ON-ORBIT EXCHANGE OF EQUIPMENT FOR GEO SATELLITES

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INTRODUCTION

Today, satellites in orbit can be functionally reconfigured through automatic or ground commands or software modifications. This on-board evolution is limited by the architecture, the redundancy approach and the on-board resources. On-Orbit Servicing seems an attractive approach as providing the satellite with additional degree of freedom in the management of its configuration and in its mission evolution.

The fleet of GEO satellites presents two interesting features for the servicing: several (up to tens) satellites on the same orbit, allowing to share the cost of a servicing system, and a permanent visibility favouring monitoring of the key operations and safety. The drawback is the GEO itself that is costly to reach and sensitive to any debris.

The key technical issues of the satellite servicing are the automatic rendezvous and docking with an operational satellite and the automatic in orbit robotic operations. In Europe, automatic rendezvous and docking has just been demonstrated with ATV. Automatic unmanned in-orbit servicing has been experimented for the first time in May 2007 in US with the Orbital Express flight demonstration.

The design of the satellites shall be adapted to make feasible the servicing tasks, integrating as needed adequate servicing provisions (connectors, grapple fixture, etc). The level of this adaptation depends on the expected services.

This paper presents some results of a study carried out on behalf of ESA by an industrial team, led by EADS Astrium with Austrian Aerospace, Dutch Space, Katholieke Universiteit of Leuven and Trasys Space. This study also benefited from Eutelsat SA consultancy.

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THE SERVICING MISSIONS

Different servicing missions could be proposed to the client satellite all along its lifetime. They have been assessed in order to select those missions which could be attractive for customers.

The selected servicing missions are summarised in the Fig 1. They all require an automatic docking capability as a minimum. Their level of impact on the satellite design depends on the service and varies from a few adaptations to a new design.

Extension of lifetime or orbit raising could be done by keeping a vehicle providing attitude control and propulsion function attached to the satellite. There are minor impacts on the satellite design. The lifetime extension or orbit maintenance service is requested following a propellant exhaust or a propulsion system failure. In case of orbit maintenance, the failure occurs during the satellite life and the servicer allows to maintain operational a satellite still having a high value. Orbit raising consists in repositioning the satellite or tugging it to the graveyard orbit.

The refuelling will require fluid connections and some adaptation of the satellite propulsion system. It concerns mainly the chemical propulsion satellites. It allows to reduce the satellite mass at launch and also to extend the lifetime of the satellite, for instance in case of propellant exhaust.

Both in-orbit repair and mission evolution services rely on automatic exchange of equipment with robotic means, and require a serviceable design of the satellites.

The repair mission consists in exchanging failed equipment because it resulted in a partial or total loss of the satellite mission, or to recover the redundancy level. It would concern platform equipment like on-board computer, gyro-package, solar array drive mechanism, battery modules, and payload equipment like antenna, drive electronics, etc. It is used on demand, when the failure has occurred. For the operator, the aim is to recover as soon as possible its economical return and thus the interest in repair depends on the time of the failure (first or last years of the satellite); for the insurer, repairing the satellite could be cheaper than supplying a new one. A major constraint on this mission is the delay of intervention: 1 year is acceptable in general, but, in case of significant reduction of mission and depending on the type of market, less than 6 months could be required.

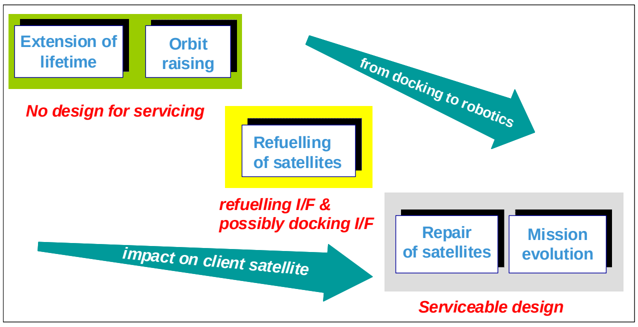

Figure 1: Servicing missions

The mission evolution consists in modifying the on-board payload after several years if required by the market evolution or to benefit from new technology. It may concern the antenna reflector, with an evolution of the ground coverage or the transponders and electronics units to modify the sharing between the RF bands (exchange of a half payload wall). It is also used on demand. However, there will be time to prepare the mission (development and manufacturing of a new payload element).

