

# TESTING AND CROSS-VALIDATION OF ON-ORBIT SERVICING SYSTEM FOR GEO SPACECRAFT REFUELLING

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The ASSIST activity is aimed to establish a standard docking interface definition enabling on-orbit operations for grasping and refuelling geostationary spacecraft. Such standard, named IIFTSS (International Intersatellite Fuel Transfer System Standard) is an intersatellite docking system composed by two major elements: an active probe or end-effector placed on the tip of a robotic arm of the chaser satellite (servicing S/C) and a berthing fixture placed on the external surface of the client satellite (serviced S/C). This paper will focus on the description of the dynamic and environmental set-ups and the results of the simulation/testing campaigns in support of the ASSIST system design evolution.

## 1. INTRODUCTION

In spite of the continuous technology enhancement and the broadening of spatial suppliers with new stakeholders, space activity remains one of the most hard and expensive business in the worldwide market. Moreover the abundance of space around the Earth is having to cope with the continuous increase of satellite's launches especially in LEO and GEO orbits. These are some of the reasons why the so-called On-Orbit Servicing (OOS) activities are increasingly taking root in the space sector. As proof of this, it can be recognised the growing interest, both from public and private investors, in activities intended to reduce (ADR - Active Debris Removal) or reuse (repair/refuel operations) satellites already in orbit.

To better analyse the refuelling operations ESA has promoted the ASSIST activity in charge of design and test a system that, minimizing the impact on the existent architecture of the target spacecraft, could allow a chaser to dock and exchange fuel and data extending the effective life of the client. With this aim GMV has built and coordinated a team together with MOOG (mechanical design, breadboard manufacturing and environmental testing), NTUA (air-bearing table dynamics and testing), DLR (contact dynamics), OHB (mission requirements and propulsion provisions) and TAS (mission requirements). Although not directly involved in the design process, ADS and Eutelsat are also fully aware of this initiative. The activity, lasted more than 2 years, has entailed several sequential steps including the design of the servicing/refuelling system, the definition of the refuelling operations, the design and validation of a Kinematic and Dynamic simulator against the data from the tests on the air-bearing set-up and with a 2:1 scaled dynamic breadboard and the realization of an environmental breadboard in full scale. A set of requirements have been defined to regulate the docking system and the refuelling operations and the standard called IIFTSS (International Intersatellite Fuel Transfer System Standard) has been proposed to become an international process. The IIFTSS has been designed taking into account different serviced S/C configurations derived from some of the European platforms and in the table below typical values in terms of mass (S/C EOL and required fuel) are shown.

**Table 1:** Spacecraft properties considered for the ASSIST analysis.

S/C Class	Mass EOL [Kg]	Dimension [m]	Required Mass MON/MMH [Kg]	Required Mass Xenon [Kg]
SmallGEO (OHB)	1800	2.5 x 2 x 3	150-600	150-200
SpaceBus (TAS)	3300	3 x 3 x 3	1000	300
SpaceTug (ADS)	3000	3 x 3 x 3	200	3000

## 2. ASSIST CONCEPT

### 1.1. Overview

The philosophy behind the ASSIST system has been developed taking into account some servicing/refuelling components allocated on-board both the serviced GEO S/C and the servicing S/C. The design has been maintained as simple as possible for what concern the modifications on the target S/C carrying all the possible loads/encumbrance on the servicing satellite. Nonetheless also the architecture of the GEO satellite shall be modified to be compliant with the servicing/refuelling requirements. The main elements involved in the development for the ASSIST concept can be decomposed in:

- Internal: modifications to fuel, gas, electrical, data architecture to allow servicing in the GEO satellite.
- External: integrated grasping/berthing fixtures with peripheral electrical, gas, liquid connectors, leak check systems, optical/radio markers for cooperative rendezvous.

