ASTEROIDSQUADS/*i*SSB - A SYNERGETIC NEO DEFLECTION CAMPAIGN AND MITIGATION EFFECTS TEST MISSION SCENARIO

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INTRODUCTION

The past two decades have brought great progress in cataloguing Small Solar System Bodies (SSSB). Currently, ~90% of Near Earth Objects (NEO) larger than 1 km diameter (Ø) are known, as well as a significant fraction of those down to Ø 140 m classified as Potentially Hazardous Objects (PHO). Almost all such objects are Asteroids (NEA, PHA), with only a few Comets (NEC, PHC) among them. [1] Although the risk of impact can not be changed by knowledge alone, the risk of surprise by large impactors of global significance has largely been retired in terms of average victims per year. Objects of sizes below the global or severe regional effects threshold but larger than Ø 20 m, of which the vast majority is yet to be discovered, pose a secondary but very significant part of the residual risk. [2] Smaller impacts also occur at shorter average intervals between events of the same size, and their effects per event become more localized and atmospheric shielding becomes progressively more efficient towards smaller impactors. The total impact energy release of such objects is on the order of 1 MtTNT or higher, of which a significant fraction couples to the surface at destructive intensity. [3,4] For all these object classes, the level of destruction on the ground only depends on the location hit by any given object, and the number of victims can be very high for a single event. [5] NEOs and PHOs by definition frequently experience close encounters with at least one of the terrestrial planets, which amplify all previous uncertainties in orbit determination by orders of magnitude. The interval for which an impact can be predicted at high likelihood with high confidence is thus limited to a few decades unless the object is locked in an orbital resonance. [6,7,8] Impact prediction requires at least one encounter within the detection range of Earth-based assets. In case radar measurements are not feasible, two encounters are required for sufficient orbit determination. [9] Unless this encounter is the terminal leg before impact on which timely detection becomes increasingly difficult, [10] the lower limit of the predictability interval is the synodic period. Except for objects in orbits very similar to Earth's, it is of the order of a few years. [9][11] Objects carrying the residual risk of surprise for rare large impacts as well as the more frequent small impactors of or below PHO size are therefore most likely to be discovered or recognized as an impending hazard within this interval before impact, if at all. Interplanetary cruise durations for rendezvous slow-push deflection campaigns are comparable unless the object is in a favourable orbit similar to those selected as scientific mission targets, with or without planetary gravity-assist fly-by opportunities. [11,12] Mitigation campaigns against large objects also require a large number of impulse or slow-push interceptor spacecraft, also due to uncertainties about high-energy deflection methods. Large numbers of relatively large interplanetary spacecraft may have to be spread over more synodic launch windows due to limitations of existing deep space flight support and high-performance launch vehicle infrastructures.

MOTIVATION

The mission scenario ASTEROIDSQUADS was developed in response to Recommendations from the 1st IAA Planetary Defense Conference (PDC'09). [13] In the field of deflection technologies, it was recommended that "• *Deflection-related testing should be included as part of science missions [...] to increase information relevant to the mitigation process. • Additional studies should be conducted to understand and quantify the momentum transferred to comets and asteroids by impulsive deflection techniques (kinetic impact and standoff, contact, and sub-surface explosions). • Fund research and conduct flight experiments to characterize and refine the effectiveness of Kinetic Impact as a deflection technique. [...]*" For the area of ground-based civil defence, it was recommended to "• *Develop protocols for providing timely warnings to responsible entities in the event that even a small NEO is detected shortly before impact. • Conduct and report [...] on a simulation of a NEO impact disaster and/or a NEO warning involving appropriate agencies at the international level.*" Several more recommendations put dangerous objects smaller than the current threshold definition for PHO status in focus. Throughout, the need for increased international participation was emphasized.

Also, programmatic mission selection requirements at the inception of the DLR R&D 'Kompaktsatellit' national small satellite programme demanded and accepted scientific and engineering challenges pushing the limits of current technology to obtain new insights, on an international level, and including inter- and transdiscliplinary cooperation encompassing various branches of scientific and engineering research as well as institutional and industrial partners.

