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Radio Science and Measuring DART-induced Deflection with Observer Spacecraft

Julie Bellerose, Shyam Bhaskaran, Steve Chesley

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Research Task Description

Motivation

- There has been little investigation on estimating binary component states and masses through radio science techniques.

- The ΔV uncertainty has significant implications for how well the AIDA mission serves as a deflection demonstration and how much can be learned scientifically from the experiment.
    - Measurable by the AIM spacecraft, depending on proximity operations and knowledge of the system.

- The ΔV uncertainty can inform the measurement of momentum transfer from the impact, and would have implications for interpreting the deflection results as an indicator of surface properties.

Overview

Simulations Setup

- Apriori uncertainty references
- Simulated data types

AIM trajectory

- 2km and 5km terminator orbits
- Flyby approaches from MASCOT-2 deployment information document (ESA)
  - 300 m altitude FB of Didymoon
  - 1500m altitude FB of Didymain
- Radio science result tables
- GM uncertainty as function of orbit altitude

Dart impact observation

- 100 km and 50 km standoff orbits for DV impact observation, 4 days, 12 days, 1 month long
- Assumes best case apriori uncertainties (x5) from 2km terminator orbit

Simulations Setup

Uncertainty Assumptions

- Didymos system parameters and apriori uncertainties from AIDA reference document, see tables of results.
- Using Didymos ephemeris and apriori covariance from JPL Solar System Dynamics Group Alain Chamberlain.
- Didymoon/Didymain orbits integrated using initial conditions from Didymos system ephemerides simulated by Eugene Fahnestock.
- Harmonics apriori uncertainty assumption from Jay McMahon (LPSC 2016)

Spacecraft desaturations

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

Simulated Data

- Simulated radiometric measurements: 7 per week, 8 hr tracks
- Simulated optical measurements (13 deg field of view, 1 pic/12 hrs, alternating between main and moon every 6 hrs, equally generated landmarks)
- Note that no pointing uncertainty is included

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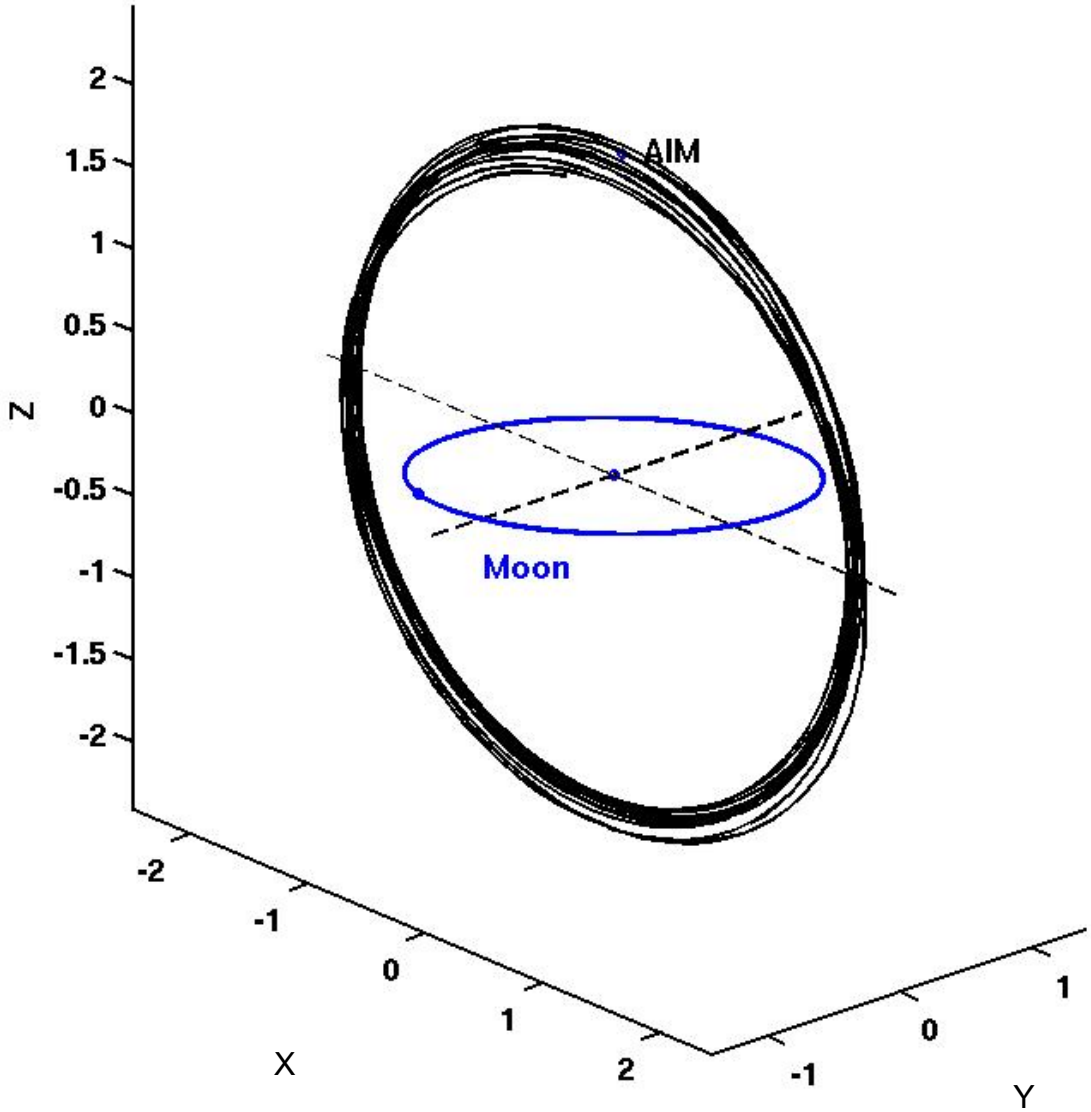
Radio Science Analysis