Most of the servicing missions are unplanned.

SERVICING SYSTEM ARCHITECTURE

Architecture description

The proposed servicing system architecture is depicted in Fig. 2. The servicing system is based on a multi-mission servicer with a logistic support. The servicer will remain in GEO for 7 to 8 years and will be able of 7 to 8 missions.

A logistic support will transport to orbit spare equipment that cannot be known at the time of servicer launch. It can be a small logistic container, with a simple, quasi passive design, able of one to three exchangeable equipments, and having a mass of a few hundred kilos compatible of a low cost launcher.

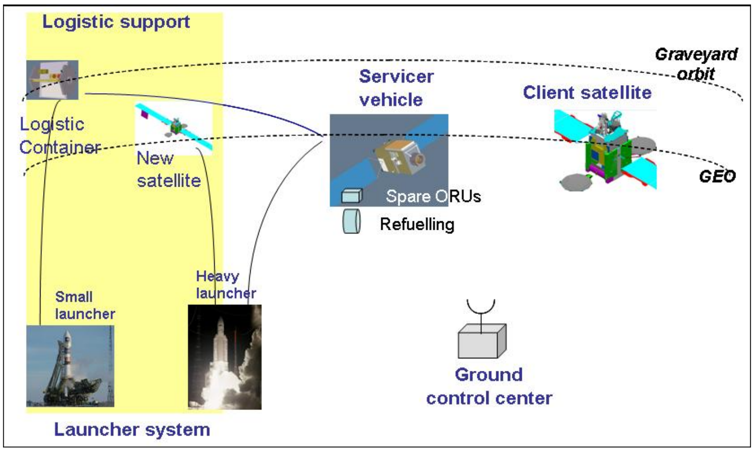

Figure 2: Overview of servicing system architecture

Composite configuration

Once docked, the satellite and the servicer form a composite. This is the attached phase that will last two or three days (except in case of lifetime extension).

This phase is driven by two main client requirements: at first, the satellite shall continue its mission as far as possible and consequently the composite shall be Earth pointed. Secondly, the outage duration shall be minimized, so that the servicing operations shall be done within a few hours during Earth night-time. The composite configuration (see Fig. 3) shows various appendages like antenna reflector and solar arrays in the lower part of the satellite. The safety areas around these appendages will make accessibility above these appendages very difficult, in particular for satellites with multi-reflectors. Therefore, the exchangeable equipments will be located on the lower part of the satellite.

The servicer vehicle is based on Astrium Eurostar 3000 platform in order to maximise the re-use of equipment and minimise the cost of servicing missions.

It is composed of a resource and a cargo module. The resource module houses the platform equipments and the bi-liquid tanks for refuelling. The cargo module allows the storage of the low or medium ORUs on panels or dedicated racks, and of large ORUs on the East side. It supports the docking system, mounted on top a tube for clearance, and the robotic system mobile on its ring.