TURNING INTEREST GROUP CONCERNS INTO STAKEHOLDER REQUIREMENTS

The two key sets of recommendations from the NEO science and planetary defence communities are however met by concerns from other fields relevant to the wider development of spaceflight. *Political concerns* include • the long-term weaponization risk, i.e. a deflection campaign may be covertly designed to hit Earth based on methods tested before; • dual-use potential of required technologies in fields restricted by international treaties, e.g. missile defence and anti-satellite weaponry; • perception of deflection tests as preparatory to the use of restricted non-conventional high energy methods in space; and • the perception of practical tests of planetary defence methods as the thin end of a very expensive wedge leading ultimately to standing defence installations, requiring permanent maintenance efforts, and potentially creating risks exceeding those of impacts on human timescales. [14] *Public or published concerns* frequently result from natural *cognitive biases* affecting recipients of popular science media coverage of the incomprehensible range encompassing extinction-level events on geological timescales as well as impressive but harmless fireball sightings every few months that nevertheless release energy on a ktTNT scale. They include • the perception of NEOs as a retired risk, either extended from reported completeness of surveys for km-class objects and their perceived exclusive relevance as global killers, or by inferring that recent missions such as Deep Impact or Hayabusa already demonstrate viable deflection methods; • the natural denial of risks related to extremely rare events of extremely high hazard which are related to a vast population of risk carriers; and • the preconception that the understood technical challenges of deflection and the possible lack of warning time always combine into an insurmountable task beyond the means of humanity, when in fact among major natural disasters the NEO hazard is the one for which we have the best prospects for prediction and mitigation. [15] The space segment of these methods includes the launch and operation of interplanetary spacecraft, and knowledge of the interplanetary environment. *Technical concerns regarding heavy launch vehicles* not restricted to but also affecting interplanetary spaceflight include • the high cost of pure test and qualification launches; • the resulting pressure to carry commercial payload already on early or even first flights; • the delays and costs resulting for launch providers and customers from early commercial flights sub-performing, including launch insurance cost and other economic ripple effects; • the strong to exclusive focus on a single mission profile, only, i.e. Geosynchronous Transfer Orbits or direct injection into Geosynchronous Orbits (GTO/GEO), also with respect to vehicle flexibility, reliability, and robustness with respect to the continuously developing mission characteristics in the mainstream segment; and • the low cadence of flights in general, and in particular for atypical or non-commercial mission profiles. Related to typical commercial mission profiles including dedicated tests are *space debris generation concerns*: • realistic GTO/GEO tests litter space with inactive, large and massive targets which are significant catalysts of exponential outbreaks of debris generation (Kessler cascade) [16]; and • these objects are left close to or transiting the most sensitive regions of Earth orbits, GEO itself, and for GTO objects, Low Earth Orbit (LEO), as well. [17] *Planetary science community concerns* include • potentially low science yield in mainly deflection-related technology missions; • significant fractions of scarce resources being tied up during extended interplanetary transit and purely technology-related operations; and • the significantly elevated risk of technology-focused interplanetary missions that even in a technological success could result in little but a lost investment in terms of the most valuable commodity involved, scientific career life work potential. [18] Perhaps surprisingly, all these concerns of independent and not necessarily related parties can be addressed individually by inverting them into common stakeholder requirements of a joint project that finds its focal point in the two key sets of recommendations related to planetary defence serving as the motivation of this study: *Planetary science community stakeholder requirements* include • significant pure science potential also beyond the immediate deflection-related context; • a fast mission scenario, without dedicated long-term commitments in preparation and operations of a high-risk technology-focused mission; • a low-cost set of instruments; • some flexibility for additional science-related instrumentation which is not required for guidance and navigation; and • a contribution to breaking the one-mission-per-career-life routine and its effects on personnel commitment and morale. *Space debris avoidance stakeholder requirements* include • a launch trajectory with low inherent debris generation risk; • non-standard orbits for all separated items; • residual launcher or payload stack most likely to escape or re-enter, also at partial completion of significant flight milestones; and • operation outside areas restricted by applicable Codes of Conduct (CoC) wherever possible at all. [17] *Heavy launch vehicle development stakeholder requirements* include • appropriate testing of all mainstream mission elements in a flight profile equivalent to near-maximum payload mass GTO/GEO configurations; • adequate simulation of typical commercial payload characteristics by the interceptor payload; • no loss of engineering data due to off-mainstream flight parameters, including deviations from expected performance; • a real functional payload to prove launch vehicle capabilities 'all-up'; • mainstream-like multiple payload separation demonstration accommodated; and • less than perfect performance tolerable by design of post-separation mission planning, also for purposes of public and customer relations. *Stakeholder requirements related to cognitive biases in recipients of relevant information* include • a strong focus on the most frequent class of NEO impact events with a significant risk attached in terms of human injury and loss of life, the sub-PHO size range of the population spectrum; • the demonstration of mitigation concepts and capabilities in a practical and highly visible way, to serve as reference point for at least a generation of recipients and funding providers; • providing a solid basis for the debunking of pseudo-science and questionable information which can not hold up in peer review processes, but nevertheless is pegged to planetary defence by otherwise motivated third parties; and • the creation of a focal point to which the promotion of understanding of and education in science and engineering can take reference. *Stakeholder requirements of concerned politics as well as proper governance, transparency, and civil rights interest groups* include • a mission design that profoundly enables independent observability of all aspects by means of amateur and educational as well as professional science communities; • an impactor design too small to carry anything of significance but its own immediately mission-related mass, without design margins to accommodate non-conventional high-energy units; • camera and data product formats very similar to pre-existing interplanetary probes to facilitate immediate open data dissemination for public review by said communities; • target selection, mission design, and limitation of possible deflection and disruption effects by fundamental laws of physics to guarantee that no adverse effects whatsoever extend to the Earth-Moon system; • small, low-cost, serialized-production spacecraft to minimize funding strains with respect to applicable budgets; and • the use of component technologies that are in all significant areas closer to commercial products than technologies perceived as 'hardened' and usually applied in the industrial/military, advanced physics, high-performance aeronautics, or space sectors. *Stakeholder requirements from the planetary defence, civil defence, disaster management, and space operations communities* include • the need to conduct realistic global exercises of the human element involved, under circumstances simulating end-to-end as closely as possible a real and immediate mitigation campaign, providing a brief but complete experience, including lessons learned from as many problem sources as possible; [19,20,21] • validation of previously established operations and communication concepts of spacecraft flotilla operations, networking, and autonomy; • augmentation of deflection-related knowledge previously gained in science missions such as Don Quijote [12]; and • a foundation to provide for all related fields confidence in the ability of the respective communities and the participating generation of individuals to handle challenges on this scale if they were to become real.

