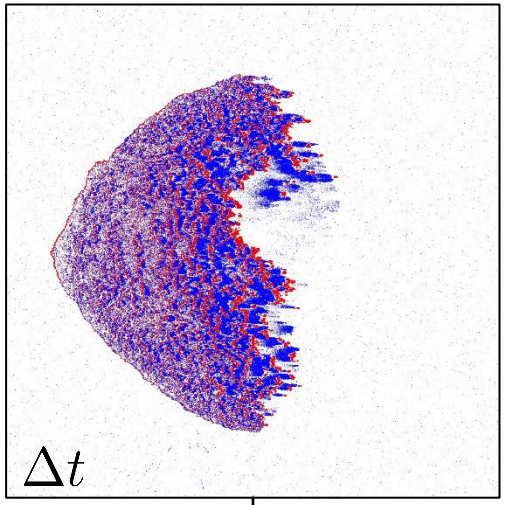
NAIF

blender



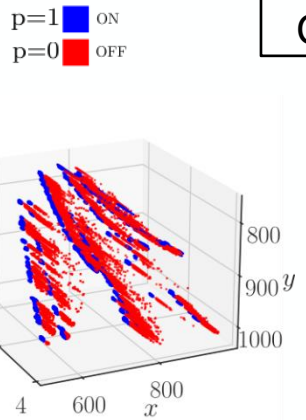
1

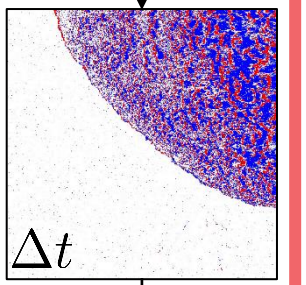
- Bennu model
- Rubble-pile texture
- Pinhole camera ($\mathbf{K}\,[\mathbf{R}|\mathbf{T}]$)



Crop

2





Mask

$\mathbf{Z}$

Observations

3

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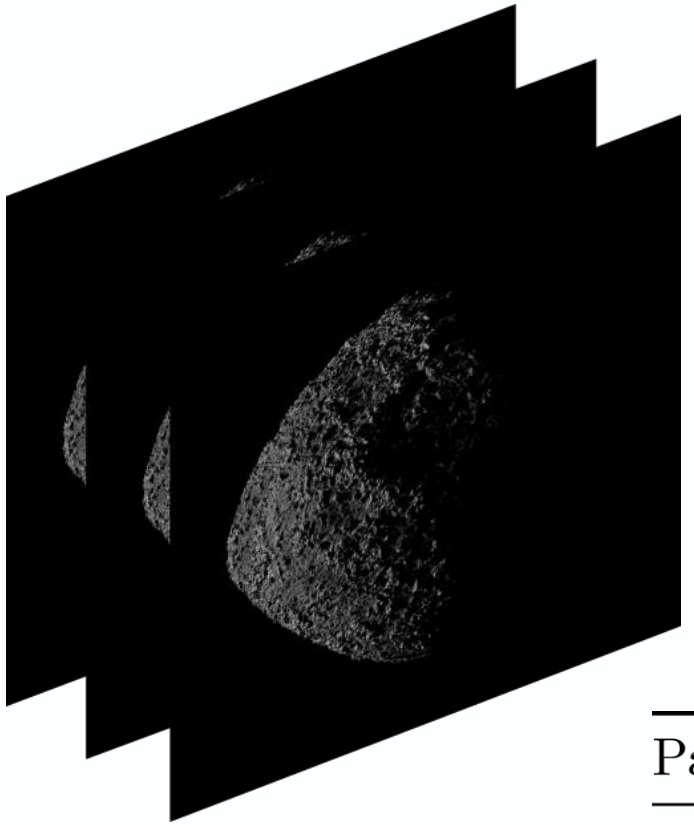
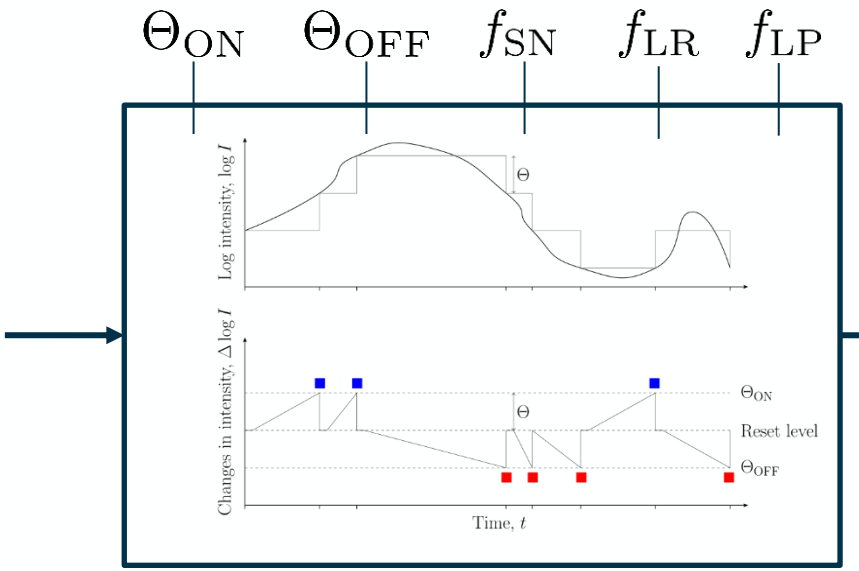
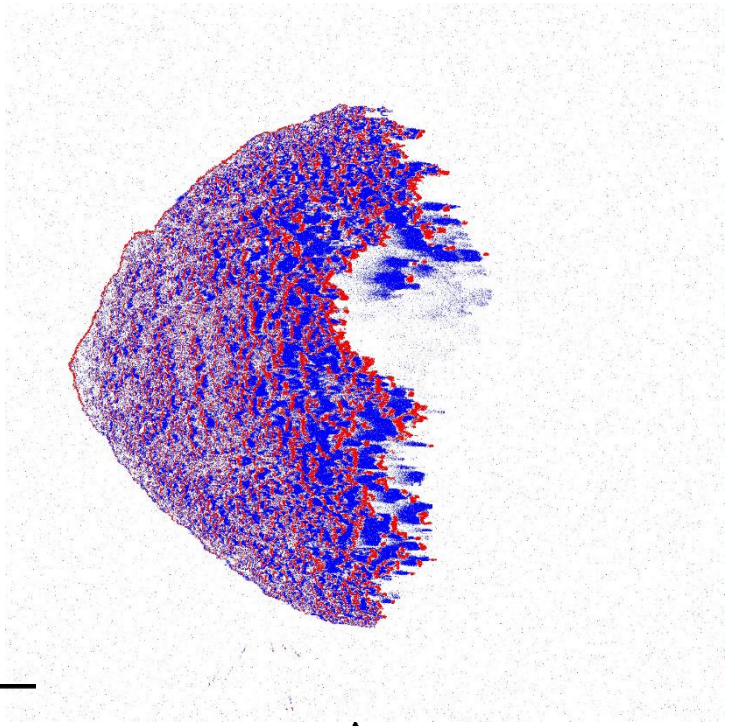
$\hat{\mathbf{x}}, \hat{\mathbf{P}}$

