SD2 – HOW TO SAMPLE A COMET

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(Received 9 August 2006; Accepted in final form 1 December 2006)

Abstract. SD2 (Sampler, Drill and Distribution System), is one of the instruments onboard the lander Philae of the Rosetta mission. This system is of primary importance for the lander mission since it is in charge to collect comet's soil samples at different depths and to distribute them to different instruments for analysis. SD2 has to meet very stringent requirements in terms of volume, mass and power consumption, operative range and severe environmental conditions. An overview of SD2 is provided, with the description of the sample acquisition and distribution procedure and an outline of the technological innovative aspects.

Keywords: Rosetta, Philae, comets, drill sample collection

1. Introduction

Currently, comets are the best candidates to answer some fundamental questions related to the origin of the Solar System and to the birth of life on Earth.

In order to answer to these questions it is necessary to closely monitor a cometary nucleus during its revolution around the Sun. For these reasons, the Rosetta mission has been selected as a cornerstone mission of the scientific programme "Horizon 2000" of the European Space Agency (ESA). After the rendezvous with comet P67/Churuymov-Gerasimenko, Philae (Ulamec *et al.*, 2002) will be released through soft landing at the surface of the nucleus and will perform a series of in-situ experiments. Mission goals include the determination of the elementary and mineralogical compositional, the identification of traces elements, and isotopic composition of cometary material from the surface and subsurface. Comet's surface strength, density, texture, porosity, ice phases and thermal properties will also be investigated together with soil structure through microscopic observations of individual grains.

All these measurements will allow a better understanding of the nucleus structure and properties (Lewis, 1995; Nuth III *et al.*, 2002) and a deeper knowledge of its mineralogical, chemical and isotopical composition and in particular of its organic components (Munoz *et al.*, 2002).

In this scenario, the multifunction device SD2 (Sampler, Drill and Distribution System) will perform all the following in-situ operations: soil drilling, samples

DOI: 10.1007/s11214-006-9134-6

collection and their distribution to the instruments after preparation. In fact SD2 is also equipped with ovens to heat the samples at different temperatures in order to induce the release of the different volatile substances to be analysed.

During comet surface operations, SD2 shall interface with three scientific instruments (Berner *et al.*, 2002) devoted to samples analysis:

- COSAC (COmetary Sampling And Composition experiment) (Goesmann *et al.*, this issue), one of the two evolved gas analysers designed to detect and identify complex organic molecules from their elemental and molecular composition,
- PTOLEMY (Wright *et al.*, this issue), the other evolved gas analyser designed to perform accurate measurements of the isotopic ratios of light elements,
- CIVA (Bibring *et al.*, this issue), composed of seven micro-cameras, six mono and one stereo pair, that take panoramic pictures of the surface. A visible light microscope coupled to an infrared spectrometer will provide data on the composition, texture and albedo of the samples collected.

2. Sampling Method

The strategy for collecting the samples (Allton, 1989; Anttila, 2004, 2005; Paties-Simon, 2006) depends on many factors, in particular on the required size and type (or shape) of the target. For this reason, it is meaningless to talk about the best strategy, as this one dramatically depends on the environment at the comet's surface and in particular on the gravity, on the mechanical and chemical soil characteristics (cohesive, hard or porous/spongy soil), on the temperature and pressure conditions and on the solar radiation. In many cases, gravity and soil characteristics are the predominant factors. However, under extreme conditions, like those on the surface of a comet, the temperature also has to be considered as a critical factor.

Among the different sample collection techniques (Ercoli Finzi, 2004; Franzen *et al.*, 2005), the drilling one has been adopted for the Philae mission because of the cometary soil properties, at the same time not very hard, but quite fragile for what concerns sample cohesion.

This is why a very slow drilling technique has been selected, with an independent actuation of the linear and rotational movements, a very accurate collecting system (Sampling Tube), a volume measurement device to meet the requirements of the sample analyzers, and a tapping station to avoid any sample dispersion.

The integrated drill sampling tube solution has been chosen for its simplicity and flexibility: the collection and release of the sample is performed by a pressure contact. In this way, the sample is protected from contamination. Moreover it is possible to collect different amounts of material at different selectable depths. The sampling tube design led to an extremely low masse and volume solution, according to the constraints imposed by the drill size.

Another very interesting SD2 capability, currently under study, is the possibility to derive soil properties from its cinematic behaviour (Koemle *et al.*, 2001; Rotta, 2006): such qualitative estimations of comet nucleus physical characteristics represent a valuable complementary data set to those coming from the scientific instruments.

3. Environmental Conditions

All SD2 operations have to be performed under extreme environmental conditions after a long period of inactivity during the cruise phase. Moreover SD2 must guarantee, prevention from thermal and chemical contamination of the material collected and meet all requirements within a very challenging mass and power budget.

The most important environmental parameters for the design of SD2 are: comet strength, temperature and pressure at the comet surface, which are very poorly known. This is why it has been necessary to take into account a wide range for each of these parameters, Table I, in order to guarantee a correct functioning of SD2, despite these large uncertainties. The results of the recent cometary mission Deep Impact (Lissen and Hopkins, 2005; A'Hearn *et al.*, 2006; Richardson *et al.*, 2006) show that the physical parameters of comet Temple-1 are compatible with those here reported.

