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Event-driven constellation mission design for in situ crater formation observation

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BACKGROUND AND MOTIVATION

Understanding the frequency and mechanisms of impact crater events helps to mitigate civil [1] and exploration [2] hazards, while understanding impact physics helps refine crater scaling laws. Better impact prediction models are crucial for effective design for planetary defense missions as e.g., the DART kinetic impact test [3] shown in Fig. 1. Crater formation has never been directly observed; current models are informed by theory and impact experiments that represent lower energies compared to naturally occurring lunar impacts. Increasing the rate of new crater detection could provide valuable insight into impact processes and the Moon provides a practical environment in which to do so.

The Lunar Reconnaissance Orbiter (LRO, [4]) and its camera (LROC, [5]) have shaped our knowledge of impact processes [6, 7], providing high-resolution, global imaging of the Moon. While LRO is anticipated to be operational until ~2030, it has already exceeded its mission duration. As LRO is a single spacecraft and crater targets are manually selected, the same region of the surface is typically re-imaged (typical altitude 50 km) at best every three months, but sometimes not for several years [7]. The highest resolution images (Fig 3.) come from the LROC Narrow Angle Camera (LROC NAC, [5]), the capabilities of which we assume can be considered ‘off the shelf’.

Figure 1. DART Impact as imaged by LICIA cube.

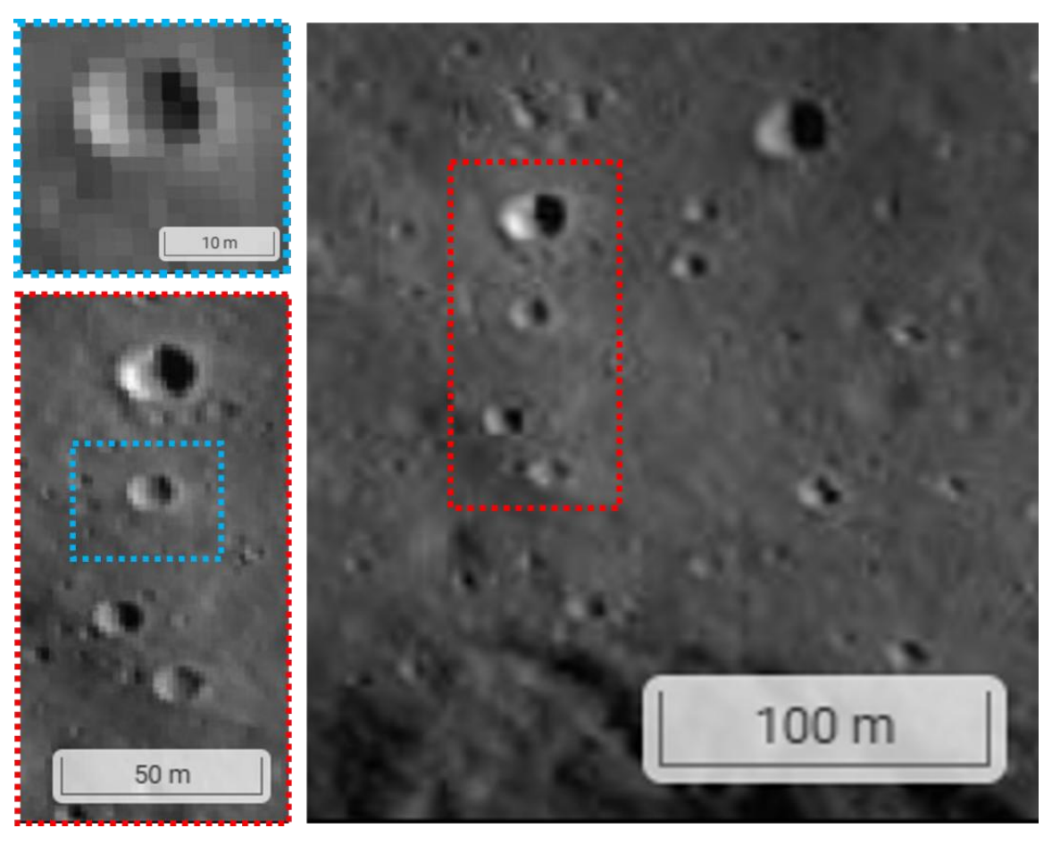


Figure 3. Example ~10 m diameter crater at -38.147°, 357.118°. Successively zooming in on central crater in the boxed red region demonstrates crater features visible at 6 pixels/diameter in the boxed blue / upper left image. Credit LROC Quickmaps.