3. Synthetic Event Processing





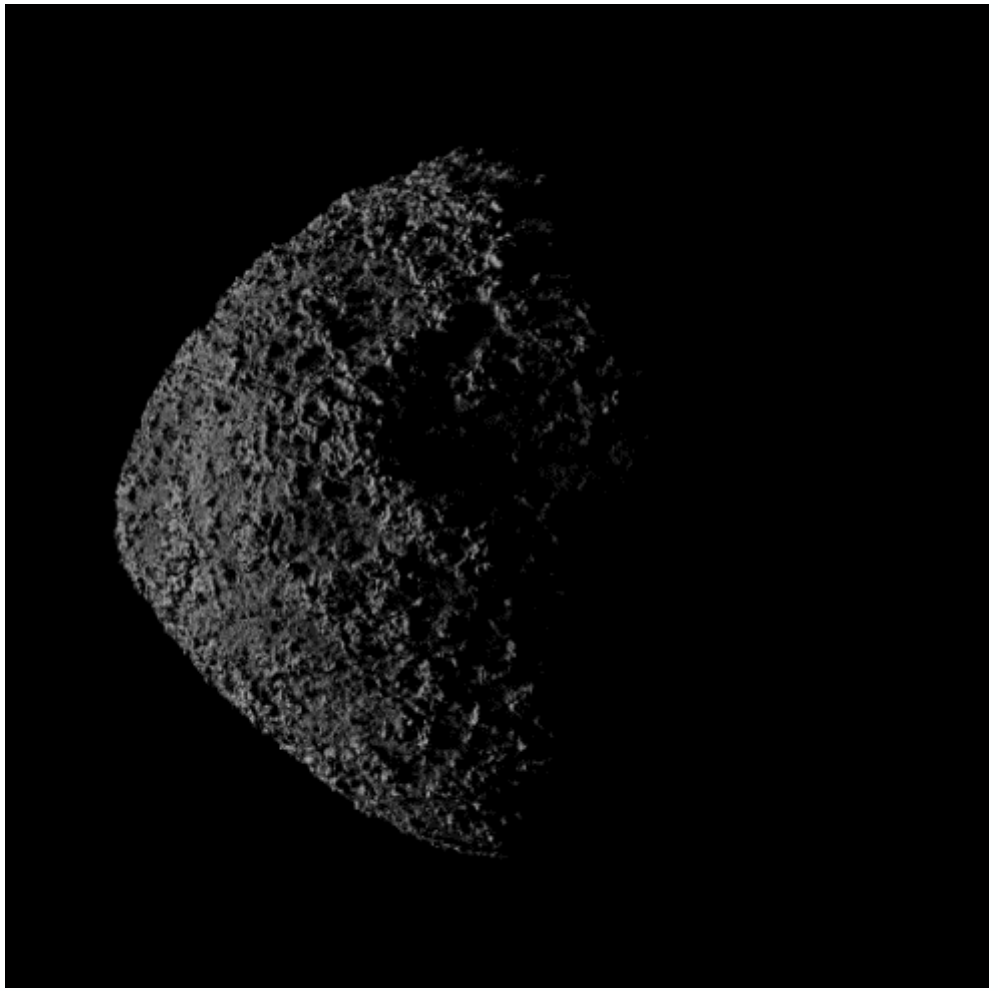
Event-camera emulation [10]