SD2 will deliver to the scientific instruments samples of tens of mm^3 (10–40) collected at a maximum depth of 230 mm. The resulting length of the drill turns out to be 530 mm because of the clearance between the Lander Balcony and the comet surface. During operations, following the mission plan established by the Principal Investigators (PIs) of the scientific instruments, SD2 will drill a certain number of holes and will collect a certain number of samples, depending mainly on the conditions after landing. The minimum mission plan is the collection of two samples from a single hole.

4. SD2 Description

The SD2 system has been conceived as a four degrees of freedom (d.o.f.) robotic system (Malychev and Magnani, 2001). Its accommodation on the Lander is shown in Figure 1.

The SD2 system (Bologna and Crudo, 2002), Figure 2, consists of three main components: the Mechanical Unit, mounted on the Lander Balcony, the Electronic Unit, with embedded the SD2 software (Bologna and Magnani, 2001), installed in the warm compartment of the Lander and the Harness for the electrical connection of the Mechanical and Electronic Units.

The total mass is about 5.1 kg with this distribution:

- Mechanical Unit $\sim$3700 g

TABLE I
Environmental parameters

Comet strength	50 Pa – 50 MPa
Temperature	-140 °C (operation on comet)/$+50$ °C (no-operation)
Pressure	10^{-5} mbar (space vacuum)/1 bar

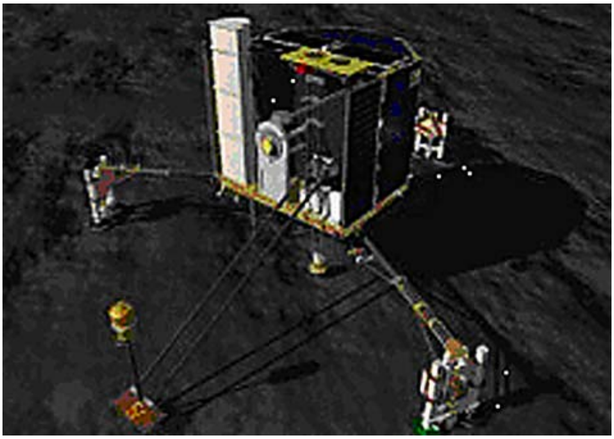

Figure 1. SD2 accommodation.

- Electronic Unit ∼1000 g
- Harness ∼400 g.
  The power consumption during operations does not exceed the following levels:

- 1.5 W average power consumption in stand-by
- 6.0 W average power consumption during drilling/sampling operations
- 14.5 W max power consumption during drilling/sampling operations.

The Mechanical Unit (Malychev and Crudo, 2001) consists of the Tool Box, the Carousel, the Volume Checker and 26 Ovens. Its configuration and main dimensions are shown in Figure 3.

The Tool Box contains the mechanisms in charge of performing drilling and sample acquisition functions in a protective structural shell, which assures that no external contamination can reach the tools and the actuators inside.

The drilling and sampling functions are integrated in a unique auger. This configuration guarantees the sample to be collected at the established/measured depth, preventing hole collapsing during sampling tool actuation. The Drill/Sampler Tool is shown in Figure 4.