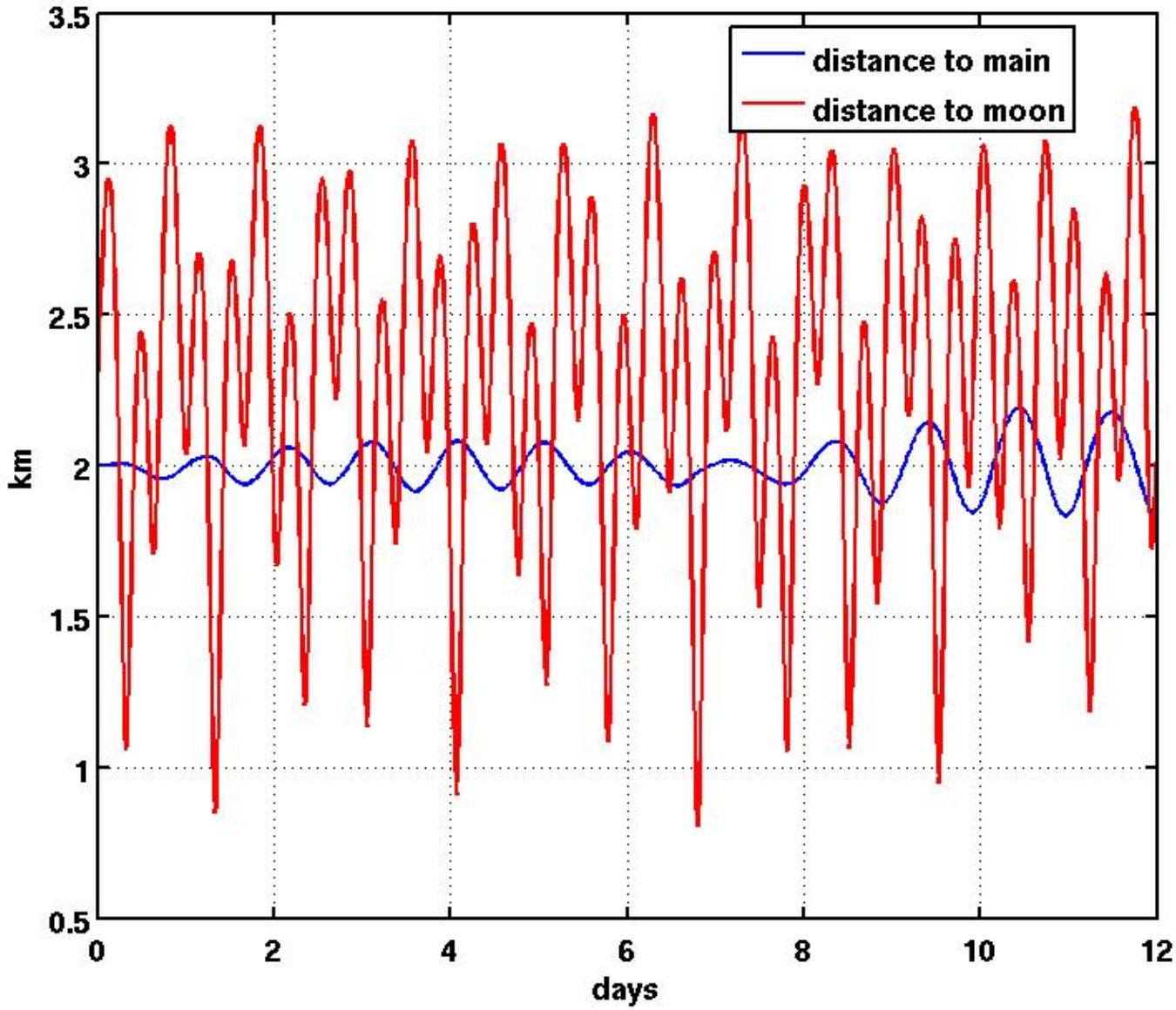
Terminator Orbits

Binary Component Flybys

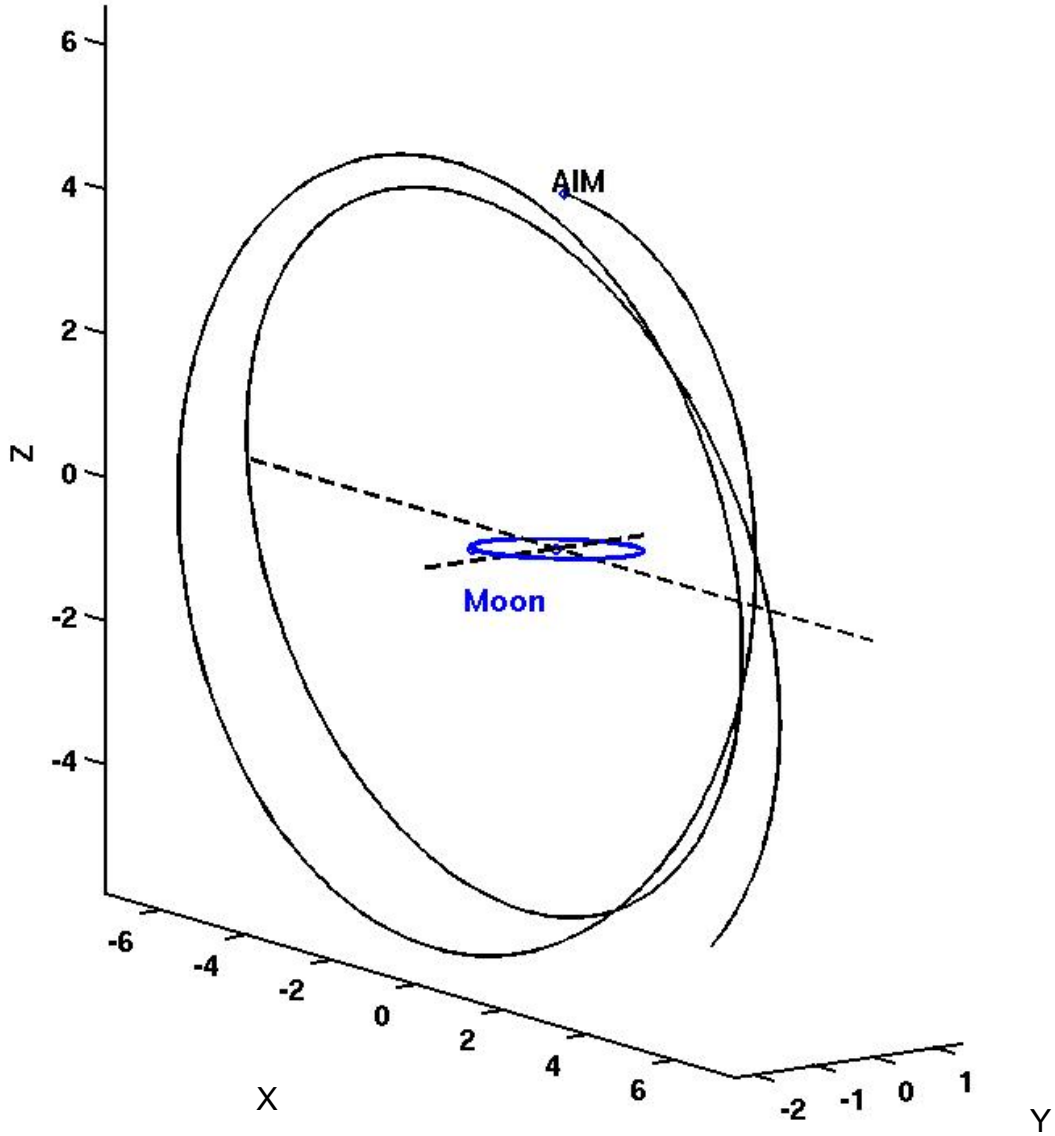
2km Terminator Orbit



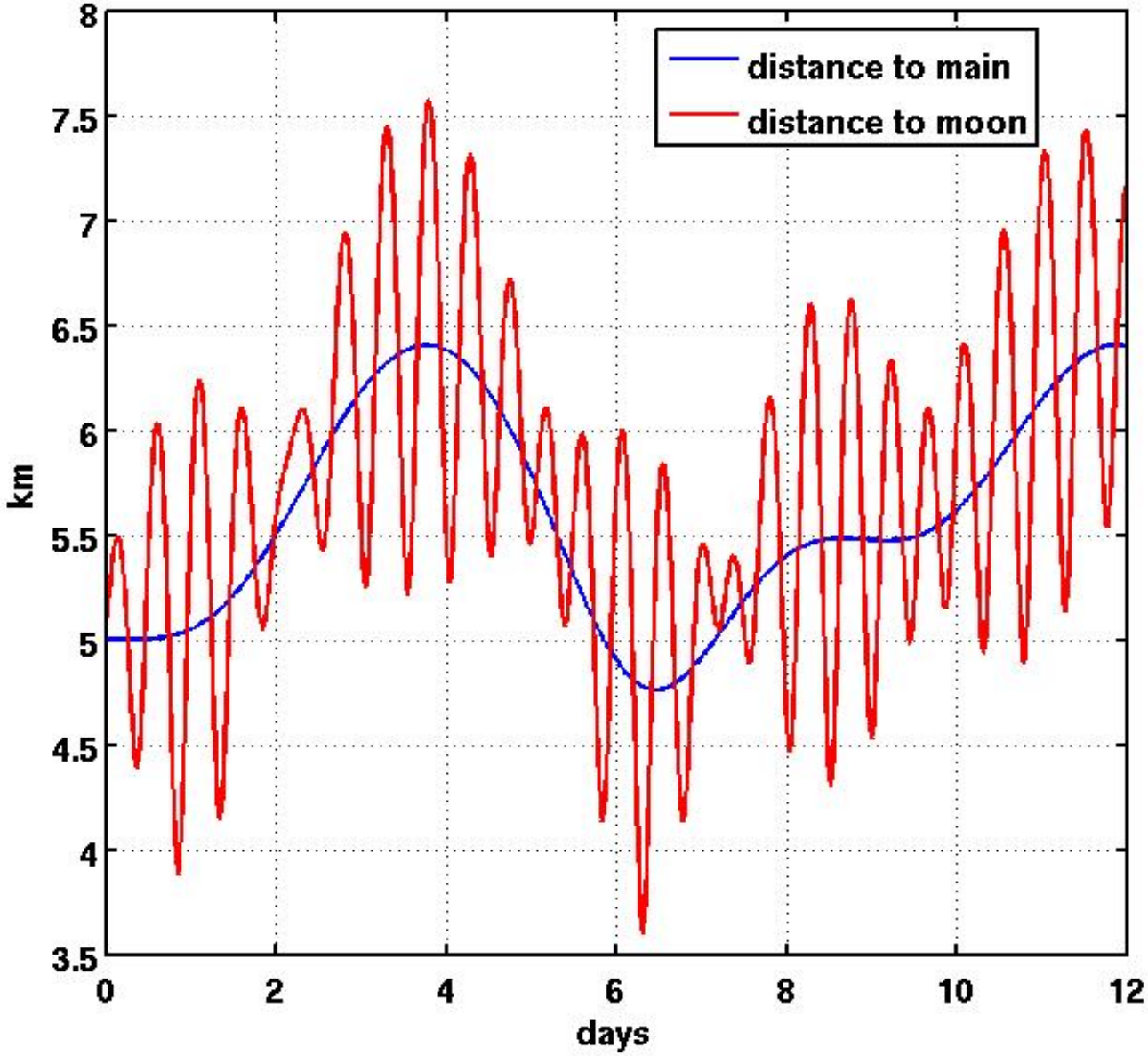
2km Terminator Orbit, Distances vs Time



5km Terminator Orbit



5km Terminator Orbit, Distances vs Time



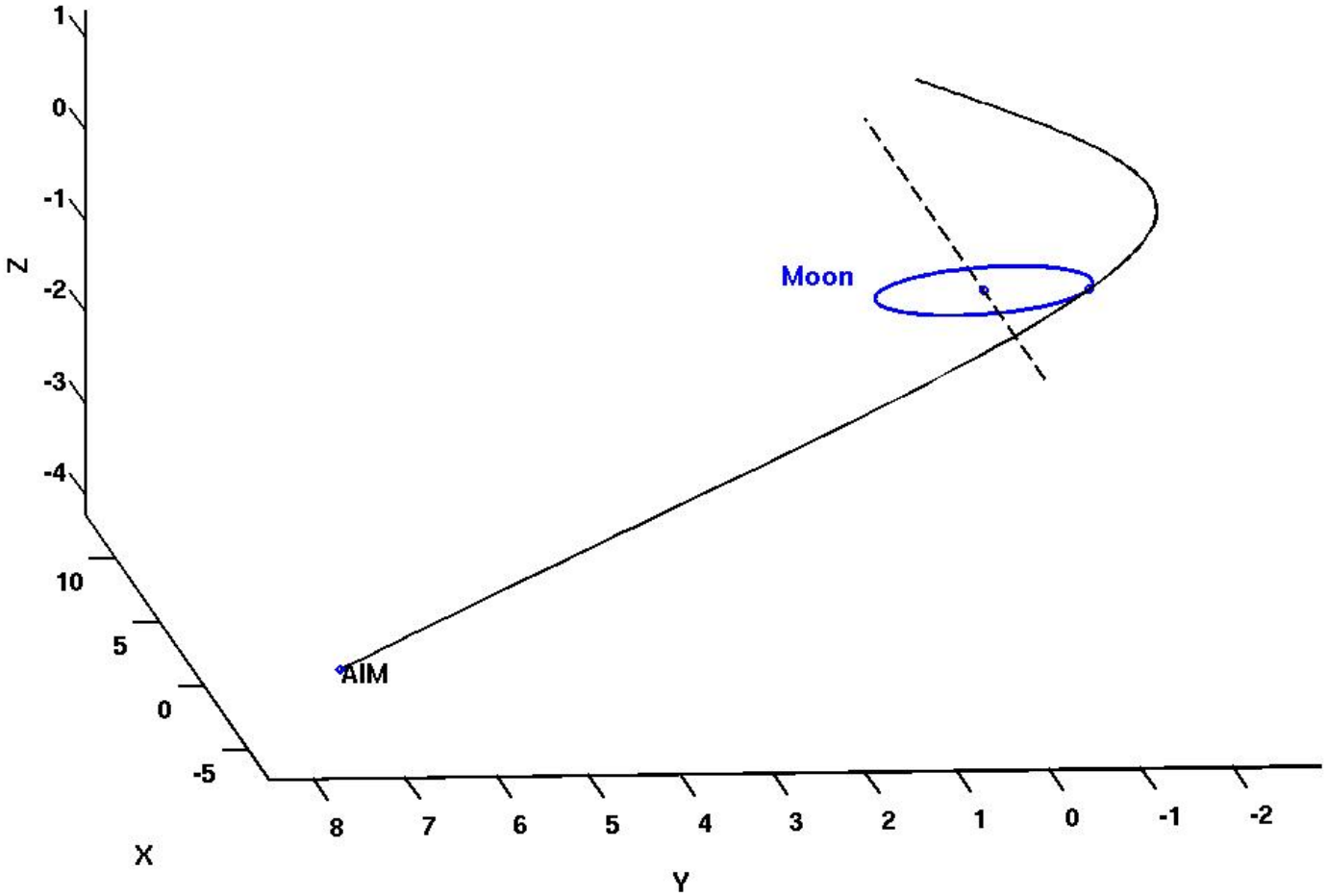
Terminator orbits (2km, 5km), "clean spacecraft" with 7*8 hrs tracking per week, with/without opnav

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)	10 km 0.0001 km/s	0.5 km 0.0001 km/s	0.04 km 2e-6 km/s	7e-5 km 5e-9 km/s	2e-2 km 2e-7 km/s	2e-4 km 5e-9 km/s
Didymoon states (max value)	1.18 km	0.05 km 0.005 km/s	0.05 km 2e-5 km/s	4e-4 km 4e-8 km/s	5e-2 km 2e-4 km/s	7e-3 km 6e-7 km/s
Didymos ephemeris		48, 105, 8 km 1e-5, 8e-7, 5e-7 km/s	0.07, 0.1, 0.07 km 2e-8, 3e-9, 8e-8 km/s	2e-4, 2e-4, 6e-5 km 1e-10, 7e-11, 7e-11 km/s	1.2, 1.7, 2.3 km 2e-7, 3e-8, 3e-7 km/s	2-3, 3e-3, 3e-3 km 7e-10, 3e-10, 4e-9 km/s
GM Didymos	3.5228e-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, -84 deg, 2.26 hrs	20 deg, 5 deg, 0.0002 hrs	Same as apriori	0.006 deg, 0.002 sec	Same as apriori	0.006 deg, 0.002 sec
Didymoon pole RA, Dec, spin period	310 deg, -84 deg, 11.92 hrs	20 deg, 5 deg, 0.01 hrs	Same as apriori	0.015 deg, 0.005 sec	Same as apriori	0.03 deg 0.01 sec
J2 main J2 moon		100% 100%	1% 99%	0.002% 0.3%	4% 100%	0.3% 97%