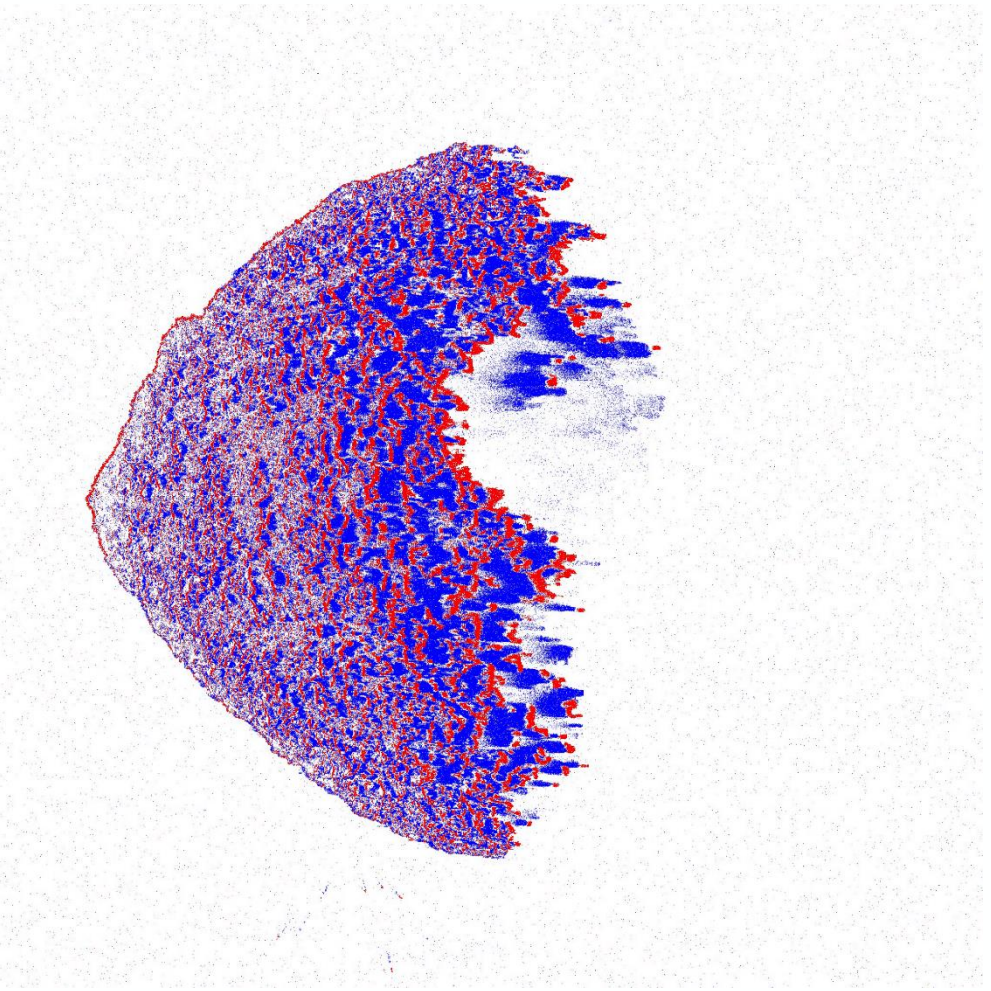
Δt

Parameter	
Θ_{ON} / Θ_{OFF}	Contrast threshold mean
f_{SN}	Shot noise rate
f_{LR}	Leak rate
f_{LP}	IIR low-pass cutoff frequency