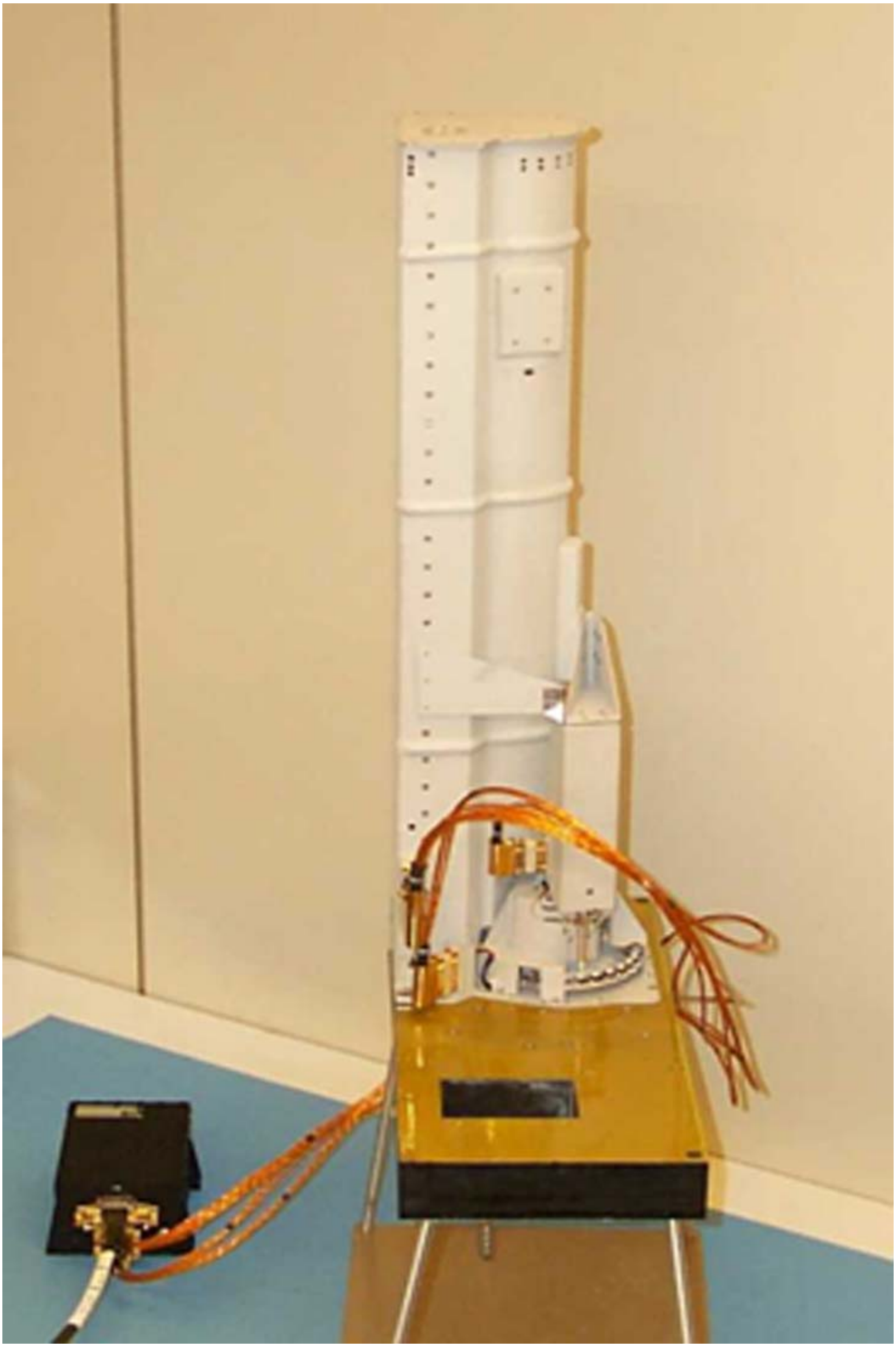

Figure 2. SD2 subsystem.

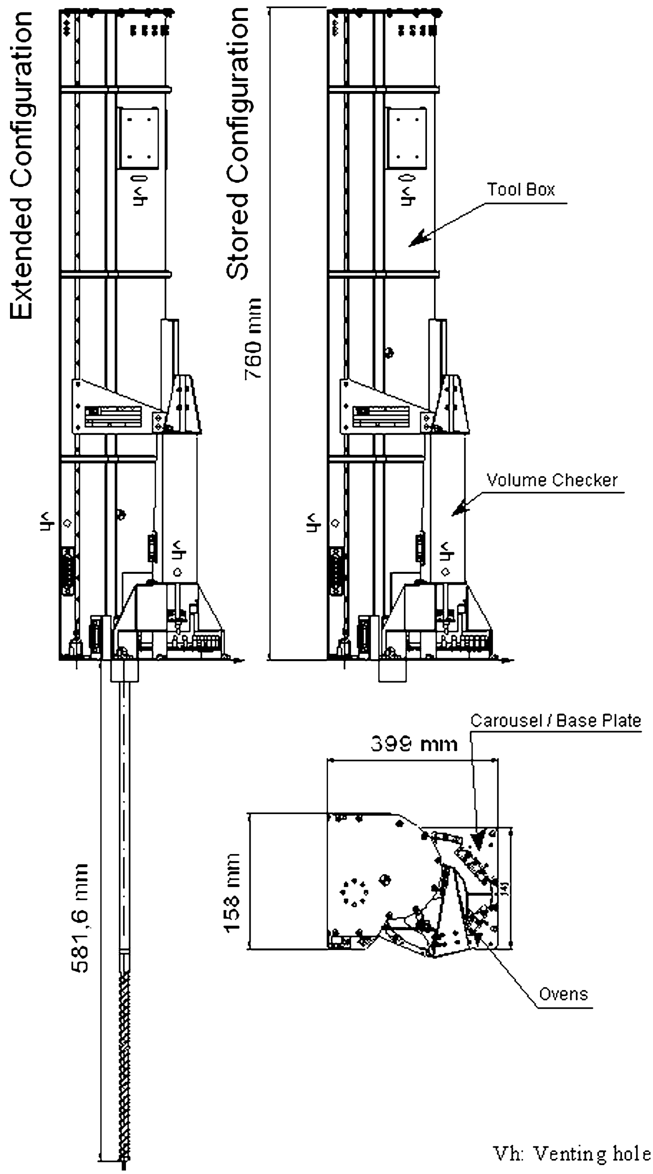

Figure 3. SD2 system in stowed and extended configuration.

The drilling bit is made of an assembly of polycrystalline diamonds, able to perforate hard materials. Even if such case is rather improbable, this solution was deemed appropriate to deal with a broad range of situations, due to the very poor knowledge of the comet nucleus mechanical properties. Position, shape and geometry of the inserts have been optimised by theoretical analysis, numerical simulations and experimental tests, in order to maximize the cutting capability with a low vertical trust of 100 N and with a low power consumption of 14.5 W.

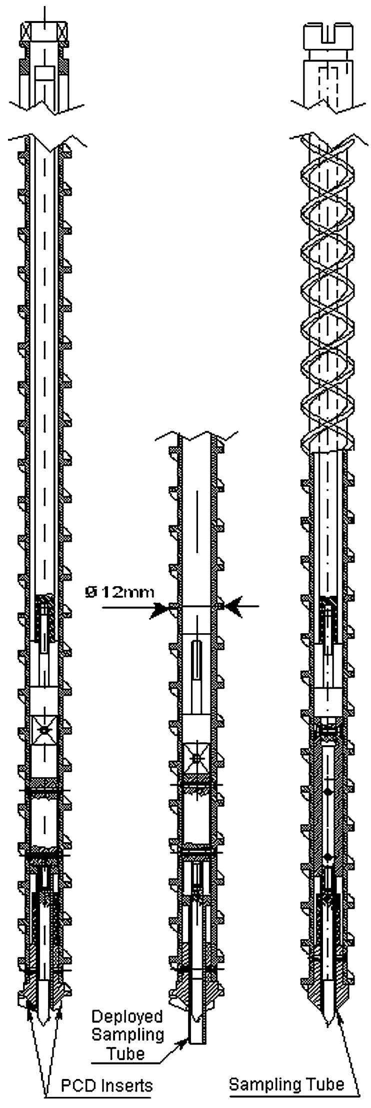

Figure 4. Drill tool.

