Simulating Planned LICIACube Imagery of DART Impact Ejecta based on Ejecta Dynamics Simulation Output

Eugene G. Fahnestock,
Emily Kramer, and Steve Chesley

Eugene.G.Fahnestock@jpl.nasa.gov

Jet Propulsion Laboratory
California Institute of Technology

DART

Introduction

- DART to impact surface of Dimorphos, secondary of binary NEA 65803 Didymos
  - at 6.12 – 6.77 km/s ← depends on launch date, per trajectory release D210308-SOC
  - on Sept. 25 - Oct. 1, 2022 ← ditto
  - in “retrograde” sense = nearly opposite Dimorphos’ orbital velocity
- Expected to liberate large quantity of ejecta!
- LICIACube will take images with its 2 cameras during fast flyby, to reveal short-timescale ejecta plume evolution, etc.
- **Here we attempt to simulate how ejecta presents in these planned images**

Note: For what follows we started with older launch date assumption and trajectory, for which:

V_{rel} = 7.205 km/s

(adjusted) impact epoch = 02-OCT-2022 21:24:40 TDB

DART mass at impact, m = 607.9 kg

Binary Dynamics Simulation

F2BP propagation of underlying motion of binary components

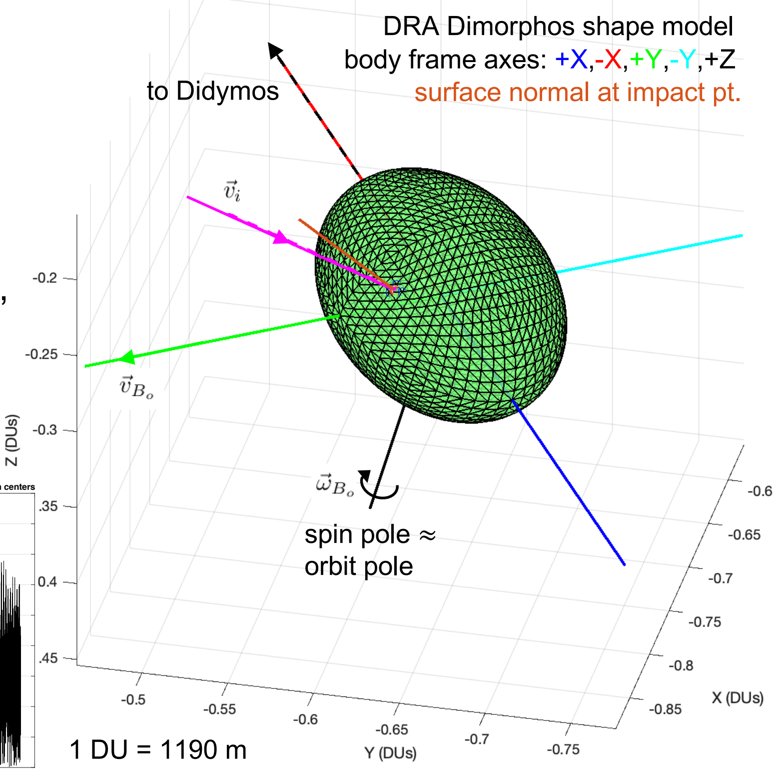
- Setup consistent with DRA at the time (v2.26)
- Propagated using GUBAS* pre- & post-impact

  (* Davis & Scheeres, 2020; https://github.com/alex-b-davis/gubas)
- Impulsive state change at impact epoch consistent with β=2 and impact geometry:

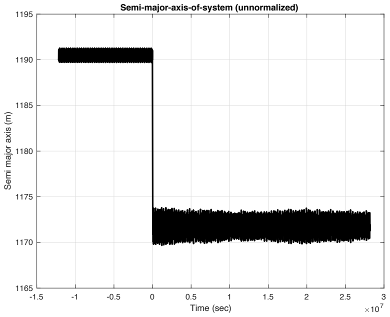
  Impact point offset 22.5 m from thru COF, toward "local west"

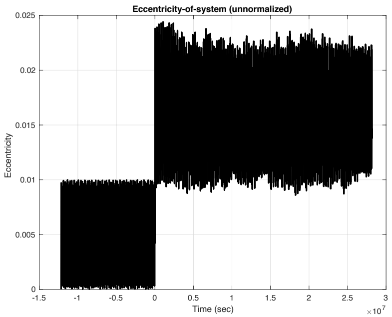
$$\vec{v}_B = \frac{\beta\, m_i\, \vec{v}_i + m_B\, \vec{v}_{B_o}}{m_i + m_B} \qquad \vec{\omega}_B = \left[A_B\,(I_B + \Delta I_B)\,A_B^T\right]^{-1}\left(\beta\, m_i\,\left(\vec{\rho}_i \times \vec{v}_i\right) \;+\; A_B\, I_B\, A_B^T \vec{\omega}_{B_o}\right)$$

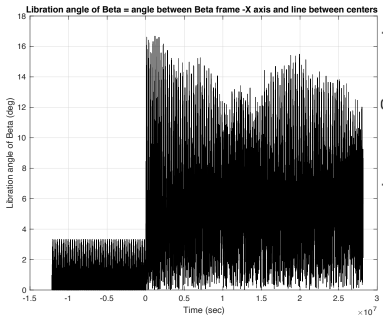
$$\vec{v}_B \approx \frac{\beta\, m_i}{m_B}\,\vec{v}_i + \vec{v}_{B_o} \qquad \vec{\omega}_B \approx \left[A_B\, I_B\, A_B^T\right]^{-1}\left(\beta\, m_i\,\left(\vec{\rho}_i \times \vec{v}_i\right)\right) \;+\; \vec{\omega}_{B_o}$$