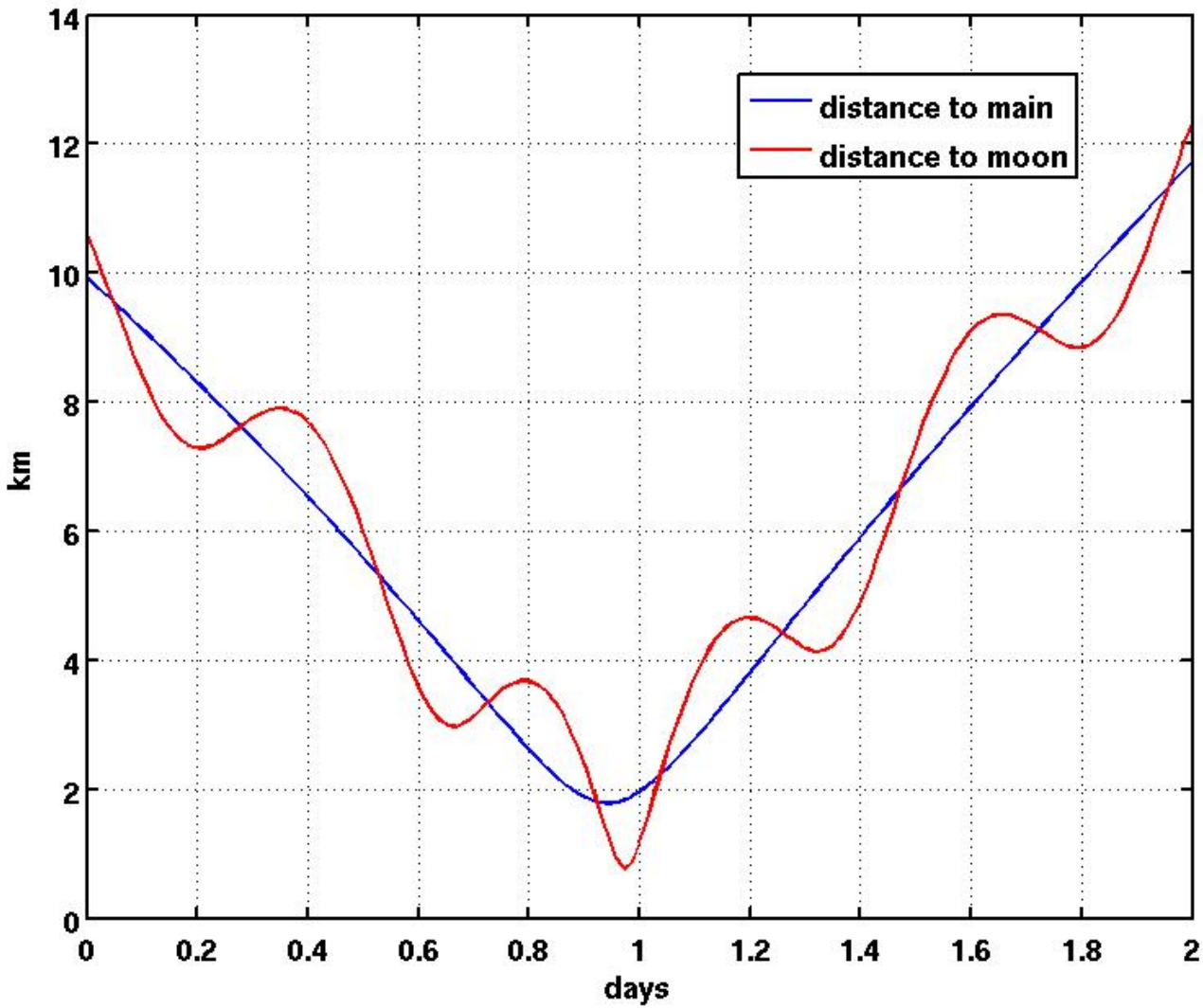
Terminator orbits (2km, 5km), with desats / 2 days, with 2*8 hrs tracking per week, with/without Opnav

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)	10 km 0.0001 km/s	0.5 km 0.00001 km/s	0.6 km 3e-5 km/s	2e-4 km 1e-8 km/s	0.3 km 4e-6 km/s	2e-3 km 5e-8 km/s
Didymoon states (max value)	1.18 km	0.05 km 0.005 km/s	4 km 5e-4 km/s	5e-4 km 7e-8 km/s	40km 5e-3 km/s	2e-3 km 2e-7 km/s
Didymos ephemeris		48, 105, 8 km 1e-5, 8e-7, 5e-7 km/s	0.007, 0.004, 0.9 km 7e-9, 3e-9, 1e-7 km/s	2e-5, 9e-6, 8e-5 km 2e-11, 2e-11, 1e-10 km/s	0.04, 0.04, 0.9 km 3e-8, 1e-8, 4e-7 km/s	5e-5, 2e-5, 2e-4 km 4e-11, 4e-11, 2e-10 km/s
GM Didymos	3.5228e-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, -84 deg, 2.26 hrs	20 deg, 5 deg, 0.0002 hrs	Same as apriori	0.007 deg, 0.002 sec	Same as apriori	0.007 deg, 0.002 sec
Didymoon pole RA, Dec, spin rate	310 deg, -84 deg, 11.92 hrs	20 deg, 5 deg, 0.01 hrs	Same as apriori	0.015 deg, 0.005 sec	Same as apriori	0.03 deg 0.01 sec
J2 main J2 moon		100% 100%	3% 100%	0.004% 0.4%	18% 100%	0.5% 100%

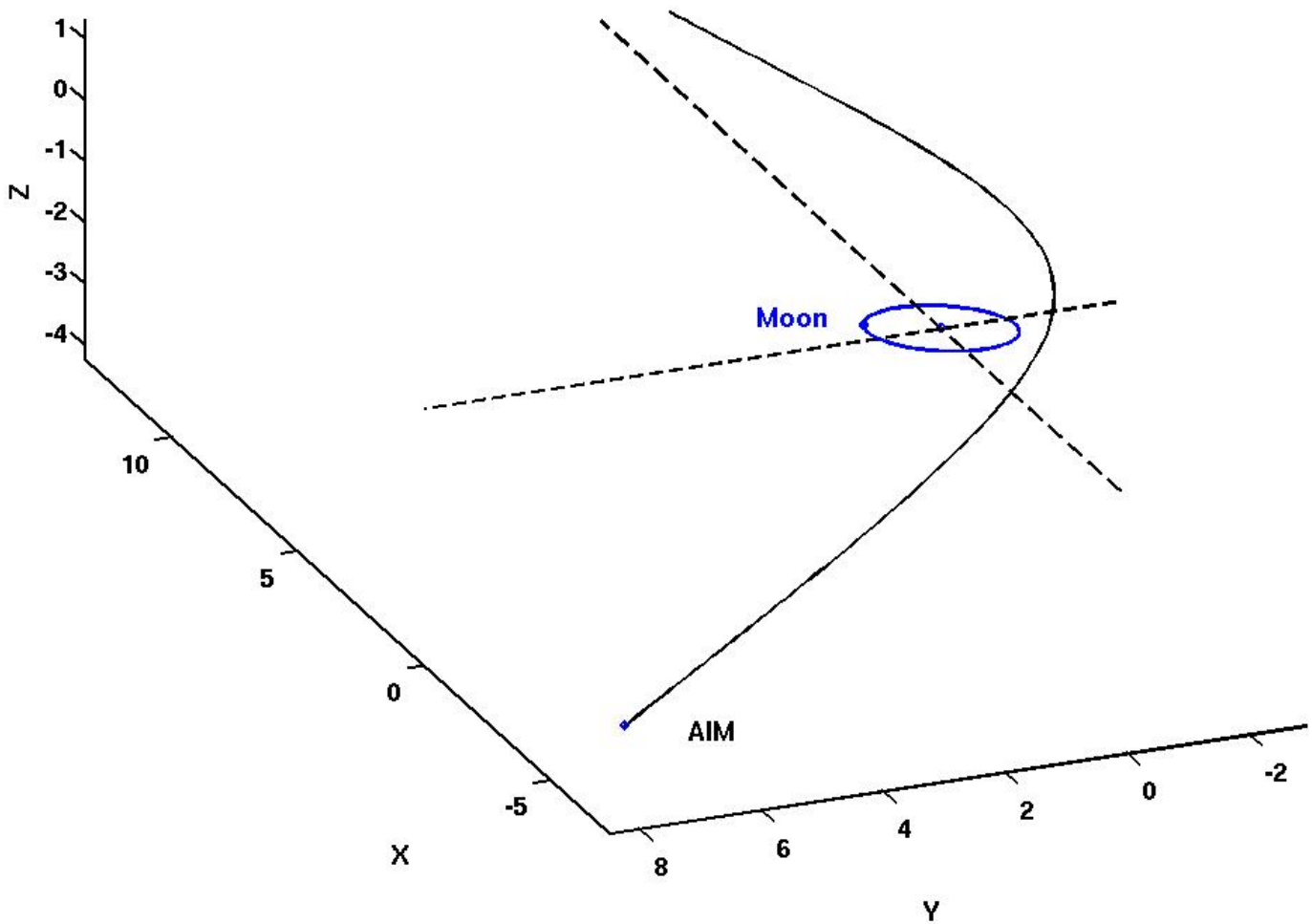
MASCOT-2 Deployment: Didymoon Flyby at 300 m altitude



