

“Automation & Robotics (A&R) within the German Space Program

On-Orbit Servicing of Satellites (OOS) as a major application field

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1. INTRODUCTION AND ABSTRACT:

The drivers for nowadays and future space missions are twofold. One major focus targets the improvement of life on earth. The other focus is science oriented and targets the exploration of the universe and our solar system in particular.

But no matter which area we are looking at, both require sound technology developments to provide the necessary means to accomplish the related goals. Therefore it is self-evident that ever since the early days of space flight the field of Automation and Robotics (A&R) played a key-role in the preparation and performance of space missions.

One of the major mid term application fields of Automation and Robotics will be the unmanned servicing of space flight infrastructure elements in the earth orbits. With this application area for the first time in history we are facing challenging requirements derived not only from a scientific and technological point of view but also from commercialization aspects.

2. VISION AND APPLICATION AREAS FOR A&R:

Besides the already started and further to be extended implementation of infrastructure elements on the earth orbits for advanced communication, navigation and observation the missions to bodies in our solar system are a steady source for new challenges and thus technical requirements. Some exemplary application areas are unmanned or manned outposts in the Langrange Points, on the Moon or on Mars. Others would be missions to the hot and cold planets incl. their moons or probes to investigate the sun.

In DLR's space program and thus for the A&R sub-program the following application fields are stipulated as the major activity areas to be worked on:

- Servicing tasks pertaining to the satellite infrastructure on the Earth orbits
- Experiment, crew and operations support for the ISS
- Erection and operation of an interplanetary infrastructure for the exploration of the solar system

The further development and increase of the capabilities necessary to provide unmanned servicing of orbital elements and the derivation of progressive, next generation satellite design features are considered as being high priority tasks to be accomplished within the years to come.

DLR considers the mastering of the capabilities for on-orbit servicing and putting in place related systems on orbit and on ground as major stepping stones on the way to manned and unmanned exploration of bodies in the Solar System. In both cases we are basically facing the same technological challenges. After being set-up in the Earth orbits doing servicing tasks as day by day space operations we can tackle tasks of the next higher level of complexity like traveling from planet to planet or building up planetary stations for exploration and later even exploitation.

2.1 Infrastructure Elements:

To accomplish the scientific and technological goals in the above mentioned application areas means to develop, launch and operate three categories of infrastructure elements: Free flying robots, mobile surface robots and service facilities for the outposts. Some of these elements will be remote controlled, widely autonomous systems, others will be developed for the at least temporary presence of men.

2.2 Capabilities and Technologies:

The implementation of these infrastructure elements is equivalent to the provision of the capabilities to reliably do interplanetary and planetary navigation, rendezvous, capturing, docking & berthing of satellites, material processing, regeneration, handling and storage, fast high data rate communication and environment monitoring and control.

Having this in mind it is easy to derive a list of technologies to focus on in the future. For example one needs advanced man-machine interfaces to directly or indirectly operate the systems. Virtual presence is here one of the major catchwords. Integrated modular real time software systems are required to control the robot incl. all subsystems. To increase the systems autonomy and to support human operators requires in particular the intelligent assessment of the robot environment. The acquisition of a broad and widely complete picture of the area of operation needs further improvement of high speed sensor data processing and the development of progressive methods for sensor data fusion. Manipulators together with advanced actuators and the parallel use of a variety of sensor types provide the necessary ability and skill to handle things. Flexible attitude detection and control needs to be put in place to allow complex maneuvers in the orbits and on planetary surfaces. Modern database technology will provide the artificial brains to the robots. It needs to be stressed, that either one of these technologies is a pre-requisite for the long term operation of the above described infrastructure elements and they are all of major importance for manned as well as unmanned missions.

2.3 A Changing World:

The modern society constantly creates increasing needs for advanced worldwide telecommunication and navigation, reliable weather forecasts, transnational agriculture planning etc.. This is of course directly translatable into technical and technological requirements for the extension and operation of an orbital infrastructure.

