On the Generation of a Synthetic Event-Based Vision Dataset for Navigation and Landing

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(*) **Speaker**
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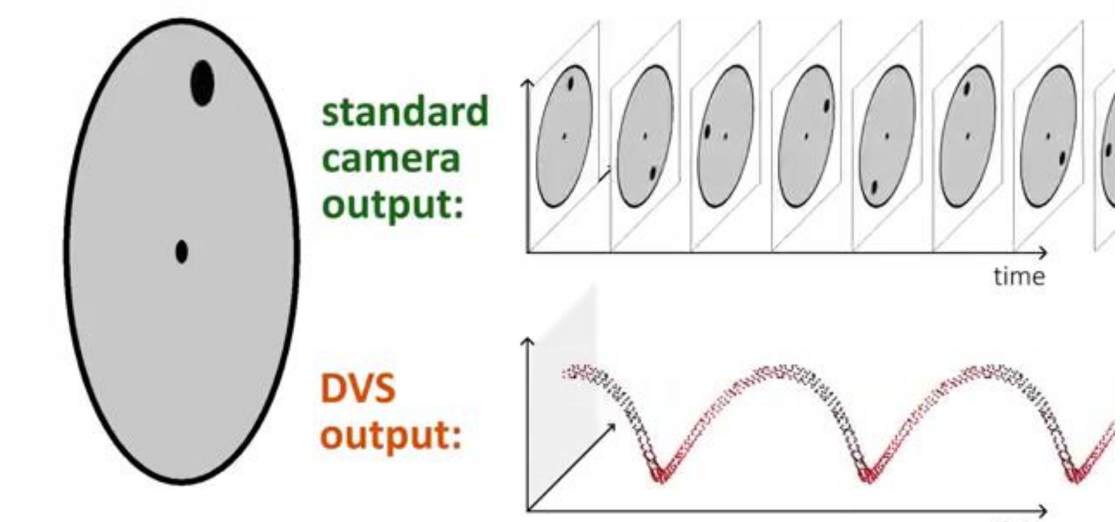
Outline

- Background:
  - Event-Based Vision
  - Towards Event-Based Cameras for Space Applications
  - Application: Lunar Landing with an Event-Based Descent Camera
- Trajectory-to-Event Pipeline:
  1. Optimal Trajectory Generation
  2. Target Body Scene Rendering
  3. Motion Field Ground Truth
  4. Synthetic Event-Stream Generation
- Outlook

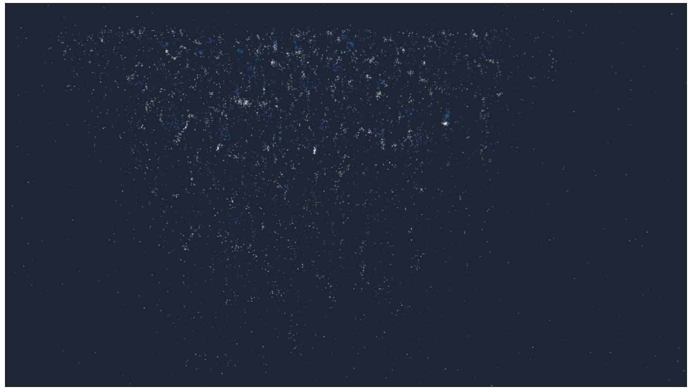
Event-Based Vision

- 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)

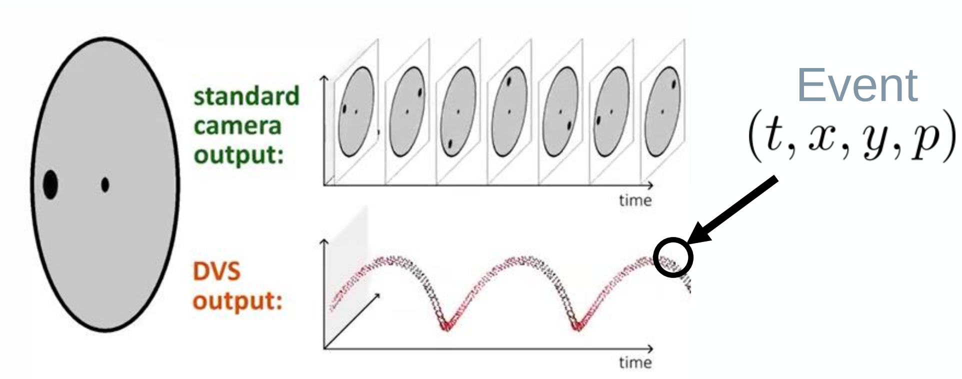
PROPHESEE EVK4 event-based camera [2]



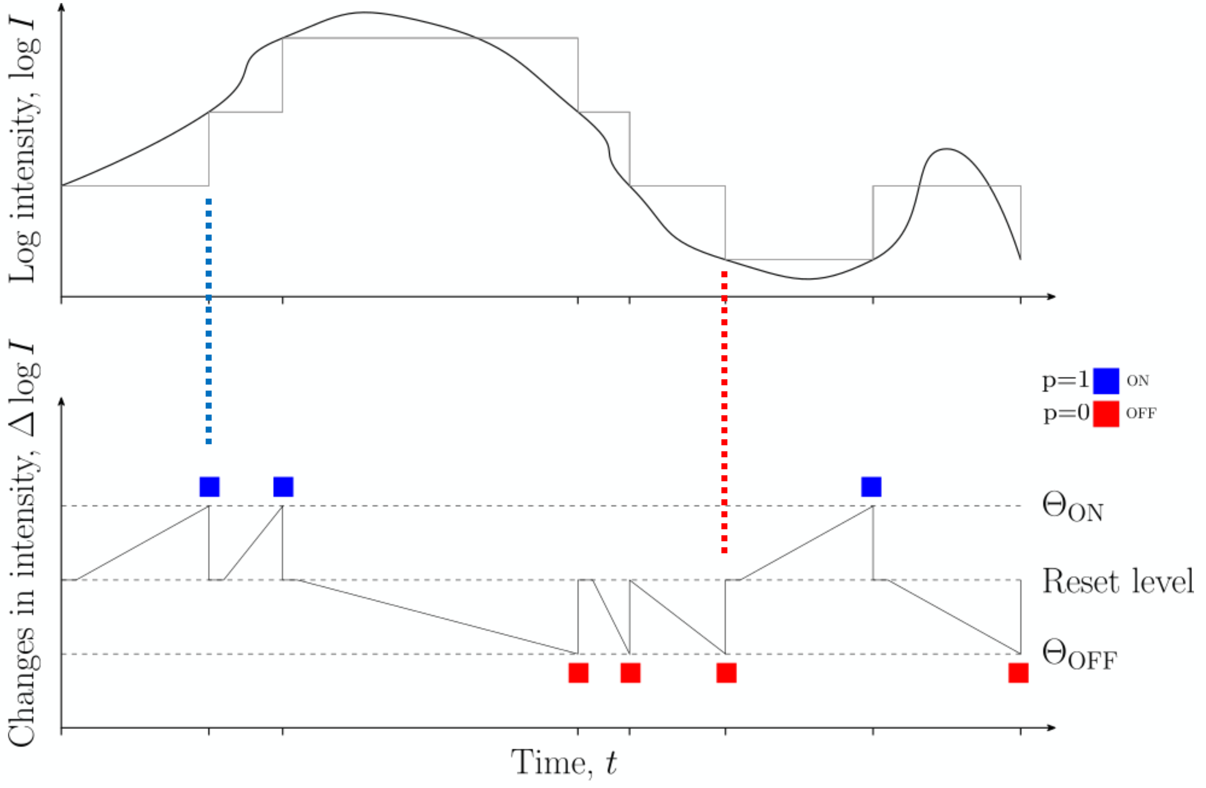
Sand hourglass captured by an event-based camera [3]

Event-Based Vision

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



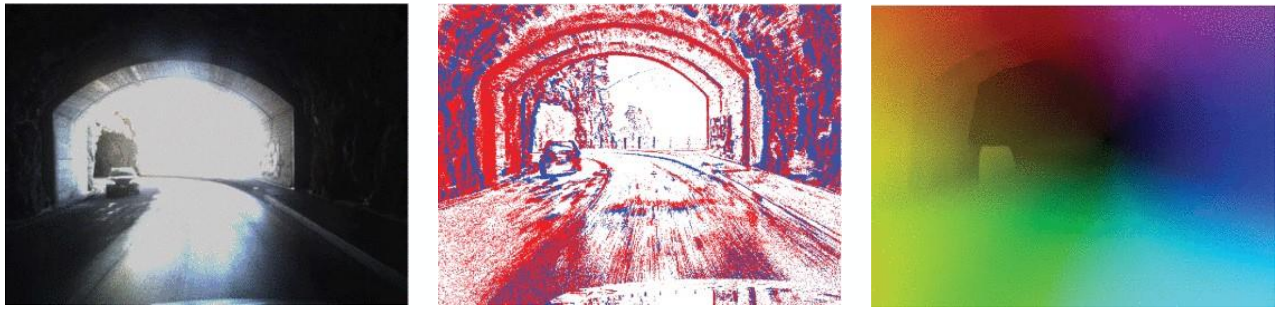
Property	Value	Unit
Motion dependent		
High dynamic range	> 120	dB
High readout rates	$2 - 120$	MHz
Low temporal resolution	$20 - 150$	μs
Low power consumption	$32 - 84$	mW



Pixel operation principle [4]

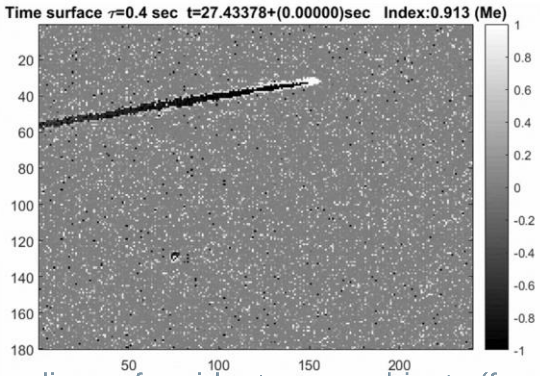
Towards Event-Based Cameras for Space Applications

- Other fields (e.g., robotics):
  - High-speed dynamics
  - Challenging lighting conditions
  - Optical flow-based navigation
- Space applications:
  - Space situational awareness
  - Tracking plumes and ejecta
  - Ventral landing based on time-to-contact

