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# Update on Determining the Mass of Didymoon and Impact Parameters through Radio Science

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Pre-Decisional Information -- For Planning and Discussion Purposes Only

# Overview

**AIDA mission concept update**

- Instrument constraints
- Mission timeline constraints

**Pre-impact Observation**

- Didymoon GM uncertainties from terminator orbits and flyby approaches

**Post-impact Observation**

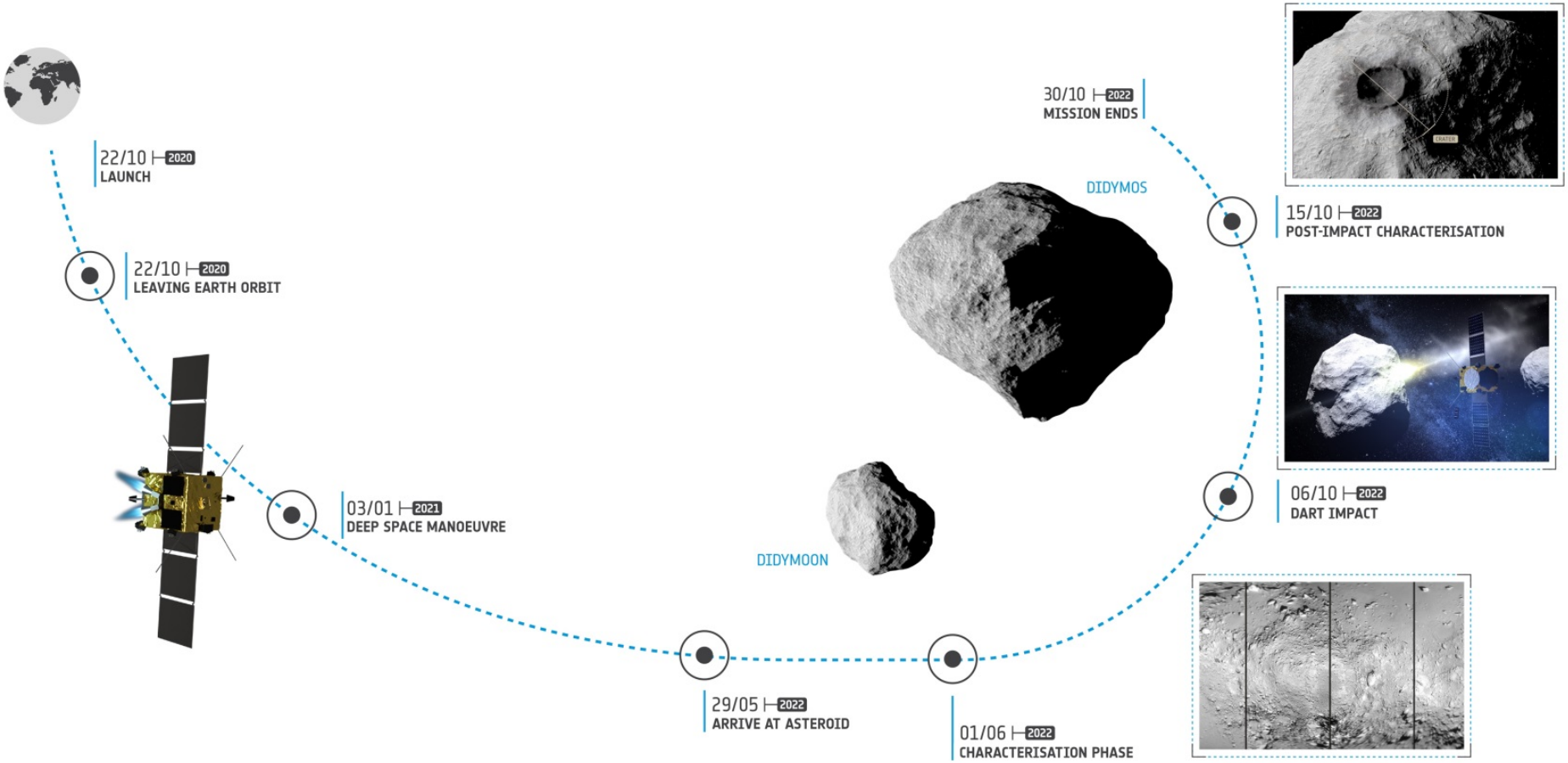
- Earlier work overview for delta-V determination
- New required standoff orbits for timeline constraints
- Momentum enhancement measurement uncertainty, i.e. delta-Beta

**Concluding remarks**

# AIDA Mission Concept Update

ESA-led orbiter de-scoped (Kuppers, ACM 2017): use communication links (X-band) and optical navigation (AIM Framing Camera) for radio science measurements.

Orbiter timeline-ish: 5 months pre-impact, 2 weeks post-impact (TBC).




Credits: ESA

# Didymos Parameters and 1-σ a priori Uncertainties

Didymos asteroid system:

775 m (+/-10%) diameter primary body.

163 m (+/-0.018 m) diameter secondary body .

1.18 km +/- 0.04 km distance between secondary and system barycenter.

Assumed density: 2146 kg/m$^3$ for both bodies, 30% uncertainty.

Component GM a priori uncertainties: ~10% and 60% for main and moon, respectively.

Other parameters and 1-σ a priori uncertainties assumptions:

| **Parameters** | **Values** | **1-sigma** |
|---|---|---|
| Didymain states | Defined at Epoch | 0.5km; 0.01km/s |
| moon states | Defined at Epoch | 0.5km; 0.01km/s |
| AIM spacecraft | Approach specific | 0.05km; 0.005km/s |
| SRP factor | 1 | 100% |
| Harmonics factor | 1 | 100% |
| Pole (RA and DEC) | 310 deg, -84 deg | 20 deg; 5 deg |
| Spin state | 2.26 hrs | 0.0001 hr |

# Radio Science Study Goals

**Determine measurability of Didymos parameters, impact DV, and Beta.**

**Uncertainty Assumptions**

- Didymos system parameters and a priori uncertainties from AIDA ref document.
- Didymos ephemeris and a priori covariance from JPL SSD Alain Chamberlain.
- Didymoon/Didymain orbits integrated using initial conditions from Didymos system ephemerides simulated by JPL SSD Eugene Fahnestock.
- Harmonics a priori uncertainty from technique by McMahon (LPSC 2016)
- Accounting for uncertainties on planetary ephemeris, DSN locations, media.

**Spacecraft desaturations**

- Modeling spacecraft using desaturations (1x / 2 days) (assume use of reaction wheels for turns, with balanced thrusters).

**Simulated Data**

- Simulated X-band radiometric measurements: 7 per week, 8 hr tracks
- Simulated optical measurements (13 and 5 deg field of view, 1 pic/6 hrs, alternating between main and moon, equally generated landmarks – full vs thin set compared)
- Pointing uncertainty included, 0.005 deg error.

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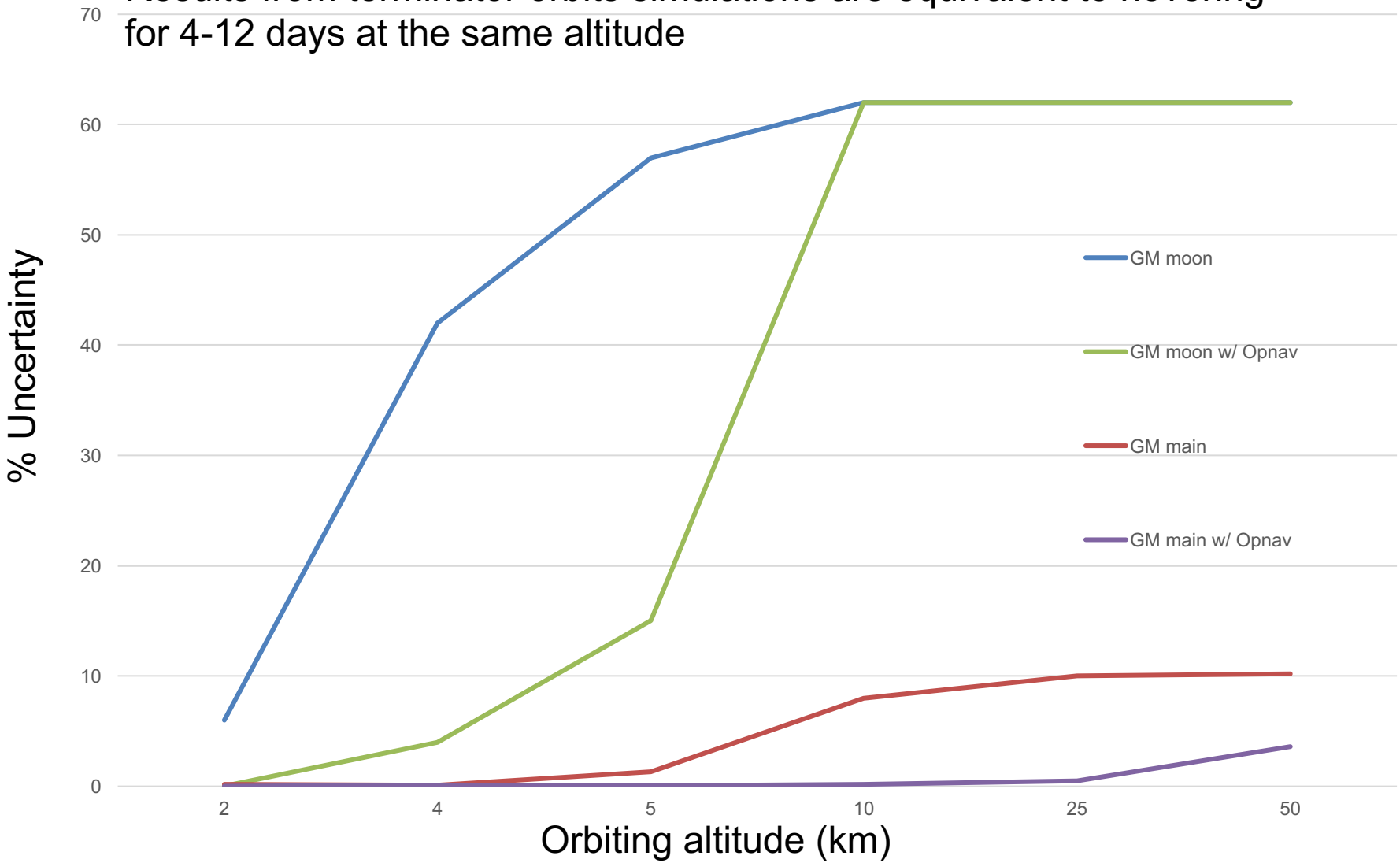
# Pre-impact Observation – Component GM

