A Remotely Controllable Thermo-Vacuum Facility for Testing Small Payloads

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Abstract. A fully equipped thermovacuum facility has been designed and assembled at Sapienza University during the development phase of LARES, a satellite of the Italian Space Agency. After the launch of the satellite in year 2012, the facility has been devoted to testing small payloads and cubesats. An upgrade of the facility allows some operations to be performed remotely. It is planned to complete the automation of the operations so that the majority of the tests could be monitored and controlled from home or during the lectures from the class. The paper will describe the facility, some test campaigns performed recently and the recent advances in remote operations.

Keywords: Thermo-Vacuum testing · Space simulator · E-Learning

1 Introduction

Qualification of space components is an activity of paramount importance since in case of failure in space there is no possibility of convenient intervention. However, we recall some exceptions such as the repairing and upgrading in orbit, with the Space Shuttle servicing missions, of the Hubble space telescope. The complex operations were carried out by five very expensive human missions. Recently a satellite servicing capabilities office has been established at Goddard Space Flight Center which will provide robotic servicing technology not only for repairing but also for maintenance and satellite disposal. It has to be considered that although robots are far less expensive than astronauts, the costs of those operations are anyway much higher than qualification tests. That is particularly true for the small payloads: the cost of a servicing mission would be probably higher than the mission itself.

In the case of LARES satellite it was of vital importance to test the Cube Corner Reflectors (CCRs) under operating conditions, reproduced inside the thermo-vacuum,

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Fig. 1. Internal test volume of the vacuum chamber. The five walls visible in black are painted with Aeroglaze Z306. A smaller nitrogen cooled shroud, used for some tests, is visible just behind the small shaft that is attached to the rotational manipulator at the top of figure.

chamber, in order to verify the CCR functionality [1]. Although the cost of the facility was relatively high, that would never compare with the cost of the mission. The satellite objective was to test frame-dragging [2, 3] of general relativity theory with an unprecedented accuracy, bringing the error from 10 %, already obtained with the LAGEOS satellites [4], to about 1 % [5] as also shown with a Monte Carlo simulation [6]. LARES was successfully put in orbit February 13, 2012 [7] and is perfectly operating since then [8],

Fig. 2. The liquid nitrogen cooled shroud removed from the chamber, with the brazed copper coil visible.

thus demonstrating the goodness and the reliability of the tests performed in the vacuum chamber. Although the satellite data analysis is still in progress [9], from the first measurements it has been verified that it behaves as the best test particle available in the solar system [10]. Behaving as an almost ideal test particle means that it can be used to probe very accurately the gravity field around Earth thus providing the scientists with the possibility of verifying the deviations of the orbit from classical Galilei-Newton mechanics.

2 Description of the Facility

The main component of the facility is the vacuum chamber that has cubic shape of 0.6 m side. Five walls are entirely covered with a copper shroud painted with Aeroglaze Z306