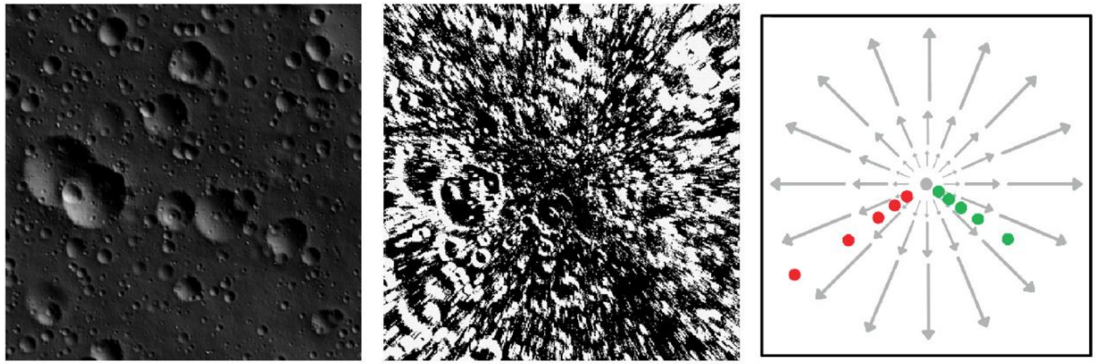


(a) (b) (c)

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



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



Event-based landing based on divergence estimation [7]

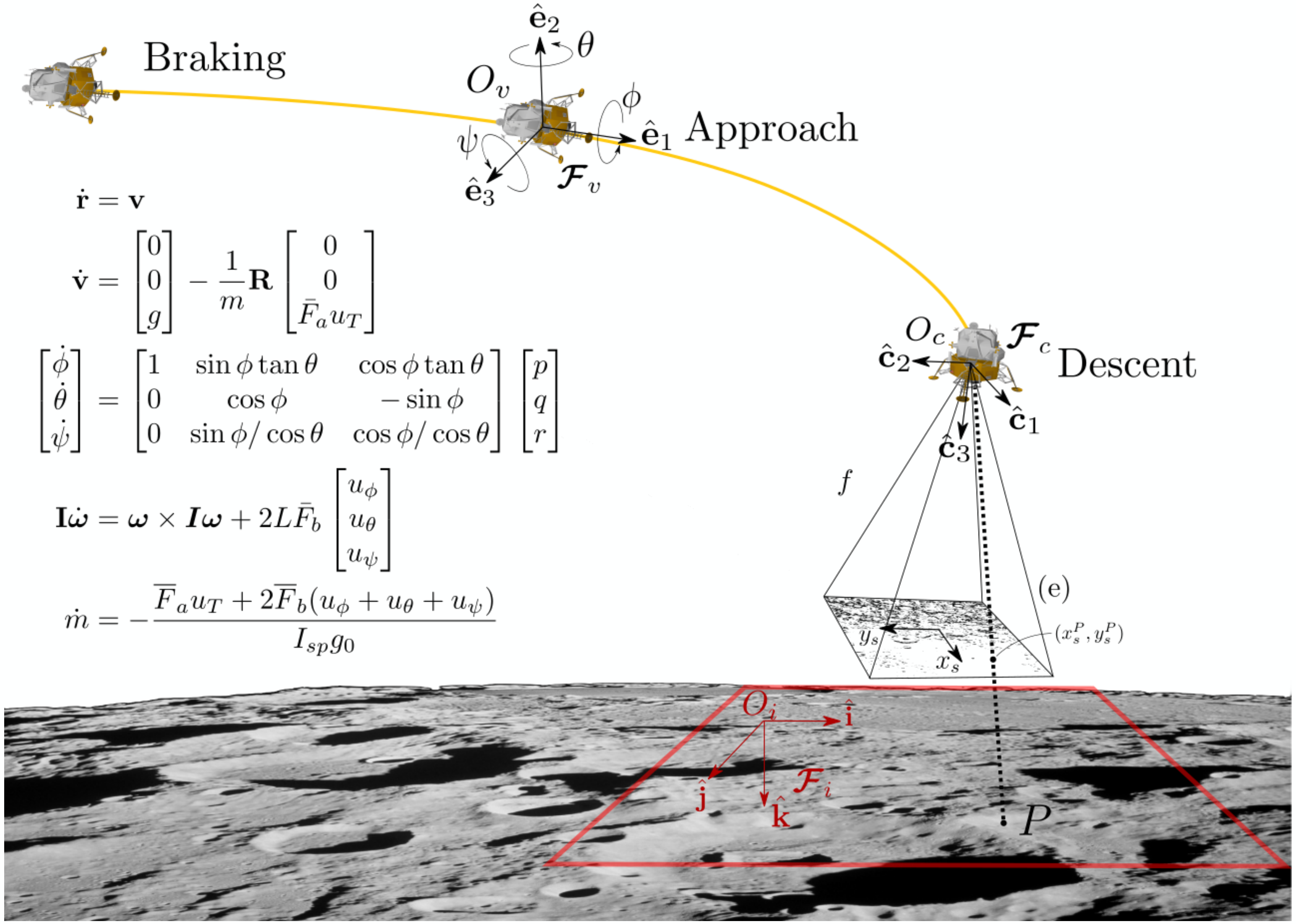
Lunar Landing with an Event-Based Descent Camera

Objective:

- simulate an event-based descent camera during approach of the lunar surface

Assumptions:

- pinhole camera model
- coincident vehicle and camera frames



$$\dot{\mathbf{r}} = \mathbf{v}$$

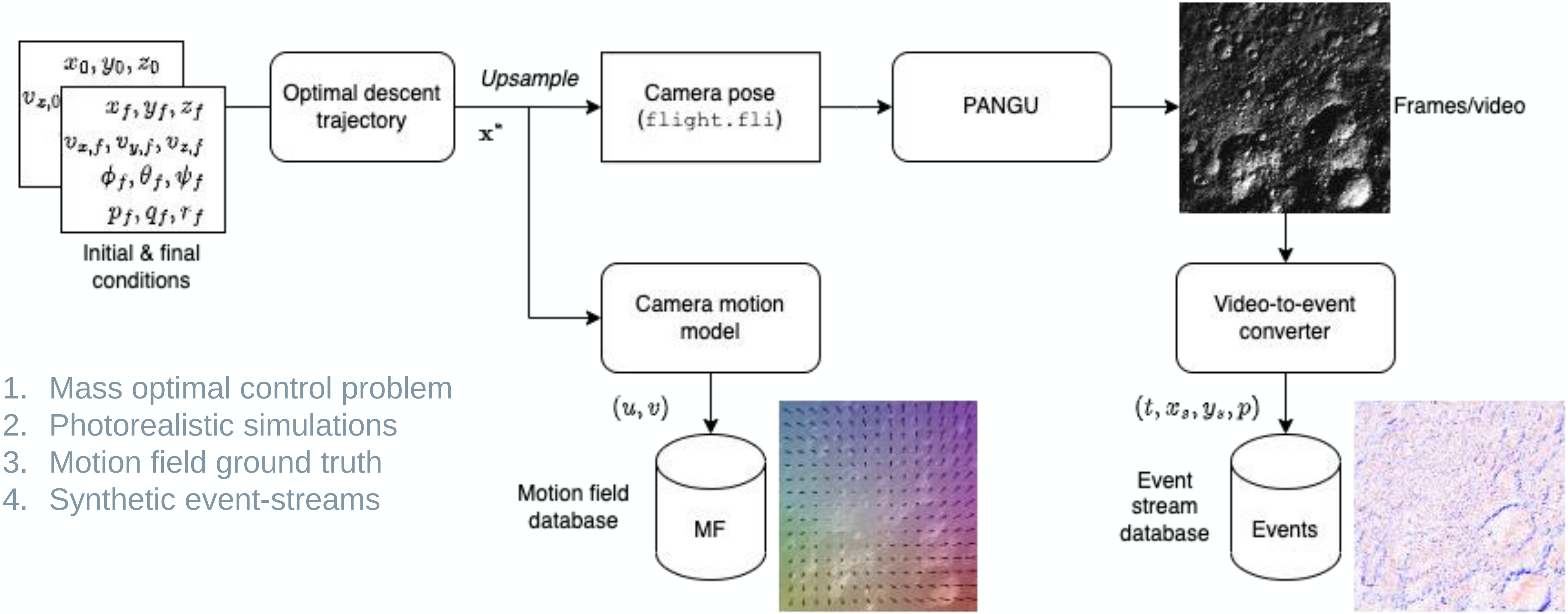
$$\dot{\mathbf{v}} = \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} - \frac{1}{m}\mathbf{R}\begin{bmatrix} 0 \\ 0 \\ \bar{F}_a u_T \end{bmatrix}$$

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi/\cos\theta & \cos\phi/\cos\theta \end{bmatrix}\begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

$$\mathbf{I}\dot{\boldsymbol{\omega}} = \boldsymbol{\omega} \times \boldsymbol{I}\boldsymbol{\omega} + 2L\bar{F}_b\begin{bmatrix} u_\phi \\ u_\theta \\ u_\psi \end{bmatrix}$$

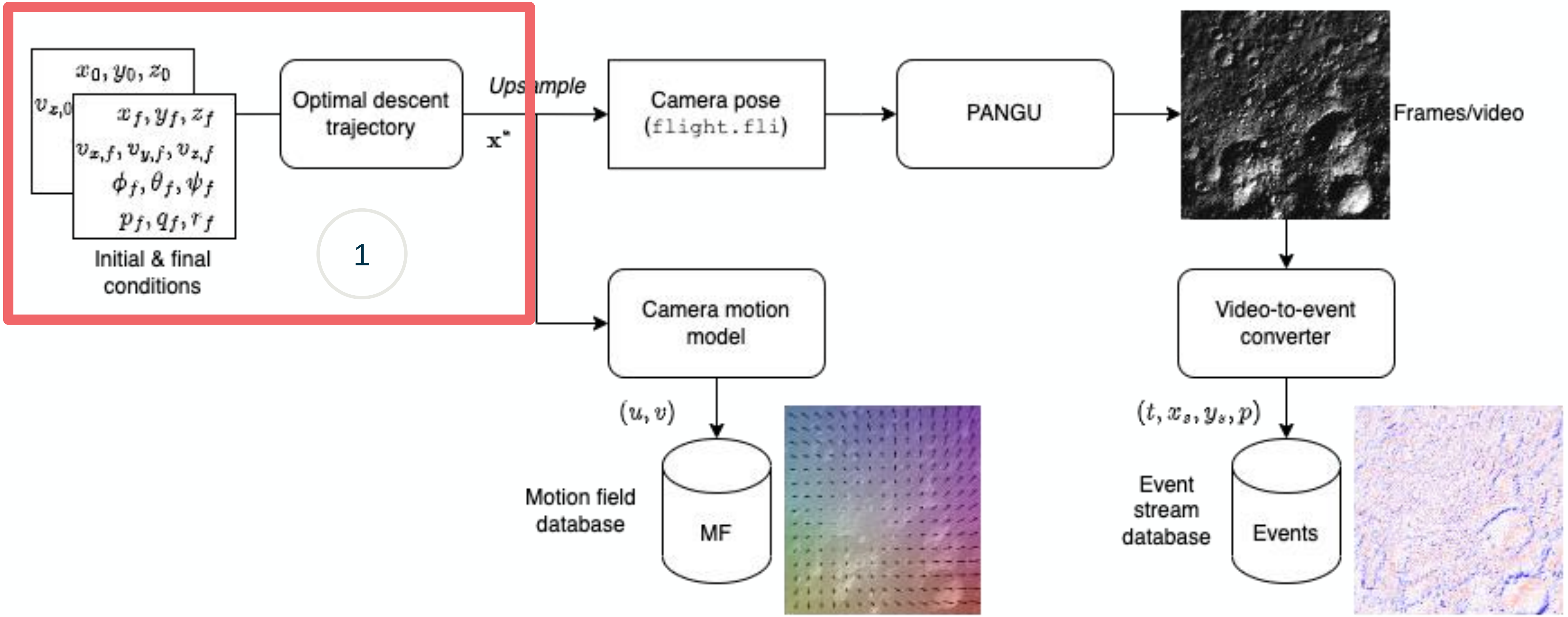
$$\dot{m} = -\frac{\overline{F}_a u_T + 2\overline{F}_b(u_\phi + u_\theta + u_\psi)}{I_{sp} g_0}$$