OBJECTIVE: determine on orbit infrastructure needed for rapid and automatic detection of crater formation

MISSION ARCHITECTURE

Constellation architecture should maximize surface coverage while minimizing cost. We consider a Cubesat swarm of N_S number of small sats in 50 km altitude circular lunar orbits.

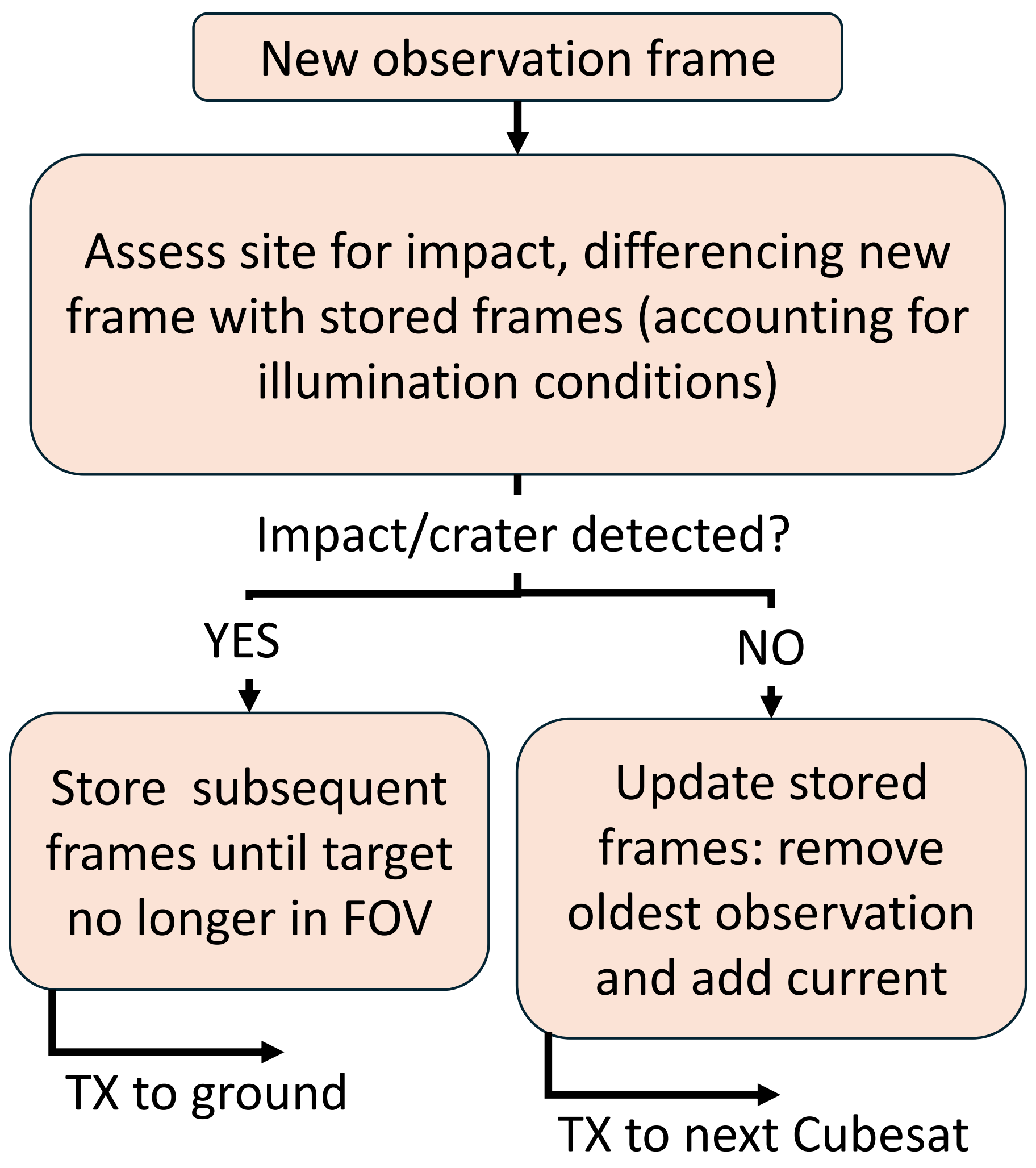
Spacecraft: Constellation of LUMIO-like spacecraft. LUMIO, ESA’s Cubesat mission for observing lunar far side impact flashes (Fig. 4) [8], is a 12U Cubesat (28 kg) with its primary payload an impact flash observing camera. We assume LUMIO can be used as-is but with an updated camera. LUMIO is approved for Element 3 of GSTP funding (assume C_{SDEV} = € 10M for NRE development [9], C_S = €1M/N_S construction [10]).

