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# The Ends of Small – Practical Engineering Constraints in the Design of Planetary Defence Missions

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## ABSTRACT

The trend in interplanetary missions has always been for capability growth. For spacecraft with a predominantly scientific mission rationale it has in recent decades mostly outgrown the capability of launch vehicles, leading to ample use of planet fly-bys and long cruise flight durations. For planetary encounters, none of these missions had a requirement to leave the ecliptical plane. A smaller class of planetary missions designed to fly on smaller launch vehicles, often with technology development as a major objective, included encounters with small objects in the ecliptical region of the solar system. There have been several interplanetary spaceflight applications suggested as options for action upon the discovery of a sustained high-risk object. However, with the exception of fast fly-bys near the nodes of the target's heliocentric orbit, it is unlikely that the target will be easily accessible when it comes to the urgent need for characterization of a hazardous object. Published mission analyses show that a large fraction of NEAs lies beyond the reach of conventional propulsion for rendezvous missions with any realistic payload mass to target at any time. Advanced propulsion methods such as solar-electric thrusters or solar sail also require minimal payload mass to employ their advantages over conventional propulsion most efficiently. They are independent of gravity-assists but still can use them if available. For Earth-orbiting missions, there is ample experience in the miniaturization of spacecraft, exemplified by the experimental perspective of cubesats. Terrestrial applications now put more computing power into the hands of the consumer, literally, than was available to the whole Apollo programme or the contemporary first wave of planetary exploration. But in its application, the trend has been from target-oriented simplicity in a multitude of individual systems towards standardized complexity. On the other hand, the way back to simplicity is not cut off – it merely has to be reclaimed by a generation not used to it.

## 1. Introduction

The trend in interplanetary missions has always been for capability growth. For spacecraft with a predominantly scientific mission rationale it has in recent decades mostly outgrown the driving requirements of the high-performance launch vehicle market. While the PIONEERS and VOYAGERS of the 1970s flew direct trajectories to their prime target, Jupiter, GALILEO and CASSINI-HUYGENS took arduous detours to gather momentum in terrestrial planet fly-bys. The leap from MARINER 10 to MESSENGER and BEPICOLOMBO mirrors this for Mercury.

For planetary encounters, none of these missions had a requirement to leave the ecliptical plane region, although for other scientific fields, this has been proposed several times. The first out-of-ecliptic mission could have been flown in 1974 by the PIONEER H spacecraft built from spares for this purpose and now on display at the National Air and Space Museum as a PIONEER 10 replica; the first actually done was launched in 1990, the ULYSSES solar polar science mission.

Concurrently, a class of planetary missions established itself which uses planetary fly-bys, if at all, to fly on smaller and therefore less costly launch vehicles, although frequently a much longer mission operations duration and cost is accepted in return. In those missions, technology development often is a major objective next to planetary science. Still, all encounters with small objects were in the ecliptical plane region of the solar system.

## 2. The Difference between Science and Application

There have been several interplanetary spaceflight applications suggested as options for action upon the discovery of a sustained high-risk object. These aim to first determine the real threat level of an object, and then, if confirmed, inform the deflection mission design early on about the object's properties. Precision orbit determination can be improved beyond terrestrial-only means [1] by coupling a planetary radar beacon to the object. The investigation of object mechanical properties requires global characterization by orbiters and in-situ studies of the surface material by landers. Such mission profiles are reminiscent of NEAR-SHOEMAKER or the HAYABUSA missions with their MINERVA or MASCOT landers. [2,3,4]

However, with the exception of fast fly-bys near the nodes of the target's heliocentric orbit, it is unlikely that nature will be as kind as the scientific planetary mission target selection process when it comes to the urgent need for characterization of a hazardous object. Experience with past temporary high-risk objects suggests the timeframe for a sequence of confirmation, characterization and, ultimately, deflection missions:

Except for virtually co-orbital objects, the lower bound of the mitigation actions timeframe is the interval of close encounters with Earth at which discovery is likely, precision observation is feasible, or an impact could occur. These intervals vary as part of a sometimes rather complex semi-regular interference cycle with a quantization of individual intervals on the order of one to a few synodic periods which in turn are of the order of one to a few years, each. A similar cycle is that of the favourability of Mars oppositions, where more and less favourite oppositions alternate, though not exactly, and the closest oppositions occur only once every few decades. Also comparable is the cycle of (99942) Apophis observation opportunities which has been extensively reported due to the recently retired collision risk of this object.

