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THE SPACE WEATHER OBSERVATION NETWORK (SWON) CONCEPT – INAUGURATION OF THE DLR ADVANCED STUDY GROUP

Volker Maiwald
German Aerospace Center (DLR), Institute of Space Systems, Department of System Analysis Space Segment, Bremen, Germany, Volker.Maiwald@DLR.De

André Weiß, Dominik Quantius, Daniel Schubert
German Aerospace Center (DLR), Institute of Space Systems, Department of System Analysis Space Segment, Bremen, Germany, Andre.Weiss@DLR.De, Dominik.Quantius@DLR.De, Daniel.Schubert@DLR.De

Frank Jansen
German Aerospace Center (DLR), Institute of Space Systems, Department of Space Systems, Bremen, Germany, Frank.Jansen@DLR.De

The DLR Advanced Study Group (ASG) is a team of engineers and scientists that investigates visionary or unusual aerospace concepts regarding their feasibility and applicability to scientific problems, in an attempt to erase the "fiction" from the "science fiction" of scientifically valid ideas and make them rigorous science. To achieve this, the ASG uses established processes and new approaches for concept analysis, like so called Concurrent Evaluation sessions. One of the first ideas investigated as a testcase for this kind of evaluation is the Space Weather Observation Network (SWON). The peculiarity of space weather for Earth orbiting satellites, air traffic and power grids on Earth and especially the financial and operational risks posed by damage due to space weather, underline the necessity of space weather observation. In recognition of the importance of such observations, even more prominent due to the impending solar maximum, we propose a mission architecture for solar observation as an alternative to more conventional mission plans, like Solar Probe (NASA) or Solar Orbiter (ESA). Based upon the first Concurrent Evaluation session of the ASG in the Concurrent Engineering Facility of the German Aerospace Center, we suggest using several spacecraft in an observation network. Instead of placing such spacecraft in a solar orbit, we propose landing on several asteroids, which are in opposition to Earth during the course of the mission and thus allow observation of the Sun's far side. This is especially advantageous due to a significant improvement (about two weeks) in the warning time with regard to solar events. Landing on Inner Earth Object (IEO) asteroids for observation of the Sun has several benefits over traditional mission architectures. Exploiting shadowing effects of the asteroids possibly reduces thermal stress on the spacecraft due to cooling down phases, while at the same time it is possible to approach the Sun closer than with an orbiter. The closeness to the Sun improves observation quality and solar power generation, which is intended to be achieved with a solar dynamic system. Furthermore landers can execute experiments and measurements with regard to asteroid science, further increasing the scientific output of such a mission. Placing the spacecraft in a network would also benefit the communication contact times of the network and Earth. Concluding we present a first draft of a spacecraft layout, mission objectives and requirements as well as an initial mission analysis calculation as the results of a one day inauguration session of the ASG.

I. INTRODUCTION

It is undeniable that spaceflight had been dreamed of and described by visionaries and writers long before it became scientific fact. Novels like Jules Verne's *From Earth to Moon* were an inspiration for scientists and engineers alike and e.g. as in the case of Hermann Oberth fuelled the interest and intention to actually enable travels to the stars, making way for works like his *By Rocket into Planetary Space* or *Ways to Spaceflight*.

Just like today's spacecraft usually begin their existence as an idea, the whole concepts of such vessels be it multi-stage rocket, shuttle orbiter or something else, are born as visionary drafts altogether (s. Fig. 1).

Recognizing the need to investigate and evaluate visionary aerospace concepts for their validity, several organizations employ specialized groups to do just this, like ESA's Advanced Concepts Team [2], Lockheed Martin's Skunk Works [3] or NASA's Team-X [4].

Likewise, for the purpose of evaluating new ideas related to astronautics, the German Aerospace Center's (DLR) site in Bremen introduced the Advanced Study Group (ASG) in 2010 by the department of System Analysis Space Segment. The ASG is organized in such a way that the study team consists of engineers and scientists from various disciplines creating a think tank capable of dealing with a broad range of scientific fields.

The group collects innovative ideas with regard to astronautics and elaborates them to viable concepts with a checked feasibility. The ultimate goal is to erase the "fiction" from the possible "science fiction" of these new ideas.