The Drill/Sampler Tool has two degrees of freedom: translation, to reach the comet surface and rotation, around its axis to penetrate under the surface. This solution allows to play with different combinations of the two movements, according to the different conditions that may occur on the comet. The sample collecting/discharging mechanism is actuated independently. The kinematics of the drill/sampler tool is shown in Figure 5.

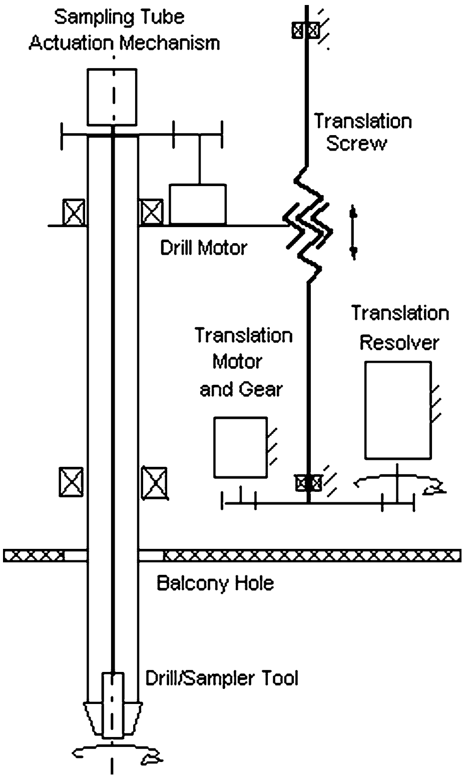

Figure 5. Kinematics of the drill/sampler tool.

After the drilling operation, the sampling mechanism collects the sample following the optimised procedure described in paragraph 5; the soil sample is delivered into an oven where it will be heated before analysis.

A dedicated electromagnetic mechanism has been designed to actuate the sampling tube, Figure 6; neither electrical slip rings nor mechanical parts in contact with relative rotation are present. In this way the mechanism is protected from frictions or locking that may happen especially in the low temperature and dusty comet environment.

The main dimensions of the auger (pitch, diameter and thickness) have been derived from theoretical analysis and numerical simulations performed on purpose, and from the tests of the Rosetta CNSR-SAS (Comet Nucleus Sample Return – Sample Acquisition System) project.

The Carousel, Figure 7, is a rotating disc on which the ovens are accommodated and provides the sample distribution to the scientific instruments.

The carousel is equipped with a stepper motor and a resolver that indicates the positions of the ovens mounted on its plate.

Figure 6. Drill sampling tube.

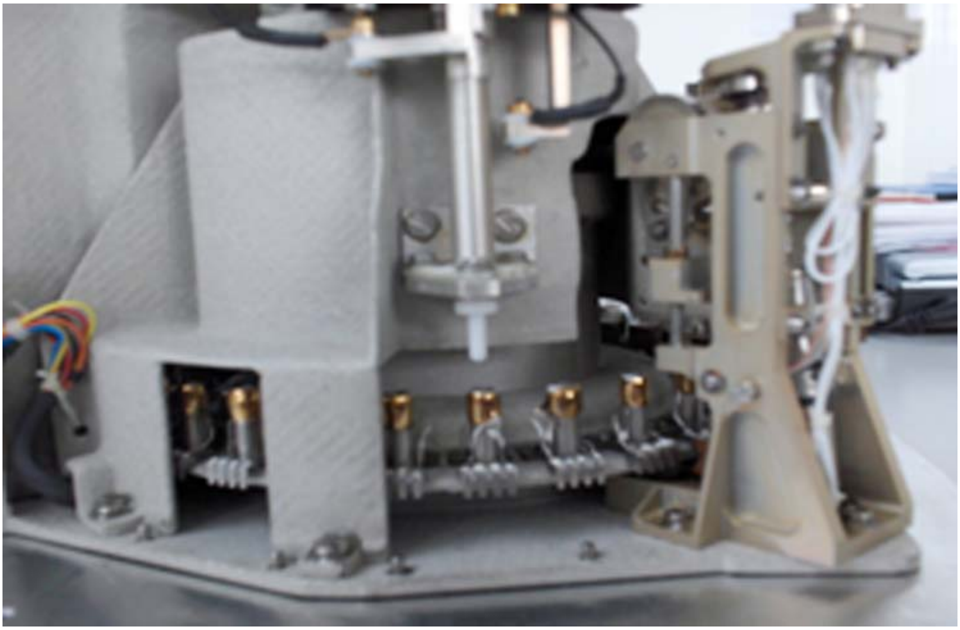

Figure 7. Carousel, ovens, volume checker and tapping station.

The Ovens, Figure 7, provide the interface between the sample and the scientific instrument.