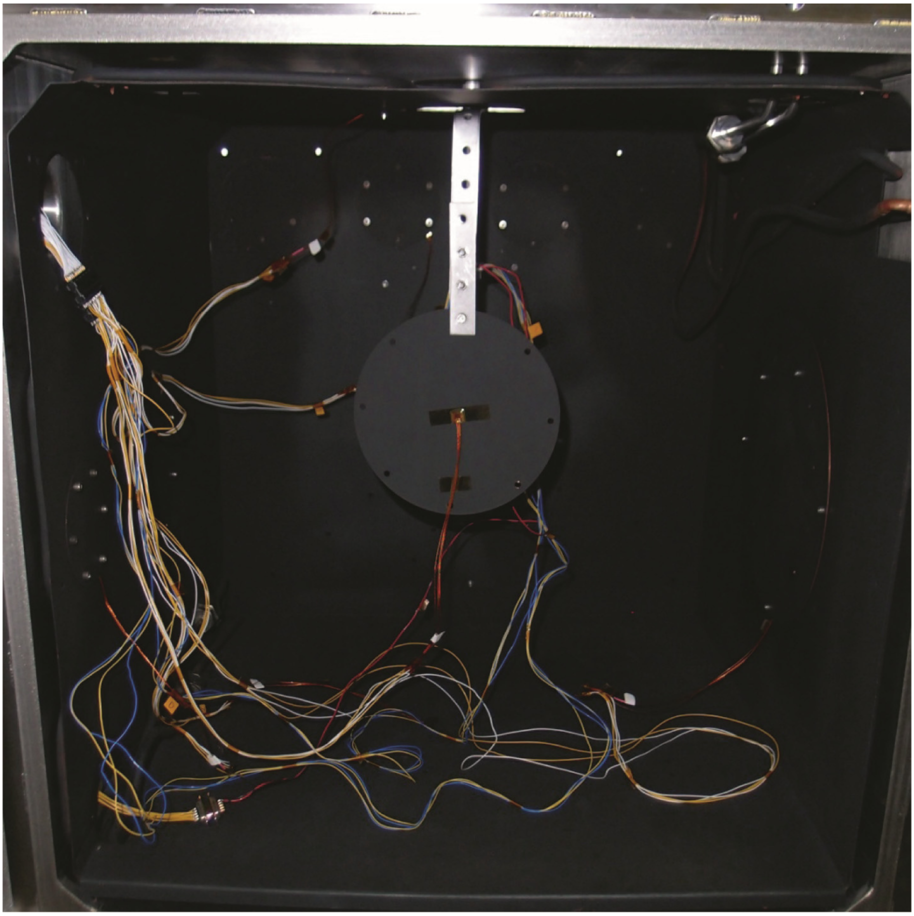


Fig. 3. The black disc in the middle of the chamber is in contact with the upper wall and cools down to −90°C. Equipped with resistive heaters for thermal control the disc can be maintained at −18°C to simulate Earth infrared radiation.

which is a special paint with thermo optical properties ($\alpha > 0.95$ $\varepsilon = 0.90$) that approach those of an ideal black body (Fig. 1) [11]. Copper coils are brazed (i.e. joined to the shroud by melting a silver alloy filler) (Fig. 2). The cooling circuit is open-loop, i.e. liquid nitrogen will flow from the Dewar, positioned outside of the lab, through a thermally isolated pipe into the coils inside the chamber and then, through a second thermally isolated pipe, released in the air outside the lab. The upgrade with a closed-loop reliquefaction apparatus is possible but not convenient because many thermo vacuum tests are performed according to the European Cooperation for Space Standardization ECSS-E-10-03A/C [12, 13], which requires only thermal cycling in vacuum and in the temperature range from the minimum to the maximum temperature limits expected during operation (which in Low Earth Orbit, LEO, means usually not under −34°C) [14]. In the next section it will be described an upgrade of the facility with an additional cooling system which fulfill the ECSS just mentioned.

The five wall shroud has several apertures in correspondence to the chamber feedthroughs, but it is possible to cover those in case the feedthroughs are not used in a particular test: that arrangement is to reduce the number of hot spots on the walls as much as possible. The door wall has a feedthrough which can be used for feeding an additional liquid nitrogen cooled shroud, but currently it is preferred the use of a disc which cools down to about −90°C which is sufficient for most tests. The cooling of this disc is obtained by radiation heat transfer with the other walls and by conduction, through the support, with one of the walls (Fig. 3). The five wall shroud is modular, in fact the floor can be removed, provided the liquid nitrogen coil is reconnected using the Swagelok fitting (Fig. 4) that guarantee perfect sealing and a relatively easy screwing and unscrewing. The shroud has been designed with this possibility because of the

Fig. 4. The Swagelock fittings can be used to remove the cooled floor of the shroud if needed, to test heavy specimens.

deformability of the thin copper shroud which cannot support weight higher than say 5 kg without experiencing macroscopic deflection of the shroud itself.

The chamber is equipped with three optical windows, the largest one has a minimal absorption in the solar extraterrestrial spectrum and is used for illuminating the test item with the solar simulator (Fig. 5, in the photograph the sun simulator has been temporarily removed to allow the view of the window). The second largest one has an optical quality of λ/20 (where λ is the light wavelength) and is required for testing, with instrumentation placed in air, optical payloads inside the chamber (Fig. 6). The third optical window is very small, positioned on the front door, and is used for visual inspections (visible in Fig. 5). A led strip is fixed on the internal part of the door to illuminate the enclosure. The side wall on the left is equipped with two electrical feedthroughs with 50 and 9 pins respectively. The first is used for transferring sensor readings to an outside acquisition system and the second mainly to power resistive heaters and illumination leds (Fig. 6).

