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ARISTOTELES - A EUROPEAN APPROACH FOR AN EARTH GRAVITY FIELD RECOVERY MISSION

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Abstract

Under contract of the European Space Agency a system study for a spaceborne gravity field recovery mission has been performed, covering as a secondary mission objective geodetic point positioning in the cm range as well. It was demonstrated that under the given programmatic constraints including dual launch and a very tight development schedule, a six months gravity field mission in a 200 km near polar, dawn-dusk orbit is adequate to determine gravity anomalies to better than 5 mgal with a spatial resolution of 100 x 100 km half wavelength. This will enable scientists to determine improved spherical harmonic coefficients of the Earth gravity field equation to the order and degree of 180 or better.

Introduction

A detailed knowledge of the Earth gravity field is of great interest in geophysical sciences and their applications. In addition orbit determination of satellites will benefit significantly from an improved gravity field model. Although a large amount of local data are available, on a global scale a large part of the Earth has not so far been covered, because of obvious natural, political and cost constraints. A spaceborne system can overcome these constraints and can provide consistent and precise data on a global scale. A comprehensive outline of the benefits of such a mission was given by the SESAME workshop (Solid Earth Science & Application Mission for Europe).

In the framework of the Earth Observation Preparatory Programme (EOPP) of the European Space Agency a system study has been performed to demonstrate the feasibility of such a programme under special constraints including dual launch, a tight development schedule and a limited financial budget. The name of the mission ARISTOTELES stands for 'Application and Research Involving Space Techniques Observing The Earth field from a Low Earth Orbit Satellite' and is a reminder of the great philosopher Aristotle who was the first to speak of gravity forces.

System Requirements

The principal scientific objective of the mission is a global gravity field determination to an accuracy better than 5 mgal in terms of gravity anomalies with a spatial resolution of 100 km half wavelength, where 1 mgal is equivalent to 10^{-5} m/s². The operational mission duration for gravity measurements is between 3 and 6 months. The orbit shall be quasi-circular, near polar with a mean altitude between 160 and 240 km, dependent

on the type of payload accommodation. The payload is a gradiometer comprising up to 8 ultrasensitive electrostatic accelerometers, here named GRADIO. As an optional mission part it is intended to raise the orbit after completion of the gravity mission to about 700 km altitude in order to perform point positioning for another 3 years.

The ARISTOTELES satellite is Earth oriented, 3-axis stabilized and shall be launched by an ARIANE 44 as lower passenger within SPELDA 10 together with ERS-2 (ESA Remote Sensing Satellite) or another Earth observation satellite. The nominal launch date is 1994. Kiruna ground station will be used for telemetry and telecommand on a time sharing basis with ERS-2. The gravity field requires an orbit restitution of better than 10 m in the radial direction.

Scientific Evaluation

Within the present study a gravity field recovery analysis has been performed in order to establish the system requirements based on the interrelations between the instrument accuracy, the orbit altitude, the operational gravity mission duration, the tensor components to be measured and the gravity field accuracy to be met. The results indicate that on the one hand a maximum orbit altitude of 200 km is allowed, assuming a two dimensional instrument accuracy of 10^{-2} E.U. and half a year operational life time (see Figure 1). On the other hand this altitude is the lower limit for a fixed GRADIO accommodation on the non-drag-free satellite because of the maximum allowed acceleration tolerance requirement of $5 \cdot 10^{-5}$ m/s² for the accelerometers. A better performance of between 3 and 4 mgal can be expected in a lower altitude of about 180 km or less if a suspended GRADIO accommodation on a drag-free satellite were selected. For this option only a 3 months gravity field mission is required.

However, Figure 1 shows that even with the measurement of the two tensor components across track and radial T_{yy} and T_{zz} respectively, the scientific requirement can be just met from a 200 km orbit. Figure 2 underlines the importance of the instrument accuracy.