MISSION DESIGN CONCEPT

Since the primary mission goal common to all potential stakeholders of ASTEROIDSQUADS is to exercise and test their contribution in NEO mitigation and deflection campaigns before a real event occurs, the mission design accepts a somewhat high but controlled level of risk in all parts. The intention is to ascend on the learning curve based on real experiences in space and on Earth. The perhaps risky opportunity presented by a first or early test launch of new or extensively modified heavy launch vehicles and the very limited number of such launches dictates that the whole mission space segment be launched as one payload stack. At the same time, the investment exposed to this risk should not exceed the efforts required for a small to lower medium-class science mission of comparable expected science yield, including possible support of the test launch adaptation in lieu of a commercial payload. The need to exercise flotilla operations in deep space requires a multiple payload approach. GTO/GEO launcher developments currently envisaged support only 1 to 4 large payloads to be separated sequentially at approximately the same time. A launch vehicle test has to demonstrate performance for a similar payload stack. A synthesis of both requirements uses a set of small interceptor spacecraft mounted on a common dispenser structure which interfaces to the largest standard payload separation interface provided. The dispenser structure may be a standard small secondary payload platform used in the selected launch vehicle, e.g. ASAP or ESPA. Minimum modifications of the standard payload interface should allow the whole launch vehicle mass accelerated to final velocity to be used as target impactor mass. All non-standard mechanical fixtures to mount interceptor spacecraft to separable multi-payload structures and the upper stage can be attached to the fittings provided for the large standard payload separation interface (cf. e.g. LCROSS). Thus, one slightly modified interceptor is attached to the structure from which a standard GTO/GEO payload is separated, and another to an adapter structure interfacing to the largest standard payload separation interface provided to enable full simulation of one standard GTO/GEO payload separation. Several interceptor spacecraft are carried akin to small secondary payloads on the standard platform available on the launch vehicle. Such a set of interceptors and attached expended launcher structures to be carried along constitutes a Flotilla Packaging Increment (FPI) of the ASTEROIDSQUADS mission and payload. A FIP mechanically simulates one large payload, in which the various adapter structures connect the interceptors akin to mechanical subunits of a larger spacecraft during launch. Propellant sloshing simulation is provided by interceptor fuel ullage. Minimum size interceptors, following the requirements for a large flotilla and non-technical concern avoidance, use a small spacecraft baseline. Due to easy in-house off-the-shelf availability, the subsystem and components construction set concept of Kompaktsatellit heritage, informally designated 'SSB', is selected, with ad-hoc modifications for br*i*ef *i*nterplanetary flight. This concept has been applied successfully in several Concurrent Engineering (CE) studies conducted by various parties at the DLR Bremen CE Facility (CEF), including the final mission selection run-off for the first Kompaktsatellit mission, ASTEROIDFINDER. Traditionally at the Bremen CEF, mission design options are designated by the mission name, which may also be used for public relations, and bus services design baseline as a technical term. Hence, this study refers to the ASTEROIDSQUADS/*i*SSB variant which was the only one studied in depth due to time constraints. Other variants also discussed initially include ASTEROIDSQUADS/GEObus and ASTEROIDSQUADS/DeepImpact. Since fundamental launch vehicle design layout studies are also conducted in-house, a launch vehicle performance model was similarly selected from a much broader off-the-shelf menu. Similarity to the published performance-to-GTO range of expectations for the next generation of large GTO/GEO launch vehicles was applied as selection criterion. Since the timing and target selection for the mission depends foremost on the development of an otherwise unrelated launch vehicle, ASTEROIDSQUADS is expected to enable Serendipitous Quantitative Understanding and Assessment of Deflection Strategies within the context of PHA mitigation.

PHASING IN TO THE PLANETARY SCIENCE ROADMAP AND DEFLECTION RESEARCH CONTEXT

The first fundamental step towards SSSB deflection research is to include a deflection-related component in planetary science missions, as recommended by the PDC'09 White Paper. [13] In currently envisaged scientific missions, one specific NEO (possibly a binary) is selected and studied extensively by a rendezvous spacecraft. Target selection and mission design follow entirely from scientific requirements which force a strong bias towards easily accessible and observable NEAs. A deflection-related objective is merely added; e.g. a gravity tractor test as part of a hovering phase, or a separate impactor spacecraft (cf. Don Quixote [12]) to determine the energy-to-impulse conversion efficiency (β parameter) relevant to kinetic impactors. As many such mission additions of a particular type are required as there are different classes of asteroids with respect to the deflection-related property to be studied. Each represents a separate fully controlled scientific experiment. The mission scenario ASTEROIDSQUADS was designed as a second step which is primarily focused on the aspects of deflection technology, campaign management, and integration with ground-based threat detection and disaster management infrastructures, with pure science as a secondary objective also applicable to NEO mitigation research. It provides an intentionally partially uncontrolled experiment, end-to-end from the (simulated) discovery of an impending impactor to the verification of the deflection achieved. It is also designed to enable full integration with concurrent exercises of mitigation measures related to the wider civil defence environment on the ground, as a source of real and unpredictable data input as well as a test of science, operations, and disaster management as well as the respective space and ground segments. Partial recovery of control over those parts of the mission which may also constitute pure science experiments is to be provided by conducting several impacts under partially varied conditions, e.g. impactor mass and impact location in the target's cross-sectional plane (B-plane). The ASTEROIDSQUADS/*i*SSB variant was chosen because it represents the minimum investment flotilla option among those discussed. A possible follow-on to a first ASTEROIDSQUADS mission may be a similar re-flight towards a well characterized target object with extensive precursors and follow-up added in separate launches. Further follow-on may be a more massive deflection test which focuses on the verification of a substantial deflection effect by employing a significantly higher total energy or momentum to be transferred. The mitigation and operations lesson-learning aspect may also be continued on a somewhat separate lane by establishing the mission types presented herein as an accepted mode of testing in every new generation of high-performance launch vehicles or interplanetary spacecraft.

ASTEROIDSQUADS COORDINATED EXERCISE VS ACTUAL DEFLECTION CAMPAIGN TIMELINES

The following table compares the hypothetical timelines for an ASTEROIDSQUADS-style coordinated global planetary defence exercise and a likely multi-spacecraft deflection campaign to be mounted against a real and hazardous impactor of the relevant SSSB sub-populations. Likely real campaign events and proposed equivalent simulation exercise milestones are listed in the same row, in the respective half of columns. The vertical double line represents the phase of concurrent civil defence exercises using live data derived from ASTEROIDSQUADS progress as unpredictable input of an intentionally partially uncontrolled experiment to test end-to-end the responses of the whole ad-hoc assembled mitigation effort. The horizontal double line represents the current state at submission of this paper. *Note* that currently, no progress beyond this state is in any way planned or endorsed. Also, operations related to precursor and effects assessment missions are not included in the table for clarity, although either should be used in both cases, depending on warning times and/or embedding of ASTEROIDSQUADS in wider NEO science programmatics, respectively. The timing and events sequences of such campaign-bracketing missions are expected to be very similar to NEA science missions.