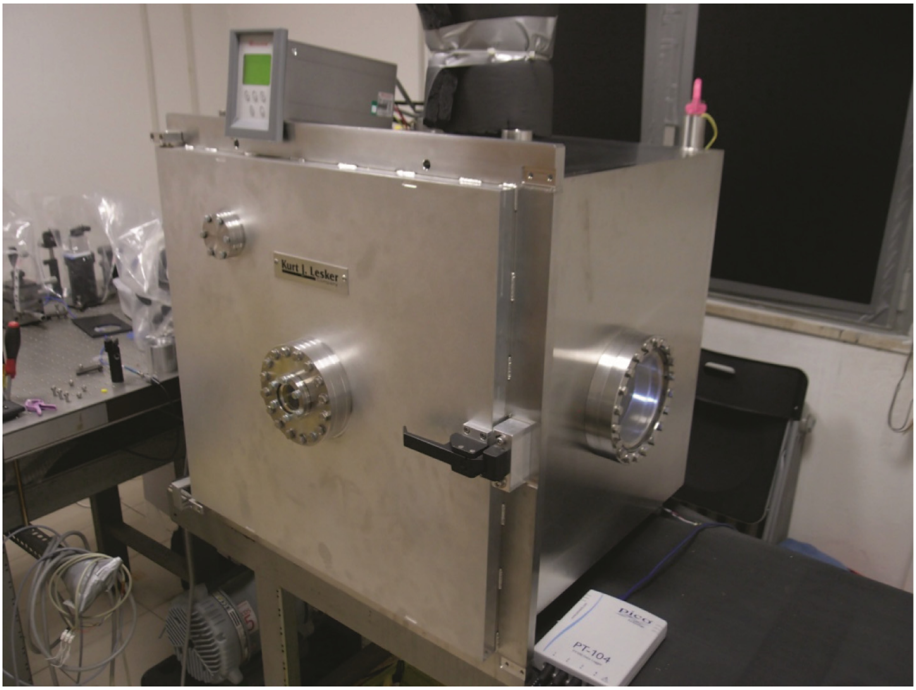


Fig. 5. The vacuum chamber, closed. The window on the right is used to illuminate the specimen under test with the beam of a Sun simulator lamp (not present in the photograph). The smaller window on the door is an inspection window.

3 Testing Activities

In this paragraph two test campaigns with different experimental set-ups will be briefly described. The first one concern the tests performed on the CCRs of LARES satellite. The second is relevant to the test performed on the 3U CubeSat (TIGRIsat) for validation of a numerical thermal model of the hardware.

3.1 CCR Testing

The LARES-Lab facility has been designed specifically to test the optical payload of LARES satellite [15]. LARES carries 92 CCRs which are used to measure the position of the satellite with an accuracy that can reach fractions of a centimeter [16]. The International Laser Ranging Service (ILRS) [17] operates a network of about 60 ground stations which measure the distance of satellites equipped with CCRs and other types of retro-reflectors by shooting laser pulses toward the spacecraft. The CCRs reflect the pulses toward the ground station regardless of the orientation of the reflectors; the distance of the satellite is then calculated by accurately timing the time-of-flight of the laser pulses. The ranging data provided by the ILRS are then processed by analysis centers; LARES data are processed by the International Space and Time Analysis Research Centre (ISTARC) located in Rome at Sapienza University [18], that provides the orbital predictions for the spacecraft.

LARES CCRs are made of Suprasil 311 optical glass; back faces of the CCRs are uncoated, the laser pulses are sent back from the front face after three total internal reflections (Fig. 7). The dihedral angles between the back faces of the CCRs mounted on satellites must be corrected for the so called velocity aberration: the back faces are manufactured introducing a small angle offset to compensate the effect of the satellite motion on the reflected signal. The offset re-distributes the energy of the reflected diffraction pattern (Far Field Diffraction Pattern, FFDP) so that the peak of the reflected energy is not in the center of the FFDP but is distributed on an annulus; this way the ground station will fall inside the annulus. On LARES the offset on the dihedral angle was 1.5 ± 0.5 arcsec. The small manufacture tolerance allowed on the offset angle could have been disrupted by temperature gradients on the CCRs due to the environmental condition in orbit and the thermo-optical properties of tungsten alloy used for the satellite body, a material that is somewhat "anomalous" for space structures. A temperature difference ΔT between the front face and the apex of the CCR will produce a change in the dihedral angle proportional to $\alpha_T\ \Delta T{\cdot}D$, where D is the front face diameter and $\alpha_T = 5.1 \times 10^{-7}\ \mathrm{K}^{-1}$ is the coefficient of linear thermal expansion of the Suprasil. The tests in the LARES-Lab were used to determine an experimental value for the expected ΔT [19] and to measure the deformation of the FFDP, having reproduced for the CCRs the best simulated operational conditions [20].

Fig. 6. The high precision optical window for optical testing. Above the window is mounted the turbo molecular pump over a vibration damper (in red). The same side of the chamber hosts the electrical feedthroughs (top and bottom right) (Color figure online).