Figure 4. LUMIO Cubesat configuration, Toputo 2023

Payload: LROC NAC equivalent camera (5000x5000 pixel CCD [5]). Development costs assume half of the original LROC contract (~$90M, [11]) can be allocated to the NAC and 10% recurring costs for components and testing C_{NACDEV} = € 40M, C_{NAC} = €4M/N_S.

Ground segment and ops:. Assume typical operations consist primarily of health checks; data is only offloaded in the event of impact detection. C_{OPS} = €200K/N_S/Y [12], with 5 ground stations at 5M€ per station $C_{COMMSDEV}$ = €25M [13].

Event driven: Reduce resources for image processing by minimizing data storage, only storing video upon impact detection (Fig. 5).



New observation frame

Assess site for impact, differencing new frame with stored frames (accounting for illumination conditions)

Impact/crater detected?

YES

Store subsequent frames until target no longer in FOV

TX to ground

NO

Update stored frames: remove oldest observation and add current

TX to next Cubesat

Figure 5. Event driven architecture block diagram

Launch: Rideshare with translunar injection, assume (C_L = 1M€ / satellite). Batch translunar injection via Space-X equivalent launch system could reduce substantially [14].

Cost model: Conservative cost estimation considering nonrecurring costs of spacecraft, camera and ground network development as well as per unit and per year construction and operations costs, with a 20% reserve (Fig. 6).

$$TOTAL = (C_{NR} + C_R) \times (1 + R)$$

$$C_R = \left(C_S + C_{NAC} + C_L + Y \times C_{ops}\right) \times N_S$$

$$C_{NR} = C_{SDEV} + C_{NACDEV} + C_{COMMSDEV}$$

C_R – recurring costs
C_{NR} – non-recurring
C_S – spacecraft cost
C_{NAC} – camera cost
C_L – launch cost
C_{ops} – operations cost
Y – years
C_{SDEV} – spacecraft development cost
C_{NACDEV} – NAC development cost
$C_{COMMSDEV}$ – communication dev. cost
R – Reserves
N_S – # satellites

Figure 6. Cost model

RESOLUTION & IMPACT RATE

Since the frequency of impacts increases with decreasing impactor size, a constellation which can resolve smaller sized craters has an improved probability of capturing the impact in real time.

Meteoroid flux: We scale the meteoroid flux at the Earth to the Moon to obtain the number of expected impacts per year. Fig. 7 shows cumulative number of impacts per year as a function of impactor size. We update the fits from [15] and [16] with 12 additional years of CNEOS impacts. The Earth impact rate is then corrected for the Moon, considering the ratio of the Earth/Moon cross sections and their respective gravitational focusing ratios (impactor density 3 g/cc, V_{inf} 20km/s [17]). The result is Eq. 1, which gives the cumulative number of impacts per year.