The upper bound is the lead time for sufficiently precise and reliable prediction of impact at a risk level that clearly justifies substantial spending efforts, be it for dedicated observations requiring extensive telescope time, precision orbit determination support and object characterization missions, or ultimately, for a deflection campaign. When this threshold of a positive impact prediction is reached is not known, although it can be expected to be much higher than any of the predictions at which virtual impactor warnings have peaked so far – e.g. 10%, ${}_{50}\backslash^{50}$ or higher. [5] For objects not locked in simple or 1950DA-like resonance with Earth [6] this is maximum confirmable lead time on the order of a few decades, due to the inherent inaccuracies of extended tracking observations and the amplification of these errors by any planetary encounter of the object, however distant. [7]

Since the target asteroid is defined by nature without regard to availability of planetary gravity-assists, any such mission will likely push the limits of available launch vehicles. Published mission analyses show that a large fraction of NEAs lies beyond the reach of conventional propulsion for rendezvous missions with any realistic payload mass to target *at any time*. Advanced propulsion methods such as solar-electric thrusters or solar sail [8] also require minimal payload mass to employ their advantages over conventional propulsion most efficiently. They are less dependent or potentially independent of gravity-assists, respectively, but still can use them if available.

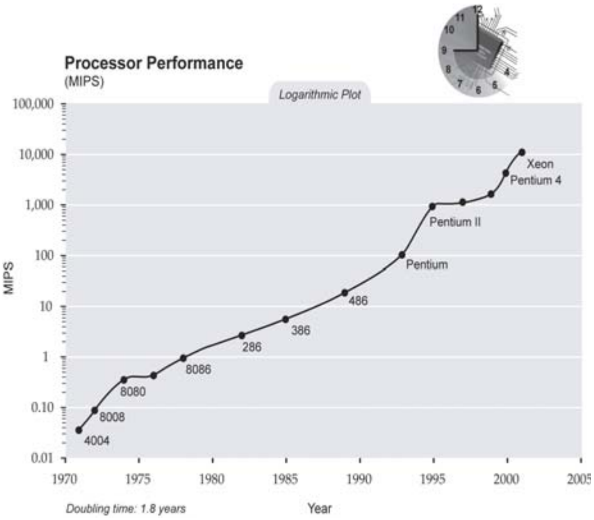
## 3. Technologies Change – Paradigms Shift

Whether apparent in the miniaturization of consumer appliances or of science payloads, the perception of trends in miniaturization is frequently tied to unique features of small design that result in capability growth from technology leaps, e.g. from discrete transistor to integrated circuit, or from vidicon to CCD imaging sensors. The latter is an example that current commercially miniaturized technologies already begin to push the fundamental limits of physics, since, for example, a quantum efficiency of 1 cannot be exceeded in the first entry interface of a sensor, and the change from vidicon to CCD has taken quantum efficiency from a few percent to the region of 80%.

### 3.1 An Example – The Development of Your Computer

If you take a look at your personal computer as it was in 1990 and as it is today, can you see the progress of technology in your work? Is your computer now 1000 times smaller than 1990? Or can you do things 1000 times faster? At that time you needed 20 seconds to boot your computer, and now 20 milliseconds? If your laptop in 1990 was able to work on battery for 1 hour, can your new laptop of today run 1000 hours, or approximately two months, with a single battery charge? Can you see the progress in computer technology?

Let's take a look at the history of computer technology in the last few years: Fig. 1 [9] shows the improvement of computing speed, from 1990 to today by a factor of 1000, and from 1970 to today by a factor of 100000. Fig. 2 shows the growing integration density of computer chips which is closely related to capacity or memory size. [10] Note the logarithmic scales of performance and capability growth.