From Trajectory To Events…



1. Mass optimal control problem
2. Photorealistic simulations
3. Motion field ground truth
4. Synthetic event-streams

1. Mass-Optimal Control Problem

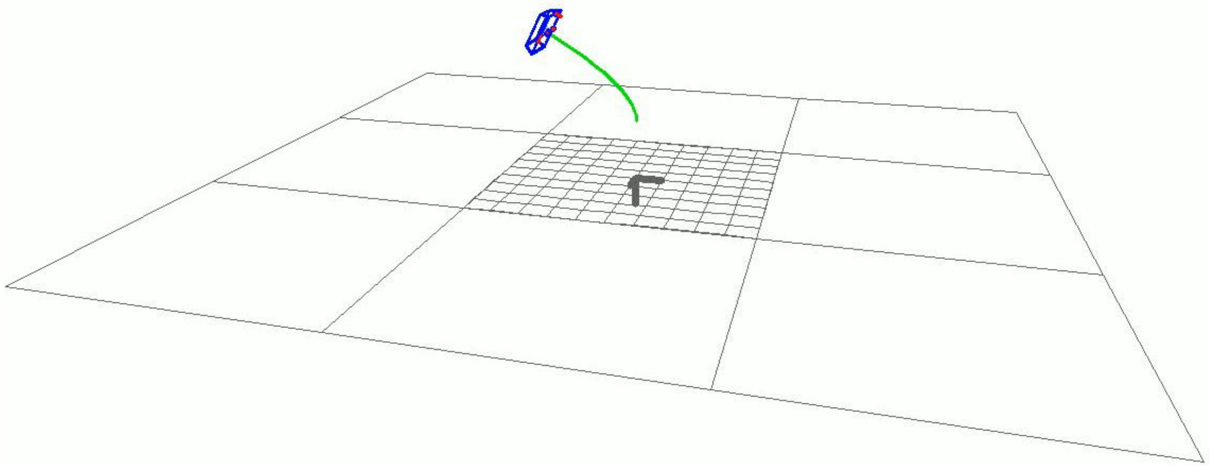


1. Mass-Optimal Control Problem

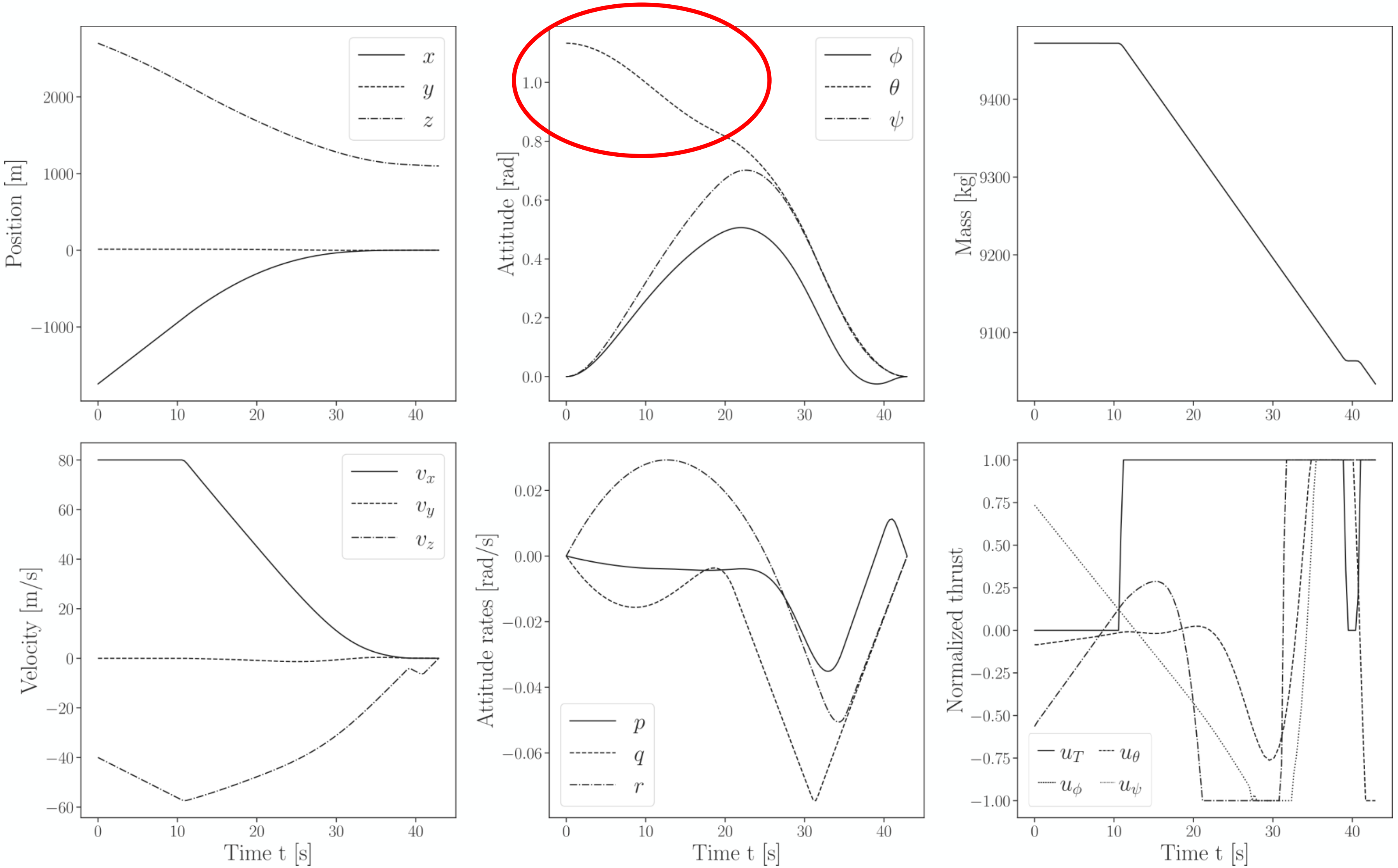
$$
\begin{aligned}
\min \quad & J(m(t), \mathbf{u}(t)) = -(1-\epsilon)\int_0^{t_f} \dot{m}(\tau)\, d\tau + \epsilon \int_0^{t_f} \mathbf{u}(\tau)^T \mathbf{u}(\tau)\, d\tau \\
\text{subject to} \quad & \dot{\mathbf{x}}(t) = \mathbf{f}(\mathbf{x}(t), \mathbf{u}(t)), && \text{Dynamic constraints} \\
& \cos\phi \cdot \cos\theta \geq \cos\lambda, && \text{Max thrust tilt} \\
& -\mathbf{1} \leq \mathbf{u}(t) \leq \mathbf{1}, && \text{Thrust limits} \\
& \mathbf{x}(0) = \mathbf{x}_0,\ \mathbf{x}(t_f) = \mathbf{x}_f && \text{Boundary conditions}
\end{aligned}
$$

AMPL

(NLP solver)



1. Mass-Optimal Control Problem

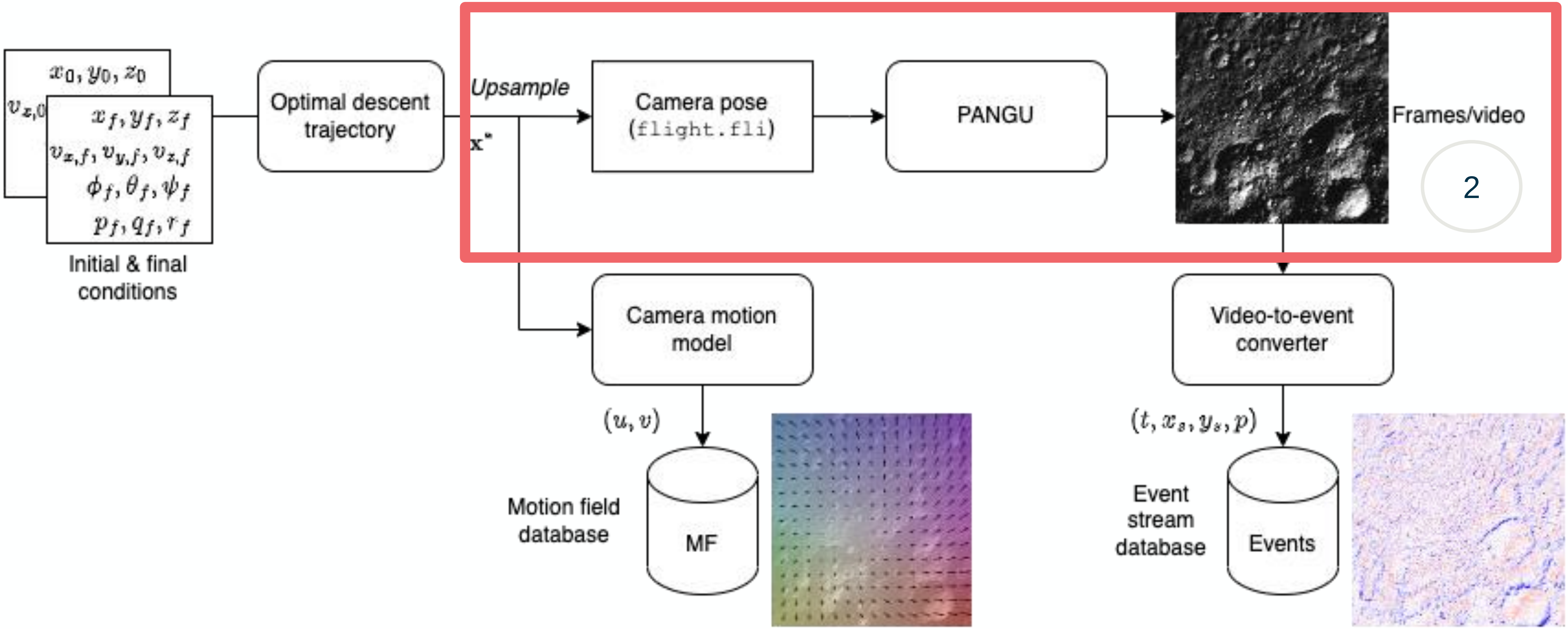


$$I_{xx} = 18941\,\mathrm{kgm}^2$$
$$I_{yy} = 20469\,\mathrm{kgm}^2$$
$$I_{zz} = 20972\,\mathrm{kgm}^2$$
$$\bar{F}_a = 44000\,\mathrm{N}$$
$$\bar{F}_b = 44\,\mathrm{N}$$

