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AIM RS

Radio Science Investigation with AIM

Executive Summary

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AIM RS: Radio Science Investigation with AIM

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1 Motivation and Goals

The Asteroid Impact Mission (AIM) is a candidate ESA mission to the binary Near-Earth Asteroid (65803) Didymos. While its main objective is to demonstrate new technologies for future deep-space missions, AIM will characterize for the first time a binary asteroid system, providing an understanding of its formation and of the origin of the Solar System. AIM can be conceived as a stand-alone mission, but it is also the ESA contribution to the proposed joint mission AIDA (Asteroid Impact & Deflection Assessment), which includes also NASA's spacecraft DART (Double Asteroid Redirection Test). DART will impact the secondary of Didymos to test and validate the kinetic impactor as a planetary protection strategy and greatly increasing the scientific return of both the missions through the detailed comparison of the Didymos system before and after the impact.

The study of multiple asteroid system is a relatively young field of research, but very important because such objects enable investigations of properties and processes that are difficult to verify by other means. Concerning binary asteroids, the existence has been dubious until 1993, when Galileo spacecraft, during a fly-by, discovered the satellite Dactyl of (243) Ida. Few years later, due to the increasing of ground-based efforts, a satellite around (45) Eugenia was discovered. Since then, many binary asteroids have been found using different observations techniques and now, binaries are known to exist among almost all dynamical classes of minor planets: NEAs binaries are a significant fraction, about 15±4%, of the entire population.

The dynamics of a binary system is extremely complicated, but also very challenging. A fundamental starting point is surely to constrain the shapes of the two rigid bodies. This because the short evolution of the system can in principle be studied using the solutions of the Full Two-Rigid-Body-Problem (F2RBP), but such solutions are strongly dependent about the assumptions on the shape models. Moreover, concerning long term behaviour of the binary, the main effects are the non-gravitational ones, like the the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect and the Binary YORP (BYORP) effect. And both of them, in order to produce a realistic evolution of the system, require a good knowledge of the shapes of the bodies involved. Knowledge which may be acquired with a Radio Science Experiment (RSE) with AIM. Such experiment would also be useful to understand the spin-orbit coupling of the binary.

This study is mainly targeted to performing numerical simulations of a radio science experiment (RSE) with AIM, focused at its precise orbit determination within the Didymos system. The goals of the study are:

- Assess the feasibility of performing Radio Science investigations of the Didymos system with the AIM mission.
- Provide a preliminary evaluation of the experiment performances, in terms of the accuracies achievable in the estimation of the scientific parameters of interest, like the heliocentric orbit of the system, the masses and the extended gravity fields of Didymos and Didymoon, and their rotational states.
- Identify the main driving parameters which affect the performances, providing reference values which maximize the scientific return of the mission.

2 Methodology

A gravity radio science experiment represents a particular application of the orbit determination of the spacecraft: the aim of the orbit determination is to estimate a set of parameters to completely define the past trajectory of the spacecraft and estimate its future evolution. While the focus of the orbit determination, as a part of the more general process of navigation, is the trajectory of the spacecraft, the focus of radio science is the accurate modelling and estimation of physical parameters of interest, such as the gravity field of celestial bodies and their rotational state.

For this reason an approach usually adopted in the data analysis of radio science experiment is the multi-arc approach, in which radiometric data obtained during non-contiguous orbital segments, called “arcs”, are jointly analyzed to produce a single solution of a set of “global” parameters, which do not vary with time. The arcs can be selected to maximize the accuracy and the reliability of the estimation of the global parameters, preferring arcs characterized by a higher information content. As a consequence, the scientific results will be obtained at the end of the mission, by post-processing of all available data, as opposed to the output of the operational orbit determination, which must be as much as possible in “real time”, to safely navigate the spacecraft. Another drawback is that the output of the multi-arc is not a continuous trajectory over the entire time span, but a series of unrelated, non-contiguous trajectory segments: the deterministic coherence of the spacecraft trajectory of the single-arc approach is replaced with a statistical-only type of coherence.