3. Simulating a Particle Ejection Episode

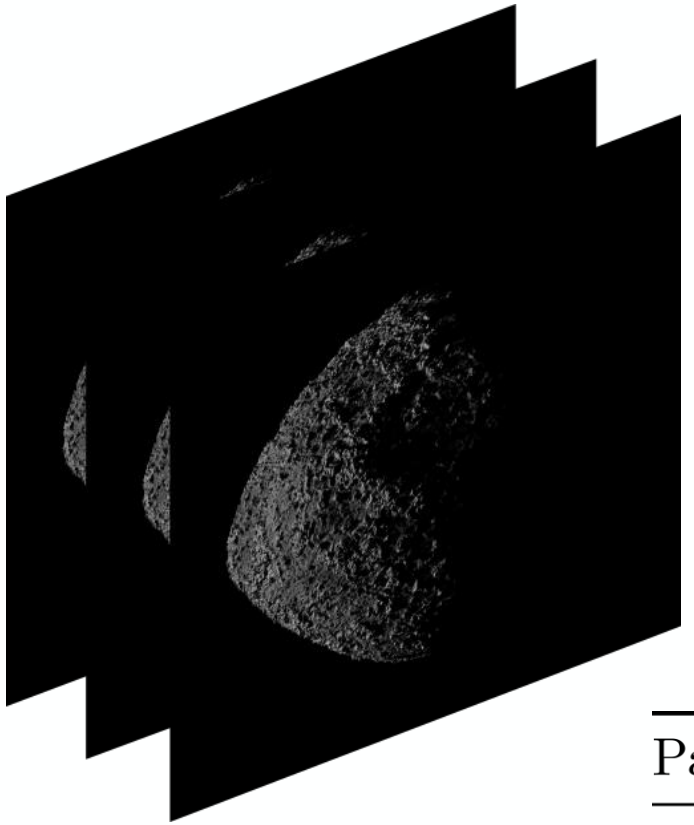


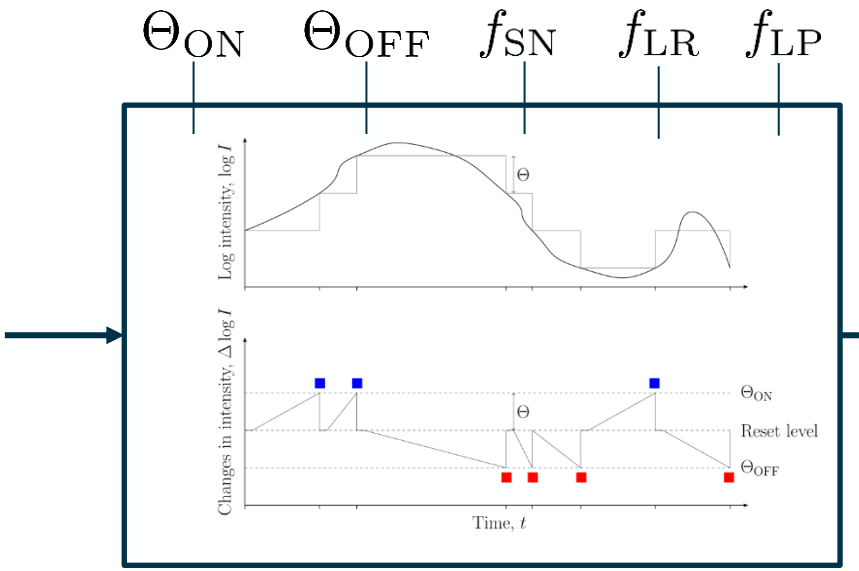
Blender



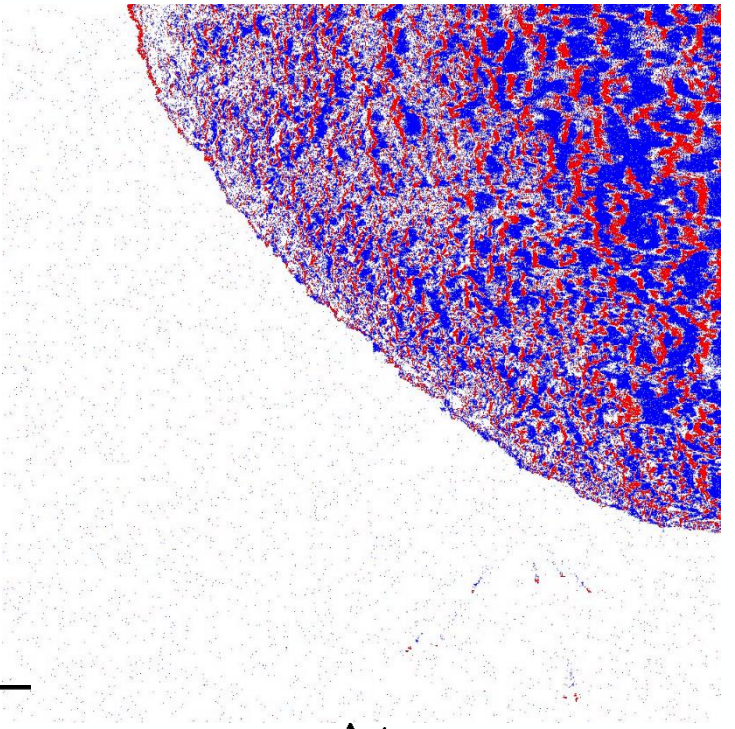
Synthetic events (noisy)

3. Synthetic Event Processing





Event-camera emulation [11]