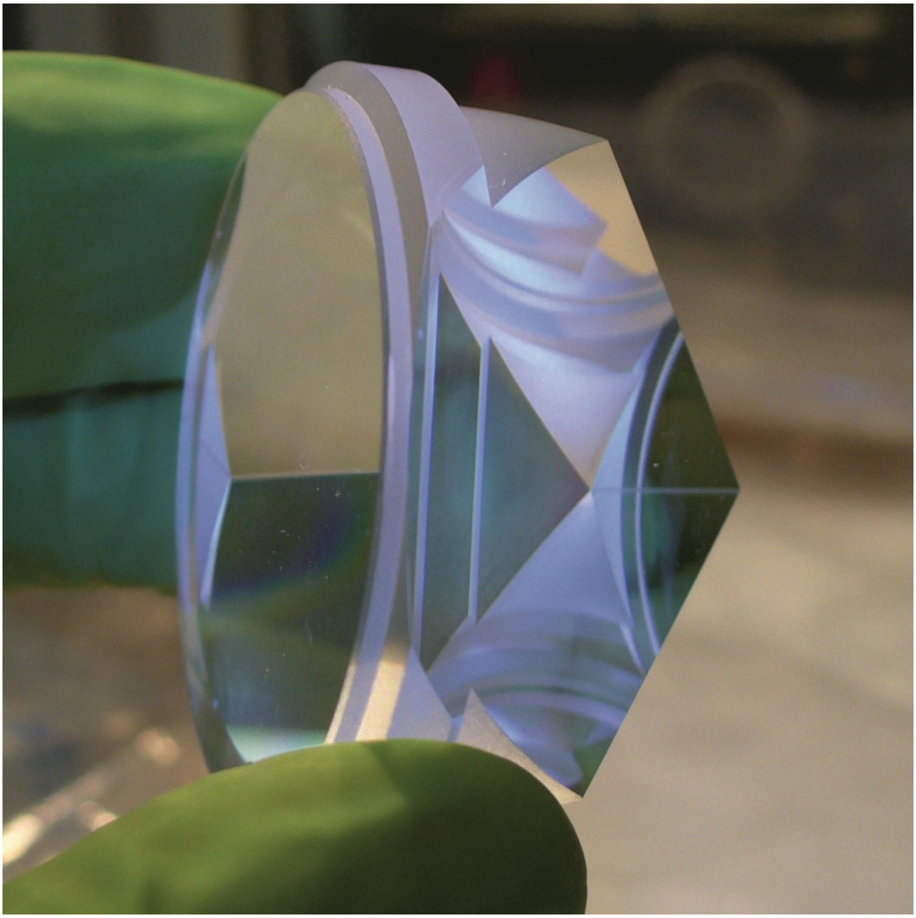


Fig. 7. A CCR of LARES satellite. The front face and the back faces are uncoated: laser pulses are reflected back to the ground station by three total internal reflections.

3.2 Thermal Testing of Tigrisat Structure

In 2012 Sapienza University of Rome in collaboration with the Task Force Iraq (Italian Ministry of Foreign Affairs), the Iraqi Ministers of Science and Technology, High Education and Transport, and the Italian Air Force, organized the First High Level Postgraduate Course in Aerospace Engineering. The participants to the course were a group of Iraqi engineers that, together with Sapienza University, designed and built the first Iraqi satellite, TIGRIsat, for monitoring sand and dust storms over Iraq. The satellite was then successfully launched in 2014, deployed by Unisat 6, a bigger satellite (developed and built by Gauss srl, Rome Italy) launched by a Dnepr rocket from the Yasny cosmodrome (Russia) [21]. The small satellite, a 3U CubeSat, carries, as main payload, an RGB wide field camera and is also a test-bed for technologies developed at Sapienza University, such as the active magnetic attitude control system, the S-Band antenna and the on-board computer [22, 23]. Because of the limits on mass and volume of the CubeSat design, and the limited power supplied by the solar cells, TIGRIsat relied on passive thermal control. So the thermal analysis was critical to assure that the satellite components (camera, battery, computer) would stay within the allowed operational limits once in orbit. To determine the temperatures on the satellite a numerical model was developed, that simulates the main components of the satellite and the worst environmental conditions in orbit. It is well known that the absorptivity over emissivity ratio (α/ε) of the satellite structure, made of aluminium alloy, was the key parameter to obtain passive thermal control. However, the α/ε ratio of the material was not known, and measuring directly α and ε was not an easy task. The solution was found testing one section of the structure in the thermo-vacuum chamber. The structure of the satellite is made of 3 cubic units (3U), side 10 cm each; one section of the structure, without the subsystems, was suspended inside the vacuum chamber and equipped with thermal sensors (Fig. 8). The structure was illuminated with the Sun simulator beam on one side, while 5 walls of the chamber were cooled with liquid nitrogen ($T = -192$°C) and the sixth side hosted the Earth infrared simulator ($T = -18$°C). The numerical thermal model was tuned on the α/ε ratio until the temperatures in the model matched the temperatures recorded on the structure during the thermo-vacuum test. The test has shown that the α/ε ratio of the metal was 0.237, a value that allows an optimal passive thermal control