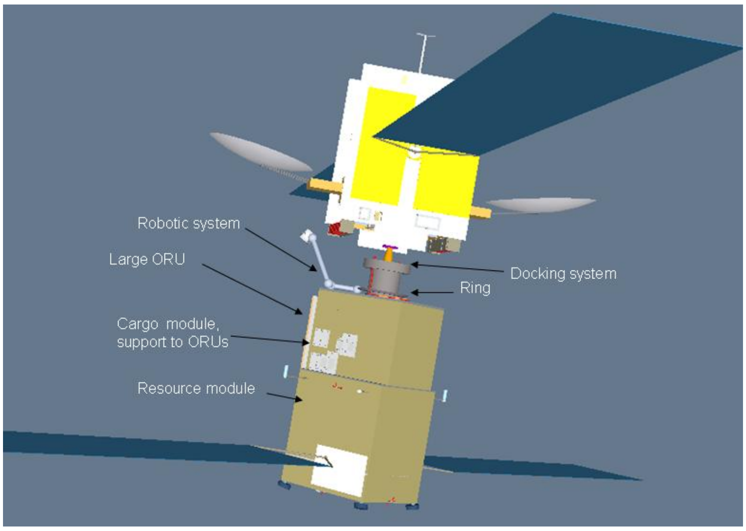

Figure 3: Composite configuration

Robotic aspects

The robotic system will be driven by the composite configuration (in particular the location of ORUs) and the minimisation of impacts on the satellite.

It shall be able to access all ORUs on the satellite and on the servicer (reachable area); it shall have the capability to manipulate a wide range of ORUs in terms of mass, size and inertia (with a grappling point not necessarily on the center of gravity); the robot and ORU trajectory shall avoid the safety areas around the satellite appendages. The robotic system shall generate minimum impact on the satellite, one exception being the grapple fixture. A high accuracy of the ORU positioning in both translation and rotation before contact with satellite is needed to minimize the sizing of alignment guides. The robotic system shall be able of rotating/screwing latches or other devices. Finally, the mass and length of the robot shall be minimised.

Based on these requirements, the robotic system taken into account is a short arm mounted on a ring located around the docking module so that it can be positioned below the adequate satellite side for a servicing operation. This position optimises the access to ORUs both on satellite and on servicer cargo and thus minimises the length (< 5m) and the mass of the arm. Such a small arm has a low insertion force capability (less than 100 N) but an adequate torque capability (more than 10 Nm). It has an integrated screwdriver.

ORU exchange operations

A typical attached phase scenario is illustrated on Fig 4. This phase will last 2 or 3 days. The robotic operations can be done during a specific period each day. One ORU (at least) could be exchanged within this period.

The servicing operations will be monitored from ground, taking advantage of the permanent visibility offered by the GEO. The ground supervision of the robotics operations relies on camera pictures to be transmitted to ground.

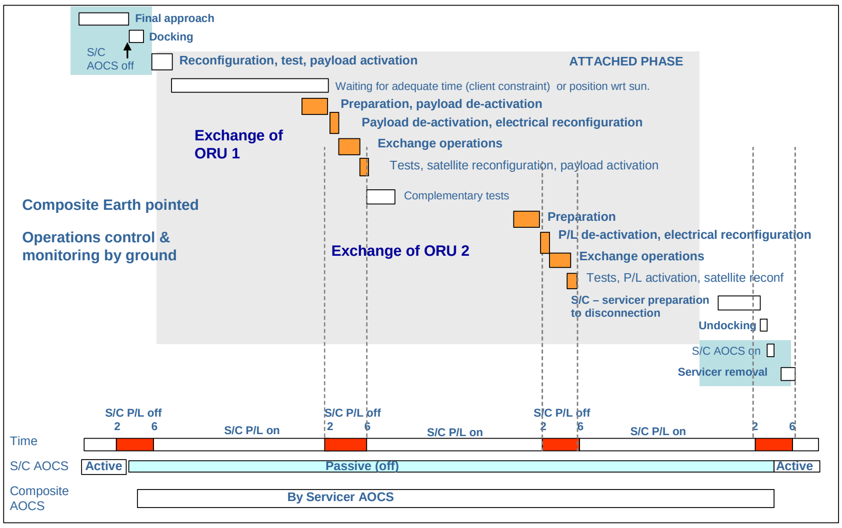

Figure 4: Typical attached phase scenario

The robot arm has a vision based closed control loop to perform autonomously the final translation of an ORU insertion until contact with satellite. Thus it provides an accurate positioning of the ORU at contact that minimises the sizing of guiding devices on the satellite. Passive targets or markers shall be installed on the satellite and ORU to support the robot positioning before its last translation. After the first contact, a force/torque sensor allows the robot to correct misalignments along the insertion. End of insertion is identified by the robot insertion force.