Mission Analysis

Using the dual launch with ERS-2, ARISTOTELES will be brought into an 780 km sun synchronous orbit with 10.30 h descending node local time. Within a drift period of about 9 months completed by final descent to 200 km the satellite moves into the operational orbit of the gravity mission. The drift period can also be used for point positioning measurements and is needed to calibrate the GRADIO instrument in space. Because

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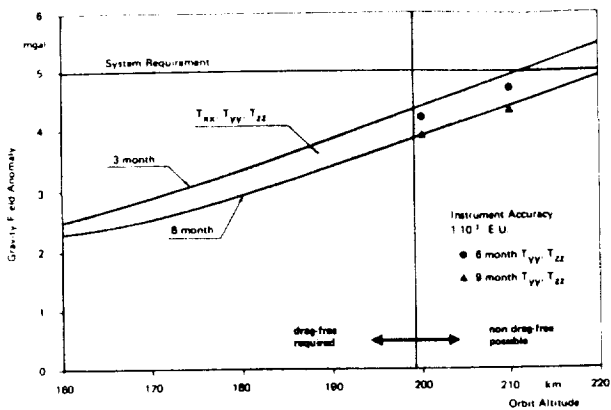


Fig. 1 : Relationship between System Performance and Main System Parameters (Instrument Accuracy 10^{-2} E.U.)

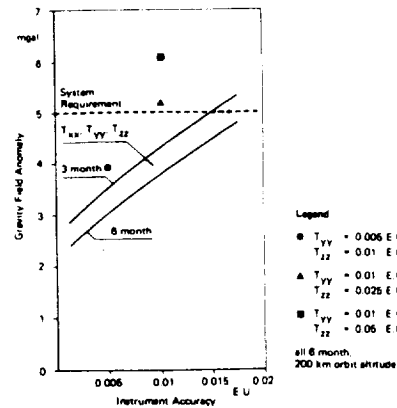


Fig. 2 : Influence of Instrument Accuracy on System Performance

of the Earth's gravity the GRADIO instrument cannot be fully tested on ground, therefore a relatively long period with low drag forces is very attractive to calibrate the instrument under low disturbance conditions.

Because of the large fuel consumption for the transfer and operational phase the originally required polar orbit must be shifted to a near polar, dawn-dusk orbit, advantageous for spacecraft design, but not covering a 600 km circle around the poles.

The optional point positioning mission for another 3 years or more is only possible when flying during the gravity mission above 200 km and using bipropellant fuel without driving the cross section area of the satellite to an unacceptable size and consequently to a higher fuel consumption during the gravity mission phase. A full mission scenario sketch is given by Fig. 3.

Instrument Design

The primary instrument of ARISTOTELES is a gradiometer formed by a set of up to 8 ultrasensitive accelerometers and a calibration device. These accelerometers with a maximum resolution in the pico-g range and sensitive either in 2 or 3 axes, have to be grouped as symmetrically as possible in a 2D or 3D framework.

Each accelerometer itself consists of a proof mass and a caging with 6 pairs of electrodes. Figure 4 shows a laboratory model of a 2D electrostatic accelerometer. The theoretical resolution limit of the proposed device is

$$10^{-2} \text{ E.U.} / \sqrt{\text{Hz}}$$

and the required bandwidth ($5 \cdot 10^{-3}$ Hz to 0.25). The maximum allowed acceleration to avoid saturation of the accelerometers is $5 \cdot 10^{-5} \text{ m/s}^2$.

In principle, two different ways of GRADIO accommodation have been studied: A drag-free accommodation, avoiding to the maximum extent the impact of surface forces on the GRADIO. The instrument is then magnetically suspended within the satellite, affected only by gravity forces, while the satellite flies around the instrument, accurately controlled by the attitude control system. In particular this accommodation option avoids air drag forces acting on the accelerometers and therefore allows flight below 200 km. However, the deceleration of the satellite

by the air drag must be compensated by nearly continuous thrusts with considerable amounts of fuel. Bipropellant fuel is then mandatory, because of the lack of qualified thrusters for hydrazine in this operational mode.

The alternative instrument accommodation option is the so-called non-drag-free version, with the GRADIO mounted isostatically on the satellite structure. Consequently, the maximum acceleration of the satellite has to be below $5 \cdot 10^{-5} \text{ m/s}^2$ demanding an orbit altitude above 200 km. In addition via cross coupling effects the air drag variations now impair the measurement and must be compensated by aerodynamic flaps. The proposed design requires that drag variations within the measurement bandwidth are damped out by a factor of one hundred.

Both instrument accommodation options have strong system impacts, and therefore a comprehensive system level trade-off had to be conducted.

Major System Options

The dominant system options are related to the GRADIO instrument:

- Drag-free or non-drag-free GRADIO accommodation,
- 2D or 3D GRADIO,
- 2D or 3D accelerometers.