### 1.2. Design

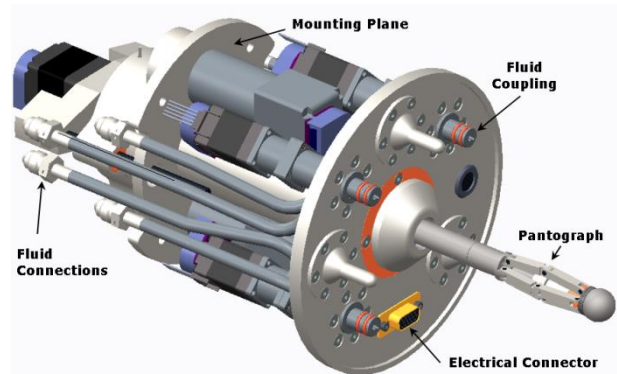
The principal concept behind the ASSIST capture system is to allow for zero force capture to ensure that the target or client spacecraft are not pushed away from each other before a latching system can be deployed. Crucially the assembly allows for clamping of the two vehicles around a central axis before any further berthing processes take place. This constrains the alignment problem to a single rotational axis which can be corrected for and, which is within the capabilities of the robotic arm from the servicing S/C.

The end-effector includes a grasping mechanism which consists of an expanding pantograph located at the end of a probe. The mating half on the client spacecraft consists of a 'drogue' type arrangement which includes a central cavity into which the capture probe pantograph is inserted. The 'drogue' is part of the berthing fixture assembly which includes fluid couplings and an electrical connector. The alignment pins have been arranged asymmetrically on the fluid plane so that the end-effector cannot be docked incorrectly.

#### End-Effector

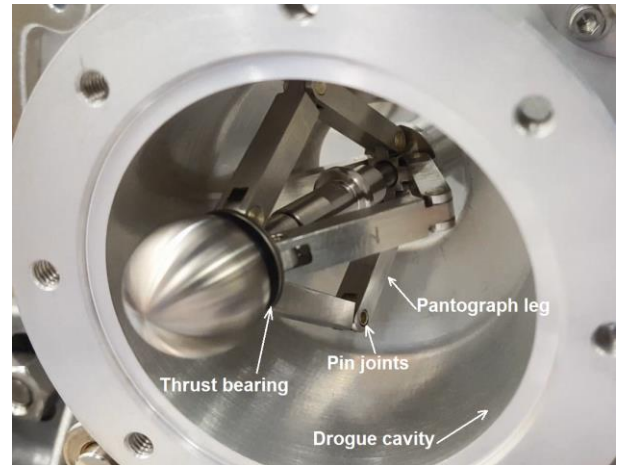
The end-effector (see Fig. 1) is foreseen to be attached to a robotic arm on the servicing S/C and includes the fluid and electrical connections and a grasping mechanism which docks with the berthing fixture on the serviced S/C. The end-effector also includes one half of the fluid coupling and an actuation mechanism which operates the valve in the client berthing fixture half. Included on the end effector are three fluid couplings (fuel, oxidiser and xenon) which connect to the berthing fixture half and seal with elastomeric O-rings. The alignment pins, fluid couplings and electrical connector

are mounted on a plane referred to as the 'fluid plane'.



**Figure 1:** End-effector.

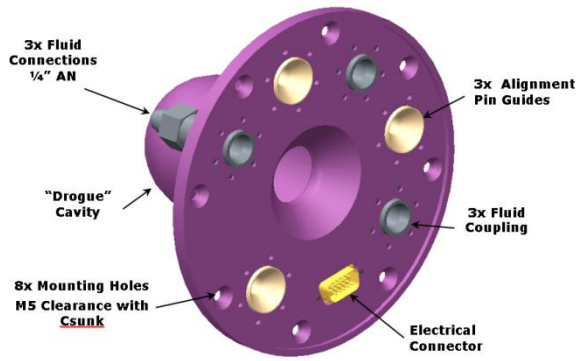
The end-effector finalizes in a probe tip actuated by a pantograph (see Fig. 2). The pantograph mechanism uses a central actuation shaft which is driven from a stepper motor at the base of the end effector. A lead screw arrangement inside the main shaft transfers the stepper motor rotation to a linear motion. As the central actuation shaft retracts linearly, the probe pantograph expands. A keyed coupling between the stepper motor shaft and actuation shaft allows the actuation shaft to move towards the stepper motor as the pantograph expands and away from the motor as the pantograph contracts.