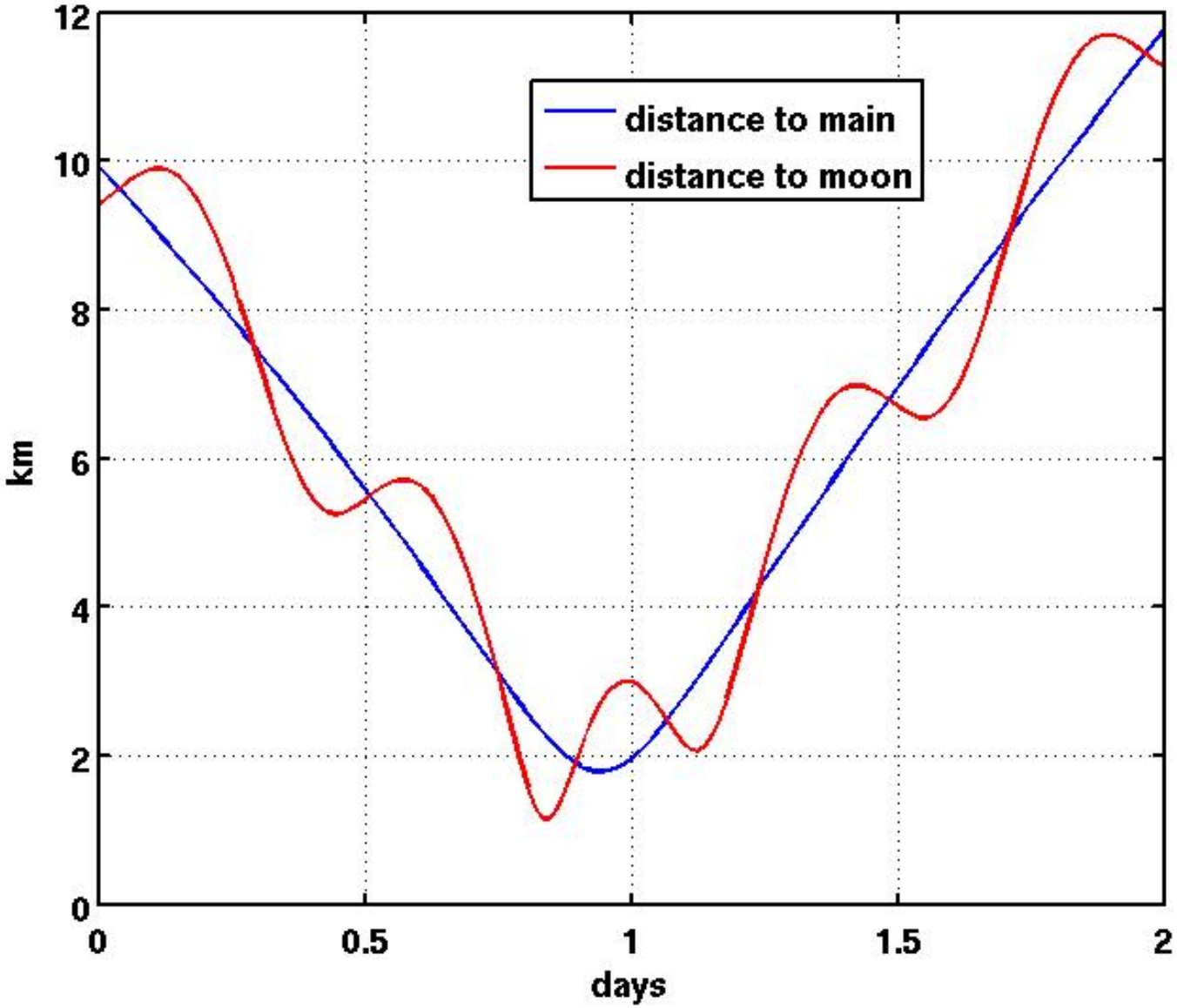
Didymoon Flyby at 300 m, Distances vs Time



MASCOT-2 Deployment: Didymain Flyby at 1500 m altitude



Didymain Flyby at 1500 m, Distances vs Time



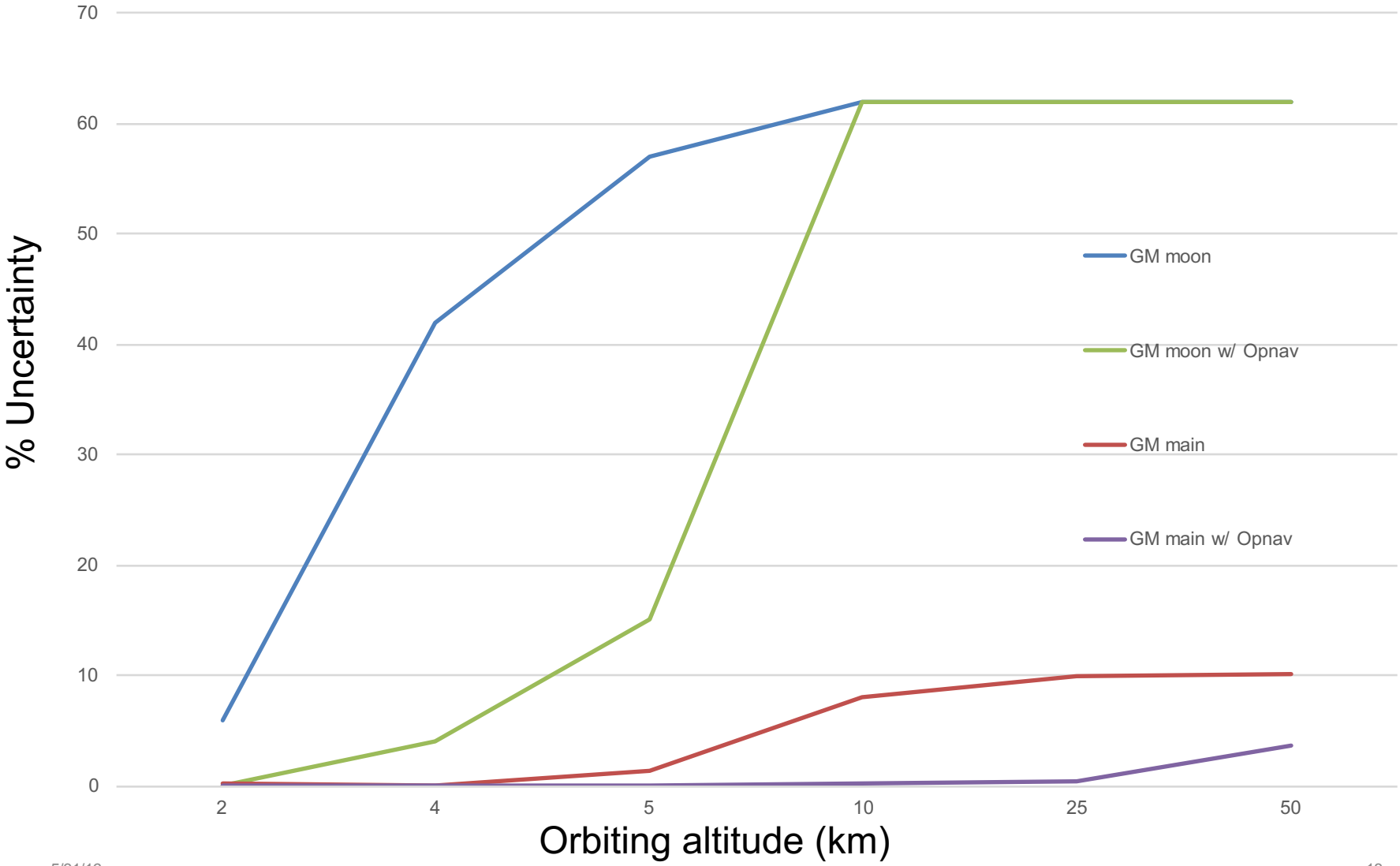
Asteroid component flybys, "clean spacecraft" with 7*8 hrs tracking per week, with/without opnav