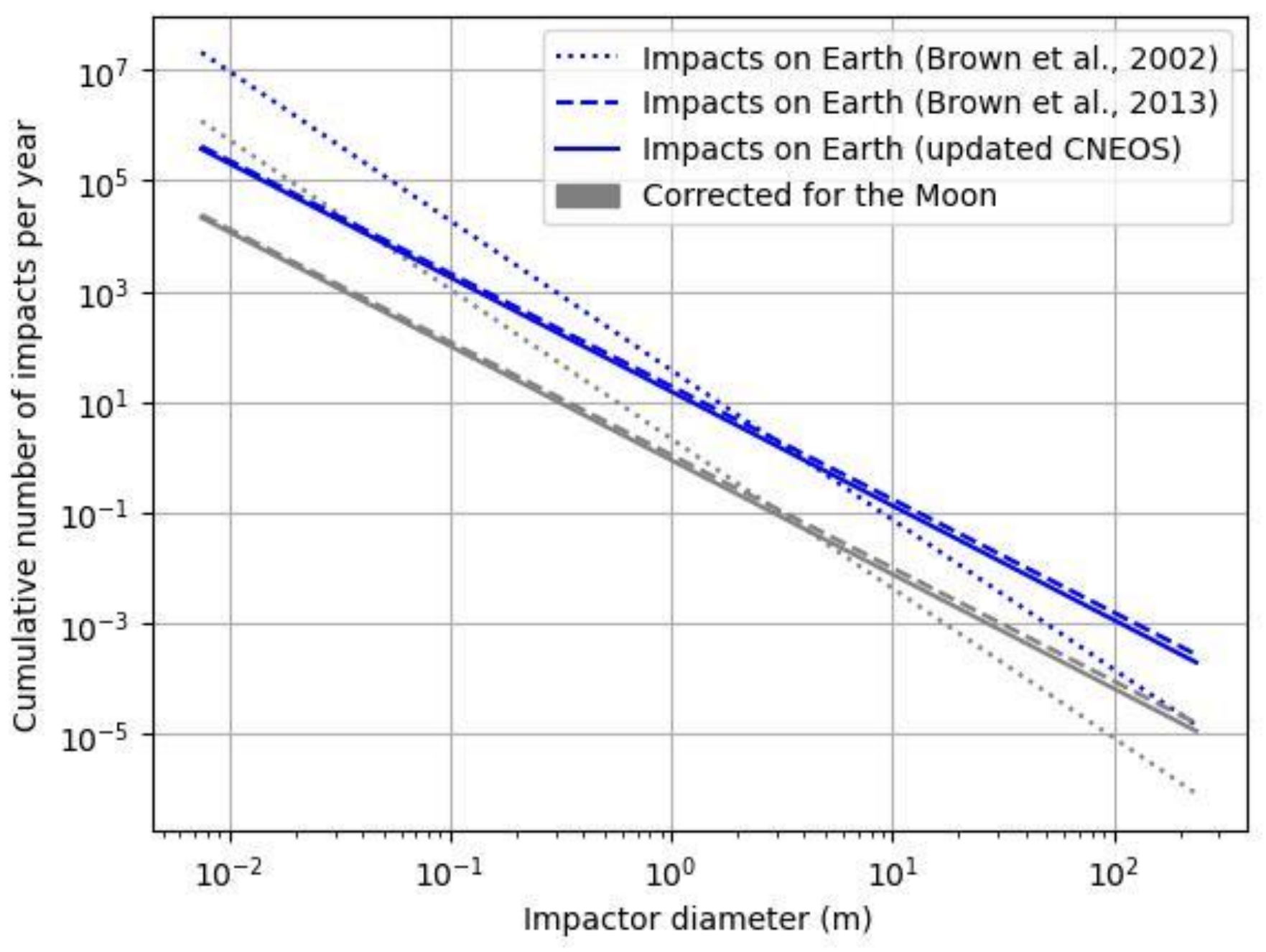


Figure 7. Metroid flux to the Moon, corrected from Earth impact rate. Prior Earth fits are shown in the dashed lines, with our updated fit as the solid blue line. Expected Lunar impacts are the solid gray line

$$N = 0.898 \times D^{-2.061}$$

Equation 1. Expected number N of impacts per year, given impactor diameter D.

Crater size and resolution: We use standard crater scaling laws (Eq. 2) with regolith target properties [18] to find the size of the resulting crater, which can then be used to determine FOV for our desired pixels/crater resolution for a given CCD geometry. Typical impactor sizes (accounting for uncertainty in scaling parameters) range from 16 to 70 cm.

$$\frac{R}{a} = K_1 \left[\frac{ga}{U^2}\left(\frac{\rho}{\delta}\right)^{\frac{2\nu}{\mu}} + \left(\frac{Y}{\rho U^2}\right)^{\frac{2+\mu}{2}} \left(\frac{\rho}{\delta}\right)^{\frac{\nu(2+\mu)}{\mu}}\right]^{-\frac{\mu}{2+\mu}}$$

R – crater radius
a – impactor size
ρ – target density
δ – impactor density
U – impactor velocity
g – gravity
K_1 – scaling constant
ν, μ – power law exponents

Equation 2. Crater size scaling laws from Holsapple et al. [18].