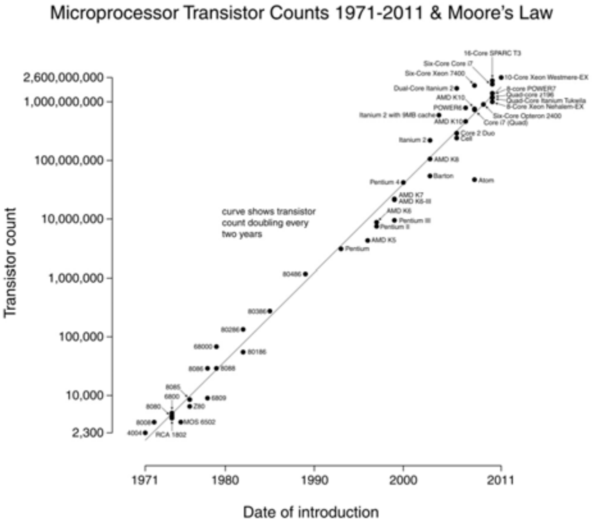


Figure 1: Growing speed – Figure 2: Growing capacity

From 1990 to today we have seen a density increase by a factor of 1000, and from 1970 to today by a factor of one million. The energy per computational unit has decreased by a factor of 1000 from 1990, and by a factor of 100000 from 1970. [11]

Then, why is your computer so large and heavy, needs so long to start and to execute programs, and why can't it run for two months with one battery charge? What would you do with a computer which is one million times slower but would also be 100000 times smaller and consume 100000 times less energy than your PC today? For sure, nothing in terms of the everyday office work environment. But for the Saturn rockets, it was enough to fly to the Moon, for the Skylab it was enough to control the whole space station, for the Voyager missions to fly as far in space as no other man-made vehicle until now. One of us (S. Montenegro) has for many years programmed (not so) small satellites which required much less than 10 million instructions per second (MIPS) of computing throughput. Today, he is involved in the development of a pico-satellite for which the spacecraft hardware designers are planning to use a 600 MIPS central processing unit (CPU). Conventional (or conventionally educated) wisdom not just here, at a technology-oriented university, finds it hard to accept the fact that for such a satellite only 5 MIPS (or maybe only 1 MIPS) are needed. If designed for requirements reduced to the realistic needs, the whole Data Management System of this spacecraft would easily fit on a single chip, even with commercially long outdated but in the meantime thoroughly space-qualified technology as would be needed beyond the usual low Earth orbit (LEO) of cubesats.

According to the development of microelectronics, we would be able today to rebuild the data management systems of the Saturn rockets, the Voyager spacecraft, the Mars Sojourner rover or Skylab in a cube of $(1\text{cm})^3$ – a computer which weighs on the order of 10 grams and consumes about 1 milliwatt. Why not?

The problem is the software complexity is growing faster than the microelectronic capacity and speed. While the microelectronic speed is doubling every 18 months the size of embedded software is doubling every 10 months (ITEA 2004). Then, when we take a look at the whole system, we see the computer is growing, that it consumes more power, and that it needs longer to execute the basic functions.

This growth, in an aerospace system, propagates immediately to the system level where it first drives up structural mass and size to be accommodated physically; then it drives up (usually solar) power generation requirements, which again need to be accommodated as photovoltaic cell area and power conversion electronics on a yet larger structure; next, the radiator area to dissipate the heat from the increased electrical consumption needs to be increased and accommodated by yet another growth increment of the structure; the spacecraft now increased in size three times already by one oversized unit may need stronger attitude control actuators which yet again drive up control requirements, power requirements, and dissipation; and so on.

Today we need 1000 times more resources to do the same work as in 1990. The problem is that computer scientists (to use a general term) are being trained to go very lavish with resources, to reuse by copying a whole system and adding some more lines (never to remove lines); they are guided to program not only what we need, but also what maybe we could need in two years (when we will not really need it). We try to take an existing system and add some new functionality without removing all the code become unnecessary; admittedly mostly because that would be really too difficult in most cases due to the intricate and sometimes intransparent structures of large software packages.

Fig. 3 shows the difference of the present approach compared to an approach strictly based on the actual needs of a system, and the respective results in terms of complexity and size in the end product.