A trade-off dealing with more than 20 different GRADIO designs has resulted in two preferred solutions: Four 2D accelerometers located at the corners of a plate (planar solution) or either 6 or 8 3D accelerometers located at the corners of an octahedron or a cube. While the first solution is associated with a fixed GRADIO accommodation on the satellite, the second should be accommodated suspended to enable achievement of the high theoretical performance of this instrument. Based on the scientific evaluation mentioned above and the very tight schedule, the planar gradiometer was selected as baseline (see Figure 6). For clarification it must be said that the 2D accelerometers measure in all 3 axis, but with degraded sensitivity in flight direction which is then of no use for gravity gradient measurements. However, this signal can support the attitude control system.

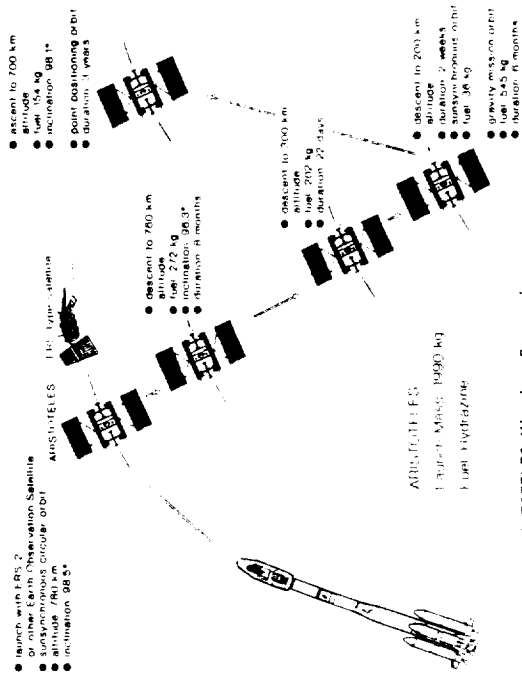


Fig. 3 : ARISTOTELES Mission Scenario

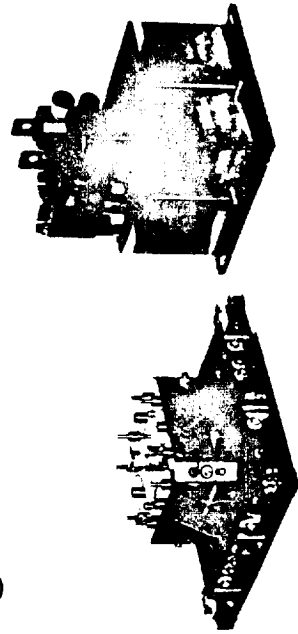


Fig. 4 : Laboratory Model of 2D Accelerometer

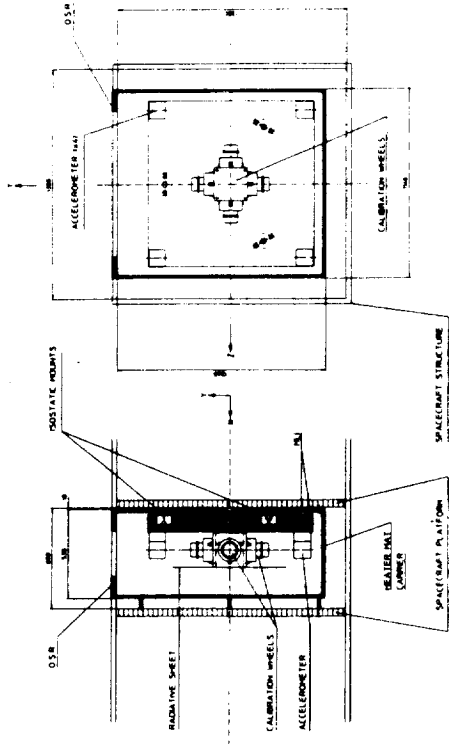


Fig. 5 : Layout of the Selected Planar GRAD10

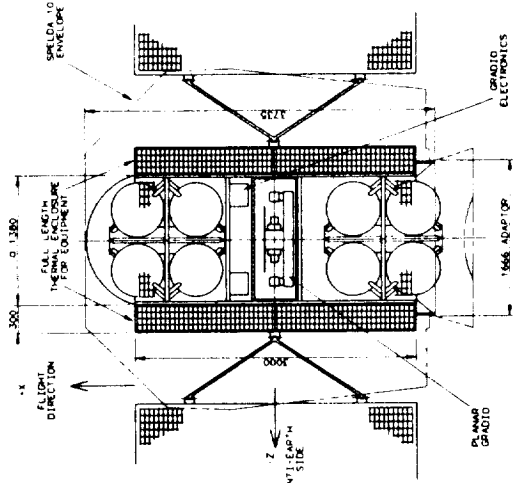


Fig. 6 : ARISTOTELES Satellite Configuration

Orbit Determination

The restitution of the gravity gradient data requires an accurate knowledge of the orbit position. The 'a posteriori' orbit determination requirement is therefore

10 m in radial direction and
1.5 km across and along track.