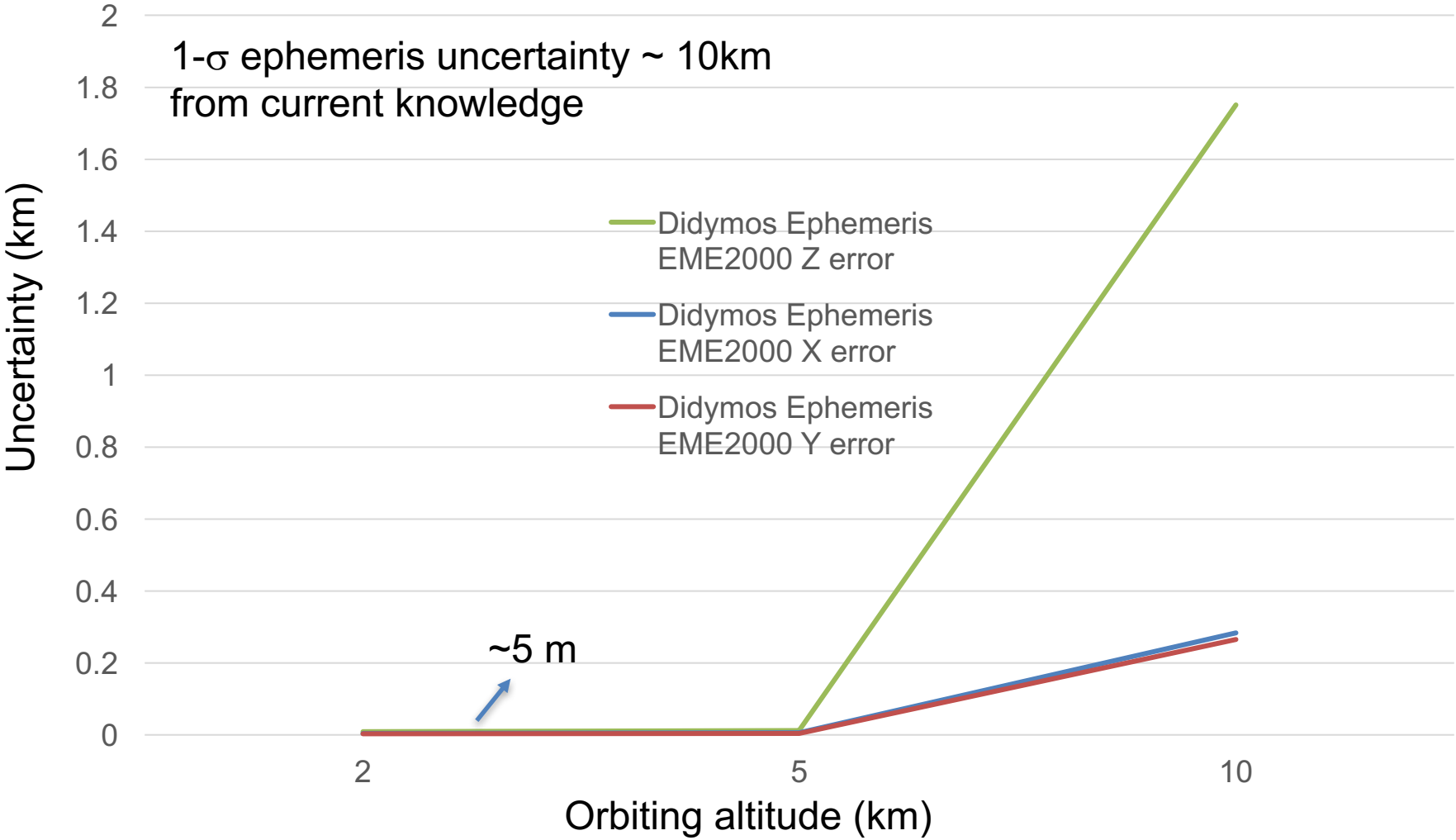
5 months

# Asteroid GM Uncertainties vs Orbiting Altitudes

Results from terminator orbits simulations are equivalent to hovering for 4-12 days at the same altitude



# Dydimos Ephemeris Uncertainties vs Orbiting Altitudes, with Optical navigation



# Pre-impact Conclusions

**GM determination:**

→ The GM of the moon asteroid can be determined to less than 5% for the moon with orbit altitudes below 4 km.

→ Results from terminator orbits compared to hovering at that altitude are equivalent when hovering for more than 4 days.

Simulations included impulse burns for orbit maintenance every 4 days

**Binary component state determination**

→ States determined to meter level below 5km, and to 10s of meters at 10km.

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# Post-impact Observation – DV and Beta

# Spacecraft Observation Platform

**Uncertainty Assumptions updated from pre-impact characterization**

- A priori update on states, GMs, pole using 2km approach pre-impact
    - Same results obtained with 4km inputs

**Spacecraft orbit maintenance – 15-day operations, pole observation**

- Impulse maneuver every 4 days to stay within “box” for > 4 days cases
- Uncertainty on DART-induced DV and orbit maintenance impulses is 1 mm/s
    - 0.43 mm/s impact for Beta = 1