But clearly, since space activities are no longer just driven by scientific goals space flight entered into a new era. Space activities started out from mainly being funded by public/governmental budgets but now more and more commercial undertakings are underway to adequately serve Earth's population. This is a new quality of space flight and consequently leads to a new quality of requirements, requirements which reflect and have to reflect the economical boundary conditions necessary to create and run viable businesses.

In future the programs of the space agencies also have to take these findings into account. They need to respond to them by reviewing critically their existing programs and, if necessary, come up with a redefinition of their programmatic emphasis.

2.4 Programmatic Emphasis:

The responsibility for scientific and exploration mission clearly remains with the space agencies. In the area of commercial utilization of space the agencies have to take a precursor role and act as a pathfinder and motor. Thus the programmatic decision at DLR was to split the effort and actions to be taken in the area of automation and robotics into three major corridors in parallel:

- End-to-end system engineering aspects and technology demonstration missions
- Market potential analyses and PPP-ventures
- Subsystem and components development where necessary and on the basis of requirements derived from to two corridors above.

These three areas will form the basis for the definition and selection of the agency funded space projects to transform the programmatic decisions into operational systems.

3. ON-ORBIT SERVICING (OOS) - THE NEXT CHALLENGE IN SPACE

3.1 Activities with respect to On-Orbit Servicing (OOS)

In 2001, besides purely technology-oriented activities, DLR decided to look at the non-technical aspects of space A&R, especially of OOS of satellites. A first study was kicked off to assess the potential market of OOS globally in a high-level approach. The study was conducted by the company JOERG KREISEL International Consultant of Germany (JKIC) and supported by sub-contractors from the UK and the US. It was the first of its kind and brought up new findings and recommendations. As a major result it became clear that the challenges and implications of OOS were not yet understood appropriately. Since OOS activities were driven by different groups, using in-coherent terminology and were spread around the globe, DLR decided to try to create an international OOS community (logo, website, for a, etc).

Around the same time (spring 2002), based on long-standing activities in space A&R and collaboration, the two agencies DLR and the Canadian Space Agency (CSA) signed a memorandum of understanding (MoU) on "Co-operation in the field of Space Robotics" with special emphasis on OOS. As one of the first activities under this MoU an bilateral workshop "OOS 2002 - Defining a Way Forward" was organized to bring together potential stakeholders and specialists on OOS from a variety of backgrounds. The workshop was held in November 2002 in Germany. 52 participants from 11 countries attended the event (see www.on-orbit-servicing.com; all presentations are available for download - this website shall soon serve as "the OOS website"). Meanwhile a follow-on study focuses on selected issues of OOS and its commercial implications. In parallel DLR supports the 2003 master class of SpaceTech (master of space systems & business engineering), which comprises a 1-year central case project dealing with OOS (results will be available in 2004).

3.1 The OOS Challenge

Servicing of satellites (OOS) could theoretically take place in all major orbits (GEO, MEO, LEO, GTO) and deal with all types of satellites (tele-communication, earth observation, navigation, science) operated by public (civil, military) or commercial entities. Furthermore servicing might be needed at various stages of a satellite life and on a scheduled or an emergency basis. The interaction between a servicer and the target satellite (see definition below) is therefore only part of the game. Mission architecture and logistics seem to require more creativity since the necessary A&R capabilities are available to a large extent. Nevertheless business economics will determine whether OOS will become a reality. Also of great importance is the overlaying political, legal and regulatory environment, which influences all of the above (e.g. in case of debris removal or de-orbiting).