Tab. 1. Comparison of real mitigation campaign and ASTEROIDSQUADS simulation exercise events

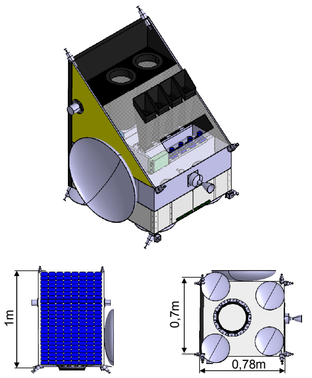
actual deflection campaign event	timing of the event by	ASTEROIDSQUADS simulation event	timing of the event by
virtual impactor discovery	nature	derivation from PDC'09 White Paper	biennial PDC
evaluation of threat and available means	impact probability rises w/ refined orbit	conceptual work on campaign design	availability of interested personnel
notification of required infrastructure	impact probability does not drop back	volunteering of co-authors	availability of interested personnel
intense tracking of the object	while detectable	PHA familiarization of co-authors	abstract submission
highly likely Earth impact confirmed	synodic period ahead	study go-ahead confirmed	abstract notification
preparation of feasibility study	coordination and information effort	conceptual work on system and subsystem design	ASTEROIDFINDER (AF) PDR preparation
deflection feasibility study (Pre-Phase 0)	first request for input from decisionmakers	CE-style ASTEROIDSQUADS planetary defence exercise feasibility study	AF PDR submission to PDC'11 (1 week)
deflection method selection and detailed feasibility study (Phase 0)	comprehensive input for decisionmakers	CE-style ASTEROIDSQUADS space segment study (A5-/*i*SSB variant, only)	≤ AF PDR ≈ PDC'11 submission (2 weeks)
detailed mission analysis and scheduling of deflection campaign	acceptance and/or end of denial of impact	identification of suitable launch vehicle tests as currently envisaged	current state of the launcher market
start of campaign implementation	formal go-ahead	agency programmatic implementation	funding obtained
interceptor spacecraft design (likely based on recent space probes)	agreement of all participants	interceptor spacecraft design (likely based on off-the-shelf small satellites)	interested parties and launcher schedule
production ramp-up and pooling of all suitable launch vehicles	infrastructure and industry capabilities	development of selected launch vehicle progresses according to provider needs	launcher market development
production of interceptor spacecraft and additional ground assets	infrastructure and industry capabilities	production of the interceptor spacecraft and additional launcher equipment	selected launch vehicle development
re-acquisition of impactor (if lost)	synodic period	search programme for suitable targets	launcher test schedule
continued refinement of target orbit	observability	cont'd successive re-selection of targets	test launch slippage
launch of flotilla progressing from storage orbits to direct injection	launch infrastructure capabilities	cont'd final launch and ground network preparations & re-selection of targets	test launch slippage cont'd, roll-out to pad
Earth departure launch window	impactor orbit, space segment capabilities	GTO/GEO-like direct injection launch of one ASTEROIDSQUADS payload stack	one test launch when launch vehicle ready
flotilla cruise operations; line-up, approach, final precursor obevations	terminal phase requirements	line-up of flotilla for several impact events and space operations exercise	target impact science, DSN availability
spacecraft arrivals at impactor	orbits geometry	interceptor target operations sequence	G&NC, science return
deflection effects application	method selected	sequential impacts and fly-bys	kinetic impact method
terminal operations data evaluation	space segment design	terminal dive movie & data evaluation	intercept geometry
preliminary assessment of deflection	observability	preliminary assessment of deflection	modelling, observation
continued impactor tracking until sufficient deflection confirmed	observability, tracking capabilities	possible confirmation of deflection by continued orbit determination of target	synodic period, precovery data

SYSTEM ENGINEERING CONSIDERATIONS

The design and development of a flotilla of mutually similar spacecraft is a challenging, though not insurmountable, task, with much of the required effort focusing on programmatic aspects. The largest practical implications of such development likely arises from the increased complexity of configuration management and system parameter tracing – both of which could be much simplified via careful and consistent homogenization of all spacecraft and by usage of advanced data repository software or MBSE approaches. Adoption of different payloads into the flotilla can only be considered where such payloads are essentially plug-and-play devices; substantially different payloads, or variations in other interfaces would likely introduce unacceptable levels of complexity into the development process, ranging from uncoordinated interfaces to inadequate attitude control. The time implications of developing such a flotilla require careful management. Verification time should be minimised by maintaining a level of standardisation such that each spacecraft can be qualified under ECSS categories A or B (ECSS-E-ST-10-02C) [22]. Means have to be found to accommodate extended storage times: both to account for storage while the rest of the flotilla is assembled, and for time spent awaiting readiness of the launch vehicle and selection of a suitable target asteroid. Such long-term storage of entire flotillae is not commonplace in the current segmented constellation launch approach. Augmented integration and storage facilities would need to be realised if mission hardware were to be based on the baseline chosen for this study, given that the current Kompaksatellit integration facilities are designed for serial development and mission cadence of small national science missions. Nonetheless, it is foreseeable that the greatest system engineering effort would not be required at the spacecraft or flotilla level, but rather at the mission level. The integration of such a large number of elements, entities and persons represents a standard System of System (SoS). While methods exist for the handling of these (mainly coming from the defence industry), there is currently very little heritage in the space industry for such developments. This is no insignificant fact: means would have to first be investigated and a methodology properly formulated and tested before such an attempted demonstration could be made. The integration of public and private entities could also prove a significant political barrier to any such missions. Were the development of such means and procedures to be initiated only after a high-risk impactor is discovered, time may be too limited to find solutions that properly integrate with established structures of civil society. Dangerous precedents of far-reaching consequences could be established, whether accidentally or out of recognized one-off necessity. Development, validation, and a practical test of the necessary procedures in times of routine legal and political environments are part of stakeholder requirements from the civil defence and political constituencies. Experience in handling such a SoS challenge may also benefit the space sector in general.