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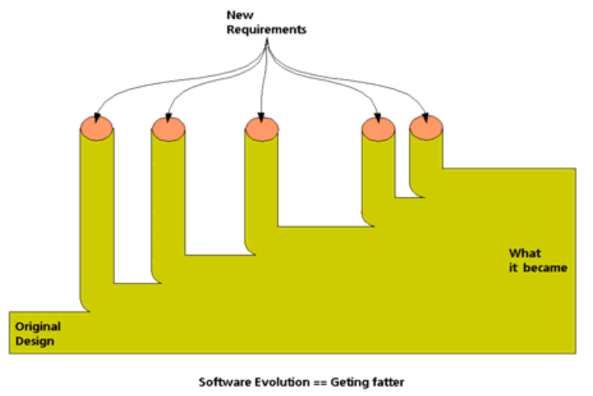
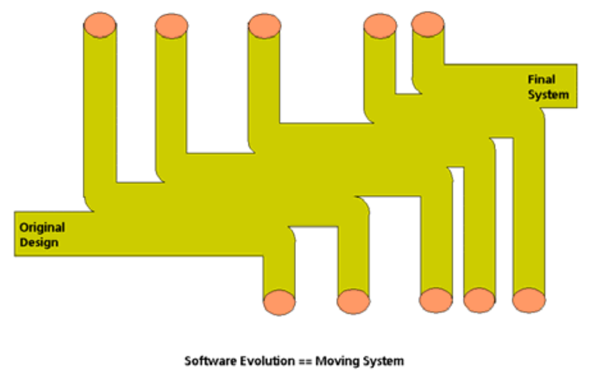
|  |  |
| How we work today | How we shall work |

Figure 3

It is recognized that the problem is not the missing microelectronics capabilities but the exaggerated software complexity in today's systems. Therefore, the irreducible complexity is we targeted in new developments. Our operating system (OS) RODOS and its middleware have only 3 K Lines of Code, while other OS + middlewares begin with 3 million lines of code.

Terrestrial mobile applications now put more computing power into the hands of the consumer, literally, than was available to the whole Apollo programme or the contemporary first wave of planetary exploration. [12,13] But in its application, the trend has been away from target-oriented simplicity in a multitude of individual systems towards standardized complexity, much so in repetition of the 'home computer' boom of the early 1980s. On the other hand, as back then and still today exemplified by vintage computing enthusiasts, the way back to simplicity is not cut off – it merely has to be reclaimed by a generation not used to it.

### 3.2 Trickle-down of Ground-based High-tech into Space

For Earth-orbiting missions, there is ample experience in the miniaturization of spacecraft at growing performance driven by economic considerations for mainstream commercial Earth observation missions as well as the experimental perspective of cubesats. This has caused a change in project philosophies at the technical level: from purely requirements-driven design growth to constraints-driven capability optimization, and from box-by-box accommodation and interfacing towards organic integration.

This experience has propagated into planetary defence related missions already, e.g. NEOSSAT, [14] tightly modelled on its successful predecessor, MOST, or the past DLR 'Kompaktsatellit' project, ASTEROIDFINDER, [15] particularly in its earlier ASTEROIDFINDER/SSB secondary launch envelope variant [16] derived from the small satellites TET and BIRD. [17] The MASCOT asteroid lander is being designed by DLR and CNES into the envelope kindly made available by JAXA on HAYABUSA-2. Also at DLR, the GOSSAMER roadmap [8] develops solar sails based on currently available technology with a first demonstrator using cubesat elements in its bus section based on the DLR CLAVIS concept, and later models aiming to fit into standard secondary payload slots of presently available launch vehicles flying into geostationary transfer orbit.

## 4. Constraints Is People

Regarding the practical limits of spacecraft design in planetary defence applications – whether related to basic threat assessment by orbit determination or target characterization by remote sensing or in-situ investigation, or ultimately, deflection – all the many spacecraft functions not only need to be conceptualized and studied on paper but have to be implemented in hardware, i.e. designed, built, tested, shipped and launched, and at that with a fundamental need for reliability that surpasses the requirements of a conventional science mission which may well (in theory, at least) be repeated at a later launch opportunity or towards another target of similar quality.