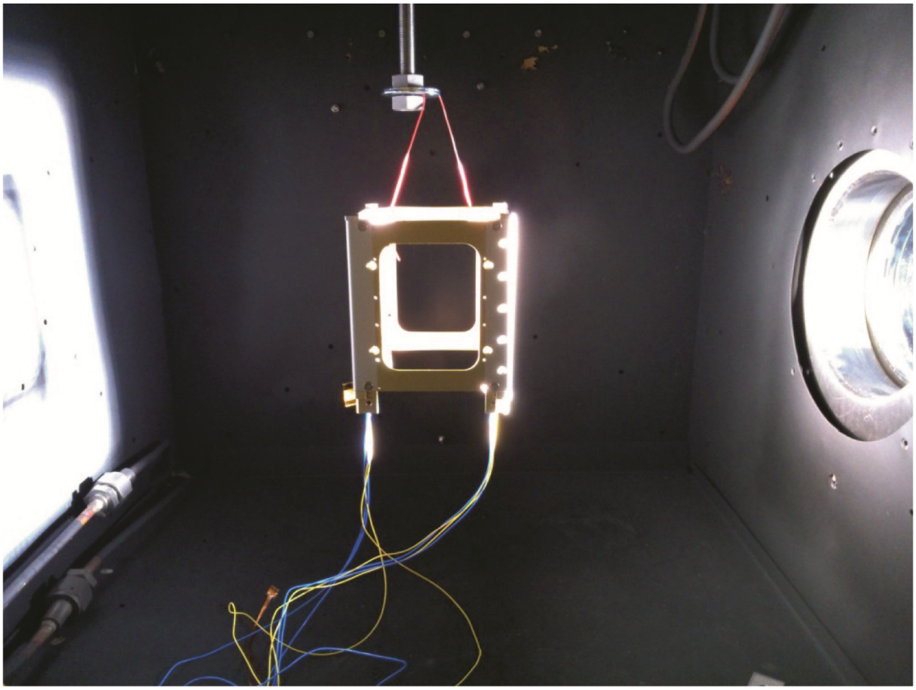


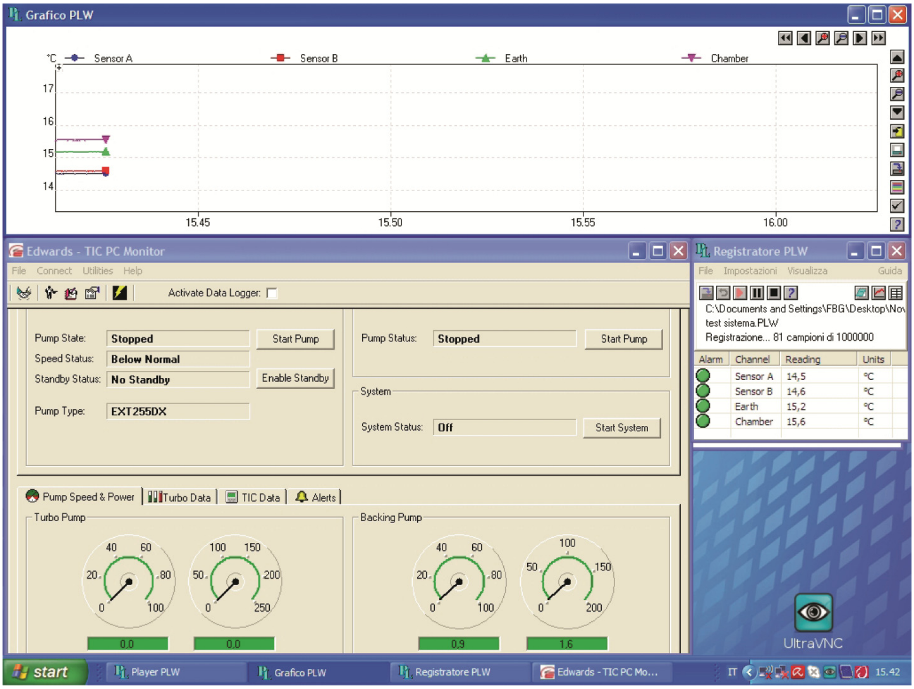
Fig. 8. One unit of the 3U structure of TIGRIsat during the thermo-vacuum test [24]. The structure is illuminated by the Sun simulator beam entering the window on the right. The cables are for the temperature sensors.

without needing coating or painting the external surfaces of the metal. The telemetry data from the operational satellite are confirming the correctness of the analysis and testing [24].