3.2 Defining Servicing

In past and current projects related to on-orbit servicing, the services have been defined in various ways. Such definitions to a large extent are either incoherent, i.e. not directly comparable, or they just cover only subsets of the potential application. In a simplified view, services are to be conducted by "servicers" (service vehicles), which serve "targets" (satellites with a particular service need). In order to understand best the potential on-orbit servicing market it is useful to look at individual servicing tasks and their issues in a rather general way. Since the study focus was to consider all possible satellite servicing activities and to simultaneously verify the influence of co-operative satellite design, it was necessary to streamline, extend and partly re-define existing definitions of potential on-orbit services. In this context 3 distinctive "classes" of satellites can be identified (* need for co-operative satellite design):

1. "Motion": a servicer moves the target in a particular way and for a particular reason^{*)}
2. "Manipulation": a servicer physically manipulates the target and/or needs to be connected to it^{*)}
3. "Observation": a servicer remotely gathers information from the target

Each of the three service classes can cover various and mutually exclusive "kinds of service", which have been defined as follows:

- "Re-Orbiting": move of target to/on its target orbit (motion)
- "De-Orbiting": move of target to graveyard orbit or initiation of destructive re-entry (motion)
- "Salvage": salvage of target to e.g. orbital station or non-destructive return to earth (motion)
- "Maintenance": re-fueling or other re-supply of the target (manipulation)
- "Repair": diagnosis and correction or repair of failures or faulty units of the target (manipulation)
- "Retro-Fit": upgrade, update or exchange of orbital replacement units (ORUs) on the target (manipulation)
- "Docked Inspection": system and fault diagnosis of the target using physical connectors (manipulation)
- "Remote Inspection": remote system and fault diagnosis of the target (observation)

Such unified service definitions can now be used to describe any means of service by e.g. combining kinds of services from the different service classes (modularized).

3.3 Servicing Baseline and Market Model

In order to capture all theoretically possible OOS options the above defined services need to be mapped to to a typical satellite lifetime. In particular it is important to identify a typical failure profile over the satellites lifetime. Doing statistics allowed to identify this profile: 5% lost by launch failures, 5% injection failures, 5 % malfunctions during the first year of operation and 50% anomalies during their final 2-3 years of life. Using this as a rule of thumb a servicing baseline can be drawn. This baseline covers emergency events as well as scheduled service needs.

Some services may be needed only at a certain period during a satellite life, others may occur repeatedly and some may occur randomly at some point within the overall satellite lifetime. Therefore the following can be stated:

- Each successful service brings a troubled satellite back to function, which theoretically – in particular when considering co-operative design – can happen more than once during on-orbit life of the same satellite (⇒ servicing loop), which is reflected by the market model.
- Re-orbiting only applies in case of injection failure and returns the targets to the servicing loop (to early-orbit-life).

- During the early-orbit phase all services may potentially apply (except for re-orbiting and maintenance!) and targets may be returned to the servicing loop.
- During the end-of-life phase basically all services potentially apply (except for re-orbiting and repair).

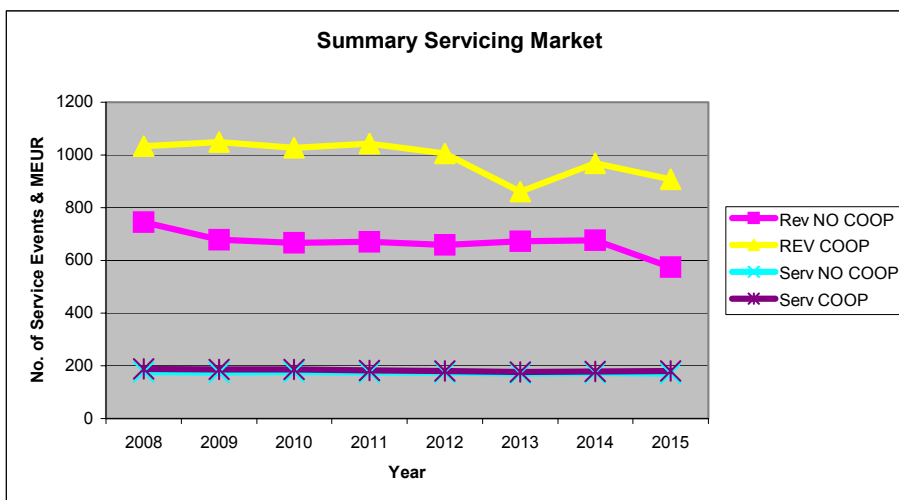
It also becomes clear, that some service types depending on the phase of on-orbit satellite life will either be of emergency or scheduled nature, e.g. retrofit (ORU exchange) during early orbit will be an emergency service, while in a end-of-life situation such service would be planned, respectively scheduled.