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 0.0001 km/s	0.5 km 0.0001 km/s	0.4 km 7e-6 km/s	0.0007 km 02e-8 km/s	0.5 km 9e-6 km/s	0.002 km 5e-8 km/s
Didymoon states (max value)	1.18 km	0.05 km 0.005 km/s	0.05 km 3e-4 km/s	0.03 km 7e-6 km/s	0.05 km 0.002 km/s	0.05 km 6e-6 km/s
Didymos ephemeris		48, 105, 8 km 1e-5, 8e-7, 5e-7 km/s				
GM Didymos	3.5228e-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, -84 deg, 2.26 hrs	20 deg, 5 deg, 0.0002 hrs	Same as apriori	0.02 deg, 0.006 sec	Same as apriori	0.02 deg, 0.006 sec
Didymoon pole RA, Dec, spin rate	310 deg, -84 deg, 11.92 hrs	20 deg, 5 deg, 0.01 hrs	Same as apriori	0.11 deg 0.05 deg 0.002 sec	Same as apriori	0.09 deg 0.04 deg 0.002 sec
J2 main J2 moon		100% 100%	90% 100%	0.7% 92%	96% 100%	0.4% 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 0.0001 km/s	0.5 km 0.0001 km/s	0.5 km 1e-5 km/s	2e-3 km 1e-7 km/s	0.5 km 9e-6 km/s	2e-3 km 6e-8 km/s
Didymoon states (max value)	1.18 km	0.05 km 0.005 km/s	0.05 km 2e-3 km/s	4e-2 km 8e-6 km/s	0.05 km 2e-3 km/s	5e-2 km 6e-6 km/s
Didymos ephemeris		48, 105, 8 km 1e-5, 8e-7, 5e-7 km/s				
GM Didymos	3.5228e-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, -84 deg, 2.26 hrs	20 deg, 5 deg, 0.0002 hrs	Same as apriori	0.02 deg, 0.006 sec	Same as apriori	0.015 deg, 0.006 sec
Didymoon pole RA, Dec, spin rate	310 deg, -84 deg, 11.92 hrs	20 deg, 5 deg, 0.01 hrs	Same as apriori	0.11 deg 0.055 deg 0.002 sec	Same as apriori	0.09 deg 0.04 deg 0.002 sec
J2 main J2 moon		100% 100%	97% 100%	1.4% 98%	96% 100%	0.45% 99%

Asteroid GM Uncertainties vs Orbiting Altitudes, with/without Optical navigation



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DART - Impact Observation from 50 km and 100 km orbit platforms

Simulations Setup – Observation Platform

Uncertainty Assumptions

- Using Didymos ephemeris and apriori covariance from JPL SSD Alain Chamberlain
- Apriori covariance on states, GMs, pole data using 2km terminator orbit case

Spacecraft orbit maintenance

- From 50km and 100km orbiting platform, over 4, 12, and 31 days
- 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

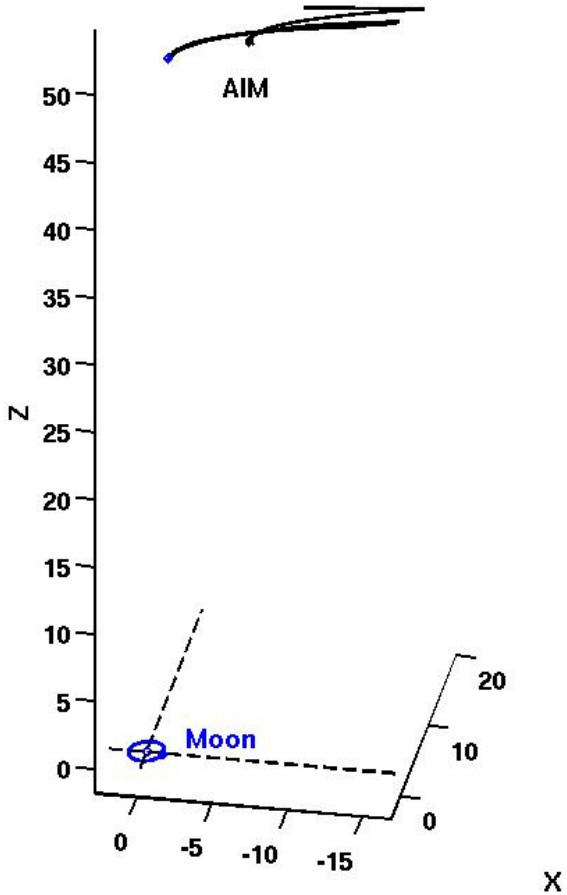
Simulated Data

- Simulated radiometric measurements: 7 per week, 8 hr tracks
- Simulated optical measurements: Didymain landmarks and component centroids
- Pointing uncertainty is not included

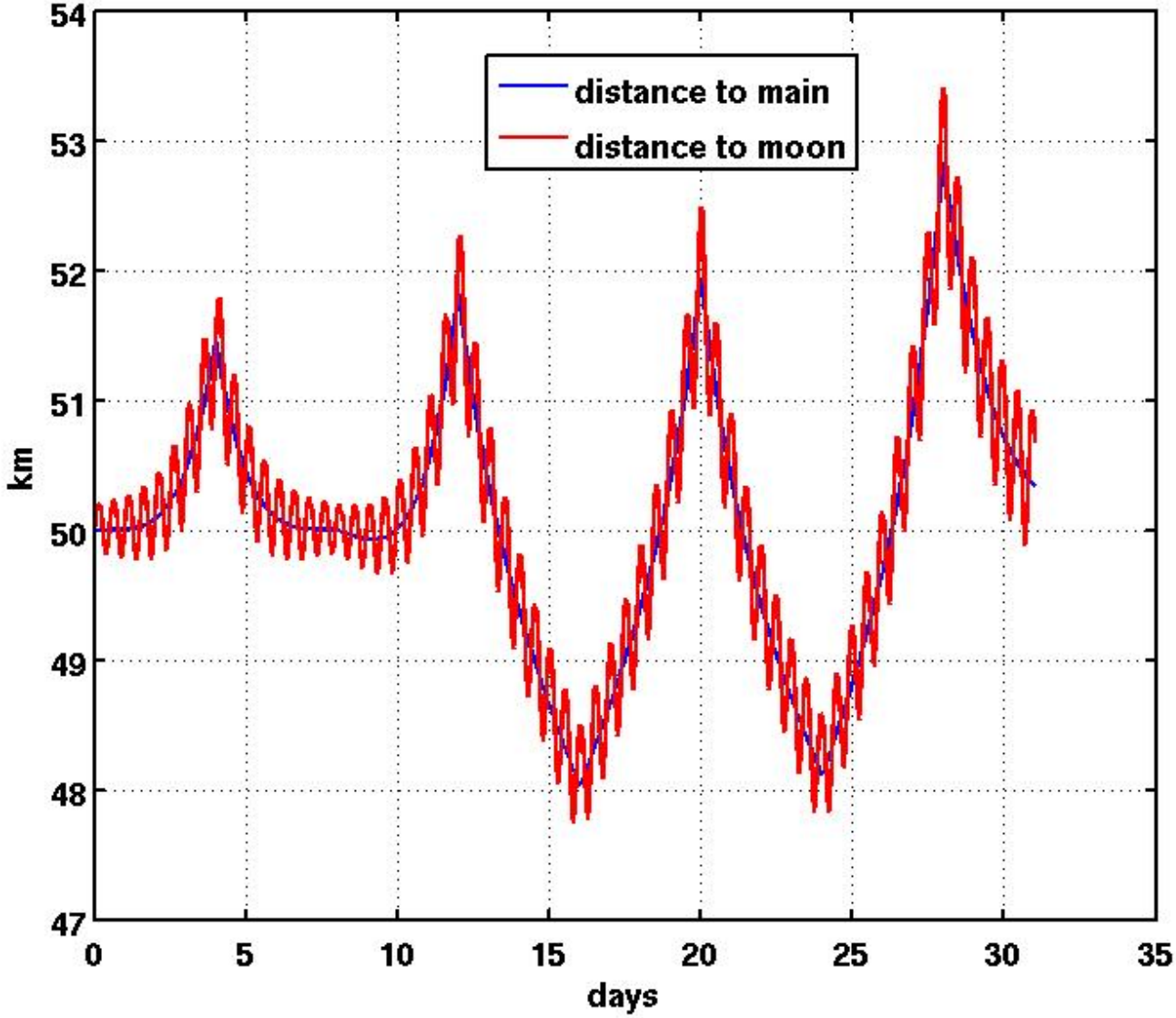
Parameters of Interest

- DV uncertainty in RTN frame: radial and transverse visible from pole observation platform
- Beta uncertainty: take DV uncertainty projected along surface normal at impact location, normalize by impact DV magnitude, obtained for "low", "moderate", "high" excitation (see Eugene Fahnestock study cases).