Δt

Parameter	
Θ_{ON} / Θ_{OFF}	Contrast threshold mean
f_{SN}	Shot noise rate
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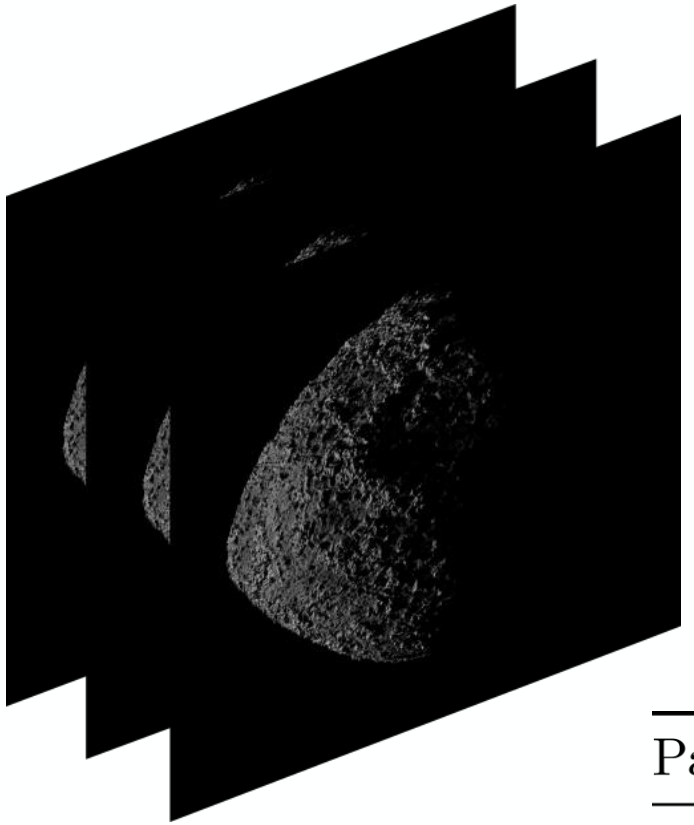
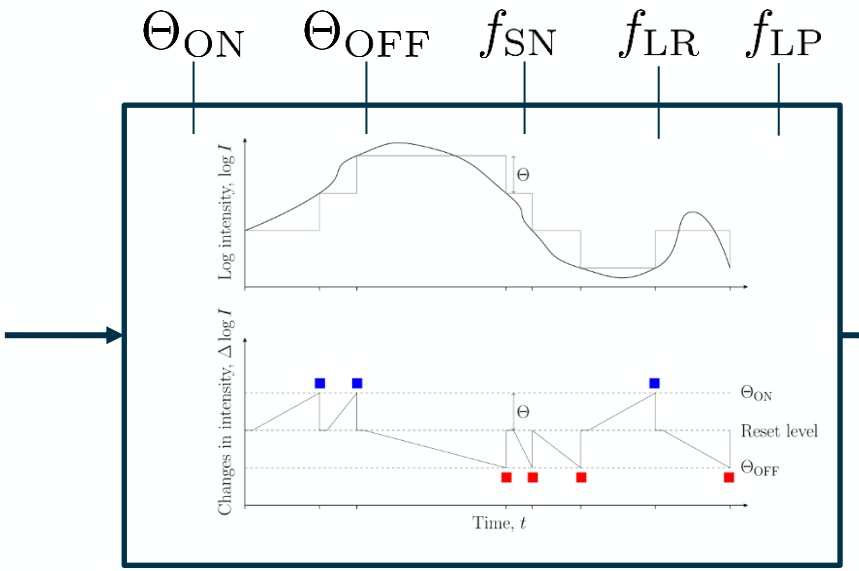
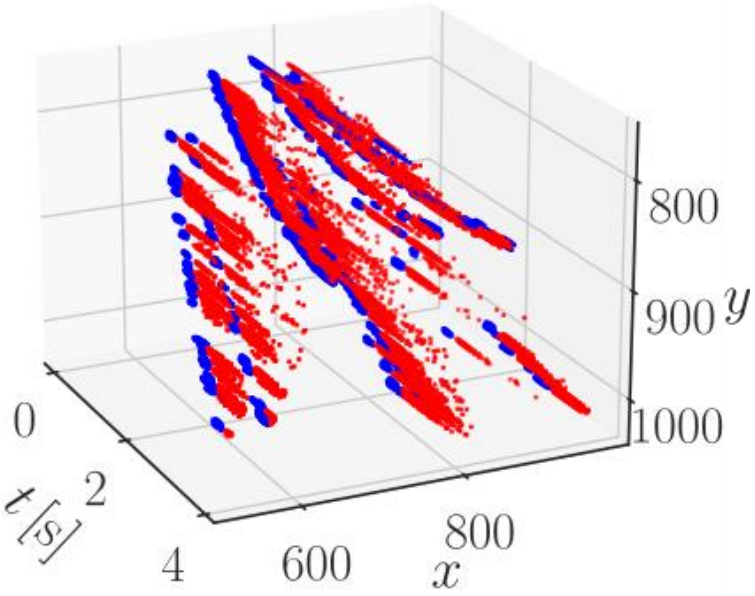
3. Synthetic Event Processing





Event-camera emulation [11]



Parameter	
Θ_{ON} / Θ_{OFF}	Contrast threshold mean
f_{SN}	Shot noise rate
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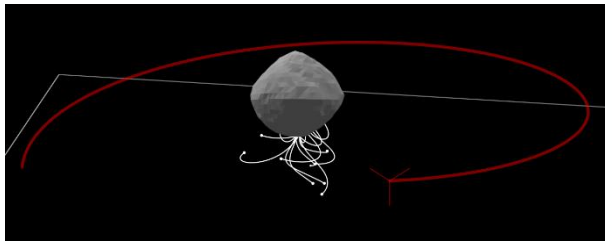
Overview

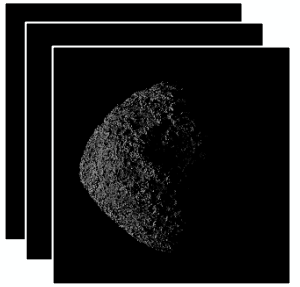


SPICE kernels:
- Particles
- OSIRIS-REx
- Sun

0

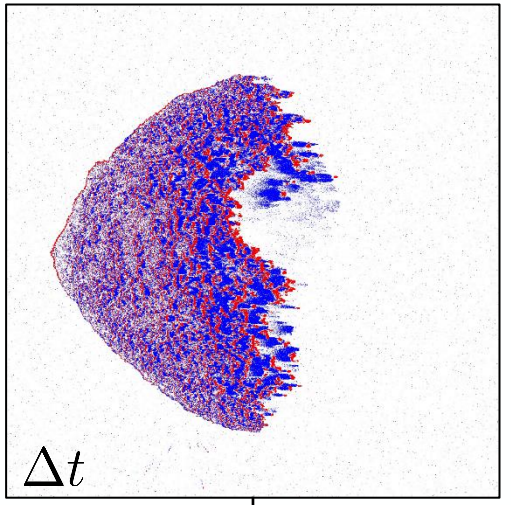
NAIF

blender



1

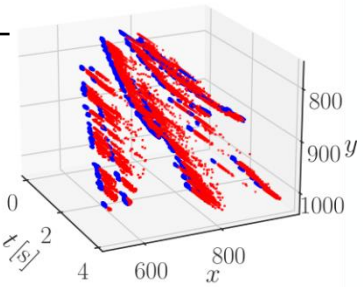
- Bennu model
- Rubble-pile texture
- Pinhole camera ($\mathbf{K}\,[\mathbf{R}|\mathbf{T}]$)