Safety corridors will be defined around the satellite appendages, taking into account the performances of the robotic arm in terms of accuracy and velocity, to prevent from any risk of collision during the motion of the loaded or unloaded robotic arm.

ORU AND SERVICING PROVISIONS

Types of Orbital Replaceable Unit (ORU)

The satellite elements (platform as well as payload ones) subject to exchange shall be configured into Orbital Replaceable Units (ORU). The design of the ORU shall be a compromise between its size and the design of the servicer and logistic support. The equipment level is a good compromise. The ORUs will differ by their implementation, size and mass, and type and number of connectors.

For implementation, internal ORUs (such as On-Board Computer, gyro-package, etc) are installed inside the satellite walls while external ORUs (like antenna reflector, solar array, battery module) are externally mounted on the walls.

Size and mass characteristics have led to gather the ORUs within three classes: small ORU having a mass of a few kg (for instance OBC, or battery module), medium ORU, having a mass of few tens kgs and a medium size (SADM, some electronic units), and large ORU having at least one dimension larger than 1m and masses from 50 to 150 kg (half payload wall, antenna reflector, solar array, etc).

The ORUs differ also by the number and type of connectors: data and power connectors are mounted to most of or all ORUs, while RF connectors appear on some payload ORU like the half payload wall. Besides, some ORUs, like some electronic units, have a ten or more connectors while other ones like antenna reflector or gyro-package have a few ones.

Servicing provisions

The servicing provisions (Fig. 5) gather the interface elements necessary to mate (or de-mate) an ORU on the satellite. They include the connectors (electrical, RF or fluids), the latching mechanisms for fixation of ORU on satellite (or on servicer or container), the launch locking devices needed to withstand the effort during launch, and the alignment devices to install automatically the ORU. Part of these elements is mounted on the ORU, the other part on the satellite, but also on vehicles (servicer and logistic container) that will transport the ORUs. The grapple fixture is fixed on the ORU and interfaces with the robot gripper for grappling and screwing.

Possible options

The selection and design of servicing provisions is driven by some main constraints and limitations.

At first, the implementation of mechanisms in the ORU shall be minimised, the front panel surface of the internal ORU shall be left clear for the radiators and the impacts on the satellite shall be minimised. The maximum robot force will restrict the direct connector mating option to ORUs having a limited number of electrical connector pins (less than 90).

The grapple fixture size and the clearance required by the gripper will limit the number of grapple fixtures on the ORU. To cope with the number of latches, use of mechanisms has to be assessed versus a new gripper capability (capture of bare bolts). The launch locking devices have to be de-mated at the first exchange and use of robot or of pyro-bolts have to be traded. An ORU not accessible in all its sides by the robot (such as antenna reflector) will require the implementation of dedicated mechanisms activating simultaneously several latches. Finally, the size of alignment/guiding devices will be

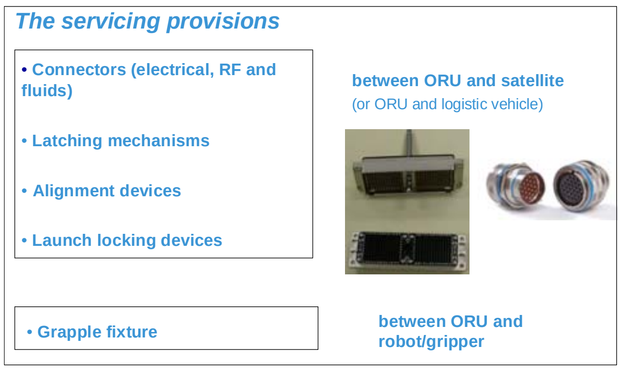

Fig. 5: The servicing provisions

driven by the robot positioning accuracy at contact.