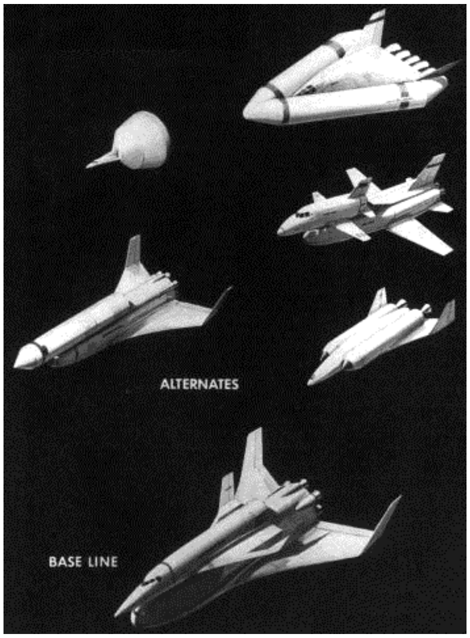

Fig. 1: Early Concepts of the Space Shuttle Transportation System [1].

The first topic to be investigated in a new process conceived for DLR's Concurrent Engineering Facility, called Concurrent Evaluation, has been the Space Weather Observation Network (SWON). This mission idea contains the proposal to use a group of landing vehicles distributed over Inner Earth Objects (IEOs) for solar monitoring to predict Sun originated space weather (e.g. Coronal Mass Ejections (CMEs), Solar Energetic Particle (SEP) events, solar radio bursts and strong changes in X-ray respectively UV emissions of the Sun) with a longer warning time than currently achievable.

Restricted due to the fact that from Earth solar observations can only see the Earth facing side of the Sun, space weather predictions cannot exceed a time frame of more than 14 days, due to the Sun's equatorial rotational period of 28 days.

Using SWON to actually look at the Earth-opposing side of the Sun could increase this amount of time by a factor of two.

As an additional benefit, the landing on several IEOs would allow further scientific investigations with regard to asteroids.

In the following we will describe the general progress of an idea through the ASG study process and a detail description of the SWON Concurrent Evaluation session conducted in late 2010 as well as its results and the lessons learned from it.

II. ASG STUDY PROCESS

II.I Objectives

Investigating, analysing and evaluating innovative concepts for astronautic applications is the overall goal of DLR's ASG think tank. More detailed objectives of the study group are i.a.:

- Analysing and driving forward future-oriented missions/ concepts
- Identification and evaluation of possible market disrupting technologies
- Developing strategies for space programmes

II.II Study Process

The ASG collects ideas from various sources, be it input from its own team, other DLR employees, or interesting external ideas into a pool of concepts by application of a questionnaire form. From this pool, ideas are chosen for further investigation.

This investigation is usually conducted by a small part of the ASG's core team, usually two experienced scientists which are promoting the idea, organize the study and give scientific input.

In addition to these two scientists, a group of about three (graduate) students conducts calculations, evaluations, surveys and other steps to elaborate the idea into a feasible concept or determine that it is in fact not feasible. Typical tasks for these three (or more) team members are:

- systems engineering,
- concept visualization (configuration, accommodation),
- providing expert knowledge (e.g. biology or medicine background).

The results of this initial study phase will be surveys of already conducted research giving an impression of current state of the art regarding the idea, an overview over technological developments in support of the idea and basic calculations concerning e.g. efficiency, gain and resources drains. One example would be limits for amount of supplied power in case of a new power generation system.

Once the study has progressed this far and the idea has been deemed valid by the study team, a Concurrent Evaluation session, a micro-study in DLR's Concurrent Engineering Facility (Fig. 2), is set up to answer critical questions, formulate requirements and propose a concept architecture with the help of a larger group of experts and scientists (s. Chapter 3).

Fig. 2: DLR Bremen's Concurrent Engineering Facility in operation during a study.

This Concurrent Evaluation session's results can then be used as input for a Concurrent Engineering study as they have been conducted for almost three years in DLR's Concurrent Engineering Facility in Bremen. Usually the student participants join ASG for a length of about six months taking part in several studies drawn from various fields, naturally matching their own scientific background. The core team members rotate for each of the study topics depending on availability and fields of expertise.