During this study the multi-arc strategy will be adopted for the radio science investigations of the AIM mission, which should be performed during a limited number of hyperbolic arcs connected to a pyramid-like reference trajectory. In particular, the results were obtained considering 8 flybys dedicated to the Radio Science Experiment, with the same AIM-Didymos-Earth relative geometry, to obtain general results. The real AIM Radio Science Experiment may employ a combination of a different number of flybys, with different geometries (e.g. gradually reducing the distance to Didymos). Then, an estimation of the experiment expected accuracy may be obtained combining the uncertainties of the single geometries provided by this study.

The following constraints on the S/C trajectory during radio science arcs apply:

- No optical measurements can be acquired during tracking periods (HGA to Earth). Different sampling frequencies of optical measurements were studied.
- Maximum Sun phase angle to acquire pictures of Didymos: 60 deg. Simulations without the phase angle constraint were also performed, to compare the results.
- No thruster maneuvers.
- The attitude with respect to the Sun must be as much constant as possible, especially near the arc pericenter, to reduce mis-modeling of the Solar Radiation Pressure (SRP) force.

As demonstrated by the recent Rosetta mission, the orbit determination and control of a spacecraft in the vicinity of a small body, like an asteroid or a comet, is a very challenging problem because of the weak gravity accelerations exerted by the body and the consequently relatively large non-gravitational disturbances.

Given the typical small relative velocities and accelerations near Didymos system, the classical Doppler measurements, usually adopted as main observable in the interplanetary orbit determination process, provide a limited information content. Hence, the spacecraft navigation must be enhanced by means of additional observations, like optical measurements obtained by the onboard cameras. When aiming at a distant target, the picture of a body provides its relative direction with respect to the spacecraft, in the camera frame (centroid). When near, the camera may be used to identify optical features on the surface of a body (landmarks), allowing to better estimate also its rotational state.

However, the optical measurements are affected by a scaling symmetry, because they do not provide direct information about the relative distance with respect to a body: the same optical measurements can be obtained changing the distance AIM-body and the size of the body by the same scale factor. The scaling symmetry affects also the estimation of the body mass: in the approximation of the two-body problem, the same orbital motion can be obtained changing the body mass by the third power of the scale factor.

Additionally, in a binary system the optical measurements provide also the accurate relative positions of the two bodies, posing a strong constraint on their relative orbital motion. In particular, the relative orbital motion provides information about the total mass of the system. Moreover, if the mutual orbital motion is measured with respect to the common center of mass, which is inertially fixed, the mass ratio can be obtained. In particular, the inertial motion of the secondary provides information mainly about the mass of the primary, and vice versa. For a binary system the scaling symmetry: the same optical measurements can be obtained changing the distance AIM-system, the distance primary-secondary, and the size of the bodies by the same scale factor.

The scaling symmetry can be broken using additional measurements, like Doppler and range, which provide absolute measurements of velocity and distances with respect to the Earth, and a priori information about the parameters.

Numerical simulations of a radio science experiment consist of performing the same orbit determination procedure that will be implemented in the analysis of real data, but using simulated data, usually generated by the same orbit determination program. The use of a realistic setup and assumptions allow to infer, before the execution of the experiments, the expected accuracy on the estimation of scientific parameters of interest. Moreover, controlling the dynamical model used to generate the simulated measurements, it is possible to provide a better understanding of the effects of the main design parameters which affect the performances of the experiment.

In this work the same models are used to compute the simulated observed and computed measurements, performing a so-called “covariance analysis”. The output of a covariance analysis is useful to compare different solutions, obtained for example using different orbital geometries, coverage assumptions, filter setups. However, the real uncertainties associated to estimated parameters are usually larger than the formal values provided by the orbit determination, because it does not take into account possible estimation biases due to errors in the dynamical model, linearization errors, colored measurement noise and other effects. For this reason, in the numerical simulations of AIM Radio Science Experiment a series of conservative assumptions were made in order to obtain more realistic estimation uncertainties:

- The adopted Doppler measurement noise is larger than the expected level by a factor of 2.
- The adopted Optical measurement noise is larger than the expected level by a factor of 10.
- The a priori uncertainties on the non-gravitational accelerations are larger than the usually adopted values by about a factor of 10.