To enable different kind of measurements, two types of ovens are available:

- 10 Medium Temperature Ovens, MTOs, with an optical sapphire prism for the analysis, by the visible and I/R microscope, of samples heated up at medium temperature (+180 °C),
- 16 High Temperature Ovens, HTOs, provided by MPS (Max Planck-Institute of Solar System), for sample heating at high temperature (+800 °C).

The Volume Checker mechanism allows measurement of the amount of material discharged into the oven. The kinematics of the Volume Checker is based on a translating rod (driven by a rotation motor) that is lowered and pushed into the oven The volume of the discharged material is measured by a displacement sensor.

This system allows, as needed, an homogeneous distribution of the material on the optical window in the Ovens equipped with the optical prism.

The kinematics of the carousel and the volume checker are shown on the Figure 8.

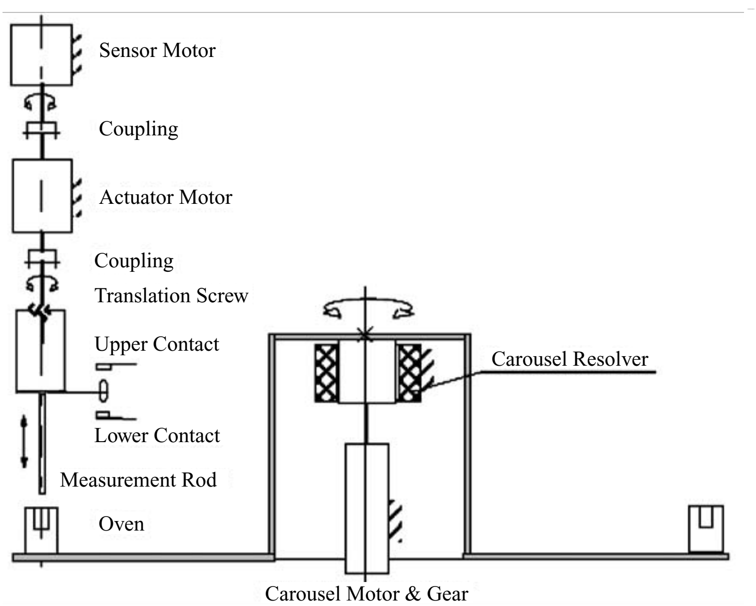

Figure 8. Kinematics of the carousel and of the volume checker.

5. Technological Aspects

During SD2 design phase, particular importance has been given to the tribological and the reliability aspects. Indeed, all materials, processes and technological solutions have been carefully selected in order to cope with these specific conditions: solid and self lubrication, brushless actuation, low friction/antijamming approaches, cutting technology for a large range of materials, low power consumption and radiation resistant electronics, and a special composite material structural. During the eleven years cruise, the SD2 system will perform only a few and very limited operations and will be kept under severe environmental conditions: very low temperature and high vacuum.

To cope with these conditions, contact less motors (stepper) and sensors have been adopted, as well as solid lubrication and materials suited for space operations. In some specific cases, the replacement of roller bearings with sliding self lubricated bearings (made of Vespel SP3 or Teflon) have been implemented.

A specific test session has been performed to demonstrate the suitability of such actuators for SD2 application.

The selected sensors are brushless resolvers. Some of them, not available among of the space qualified ones, have been derived from commercial products and properly modified and tested to operate in the extreme environmental conditions.

In order to cope with the low mass budget and the high frequency eigenvalues requirements, special carbon fibre composite material has been selected among the ones already successfully used for cryogenic tanks. In fact they present high capability to withstand the critical environment, with good impact resistance and damage tolerance for a wide range of applications.

For the structural parts of the drill tool, austenitic stainless steel has been preferred for its mechanical properties, being not brittle at low temperature.

The Medium Temperature Ovens, made of Platinum to minimises sample contamination, Figures 9 and 10, provide a closed volume to store soil material and ensure adequate volume sealing during medium temperature experiment. The Sapphire Prism provides the optical path from the sample to the optical instruments (visible and I/R microscopes). The Thermal Coil performs heating of the sample inside the oven and the electrical contacts provide electrical interface to the tapping station.

The Support Structure ensures mechanical interfaces of the oven and the Thermal Sensor allows temperature measurement during sample heating.

During the operations the ovens will interface with the tapping stations, realized by MPS, to seal the oven and to convey the emitted gas to the instruments for analysis. Specific technological processes have been used for the manufacturing of the Medium Temperature Ovens: Sapphire prism brazing (after metallization) to the Platinum Oven's base, Platinum Oven brazing to the Titanium Support, ceramic insulation of the wound Platinum wire and cryogenic adhesive, tested at -195 °C, to lock structural screws.

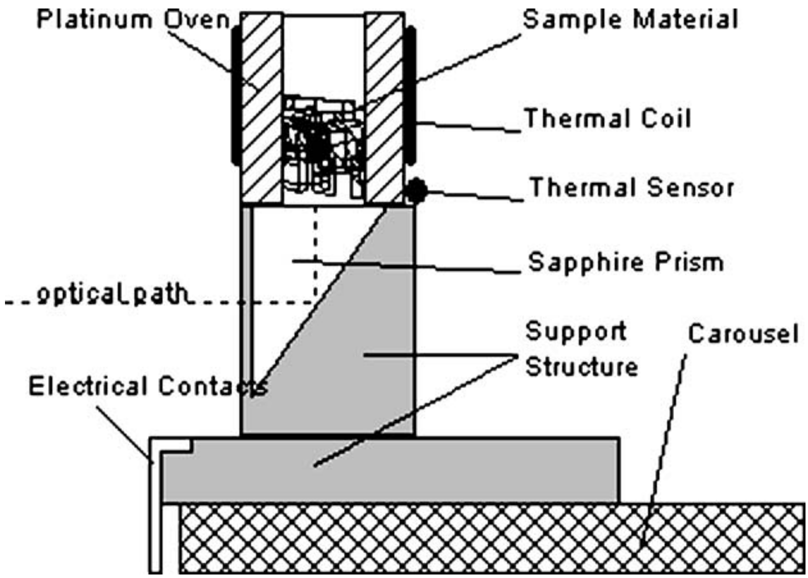

Figure 9. Medium temperature oven design.