1 DU = 1190 m
ICRF aligned, origin at barycenter





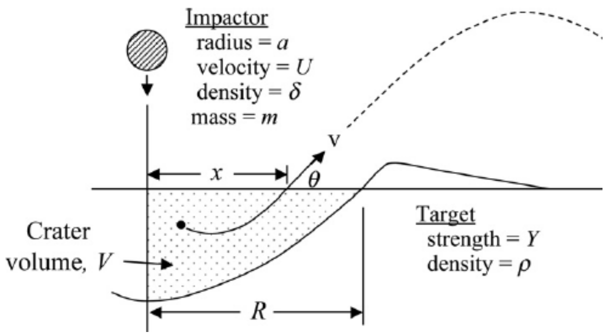


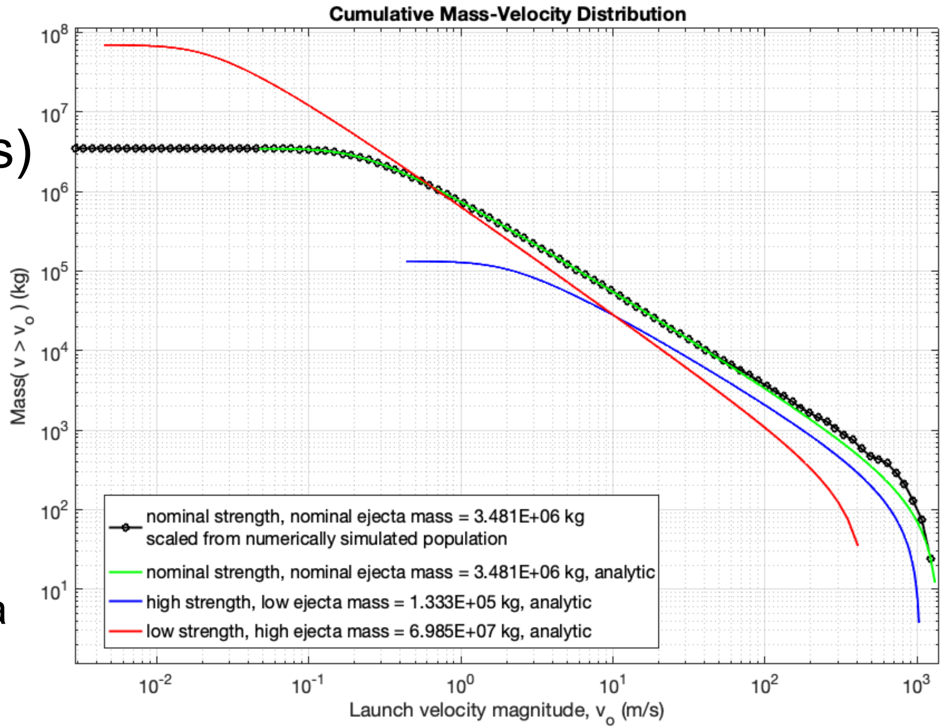
DART

Ejecta Initialization

Using Crater Scaling Equations (CSEs)

K.R. Housen, K.A. Holsapple / Icarus 211 (2011) 856–875





- Explored bounding low, high, & nominal ejecta mass cases
- For what follows, we use nominal mass case:

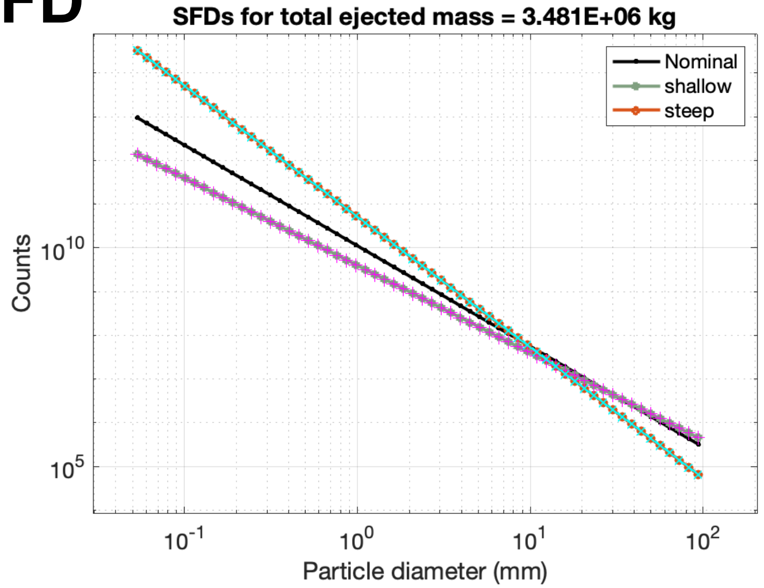
Dimorphos surface bulk density, ρ = 2111 kg/m^3
assumed surface cohesive strength, Y = 100 Pa
assumed surface porosity = 35%
Dimorphos centroid to impact point vector in inertial frame (ICRF) = [-63.68 17.39 38.41] m
surface acceleration, g (net of gravity & centripetal) = 5.927E-05 m/s^2
DART equivalent radius, a = 0.5 m
DART mass, m = 607.9 kg
DART bulk density, δ = 1161 kg/m^3
$V_{rel} = U$ = 7.205 km/s

ν = 0.4
μ = 0.41
C_1 = 0.55
k = 0.3
H_1 = 0.59
H_2 = 0.39
n_1 = 1.2
n_2 = 1.0
p = 0.3

crater duration = ~137.84 seconds
final crater radius, R = ~17.65 m
total ejected mass = 3.481E+06 kg
max ejecta launch speed (surface relative) = 1.403 km/s
min ejecta launch speed (surface relative) = ~0 m/s
ejecta particle grain density = Dimorphos surface bulk density
(i.e. gross assumption that all porosity is micro-porosity!)