All this needs to be done by people, not just trained and educated, but experienced in interplanetary spaceflight *and* their respective specialization in spacecraft engineering and/or planetary science. Unlike the spaceflight environment of the 1960s and early 1970s when Earth-orbiting missions were sometimes flown on a weekly basis, today's spaceflight environment is on the industrial side as well as on the government side extremely optimized for the current low cadence of flights. Facilities that could by their technological means support a much higher activity are often limited by available staff, following the budgetary principle 'Cost is People'. The frequency of interplanetary missions as well as of commercial launches has been fairly stable since the end of the 1970s, and military launches have declined mainly with the paradigm shift from film-recovery to image transmission spacecraft which caused other mission types using similar spacecraft bus technology to follow suit and design for longer orbital lifetime at around the same time. [18,19] The long duration of this stable environment has also resulted in a similarly stable supply or equilibrium flow of trained people into and through space employment, remembering that even under the most favourable circumstances it takes at the very least about a decade to take an individual from graduation in school to having achieved spaceflight experience in a flown mission.

In common practice, a significant fraction of the available workforce is dedicated to feeding institutional processes such as project milestone reviews and formal documentation requirements rather than doing actual design and construction work that directly affects the end product. This is the result of a project environment that is well established, formed on longstanding experience, and thus well able to avoid costly mistakes by meticulous application of standardized materials and procedures as well as rigorous review of each action. Its success is shown in the high success rate of spacecraft today, commercial as well as scientific. It is well adapted to the demand for low failure rate, high cost efficiency results derived in great depth and detail from precise user requirements into an open design space, though maybe under a programmatic cost cap, within a framework of long-term planning along conceptual roadmaps paved by community consensus. But it is also liable to become cumbersome and slow in reaction to technological change as well as unexpectedly emerging challenges.

In contrast, although there were early precedents of methods more akin to such modern times [20], the high-cadence environment of the early 1960s generally seems to have accepted an approach that sometimes bordered on ‘shoot and hope’ when observed through today’s standards [13] but mostly preferred incremental development by trial [18,19] which ultimately lead to a well-tested platform that was frequently re-used once available, such as the wide range of upper stages and spacecraft bus models of the Agena series. When extraordinary events happened, it was possible in this environment to exchange payloads quickly. For example, the spacecraft 1962βκ (Starad) was created by pulling a standard payload out of the flight line and replacing it by a specialized set of radiation detectors to measure the particle products of Soviet high-altitude nuclear tests which were conducted over a then inaccessible area of Central Asia. [21] This was possible because a large fraction of the emerging space industry grew from an aeronautical industry that was still used to mass production ranging into the 1000’s of flight models. With this tradition came a similarly high production capability for mission-critical high-reliability parts which were frequently derived from aircraft experience. Specialized production experience, refurbished and occasionally ‘new old stock’ parts from this era still keep 60 year old designs airborne, such as the B-52 or 707-derived aircraft which have a high production volume in common. Rarer and exotic aircraft however lacked this benefit and had to be retired, e.g. the SR-71. [22-31]

However, in today’s environment, the need for space-grade parts has dropped not just with flight cadence but in electronics also with increased integration (cf. Fig. 2). Where once thousands of space-qualified discrete transistors or small-scale integrated circuits of the same or at most a few standard types were flown or used in hundreds of flight models [12,32] to perform a limited set of essential control and guidance functions supported by a wide range of other electromechanical, hydraulic, pneumatic and purely mechanical functional units, now a few high-end integrated circuits do most of all these jobs except for the direct actuator functions in spacecraft designed to remain in service for a decade or more. Where now performance or cost drives the design, relatively new commercial parts are merely screened and repackaged for the relevant environmental requirements, including radiation tolerance which tends to drive missions down to well beneath the radiation belts. [33,34] By the time promising parts are through full space-grade modifications including special semiconductor production processes and formal qualification, they are obsolete by a few generations when compared to similar-function device families in the commercial market where performance upgrades occur on monthly scales, new devices follow every other year, and ‘legacy’ devices may only continue in production for a few years at most until the production line has to make way for new equipment in a ‘fab’ floor space round-robin rotation.