A pre-study lasts between one and three months, which can be adapted during the study in case more or less work is required to gather the knowledge necessary for a sufficiently sound result.

While ASG is still in its infancy it is the goal for its future endeavours to have two to three study groups working in parallel on various subjects.

II.III Study Topics

The ASG is fed from a pool of ideas. While the before mentioned SWON concept has been the test case for the Concurrent Evaluation method, there are further, even more advanced visions in the idea pool.

One idea is the Space-Blast Pipe, a launcher concept alternative to common rockets (Fig. 3). The spacecraft is accelerated not by propellant exhaustion but due to pneumatic principles. The evacuated tube, the actual blast pipe, houses at its bottom a platform which carries the payload. A reservoir below the platform is flooded with gas which in turn accelerates it upwards through the tube – initial calculations have shown that velocities of several km/s are possible [5].

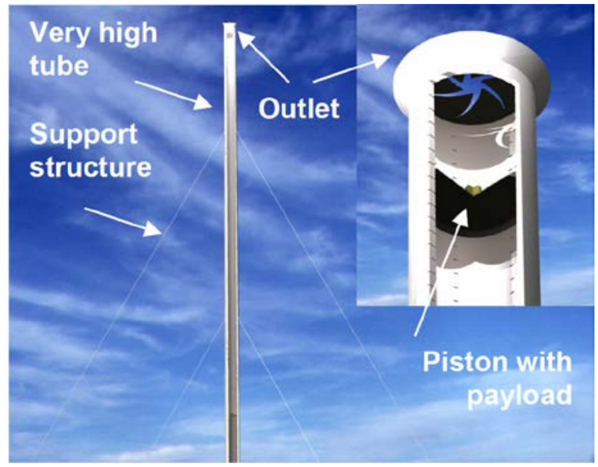

Fig. 3: The Space-Blast Pipe concept [5].

One range of subjects for the ASG is also human spaceflight, especially with regard to human habitats in space or on the surface of a planetary body.

To cover nutrition needs of a human habitat population, a so called Micro-Harvester could be used (Fig. 5). Optimization of resources and supplying the respective crop with conditions matching its current phase of growth would be the main goal for such a system while the plant is transported through it, comparable to a conveyor belt in a factory [6,7].

Fig. 5: Possible application of the Micro-Harvester concept [6,7].

III. CONCURRENT EVALUATION

The Concurrent Engineering (CE) process assembles experts from various fields of expertise, e.g. *Thermal Control* System, *Mission Analysis*, *Propulsion* or *Cost*, in a respective environment, which allows unhindered, direct and quick communication as well as exchange of data and design parameters between the various disciplines.

The process is usually divided into off-line work and moderated sessions. The former is used for calculations, investigations and documentation of work results, while the latter serves to inform the whole study team of the study progress via presentations and roundtables. Data needs are also addressed then and design issues are discussed by the whole team. Common parameters that are exchanged between the disciplines are mass, power needs, operation temperatures of components, dimensions, costs and risk.

The design process is aided by media equipment that allows the visualization and quick exchange of data and enables undisrupted communication, including the consultation of external study participants, possibly in a very distant location.

To exploit the advantages of a CE environment as present at DLR's Institute of Space Systems in Bremen for the ASG, Weiß et al. [8] implemented a method for evaluating missions with a similar concurrent approach as used during Concurrent Engineering studies, which is labeled Concurrent Evaluation and encompasses studies of short duration (usually one day to two days) in difference to full-fledged Concurrent Engineering studies of more than one week.

This evaluation is to be used for ASG and has been with the Space Weather Observation Network (SWON) mission concept. The Concurrent Evaluation method has been used for a Mission Architecture Definition (MAD) during this first micro-study session in September 2010.

Several questions are to be answered, if preliminarily, during such a session:

- What are the mission/ science objectives?
- What are the technological challenges (development needs)?
- How and when can the mission target be reached?
- What are the mission risks?

Similar to the Concurrent Engineering process, the MAD begins with introductory presentations, clarifying on the content of the idea, the science or payload side of the mission and possible mission analysis (Fig. 6), where applicable.