3.4 Generic inputs

The above describe market model was developed on the basis of generic inputs. Those were the >500kg saltellite population, the service definition, satellite failure profile and the servicing baseline (see above). Furthermore credible assumptions on probabilities of OOS events and related prices needed to be created. Other assumptions about the different satellite types in the various orbits, co-operative/non-cooperative design, benefits for the customers of the various services etc. have been used for validation. The validation process led to the identification of drivers and the other issues related to OOS from which then recommendations for policies and new activities in both areas technology and commercialization could be derived.

3.5 Overall Potential OOS Market

The investigations during the study identified a need of approximately 100 services annually. Overall this results in an potential OOS-market in the range of EUR 0.5-1 bill p.a. On the one hand these are promising figures but on the other hand at the time being it is still unclear which percentage of this potential market can really be captured and if so, within what timeframe. It is not surprising that co-operative satellite design will be a major driver of this market. On average it'll enable a number of high-value services which represent roughly a 30% market share. However, even without co-operative satellite design the OOS market will be in the several hundred million € (Euro) range. These figures are quite comparable to market values of projects like Galileo or Infoterra (direct revenue potential), which became possible only due to sound political backing and initial public funding.



3.6 The OOS Questions

The OOS issue raises 2 major questions. Number one: "What is the service need?" and number two: "Is such service feasible?".

Therefore, as already mentioned above, satellite failures have to be clearly understood in terms of their technical causality, their probability and the time of their occurrence during the satellite life. This will be the prerequisite to determine the impact of specific failures on individual missions and on the operator of the satellite respectively. Only by understanding the operator's (and maybe the insurer's) situation one can estimate the value of a service and decide, whether there is a need for it or not.

In return a servicer needs to be designed based on such service needs and its timeliness, availability of technology especially in the area of A&R, the target satellite's orbit, the target satellite's design, etc.. However, such servicer design has to be developed and optimized to be able meet cost and other economic requirements. Only if these two streams can be matched OOS will become a reality.

3.7 OOS 2002 Workshop Vision

At the OOS 2002 workshop a vision for OOS was developed. Obviously OOS needs international collaboration and immediate actions. In order to develop OOS and to make it part of future space infrastructure, activities need to be launched at the level of space agencies, industries, legal and regulatory bodies. Within the next 20 years several major actions will be necessary. Regulatory bodies should allocate a frequency band dedicated to OOS and set the legal framework for satellite disposal and debris issues. Industry needs to develop a commercial business case for OOS and to demonstrate its in-orbit servicing capabilities. This may lead to a first generation OOS within approximately 10 years and orbital supply platforms in a 20 years timeframe. Within the next five years, the space nations and their agencies should develop a OOS policy incl. A budget line and coordinate their individual efforts on international level. An important element will be a technology development roadmap of the space agencies. The International Space Station (ISS) and its utilization should be incorporated into these activities and considerations. It could benefit from dedicated OOS and at the same time serve as demonstrator platform. Within the coming 10 years on agency level a paradigm shift towards an infrastructure availability needs to take place. It should target a large space infrastructure assembly and full servicing availability in something like 15 -20 years from now.