4 Facility Upgrade and Relevant Remote Control

Sometimes tests run over a long period of time, and in those cases it would be convenient to have remote access to the controls of the facility. The additional cost for automation is relatively accessible giving the facility an increased potential, being possible to conveniently run tests also overnight. Particularly interesting is the use for didactic purposes: the possibility during the class not only to show a running test, but also interact with the facility by acquiring data and providing inputs. Furthermore access through internet will allow, with proper permissions, to control the test from home or anywhere else.

Remote operation of labs, test machines and simple manufacturing processes for teaching is a recent trend, which will be further exploited in the future [25–29]. However a search in the available literature did not produce any example of remote operated space environment simulators [30]. Didactic activities of the Aerospace Engineering University courses include experiment about thermodynamics, heat transfer and thermal control, focused on space components, and testing of small payloads for space mission, or even design and testing of microsatellites (such as CubeSats). Indeed, from 2000 the



Pump State: Stopped

Speed Status: Below Normal

Standby Status: No Standby

Pump Type: EXT255DX

Pump Status: Stopped

System Status: Off

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Registrazione... 81 campioni di 1000000

Alarm	Channel	Reading	Units
🟢	Sensor A	14,5	°C
🟢	Sensor B	14,6	°C
🟢	Earth	15,2	°C
🟢	Chamber	15,6	°C

Fig. 9. A screenshot from the server PC, showing the softwares for temperature monitoring (top and center right), for the turbomolecular pump control (down) and for pressure monitoring (not shown in this screen shot). The VNC icon is also visible bottom right) [30].

School of Aerospace Engineering of Sapienza University of Rome launched several microsatellites and nanosatellites developed by students, PhD students and students of postgraduate courses [31, 32]. Some of these microsatellites or some payloads where tested in the LARES-lab thermovacuum facility. Some tests required more days to be completed, in particular when thermal cycling is involved; however, since the facility is not automated or remote controlled, long duration tests required the presence of operators also during the night. Furthermore, a remote controlled facility will be a valuable aid for teaching, allowing the students to perform long duration experiments and to collect data out of the lesson hours.

At the moment it is possible to access a computer in the facility, referred to as "the server", by using a Virtual Network Computing system (VNC), from any computer or even portable devices with an Internet connection, such as smartphones and tablets, referred to as "the clients". The server is running the software for controlling the turbo-molecular pump and read the pressures, and the acquisition software for recording data from temperature sensors, strain gages and fibre optic sensors (Fig. 9). It is also possible to record pictures from a webcam that can be used to monitor the test from the inspection window on the chamber, for example to verify the orientation of the specimen. The VNC system allows to control the server desktop, to switch on and off the turbo-molecular pump, to record the pressure, to configure and to start and stop data acquisition. The actual configuration was devised having in mind the necessity, for the authorized operators of the lab only, to control the running tests from a remote computer, even from

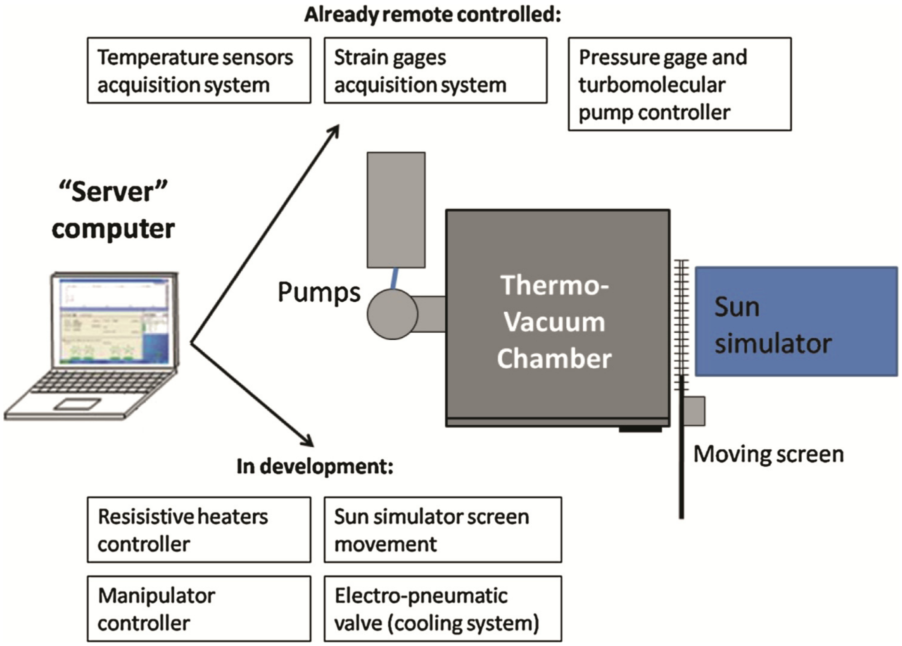

Fig. 10. Scheme of the LARES-lab illustrating the systems already remote controllable and the planned upgrades.