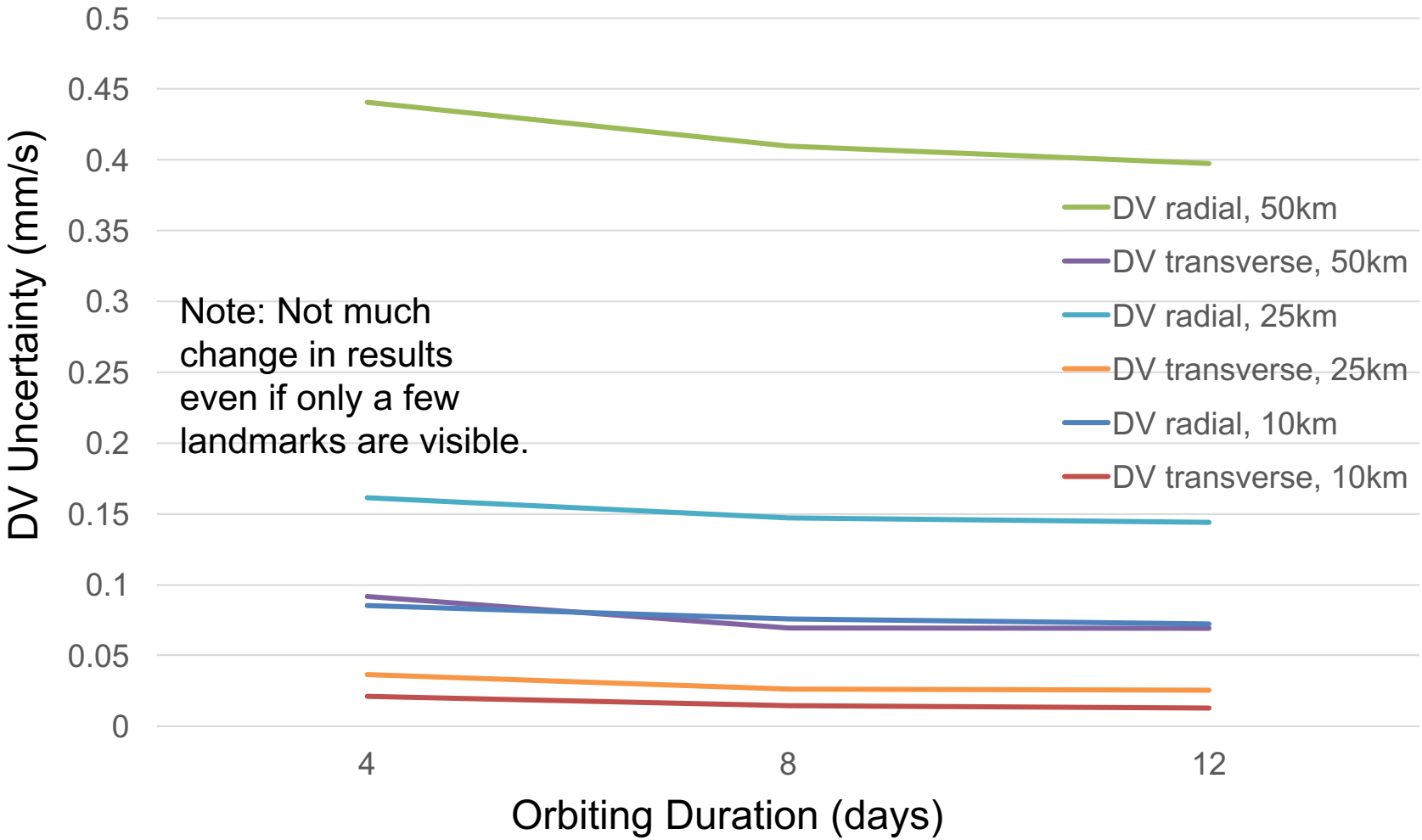
**Simulated Data**

- Simulated radiometric measurements: 7 per week, 8 hr tracks
- Simulated optical measurements: Didymain landmarks and component centroids
- Pointing uncertainty included

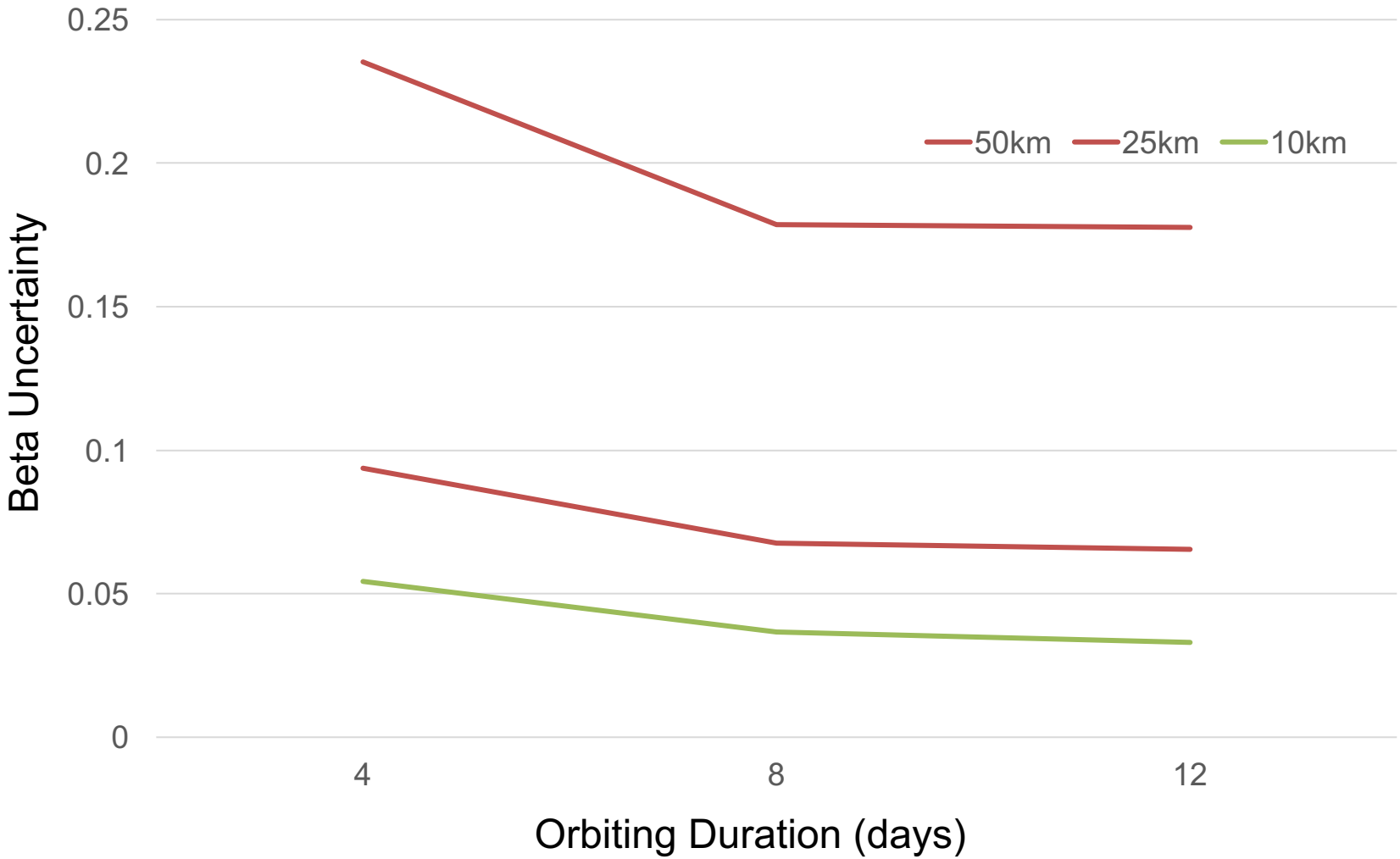
**Parameters determination**

- DV uncertainty in radial and transverse visible from pole observation
- Beta uncertainty: DV uncertainty projected along surface normal at impact location, normalize by impact DV magnitude.

# Delta-V Uncertainties vs Observation duration, with Optical Navigation



# Corresponding Beta Uncertainties for Assumed Impact and Observation Platforms



# Post-impact Conclusions

**$\Delta$V – results for 12 days observation**

→ 100km: $\Delta$V uncertainty < 0.6 mm/s and ~ 0.1 mm/s (transverse, radial).

→ 50km: $\Delta$V uncertainty < 0.4 mm/s and ~ 0.07 mm/s (transverse, radial).

→ 25km: $\Delta$V uncertainty < 0.15 mm/s and < 0.03 mm/s (transverse, radial).

→ 10km: $\Delta$V uncertainty < 0.08 mm/s and < 0.01 mm/s (transverse, radial).

**Beta**

Beta is directly linked to the body physical properties, varies from ~0.6 to 2.5, between major soil material (Cheng, 2016; Holsapple, 2013).

→ Require 3-$\sigma$ at 0.75?...

→ Beta uncertainty drops to **0.18, 0.07, and 0.04** (1-$\sigma$) for the 50km, 25km, and 10km standoff observation platform, respectively.

**→ Radio science using optical navigation during 12 days observation between 25 km and 10 km altitude can well satisfy 3-$\sigma$ uncertainty measurements for soil differentiation.**

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# Thank you!

Questions?