This experience already befell the ‘Apollo gate’, a circuit designed in the early 1960s which was only continued into the 1970s in production due to and specifically for its use in the Apollo Guidance Computer (AGC). There were no other users left in the end. [12]

A side effect of this trend is that production runs of specifically modified semiconductor processes for space-grade parts which are hence radiation-hard by design and not just picked to be likely radiation tolerant only occur every few months to about annually, whereas the whole production life cycle of the commercial equivalents of such parts onto which these runs are piggy-backed usually spans only a few years. This means that these parts in their fully space-qualified version are only available a few times, ever, and all orders are pooled during a long lead time to justify every specially set up production run. However, not just semiconductors are affected: A space-qualified battery cell which has been frequently used since the late 1990s derived from one of the first commercial laptop computer battery cell types in large-scale production is now only produced once a year specifically for its space application, by one facility for one customer. In the launch vehicle sector, several critical points of the production chains scaled down after the economic collapse of the former Soviet republics depend on a few experienced people many of whom continue to work well beyond retirement age. [35] This problem is not unknown in the West: when the attitude control thrusters of the GALILEO spacecraft en route to Jupiter experienced anomalies, the people who had manufactured them as part of the German contribution to the mission were no longer available because they had long since left the company, were retired, or had passed away. [36] Of the authors, some (J.T. Grundmann, C. Lange) had similar experiences when looking for specific team members with knowledge of specific design features of the BIRD satellite [17] or the PHILAE lander which were to be re-used on ASTEROIDFINDER/SSB [16] and MASCOT [37], respectively, only a little over a decade later. This casts some doubt over the concept of 'simply' re-building previously flown space probes when a planetary defence mission has to be set up quickly as previously assumed by one of the authors (J.T. Grundmann) [38,39,40] under the assumption that the detection of a threat is possible at least unless impact is imminent [41].

Occasionally, however, there can be scientific missions that break the mould because they fit into a promising though maybe limited gap and can at the same time draw on work which has previously been done, though in an unrelated context or for another mission, demonstrating the value of re-use; one such example is MASCOT [37].

## 5. Conclusions

The focus of the original question – when does it get too small to do the job safely, where and what are the practical and physical limits of getting smaller? – has thus shifted but not blurred.

On the technological side, many methods promising for deep space and already well-tested in the millions of production units in the commercial world do exist. It is no longer entirely 'out of this world' to send a microsatellite-class solar sail which for all practical purposes never runs out of fuel towards a rendezvous with a potentially hazardous asteroid to drop a cell phone sized lander, or a few of those, to investigate its properties. Or to send another towards the Sun to spiral-reverse onto a retrograde collision course to deflect a recognized hazardous asteroid by a high specific energy impact. These technologies constitute the geometrically-small End of Small, and it still seems to have ample room for development left at least in space applications. [42]

On the side of those supposed to design and build these missions, we already live hard against the other End of Small: whatever should once become an urgent necessity, literally, in planetary defence spaceflight will have to be accomplished by those who are already there – in space jobs – and done with what is there, as space hardware. Here, stocks are at best low in the current model of space activities. Often, people in space work unpaid overtime or accept lower payment because they actually want to do their jobs, at least as long as their projects are able to support them. Often, critical components are custom-made long-lead items of which a few used and worn down in tests may still remain functional and in storage somewhere; with luck, a whole lot had to be purchased once upon a time to fly but a few, and the leftovers were too specialized to be sold for other than scrap. Change is however not impossible: if a small fraction of the means available to the flagship missions that indeed pave new roads in space is set aside to conduct small frequent-flyer missions that use these new roads, a much larger number of teams and people could gain that kind of experience in space which would be dearly needed if the scenario developed for the tabletop exercise at the end of this conference suddenly became real.

## REFERENCES

[1] S.J. Ostro, J.D. Giorgini, The role of radar in predicting and preventing asteroid and comet collisions with Earth, in: Mitigation of Hazardous Comets and Asteroids. M.J.S. Belton, T.H. Morgan, N. Samarasinha, D.K. Yeomans, (eds.), Cambridge, pp.38-65, 2004.