home, in case of long duration tests, and was not intended to be used by students. Indeed, the actual VNC system leaves too much freedom of control over the server PC (i.e. the possibility of deleting files, install or uninstall software) to a remote operator. Moreover, the connection allows only one client at a time to access the server, and there is not a system to manage multiple accesses. We are testing a desktop sharing software for providing multiple accesses to the students using TeamViewer. This software can give the possibility of multiple accesses while controlling the privileges of the clients. A possible scenario for the teacher is to create an on-line meeting with the students for showing an ongoing experiment and giving the possibility to some of them to operate the remote lab under his supervision.

The automation and remote control of the various components involves different levels of difficulties and costs, depending on the chosen implementation. Some components require only a USB connection to the server PC, other will need an external interface (to provide enough power, for example) that will be controlled by the server.

The scheme in Fig. 10 shows which systems are already remote controllable, and which ones are under implementation.

4.1 Manipulator

The manipulator will be upgraded to be controlled by the server and thus by the clients. A stepper motor will be coupled to the manipulator shaft by a drive belt. A controller will be used to interface the server, connected by a USB cable, to the stepper motor in order to control the rotation of the manipulator. The possibility that the motor will introduce unwanted vibrations has been evaluated: in such a case it is possible to install a passive vibration dumper under the manipulator. A similar passive dumper is already mounted under the turbo-molecular pump (Fig. 6).

4.2 Cooling System

The vacuum chamber is already equipped with a liquid nitrogen cooled shroud on five walls, to simulate thermal radiation toward deep space. The shroud can reach a temperature of −190°C using an open cooling circuit: the liquid nitrogen flows through a copper pipe soldered/brazed to the shroud and is then evaporated and dispersed outside the lab. The circuit is fed by a pressurized Dewar. The conversion of the cooling system for remote operation is not a trivial task. The flow shall be controlled by a valve capable to resist to the pressure and the temperature of the liquid nitrogen. The valve shall be operated either by a command of the operator or by an automatic system that reacts at the input from thermometers fixed on the shroud. An automatic controlled valve is intended to avoid wasting too much liquid nitrogen, while maintaining the temperature around the set value, with some oscillations (small variations are allowed since they do not have a significant impact on the test). An automated valve can be either electromechanically operated or electro-pneumatic operated. Electromechanically operated valves use solenoids to develop the magnetic force needed to overcome the elastic force of a spring, hence this kind of valve develops a high peak power and needs a high power to maintain the open position. So to connect the valve to the power line an additional power