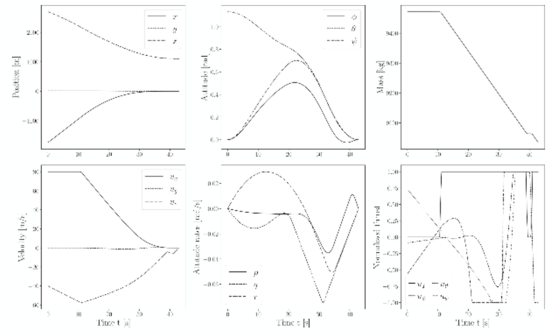
$$m_0 = 9472\,\mathrm{kg}$$
$$z_0 = 2700\,\mathrm{m}$$
$$v_{x0} = 80\,\mathrm{ms}^{-1}$$
$$v_{z0} = 40\,\mathrm{ms}^{-1}$$
$$\theta_0 = 1.133\,\mathrm{rad}$$

$$z_n = 1100\,\mathrm{m}$$

2. Photorealistic Landing Simulations



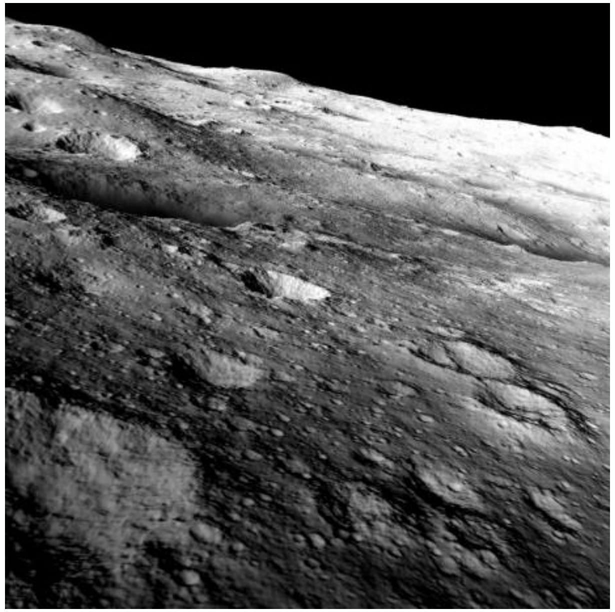
2. Photorealistic Landing Simulations



Upsample to $\mathrm{FPS} = 100\,\mathrm{Hz}$

Planet and asteroid natural scene generation utility [8]

- Parameters:
    - Lighting conditions
    - Reflectance
    - Resolution
- Features:
    - Craters
    - Boulders
    - Horizon



$\gamma_s = 55^\circ, \quad \alpha_s = 15^\circ$

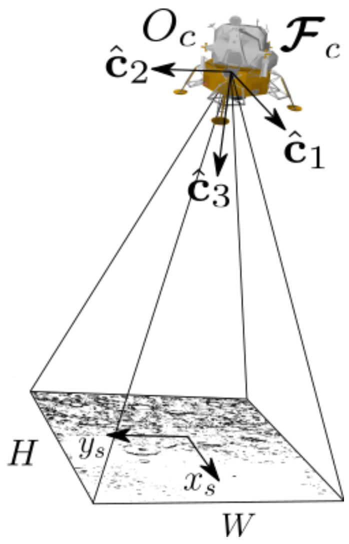
$\gamma_s = 155^\circ, \quad \alpha_s = 2^\circ$

$$\mathbf{K} = \begin{bmatrix} f & 0 & W/2 \\ 0 & f & H/2 \\ 0 & 0 & 1 \end{bmatrix}$$

$$f = \frac{W}{2 \tan \frac{\vartheta}{2}}$$

$$\vartheta = 45^\circ$$

$$H = W = 1024$$

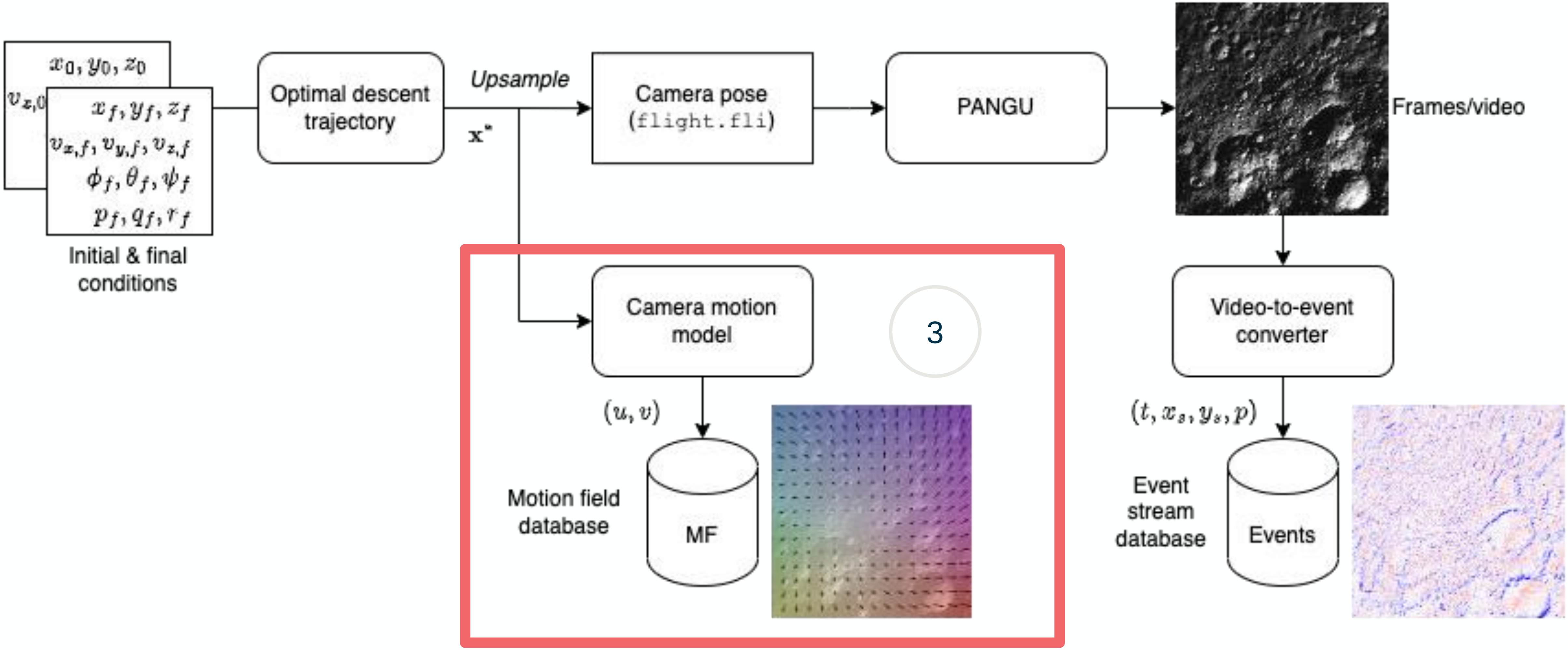


2. Photorealistic Landing Simulations

Approach

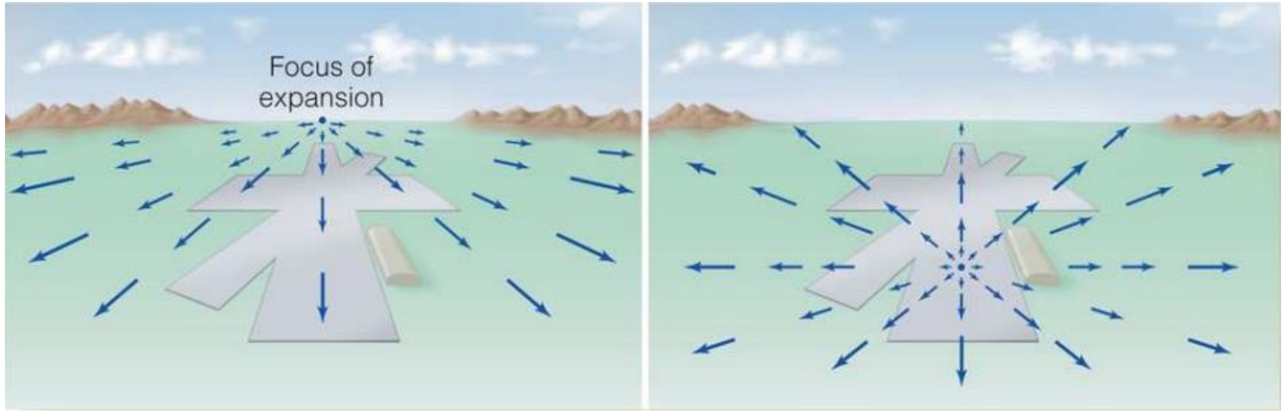
Descent

3. Motion Field Ground Truth

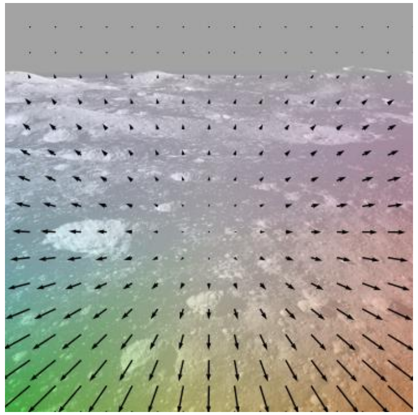


3. Motion Field Ground Truth

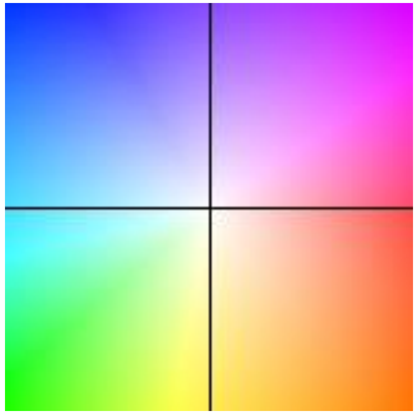
Projection of the relative velocity of a 3D object into the image plane:



Motion field during landing [9]



Flow during descent



Directional colormap

Motion field equations

$$\begin{bmatrix} u \\ v \end{bmatrix} = \frac{1}{Z} \begin{bmatrix} -f & 0 & x_s \\ 0 & -f & y_s \end{bmatrix} \begin{bmatrix} v_{c,x} \\ v_{c,y} \\ v_{c,z} \end{bmatrix} + \begin{bmatrix} \frac{x_s y_s}{f} & -(f + \frac{x_s^2}{f}) & y_s \\ f + \frac{y_s^2}{f} & -\frac{x_s y_s}{f} & -x_s \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

Inverse depth map

$$h(x_s, y_s) = \frac{1}{Z}$$

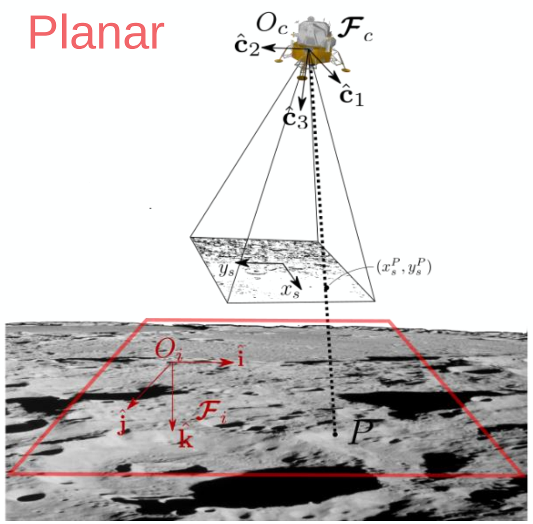
3. Motion Field Ground Truth

Projection of the relative velocity of a 3D object into the image plane:

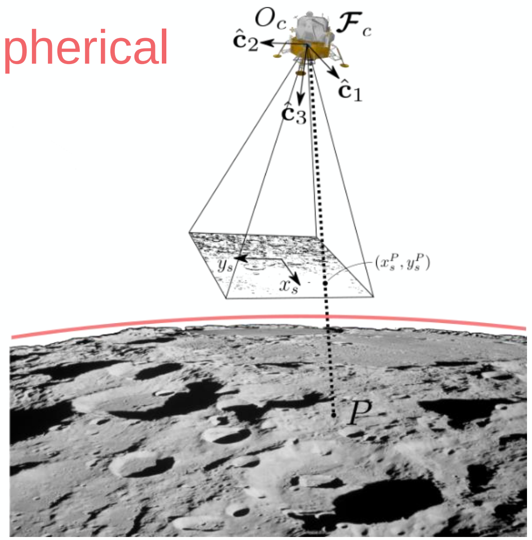
$$\begin{bmatrix} u \\ v \end{bmatrix} = \frac{1}{Z}\begin{bmatrix} -f & 0 & x_s \\ 0 & -f & y_s \end{bmatrix}\begin{bmatrix} v_{c,x} \\ v_{c,y} \\ v_{c,z} \end{bmatrix} + \begin{bmatrix} \frac{x_s y_s}{f} & -(f+\frac{x_s^2}{f}) & y_s \\ f+\frac{y_s^2}{f} & -\frac{x_s y_s}{f} & -x_s \end{bmatrix}\begin{bmatrix} p \\ q \\ r \end{bmatrix}, \qquad h(x_s, y_s) = \frac{1}{Z}$$

inverse depth map

Planar



Spherical



$$h(x_s, y_s) = -\frac{A}{z}$$

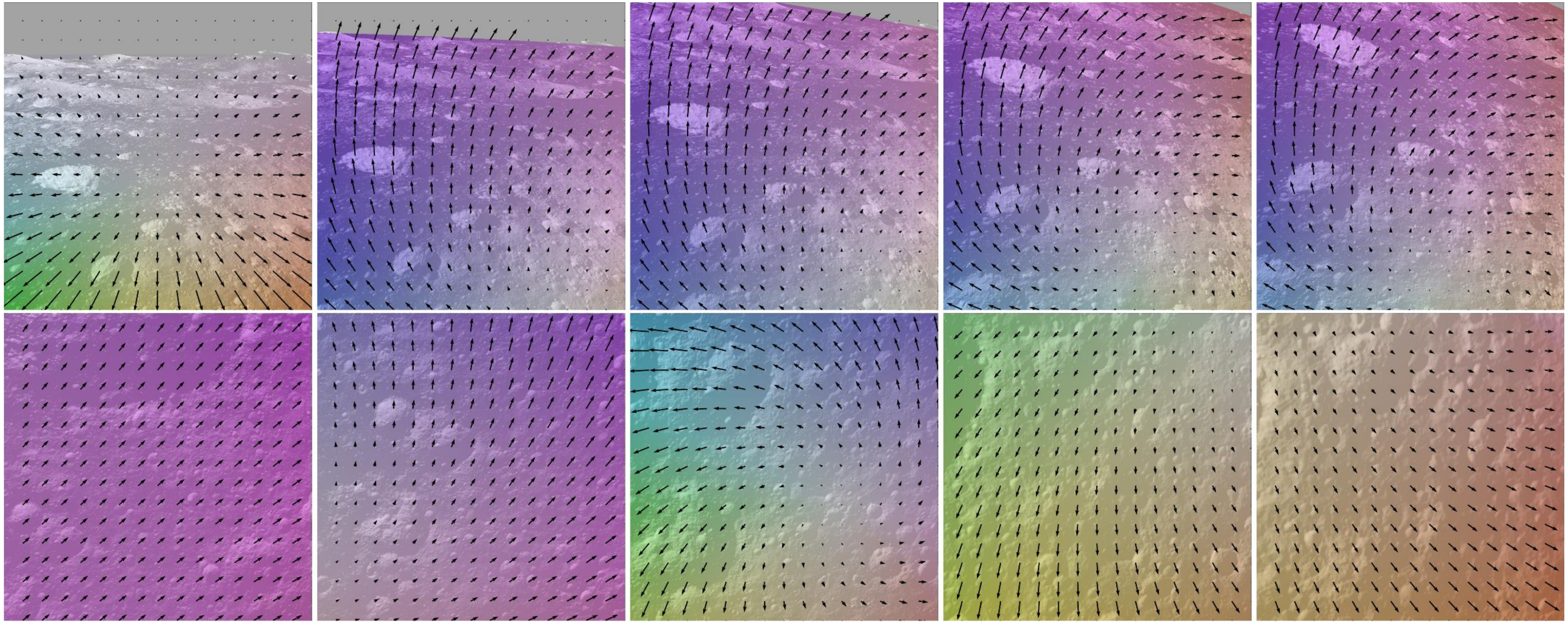
$$h(x_s, y_s) = \frac{B}{(R-z)A - \sqrt{(R-z)^2 A + 2zRB}}$$

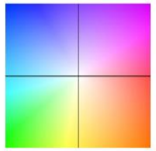
3. Motion Field Ground Truth

Using the spherical assumption for lunar landings with $R = 1737400 + \mathrm{mean}(h_{\mathrm{DEM}})\ [\mathrm{m}]$:

Approach

Descent

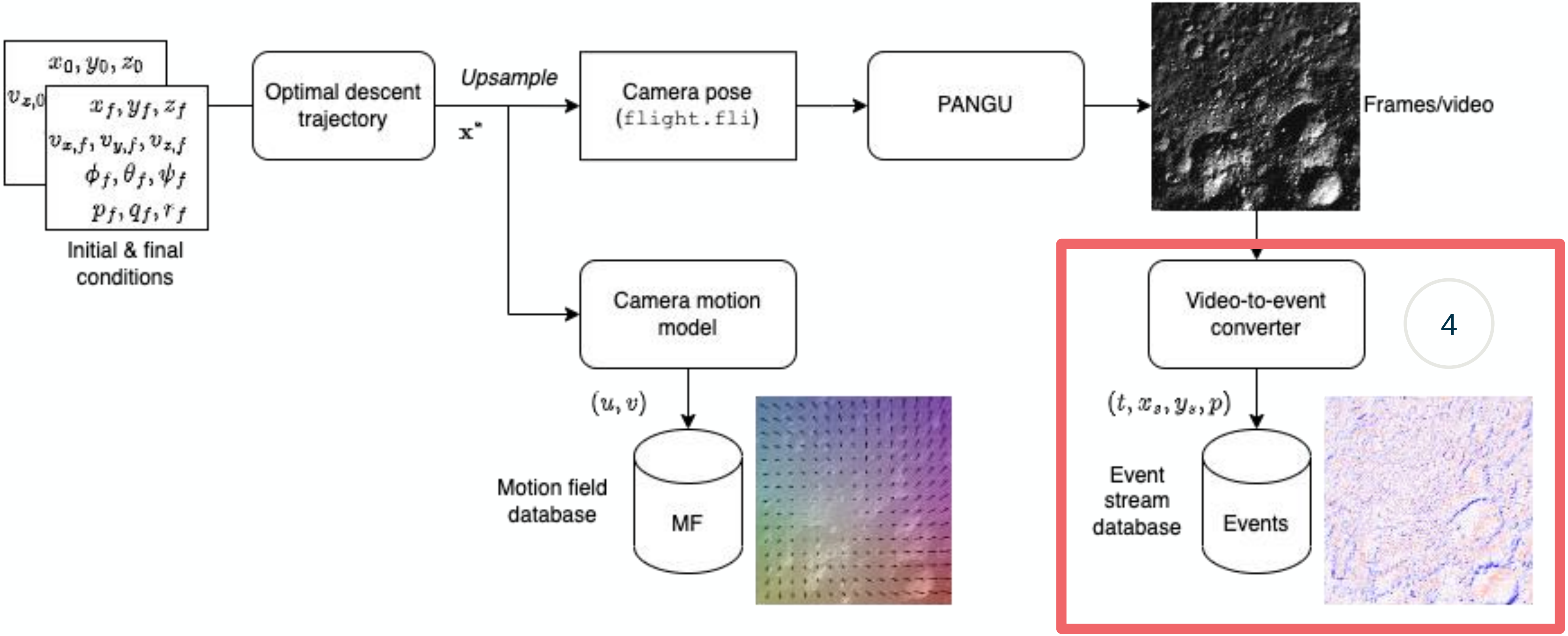




directional colormap

$t = t_0$ $t = \frac{1}{4} t_f$ $t = \frac{1}{2} t_f$ $t = \frac{3}{4} t_f$ $t = t_f$

