The ROSETTA/CNSR Mission

A possible application of electric propulsion to interplanetary missions

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1. SUMMARY AND INTRODUCTION

The European Space Agency (ESA) has selected a Comet Nucleus Sample Return (CNSR) mission, named ROSETTA, as the planetary cornerstone in its long term plan. The major scientific objective of Rosetta is to return a comet nucleus sample to earth, while preserving its fundamental chemical, isotopic and structural properties, essential features for resolving fundamental aspects of astrophysics and of the origin of the solar system.

This mission, which has also been recommended by the Solar System Exploration Committee of the Nasa Advisory Council, is being planned as a collaborative programme by NASA and ESA, with a baseline launch date in 2001. Both agencies are conducting parallel mission design and engineering studies, while a technology oriented programme has been initiated by ESA to demonstrate the feasibility of the proposed solutions and required technologies.

A major Mission Definition Study conducted by ESA in collaboration with European industry has explored selected mission options utilising chemical or electric propulsion, direct or earth gravity-assist trajectories, in-situ or remote sampling, and sample recovery in LEO or directly at the earth's surface by means of retrobraking or aerobraking.

In terms of mission opportunities, the most flexible mission design is the so-called 'hybrid', which utilises electric propulsion for the earth to comet cruise and chemical propulsion for the earth return phase. This type of mission, which would also be compatible with an Ariane-5 launch, features an electric propulsion stage based on 6 RIT-35 thrusters, 32 kw of power and provides a velocity increment of 8.5 km/s; this electric stage is jettisoned at comet encounter after perihelion. Despite the satisfactory mission opportunities provided by the hybrid mission, the level of financial support provided by ESA to electric propulsion development and the associated high complexity and cost of an electric propulsion module have led to this hybrid mission being considered as an alternative back-up.

The proposed baseline mission is based on a Titan-Centaur G' launcher and a stack of three spacecraft, functioning respectively as cruiser, lander and aerocapsule; the total launch mass is 4000 kg, including 2300 kg of biliquid propellant stored in the cruise spacecraft. The earth-comet cruise features a two years-earth-gravity-assist trajectory and necessitates a supplementary velocity increment of 1800 m/s by the spacecraft chemical propulsion system. The resulting trajectory will encounter the comet Churymov-Gerasimenko at aphelion, at 5.5 AU, 4.5 years after launch. The spacecraft will land on a preselected site, where sampling will be carried out by drilling/scooping mechanisms. The cruiser and the aerocapsule will then be injected into an earth return trajectory (Delta-V = 900 m/s), leaving the lander spacecraft behind on the comet. The aerocapsule will be recovered on earth following an autonomous parachute-assisted re-entry 3.5 years after comet departure and 8 years after launch, in the year 2009.

2. MAJOR SCIENTIFIC OBJECTIVES

The mission objective is to return a comet nucleus sample to earth, preserving such fundamental properties as:

- The chemical and isotopic composition of the individual molecular species of remaining volatile compounds.
- The chemical, isotopic and structural state of the individual phases and crystals constituting higher temperature condensates and aggregates, and
- The complex hydrocarbon compounds and their aggregates.

To acquire cometary samples that allow the desired investigations, the ROSETTA mission must:

- Rendezvous to an active and fresh comet with a large perihelion distance.
- Characterize the surface of the nucleus into active and inactive regions, conduct high resolution imaging of the sampling site and provide in-situ characterization of the sampling site.
- Acquire three classes of samples:
  - one that preserves stratigraphy to a depth of at least 1 m
  - one containing the most volatile components, sealed to prevent any loss of such volatiles,

- and surface samples intended to provide a larger volume of non volatile components for analysis

. Store the samples until return to earth at temperatures corresponding to the ambient temperature at the sampling site, but in any case below 160 K.

. Distribute cometary samples to scientists for study in establihsed laboratories.

3. MISSION DRIVERS AND CRITICAL ASPECTS

a) Propulsion and Mission Opportunities

Rendezvous with the comet requires high launch energy and large post-launch velocity increments; this makes the launch mass a very critical factor in the search for sufficient mission opportunities and the propulsion system becomes of primary importance in the mission design.

b) Sampling, Safety and Autonomy

The large uncertainties that affects existing models of the cometary nucleus in terms of surface features, composition and environment, demand high flexibility in the sampling scenario, which becomes heavily dependent on the rendezvous orbital location.