The simulation procedure adopted during this study is the following:

A. Setup of the dynamical and measurement models.
B. Generate simulated observed measurements, for each experiment arc:
    1. Compute Didymos system’s trajectory within the Solar System as a solution of a Restricted 2-Body Problem with the Sun.
    2. Compute Didymos secondary trajectory around Didymos primary numerically integrating the equations of motion.
    3. Compute Didymos primary trajectory around Didymos system’s center of mass given the trajectory of Didymos secondary around the center of mass and the heliocentric trajectory of Didymos system’s center of mass.
    4. Compute spacecraft’s trajectory with respect to the Didymos system numerically integrating the equations of motion.
    5. Computation of simulated observed measurements (observed observables), assuming the measurement models, the observation schedule and the noise levels.
C. Multi-arc orbit determination:
    1. Computation of simulated measurements (computed observables) following the same procedure as in point B.

2. Generation of pre-fit residuals as (simulated) observed minus computed observables. Because the same model is adopted for the two set of measurements, the residuals are given by the sum of the simulated noise and the numerical noise.
3. Filter setup: definition of a priori covariance, stochastic properties, and local and global parameters. Global parameters do not vary with time and affect the measurements of all the arcs, while local parameters affect only the measurements of one arc.
4. Multi-arc least squares filter to compute the estimated value and the covariance matrix of a set of solve-for parameters. Because the same model is adopted for the two set of measurements, the solution must be statistically compatible with the a priori values adopted in the simulation.

3 Main Results

The main result of the numerical simulations is that the AIM gravity science experiment at Didymos proved feasible, using realistic assumptions on the technological capabilities of the space and ground segment. Shorter pericenter distances increase the attainable accuracy, but good results can be obtained at large distances using optical navigation images.

In particular, a summary of the formal uncertainties achievable in the estimation of main parameters of interest is provided in Table 3.1, for different AIM-Didymos distances, using both Doppler and optical measurements (with a phase angle constraint of 60 deg). Three cases were studied in details:

- Approach (rp = 35 km): this case provides a reference solution for long distances operations, as during the Early Characterization Phase of the AIM mission. Being outside the sphere of influence of Didymos for the entire duration of each arc, the Doppler observables are expected to provide low information content about the gravity fields of the bodies.
- High Flyby (rp = 10 km): this case provides a reference solution for medium distances operations, as during the Detailed Characterization Phase of the mission. Being near the boundary of the sphere of influence of Didymos the Doppler observables are expected to provide a certain information content about the gravity fields of the bodies.
- Low Flyby (rp = 2 km): this case provides a reference solution for short distances operations, as during the payload deployment phase of the mission. Being inside the sphere of influence of Didymos the Doppler observables are expected to provide a large information content about the gravity fields of the bodies.

Table 3.1 Summary of best formal uncertainties achievable by the AIM Radio Science Experiment. Three cases are compared: 1) Approach: pericenter distance of 35 km; 2) High Flyby: pericenter distance of 10 km; 3) Low Flyby: pericenter distance of 2 km.