SPACE SEGMENT AND INTERCEPTOR CORE SPACECRAFT

The space segment of ASTEROIDSQUADS consists of the interceptors arranged in FIPs and the launch vehicle, of which all expended structures accelerated to the final velocity are carried as part of the kinetic impact deflection mass. Fig. 1 shows the accommodation of the ASTEROIDSQUADS/*i*SSB design variant and the key subsystems which are mostly derived from the ASTEROIDFINDER unified secondary payload envelope baseline design used before the current, more evolved and spacious simplified baseline. [23]



Dimension	1m x 0,78m x 0,7m + a few negotiable protrusions
Sunshield	50 degree
Mass	179 kg incl. 35 kg instruments & 25 kg propellant
Payload	2 x Narrow Angle Cameras 4 x Medium Angle Camera 4 x Wide Angle Camera
Communication	1 x Ka-band antenna 2 x X-band antenna 4 x Interlink antenna
ACS	Propulsion (8 x 1N thrusters, 1x 400N thruster)

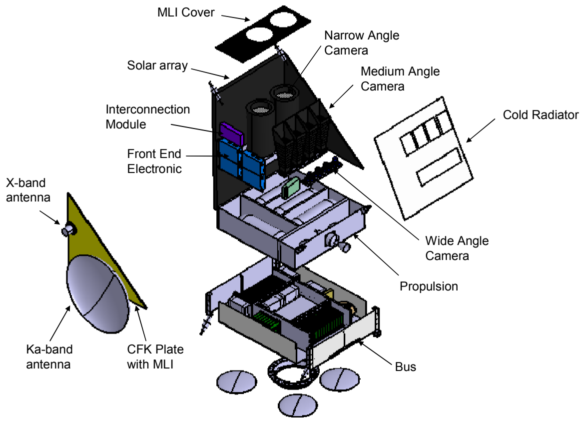


Fig. 1. Accommodation of the ASTEROIDSQUADS/*i*SSB design variant

IMPACT SEQUENCE DATA GENERATION AND SPACECRAFT COMMUNICATIONS

A battery of three different camera types is used as the combined main science, optical navigation support, and deflection method effects assessment instrument. At least two cameras of each type are employed. These are derived from formats used on interplanetary probes: [24] high-resolution-oriented Narrow-Angle Cameras (NAC) with a limited Field of View (FoV); reduced-resolution or TV-format Medium-Angle Cameras (MAC) for elevated frame rate final approach coverage at acceptable resolution, and high-frame-rate-optimized Wide-Angle Cameras (WAC) for last-millisecond imagery of the target surface and impact area. For the purpose of this study, the on-chip Electron-Multiplied Charge-Coupled Device (EMCCD) imaging sensor technology used in the ASTEROIDFINDER instrument was baselined, with the assumption that pixel clock is only limited by the respective sensor maximum rates. Resolution in brightness may be sacrificed to some extent in favour of high frame rates, e.g. by fast look-up table compression, or parallel transmission from two camera channels at halved resolution. EMCCD technology mainly reduces read-out noise at low light input per frame, but may not be required for all camera types since the target becomes brighter at close ranges so that photon shot noise may dominate. For MAC and WAC, the optical system is very small so that >2, each, may be used. This enables fixed filter colour imagery and rolling read-out for frame rate maximization. Additional instruments may replace cameras not required for trajectory control if interfaces are compatible, e.g. fast dust counters or analyzers. WAC images are generated until impact, but a fast impact analysis sensor integrated along the structure may take over on contact; the shock wave travels in ~50 µs from the sunshield tip to the bus section. Various communication links have to be considered for each satellite. Most important is the high data-rate inter-spacecraft link used to transmit the huge amount of image data produced during the final approach to the asteroid to the next incoming impactor which acts as a relay. Taking into account that the cameras generate data streams with different frame rates and resolutions depending on their distance to the asteroid, a data volume of more than 50 Gbit must be expected. Since the data need to be transmitted within an interval of around 5 minutes before impact, imagery has to be acquired up to the point of impact, and the required data generation rate can reach up to 150 Mbit/s, immediate live transmission is required. The most interesting data is created at the end of the transmission at a slightly lower data rate around 128 Mbit/s. Since close-up images can only be obtained during this last phase of less than 1 s duration, it is also considered as driving the design of the high data-rate inter-spacecraft link. The data received by the next incoming impactor needs to be forwarded to Earth and/or later impactors at a much lower data rate, about 5 Mbit/s. However, the maximum distance the high data-rate inter-spacecraft link can cover is traversed by the receiving spacecraft in ~25 minutes. If it is intended to impact as well, only the last few percent of image data can be forwarded, playing backwards from impact until the relaying node has to abort retransmission to reorient itself for impact guidance autonomously. Alternatively, the second spacecraft may pass in a close fly-by of the target object just outside the ejecta plume, conduct other observations, forward the preceding spacecraft's and its own data completely, and then continue remote observation of events. [25,26]

Tab. 3. Camera parameters study baseline applied to a Ø140 m PHA approach towards impact at 17 km/s

channel	FoV, °	sensor pixel	pixel clock, MHz	frame rate, 1/s	target >1 pixel, km distance	target >1 pixel, s to impact	target full FoV, km distance	target full FoV, s to impact	distance flown per frame, km	target full FoV frames to impact
NAC	1.5	1024^2	20	17	5476	322	5.4	0.32	1	5
MAC	5	512^2	15	48	821	48	1.6	0.09	0.35	5
WAC	15	128^2	18	966	68	4	0.5	0.03	0.018	30