**Figure 2:** Detailed probe-tip mechanism including the pantograph and the inner part of the Berthing Fixture.

#### Berthing Fixture

The berthing fixture (see Fig. 3) provides the serviced S/C with one half of the grasping mechanism, which the servicing robotic arm end effector docks with. This consists of a 'drogue' type arrangement which includes a central cavity into which the capture probe is inserted. The provisions on the serviced S/C include three guide receptacles which allow the alignment pins to engage and centralise the whole system. Note that the guide pins are positioned asymmetrically such that the docking cannot occur in the incorrect orientation, guaranteeing the correct pairing of the fluid couplings.



**Figure 3:** Berthing Fixture.

There are three fluid couplings and one electrical connector (ad-hoc DB-9 or alternatively the Souriau 8977 model) in the proposed design. This allows a hybrid GEO platform (MMH, MON and Xenon) to be refuelled. The baseline design of the berthing fixture is to have common parts for both Small GEO and Large GEO platforms with the exception of the third fluid coupling which will be used for Xenon refuelling. This coupling could be replaced with a blanking plate whenever is not required.

### 3. VALIDATION SIMULATOR

#### 3.1. Kinematic and Dynamic Simulator

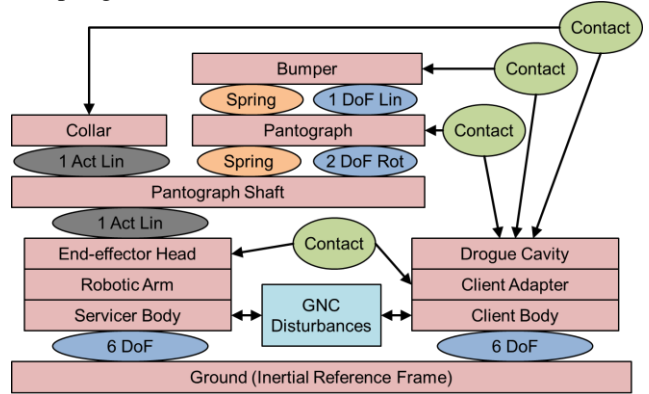
The design of the ASSIST system has been supported during all the development phase by the results of a software capable of simulate the behaviour of the components involved in the approach between the servicing and serviced S/Cs.

The K&D simulator, developed in Matlab/Simulink environment, has been designed taking into account the real components of the dynamic breadboard during the phase of the rendezvous and docking.

The architecture of the ASSIST simulator whose main components are listed below, is shown in Fig. 4:

- A common inertial reference frame (Ground).
- S/C propagators: position and attitude of the involved satellites.
- Contact Dynamics Model to compute the Forces/Torques involved during the contact among the different components of the ASSIST system.
- For the Servicing spacecraft Multi-Body System simulating the exchange of Forces/Torques acting on the chain from the spacecraft body till the tip of the End-Effector
  - S/C Rigid central body
  - Robotic arm
  - End-Effector head (sensitive to contact)
  - Pantograph central shaft and legs (legs sensitive to contact)
  - Bumper on the probe tip (sensitive to contact)
  - Sliding Collar (sensitive to contact)
- Multi-Body for the Serviced spacecraft:
  - S/C Rigid central body

- Berthing Fixture inlet (sensitive to contact)
- Drogue cavity (sensitive to contact)
- Disturbances Forces/Torques.
- Contact models between all sensitive components.
- Flexible elements to simulate angular and linear springs.



**Figure 4:** Simulator Architecture.

#### 3.2. Cross-Correlation description

Apart from the support to the design evolution until the final version for the ASSIST configuration, the simulator has been also validated correlating its behaviour/outputs with the same tests performed on the dynamic breadboard (described in 4).

Contrary to the initial purposes to simulate a set of nominal cases with common initial conditions, it has been finally identified a different approach simulating exactly the same cases run on the real setup and extracting the data to initialize the simulator from the dynamic test outputs. The complete set of tests are shown in Tab. 2.