Parameter		Approach (rp = 35 km)	High Flyby (rp = 10 km)	Low Flyby (rp = 2 km)	Comments
Spacecraft Position (m)	**Radial**	320 (0.9%)	7.7 (<0.1%)	0.54 (<0.1%)	Approximate radial uncertainty at C/A epoch with respect to Didymos primary (average over arcs). Reference value for relative uncertainty:

					pericenter radius.
Didymos Secondary Position (m)	**Radial**	11 (0.9%)	1.1 (<0.1%)	0.55 (<0.1%)	Approximate radial uncertainty at C/A epoch with respect to Didymos primary (average over arcs). Reference value for relative uncertainty: 1.2 km.
Didymos GM (km^3/s^2)	**Primary**	7.0 x10^{-10} (2%)	5.9 x10^{-11} (0.2%)	1.8 x10^{-11} (<0.1%)	
	Secondary	1.4 x10^{-11} (4%)	5.1 x10^{-12} (1.6%)	3.2 x10^{-12} (1%)	
Didymos Frame (deg)	**Primary Pole**	0.25	0.07	0.13	RSS of RA and DEC uncertainties. Didymos frame not estimated during approach because the distance from Didymos is considered too large to observe landmarks.
	Secondary Pole	N/A	0.37	0.42	
	Secondary Libration	N/A	0.03	0.04	Libration amplitude at orbital period. Not estimated during approach because the distance from Didymos is considered too large to observe landmarks.
Didymos Landmarks Position (m)	**Primary**	4.0 (1%)	3.5 (0.9%)	4.0 (1%)	RSS of 3-d position uncertainty. Approximate average values over all landmarks. Reference values for relative uncertainty: average radii (primary: 390 m; secondary: 81.9 m). Didymos secondary landmarks not estimated during approach because the distance from Didymos is considered too large to observe landmarks.
	Secondary	N/A	1.3 (2%)	1.2 (1%)	

To compare the different measurement strategies a set of simulations were performed, with the following procedure: for each measurement strategy and for each pericenter radius, a set of simulations are performed covering all the possible orbital planes, and the best uncertainty is selected. Different pericenter radii are compared.

The following measurements strategies were compared, to assess the information content provided by Doppler and Optical Navigation (OPNAV) images:

- Doppler: only Doppler measurements are processed, acquired at the beginning and end of the arc, and around the C/A (base coverage).

- Doppler (full): only Doppler measurements are processed, assuming a continuous coverage of the tracking stations.
- Optical: only optical measurements are processed, acquired during the entire arc duration. No Doppler measurements are collected, so the number of optical measurements is larger than Doppler+Optical strategy.
- Optical (phase): only optical measurements are processed, acquired during the entire arc duration, with a phase angle constraint of 60 deg. No Doppler measurements are collected, so the number of optical measurements is, in general, larger than Doppler+Optical (phase) strategy.
- Doppler+Optical: both Doppler and optical measurements are processed, assuming the base coverage for Doppler. The optical measurements are acquired between the tracking passes.
- Doppler+Optical (phase): both Doppler and optical measurements are processed, assuming the base coverage for Doppler. The optical measurements are acquired between the tracking passes, with a phase angle constraint of 60 deg.

The formal accuracy of Didymos primary and secondary GMs, as a function of the orbital plane, are represented in Figure 3.1 and Figure 3.2, respectively.