While spacecraft safety due to environmental hazards is a major concern for a perihelion rendezvous, the landing of the spacecraft in a safer aphelion environment requires demanding autonomy features due to the large communication distance.

c) Sample Preservation and Recovery

The requirements for avoiding thermal, mechanical and chemical contamination of the cometary sample constrain not only the sampling techniques but also the sample recovery scenario on earth. Depending on the recovery mode, high heat loads and peak acceleration are experienced during the atmospheric passes, which need to be properly controlled. Finally, an high landing accuracy is required to ensure prompt recovery.

4. MAJOR MISSION TRADE-OFFS

The CNSR mission can be designed in a number of different ways. Among the parameters entering the process of optimally shaping the mission, the following are especially important:

- encounter location: aphelion, perihelion, post-perihelion
- launcher: Ariane-5, Titan-Centaur, HLV
- on-board propulsion: chemical, electric, hybrid
- trajectory: direct or delta-vega
- Sampling: in-situ or remote
- Sample recovery: directly on earth or via Space Station
- Mission duration

A perihelion mission, which has to be based entirely on electric propulsion, provides sufficient mission opportunities with an Ariane-5, but involves a maximum cometary hazard; it may therefore only be acceptable in conjunction with a minimum scientific return (remote sampling by a tethered harpoon).

Aphelion and post-perihelion missions both require a Titan-Centaur launcher, and are compatible with a landing and in-situ-sampling scenario.

The aphelion mission can be best accomplished with chemical propulsion, provided a delta-vega manoeuvre is incorporated in the trajectory.

In the case of the hybrid mission, an electric propulsion stage is used for the earth-comet cruise; this stage is jettisoned before landing and chemical propulsion is used for the earth return phase.

Finally, as regards sample recovery, the only acceptable scenario is the one based on direct and guided re-entry by single-pass aerocapture; recovery into LEO using the Space Station-based OMV appears to be more complex and more critical from a thermal point of view.

It can be concluded that a reliable mission design that satisfies all of the requirements can be based either on:

- an all-ballistic trajectory with delta-vega and aphelion encounter, or
- a hybrid mission to post-perihelion

using a Titan 4-Centaur G' launcher or equivalent.

5. THE SELECTED MISSION SCENARIO

5.1 Launch and Cruise Phase

The spacecraft is injected into an escape trajectory by a Titan-Centaur, nominally in the 2001 launch period.

In the case of chemical propulsion, this trajectory is corrected one year after launch by a deep-space manoeuvre which will ensure an earth swing-by at a distance of 500 km one year later. Additional mid-course manoeuvres at up to 1800 m/sec are needed to place the spacecraft on a closed-encounter trajectory at the aphelion of comet Churymov-Guerasimenko at 5.5 A.U.

In the hybrid SEP-ballistic propulsion option, the solar electric propulsion stage applies a low continuous thrust after launch so as to

progressively increase the heliocentric energy to that of the comet Tritton at a post-perihelion encounter point at 1.5 A.U. The SEP stage is then jettisoned, after delivery of a velocity increment of 8.5 km/s.

The respective flight paths for an aphelion and a post-perihelion encounter are shown in Figures 1 and 2.