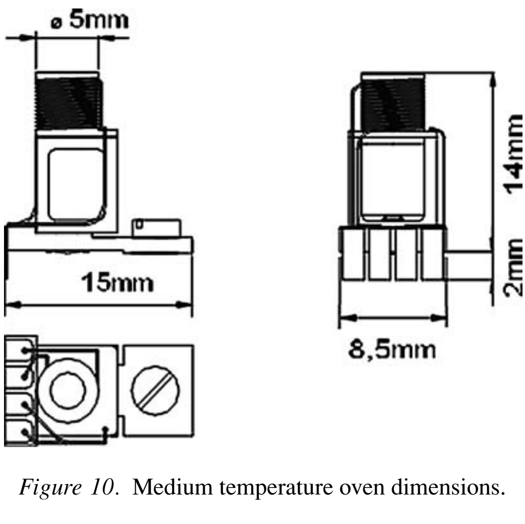

Figure 10. Medium temperature oven dimensions.

6. Sampling Principles

The procedure of sample acquisition and discharge is shown in Figure 11. Once the sampling depth has been reached (A), the drill is retrieved for 1 mm up (B), in order to allow the sampling tube release (C). In this way the sampling tube is pushed against the bottom of the hole, preventing the falling back of the chips uplifted at the sampling spot. Then a coring action (D) is performed and during this operation the

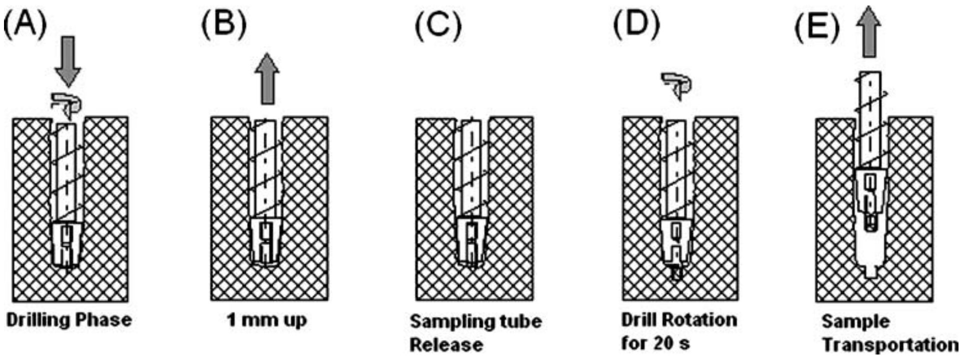

Figure 11. Sample acquisition procedure.

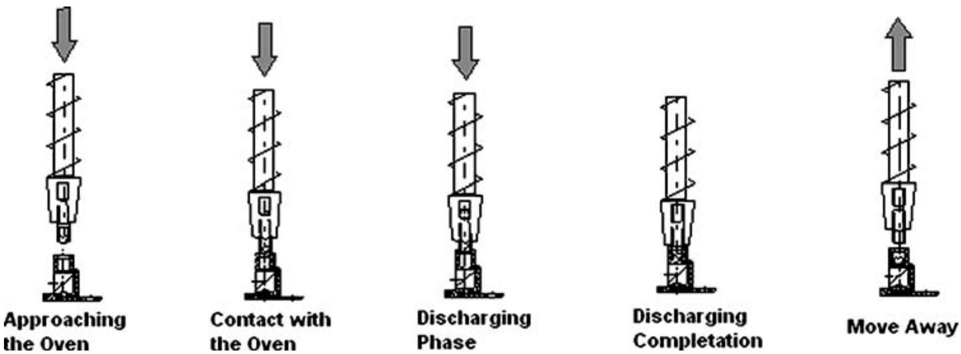

Figure 12. Sample discharge procedure.

sampling tube acts as a coring device, pressed by its own internal pushing spring. At this point the coring action is stopped and the drill rod uplifted (E).

The discharging operation, Figure 12, is performed by pushing the sampling tube at the oven entrance and exploiting during the pushing action a piston effect of the central part of the drill bit. Such sampling and discharging sequence has been tested several times, always successfully, in different environmental conditions with several types of material.

As results of one of these tests, Figures 13 and 14 show, a Medium Temperature Oven filled with collected material ready for processing, that is Volume Checker activation and scientific instrument analysis.

7. Control and Communications

All the electromechanical parts of SD2 are controlled by the SD2 Electronic Unit, designed and realized on purpose, that provides also SD2 interfaces to the Lander

Figure 13. SD2 medium temperature oven with sample inside.

CDMS (Command & Data Management System) (Crudo and Bologna, 2002) and to the Power System.

The Electronic Unit architecture is shown in the block diagram of Figure 15.