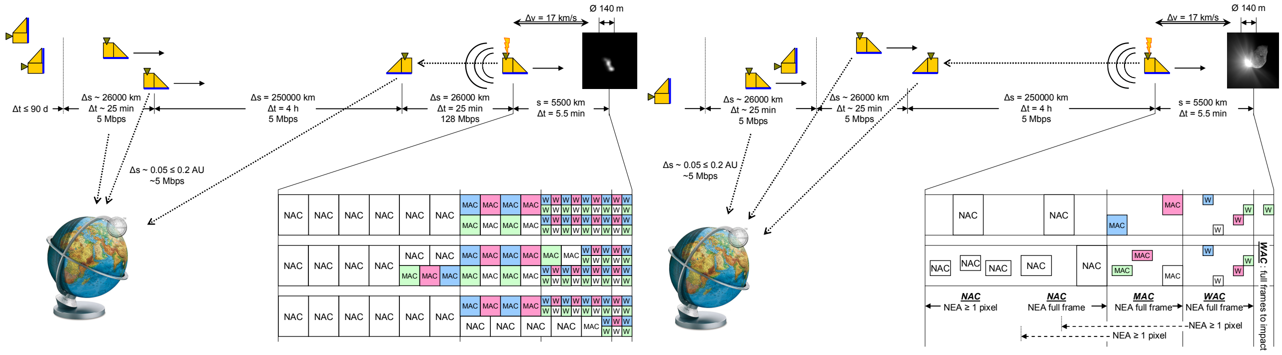


Fig. 2. Terminal approach formation sequence and activity pattern

ATTITUDE AND ORBIT CONTROL SYSTEM

The Attitude and Orbit Control System (AOCS) employs among others the following units: • four angular rate sensors arranged in a tetragon to determine spacecraft angular rates during agile manoeuvres; • a set of sun sensors is used which allows determination of the sun vector with a spherical field of view, which is essential to allow recharging of the batteries; • for precise attitude determination, a star camera is used, with the alternative option to use images of the payload cameras fed into a star identification algorithm; • for the actuator side, a minimum of eight attitude control thrusters are used to allow fast reorientation, augmented for orbit correction manoeuvres by one additional large trajectory control thruster. This thruster and propellant tanks are added between the ASTEROIDFINDER-derived bus and payload sections as an additional propulsion module which has been derived from a CEF study of a formation-flying Earth observation satellite. [27] The sensor/actuator package is built of standard off-the-shelf components. The most challenging task of the AOCS is control during terminal approach and formation flying in cruise. The feasibility of line-of-sight terminal collision course guidance towards Ø 100 m class targets with an encounter velocity of several km/s has been studied, including detailed model simulations of image-processing-based solutions. [28] The line-up and maintenance of the formation is challenging due to the fact that the satellites need to communicate with each other and point the high gain antennae towards Earth in alternating successive task assignment phases. The formation has to be lined up along the line-of-sight to the target object and kept so to allow controlled impacts and their monitoring as well as data relay operations. Formation flying under partial or fully autonomous control during brief but crucial high-intensity phases as well as energy-conserving cruise operations with many spacecraft is presently considered a challenge, but such mission concepts are currently under intense investigation, and first feasibility demonstrations have successfully been conducted in LEO and various ground-based environments.

LAUNCH VEHICLE MODEL

For the analysis of the launch vehicle ascent an off-the-shelf study model of a hypothetical ARIANE 5 with an updated cryogenic upper stage was used. The assumed version has a payload performance of 10.3 t into GTO with a gross lift-off weight of 790 t. With the ASTEROIDSQUADS/*i*SSB payload, the gross lift-off mass is 784 t. An overview and summary of the masses of the upper stage configuration for the ASTEROIDSQUADS/*i*SSB mission is given in Fig. 3. The configuration consists of the upper stage with an attached adaptor cone, one Sylda 5 (SYstème de Lancement Double Ariane) carrier, [29] two ASAP 5 (Ariane Structure for Auxiliary Payload) structures, [30] 20 interceptor spacecraft, two of which carry adaptor cones, and a short fairing. The rationale behind the intentionally *not* optimized simulated ascent is to use *exactly the same* burn profiles and significant vehicle test parameters as for a standard GTO ascent. This approach leads to suboptimal performance traded for more realistic testing of the launch vehicle. Due to the lighter payload, the ASTEROIDSQUADS/*i*SSB mission achieves a higher altitude and greater end velocity compared to the standard GTO mission. For comparison, both trajectories are plotted in Fig. 3. At upper stage engine cut-off at 1250 s total mission time, the configuration minus the fairing reaches an inertial end velocity of 10.8 km/s at an altitude of 1100 km. Higher altitude may also facilitate safe tracking of the faster trajectory. For GEO injection flight profile tests, the circularization burn after ~6 h may provide some re-target capability if on-board trajectory optimization or a command capability is to be applied, e.g. if the GTO leg was sub-performing. For a flotilla exercise, it also simulates a large deep space manoeuvre with associated burn errors. More such events can be simulated in super-GTO or high-latitude launch site profiles. Performance may be increased by a lunar fly-by under favorable circumstances, or by trading standard GTO likeness for a properly optimized flight profile.