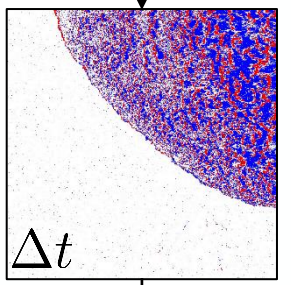


p=1 ON
p=0 OFF

Crop

2





Mask

3

Observations $\mathbf{Z}$

Track Maintenance

Data Association

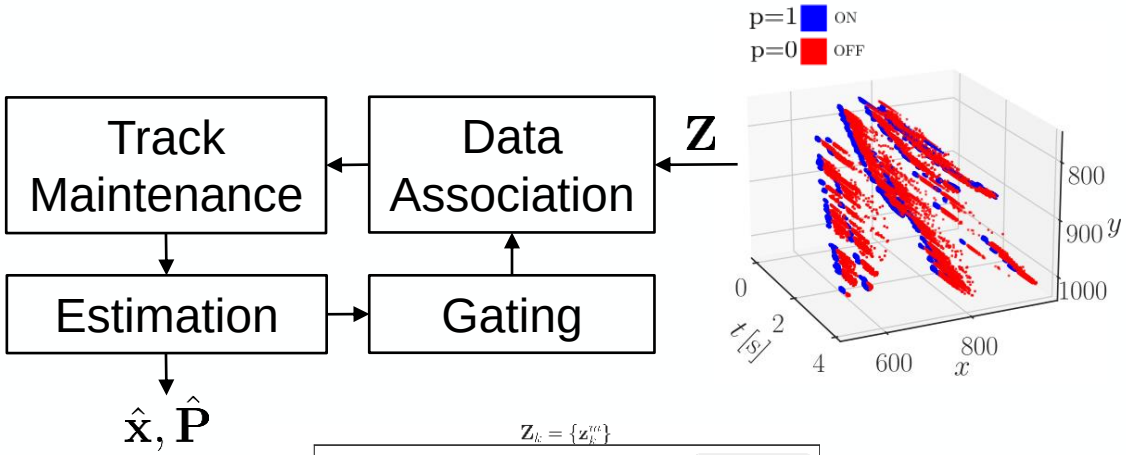
Estimation

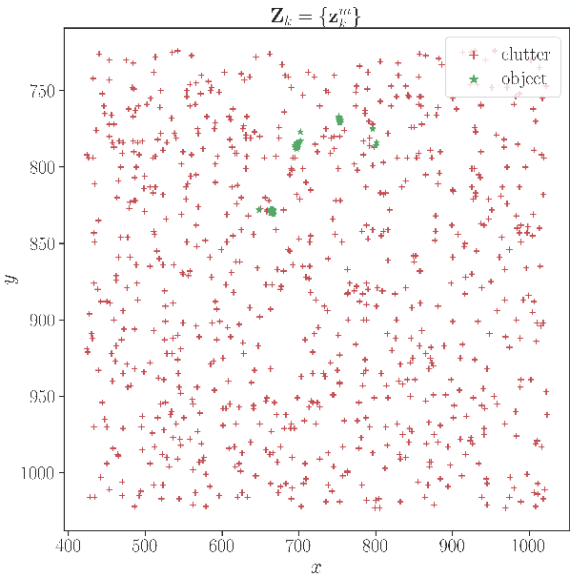
Gating

$\hat{\mathbf{x}}, \hat{\mathbf{P}}$

4. Tracking Particle Ejection Events

- MOT problem description:
  - Unknown and time-varying number of objects
  - Unknown object detections
  - Unknown data association (object vs clutter)
  - Unknown number of detections caused by a single object
  - Object birth/death as they enter the FOV