4. FROM PROGRAM TO PROJECTS

Since many years now the German Space Program and its A&R subprogram in particular follows the above mentioned programmatic lines and takes the findings concerning OOS into account. The selection of present studies and projects reflects the described programmatic decisions. The contents and the priorities of the activities were determined accordingly and they have a clear technological heritage from past developments and missions. Advanced modular ground control systems and ground based operations support, e.g. through ground radar guidance, build another important field of work to provide adequate preconditions for successful missions. In addition the agencies portfolio of space activities got enriched by business and market considerations, especially in the area of on-orbit servicing.

At the time being DLR concentrates on ISS applications and unmanned on-orbit servicing. In detail the current projects and studies are:

ROKVISS, Robotic component verification of ISS

VITAL IV, Virtual reality (VR) system as an advanced tool (MMI) for design, experiment preparation, training and operation of space systems

RASAV, Radar based methods for the measurement of satellite orbits and dynamics

TECSAS, Technology satellite for verification and demonstration of space systems
MARTPOOS, Market potential for on-orbit servicing (OOS) of satellites (already described above)

4.1 ROKVISS

The goal of the ROKVISS mission is the in-flight qualification of DLR's light weight manipulator for space applications. Lightweight means here that the manipulator is able to carry loads under earth gravitation in the order of its own weight. In laboratory experiments for example a 13 kg manipulator based on this special joint technology was able to lift a 10 kg mass and move it around.

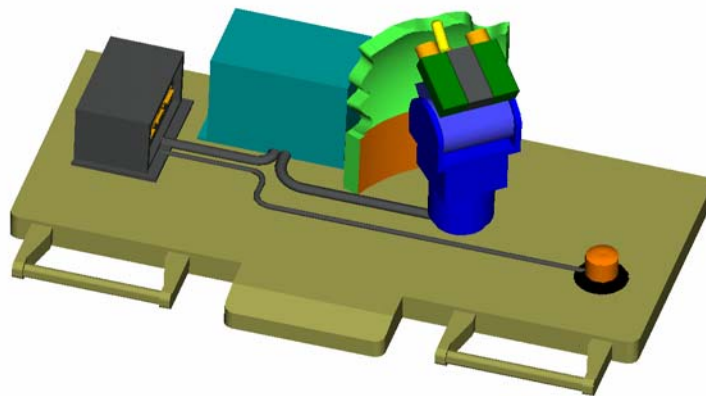
For verification and qualification of the H/W a test manipulator will be accommodated on the outside surface of the Russian Service Module of ISS. There it will be operated periodically throughout one year of experimenting.

The on-board system will be connected to a ground station via a direct link.

Besides the space qualification another goal of the mission is the test and verification of different operation modes. E.g. it will be demonstrated a fully autonomous mode, a ground commanded mode with an operator in the loop and signal round trip times longer than 500 ms and a tele-presence mode with maximal 500 ms signal round trip time.

In addition the downstream data sets will be analyzed by software algorithms developed at DLR together with the Canadian Space Agency, CSA. These algorithms will allow to identify the actual robotic parameters under mikro-g conditions and will determine the contact dynamics during the robotic experiments. Through a file upload it will then be possible to online optimize the on-board controller as well as the on-ground simulator and thus the dynamic and kinematic behavior of the manipulator system (flight unit).

The onboard experiment set-up is shown in the following sketch.



It consists of 2 joint units, the electronic box, an antenna and a wide angle camera for the observation of the manipulators neighborhood.

4.2 VITAL

One of main goals of VITAL was and is the development and implementation of a virtual reality system (VR-system) to enable astronauts, operators and scientists to be virtually present where real presence would be not desirable. Such systems build an amendment to the automation technology in the past which mainly focused on remote commanding and analyses of down link data. With the VR system a new quality is added in the sense that a person can dive into a virtual world, experience it and interact with it in the same way as in reality. Thus the system is not only a valuable tool

during the mission, it's as well extremely useful already in the preparation phase. Applications are wide spread from space system design over the provision of realistic mission training and simulation to remote control of space systems. An operator does not longer need to be an expert for the system he wants to use. So called virtual methaphers provide him with the capability to intuitivly control the on-orbit system. It's also a very useful tool with respect to the publication and demonstration of mission objectives and results. Space can easily be made available to the average person. All displayed objects and their interaction resemble 1:1 reality and are computer animated on the basis of data collected by sensors on space probes and robots.