Ejecta Dynamics Propagation & cSFD

- Initial states translated to barycentric inertial frame
- RF3BP: collision-less, no inter-particle interaction
- Active force models:
    - Gravity of binary components, polyhedral, turned off >1000 km from barycenter
    - SRP (cannonball, inc. body shadowing)
    - Differential solar gravity ("solar tides")
- Ejecta flagged as "escaped" once crossing plane 200 km anti-sunward (+R in RTN frame) with $E_{2BP} > 0$
- Ejecta size range: 0.05–100 mm, 50 μm – 0.1 m
- Cumulative Size Frequency Distribution (cSFD) power-law slopes:
    - "shallow" = -2.0
    - nominal = -2.3017 ← Itokawa heritage
    - "steep" = -2.99

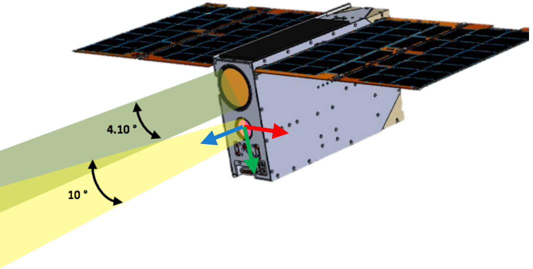


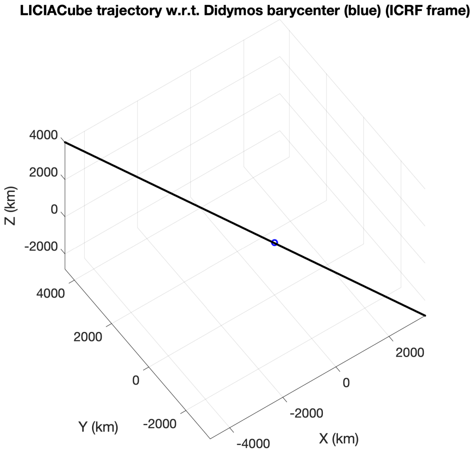
- For what follows, we use nominal slope
- $N \geq$1e6 particles propagated to 90 days duration, or to sooner return impact, transfer impact, or escape
- Full population scaled from propagated population using particle multipliers

DART

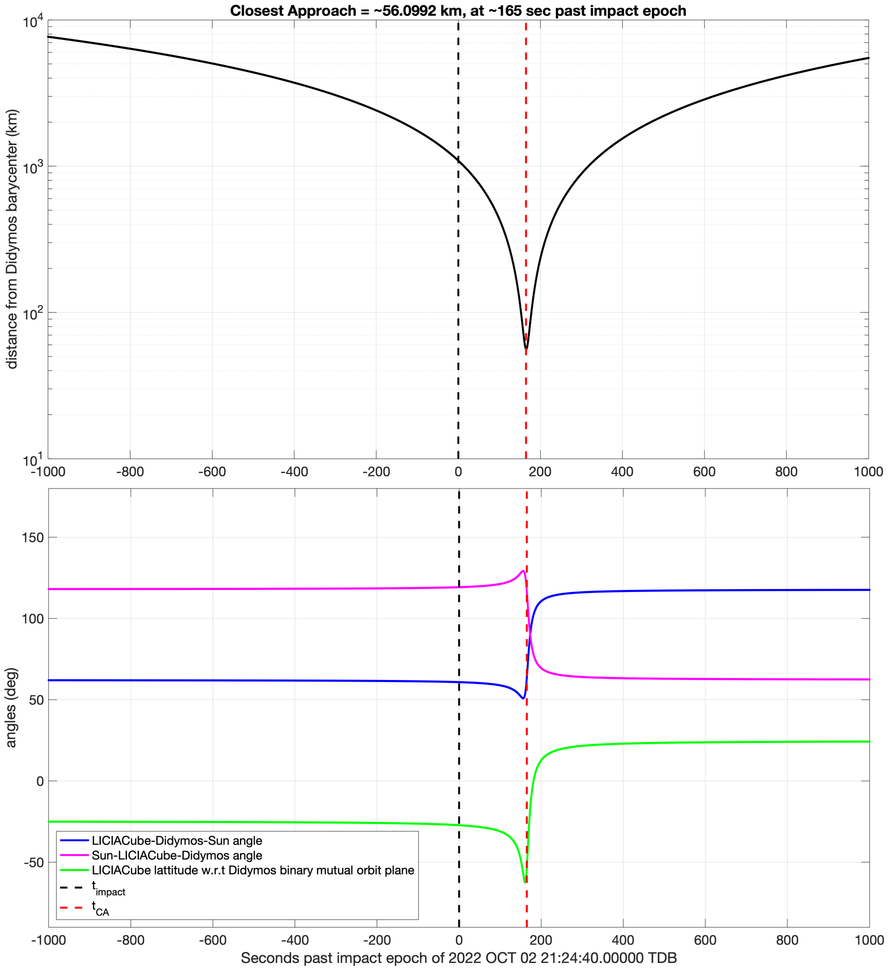
LICIACube Observation Plan

Fly-by geometry & pointing





- PL2's long pixel dimension aligned to red ($\hat{y}_{LBF}$) unit vector
- Boresight (blue, $\hat{z}_{LBF}$) assumed maintained pointed from current LICIACube position to centroid of target (Dimorphos)