4. Synthetic Event Generation



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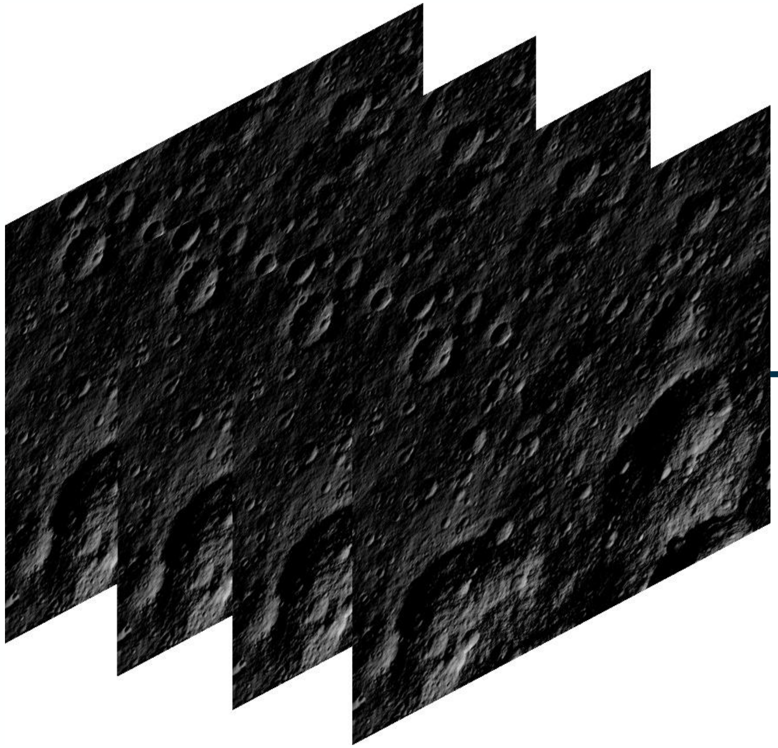
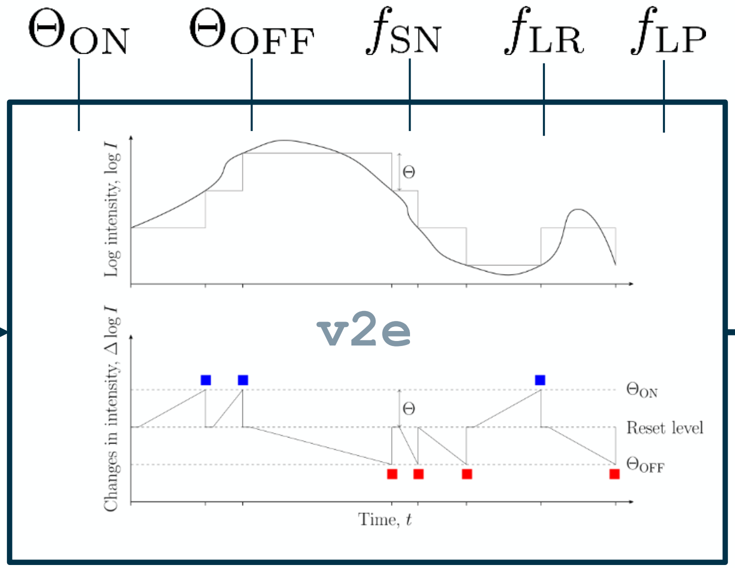
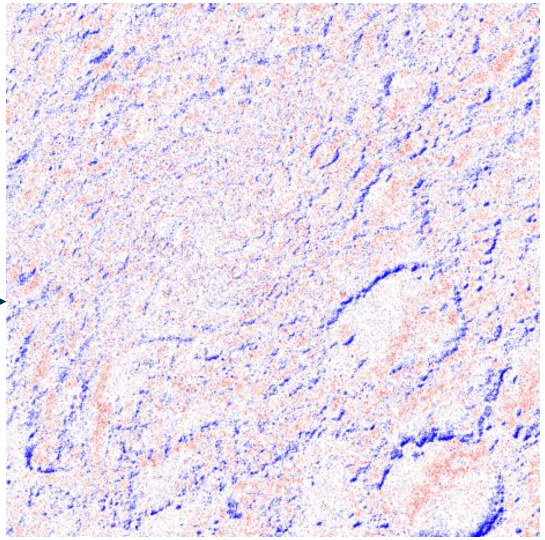
4. Synthetic Event Generation



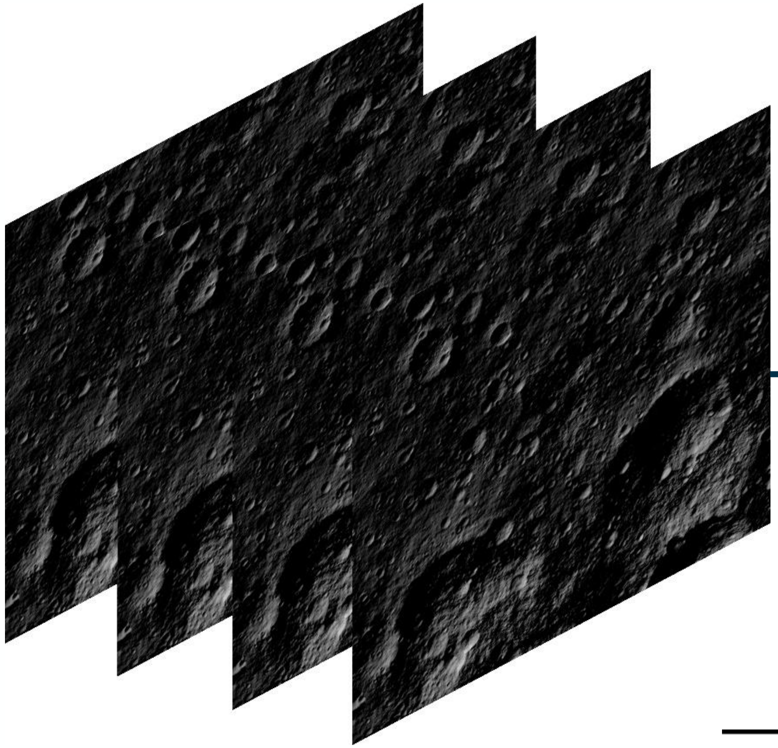


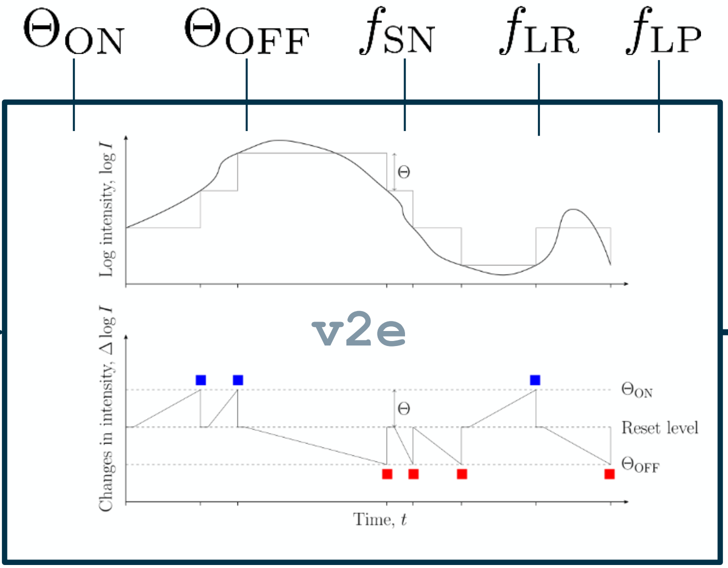
Event-camera emulation [10]