**Table 2:** Initial conditions for the Correlation tests.

Test Case	Angular misalignment	Lateral displacement	Approach velocity [mm/s]
TC-DT-X01	Aligned axes	Off-centered trajectory	10
TC-DT-X02		Centered trajectory	5
TC-DT-X03		Off-centered trajectory	10
TC-DT-X04		Centered trajectory	5
TC-DT-X05	Maximum tilted angle (11.3°)	Off-centered trajectory	10
TC-DT-X06		Centered trajectory	5
TC-DT-X07		Off-centered trajectory	10
TC-DT-X08		Centered trajectory	5
TC-DT-X09	Minimum tilted angle (-11.3°)	Off-centered trajectory	10
TC-DT-X10		Centered trajectory	5

Different combinations of mass ratio for the Chaser and Target robots have been also considered:

ASSIST-TC-DT-1XX: Low for both S/Cs

ASSIST-TC-DT-2XX: Low Chaser, Medium Target

ASSIST-TC-DT-3XX: High Chaser, Low Target

ASSIST-TC-DT-4XX: High Chaser, Medium Target

ASSIST-TC-DT-5XX: High Chaser, High Target

### 3.3. Results

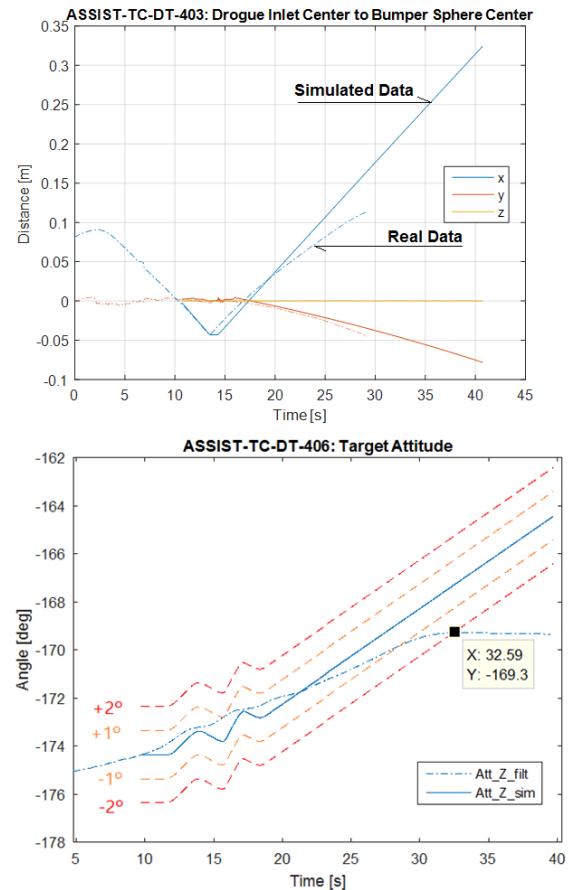
The cross-correlation has been performed calculating for all the 50 tests (10 test cases x 5 possible mass ratios) the time (in seconds) within which the simulated and real data remained under certain thresholds.

- Chaser position: time within which the difference of position of the geometrical centre of the chaser is below 1 cm per axis (minimum value between the X-Y axes).
- Chaser attitude: time within which the difference of attitude of the chaser robot is below 1 (and 2) degree.
- Chaser velocity: time within which the difference of velocity of the geometrical centre of the chaser is below 0.0005m/s per axis (minimum value between the X-Y axes).
- Target position: time within which the difference of position of the geometrical centre of the target is below 1 cm per axis (minimum value between the X-Y axes).
- Target attitude: time within which the difference of attitude of the target robot is below 1 (and 2) degree.
- Time inside Drogue: time of the pantograph inside the drogue.