LICIACube Observation Plan

Camera specs. & image capture times

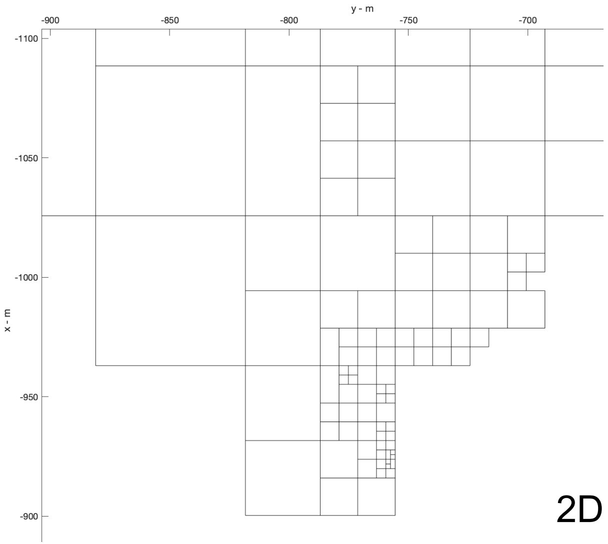
Property	PL1 = LEIA	PL2 = LUKE
focal length	393 mm	70 mm
f-number	5.2	5
diag. FOV	$\pm 2.05°$	$\pm 5°$
iFOV	25 μrad	75 μrad
pixel dims	2048 x 2048	2054 x 1090
color filters	Panchrom. (400 – 900 nm)	RGB
pixel bit depth	12 bit	8, 10 bit
integration time range	0.1 ms – seconds	--
integration time granularity	0.1 ms	--
chosen integration times	0.3, 0.6, 0.9 ms	0.3, 0.6, 0.9 ms
Frame rate	up to 7 fps	up to 5 fps
Image size	~6.3 MB/image	~2.8 MB/image (10 bit)

```
For impact epoch 02-OCT-2022 21:24:40.0000 TDB

PL1:
epoch                            w.r.t. impact (s)   w.r.t. C.A. (s)
02-OCT-2022 21:23:54.4100 TDB         -45.5900         -211.0000
02-OCT-2022 21:24:03.4100 TDB         -36.5900         -202.0000
02-OCT-2022 21:24:12.4100 TDB         -27.5900         -193.0000
02-OCT-2022 21:24:21.4100 TDB         -18.5900         -184.0000
02-OCT-2022 21:24:30.4100 TDB          -9.5900         -175.0000
02-OCT-2022 21:24:39.4100 TDB          -0.5900         -166.0000
02-OCT-2022 21:24:48.4100 TDB           8.4100         -157.0000
02-OCT-2022 21:24:57.4100 TDB          17.4100         -148.0000
02-OCT-2022 21:25:05.4100 TDB          25.4100         -140.0000
02-OCT-2022 21:25:11.4100 TDB          31.4100         -134.0000
02-OCT-2022 21:25:17.4100 TDB          37.4100         -128.0000
02-OCT-2022 21:25:23.4100 TDB          43.4100         -122.0000
02-OCT-2022 21:25:29.4100 TDB          49.4100         -116.0000
02-OCT-2022 21:25:35.4100 TDB          55.4100         -110.0000
02-OCT-2022 21:25:41.4100 TDB          61.4100         -104.0000
02-OCT-2022 21:25:47.4100 TDB          67.4100          -98.0000
02-OCT-2022 21:25:53.4100 TDB          73.4100          -92.0000
02-OCT-2022 21:25:59.4100 TDB          79.4100          -86.0000
02-OCT-2022 21:26:05.4100 TDB          85.4100          -80.0000
02-OCT-2022 21:26:11.4100 TDB          91.4100          -74.0000
02-OCT-2022 21:26:17.4100 TDB          97.4100          -68.0000
02-OCT-2022 21:26:23.4100 TDB         103.4100          -62.0000
02-OCT-2022 21:26:29.4100 TDB         109.4100          -56.0000
02-OCT-2022 21:26:35.4100 TDB         115.4100          -50.0000
02-OCT-2022 21:26:41.4100 TDB         121.4100          -44.0000
02-OCT-2022 21:26:47.4100 TDB         127.4100          -38.0000
02-OCT-2022 21:26:53.4100 TDB         133.4100          -32.0000
02-OCT-2022 21:26:56.4100 TDB         136.4100          -29.0000
02-OCT-2022 21:27:02.9100 TDB         142.9100          -22.5000
02-OCT-2022 21:27:09.4100 TDB         149.4100          -16.0000
02-OCT-2022 21:27:15.9100 TDB         155.9100           -9.5000
02-OCT-2022 21:27:23.4100 TDB         163.4100           -2.0000
02-OCT-2022 21:27:24.1600 TDB         164.1600           -1.2500
02-OCT-2022 21:27:24.9100 TDB         164.9100           -0.5000
02-OCT-2022 21:27:25.6600 TDB         165.6600            0.2500
02-OCT-2022 21:27:26.1100 TDB         166.1100            0.7000
02-OCT-2022 21:27:27.7300 TDB         167.7300            2.3200
02-OCT-2022 21:27:29.3500 TDB         169.3500            3.9400
02-OCT-2022 21:27:30.9700 TDB         170.9700            5.5600
02-OCT-2022 21:27:32.5900 TDB         172.5900            7.1800
02-OCT-2022 21:27:34.2100 TDB         174.2100            8.8000
02-OCT-2022 21:28:25.4100 TDB         225.4100           60.0000
02-OCT-2022 21:29:25.4100 TDB         285.4100          120.0000
02-OCT-2022 21:30:25.4100 TDB         345.4100          180.0000
02-OCT-2022 21:31:25.4100 TDB         405.4100          240.0000
02-OCT-2022 21:32:25.4100 TDB         465.4100          300.0000
02-OCT-2022 21:33:25.4100 TDB         525.4100          360.0000
02-OCT-2022 21:34:25.4100 TDB         585.4100          420.0000
02-OCT-2022 21:35:25.4100 TDB         645.4100          480.0000
02-OCT-2022 21:36:25.4100 TDB         705.4100          540.0000
02-OCT-2022 21:37:25.4100 TDB         765.4100          600.0000

PL2:
epoch                            w.r.t. impact (s)   w.r.t. C.A. (s)
02-OCT-2022 21:25:05.4100 TDB          25.4100         -140.0000
02-OCT-2022 21:25:11.4100 TDB          31.4100         -134.0000
02-OCT-2022 21:25:17.4100 TDB          37.4100         -128.0000
02-OCT-2022 21:25:23.4100 TDB          43.4100         -122.0000
02-OCT-2022 21:25:29.4100 TDB          49.4100         -116.0000
02-OCT-2022 21:25:35.4100 TDB          55.4100         -110.0000
02-OCT-2022 21:25:41.4100 TDB          61.4100         -104.0000
02-OCT-2022 21:25:47.4100 TDB          67.4100          -98.0000
```

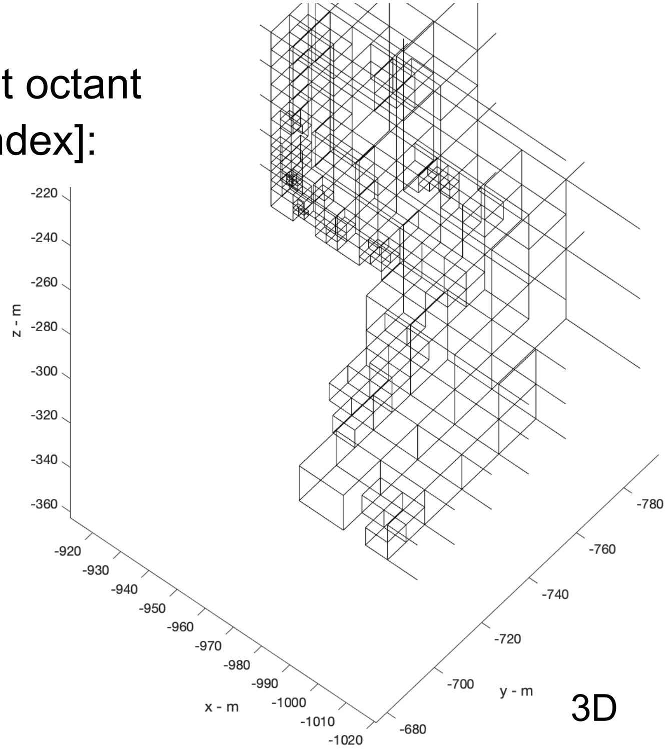
Interface to Image Simulation

3D spatial number density in gridded interface data files (“cube files”)