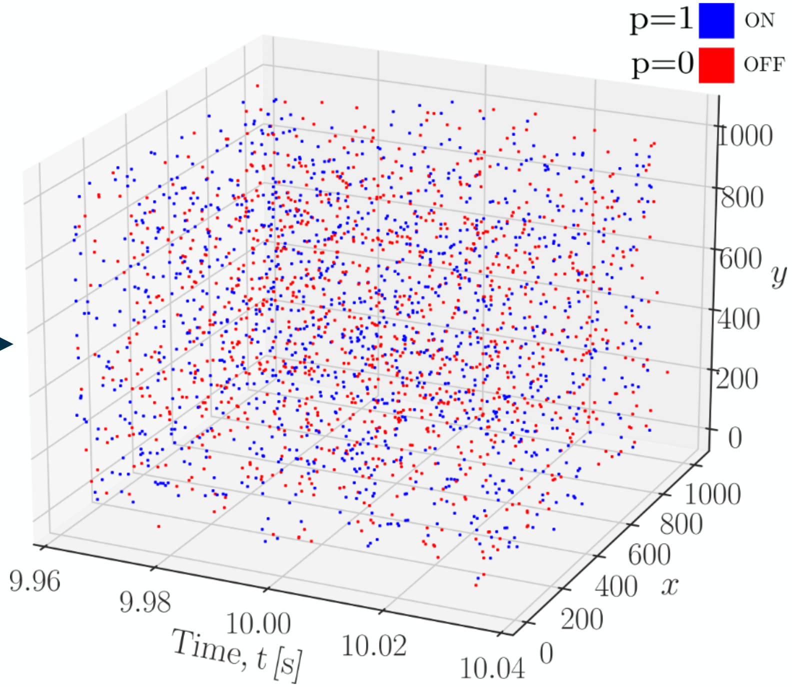
Δt

4. Synthetic Event Generation



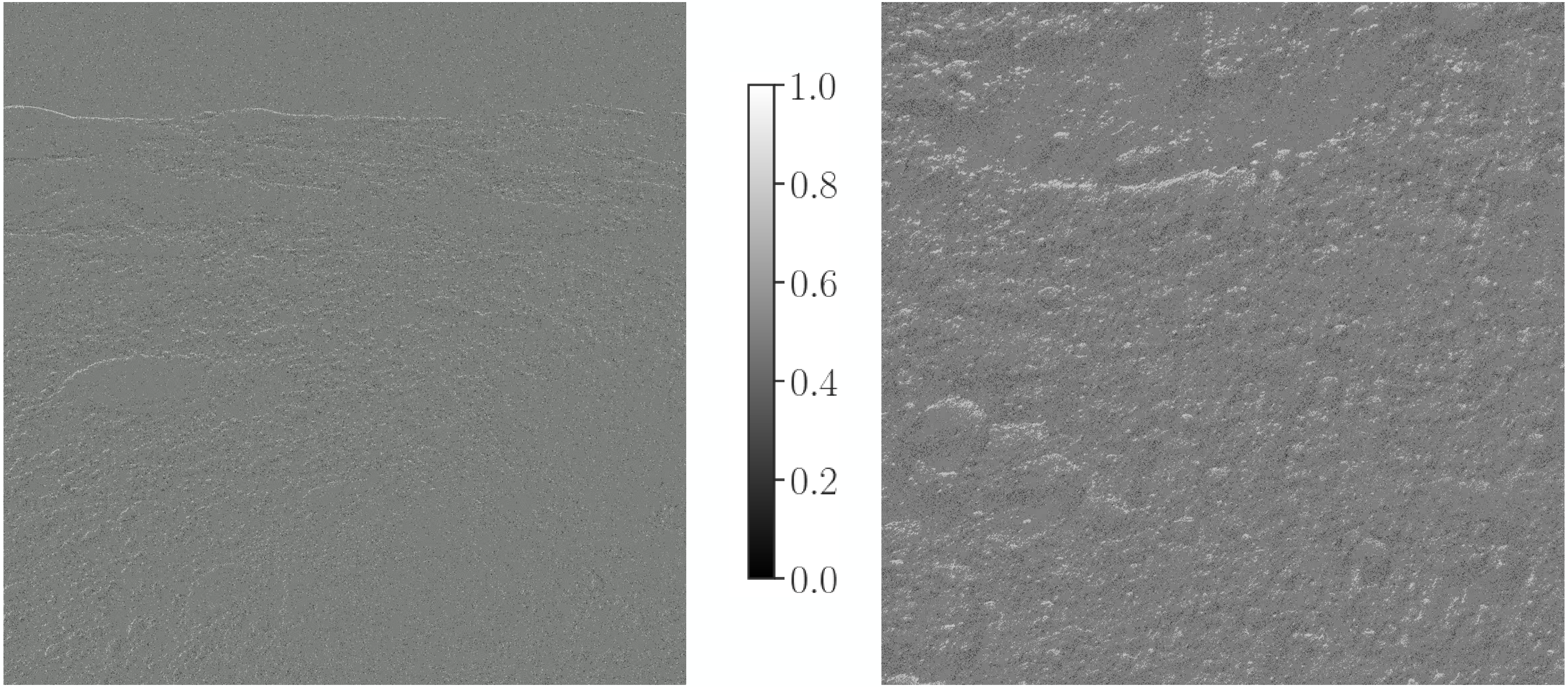


Event-camera emulation [10]



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

4. Synthetic Event Generation

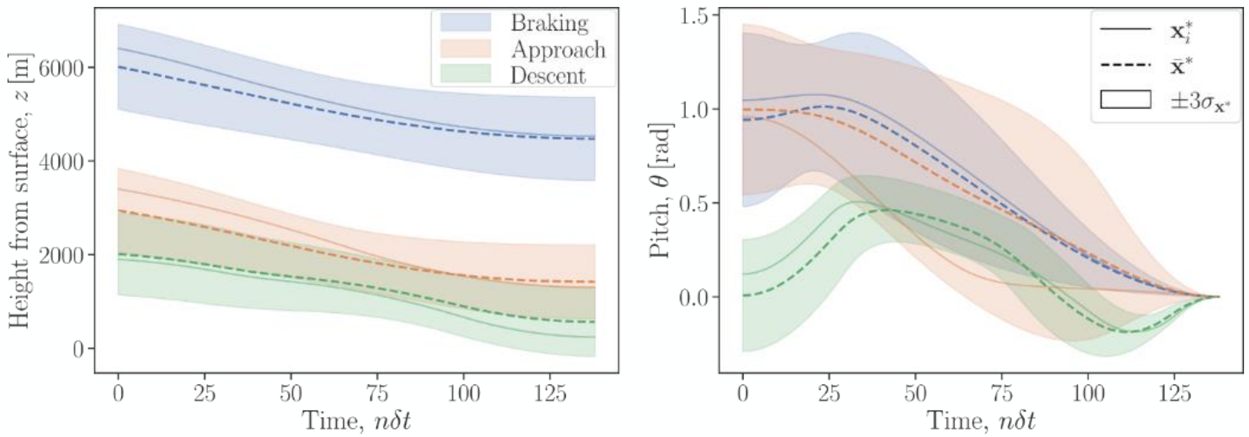


Approach Descent

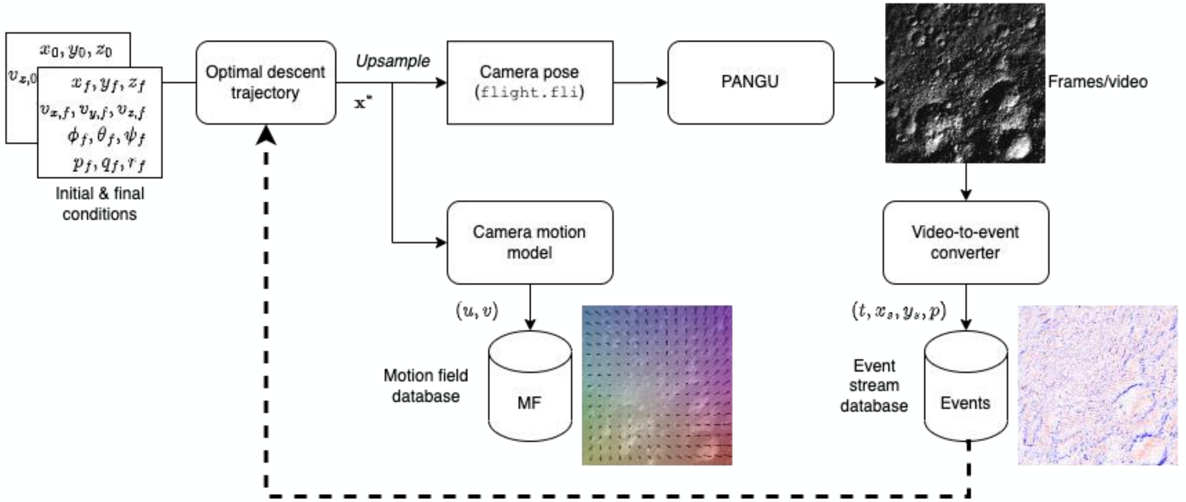
Summary

- Event-based dataset:
  - 500 optimal landings (**ground truth**)
  - 500 event-streams (**input**)
  - ~5000 frames/landing (100 Hz)
  - Different landing profiles and lighting conditions

- Trajectory-to-events pipeline:
  - promote the generation of new event-based datasets
  - consider different trajectory inputs



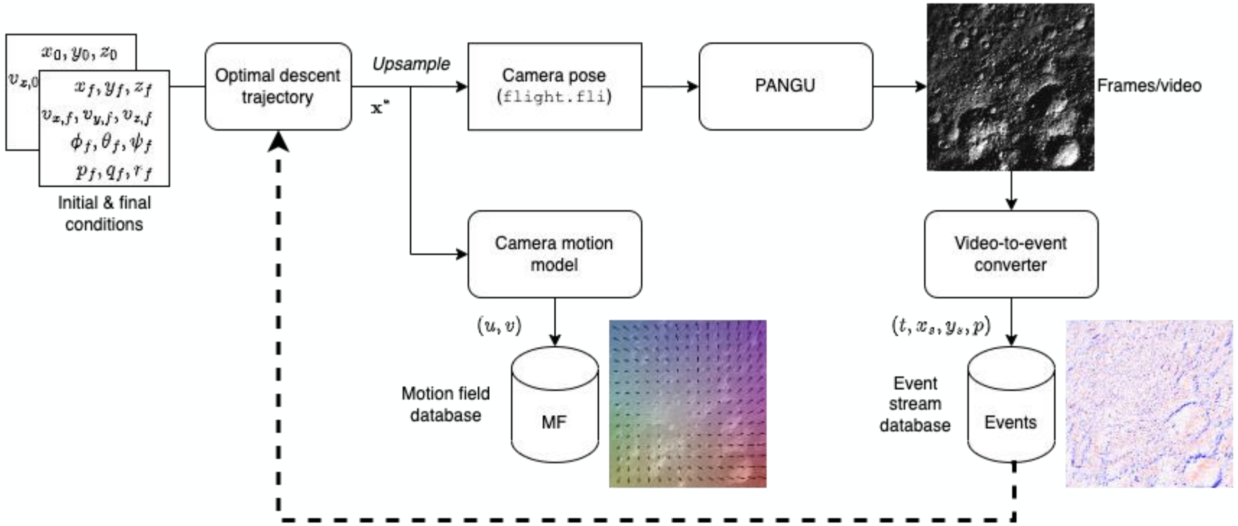
Event-based dataset overview: trajectories



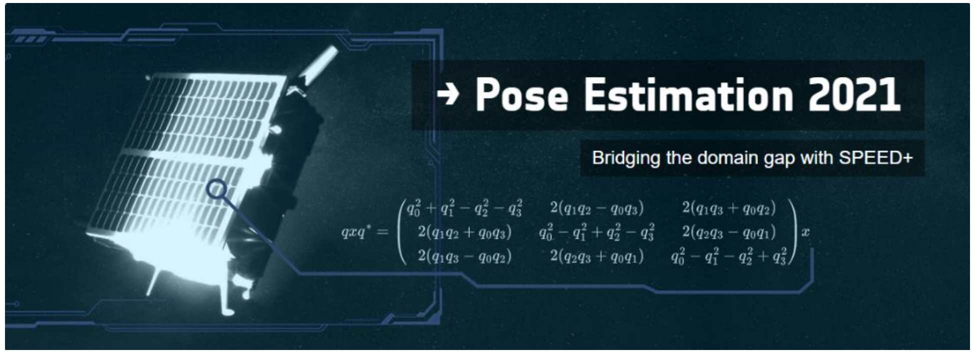
Trajectory-to-events pipeline:
gitlab.com/EuropeanSpaceAgency/trajectory-to-events

Outlook

- Develop algorithms to solve for the pose of the spacecraft from event-streams
  - Design a Kelvins data challenge on the reconstruction of pose from events
  - Validate inverse problem solutions on synthetic and *real* landing event-streams
- Consider other use cases where event-based camera can complement vision-based navigation (motion estimation, terrain relative navigation, etc.)