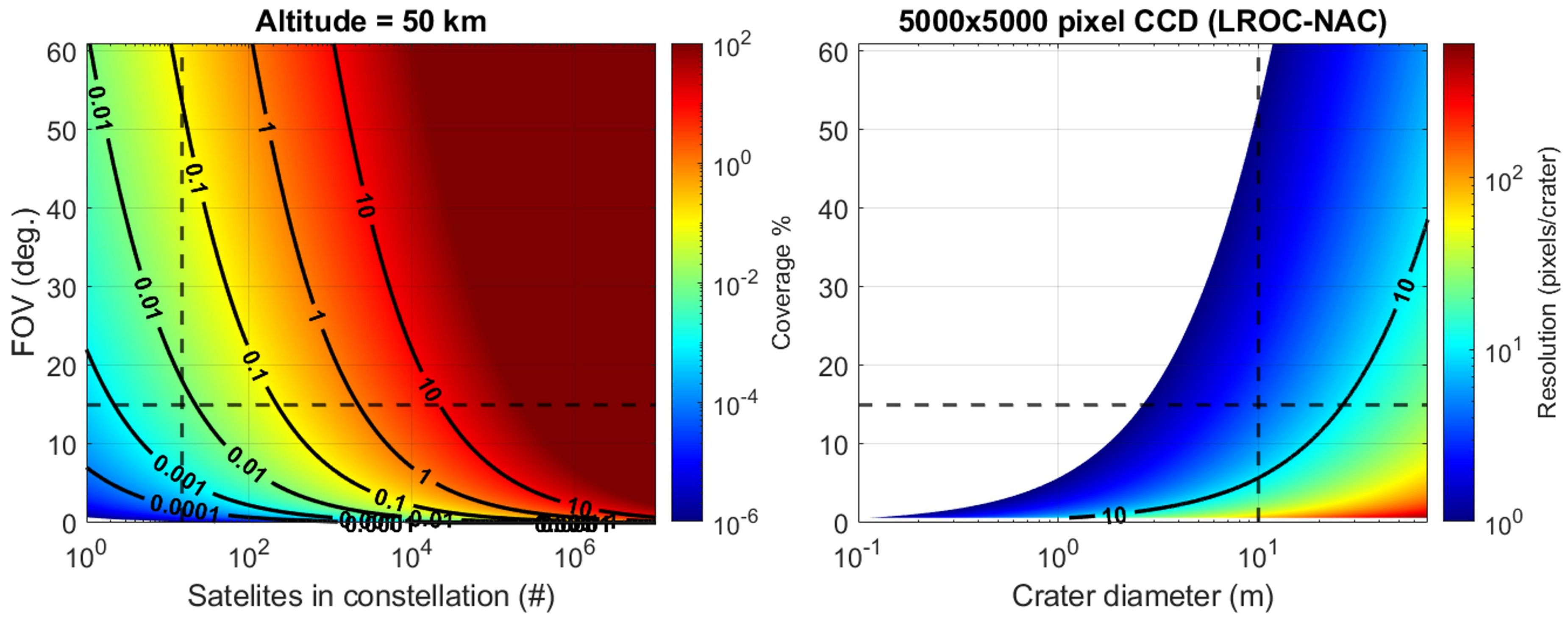


Fig 8. Left) FOV vs number of satellites with contours of coverage. Right) FOV vs crater diameter with contours resolution in pixels per crater diameter. Dashed lines show the baseline design

Impact rate: Knowing the camera FOV sets the portion of the lunar surface covered by a single spacecraft and thus, the surface coverage for a given N_s. Combined with the knowledge of the expected flux to the surface (integrate Fig. 7 to get total impacts per year), and accounting for half-time solar illumination, the time to record one impact is computed.

Baseline design: With 10 m craters as a minimum resolvable target, we select a 15 deg FOV and N_s = 15, yielding surface coverage of 0.022%. This design yields a **required mission duration to observe 1 impact to be 10-20 yrs**. Using the upper bound and the cost model from Fig. 6, we estimate such a mission would have a **total program cost of €280M**. Figure 9 illustrates how costs change depending on constellation configuration vs ESA and NASA mission budgets [19].