In order to select servicing provisions, several solutions have been defined and traded-off. These solutions were driven by the connector mating options and the number of gripper interfaces. They have been gathered in four main categories.

In the first one, the connectors are mated by the robot, at end of insertion. This option is limited to ORU with less than typically 90 pins on the connectors. The robot force for mating generates loads on the ORU structure and receptacle.

In the second one, the connectors are mated while latching. The robot gripper provides the adequate torque to activate the latches and the resulting force allows the connector mating. A symmetrical latching is needed to keep alignment of pins with the receptacle that can be done by parallel (complex mechanism) or sequential activation of two latches. Symmetrical latching and effort generated on the structure are key issues.

In the third one, the connectors are mounted on mobile connector plates installed on ORU and actuated by motorised mechanisms commanded by the robot, or a mobile receptacle is actuated by a motor commanded by the satellite. Issue is the mass and power aspects, especially if several mechanisms are necessary.

The last category relies on the use of Zero Insertion Force connector (ZIF) that can gather several conventional connectors and are commanded (mobile part) by the robot gripper. Issue is the adaptation of equipment design.

Various options have also been assessed for the latches and the alignment devices.

Proposed approach

The proposed approach is illustrated on Fig. 6. It relies on the use of ZIF connectors for electrical (data and power) connection as it minimizes the effort on the ORU and receptacle structure, simplifies the operations and re-uses ground technology. The mating requires a rotation of 90° that is commanded by the gripper screwdriver through a grapple fixture. The use of conventional connectors with direct mating by the robot is proposed when possible, thus for ORU with few connector pins. For RF connections, motorised mechanisms for mating are recommended.

The type of **latching mechanisms** depends on the requirements, mainly if only mechanical link is needed or if a close contact is required for thermal or bonding aspects. Possible solutions are rotating lock (a single actuation for single or multiple locks) or captive bolt type. The type of **launch locking mechanisms** depends on the de-activation mode, as it is used only during launch and will not be re-installed after ORU exchange; it could be pyro-bolts, commanded from the satellite, or captive bolts commanded by the robot. It is proposed to use captive screw devices for both latching and launch locking so as to have the same interface for both mechanisms and to ensure adequate contact between ORU and satellite receptacle and satellite wall. The number of latches and launch locking depends on the size of the ORU.

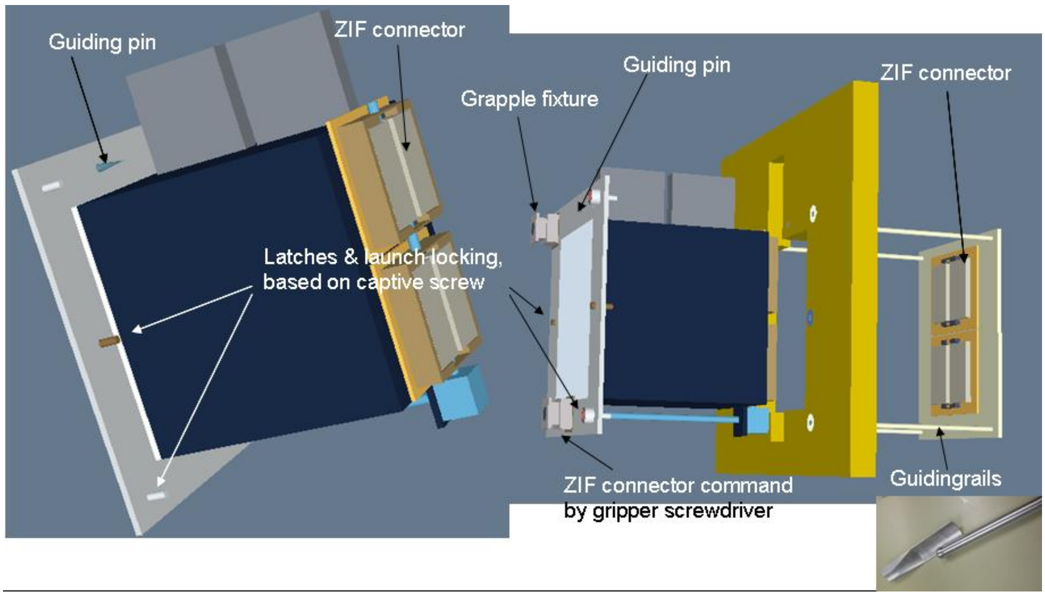

Figure 6: Proposed approach for servicing provisions (case of internal ORU)