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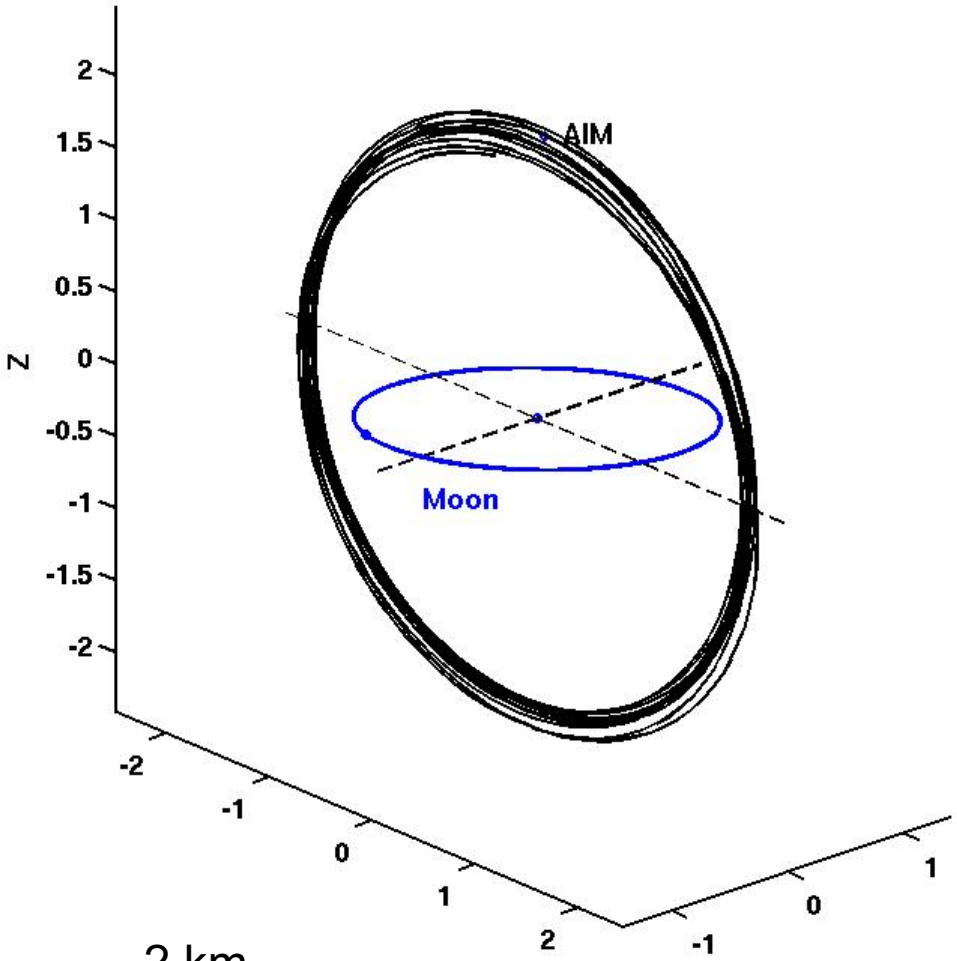
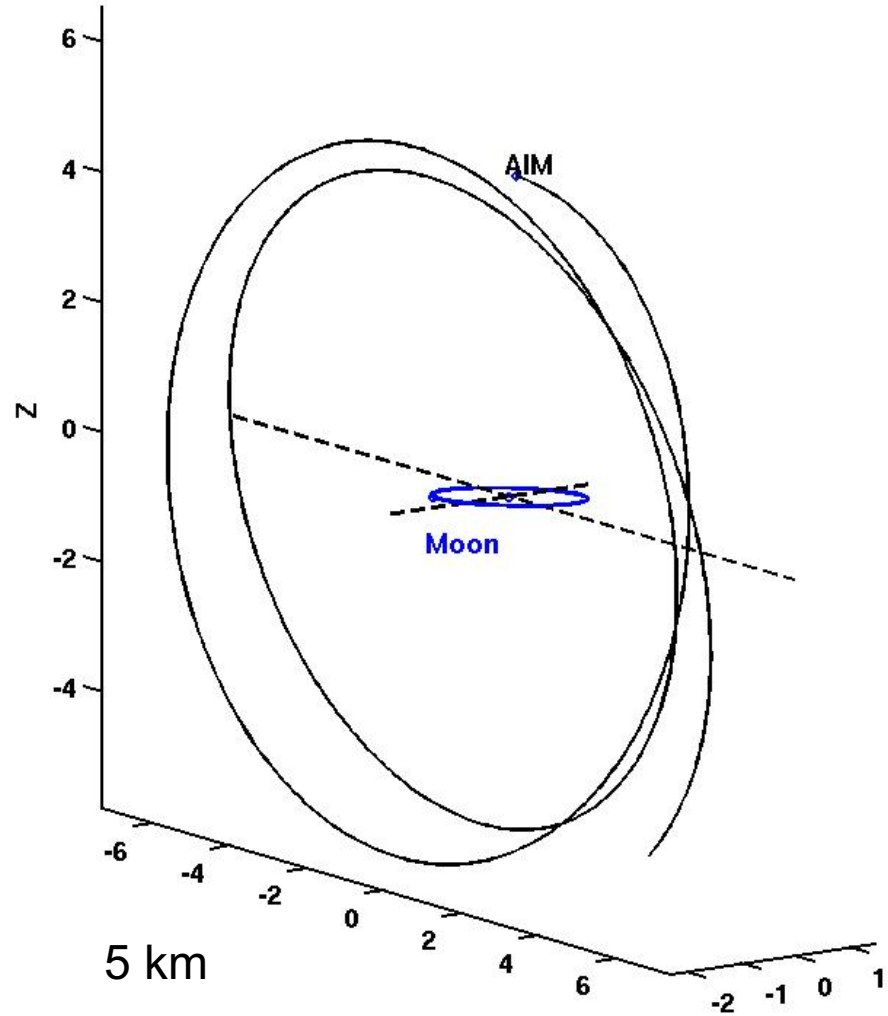
# Backup slides