- One such file at each unique image capture time
- Define grid of base cubes with origin s.t. all ejecta lies in first octant
- For each unique [particle size bin + non-empty base cube index]:
  - Enter recursive subdivision algorithm that tests sub-cubes formed by bisection along each cardinal axis
  - Don’t do another level of subdivision if that would result in # of actually simulated particles in non-empty sub-cubes < n
  - # of actually simulated particles in non-empty sub-cubes scaled to full pop. using particle multipliers, divided by volume



2D

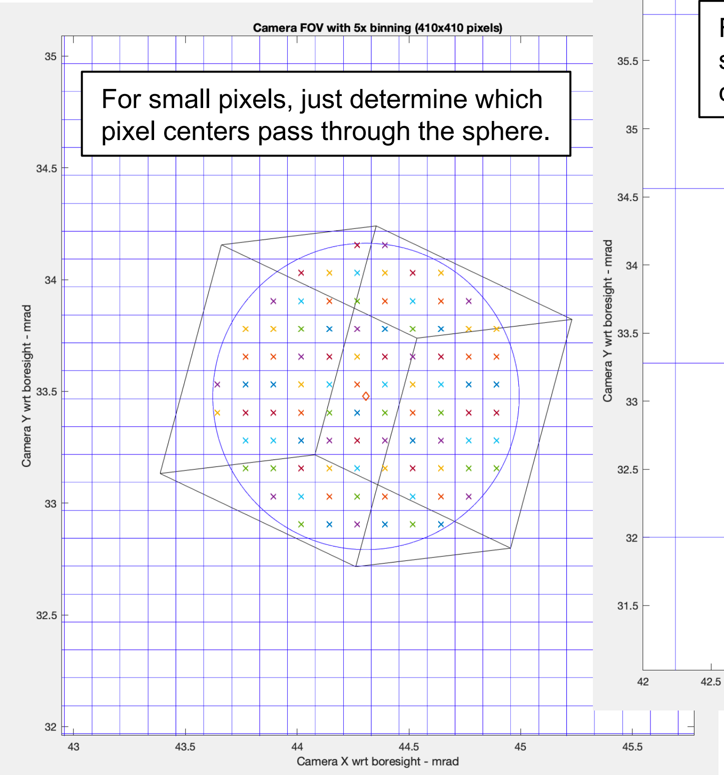


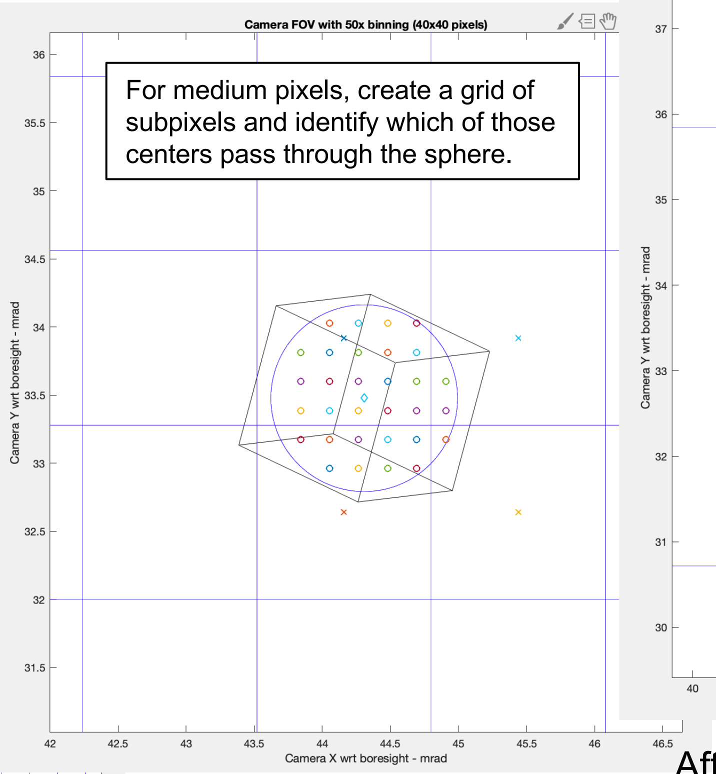
3D

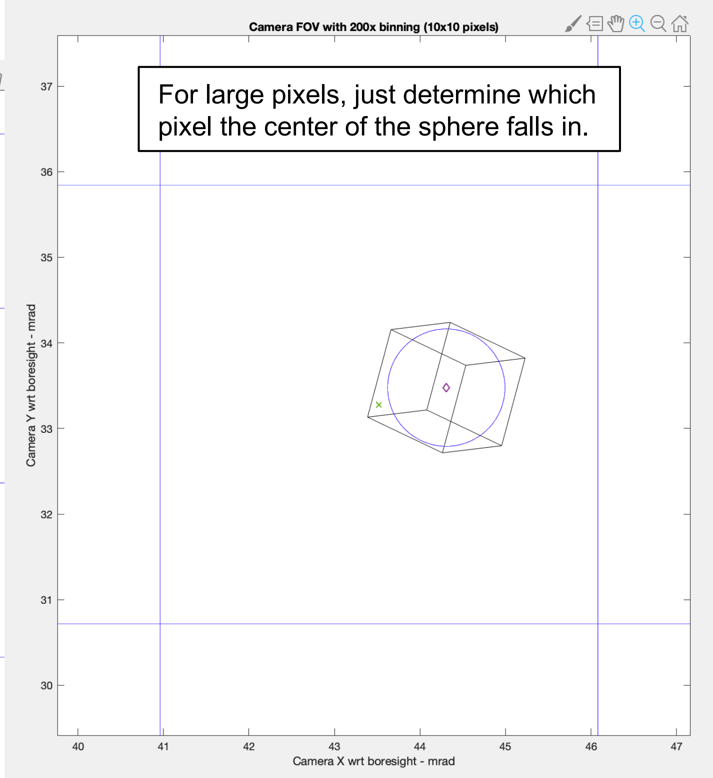
Mapping Cubes onto Pixels

Replace cube with equivalent volume sphere when figuring which pixels it falls on.