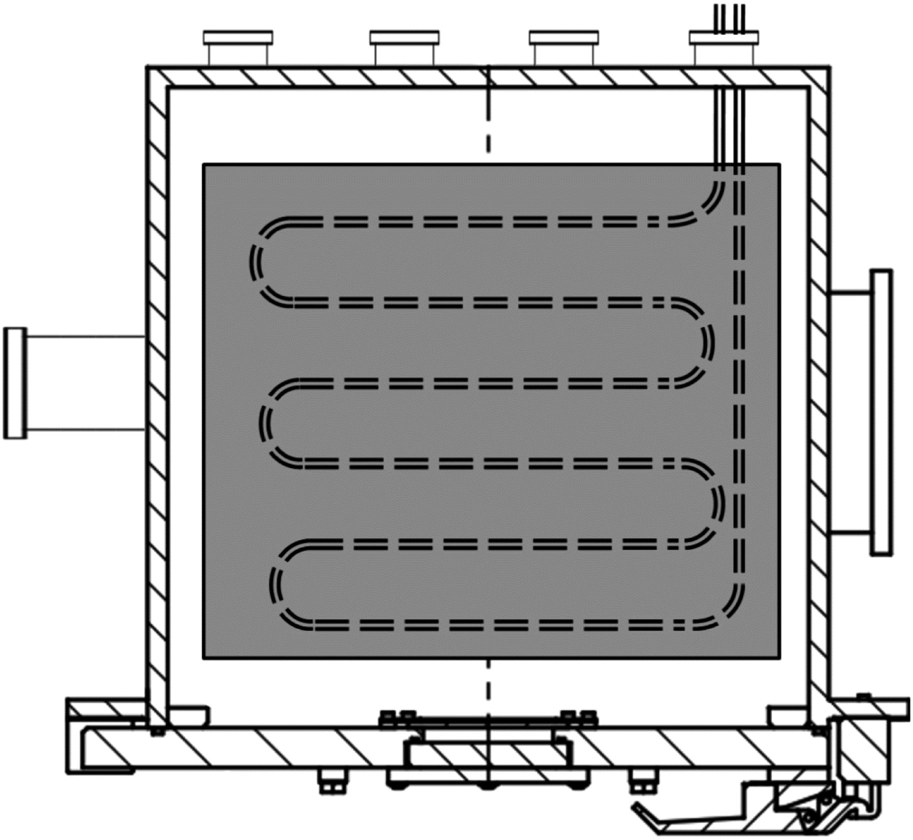

Fig. 11. Scheme of the additional closed-loop cooling system (top view). An aluminum plate, thickness 2.5 cm, is cooled by a copper coil. Inside the coil circulates the refrigerating fluid from an external cooling unit. The pipes of the coils are connected with the external cooling unit via a feedthrough on the back of the chamber.

relay is needed. Electro-pneumatic valves, instead, are operated by a pressurized air circuit and, for our application, are more convenient than electromechanical valves. Indeed, electro-pneumatic actuation allows not only to open and close the liquid nitrogen flux but also to control the flow by partial opening of the valve.

An additional closed-loop cooling system is under development (Fig. 11). With respect to what reported in ref. [30] this second cooling system will allow to reach a temperature of about −50°C sufficient for most tests for LEO environment. Differently from the liquid nitrogen circuit in this case it is used a closed-loop circuit. Also as requested by the ECSS procedures, in this case the heat transfer from the massive metallic heat sink and the test item is mainly obtained through conduction. Aim of those types of tests is to cycle the temperature on the test item in the required range of temperatures. In other words the temperature is imposed on the specimen to prescribed values as a function of time.

4.3 Resistive Heaters

Resistive heaters are used to control the temperature on the items under test or on the disk that simulates the Earth infrared radiation and that has to be maintained at a temperature of −18°C [13]. The experience gained with the testing activities showed that an automatic feedback control, to maintain the specimen temperature stable (i.e. allowing variation of less than 2°C/hour), is not required, once the voltage and the limit current have been manually set on the power unit. The power unit can then be controlled by a software on the computer, allowing remote setting of the heaters.

4.4 Pumps

The thermo-vacuum chamber is equipped with two pumps: the first stage pump (scroll pump) is used to bring the pressure to less than 5 mbar, then the second stage pump can be switched on to obtain a pressure of less than 10^{-5} mbar, as required by ECSS regulations for space environment simulation. Indeed the pressure inside the chamber is typically 10^{-6} mbar, and even less with the liquid nitrogen cooling circuit on.

The turbo-molecular pump can be switched on and off remotely by the control software, provided that the pressure is below 5 mbar.

The scroll pump cannot be controlled remotely and is switched on once the test has been prepared and the vacuum chamber has been closed. The scroll pump is designed to operate continuously for days, to maintain the pressure at a level which is safe for switching on the turbo-molecular pump (i.e. less than 5 mbar). The upgrade foresee the use of an external switch that will allow to operate also the scroll pump remotely. This is a relatively easy task since there is no need of speed or power control.

4.5 Sun Simulator

The sun simulator uses a Xenon arc lamp to simulate solar radiation over a 12 × 12 cm area. The arc lamp requires a dedicated 6 kW power circuit and can be damaged if switched on and off too often, moreover the procedure to switch on the lamp is not straightforward. Therefore the solution to control the Sun simulator, already adopted for the testing activities, is to leave the lamp on and to stop the beam entering the chamber by interposing a removable screen between the lamp and the window. The screen is at the moment moved manually by the operator, but a remote controlled servomechanism is under development. The mechanism will be operated by the computer (“the server”) but can of course be controlled also by the clients.

5 Conclusions

LARES-Lab is a thermo-vacuum facility created for the LARES mission, and used to test and qualify satellite components for LARES and other small missions. Also, the facility is used for teaching and didactic activities. At the moment the facility allows remote monitoring of the temperature and pressure sensors and to switch on and off the turbo-molecular pump. A new upgrade concerning a closed-loop cooling system is under design. This will complement the open-loop cryogenic system. The lab is being upgraded to allow remote control of many subsystems, such as the manipulator, the resistive heathers, the Sun simulator and the cooling systems (both open and closed-loop). This way the capabilities of the lab will be improved both for testing and research activities as well as for teaching and e-learning. Remote access to the lab will provide the researchers and the students a way to perform and follow experiments of a certain complexity from the classroom or even from home.

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