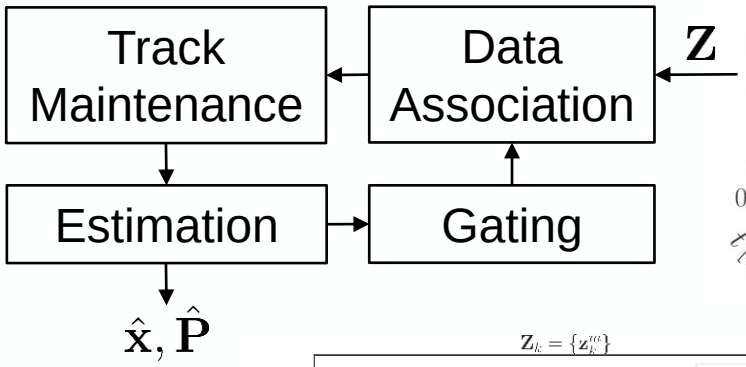


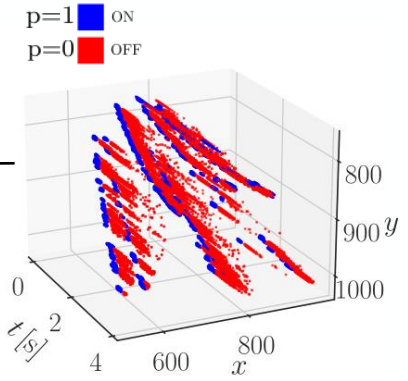
Example observation over Δt

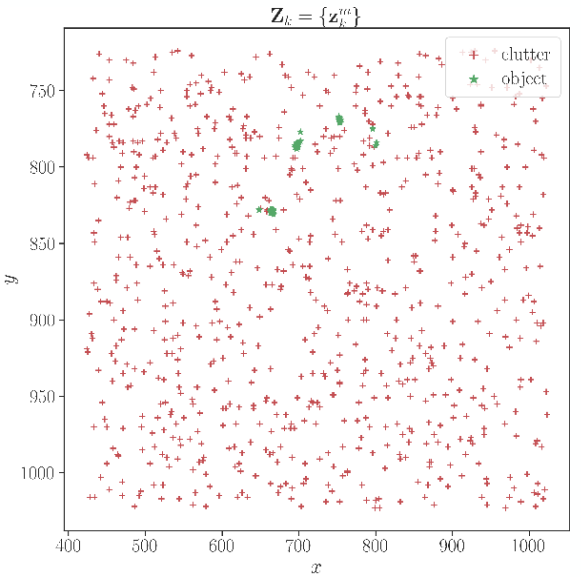
4. Tracking Particle Ejection Events

- MOT problem description:
  - Unknown and time-varying number of objects
  - ➢ **Unknown object detections**
  - ➢ **Unknown data association (object vs clutter)**
  - Unknown number of detections caused by a single object
  - Object birth/death as they enter the FOV

- n-MOT subproblem:
  - 6 particles
  - Motion model: constant velocity model
  - Global nearest neighbour based on Kalman filtering