RECOMMENDATIONS

- Improved CCD will enhance capture rate by allowing smaller craters (and therefore, more frequent impactors) to be captured, reducing mission time and improving coverage rates
- Mission requires substantial investment comparable to ESA/NASA Flagship missions, a result of large upfront development costs (Ground station and communications infrastructure

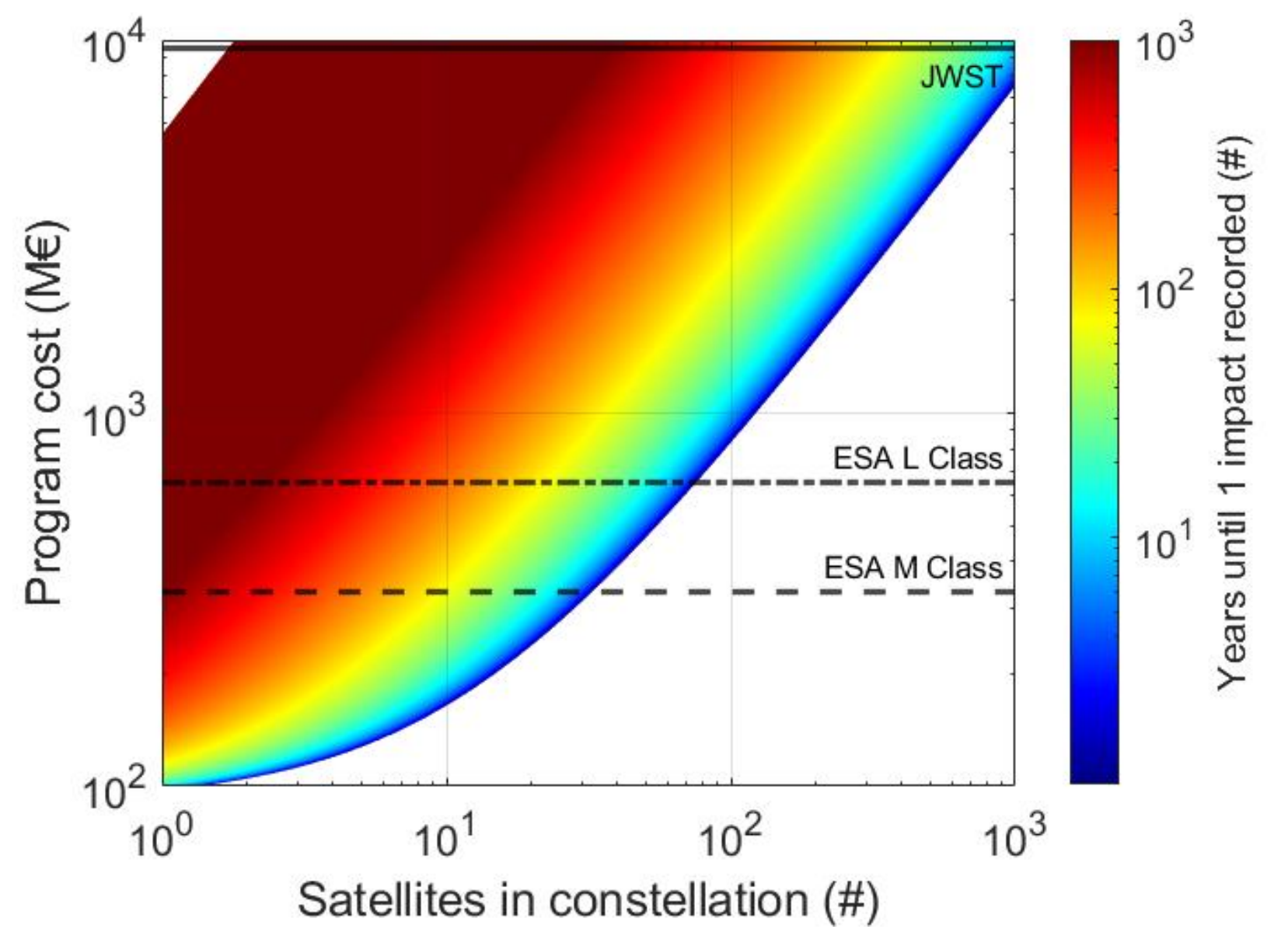


Figure 9. Constellation costs vs number of satellites, colored by years until impact detected

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