After these presentations, an initial feedback is gathered from the assembled experts to identify problems, requirements, general points of discussion.

Weighting these discussion points allows then the direct solving of the relevant problems in the order of their importance for the mission.

With respect to these discussion points, iteratively several mission scenarios are evaluated or sketched by the design team. Derived from the mission objectives, the design team defines the necessary subsystems and their tasks as well as the requirements for the system.

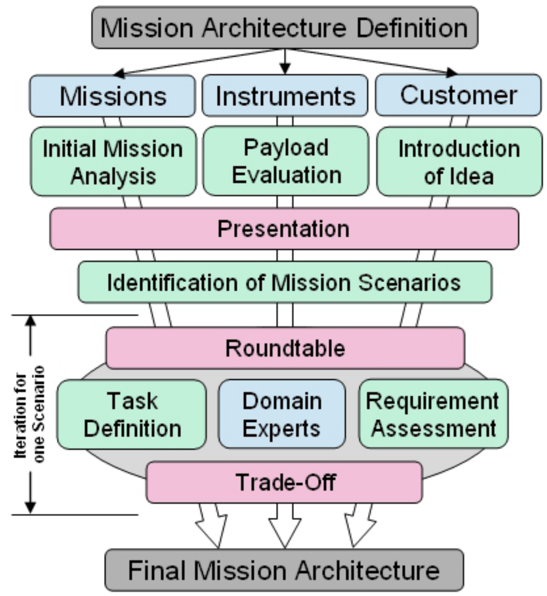

Fig. 5: A sketch of the Mission Architecture Definition Process in form of a Concurrent Evaluation.

The final mission scenarios are weighted against each other in a trade-off at the end of the study, regarding advantages and disadvantages of each mission scenario.

The results of the study, respectively the final mission architecture, are documented in a report to form the basis for a future full Concurrent Engineering study.

IV. SWON

The Space Weather Observation Network has been investigated in ASG's first Concurrent Evaluation session, to analyse the concept and to validate and test the process for defining mission architectures.

As described in Section 3, the discussion points are depicted according to their respective weights – as assigned by the study team – in Fig. 7.

Major study issues have been the advantages of the solar observation realized with the exploitation of asteroids as base of operations. Furthermore it has been discussed what technology developments are required, environmental conditions in the vicinity of such asteroids and their properties, e.g. rotational periods as they dictate and influence the observation.

IV.I Mission Objectives

The major science objective of SWON is the observation, continuous, of the solar far-side when viewed from Earth. Currently only Earth-facing observations are possible and resulting from the Sun's rotational period of about 28 days, forecasts cannot exceed a warning time of 14 days – something that can be remedied if the portion of surveyed solar atmosphere is increased by a change of perspective to a view from behind the Sun.

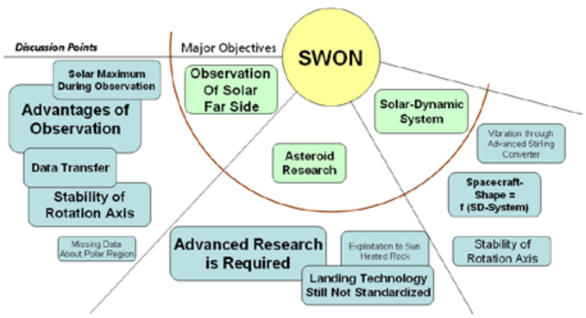

Fig. 7: The weighted discussion points of the SWON study.

Observing the far side would allow to extend by a factor of two the viewing time of coronal mass ejections (CMEs), solar storms and indicators for space weather events e.g. sun spots originating at the far side of the Sun increasing the warning time up to a maximum of 28 days.

The peculiarity of space weather for Earth orbiting satellites, air traffic and power grids on Earth and especially the financial and operational risks posed by damage due to space weather, underline the necessity of space weather observation – especially under the security aspects, which resulted into ESA's Space Situational Awareness program and related EC activities [9].

Using observatories on Inner Earth Objects furthermore is a very convenient opportunity to place instruments on small bodies which could also analyse the asteroids as well, which is the second science objective of the mission.

Third, a technological objective is to validate a solar-dynamic (SD) power system.