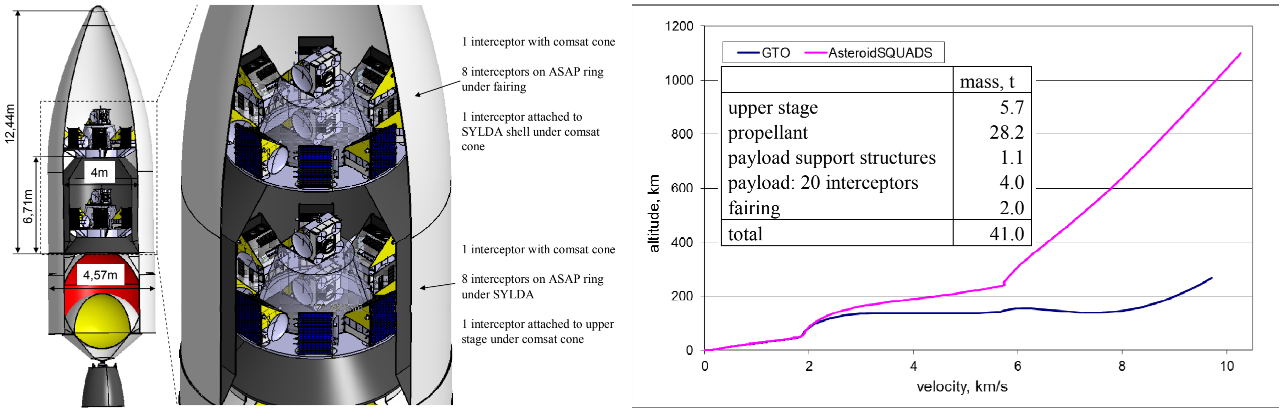


Fig. 3. ASTEROIDSQUADS/*i*SSB payload stack on a hypothetical ARIANE 5 with an updated cryogenic upper stage

GROUND SUPPORT EQUIPMENT

The Electrical Ground Support Equipment (EGSE) concept for ASTEROIDSQUADS is driven by the production, storage, launcher integration phases. While the EGSE for production phase could be similar to ASTEROIDFINDER (Fig. 4, l.), but multiplied according to the number of flotilla elements integrated in parallel, the storage phase would require one basic set of Spacecraft Check-Out Equipment (SCOE) for each of the flotilla elements. Since all elements have to be kept in a defined state and monitored regularly, the basic functionality of each SCOE set is electrical power supply and measurement as well as access to the data bus of the respective element. The SCOEs are connected to a central SCOE Controller through an Ethernet network, which monitors all flotilla elements connected to it (Fig. 4, r.). This central SCOE controller monitors battery voltages of each element permanently and initiates basic health checks of all elements in certain intervals, so that flight units are not active except for short periods in long intervals in order to prevent early degradation. Integration of the flotilla to the launcher is the most demanding part of the Assembly, Integration, and Verification (AIV) process and for EGSE. Depending on personnel and time available, there are the following options: • 1.) 2..3 teams of AIV engineers available at the launch site, each working on one incremental package. The spacecraft are integrated and checked out sequentially within their increment if there is enough time available; • 2.) 4..6 teams of AIV engineers are available at the launch site. Of these, 2..3 are assigned for integration of the spacecraft to the launcher while the others conduct final check-out. Each pair of integration and check-out team works on separate increments of the stack, as in option 1. • 3.) Each flotilla element is assigned to an AIV engineering team integrating the element on the launcher, including final checkout. The number of Launch Site (LS) SCOE sets varies depending on the option: for options 1 and 2, 2..3 sets of LS-SCOE are sufficient, whereas option 3 requires as many LS-SCOE sets as there are flotilla elements in the stack; here 20. The LS-SCOE sets are composed of an electrical power Check-Out Element (COE), an RF COE, and a data handling COE.

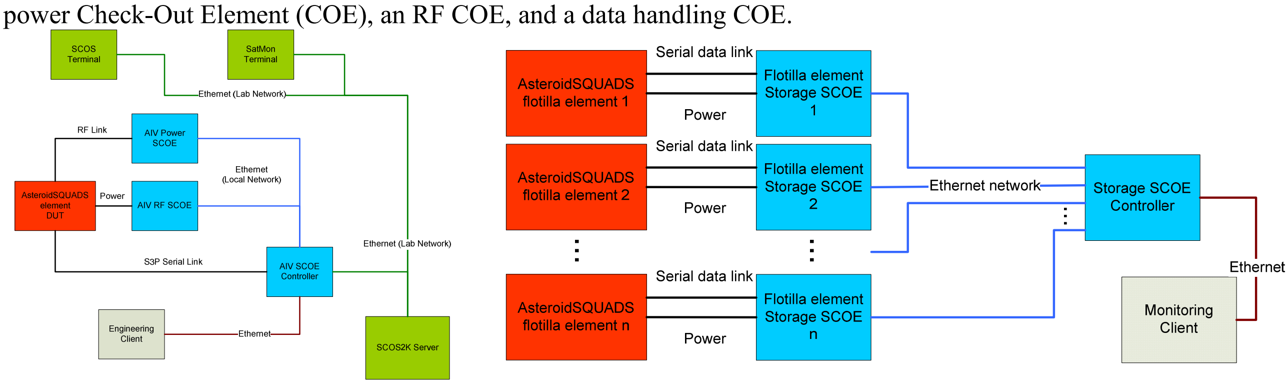


Fig. 4. - l: ASTEROIDFINDER-derived production EGSE - r: ASTEROIDSQUADS networked flotilla SCOE

MISSION ANALYSIS FEASIBILITY INVESTIGATION

The feasibility of formation flying strategies to intercept PHA-like targets was assesed by an analysis of close approaches towards the PHAs Toutatis, 1999 RQ_{36}, 1950 DA, and Apophis. An ASTEROIDSQUADS/*i*SSB formation consisting of 20 spacecraft and launch by the ARIANE 5 study model on a GTO-like profile within an interval from 2016 to early 2020 were assumed. Instead of placing the formation in GTO, the excess payload capability of the launcher is used to escape Earth with a hyperbolic excess velocity of 3 km/s. With the respective velocity vector, daily trajectories have been calculated for a launch time of 23:20 within this interval, and compared to the orbits of the above mentioned