# Terminator Orbits



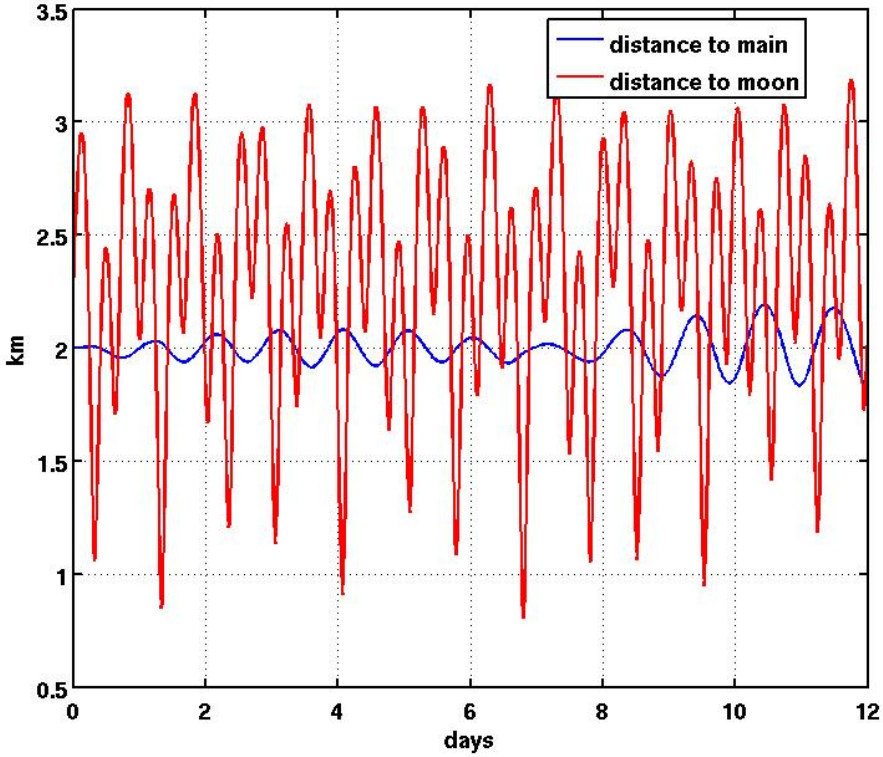

2 km



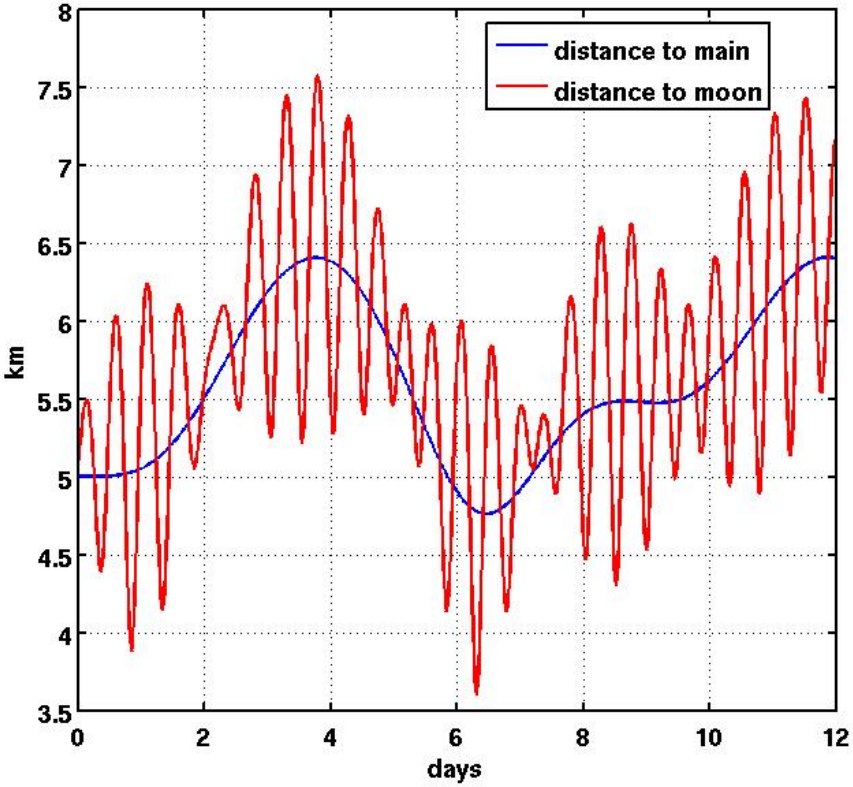

5 km

# 2km Terminator Orbit, Distances vs Time

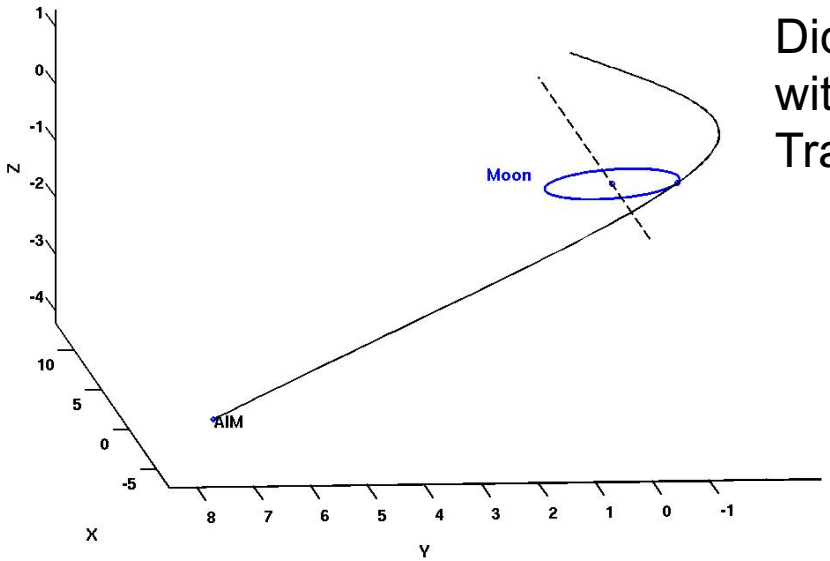
2 km terminator orbit



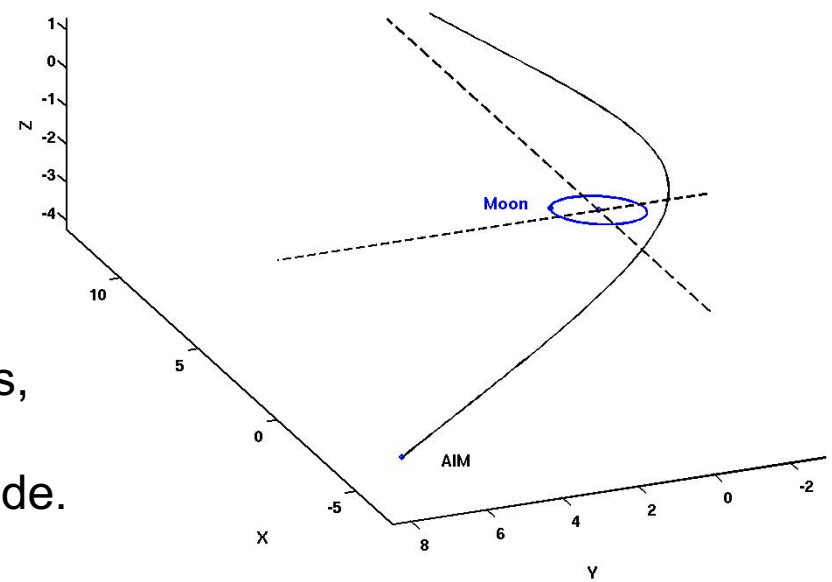

5 km terminator orbit



# Flyby Approaches

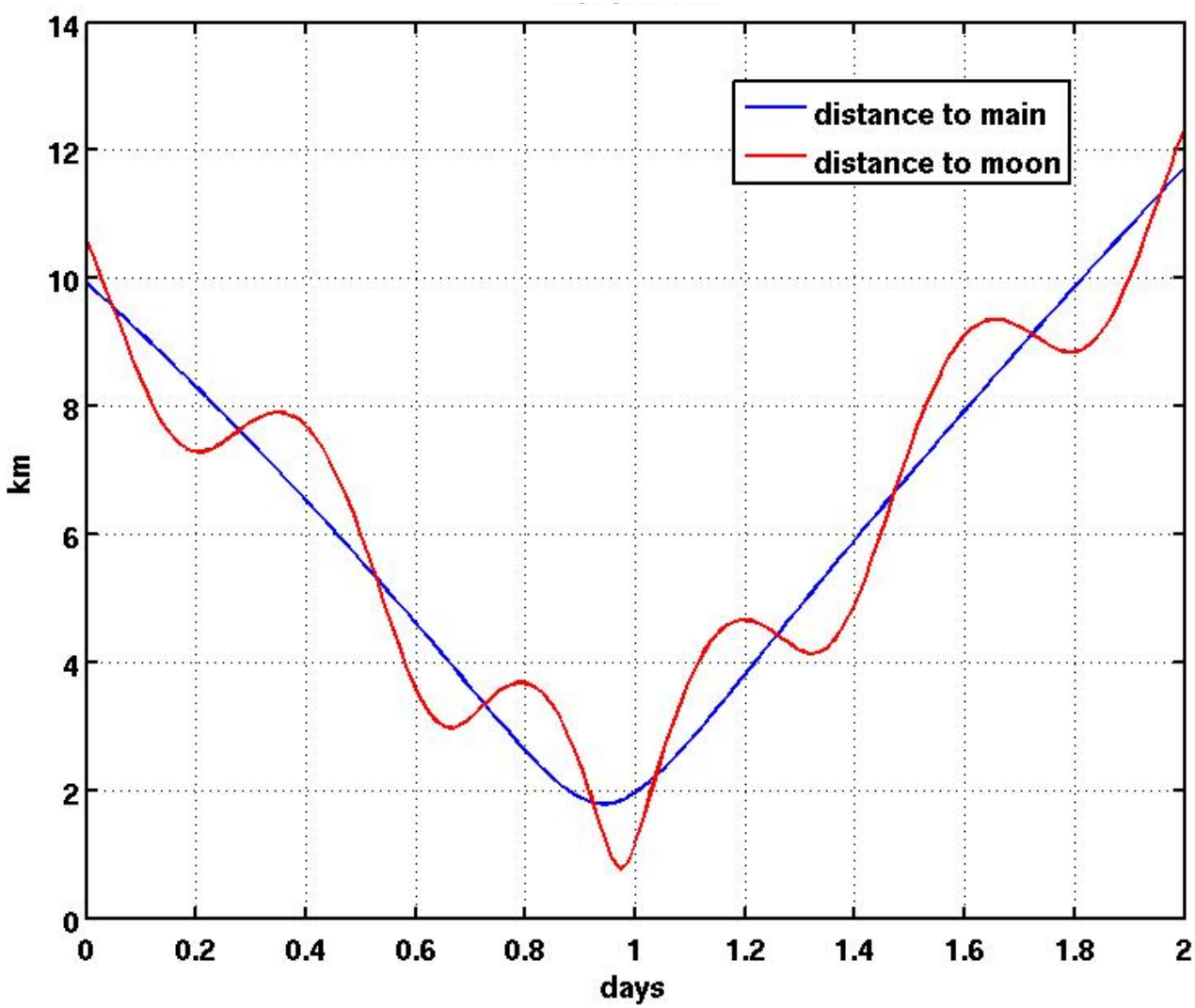



Didymoon flyby simulated over 24 hrs, with a close approach at 300 m. Trajectory injection from 10 km altitude.

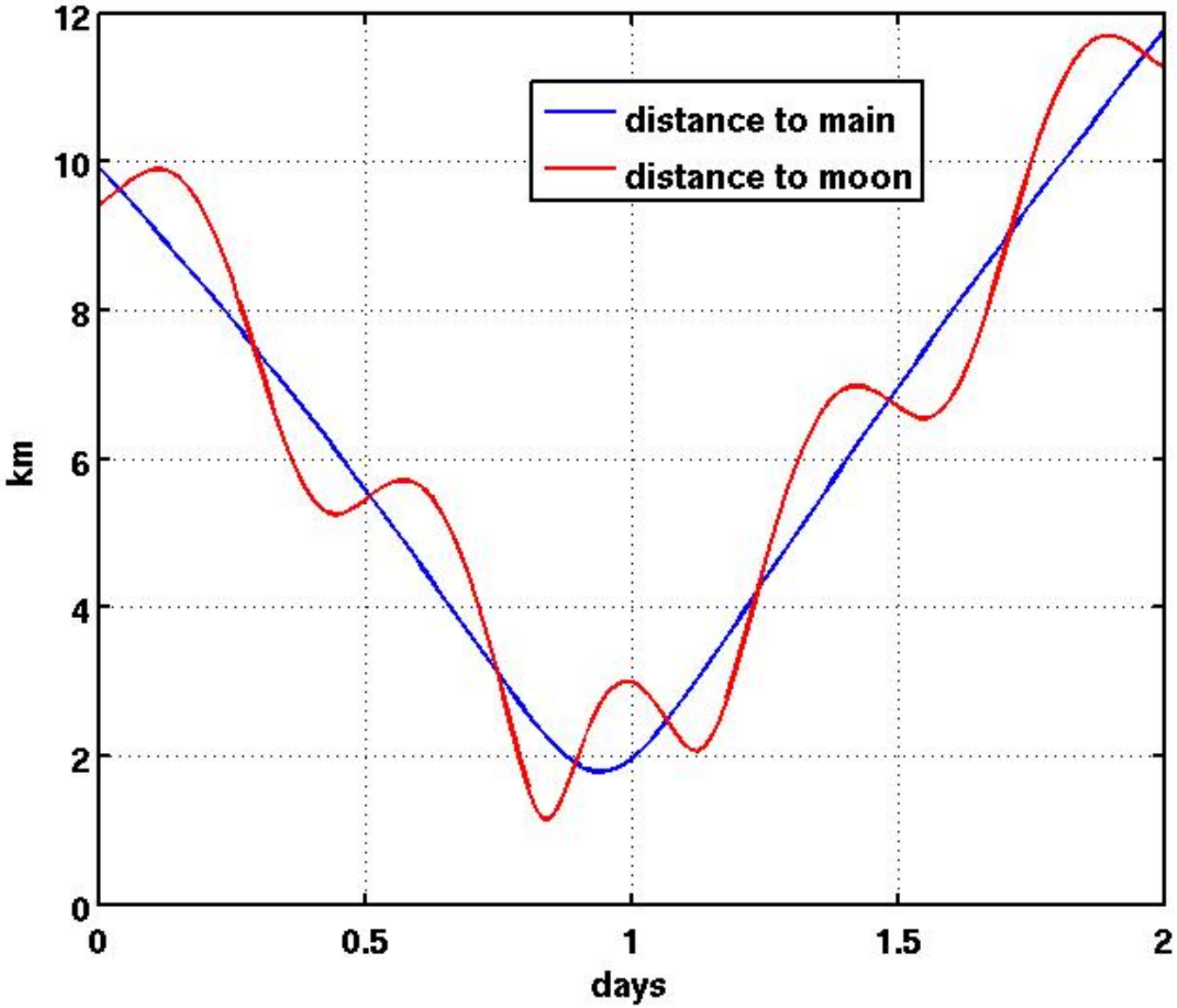



Didymain flyby simulated over 24 hrs, with a close approach at 1500 m. Trajectory injection from 10 km altitude.