Three cases:







After “filling” the pixels by looping over all cubes, you can create the image.

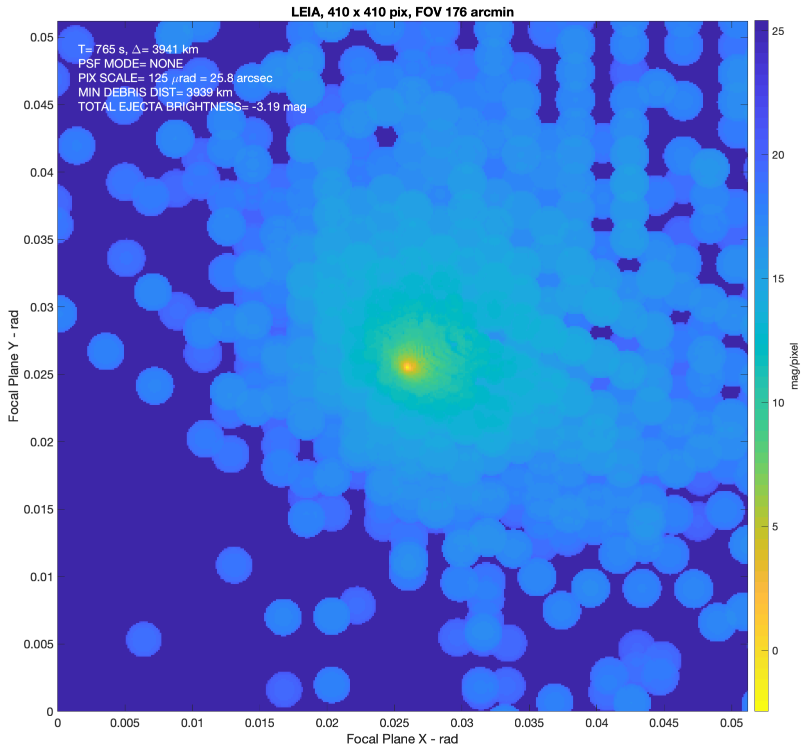
Photometric Model

Converting # of particles per pixel, for each size bin, to brightness:

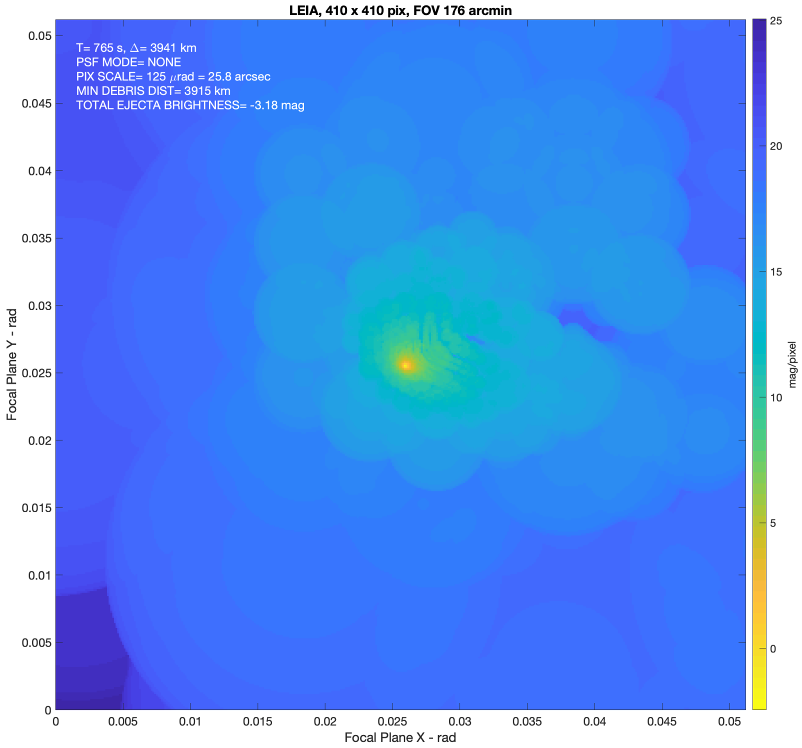
- Recall our particle size range is 0.05 – 100 mm
- Follow Hergenrother's model from Bennu particles (1 – 50 mm)
- $V = H + S\,\phi + 5 \log10 (R\Delta)$
  - H: absolute mag
  - S: phase slope = 0.013 mag/deg (Hergenrother, 2020)
  - ϕ: phase angle
  - R: Heliocentric distance (in au)
  - Δ: Observer distance (in au)

Simulated LEIA (PL1) Images

Default >100 base cubes per axis (fine)
# of levels of subdivision limited to 10



Default >10 base cubes per axis (coarse)
# of levels of subdivision limited to 13

