LOW-THRUST: THE FAST & FLEXIBLE PATH TO APOPHIS. S. Chand[1]*, J. T. Grundmann[1#], [1]DLR German Aerospace Center, Institute of Space Systems, Robert-Hooke-Strasse 7, 28359 Bremen, Germany, * Suditi.Chand@dlr.de, #jan.grundmann@dlr.de.

Introduction: By the time of Apophis' fly-by on Friday, April 13th, 2029, more satellites than have ever been launched since the beginning of the space age to this day will reach low Earth orbit (LEO). Almost all of them will be microsatellites of less than ≈250 kg equipped with solar-electric propulsion (SEP). [1]

Proposed Missions to Apophis At this conference, several missions to Apophis are proposed.

Apophis Express leverages the high performance of a SLS Block#1 launch vehicle to insert a payload of up to 25 t into a near-escape orbit that then brakes by 6.1 km/s to rendezvous, grab a sample, and transfer it to Earth by re-entry capsule. [2]

A Remote-Sensing Small Spacecraft Mission carrying lidar, imagers, bolometers, and a deployable set of laser reflector arrays to be dropped on Apophis is proposed by Smith et al. Launching in 2026, it cruises for ~20 months to then operate at altitudes of 1.2 to 0.5 km for several months before moving out to a more distant location for long-term monitoring after the encounter. [3]

A Radar Package is proposed by Herique et al. [4] based on work for the AIM and HERA missions which use nano-scale sub-spacecraft landing (cf.[5]) or orbiting in the vicintity of their target, (65803) Didymos S1, a.k.a. 'Didymoon'.

Apophis Pathfinder is a quick fast-fly-by mission of two, <50 kg class spacecraft to see Apophis soon from close up, envisaged to lanch in 2022/23 and arriving within a year. [6]

OSIRIS-REx has likely sufficient resources to use the return of its samples in September 2023 for an Eath gravity-assist to rendezvous with Apophis in the days of its encounter with Earth. [7]

Reconnaissance of Apophis (RA) is a small, ~180 kg spacecraft mission envisaging to launch in early 2024 for a 'slow' fast fly-by in 2026 followed by rendezvous in the summer of 2028 to stay all the way through the Earth encounter. It uses SEP. [8]

PHACE is a 6U cubesat mission launching on the day of closets approach to chase after Apophis for a 120-day post-encounter mission. It leaves Earth at a high departure velocity which is challenging to achieve with COTS cubesat SEP thrusters. [9]

Low-Thrust Technology Options SEP has become a mainstram propusion method also for exploration missions, e.g. the JAXA mission HAYABUSA2. After the first interplanetary solar sail, IKAROS, also by JAXA, solar sailing has made recent advances towards small spacecraft solutions, e.g. the recently launched LIGHTSAIL-2 and the NEA SCOUT nearing a rideshare launch on a lunar mission. DLR has qualified solar sail technologies in the GOSSAMER-1 project [10,11] and adapted these for large photovoltaic arrays needed by SEP in the follow-on GOSOLAR project designed for smallsat bus systems like the in-house studied S2TEP concept. [12]

Concept of an Easier Approach: Experience from these projects and studies, in particular within the framework of the GOSSAMER Roadmap to Solar Sailing mission studies [13-16] has shown that the effort to develop, trade design options and optimize the related treajectories of low-thrust spacecraft is not insignificant, in particular for the early study phases of planetary missions. Once small spacecraft are envisaged with the intention of using low-cost secondary passenger "piggy-back" launch opportunities, the problem becomes more complex. On the trajectory analysis side it becomes necessary to patch an uncertain lauch date of e.g. a GTO rideshare option to an optinized interplanetary trajectory starting from the common Earth escape condition, c3 ≈ 0. On the spacecraft side, small spacecraft benefit more from careful optimization and 'organic' integration of their subsystems which can be achieved by dedicated design or/and careful selection of off-the-shelf devices. (cf. [17-21])

Apophis is a special case because many missions have been proposed already, and it remains a popular 'poster case' target for mission analysis work related to near-Earth asteroids (NEA) or planenetary defense. Therefore it is possible to compile results from this body of work to create a trade space relating possible launch dates, arrival dates, and required spacecraft performance to achieve these already published trajectories. On this canvas, a proposed mission concept or spacecraft design can be evaluated quickly with regard to its launch windows and flexibility in case of delays. Conversely, the low-thrust mission analysis community can use the expected performance of spacecraft designs still in their early phases to focus their own effort to generate viable trajectories for these missions. An optimal way to facilitate this iteration and proceed quickly with the design of proposed missions to Apophis is to bring the communities together in direct and instant communication in a Concurrent Engineering Facitlity (CEF). [22-24]

Conclusion: Regarding the missions proposed to investigate Apophis before, during and after its close encounter with Earth, it appears beneficial to consider low-thrust, high delta-V propulsion. SEP has become the most frequently applied method but also solar sailing may offer interesting capabilities. [25] To enable quick design trades and to move ahead with the design trades and optimizations in early study phases of Apophis rendezvous and soonest-fly-by missions, the use of already published or computed trajectories appears useful.

Acknowledgments: The concept of a trajectory catalog grew from our work related to the DLR projects MASCOT, MASCOT2, GOSSAMER-1, GOSOLAR, and their follow-ons which all started with studies in the CEF at DLR Bremen. It was propelled forward at the International Symposium on Solar Sailing (ISSS) 2019 in Aachen, Germany.

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