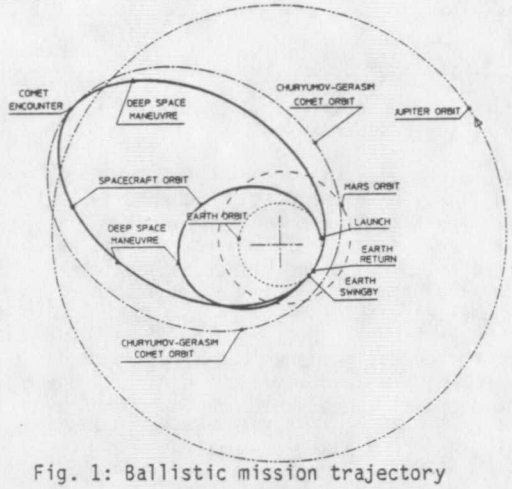

Fig. 1: Ballistic mission trajectory

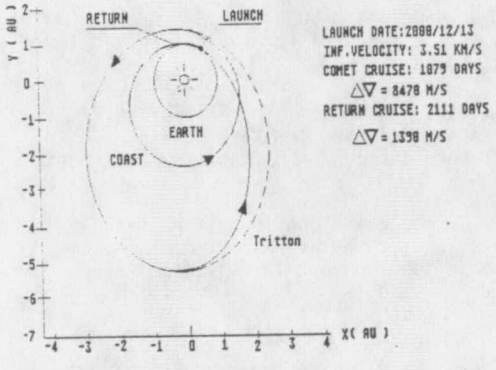

Fig. 2: Hybrid mission trajectory

5.2 The Approach and Landing Phase

Under worst-case detection conditions, i.e. for an aphelion encounter, the comet will be detected against the star background at about 2000000 km by the S/C high resolution camera. Ground tracking navigation will continue until few thousands km distance, when relative range measurements with the on-board radar altimeter are possible. An autonomous on-board navigation will follow, with the spacecraft drifting slowly towards the nucleus. A remote-sensing programme will be undertaken at a distance of 100 km to provide comet characterisation and landing-site selection by earth-based image processing.

The spacecraft will then be moved down to about 20 km above surface and penetrator-carrying the RF beacons will be dropped, to be used later as navigation aids during descent.

The slow descent to the selected site will then proceed with the S/C autonomously aiming at the radio beacons, and the scanning radio-altimeter being used in combination with the gyroscopes toprovide the "horizontal" attitude reference.

A schematic of the above strategy is shown in Fig. 3.

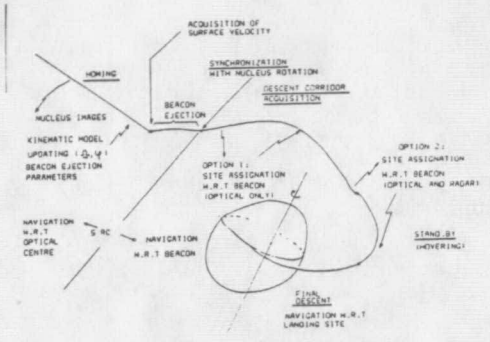

Fig. 3: Approach and landing scenario

5.3 Surface Operations

After touch-down, the lander will be safely anchored using suitable anchoring devices. These are required in order to compensate for the forces and torques generated during sampling in the microgravity cometary field ($10^{-4}/10^{-5}$ g).

Surface and subsurface samples will be collected by scooping and drilling mechanisms and stored in a special sealed canister housed in the aerocapsule. The baseline design of the sampling facility provides the ability to sample at different locations within a 1 m radius and down to depths of 3 m. Execution of these operations may require several days.

5.4 Ascent and Earth Return

At the completion of the sampling sequence, the earth-return vehicle with the aerocapsule will separate from the bottom section of the spacecraft containing the sampling and anchoring devices and the scientific instruments.

After its kinematic parameters have been accurately determined from the ground, the two spacecraft stack will be pointed in the appropriate direction and a 900 m/s delta-V manoeuvre executed to put it on its return trajectory.

After 3.5 years of return cruise, the aerocapsule will be targetted into a pre-selected re-entry corridor and separated from the cruiser spacecraft. The latter will follow a hyperbolic trajectory and will escape from the earth to prevent any hazard from the RTG.

The aerocapsule, with its subsystems activated before separation and its navigation and control elements loaded from the ground will then proceed autonomously with re-entry at a relative arrival velocity of 10-11 km/s. Lift vector control will be used to navigate in such a way that for heat rate, acceleration, impact-velocity and landing-accuracy constraints are not violated.

Jettisoning of the heat shield and deployment of a parachute will be the last two (autonomous) mission events: they will allow an acceptable sample temperature and impact velocity to be maintained.

An artist's impression of the above mission scenario is shown in Figure 4.