SD2 is powered with a 28 V power line from the Lander's Primary Bus, devoted to the Mechanical Unit, and auxiliary power lines +5 V, −5 V, +12 V, −12 V from the Lander's Secondary Converters.

Communications to CDMS are performed via redundant serial communication lines.

Once powered the subsystems performs self-checks and then waits for CDMS commands, a set of software commands that can be sent separately or organised in a dedicated mission plan. Before execution, commands are validated by suitable checks; the next command can be accepted only when the previous one is finished.

The unit incorporates the C-DPU (Common Digital Processing Unit) board, specially developed by DLR (Deutsches Zentrum fur Luft- und Raumfahrt) for the Rosetta Lander project, a low power consumption board based on the rad-hard Harris microprocessor HS-RTX2010RH and the rad-hard Actel FPGA 1280. Three interface boards have been developed on purpose to interface actuators and sensors,

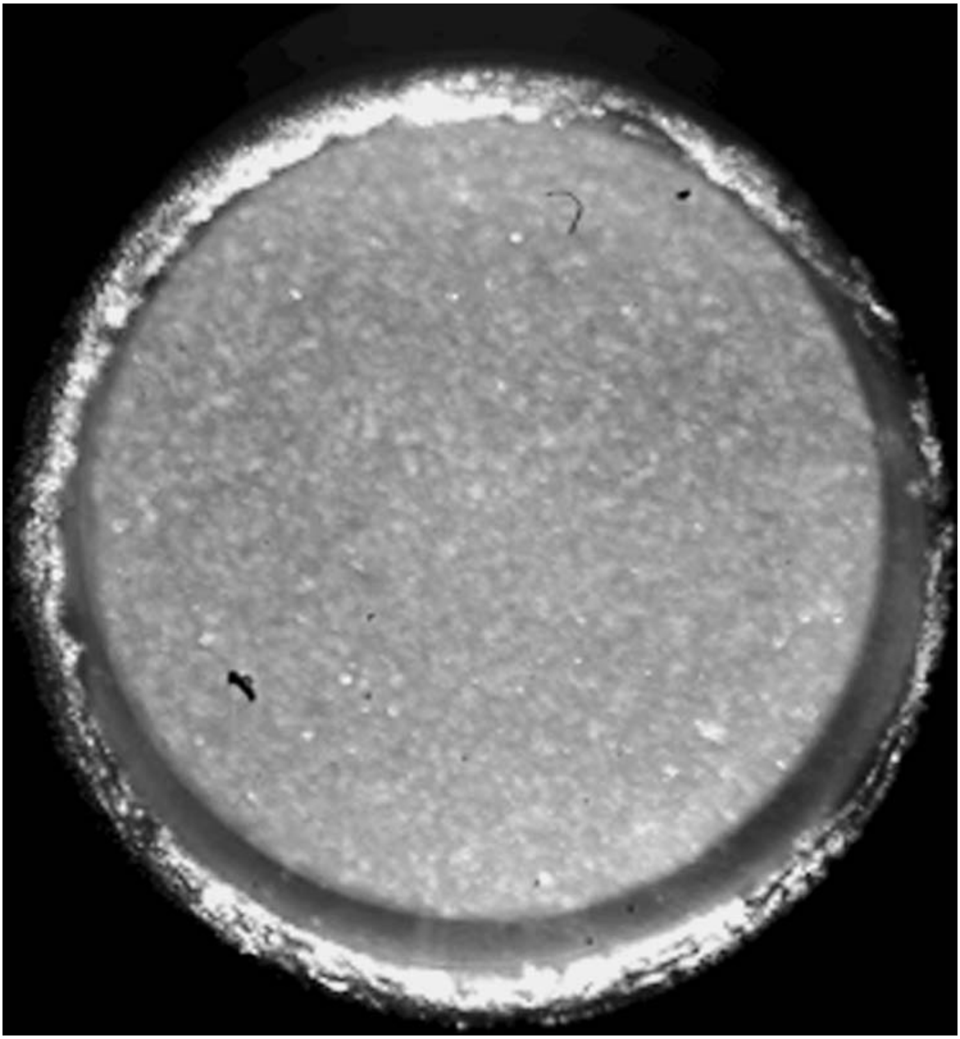

Figure 14. SD2 oven picture taken by CIVA during test.

each one commanded by the C-DPU board through the microprocessor G-bus; the logic and I/F circuitry is implemented with an Actel FPGAs. Each of the board functions can be powered on/off separately to optimise the power consumption both in stand-by and during operations.

8. Modelling, Testing and Commissioning

During the SD2 development several electrical and mechanical breadboards have been manufactured and tested in order to find out the best solution to satisfy all the environmental, mechanical and electrical requirements.