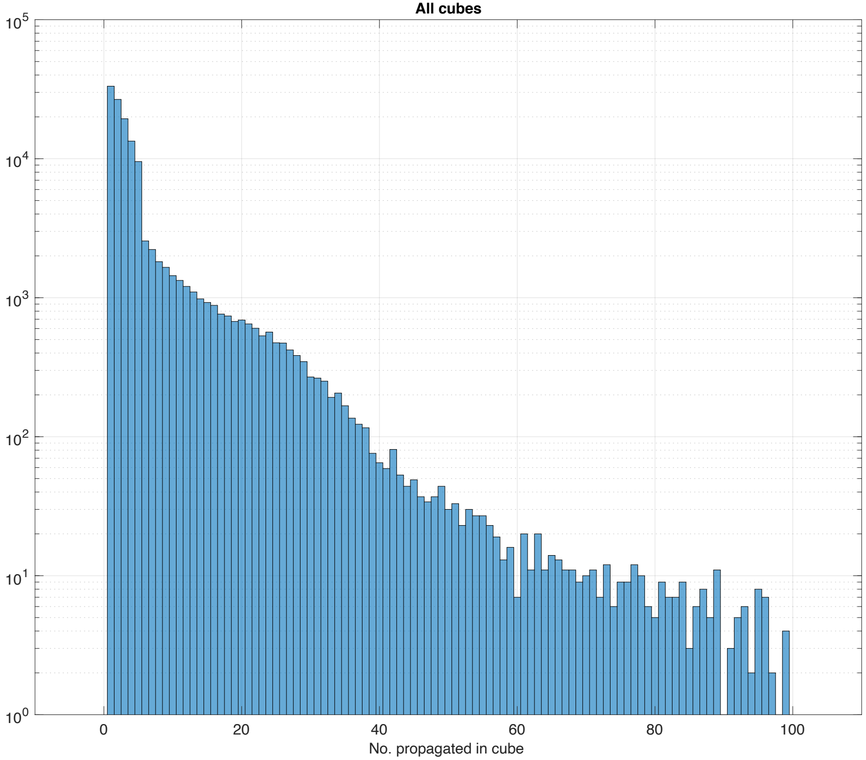


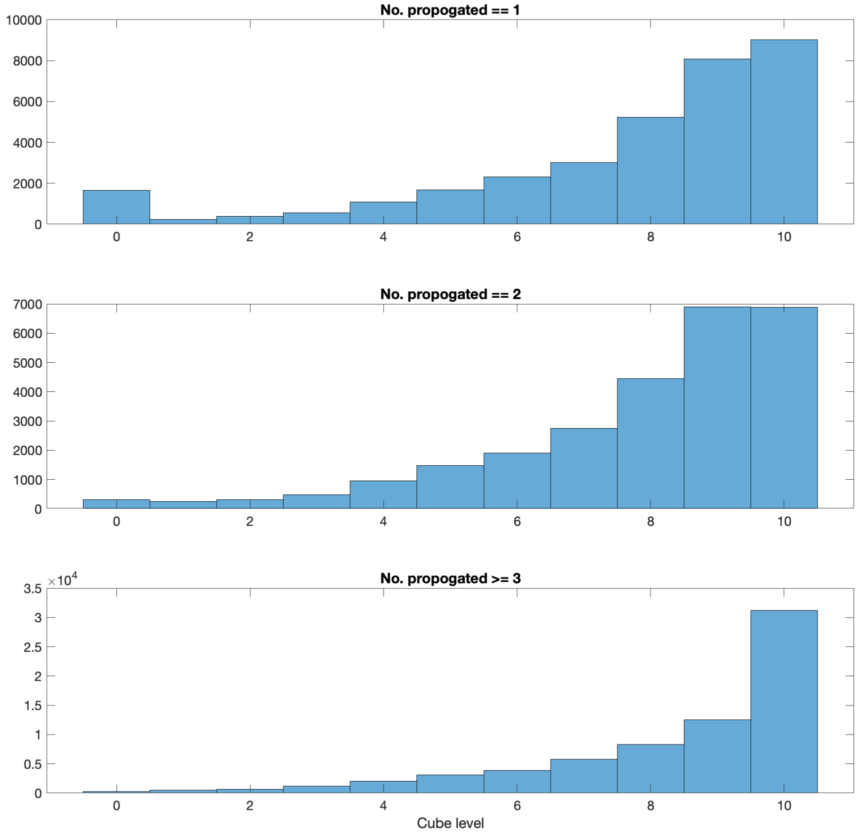
Backup Slides

Results of Subdivision

Default >100 base cubes per axis (fine)

# of levels of subdivision limited to 10





Simulated LEIA (PL1) Image

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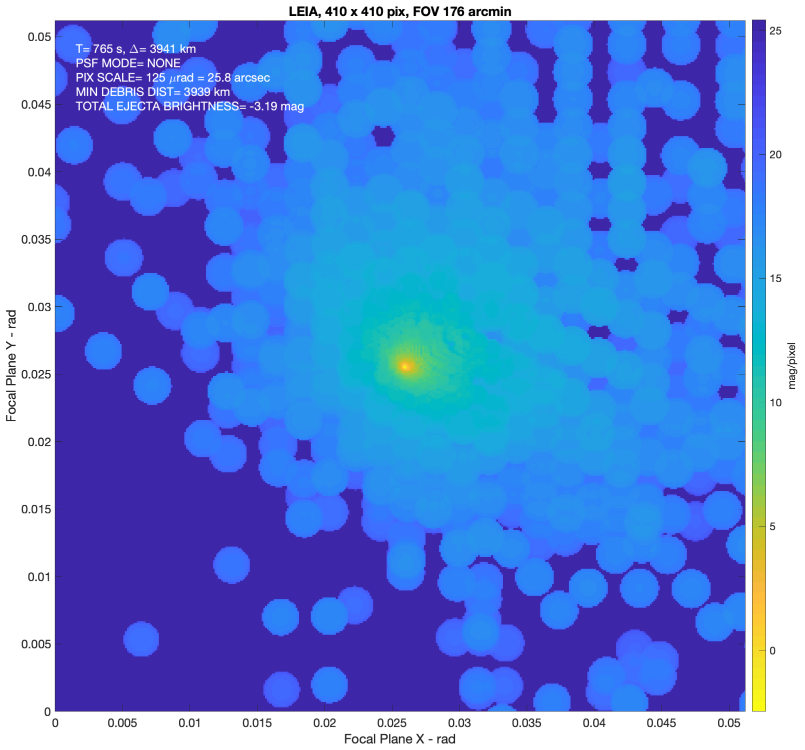