VITAL was a 4-step program. At first a study was understaken to proof of the usability and benefit of virtual reality concepts (S/W & H/W) for space applications. In a second step DLR contracted the development of the VR-system on work stations and its demonstration by performing a satellite capture and repair task in the laboratory. The ready developed and tested system was then transformed into a PC version to reduce the very high cost of computer hardware for the potential scientific users. During the last step a pilot application of the VR-system was implemented. It got prepared to be used for astronaut training and experiment preparation - and perhaps in furture also for operation - in Columbus Orbital Facility (COF) of ISS.

4.3 RASAV

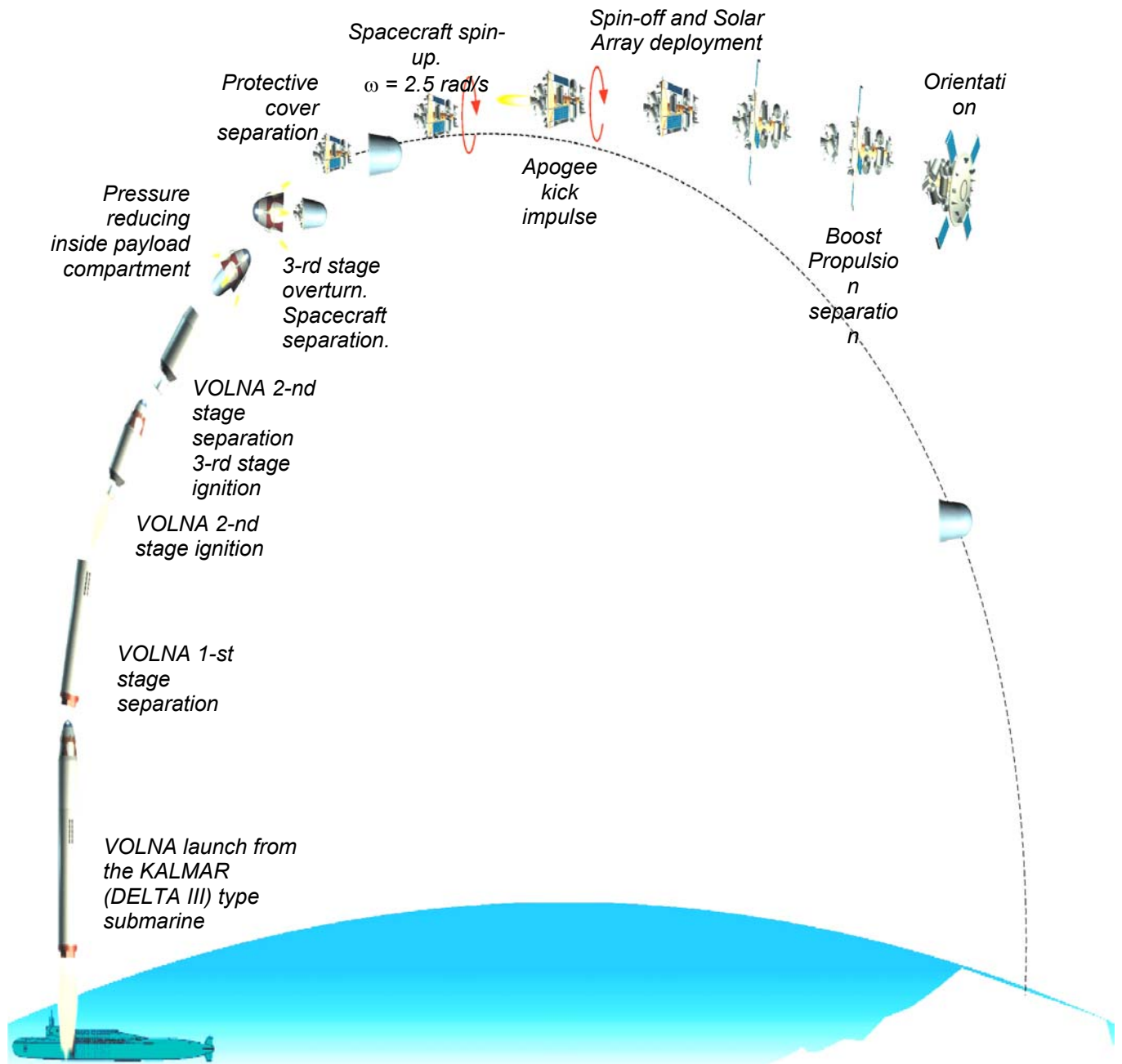
RASAV is a support activity to perform safely orbit maneuvers in low earth orbits up to geo-stationary orbits. Ground radar based measurements together with advanced failure compensation models provide comprehensive knowledge about the satellites orbital data and it's dynamics. Further a mathematical method to calculate the orbit progression over time and the implementation of a real time tracking algorithm which is independent of the availability of orbit parameters is currently under development. On top of that work a continuos improvement of existing data processing methods is carried on to create radar images and radar movies of object on the orbits. This features aims in particular at the assessment of the systems status in case a failure occurs.