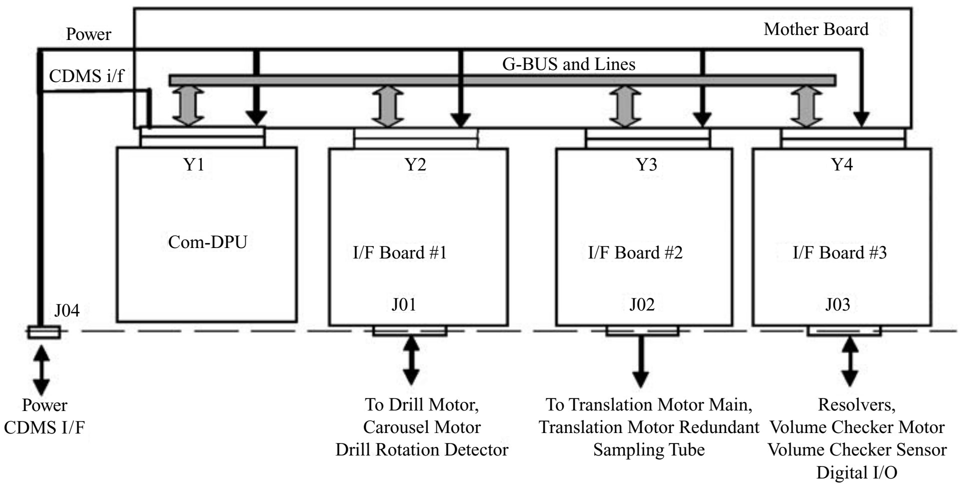

Figure 15. Electronic unit block diagram.

Particular attention has been dedicated to the Drill tool verification for what concerns mechanical loads and eigenfrequencies at launch, carbon fibre structure resistance, Drill box sliding carriage functionality and resistance, actuators and mechanisms functionality.

Following space practices, four models have been manufactured and tested: the Structural and Thermal Model (STM), integrated into the STM Lander for relevant verifications, the Engineering Model (EM), integrated into the EM Lander to perform primarily electrical and EMC (Electromagnetic Compatibility) verification, the Engineering Qualification Model (EQM), which has been tested and the Flight Model (FM) which has been subject to the acceptance test campaign.

In particular the test campaign included:

- functional testing under ambient conditions, as represented in Figure 16 that shows a typical force vs. time profile during a drilling and sampling operation (Soavi and Magnani, 2001),
- vibration testing (sinusoidal and random at the qualification load levels),
- several sample collections and discharges into the ovens at cometary representative conditions (-150 °C, high vacuum).

The commissioning phase (Foulger and Gaudon, 2004) started immediately after launch to check the status of SD2. During the active checkouts, successfully realized till now, the carousel rotated and the resulting position of the ovens respect to the scientific instruments has been verified. The Table II summarizes carousel and volume checker movements.

A Rosetta Lab (Dainese, 2006), is currently under installation at the Politecnico di Milano, making use of SD2 Spare Model. This facility will allow to perform in

TABLE II
Carousel and volume checker movements

Carousel movements	
Oven number	Final position
12	Under CIVA [4320 arcmin]
10	Under CIVA [5760 arcmin]
12	Under CIVA [6480 arcmin]
10	Under CIVA [7920 arcmin]
0	Zero position [0 arcmin]
8	Under CIVA [9360 arcmin]
8	Under CIVA [7200 arcmin]
8	Under PTOLEMY [5040 arcmin]
1	Under COSAC [5760 arcmin]
2	Under COSAC [6480 arcmin]
Volume checker movements	
Move UP	
Move DOWN-UP	

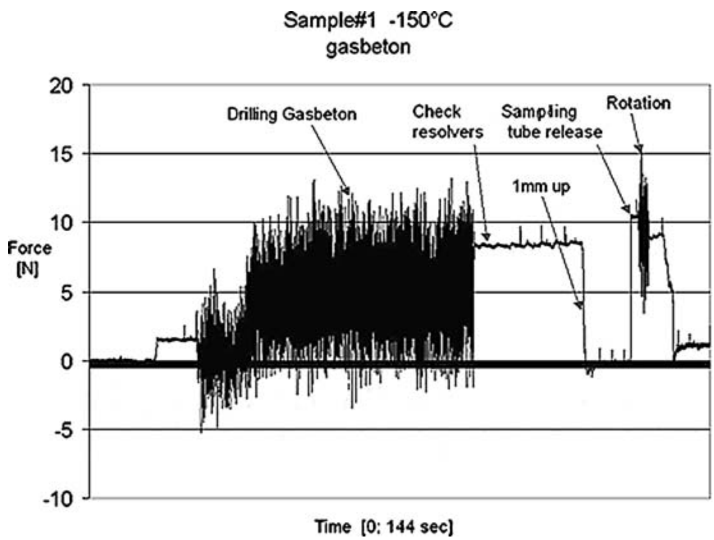

Figure 16. Drilling/Sampling force-time profile.

a very realistic way on the Earth the operations that SD2 will perform on the comet in 2014, simulating different sampling scenarios, according to the different landing conditions that can occur. Furthermore, following a method newly developed, it seems possible to establish a correlation between the Drill movements and the soil characteristics. This very exciting opportunity to access to cometary mechanical properties further increases its scientific value.

9. Conclusions

The SD2 System has been designed to guarantee its functions, drilling and soil sample handling, in a critical thermo-vacuum environment and to meet the stringent mass/power requirements of the Rosetta mission.

This challenge has been achieved adopting very innovative technological solutions (cutting technique and drill-sampling design, composite materials, dry lubrication, brushless actuators, medium temperature ovens design, rad-hard electronics), that make of SD2 a jewel of technology and design.

The passive and active checkouts already performed in order to evaluate the status of the system show that SD2 activity is consistent with the expectations.

The activities, now in progress at the laboratory at Politecnico di Milano, will allow to test different mission plans, to simulate several different landing scenarios and to implement suitable strategies to face emergency conditions.

Future space missions for Solar System exploration, that require in situ analysis, will take advantage from the experience gained through SD2.

Acknowledgements

We acknowledge the financial support of Italian Space Agency (ASI), and CIVA team for the oven images.

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