Inverse problem: reconstructing pose from event-streams
gitlab.com/EuropeanSpaceAgency/trajectory-to-events



Past spacecraft pose estimation competition held on Kelvins
kelvins.esa.int

Thank you

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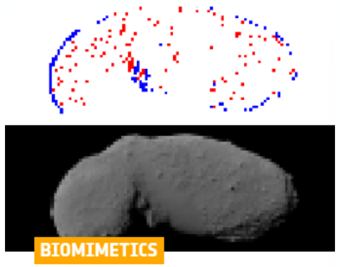
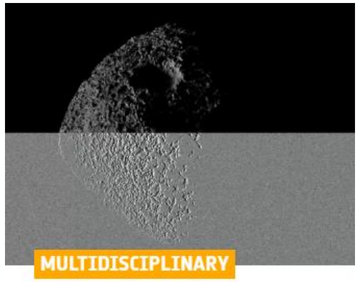
gitlab.com/EuropeanSpaceAgency/trajectory-to-events

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

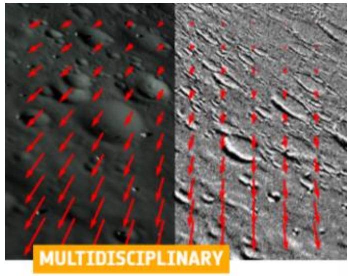
Any questions?



Event-based vision in space



Dynamic Vision for Active Asteroids: Multiple Particle Tracking



Event-based Vision for Navigation and Landing

Resources

[1] Mueggler, E. et al. (2014). Event-based, 6-DOF pose tracking for high-speed maneuvers, 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems

[2] Prophesee EVK-4, https://www.prophesee.ai/event-camera-evk4/

[3] X-Ray Imaging Goes Neuromorphic, https://www.esa.int/gsp/ACT/news/2023-04-12-event-tomography-experiments-1/

[4] Gallego, G. et al. (2022). Event-based vision: A survey. IEEE Transactions on Pattern Analysis and Machine Intelligence

[5] Gehrig, M. et al. (2021). E-RAFT: Dense Optical Flow from Event Cameras," 2021 International Conference on 3D Vision (3DV)

[6] Afshar, S. et al. (2020). Event-Based Object Detection and Tracking for Space Situational Awareness, IEEE Sensors Journal

[7] McLeod, S. et al. (2023). Globally Optimal Event-Based Divergence Estimation for Ventral Landing, Computer Vision – ECCV 2022 Workshops. ECCV 2022. Lecture Notes in Computer Science.

[8] Martin, I., & Dunstan, M. (2021). PANGU v6: Planet and asteroid natural scene generation utility.

[9] Gibson, J. J. (1950). The perception of the visual world. Houghton Mifflin.

[10] Hu, Y. et al. (2021). v2e: From Video Frames to Realistic DVS Events. 2021 IEEE/CVF Conference on Computer Vision and Pattern Recognition Workshops (CVPRW), Nashville, TN, USA, 2021

Extra slide: 12 DOF Lunar Lander Trajectory

$$\dot{\mathbf{r}} = \mathbf{v}$$

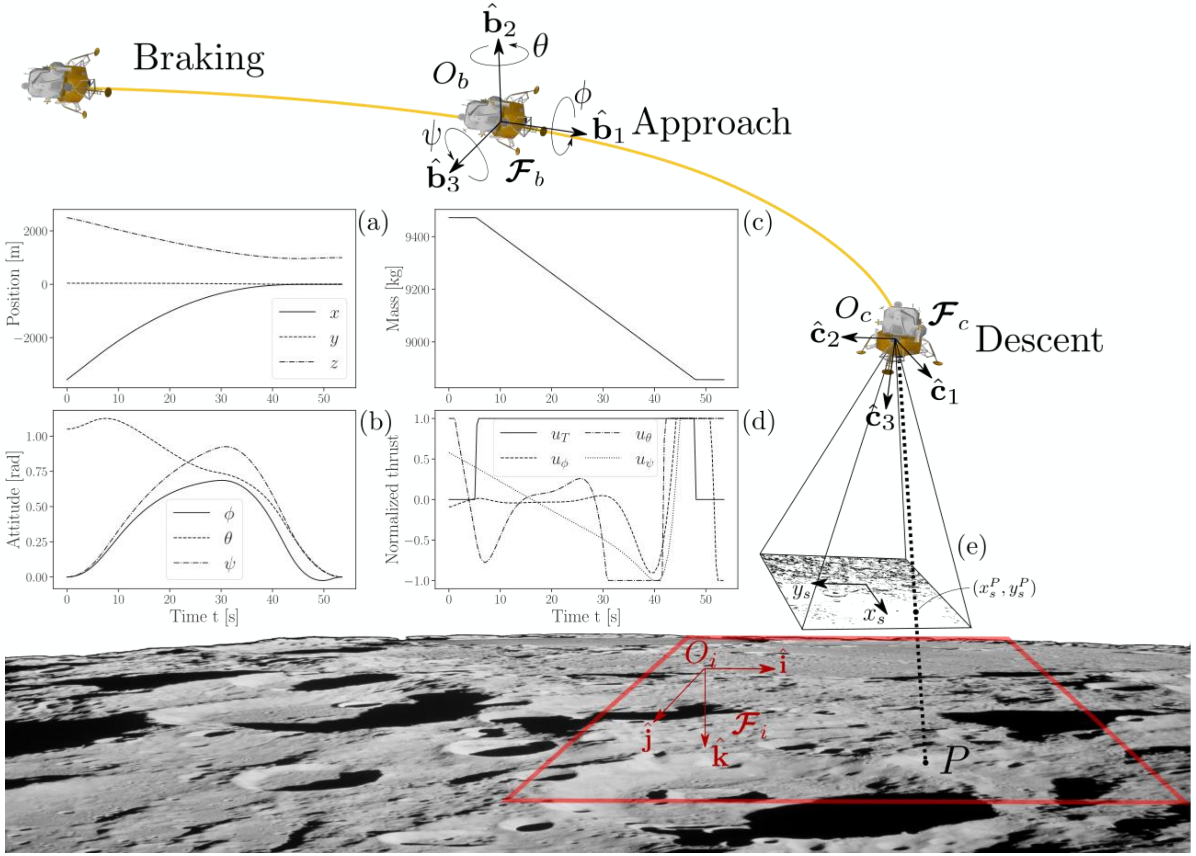
$$\dot{\mathbf{v}} = \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} - \frac{1}{m}\mathbf{R}\begin{bmatrix} 0 \\ 0 \\ \bar{F}_a u_T \end{bmatrix}$$

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi/\cos\theta & \cos\phi/\cos\theta \end{bmatrix}\begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

$$\mathbf{I}\dot{\boldsymbol{\omega}} = \boldsymbol{\omega} \times \boldsymbol{I}\boldsymbol{\omega} + 2L\bar{F}_b\begin{bmatrix} u_\phi \\ u_\theta \\ u_\psi \end{bmatrix}$$

$$\dot{m} = -\frac{\overline{F}_a u_T + 2\overline{F}_b(u_\phi + u_\theta + u_\psi)}{I_{sp}g_0}$$

$$\mathbf{R} = \begin{bmatrix} \cos\theta\cos\psi & -\cos\phi\sin\psi + \sin\phi\sin\theta\cos\psi & \sin\phi\sin\psi + \cos\phi\sin\theta\cos\psi \\ \cos\theta\sin\psi & \cos\phi\cos\psi + \sin\phi\sin\theta\sin\psi & -\sin\phi\cos\psi + \cos\phi\sin\theta\sin\psi \\ -\sin\theta & \sin\phi\cos\theta & \cos\phi\cos\theta \end{bmatrix}$$



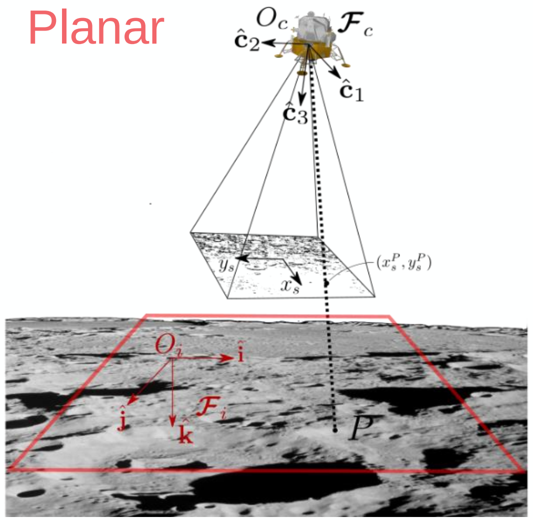
Extra slide: Motion Field Ground Truth

Projection of the relative velocity of a 3D object into the image plane:

$$\begin{bmatrix} u \\ v \end{bmatrix} = \frac{1}{Z}\begin{bmatrix} -f & 0 & x_s \\ 0 & -f & y_s \end{bmatrix}\begin{bmatrix} v_{c,x} \\ v_{c,y} \\ v_{c,z} \end{bmatrix} + \begin{bmatrix} \frac{x_s y_s}{f} & -(f + \frac{x_s^2}{f}) & y_s \\ f + \frac{y_s^2}{f} & -\frac{x_s y_s}{f} & -x_s \end{bmatrix}\begin{bmatrix} p \\ q \\ r \end{bmatrix}, \qquad h(x_s, y_s) = \frac{1}{Z}$$

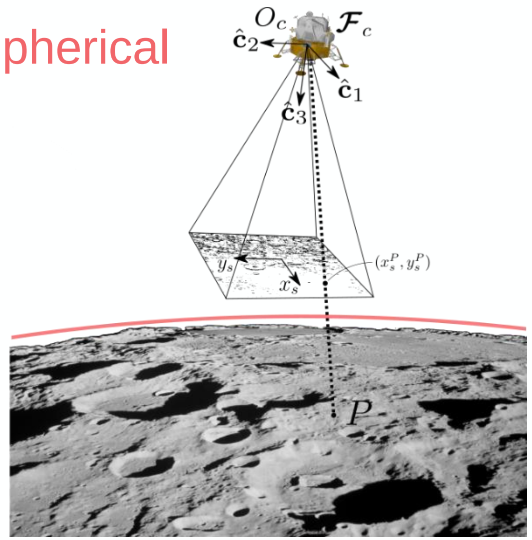
inverse depth map

Planar



$$\boxed{\begin{aligned} A &= -x_s \sin\theta + y_s \sin\phi\cos\theta + \cos\phi\cos\theta \\ B &= x_s^2 + y_s^2 + 1 \end{aligned}}$$

Spherical



$$h(x_s, y_s) = -\frac{A}{z}$$

$$h(x_s, y_s) = \frac{B}{(R-z)A - \sqrt{(R-z)^2 A + 2zRB}}$$