<u>IV.II Mission Considerations</u>

To achieve the primary science objective, solar observation, two general mission architectures can be used:

- A telescope based platform placed at distances of about 1 AU (e.g. Libration Point 3)
- A lightweight, pure sensor-based solution within Earth's orbit

As the first option is not a new mission architecture, the study team concentrated on the second option, in this case by regarding landing of such a payload on an asteroid within Earth's solar orbit appropriately timed to place it behind the Sun.

Solar-dynamic systems have already been considered for application in space based systems (e.g. as candidate for the International Space Station) but up to now no mission has been realized.

With a rotation period of a few hours, asteroids present a suitable environment for SD systems. After being charged during the day-time, the thermal storage can be used to generate power during the eclipse times. Current systems are forced to reduce their scientific operations at night as the thermal subsystem requires more power to convert electrical to thermal energy, which is not true for SD systems.

	Period[y]	a[AU]	e	i[°]
2003 CP_{20}	0.637	0.741	0.322	25.617
2004 XZ_{130}	0.485	0.617	0.454	2.953
1996 DK_{36}	0.576	0.692	0.415	2.017
2004 JG_6	0.506	0.635	0.531	18.945
2005 TG_{45}	0.562	0.681	0.372	23.329
2006 KZ39	0.475	0.609	0.541	9.925
2006 WE4	0.695	0.784	0.182	24.767
2007 EB26	0.405	0.548	0.786	8.461
2008 EA32	0.483	0.615	0.304	28.262
2008 UL90	0.579	0.694	0.380	24.307

Table 1: Properties (orbit period, semimajor axis, eccentricity and inclination) of Inner Earth Objects known during the SWON study.

While the asteroid rotation is beneficial from the thermal point of view, it precludes the primary mission objective of continuous monitoring of the Sun. To balance that, a second lander could be placed on the opposite asteroid side, therefore granting increased observational opportunities.

As there is no asteroid always opposing Earth, a network of asteroids would have to be utilized to achieve continuous coverage of the far side of the Sun, all known IEOs are listed in Table 1.

<u>IV.III Payload Considerations</u>

To fulfil the science objectives with regard to solar observation, the following instrument payload with a power drain of 2.5 W and a mass of 1.5 kg is assumed for a SWON lander vehicle:

- Flux-Gate Magnetometer
- Particle Monitor
- Gamma and X-Ray Flux Monitor
- Extreme Ultra-Violet Flux Monitor
- Small Optical Camera

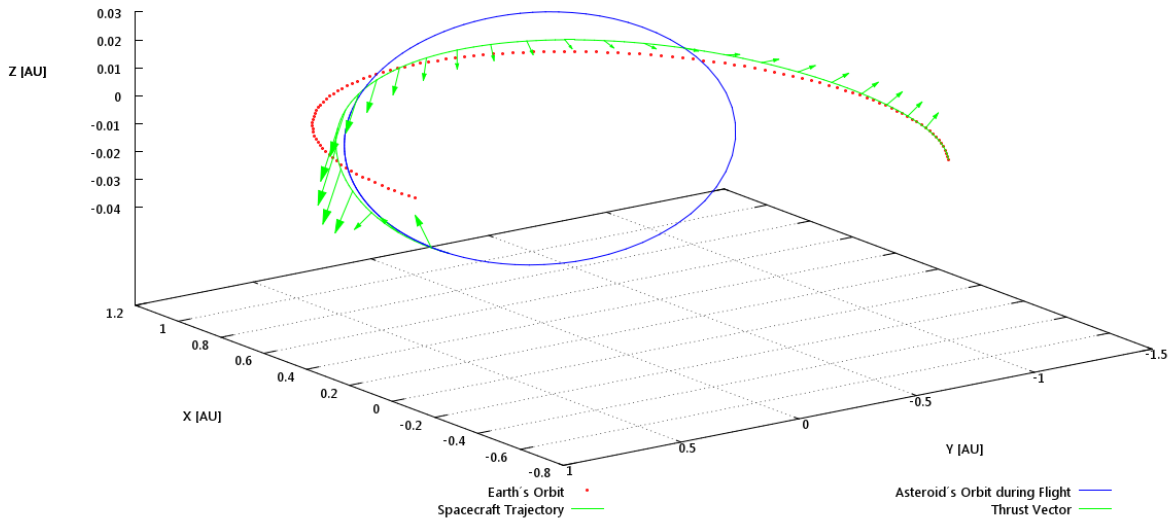

Fig. 8: Rendezvous trajectory for 2004 XZ_{130}. Green is the trajectory with thrust direction, blue is 2004 XZ_{130}'s orbit and red is Earth's orbit during transfer.