[2] A. Fujiwara, J. Kawaguchi, D.K. Yeomans, M. Abe, T. Mukai, T. Okada, J. Saito, H. Yano, M. Yoshikawa, D.J. Scheeres, O. Barnouin-Jha, A.F. Cheng, H. Demura, R.W. Gaskell, N. Hirata, H. Ikeda, T. Kominato, H. Miyamoto, A.M. Nakamura, R. Nakamura, S. Sasaki, K. Uesugi, The Rubble-Pile Asteroid Itokawa as Observed by Hayabusa. *Science*, **312** (5778), 1330-1334 (2006)

[3] C. Lange, R. Findlay, C. Grimm, J.T. Grundmann, T.-M. Ho, L. Witte, T. van Zoest, "How to build a 10 kg autonomous Asteroid landing package with 3 kg of instruments in 6 years?" – Systems Engineering challenges of a high-density deep space system in the DLR MASCOT project, 2624640 (1325), SECESA 2012.

[4] R. Findlay, T.-M. Ho, C. Lange, S. Wagenbach, L. Witte, C. Ziach, J. Biele, C. Krause, S. Ulamce, T. Spohn, T. Okada, H. Yano, and the MASCOT project team, A Small Asteroid Lander Mission to Accompany HAYABUSA-II, Proceedings of the 63rd International Aeronautical Congress, Naples, Italy, 2012, IAC-12-A3.4.7.

[5] J.T. Grundmann, Small Solar System Body Mitigation: A Realist's Approach, IAA-WPP-301 P206, 1st IAA Planetary Defense Conference 2009

[6] J.D. Giorgini, S.J. Ostro, L.A.M. Benner, P.W. Chodas, S.R. Chesley, R.S. Hudson, M.C. Nolan, A.R. Klemola, E.M. Standish, R.F. Jurgens, R. Rose, A.B. Chamberlin, D.K. Yeomans, J.-L. Margot, Asteroid 1950 DA's Encounter with Earth in 2880: Physical Limits of Collision Probability Prediction, Science **296**, 132 (2002)

[7] A. Milani, S.R. Chesley, M.E. Sansaturio, F. Bernardi, G.B. Valsecchi, O. Arratia, Long term impact risk for (101955) 1999 $RQ_{36}$, arXiv:0901.3631v1 [astro-ph.EP] 23 Jan 2009

[8] Gossamer, DLR Institute of Space Systems dept. System Conditioning projects page, 2013-04-08, http://www.dlr.de/irs/en/desktopdefault.aspx/tabid-6931/11365_read-26354/

[9] R. Kurzweil, http://www.singularity.com/charts/

[10] http://en.wikipedia.org/wiki/Moore%27s_law

[11] R. Saracco, http://www.blog.telecomfuturecentre.it/tag/energy/

[12] E.C. Hall, Journey to the Moon - The History of the Apollo Guidance Computer, AIAA, 1996

[13] R.C. Hall, Lunar Impact - A History of Project Ranger, NASA SP-4210, 1977

[14] A. Hildebrand et al, The Near-Earth Object Surveillance Satellite (NEOSSat) Will Search near-Sun along the Ecliptic Plane to Efficiently Discover Objects of the Aten and Atira Orbital Classes, 1700_Hildebrand May9, 2nd IAA Planetary Defense Conference 2011

[15] R. Findlay, O. Essmann, J.T. Grundmann, H. Hoffmann, E. Kührt, G. Messina, H. Michaelis, S. Mottola, H. Müller, J.F. Pedersen, A Space-based Mission to Characterize the IEO Population, P02_2149803, 2nd IAA Planetary Defense Conference 2011

[16] J.T. Grundmann, S, Mottola, V. Baturkin, J. Behrens, B. Biering, M. Drentschew, From Observational Geometry to Practical Satellite Design: ASTEROISFINDER/SSB, P117, 1st IAA Planetary Defense Conference 2009

[17] J.T. Grundmann, S. Montenegro, H. Wüsten, "Utilisation of the BIRD Satellite after its End of Operational Life," *Proceedings of the 4S Symposium [Small Satellite Systems and Services]*, ESA SP-660 (DVD).