4.4 TECSAS

At the time being TECSAS is the central activity in the German A&R program. The TEChnologiY SATellite for demonstration and verification of Space systems will be developed by German industries and research institutes in cooperation with the Russian Babakin Science and Research Space Center in Moscow. Further the Canadian Space Agency (CSA) is interested to contribute to the mission.



For the TECSAS mission two small satellites of the 200 kg class will be used. The spacecrafts will be launched into a 500 km orbit by a Volna rocket and an additional boost propulsion system. For the operational phase of the mission the boost engine incl. the tanks will be separated from the satellite.



Once the satellites are operational in orbit the mission shall proof the availability and advanced maturity of the technologies necessary for unmanned on-orbit servicing (OOS) of space infrastructure elements from low earth orbits up to the geo-stationary positions. During the different mission phases the following features will be demonstrated:

- Approach and rendezvous
- Inspection fly around
- Formation flight
- Capture
- Stabilization and calibration of the coupled satellite pair
- Flight maneuvers with coupled satellite pair
- Manipulation of the target satellite
- Active ground control via tele-presence
- Passive ground control during autonomous operations
- Thrust control for disposal or de-orbiting
- De-coupling of the compound

Especially in the light of future commercial applications of these technologies it'll be an important result of the mission to demonstrate the dramatically different complexity of cooperative and non-cooperative targets for such servicing tasks. Thus this mission will represent a major mile stone for the definition of future satellite design and business driven space operations.

5. CONCLUSION:

Since many years science and industry use automated and widely autonomous systems in a broad spectrum of applications. Nowadays production, manufacturing and fabrication is no longer conceivable without sophisticated automation and robotics. This is still different in space flight. Despite of some spectacular successes in the past the utilization of "intelligent" systems in space missions is still in an initial state. Commercial oriented missions to provide services like inspection, maintenance, refueling, re- and de-orbiting, station keeping etc. are even more in their very beginnings.

Thus DLR Space Management puts major emphasis on the enhancement of space system autonomy and the level of automation on the basis of requirements created by the public and the commercial domain for future space utilization.

Tasks inside and outside of the International Space Station (ISS) as well as on-orbit servicing of satellites (OOS) and the exploration of the solar system and other celestial bodies will benefit from those developments. The combination of new information technologies, highly integrated mechatronics and advanced actuators and sensors together with powerful simulation tools will open up a large array of space applications in the future.