The three monitors and the camera can be equipped with the Medipix / Timepix detectors [11, 12].

The frequency of measurements is to be at least 60 Hz, and data should be transmitted every hour at least to allow a dense surveillance of solar activity.

As stated a solar dynamic generator, closely related to radioisotope thermoelectric generators (RTG), will serve as primary power source for a lander vehicle. These systems use solar power as heat source and not isotopes, thus rendering them safer. They have been considered for several missions before, however none have actually been conducted yet [12].

The basic element of common RTGs, are thermocouples. Thermocouples are based on the Seebeck effect and generate voltage when subject to a thermal gradient. Their efficiency lies between 3 and 7% [13].

While already in use, e.g. on the Cassini spacecraft, the rather low efficiency rate lead to the development of a more effective heat converter, intended for future deep space missions. It is called “Advanced Stirling Converter” (ASC) and can achieve efficiency rates of up to 30% [13].

ASCs were planned to be used on NASAs cancelled Titan Mare Explorer, originally set to launch in 2015. Even though the mission is currently on hold, the development of ASCs is already quite advanced.

Current models achieve 3.5 W/kg at 850°C and the smallest available unit weights 1.5 kg, resulting in an available output of 5.25 W. Initial calculations taking into account Venus’ solar distance as a limit, the required concentrator area is estimated to be 1.09 m² for SWON.

IV.IV Preliminary Mission Analysis

Before the Concurrent Evaluation study a preliminary mission analysis has been calculated with the help of *InTrance*, an optimization code combining evolutionary algorithms with artificial neural networks [14].

The initial calculations, using a very basic spacecraft model, showed that a rendezvous with more than one asteroid is probably not feasible in the given mass range and with electrical propulsion, but flybys could possibly be achieved with a number of about three asteroids. This has been the reason why it has been discussed during the study to have the carrier vehicle bring the landers into the vicinity of the possible target asteroids but have the actual rendezvous manoeuvre be done exclusively by the lander vehicles in order to save fuel mass.

Once the spacecraft had been specified more thoroughly during the MAD session, mission analysis has been redone using all known IEO as listed in Table 1.

The properties of the spacecraft used for the refined calculation are as follows:

- m_{dry}: 250 kg
- 50 kg < m_{fuel} < 250 kg
- P_0 (at 1 AU): 14 kW
- 2 RIT-22 ME engines (1.365 kW < P_{ops} < 6.209 kW, I_{sp} = 4700 s),

where m_{dry} is the spacecraft's dry mass, m_{fuel} the range of allowed fuel mass on board, P_0 the solar power supply at a solar distance of 1 AU, P_{ops} the power for the operation of the engines and I_{sp} their specific impulse. Ratios for power specific mass flow and thrust, where assumed to model the changes due to difference in solar distance variation.

Two possible targets were found using *InTrance*. Assuming a flight time of about half a year, the launch date was first varied from end of March to end of August 2024, thus ensuring an arrival before 2025, when a solar maximum is expected. The second calculation has been done for a launch date in 2013 to check the possibility of a rendezvous for the next solar maximum in 2014.

For the first target, 2004 XZ_{130}, the trajectory is depicted in Figure 8.

The colour blue denotes the target asteroid's orbit around the Sun, red is Earth's path around the Sun during the transfer and green the actual spacecraft trajectory along with the thrust direction. It is clearly visible that the spacecraft has to adapt the radius of its orbit and especially the inclination.