Several challenges have been faced during the correlation phase and the analysis performed highlights some critical points:

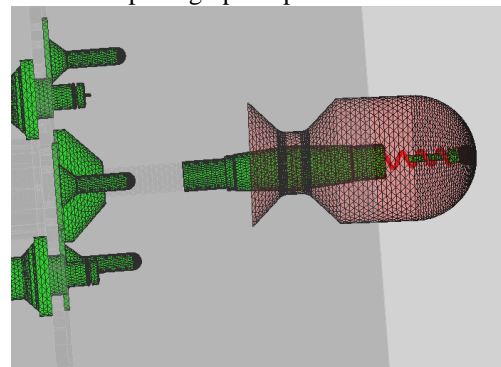
- A re-sampling procedure on variably sampled real data from the Dynamic Tests has simplified the comparison with the constant sample time data of the simulator.
- Most of the real data have a natural noise level that required a pre-filtering phase (another good reason to perform a preliminary re-sampling process).
- The Torque/Force sensors on the chaser side have, in the Dynamic Tests results, comparable values on all the directions (X, Y, Z); this does not happen for the Simulator where the decoupling between forces and torques works efficiently and the output is mainly recorded on the X-Y plane for the force and around the Z axis for the torque.
- The initial conditions selection to initialize the simulator play a very important role in the correlation frame: the use of real data output (noisy values) to initialize the simulator introduces a meaningful level of uncertainties in the simulation process and its outputs.
- Some disturbances on the Dynamic breadboard cannot be contemplated in the simulator even though they have a practical influence on the variables under exam: an example is the air movement around the air-bearing table that can push and change the velocity of the robots when other forces/torques don't act on the system.

Fig. 5 shows an example of the correlation results.



**Figure 5:** Correlation between real data from the dynamics testbench (dash-dot lines) and simulator output. Dashed lines in lower figure represents the threshold criteria (1&2 deg) for the attitude.

Particular attention has been paid to the time in which the pantograph remains inside the drogue (example shown in Fig. 6) that with a mean value of 1.4s has given a useful indication of the time available for the actuation of the pantograph to perform a soft docking.



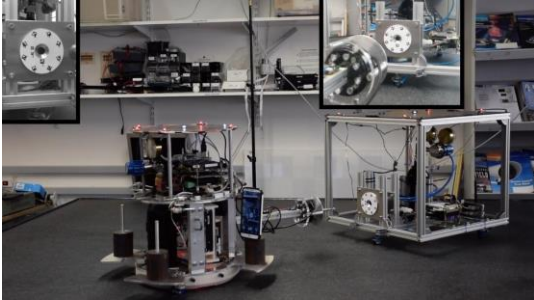
**Figure 6:** Pantograph inside the Drogue cavity.

With the criteria boundaries defined above it has been found that the periods in which the simulator is reliable to follow the real data is around 35% of the comparison time (max 30s).

## 4. DYNAMIC TEST

### 4.1. Experimental Facility

At the NTUA Control Systems Laboratory (CSL), an air-bearing Space Robotic Emulator facility ([1], [2]), has been developed for the purposes of the lab's academic research as well as for use in applied research projects, see Fig. 7.



**Figure 7:** Active robot (left) with probe and passive robot with drogue in an ASSIST docking test.

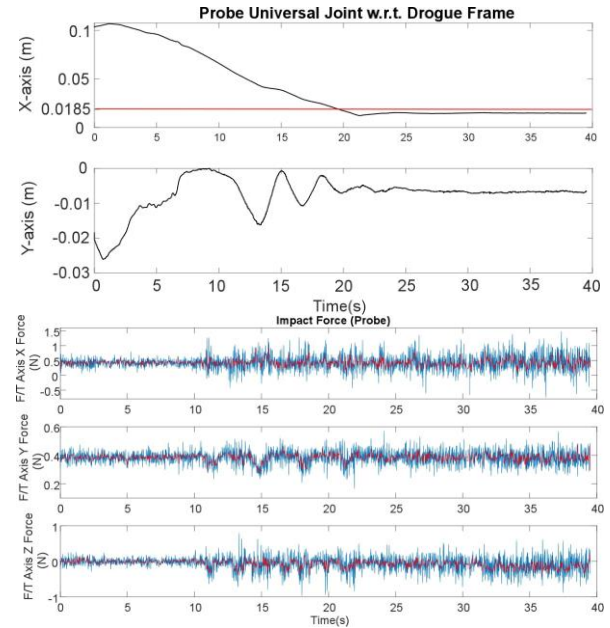
It consists of a 2.2m x 1.8m granite table of extremely low flatness, three autonomous robots (two active and one passive), workstations and other peripheral devices required for the operation. The robots, equipped with CO<sub>2</sub> tanks use air bearings to move on the table with near-zero friction. In addition, since they are fully autonomous, no external forces except for the robots' weight (which is cancelled out by the bearings lift-force, normal to the table surface) are applied, and the robots move on the table as if they were in an orbital environment, although in 2D. Both active robots use thruster pairs and reaction wheels for their motions. The weight of all robots is adjustable, as are also the external dimensions of the passive robot. For the ASSIST project needs, a drogue breadboard was installed on the passive robot (Target), while a probe breadboard was installed on one of the active robots (Chaser). For the robot localization on the granite table, a very fast and accurate commercial Phasespace MoCap system was used.