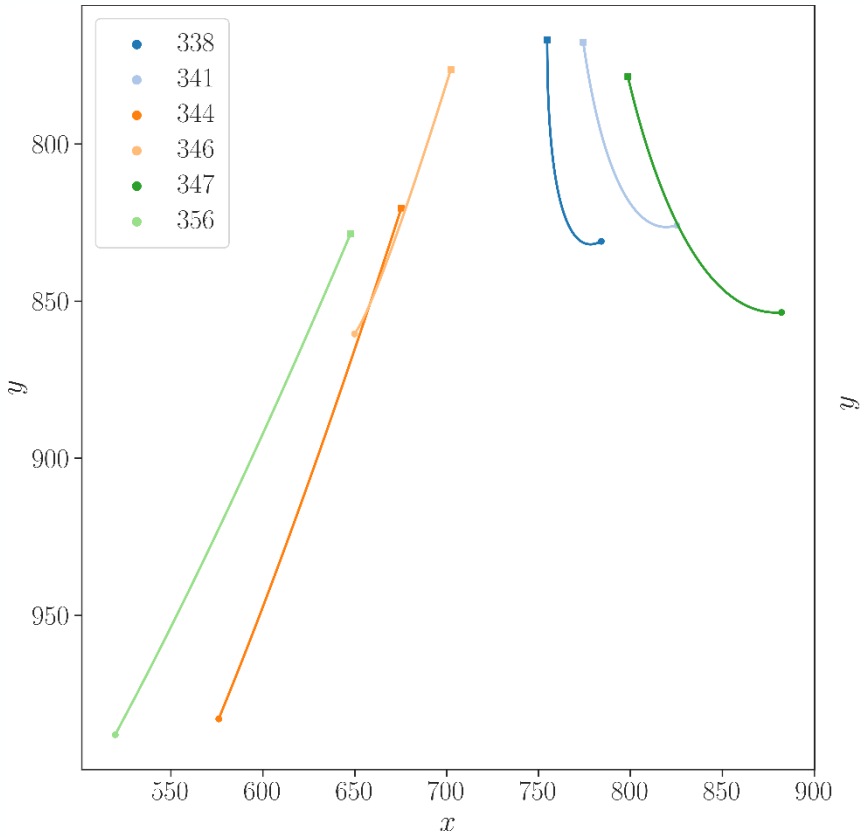




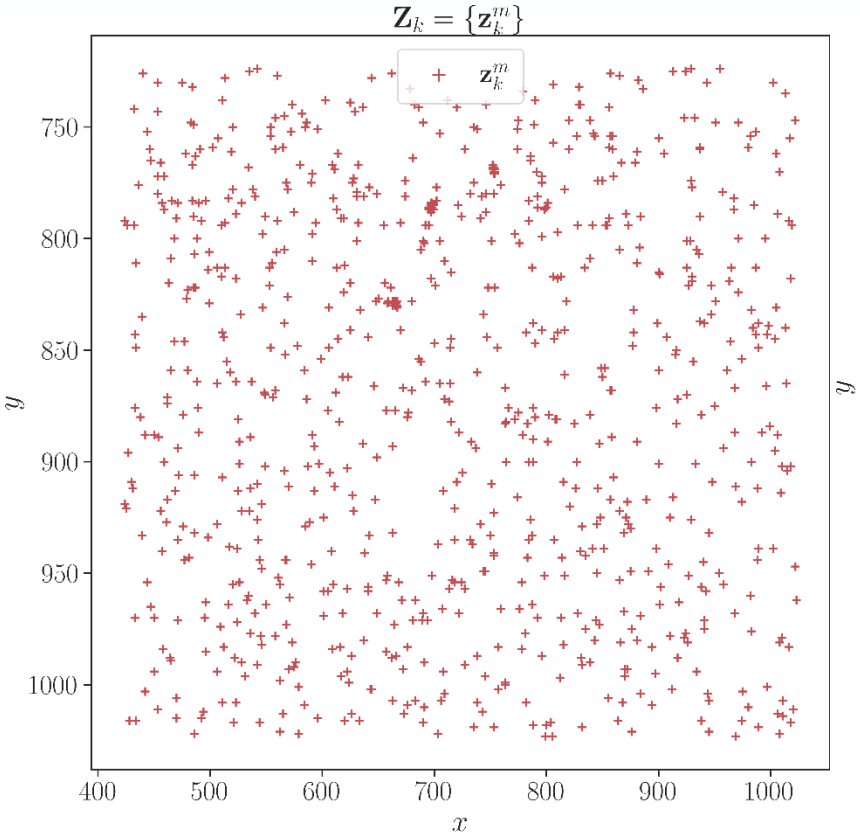


Example observation over Δt

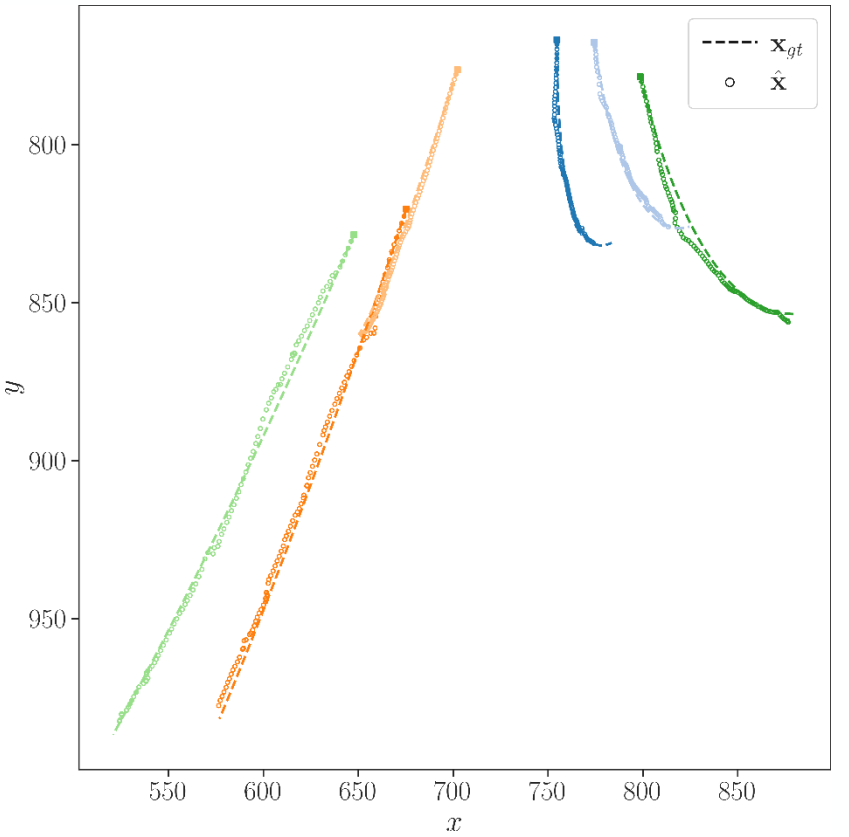
4. Tracking Particle Ejection Events



Ground truth trajectory for 6 particles



Example observation



Global nearest neighbour (GNN) tracking

Moving Forward

- MOT:
  - Object birth/death
  - Unknown number of particles
  - Object extent, i.e., multiple measurements coming from single object

- Event-based tracking:
  - Account for the polarity of events (e.g., as part of the object spatial extent)
  - Account for the high temporal resolution

- Extensions:
  - Estimating the origin of the ejecta
  - Orbit determination

Thank you for your attention

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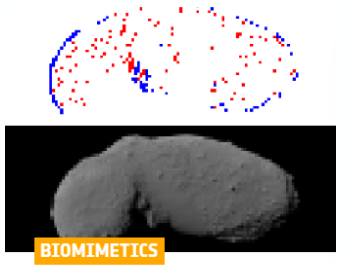
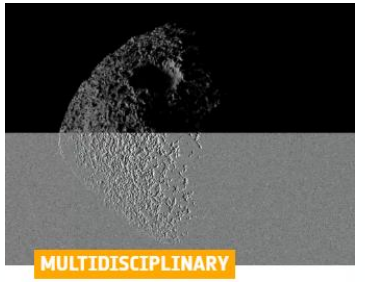
github.com/jazzalin/escape-bennu

ESA Advanced Concepts Team
https://www.esa.int/gsp/ACT/

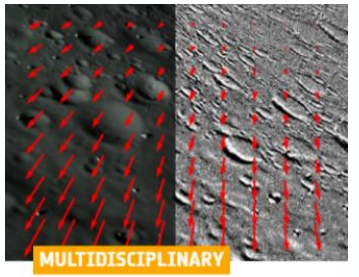
Any questions?



Event-based vision in space



Dynamic Vision for Active Asteroids: Multiple Particle Tracking



Event-based Vision for Navigation and Landing

Resources

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