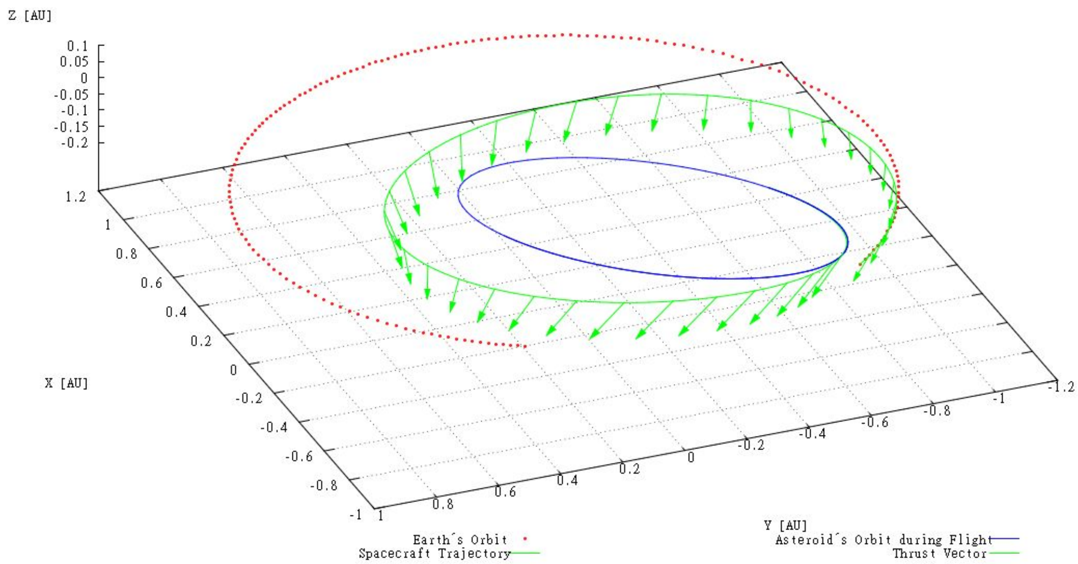

Fig. 9: Rendezvous trajectory for 2006 KZ_{39}. Green is the trajectory with thrust direction, blue is 2006 KZ_{39}'s orbit and red is Earth's orbit during transfer.

The launch epoch for this transfer is the 12th May 2024, the arrival will be 229 days later on 27th December 2024. The transfer takes 87.6 kg of xenon propellant and results in a difference in velocity to the target of 0.108 m/s at a positional accuracy of 693.2 km.

While at the end of this trajectory, 2004 XZ_{130} is not opposite of Earth relative to the Sun, it has a different orbit that will place it soon at such a position. An actual proximity to Earth during the initial encounter could furthermore benefit the rendezvous and arrival operations.

The second possible target is 2006 KZ_{39}, as determined by *InTrance* calculations, and the transfer to it is shown in Figure 9 with the same colour coding as before. And again the largest effort by the propulsion system is given into changing the inclination as visible through the thrust vector direction.

The launch date for this transfer is 1st of May 2013 and the arrival date is the 21st February in 2014. A total of 161.5 kg of fuel are needed to make the journey and the final velocity difference at this trajectory is 188.2 m/s with an accuracy of 21,490 km.

While the rendezvous conditions are very close to the given maximum velocity difference of 200 m/s and of far less quality than the previous example, the position of 2006 KZ_{39} at the end of the trajectory is far more favourable for viewing Sun's backside because it is almost opposite to Earth. This calculation shall therefore show the possibility to attain such a configuration, even though execution of the mission at that early date can possibly be excluded.

IV.V System Considerations

During the course of the study, the experts discussed three different mission scenarios, for a prolonged observation of the Sun's backside when viewed from Earth. Two major outlines have been debated during the study:

I. A standard satellite mission (e.g. at Libration Point 3, generally: behind the Sun) (designated Option 1)
II. A mission exploiting IEOs as observation points

The latter alternative, which has been the initial mission idea, was studied in two variations regarding the mission size:

a) Landing of a single vehicle on one asteroid as proof of concept (designated Option 2)
b) Implementation of a full network for ongoing observation over a long duration by deploying several landers (designated Option 3)

One major result of the Mission Architecture Definition study was, that the envisioned full observation network was impossible to realize due to the general lack of knowledge regarding asteroids.

It was therefore decided to combine a technology demonstrator for the envisioned concept with already existing asteroid mission plans. As some of the participants of the SWON study were already involved in the MASCOT CE study has been used as baseline design.