### 4.2. Dynamic Tests, Results and Validation

The CSL Space Emulator has been used to perform a set of docking test cases aiming to validate the ASSIST K&D simulator. During those tests the berthing probe-drogue mechanism was tested in terms of contact forces, proper insertion of the probe in the drogue inner cavity, and time in which the probe tip and the pantograph remain inside the cavity, before they (if they ever) bounce off the cavity. A total of 50 test cases (5 test scenarios x 10 impact conditions test cases as shown in section 3.2) with probe flexibilities were selected.

Fig. 8 shows the relative probe/drogue motion for high/medium Chaser/Target masses, and for off-centred, low velocity impact, with 11.3° impact angle. Probe/drogue relative x-motion below the red line means the probe pantograph is inside the drogue cavity,

indicating a successful docking in this specific test. Moreover, in Fig. 8 the probe F/T sensor readings, detecting the initial probe/drogue contact after 10 s.



**Figure 8:** Probe-Drogue relative motion (top two plots) and Probe F/T sensor impact force detection (bottom three plots).

After the performed experiments some general conclusions and comments were pointed out:

1. For the same robot masses and roughly the same impact conditions, as the lateral spring becomes softer, generally the docking success becomes higher.
2. The experiments with zero relative angle and no offset ("head-on" impacts) were always docking failures, since the probe entered the drogue cavity, hit the far end and bounced back equally unhindered, giving the pantograph very little time to open.
3. When the probe went into the drogue cavity with an angle, in most of the cases this angle increased after the impact causing the mechanism to momentarily lock and increase the time that the probe stayed in the cavity (the case also seen in Fig. 8).
4. The observed success/failure rates imply that the best strategy is to try the docking with an inclined trajectory and low impact velocity.
5. Operationally speaking, capture at a misalignment limits the available capture envelope. Therefore, what is needed is a strategy combining the needed aspects of both aligned axes (i.e. larger capture envelope) and misaligned axes (i.e. locking the pantograph inside the drogue cavity).

## 5. ENVIRONMENTAL TEST

The testing was aimed at demonstrating the docking procedure, fuel transfer and undocking in a representative thermal vacuum environment. Functional testing was also performed to understand the



107	FC1	4.6E-6 @0.00barG	3.6E-7 @23.014barG	22.2
186	FC2	2.2E-8 @0.09barG	3.3E-8 @23.22barG	8.7
192	FC1	3.4E-8 @0.03barG	5.8E-8 @23.24barG	8.2
281	FC1	9.1E-8 @0.04barG	1.1E-7 @23.12barG	5.0
286	FC2	3.3E-8 @0.04barG	6.5E-8 @23.02barG	5.0
308	FC2	3.3E-7 @0.01barG	6.4E-7 @23.15barG	55.3
314	FC1	9.7E-7 @0.06barG	1.3E-6 @23.16barG	55.5
399	FC2	4.6E-7 @0.04barG	1.2E-6 @23.42barG	59.4
404	FC1	4E-7 @0.01barG	6.5E-7 @23.01barG	57.4
422	FC2	2.5E-7 @0.02barG	2.7E-7 @23.18barG	23.7
423	FC1	1.1E-6 @0.02barG	1.4E-6 @23.0barG	23.6
477	FC2	2.0E-7 @0.02barG	3.3E-7 @23.35barG	24.1
478	FC1	1.1E-6 @0.04barG	1.3E-6 @23.08barG	23.8

### Liquid Transfer

Maximum pressure drop across the berthing fixture valve was 0.56bar at 28.9g/s for fluid coupling one and 0.56bar at 28.41g/s for fluid coupling two. There was no discernible difference in the results at the hot and cold temperature extremes.