Different types of **alignment devices** are proposed. For external ORUs, cone and pin, or balls in cup and in groove are possible solutions according to the size (small, medium, large) of ORU. For internal ORU, the problem is to ensure both contacts of rear front panel with satellite wall and bottom side of ORU (connectors) with receptacle connectors. Alignment guide could be based on balls mounted on the edge of ORU and sliding on angular guiding rails, and on classical guiding pin on the front panel.

Micro-square grapple fixture has been selected to minimize the required surface on the ORU. The gripper will be equipped with a screwdriver for activation of latches and ZIF connector mating. Design of the gripper to capture bare bolts for screwing is a technical challenge that would minimise the number of grapple fixtures. Specific mechanisms and tools could be used when all the sides of the ORU cannot be accessible.

ORU description

The **internal ORU** (see Fig. 6) will be equipped with a front panel (base plate) that will be latched on the wall of the satellite. This panel will play the role of a radiator for the equipment heat dissipation. All the connectors will be gathered on the back side of the equipment. One or several ZIF connectors will be used, according to the equipment. The connector receptacle on the satellite side is mounted on a flexible support, giving a degree of freedom in the insertion direction. Latches and launch locking captive screws are mounted on the front panel. Each of them would need a grapple fixture to be activated, unless using a common mechanism or having the robot designed to capture bare bolts. Use of spring in the bottom of the screw gives also a degree of freedom when latching, avoiding problems of hyperstaticity. A guiding pin is implemented on the front panel back side to help the alignment of the captive screws. Another one is mounted on the rear side of the equipment in case of conventional connector.

For most of the **external ORUs,** the design will remain close to the current one. For instance, battery module shall have a good contact with battery plate for thermal dissipation; that is a driver for the selection of latching system. They will be also equipped with micro-square grapple fixtures, latches and launch locking mechanisms and guiding pins.

IMPACTS ON CLIENT SATELLITE

The servicing capability, and in particular the exchange of ORU, results in main impacts on the satellite configuration, the satellite systems and the design of equipment. A specific serviceable design has to be defined for the satellite.

First of all, the satellite configuration (see Fig. 7) shall allow the accessibility to all the exchangeable equipments. Thus, all service module ORUs shall be mounted below the main floor level, on lateral panels. The most dissipating ones shall be mounted on North and South walls. The batteries are installed so that they facilitate the access of their modules to the robot. The payload ORUs are mounted on the North and South walls, except the antenna reflector.

The satellite **thermal architecture** will be deeply modified as each internal ORU has its own independent thermal control. Besides, the removal of an ORU leads to expose to outer space (sun or cold space) the surface and elements located behind the ORUs for a transient period that impacts the internal thermal equilibrium. Therefore, the entire ORU cavity will be insulated with MLI to avoid any coupling. The half payload wall shall be autonomous in order to be exchanged, so that a re-design of payload wall thermal control is necessary.

Additional structure is needed to support the servicing provisions: below the main floor for internal ORUs to support the connector receptacle and the guiding rails; re-enforcement around the servicing provisions for external ORU. Besides, interface ring will be needed to install fluid connectors and interface mechanisms for locking of servicer after docking.

The propulsion system will include additional valves, piping and fluid connectors.