PHAs. Each trajectory was plotted for 500 days. A close approach was assumed at a distance of 10^6 km to a PHA (Fig. 5). Opportunities are present several times a year. Note that • presently, about a dozen known objects transit an Earth-centred sphere of 0.2 AU radius per month; [31] • the frequency of opportunities improves approximately in proportion to the number of detected PHOs and sub-PHOs; • the presently estimated completion of surveys is at 8% and <1% for NEOs of Ø 300 and 100 m, respectively; [2] and • the population of targets suitable for ASTEROIDSQUADS is hence likely to grow by almost two orders of magnitude by the time the PanSTARRS and LSST surveys just begun have reached their completion goals towards the end of this decade. [32,33] A reference scenario for an ASTEROIDSQUADS/*i*SSB launch on March 3rd, 2018, to intercept Apophis was used to calculate ΔV requirements, flight time, and feasibility of a formation strategy that allows 8 h intervals between impacts. Apophis was chosen for its favorable conditions for an interception due to the smaller eccentricity compared to the other candidates and an orbital period close to Earth's, 323.5 d. The formation strategy has been the following: • Spacecraft flying in close pairs; • the first one scans the asteroid and transmits data to the second one; • once the first spacecraft has impacted, the second one turns towards Earth to forward the data; • during the final moments before impact, the pair's second spacecraft turns towards the asteroid for terminal Guidance and Navigation Control (G&NC). The ΔV requirements of the Apophis scenario are summarized in Tab. 4. For clarity, 3 close pairs are presented, and a single spacecraft with a time difference of 72 hours between its own impact and the first, to also address requirements of a formation of 10 pairs, distanced by 9 time intervals of 8 hours. First impact occurs 485 d after launch. The midcourse manoeuvre requirements do not significantly change between pairs. The significant difference in total ΔV is due to formation spreading which results in a difference of ~76 m/s; differences are in the range of 10 m/s per 8 hours of delay. While the total ΔV requirement exceeds current design parameters for ASTEROIDSQUADS/*i*SSB, there is room for optimization. It would be possible to distribute ΔV's in a more balanced way. The zero-point may be placed in the middle of the formation or with the heaviest impactor, e.g. that which is attached to the upper stage. The total ΔV gain possibly puts the required ΔV at ~428 m/s for the given scenario, just within the total the design can supply. This may be further reduced by diverting from a strictly standard-GTO-like launch vehicle flight profile to a properly optimized one.

Tab. 4: ΔV requirements for the ASTEROIDSQUADS formation approach to Apophis.

spacecraft ID	delay to 1st impact	formation spreading, m/s	mid-course, m/s	total ΔV, m/s
Asteroid Squads 1-1	0	n/a	386.004	386.004
Asteroid Squads 1-2	+25 min	0.787	390.881	391.668
Asteroid Squads 2-1	+ 8 hours	11.063	389.931	400.994
Asteroid Squads 2-2	+ 8 hours + 25 min	9.508	390.196	399,704
Asteroid Squads 3-1	+16 hours	22.523	396.574	419.097
Asteroid Squads 3-2	+16 hours + 25 min	22.389	396.574	418.963
Asteroid Squads final	+ 72 hours	75.855	389.667	465.522

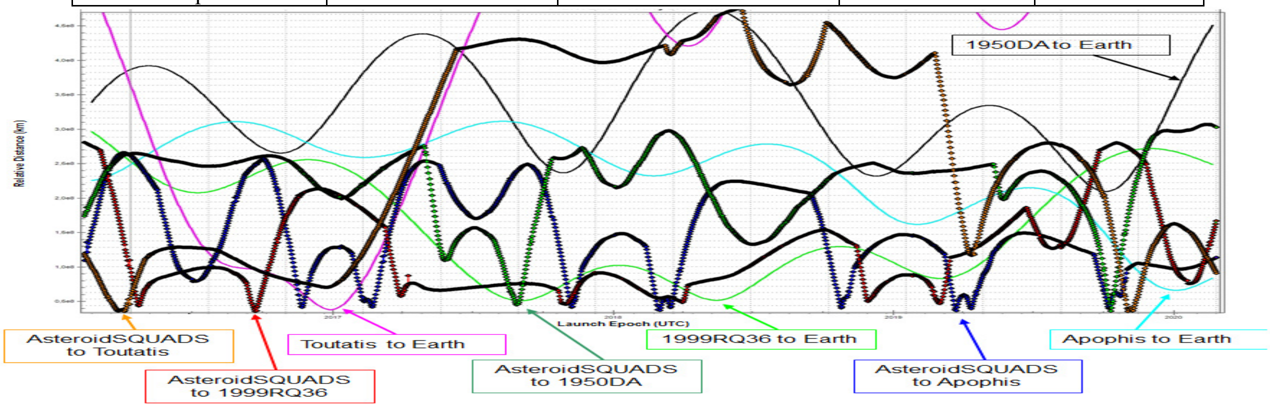


Fig. 5. Collision course close approach opportunities for high science value PHA targets, 2016 to 2020

FINAL NOTE ON EARTH PROTECTION ISSUES

Probably the most significant concern about any deflection technology, whether to be realized for a real mitigation campaign or for an exercise, is its immediate weaponization potential for abuse by deflecting a non-threatening object towards a controlled collision with Earth. For ASTEROIDSQUADS/*i*SSB, "a quick back-of-the-envelope calculation shows the system presented is useless for deflection. It will deflect a 100 m object by about 1 cm/s. This gives a deflection of the impact of 2 km or less after 90 days." [34] Also, the kinetic impact method works to a significant extent by creating a plume of impact ejecta which add to collision momentum transfer by energy-to-momentum conversion. The plumes of successive impacts evolve into a substantial dust coma around the target which greatly increases its apparent brightness. All deflection methods create plumes or comae, including the relatively faint ion engine exhaust of gravity tractors. Regardless of the intent, sponsor, or method involved - covert SSSB deflection is therefore impossible.

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