## 6. INDUSTRY ASSESSMENT

The commitment of different satellite interested parties (manufacturers, operators) has been considered as crucial to examine the ASSIST system and the requirements for foreseen international fuel transfer standard. The stakeholders have participated with different degree of involvement: OHB and TAS have been included in the design of the refuelling system and in the definition of the standard; ADS and Eutelsat entered at a later time and played a role of reviewer.

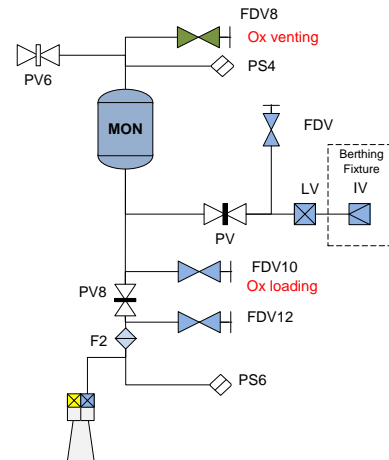
### 6.1. OHB

For the refuelling of telecom satellites, not only the servicer but also the client satellite needs to be adapted to support this function. As already stated above, to make this option more attractive to the customers and platform providers, it has to be ensured that the impacts on the satellite design are minimized and that the processes as well as interfaces are standardized. Standardization is considered an asset to facilitate the diffusion of the system potentially onboard different platforms of any provider. A minimized impact of internal provisions ensures that accommodating these provisions do not lead to major complication (technical and in terms of costs), nor will introduce additional risks in the development and commissioning of the satellite. With the above mentioned objectives, OHB System supported ASSIST by assessing required internal provision on the client side and contributing to the standardization effort. The list of internal provisions includes:

- Refuelling propulsion branch
- Accommodation areas
- Structural impacts
- Refuelling operations
- Inter Satellite Communication and Control
- Refuelling AOCs Mode

The refuelling branch, for example, requires extending

the standard chemical propulsion block by including a small branch that consists of a pyro-valve, a solenoid or latch valve and the berthing fixture with an internal isolation valve. For a bipropellant system two of these branches are required.



**Figure 12:** Example of MON-refuelling branch (right). This simple design is mostly also applicable for electric propulsion. The only changes are that the pyro-valves need to be exchanged with a normal latch or solenoid valve and the additional test port (FDV) can be skipped. All selected components use standard interfaces (e.g. 28 V valve interface) available on GEO communication satellites due to the existing propulsion system needs. Overall, the first assessment of required internal provisions show that only limited effort is required to adapt current telecommunication platforms (e.g. Small GEO) to support refuelling. The main problem has been identified in the refuelling operations of Xenon for electrical propulsion. Contrary to chemical propellant, a fast refuelling is not possible due the thermal management. To avoid complex re-design of the client or performance losses, the easiest mitigation measure is to perform either the Xenon refuelling with a lower propellant mass or to plan for a longer refuelling that, due to its long duration (1-2 month) should be analysed more in detail specially from a mission analysis point of view.