Results of Subdivision

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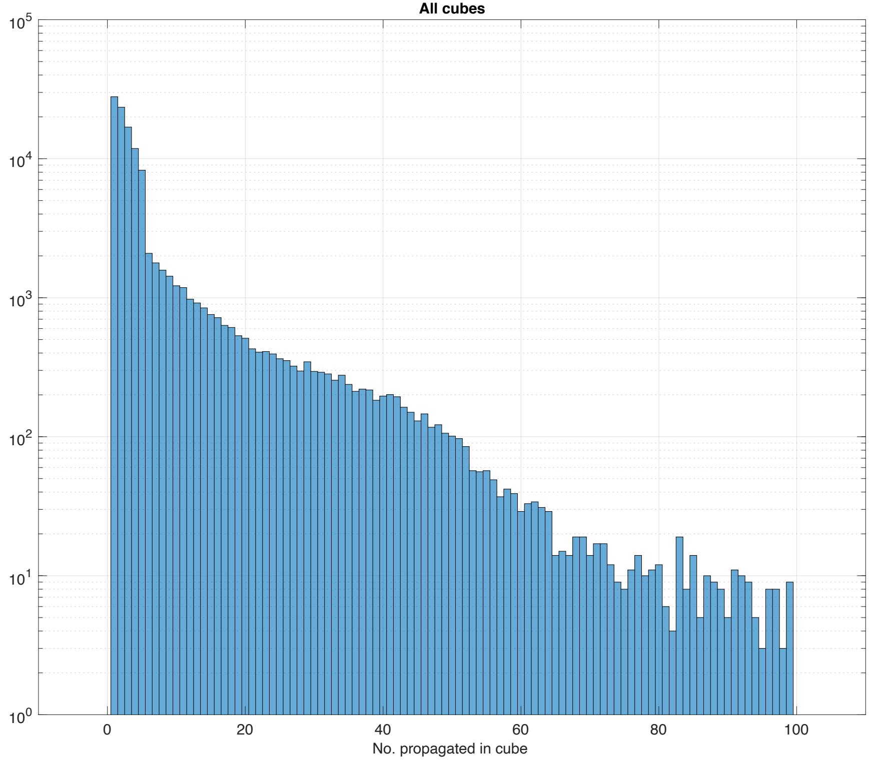
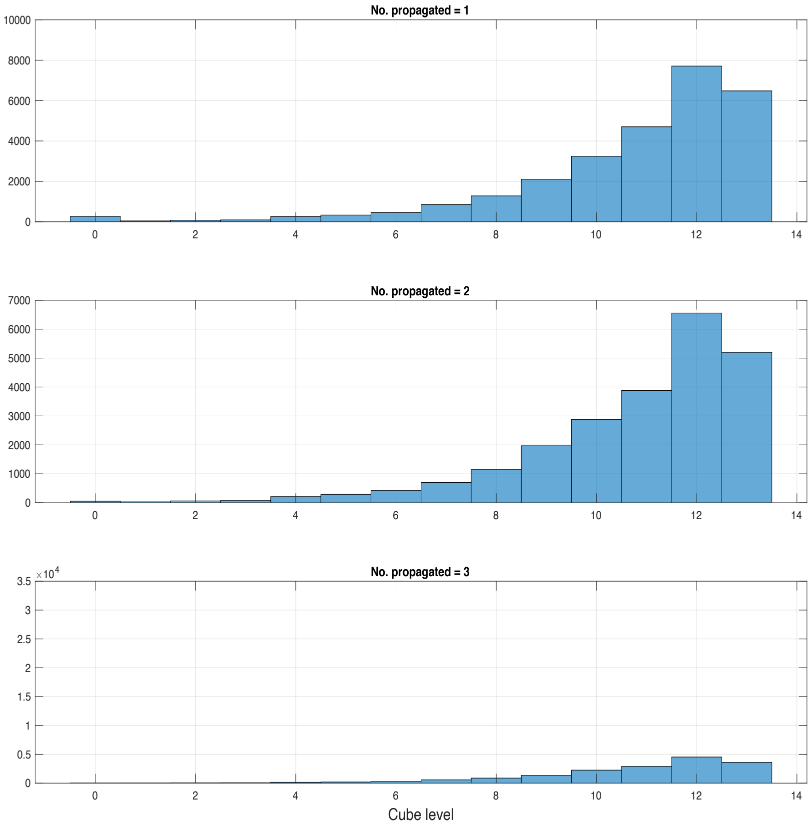
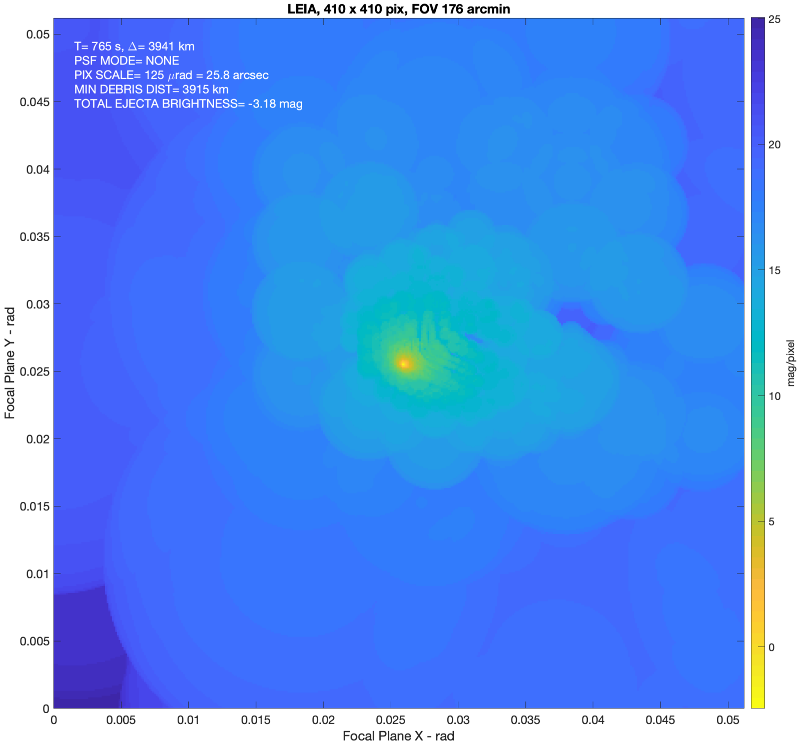




This document has been reviewed and determined not to contain export controlled technical data.

Simulated LEIA (PL1) Image

Default >10 base cubes per axis (coarse)



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California Institute of Technology

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