Electrical architecture and on-board software will have to take into account the attached phase

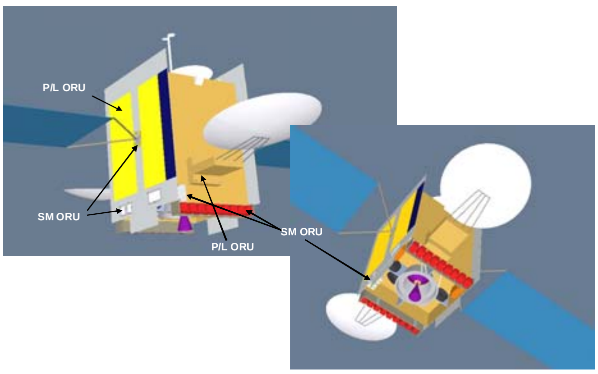

Fig. 7: Illustration of impacts on satellite

BREADBOARD AND GROUND TEST

To verify the feasibility of the proposed servicing provisions concept, a ground test has been defined. It has been done on a breadboard representative of the ORU type and on servicing provisions the most frequently used by the ORUs. To that aim, a small internal ORU has been selected, with electrical connectors, captive screw type latches and alignment with guiding rails and guiding pins. RF connectors, as needed in one payload ORU and fluid connectors, as mounted on the docking interface, have not been tested. ZIF and conventional connectors have been taken into account to test both nominal and alternative solutions.

Mock-up and test facilities

The ground tests have been carried out in the laboratories of the Katholieke Universiteit of Leuven using the laboratory robot and associated ground facilities. The demonstrator includes the satellite part mock-up representing the wall on which the ORU is mounted, the ORU breadboard and the servicing provisions breadboard mounted on both the ORU and the satellite mock-up. In particular, two ZIFs and one conventional connector were installed on the ORU and relevant receptacle on the satellite. Ground facilities and breadboard are illustrated in Fig. 8.

The ORU breadboard was also equipped with two grapple fixtures, one for the command of ZIF mating, the other one for the activation of the latch. A guiding pin and a bonding interface have been installed on the front panel. On the rear side of the satellite mock-up, cabling link the connector outputs to the power source and equipment for the power and data continuity tests.

Fig. 8: View of ground facilities and breadboard

A gripper breadboard, equipped with a screwdriver, has been installed on the robot end effector, mounted on the force torque sensor. A test environment, based on Dreams tool, allowed the interface with the operator for telemetry display and test sequence command.

Test sequences

Two test campaigns have been done, one for the mating of the ZIF connectors, the other for the direct mating of conventional connector. Each test campaign includes the capture of the grapple fixture, the de-mating, extraction and removal of ORU, the insertion and latching of ORU, the verification of connection performance with electrical continuity tests and bonding test.

CONCLUSIONS

In conclusion, the commercial GEO telecommunication market can benefit from in-orbit servicing both on technical and economical aspects.

Repair or payload evolution will rely on exchange of equipment. They will occur at long term with an important re-design of the satellite to allow this exchange.

The proposed servicing system relies on a servicer vehicle staying in GEO and on a logistic support, typically a container, to bring equipment when necessary.

Automatic on-orbit servicing operations require the implementation of adequate servicing provisions for ORU mating and ground supervision for safety aspects.

The proposed baseline concept of servicing provisions covers all the identified ORUs, taking into account their specifics. Conventional electrical connectors have been kept for the equipment having a low number of pins, compatible with direct mating. For the other equipment, ZIF connectors are proposed. They rely to day on ground technology.

Requirements on robotic system have been identified: reduced size and mass, integrated screwdriver, wide range of ORU mass, size and inertia, vision based control for final approach. In addition, capability to capture and activate a bare bolt is a challenge that would reduce the number of grapple fixture.

Implementation of flexibility in the connector receptacle and captive screw appear as a factor of good mating of the ORU.

Ground tests of a typical ORU with representative servicing provisions have been successfully carried out showing the feasibility of the proposed concept.

Implementing servicing with exchange of equipment on a fleet of satellites is a long term programme and involves the development of servicer vehicle and a new generation for satellite being serviceable, with technical challenge like an automatic in-orbit robotic operations.