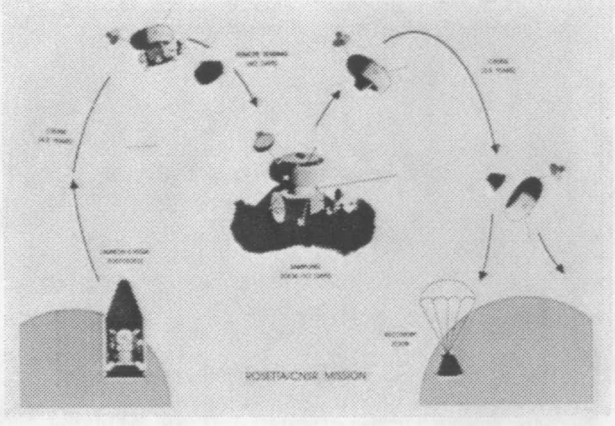

Fig. 4: Artist's impression of the Rosetta mission scenario

6. SPACECRAFT DESIGN CONCEPTS

The main concepts followed in the selection of candidate spacecraft designs have been minimisation of the launch mass and the reliability of the operating scenario.

From this point of view, two alternative spacecraft concepts have been identified: one that minimises the overall system mass, related to the hybrid mission, and one that involves the minimum complexity and is related to the all-ballistic mission.

Both configurations exclude in-orbit rendezvous and docking and the use of a tethered harpoon for the sampling scenario, two options that received some consideration during the study. Both spacecraft designs have been optimised for a landing scenario based on artificial landmarks and for a direct re-entry to earth by aerocapture.

The major difference between the two designs is due to the electric propulsion stage, which adds considerable complexity to the overall "hybrid" configuration.

6.1 The Ballistic Spacecraft Design

The generic spacecraft concept consists of a stack of three separate modules:

- the cruiser, containing all necessary propellant for both cruises and ensuring all intelligent functions and handling the communication and management of the whole spacecraft. It also provides the required electrical energy by means of an RTG and storage batteries.

  The cruiser design is driven by a propulsion system which features two 400 N engines and 6 conospherical tanks, which can accommodate up to 2500 kg of bipropellant. Its mass is 2940 kg including 2300 kg of bipropellant.

- The lander, with all its scientific equipment and sampling devices, will remain on the comet and will therefore also carry all the equipment not required for the return cruise. Its total mass is 660 kg.

- The re-entry capsule, of the Apollo-type, designed to carry the cometary samples and to protect them during earth re-entry. It weights 400 kg.

The overall spacecraft configuration is shown in Fig. 5, its basic modules in Fig. 6, and its propulsion system concept in Fig. 7.