	Demonstrator	Network
Mission Duration	2 years to cover the complete solar maximum	> 2 years, to justify costs
Target Acquisition	Minimum of 14 days observation time (half a rotation)	Continuous solar observation
Misc.	Asteroid composition and properties need to be known	

Table 2: Preliminary mission requirements for SWON.

	Demonstrator	Network
Max dry mass	250 kg	900 kg (scaled up from demonstrator for several landers)
Instruments	Placement unobstructed from view	
Payload mass	Equal share of instruments for solar and asteroid science (ca. 5-6 kg total)	
Communication	Undisrupted contact to Earth	

Table 3: Preliminary system requirements for SWON.

MASCOT respectively its smaller brother MASCOT-XS is currently intended to accompany Hayabusa-2, set to launch in 2014. The present study resorts to an earlier design version with autonomous landing/ stabilization capabilities. The configuration utilizes a landing gear derived from Rosetta's Philae and has an overall wet mass of 43 kg, including an available payload mass of 7.5 kg [15].

Furthermore as planned for MAD studies, the team formulated the system (Table 2) and mission (Table 3) requirements.

One complication identified during the study has been the asteroid environment. First, the rotation periods and axes of asteroids are usually not stable, which means predictions about observation durations, target acquisition of the Sun, etc. are difficult to obtain.

Actual landing on the target can be challenging due to uneven surface structures and generally unknown properties like e.g. surface strength. Low gravity of the target requires anchoring on the surface. As for Option (3) several targets are necessary, it has to be checked how dissimilar the possible targets are regarding their properties and if it is possible to design a lander suitable for a broad range of asteroids or if each lander has to be individually adapted to its target.

It has to be investigated whether the heated rock/ material of the asteroid around the lander has effects on the thermal generator process or whether it can even be exploited.

IV.VI Open Issues

Due to the fact that the SWON MAD study took place on only one day (although intensive preparation and analysis in the aftermath took place), there are several issues that need further in-depth attention as they are mission critical. These issues include the investigation of:

Communication Concept

- How can a durable communication link with Earth be ensured?
- Data transfer has to be allowed at least once every hour.
- Is the network architecture exploitable for communications?
- Can the carrier vehicle be used as a relay?

Science on the carrier vehicle

- Can the carrier vehicle of Option (2) be used for further science, if so, how?
- What scientific payload should be onboard of Options (2) and (3) besides the lander vehicles?

Solar Dynamic Power Generator

- Operational characteristics need to be specified
- What effects are caused by vibrations?
- What medium is used for heat storage and what are its properties?

Target rendezvous scheme

- Should the rendezvous with each target be performed by the carrier vehicle or by each lander itself after a flyby of the carrier vehicle?

These questions could be answered by further investigation of the subject in form of a continued study possibly in DLR's Concurrent Engineering Facility.

IV.VII Lessons Learned

Besides the engineering aspect also the MAD methodology has been evaluated in the study aftermath.

It was shown that due to the restricted amount of time available for the study, a clear structure of the discussion was necessary. The study moderator is required to keep the discussion open and prevent debates between merely very few members of the study team about minor issues.

The initial feedback round proved to be effective in starting the discussion and identify study contents.

Furthermore the noting/ recording of major issues the above described mind map allows efficient use of the study time.

It has also been shown that the scientific mission requirements should be set very early in the process, to prevent changes during the study, which make the previous study work useless. Clear science goals and requirements are mandatory for efficient time allocation for the various to be discussed issues. The same is true for calculations of subsystems or conditions, which are regarded as showstoppers or mission critical right from the start in this case the possible power output of a ASC.

V. CONCLUSION AND OUTLOOK

The DLR Advanced Study Group is a recently created think tank tasked with analysing and studying visionary, yet not unrealistic, missions and system concepts with regard to astronautics. Currently still in the building phase, ASG uses i.a. the DLR's Concurrent Engineering Facility for one-day studies for defining mission architectures and formulating requirements and objectives, e.g. as preparation of full-fledged CE studies. A test case implemented for the Space Weather Observation Network has proven the concept of these one-day studies.

The next steps will encompass the setting up of study teams for numerous studies, while the study processes are tested and where necessary adapted.

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