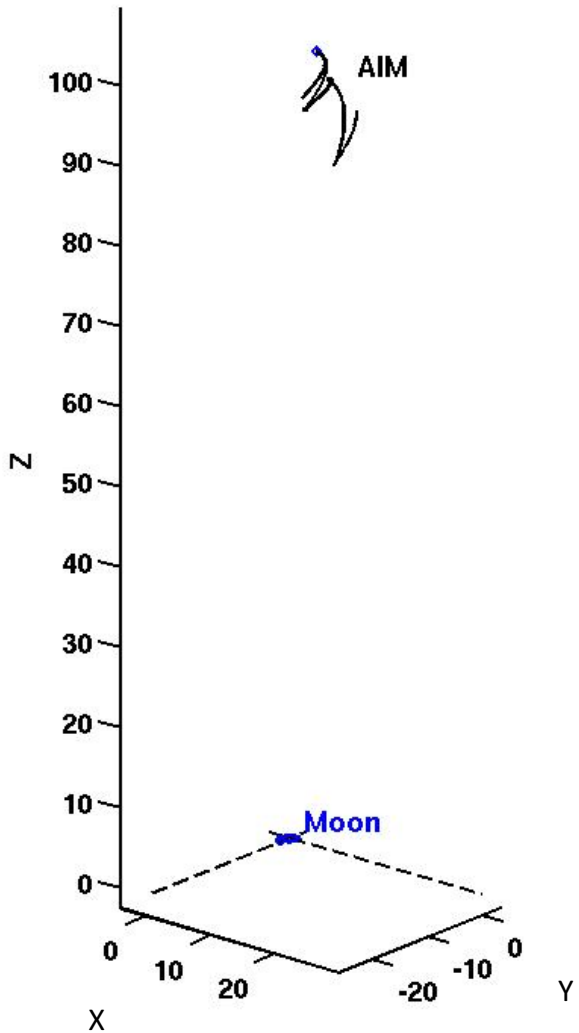
50 km Standoff Orbit



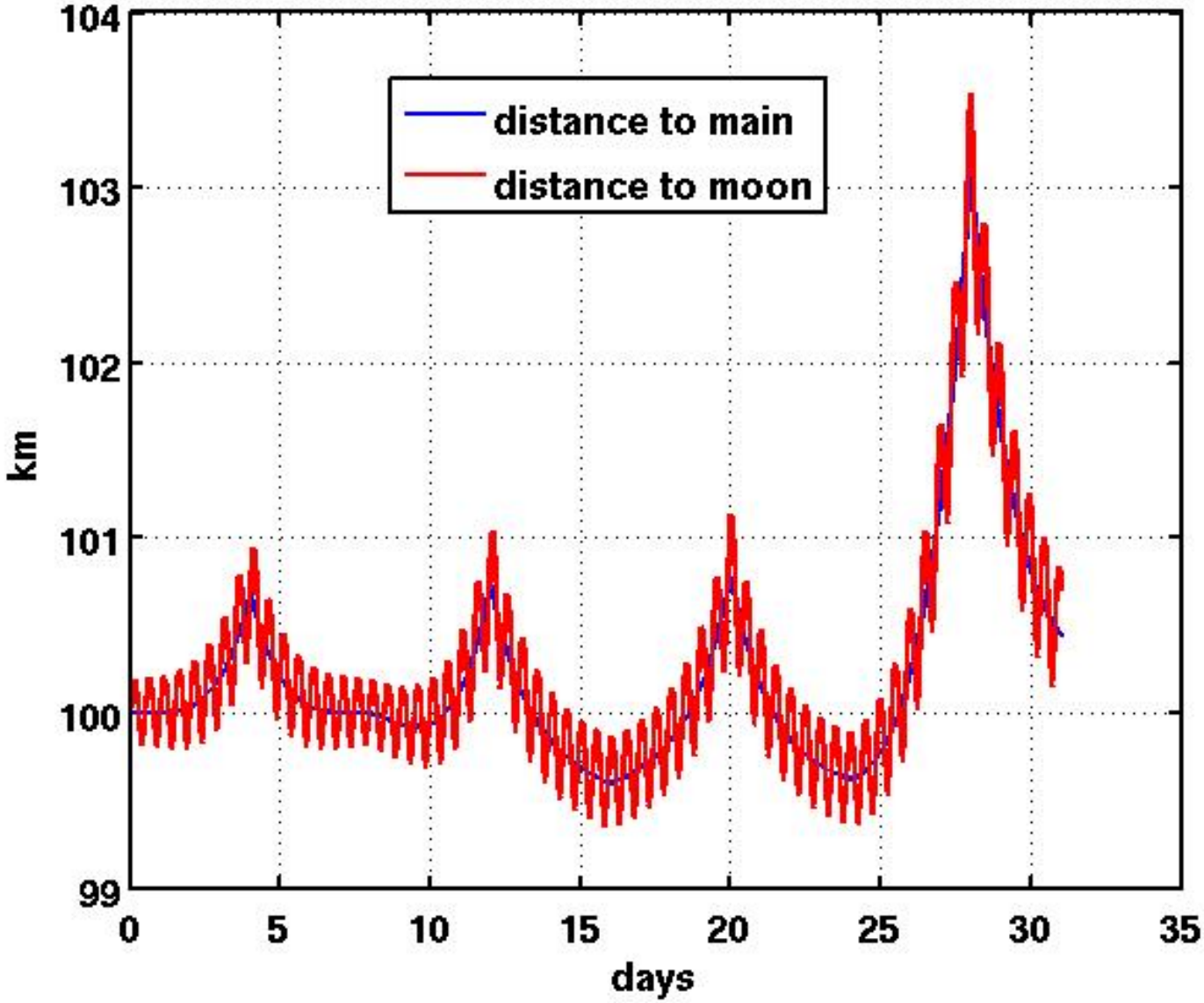
50km, Distances vs Time



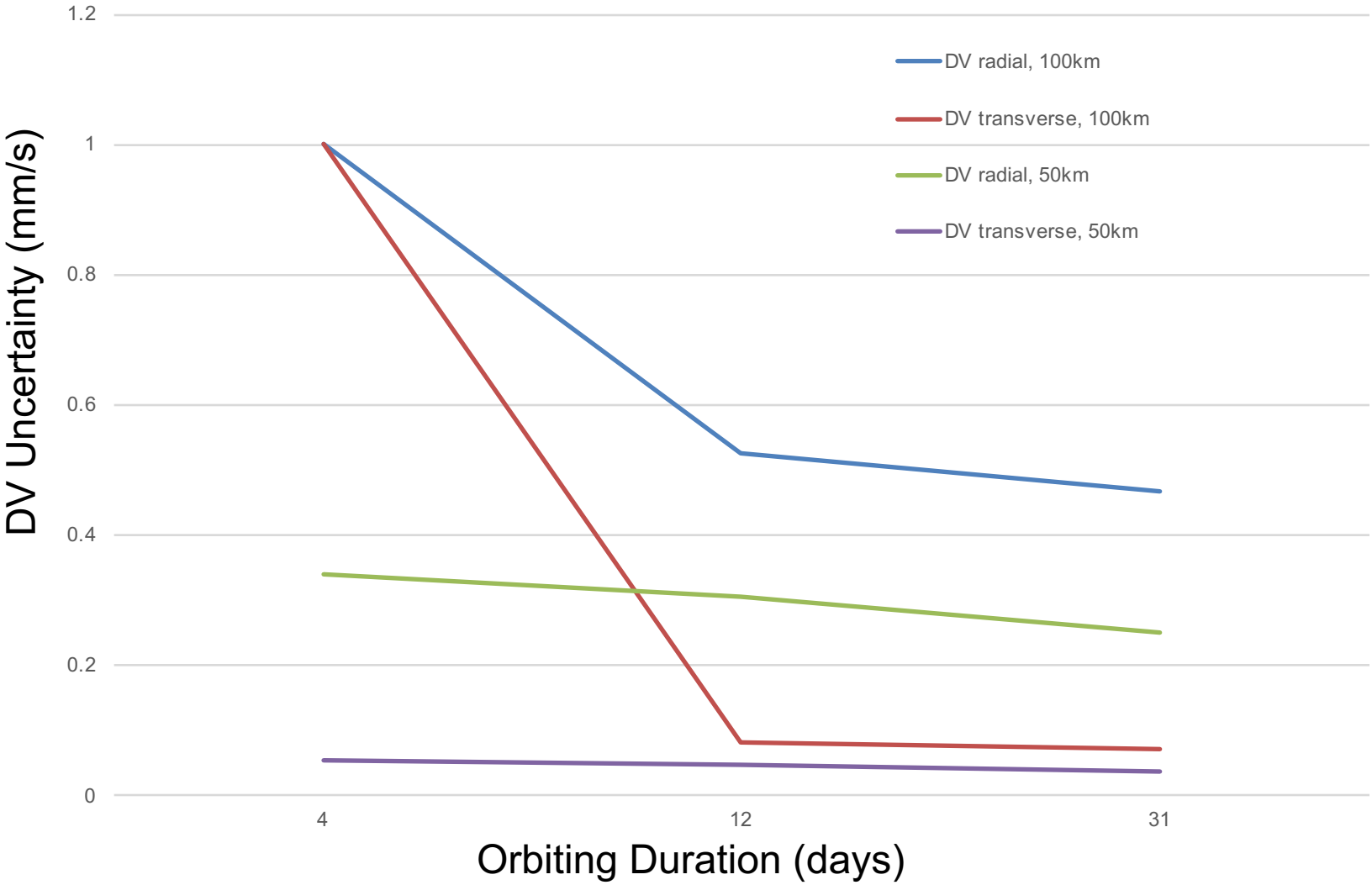
100 km Standoff Orbit



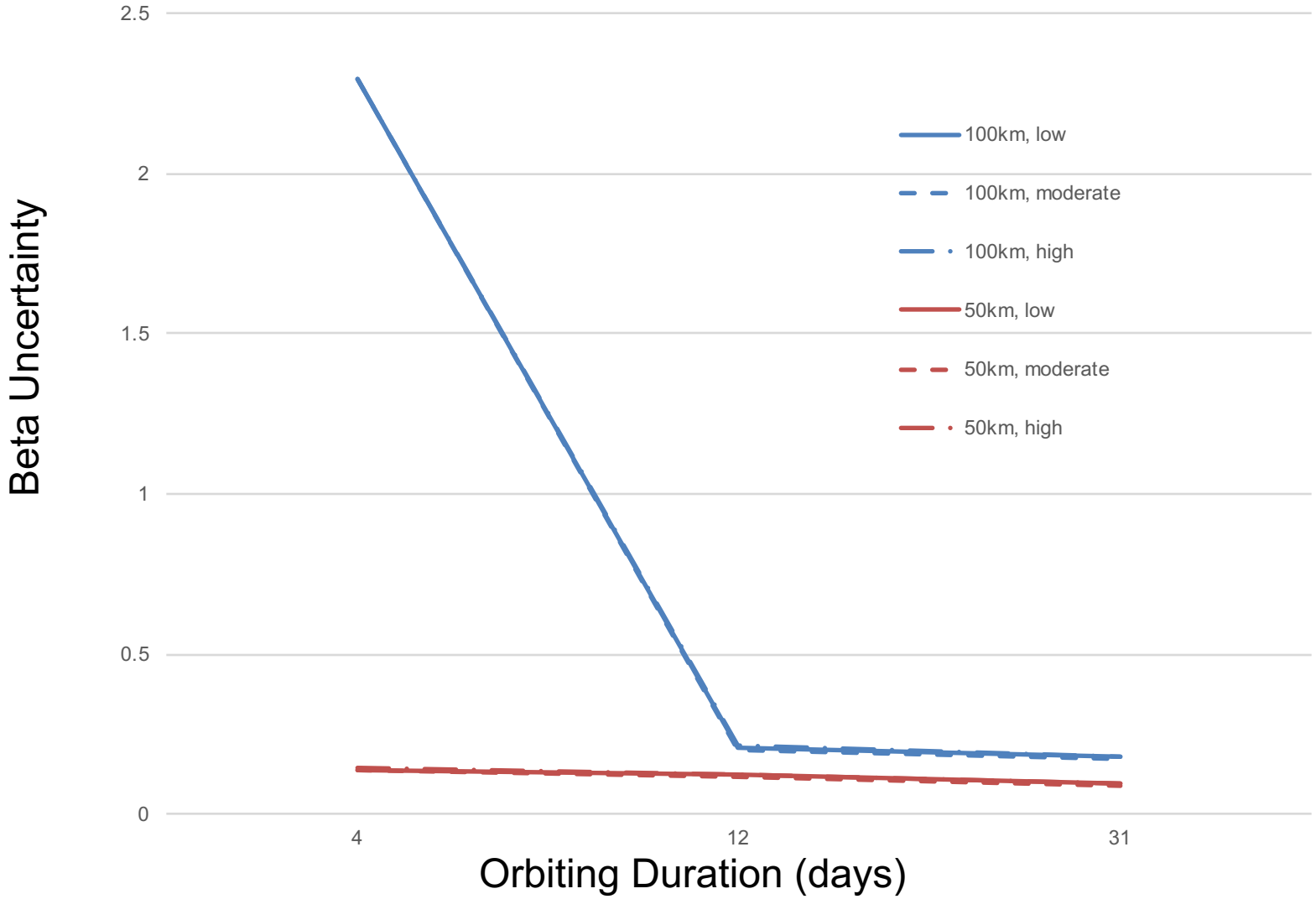
100km, Distances vs Time



DV Uncertainties vs Time for 100km and 50km Orbiting Platforms, with Optical Navigation



Corresponding Beta Uncertainties for Low, Moderate (Beta = 1.2), and High (Beta = 2) Excitation Impact Study Cases (0.43 mm/s impact), for both 100km and 50km Platforms



Conclusions and Future Work

Conclusions

Determined the measurability of Didymos system states, GMs, pole, harmonics uncertainties under "typical" operations conditions.

- Using radiometric and optical simulated data
- Optical navigation is key in determining system parameters

Orbiting altitudes below 5km with Optical navigation give best results for reducing system uncertainties.

- 2km orbit most stable with best results

For DART impact measurability, DV uncertainty down to 0.1 mm/s can be obtained (in transverse direction from a pole observation) with orbiting platform at 50 km

- 0.5 mm/s for a 100 km platform

Future Work

Detailed analysis for DART-induced impact DV measurability as function of stand off orbit duration:

- Up to 90 days, including pole and equatorial standoff locations, other phase angles?
- Include pointing uncertainty

How easy is it to get into a 2 km orbit?

- Long term orbit stability, insertion maneuvering and trim orbit schedule

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Backup slides

Software Configuration

Configuration:

- Epoch: May 15 2022 ET
- Data cutoff: 4, 5, or 12 days
- Radiometric and optical navigation data simulated (8 hr track / day, 1 picture of component / 12 hr with 6 hr offset)
- Data weights:
  - F2: 0.03 Hz, SRA range: 20 RU

Estimated Parameters:

- AIM states, Didymoon states, Didymos ephemeris
- Solar radiation (factor)
- Stochastics used for desats maneuvers (48 hr batches)
- Component GM, pole RA, DEC, spin rate, J2
- DV impact

Consider Parameters:

- DSN Station Locations, media