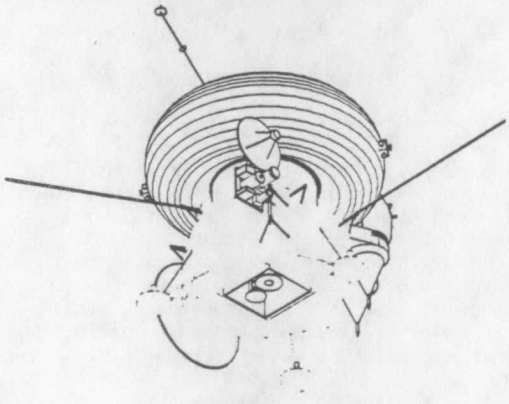

Fig. 5: "Ballistic" spacecraft configuration

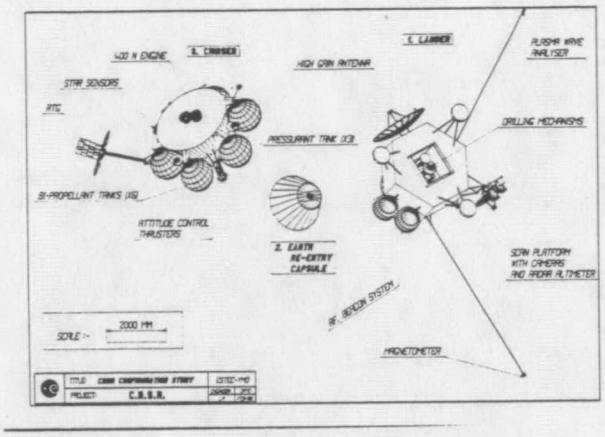

Fig. 6: The 3 modules for the ballistic mission

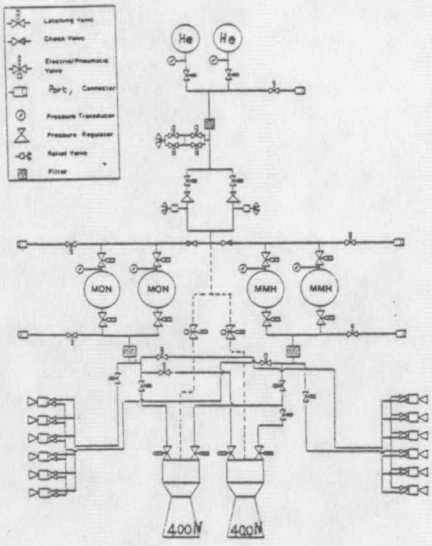

Fig. 7: Layout of the chemical propulsion system

6.2 The Hybrid Spacecraft Option

In this case the earth-comet cruise phase makes use of an electric-propulsion stage which is separated before comet rendezvous, the earth-return phase utilising a bipropellant system. The other spacecraft modules, i.e. the cruiser and the aerocapsule, are very much the same as for the all-ballistic mission.

The overall configurations of the hybrid spacecraft and the propulsion system are shown in Figs 8 and 9.

The electrical-propulsion module consists of six RIT-35 thrusters, two of which are for redanduncy, utilising mercury as propellant. The maximum thrust is 200 mN per engine at 1 A.U. and the specific impulse is 33.0000 NS/kg at 2.5 KV and 2.5 A. With a mass flow rate of 6 mg/s of Hg per thruster, a typical mission profile results in a thruster firing time of 625 days.

The total mass of the electric module is 2800 kg, including 960 kg of propellant. The power subsystems take the major share of the mass budget: 1350 kg, of which 900 kg are allocated to a 32 kw solar array, consisting of two wings of 32 x 4 m^2 each.

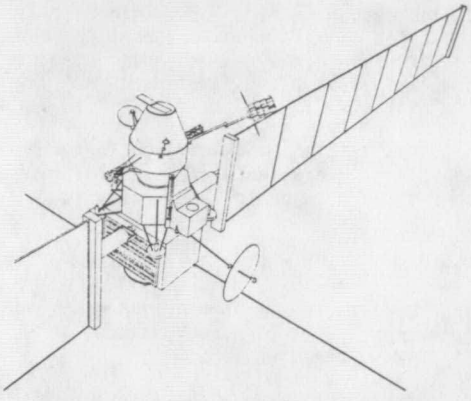

Fig. 8: "Hybrid" spacecraft configuration

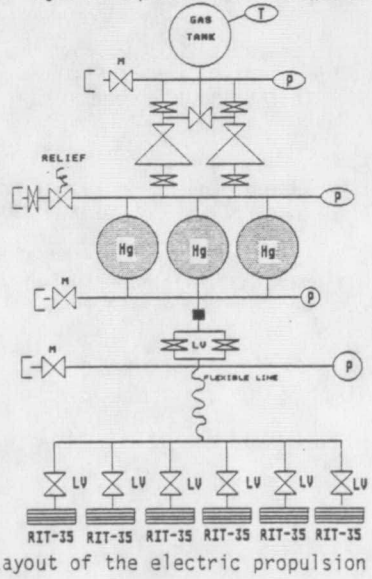

Fig. 9: Layout of the electric propulsion system

7. CONCLUSIONS

The feasibility of the proposed scenario for returning an undisturbed sample from a cometary nucleus to earth depends on the verification of two major assumptions, namely:

- the capability of acquiring useful samples from a body whose composition is only speculated. This aspect requires high flexibility from the sampling facility.

- compatibility with launch energies anticipated for the year 2000, or as on alternative option, the use of an electric-propulsion module.

The clear advantages offered by the electric-propulsion system in terms of mission opportunities and planning appears to be more than counterbalanced by major concerns about its complexity, cost and development uncertainties.

Given this situation, the decision to go ahead with a ballistic mission based on a Titan-Centaur launcher appears to be the less risky route.

References

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