[18] C. Peebles, The Corona Project: America's First Spy Satellites, Naval Institute Press (U.S.A.) / Airlife Publishing (UK), 1997, ISBN 1-55750-688-4 – also: http://www.nro.gov/foia/declass/collections.html

[19] D.A. Day, J.M. Logsdon, B. Latell (ed), Eye in the Sky: The Story of the Corona Spy Satellites, Smithsonian Institution Press, 1998, ISBN 1-56098-830-4 - also: see above

[20] D.P. Mitchell, Sputnik III - http://mentallandscape.com/S_Sputnik3.htm

[21] G. Kuck, in a comment during this conference

[22] D.J. Shayler, Disasters and Accidents in Manned Spaceflight, Springer Praxis, 2000

[23] H. Gavaghan, Something New Under the Sun - Satellites and the Beginning of the Space Age, Springer Copernicus, 1998

[24] T.A. Heppenheimer, Countdown: A History of Spaceflight, John Wiley & Sons, Inc., 1997

[25] J. Harford, Korolev: How One Man Masterminded the Soviet Drive to Beat America to the Moon, John Wiley & Sons, Inc., 1997

[26] J.N. Gibson, The Navaho Missile Project – The Story of the »Know-How« Missile of American Rocketry, Schiffer Military History Books, 1996

[27] J. Miller, Lockheed Martin's Skunk Works – The Official History – Updated Edition, Midland Publishing, 1995

[28] B.R. Rich, L. Janos, Skunk Works, Warner Books, 1994

[29] W.A. McDougall, ...The Heavens and the Earth - A Political History of the Space Age, Johns Hopkins, 1985

[30] M. Wade, http://www.astronautix.com

[31] S. Grahn, http://www.svengrahn.pp.se

[32] J. Ward, A Transistor Museum Interview with Dr. George Ludwig – The First Transistors in space – Personal Reflections by the Designer oft he Cosmic Ray Instrumentation Package for the Explorer I Satellite, transistormuseum.com, 2007

[33] J.C. Springman, J.W. Cutler, Photodiode Placement & Alogorithms for CubeSat Attitude Determination, CSW_04182012, CubeSat Developers' Workshop 2012

[34] J.C. Springman, J.W. Cutler, H. Bahcivan, Initial Flight Results of the Radio Aurora Explorer, IAC-11.B4.4.5

[35] personal communication from the respective manufacturers and/or service providers

[36] D. Fischer, Mission Jupiter, Birkhäuser, 1998, ISBN 3-7643-5832-7

[37] J.T. Grundmann, V. Baturkin, J. Biele, A. Bellion, E. Canalias, L. Celotti, F. Cordero, M. Deleuze, R. Findlay, S. Fredon, C. Grimm, J. Hendrikse, F. Herrmann, T.-M. Ho, E. Jurado, C. Krause, R. Kroth, E. Ksenik, S. Kuss, C. Lange, M. Lange, M. Maier, L. Melac, O. Mierheim, P. Neugebauer, T. Okada, S. Reershemius, J. Reill, B. Schäfer, H.-J. Sedlmayr, K. Stohlmann, N. Termtanasombat, S. Ulamec, M. Wrasmann, T. Yoshimitsu, C. Ziach, T. van Zoest, "You've got 2 Years, 6 Months, 1 Week and 48 Hours!" – the Ongoing Engineering Adventure of MASCOT and its Implications for Planetary Defence Missions, IAA-PDC13-04-06P (this conference)

[38] J.T. Grundmann, Betrachtung des Missionsszenarios zur Verhinderung von Einschlägen von Asteroiden auf die Erde unter Berücksichtigung des Bedrohungspotentials und der technischen Möglichkeiten, RWTH Aachen, D 2006-03

[39] J.T. Grundmann, Zuverlässigkeit von Raumflugkörpern, RWTH Aachen, 30.11.2005

[40] J.T. Grundmann, S. Mottola, M. Drentschew, M. Drobczyk, R. Findlay, A. Heidecker, R. Kahle, E. Kheiri, A. Koch, V. Maiwald, O. Mierheim, F. Nohka, D. Quantius, P. Zabel, T. van Zoest, ASTEROIDSQUADS/*i*SSB – a Synergetic NEO Deflection Campaign and Mitigation Effects Test Mission Scenario, IAA-WPP-323 S5_0910_2162714

[41] L.K. Kristensen, Apparent motion near the Earth, Proceedings of the Conference Asteroids, Comet, Meteors. ESA SP-500, pp.829-832, July/November 2002

[42] University of Michigan, http://thetechjournal.com/electronics/computer/one-cubic-millimeter-computer.xhtml