# Didymoon Flyby at 300 m, Distances vs Time



# Didymain Flyby at 1500 m, Distances vs Time



# Asteroid component flybys, "clean spacecraft" with 7*8 hrs tracking per week, with/without opnav

| Parameters / Uncertainties | Nominal Values (at Epoch) | Apriori (%) | FB moon 300 m alt. | FB moon 300 m with Opnav | FB main 1500 m alt. | FB main 1500 m with Opnav |
|---|---|---|---|---|---|---|
| AIM states (max value) | 10 km<br>0.0001 km/s | 0.5 km<br>0.0001 km/s | 0.4 km<br>7e-6 km/s | 0.0007 km<br>02e-8 km/s | 0.5 km<br>9e-6 km/s | 0.002 km<br>5e-8 km/s |
| Didymoon states (max value) | 1.18 km | 0.05 km<br>0.005 km/s | 0.05 km<br>3e-4 km/s | 0.03 km<br>7e-6 km/s | 0.05 km<br>0.002 km/s | 0.05 km<br>6e-6 km/s |
| Didymos ephemeris | | 48, 105, 8 km<br><br>1e-5, 8e-7, 5e-7 km/s | | | | |
| GM Didymain | 3.49e-8 | 10% | 5% | 0.06% | 7% | 0.06% |
| GM Didymoon | 3.222e-11 | 62% | 59% | 10% | 62% | 14% |
| Solar pressure | | 100% | 43% | 4% | 100% | 6% |
| Didymain pole RA, Dec, spin rate | 310 deg,<br>-84 deg,<br>2.26 hrs | 20 deg,<br>5 deg,<br>0.0002 hrs | Same as apriori | 0.02 deg,<br>0.006 sec | Same as apriori | 0.02 deg,<br>0.006 sec |
| Didymoon pole RA, Dec, spin rate | 310 deg,<br>-84 deg,<br>11.92 hrs | 20 deg,<br>5 deg,<br>0.01 hrs | Same as apriori | 0.11 deg<br>0.05 deg<br>0.002 sec | Same as apriori | 0.09 deg<br>0.04 deg<br>0.002 sec |
| J2 main<br>J2 moon | | 100%<br>100% | 90%<br>100% | 0.7%<br>92% | 96%<br>100% | 0.4%<br>99% |

# Asteroid component flybys, with desats / 2 days, and 7*8 hrs tracking per week, with/without opnav

| Parameters / Uncertainties | Nominal Values (at Epoch) | Apriori (%) | FB moon 300 m alt. | FB moon 300 m with Opnav | FB main 1500 m alt. | FB main 1500 m with Opnav |
|---|---|---|---|---|---|---|
| AIM states (max value) | 10 km<br>0.0001 km/s | 0.5 km<br>0.0001 km/s | 0.5 km<br>1e-5 km/s | 2e-3 km<br>1e-7 km/s | 0.5 km<br>9e-6 km/s | 2e-3 km<br>6e-8 km/s |
| Didymoon states (max value) | 1.18 km | 0.05 km<br>0.005 km/s | 0.05 km<br>2e-3 km/s | 4e-2 km<br>8e-6 km/s | 0.05 km<br>2e-3 km/s | 5e-2 km<br>6e-6 km/s |
| Didymos ephemeris | | 48, 105, 8 km<br><br>1e-5, 8e-7, 5e-7 km/s | | | | |
| GM Didymain | 3.49e-8 | 10% | 7% | 0.15% | 7% | 0.1% |
| GM Didymoon | 3.222e-11 | 62% | 62% | 25% | 65% | 15% |
| Solar pressure | | 100% | 95% | 65% | 100% | 65% |
| Didymain pole RA, Dec, spin rate | 310 deg,<br>-84 deg,<br>2.26 hrs | 20 deg,<br>5 deg,<br>0.0002 hrs | Same as apriori | 0.02 deg,<br>0.006 sec | Same as apriori | 0.015 deg,<br>0.006 sec |
| Didymoon pole RA, Dec, spin rate | 310 deg,<br>-84 deg,<br>11.92 hrs | 20 deg,<br>5 deg,<br>0.01 hrs | Same as apriori | 0.11 deg<br>0.055 deg<br>0.002 sec | Same as apriori | 0.09 deg<br>0.04 deg<br>0.002 sec |
| J2 main<br>J2 moon | | 100%<br>100% | 97%<br>100% | 1.4%<br>98% | 96%<br>100% | 0.45%<br>99% |

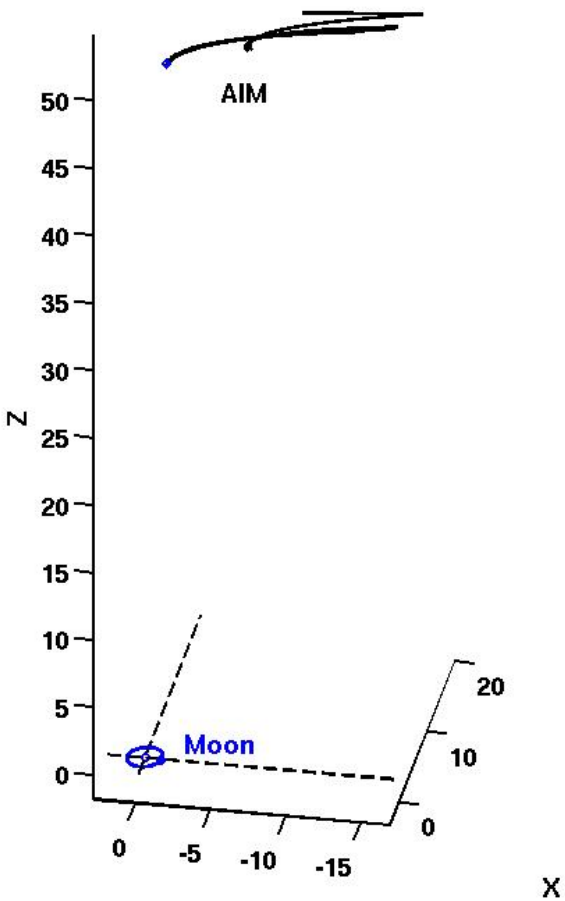
# Terminator orbits (2km, 5km), “clean spacecraft” with 7*8 hrs tracking per week, with/without opnav