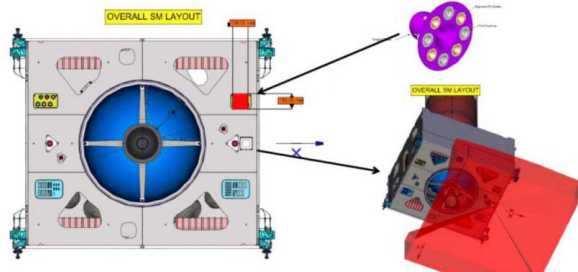
### 6.2. Thales Alenia Space (TAS)

The analysis on the impact of the external provision for the refuelling operations on the platform configuration has been performed for a wide range of satellites. The assessment performed to identify the best position to accommodate the berthing fixture component on the client S/C has underlined different interesting items:

- The dimension of the element to be mounted on the serviced S/C (15x15x15 cm) can be considered as acceptable in basically all the platforms examined.
- The position of the berthing fixture shall be decided case by case because also depending on the existing refuelling branch position.
- The accommodation shall also consider the position

of existing platform sensors and their use during the approach phase.

As an example in Fig. 13 is shown the anti-Earth face of a Spacebus platform (by TAS) that, due to the P/L accommodation on the other surfaces of the platform, results to be the most apt area for the ASSIST module.



**Figure 13:** Spacebus CAD view and Berthing Fixture accommodation.

The dimension of the berthing fixture are not an issue for physical accommodation but the FOV of the Sun sensor (the red volume in Fig. 13) used during possible Safe mode would be obstructed by the chaser spacecraft. This has suggested that a specific Refuelling mode is not only indispensable for the servicing S/C but also for the serviced S/C. Despite the baseline scenario for refuelling operations not require the use of electrical connectors the ASSIST system has tested one (see Ch. 5) considering the possibility of exchange data between the involved spacecraft. With this aim it has been also performed a preliminary trade-off identifying the CAN data bus as the preferred solution for the data transmission: in fact this has been recognized as a potential data link protocol for space applications and in spite of having a low number of required pins (e.g. circular connectors or D-sub at 9-pins) it would allow to take advantage of its multi-master serial bus capabilities to send commands by a master unit located inside the serviced or the servicing spacecraft.

### 6.3. Airbus Defence and Space (ADS)

The ASSIST initiative is seen by ADS as an important contributor enhancing OOS capabilities for long term platforms. In fact, developing such interface will help simplifying the capture and servicing operations, as well as preparation of operations, enabling generalization of OOS. For the short/mid-term, even before the complete definition of the standard platform families compatible with ASSIST type concepts, one may envisage such concept for connection between On Orbit Servicing vehicles and in orbit fuel tanks launched separately.

Taking a look to the ADS closer programs also the case of the SpaceTug initiative, aiming at servicing existing GEO spacecraft early 2020's, dealing with recent platform families not prepared to embark the ASSIST system, could be considered as a pioneer in its kind and the knowledge gained through this activity could provide useful improvement/enhancement to the ASSIST mission baseline.

### 6.4. Eutelsat

Despite the fact that Eutelsat does not itself produce platforms, as one of the main European communication satellite operators, it encourage the prime manufacturers to move towards designs that are more “service friendly” and compatible with future infrastructures where in-orbit refuelling, servicing and replacement of key modules on satellites can be commonplace. Although from an operation point of view the advance of the capabilities examined in the ASSIST project will imply the development of new strategies (satellites in joint configuration, transfer of fluids/gases) and the handling of potentially risky scenarios (Docking, Demating), the reuse of platforms in a manner which avoids depletion and achieves the extension of their active life can be considered a very promising benefit.

## 7. CONCLUSIONS

In this paper the ASSIST system and the results of the tests performed on it is presented. Through the properties of the class of the potential S/Cs from the European manufacturer that could be involved in the development of a OOS system, a device to dock and transfer fluids and data between 2 satellites has been designed and a standard has been sketched. The evolution of the design of the system has been helped by a K&D simulator as a contribution of GMV/DLR. The data from the simulator have been correlated with the outputs from the air-bearing table tests (NTUA) demonstrating (for short periods of time) a good accordance with the real tests. Thermal, leakage, liquid transfer test have been performed on an environmental model (Moog). The participation of the biggest European satellites manufacturer/operators has been useful to define the process of standardization of the requirements for the docking and refuelling operations; OHB and TAS have actively contributed to identify key points around the internal and external provisions of a servicing/refuelling system for GEO satellites while ADS and Eutelsat have reviewed the work providing feedback and supporting the activity.

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