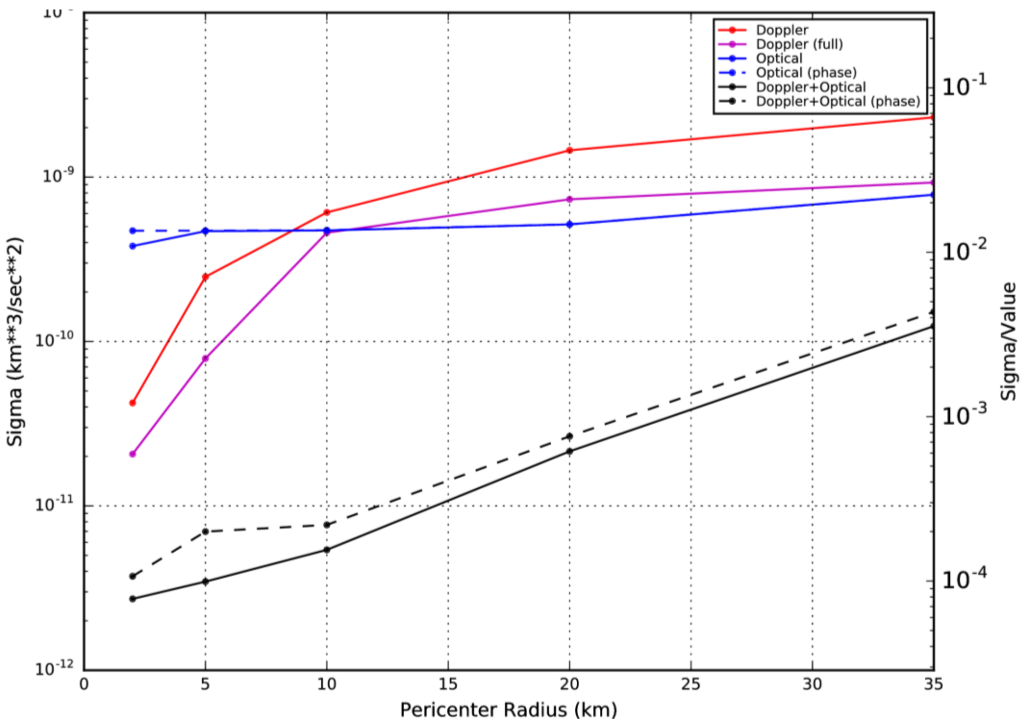

Figure 3.1 Measurement strategies comparison: Didymos primary GM formal uncertainty vs pericenter distance. For each pericenter distance the minimum uncertainty over all the possible orbital planes is displayed.

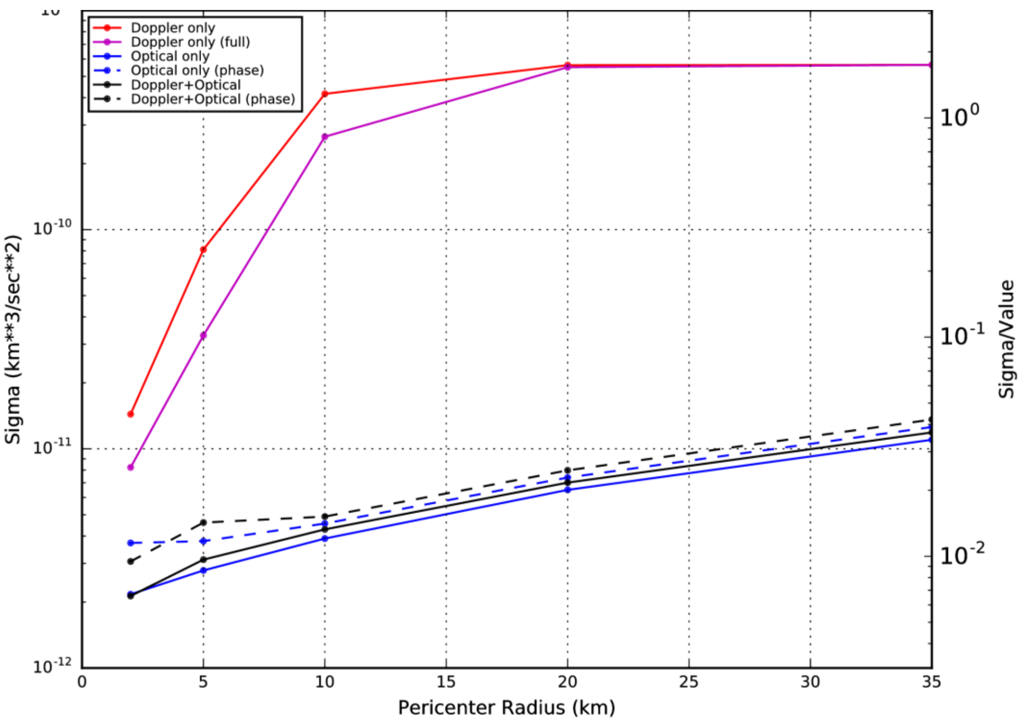

Figure 3.2 Measurement strategies comparison: Didymos secondary GM formal uncertainty vs pericenter distance. For each pericenter distance the minimum uncertainty over all the possible orbital planes is displayed.