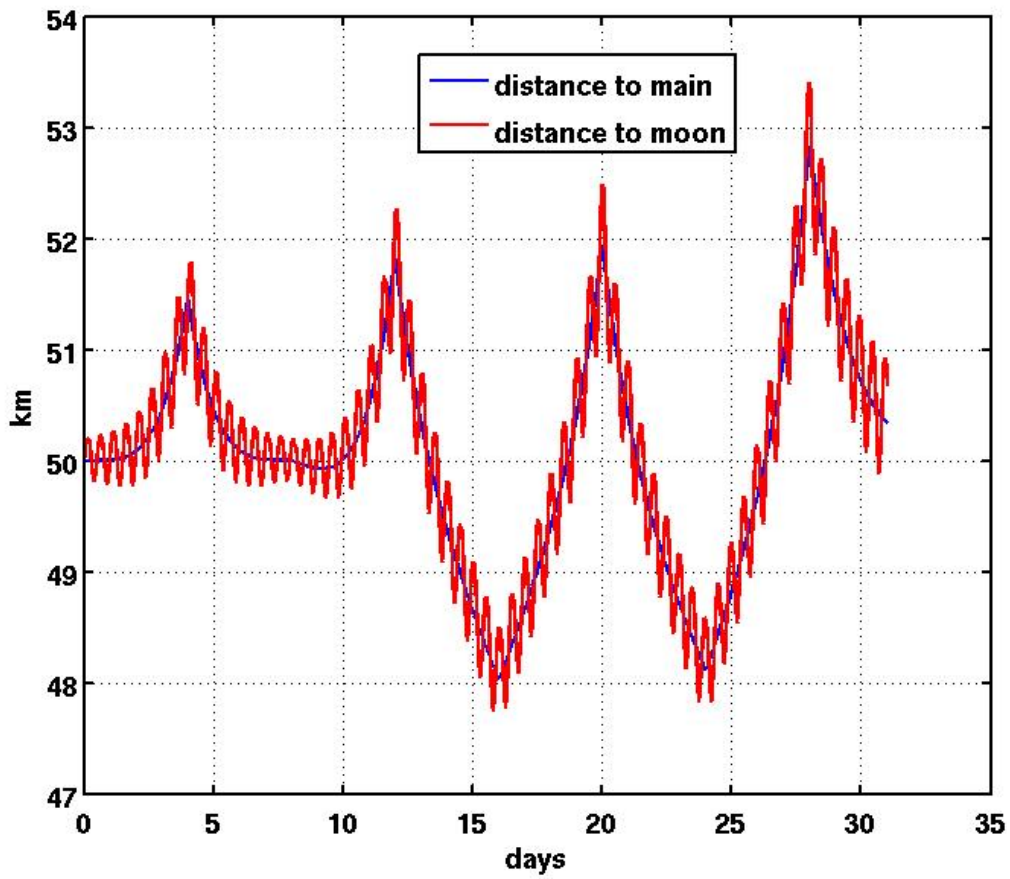
| Parameters / Uncertainties | Nominal Values (at Epoch) | Apriori (% of nominal) | 2km orbit (12 days) | 2km orbit with Opnav (12 days) | 5km orbit (12 days) | 5km orbit with Opnav (12 days) |
|---|---|---|---|---|---|---|
| AIM states (max value) | 2/5 km<br>0.0001 km/s | 0.5 km<br>0.0001 km/s | 0.04 km<br>2e-6 km/s | 7e-5 km<br>5e-9 km/s | 2e-2 km<br>2e-7 km/s | 2e-4 km<br>5e-9 km/s |
| Didymoon states (max value) | 1.18 km | 0.05 km<br>0.005 km/s | 0.05 km<br>2e-5 km/s | 4e-4 km<br>4e-8 km/s | 5e-2 km<br>2e-4 km/s | 7e-3 km<br>6e-7 km/s |
| Didymos ephemeris | | 48, 105, 8 km<br>1e-5, 8e-7, 5e-7 km/s | 0.07, 0.1, 0.07 km<br>2e-8, 3e-9, 8e-8 km/s | 2e-4, 2e-4, 6e-5 km<br>1e-10, 7e-11, 7e-11 km/s | 1.2, 1.7, 2.3 km<br>2e-7, 3e-8, 3e-7 km/s | 2-3, 3e-3, 3e-3 km<br>7e-10, 3e-10, 4e-9 km/s |
| GM Didymain | 3.49e-8 | 10% | 2% | 0.01% | 0.2% | 0.013% |
| GM Didymoon | 3.222e-10 | 62% | 6% | 0.02% | 57% | 15% |
| Solar pressure | | 100% | 60% | 0.2% | 5% | 0.08% |
| Didymain pole RA, Dec, spin period | 310 deg,<br>-84 deg,<br>2.26 hrs | 20 deg, 5 deg,<br>0.0002 hrs | Same as apriori | 0.006 deg,<br>0.002 sec | Same as apriori | 0.006 deg,<br>0.002 sec |
| Didymoon pole RA, Dec, spin period | 310 deg,<br>-84 deg,<br>11.92 hrs | 20 deg, 5 deg,<br>0.01 hrs | Same as apriori | 0.015 deg,<br>0.005 sec | Same as apriori | 0.03 deg<br>0.01 sec |
| J2 main<br>J2 moon | | 100%<br>100% | 1%<br>99% | 0.002%<br>0.3% | 4%<br>100% | 0.3%<br>97% |

# Terminator orbits (2km, 5km), with desats / 2 days, with 2*8 hrs tracking per week, with/without Opnav

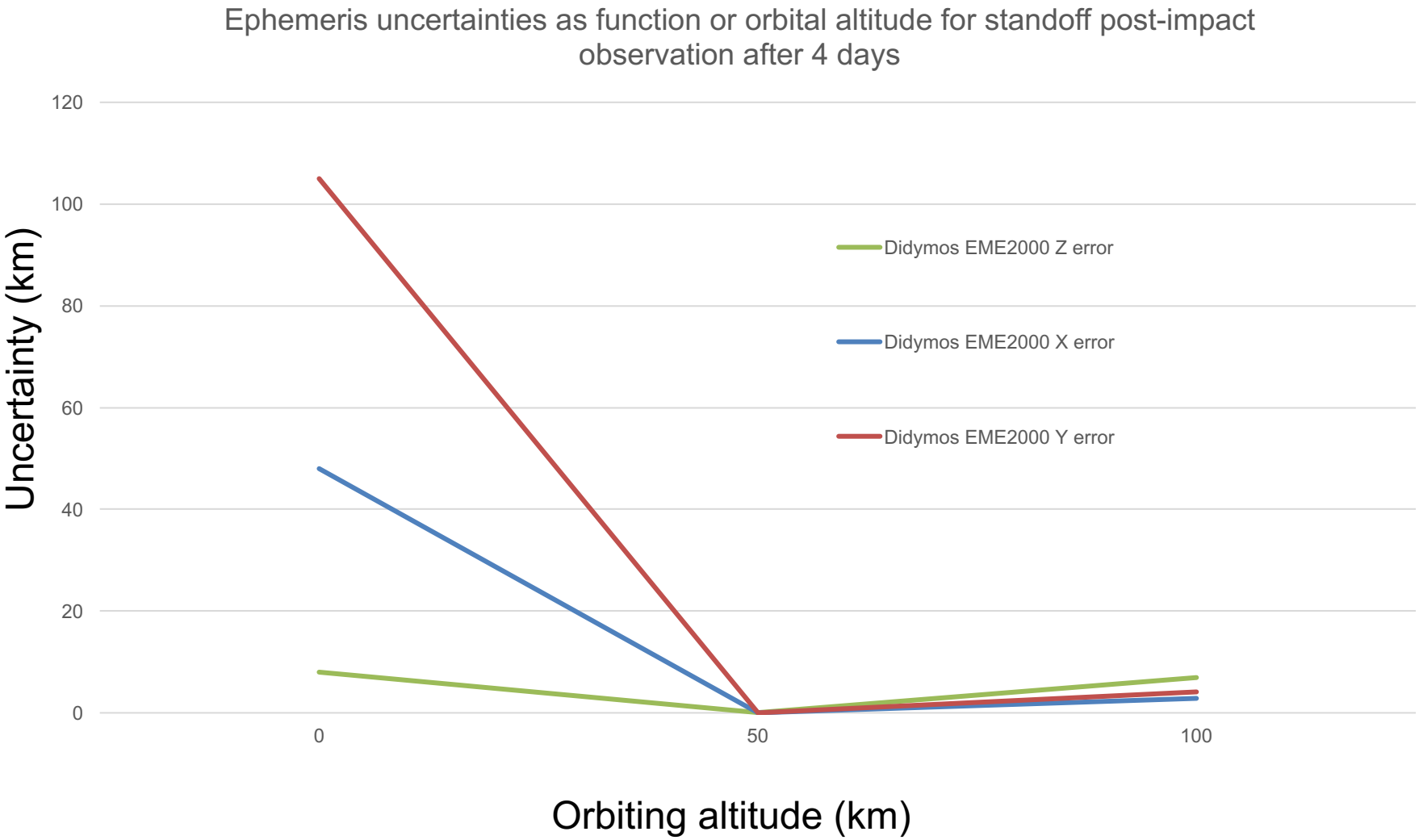
| Parameters / Uncertainties | Nominal Values (at Epoch) | Apriori (% of nominal) | 2km orbit (12 days) | 2km orbit with Opnav (12 days) | 5km orbit (12 days) | 5km orbit with Opnav (12 days) |
|---|---|---|---|---|---|---|
| AIM states (max value) | 2/5 km<br>0.0001 km/s | 0.5 km<br>0.00001 km/s | 0.6 km<br>3e-5 km/s | 2e-4 km<br>1e-8 km/s | 0.3 km<br>4e-6 km/s | 2e-3 km<br>5e-8 km/s |
| Didymoon states (max value) | 1.18 km | 0.05 km<br>0.005 km/s | 4 km<br>5e-4 km/s | 5e-4 km<br>7e-8 km/s | 40km<br>5e-3 km/s | 2e-3 km<br>2e-7 km/s |
| Didymos ephemeris | | 48, 105, 8 km<br>1e-5, 8e-7, 5e-7 km/s | 0.007, 0.004, 0.9 km<br>7e-9, 3e-9, 1e-7 km/s | 2e-5, 9e-6, 8e-5 km<br>2e-11, 2e-11, 1e-10 km/s | 0.04, 0.04, 0.9 km<br>3e-8, 1e-8, 4e-7 km/s | 5e-5, 2e-5, 2e-4 km<br>4e-11, 4e-11, 2e-10 km/s |
| GM Didymain | 3.49e-8 | 10% | 4% | 0.02% | 6% | 0.016% |
| GM Didymoon | 3.222e-10 | 62% | 24% | 0.03% | 58% | 28% |
| Solar pressure | | 100% | 96% | 24% | 84% | 26% |
| Didymain pole RA, Dec, spin rate | 310 deg,<br>-84 deg,<br>2.26 hrs | 20 deg, 5 deg,<br>0.0002 hrs | Same as apriori | 0.007 deg,<br>0.002 sec | Same as apriori | 0.007 deg,<br>0.002 sec |
| Didymoon pole RA, Dec, spin rate | 310 deg,<br>-84 deg,<br>11.92 hrs | 20 deg, 5 deg,<br>0.01 hrs | Same as apriori | 0.015 deg,<br>0.005 sec | Same as apriori | 0.03 deg<br>0.01 sec |
| J2 main<br>J2 moon | | 100%<br>100% | 3%<br>100% | 0.004%<br>0.4% | 18%<br>100% | 0.5%<br>100% |

# 50 km Standoff Orbit

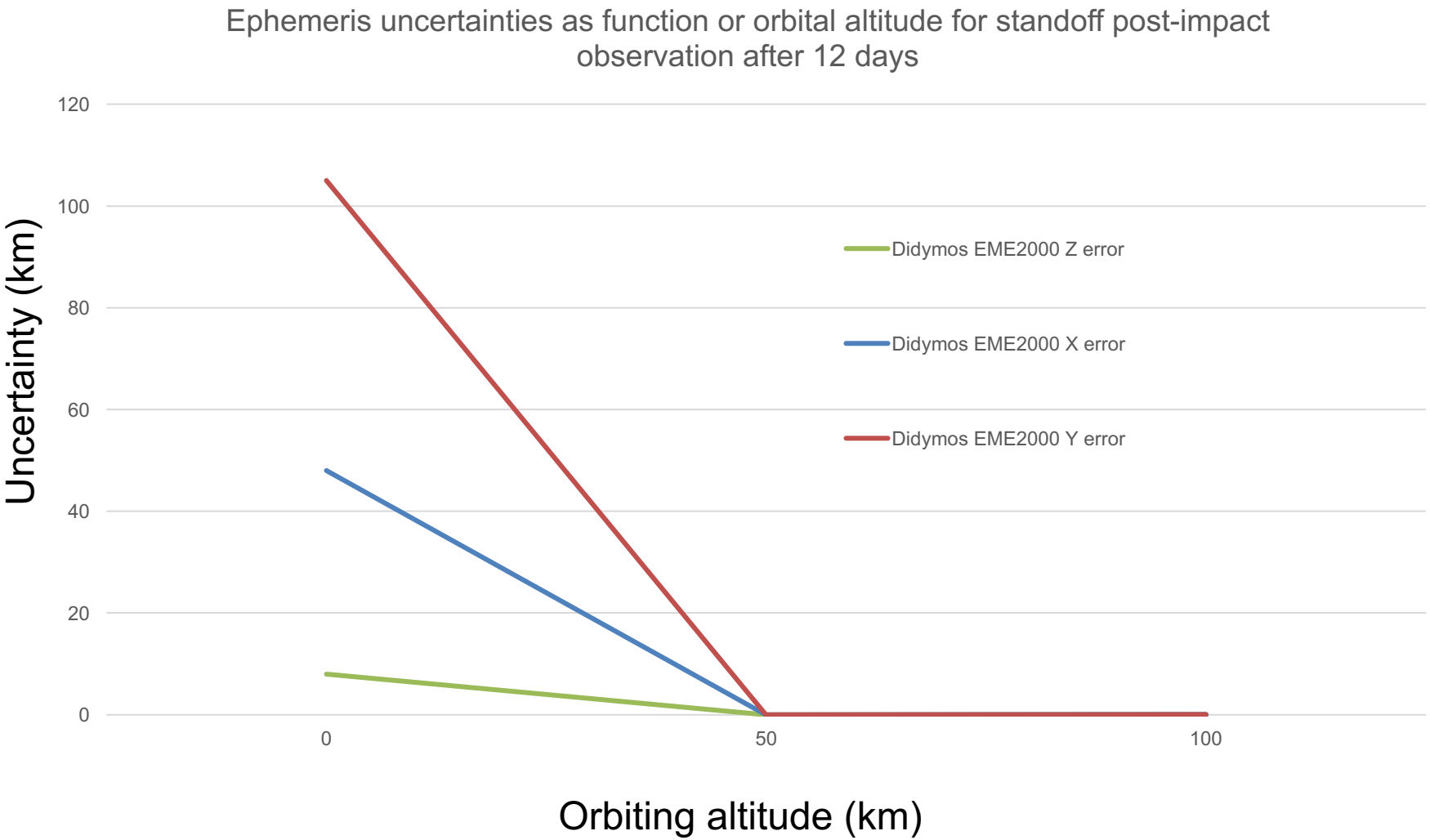


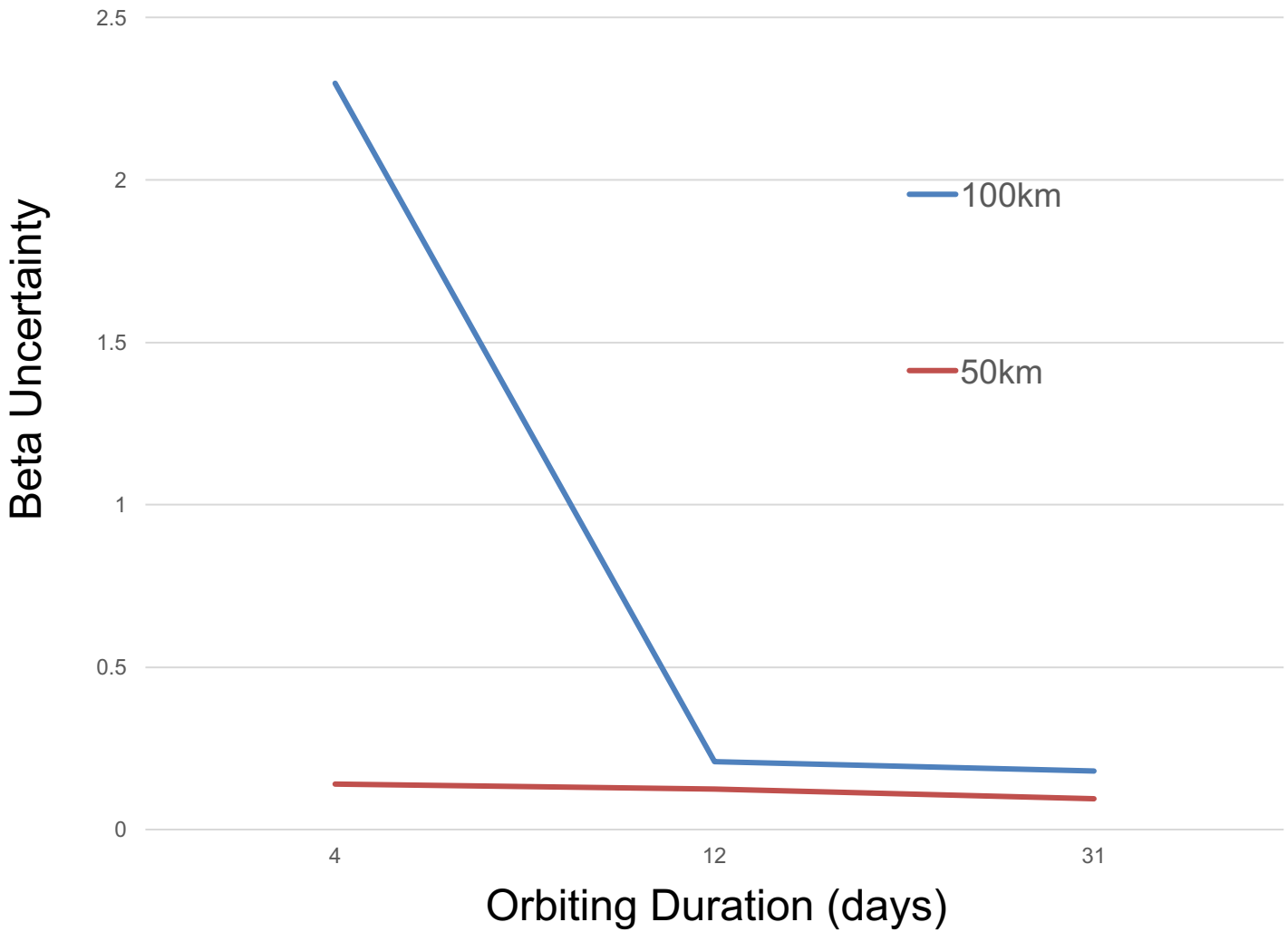
# After 4 days… Dydimos Ephemeris Uncertainties vs Orbiting Altitudes, with Optical navigation



# After 12 days… Dydimos Ephemeris Uncertainties vs Orbiting Altitudes, with Optical navigation



# Corresponding Beta Uncertainties for Assumed Impact and Observation Platforms



# AIM Framing Camera

Table 3: Main specifications of the AFC (from Sierks et al., 2011)

| Item | Specification |
|---|---|
| Focal length | 150 mm |
| F-number | 7.5 |
| BFL | 19 mm |
| Field Of View (FOV) | 5.5° x 5.5° |
| IFOV | 93.7 $\mu$rad |
| Field of Curvature | $< 10$ $\mu$m |
| Distortion | $< 0.1\%$ |