As a result, OPNAV images proved to be crucial to improve the estimation accuracy of the scientific parameters of interest.

In particular, the information about the GM of Didymos primary is provided by both Doppler and optical measurements. The Doppler shift provide a measurement of the bending of the trajectory of AIM due to the gravity of the Didymos system, while OPNAV images provide a measurement of the primary GM reconstructing the orbital motion of the secondary. Hence, Doppler measurements are better for distances smaller than 8-10 km, when AIM enters the system sphere of influence and it experiences a significant delta v during the arc, while for larger distances the optical measurements are better. The best accuracies are obtained using both Doppler and OPNAV images, so that the formal uncertainty decreases by more than a factor 10, with respect to Doppler only and OPNAV only.

On the other hand, the GM of Didymos secondary is estimated mainly from optical measurements of Didymos primary, i.e. observing the wobble of the body around the common center of mass due to the mutual orbital motion, while the gravitational effect on AIM, measured by Doppler, is significant only for distances smaller than 5 km. For distances larger than 5 km the best results are obtained with optical measurements only. However using both Doppler and optical measurements the formal uncertainty increases by less than 10%, while the estimation is more reliable and robust (e.g. to a constraint in the phase angle).

In general, the implementation of the phase angle constraint on the acquisition of OPNAV images does not prevent reaching the required level of accuracy.

A series of parametric studies were performed to study the sensitivity of the performances of the Radio Science Experiment to different parameters like the orbital geometry, the arc length, the time scale of the variation of the non-gravitational accelerations, the Doppler noise level, the sampling frequency of the optical measurements, and the number of landmarks. As a result the main factor driving the estimation accuracy is the orbital geometry. Then, if a good geometry is chosen, the uncertainties are stable with respect to the other parameters, especially if both Doppler and optical measurements are used.

Finally, the ground segment needs to perform the AIM Radio Science Experiment were evaluated. The ground segment participates to the AIM Radio Science experiment in two ways: to generate radiometric observables by tracking the AIM spacecraft during dedicated passes, and to download additional data which are needed for the orbit determination process, like spacecraft telemetry and pictures to be used as optical measurements.

Regarding the generation of radiometric observables, the operational requirements are qualitatively the same as during classical navigation operations. The scientific return can be maximized minimizing the noise on radiometric observables, to improve the estimation uncertainties. The current capabilities of ESA Deep Space ground stations are sufficient to meet only the worst Doppler performance target assumed during this study. To improve the end-to-end Doppler noise levels the following ground station enhancements must be made: implementation at ESA stations of a water vapor radiometer-based calibration system to remove the effects of Earth's wet troposphere by about 80-90% (currently in development); addition of Ka-band transmit capability (currently in development). However, the numerical simulations showed that the experiment performances are relatively insensitive to the noise level on Doppler measurements.

On the other hand, the numerical simulations of the Radio Science Experiment showed that the performances are dramatically improved using optical observables. The optical measurements are obtained by the onboard cameras: the pictures collected during the radio science experiment must be transmitted to the Earth, where they will be processed and used in the orbit determination procedure. Hence, increasing the transmission data rate is crucial for the Radio Science Experiment, allowing the acquisition of a larger number of optical measurements, and consequently increasing the stability and accuracy of the estimation. Moreover, increasing the data rate would increase the scientific return of the entire AIM mission. To obtain an higher data rate using a classical radio link two strategies may be implemented: increase the carrier frequency of the signal: switching from the classical X-band to the Ka-band would allow to increase the data rate by a factor 2 to 4; use an antenna with a larger gain: using an antenna with a diameter of 64 m, such as the Sardinia Radio Telescope, would allow to increase the data rate by a factor of about 2, with respect to a baseline ESA DS antenna (factor of 3 if both the baseline and large antennas are used).