This requirement cannot be met by normal S-band tracking, but requires special equipment. For ARISTOTELES a Precise Range and Range Rate Microwave Tracking Equipment named MTS/PRARE similar to the PRARE system to be flown on ERS-1 will be used. Optionally the use of the Global Positioning System (GPS) is under discussion.

When using MTS/PRARE for orbit determination, with the same on-board equipment, geodetic point positioning can be performed by scientists, requiring only additional dedicated PRARE ground stations, to be operated independently by the scientists themselves.

Satellite Configuration

The GRADIO instrument has dictated all of the principal features incorporated in the satellite configuration. The need to fly GRADIO at the minimum possible altitude results in a significant drag force. To provide a mission of long enough duration for recovery of adequate scientific data, the effect of the drag must be minimised. The cross sectional area presented to the 'airflow' is thus reduced resulting in a long slender satellite body limited by accommodation constraints of the AR44 SPELDA 10 payload carrier assembly (see Figure 6). The electrical energy demand is large enough to require solar array wings as well as the body mounted solar arrays, but these must be edge on the airflow again not only to minimise drag, but also to avoid large disturbance torques on the satellite and thereby affecting GRADIO. In consequence it is only possible to fly in near dawn-dusk orbits, placing a minor restriction on scientific return in relation to tidal effects from the sun.

That the GRADIO instrument measures the gravity field of the satellite as well, has unusual consequences for the satellite internal layout in addition to the above mentioned drag minimisation. The instrument must be placed not only at the centre of gravity of the vehicle, but this centre of gravity must also be the neutral point for the gravitational attractions of all components to minimise their influence. Symmetry is thus of major importance, and the heavier units should be placed as far away from GRADIO as possible. The supporting electronic subsystems contained in pods on the sides of the body meet this requirement in principle, while also assisting thermal stability close to GRADIO since significant variable heat generation is remote from the instrument.

The largest masses are however the fuel (approx. one ton in total) in the 16 tanks. Normally under manoeuvring accelerations the fuel in the tanks moves or 'sloshes'. To almost totally remove this effect, tanks with stable metal diaphragms are

used, restraining the fuel to one end of the tank. The fuel used during the period of GRADIO measurements also is contained only in the outer tanks, i.e. furthest from GRADIO. The fuel in the inner tanks is used during initial manoeuvres to place ARISTOTELES in the correct orbit.

In addition, the symmetry requirement can only be met by positively monitoring fuel consumption from the individual tanks, in order to maintain the centre of gravity within fractions of a millimetre of the GRADIO centre.

Tab. 1 : ARISTOTELES Satellite Properties

o	Satellite Mass	dry	960 kg
		launch	1990 kg
o	GRADIO Mass		65 kg
o	Power at Solar Array		1080 W
o	GRADIO Power Consumption		60 W
o	S-Band Telemetry		1 Mbps
o	Data Storage (36h)		260 Mb

Subsystem Characteristics

The majority of the subsystems for ARISTOTELES are conventional in character with special attention being paid to satellite structural and thermal effects on GRADIO. However, the performance of the attitude and orbit control system is intimately linked with the orientation and control of GRADIO and thus to the quality of the instrument data output. Because the instrument is attached to the spacecraft structure, it is directly affected by drag forces and spacecraft disturbances, placing high demand on control accuracy.

Conclusions

The ARISTOTELES system study² proved that a spaceborne gradiometer can meet an Earth gravity field determination requirement of better than 5 mgal with a spatial resolution of 100 km half wavelength. The required orbit altitude is about 200 km or less with an instrument accuracy of better than 10^{-2} E.U. given that at least the tensor components I_{yy} (across track) and I_{zz} (radial) were measured. This is achieved by means of a 2D GRADIO directly attached to the satellite structure. Although a suspended accommodation of a 3D GRADIO with at least 6 3D accelerometers promises better results, the fixed GRADIO solution has been selected as baseline to meet the tight schedule which may not allow the more challenging approach. The lower instrument performance of the 2D fixed GRADIO can be partly compensated for by a gravity mission of six months instead of three and a high performance AOCSS subsystem.

References

- 1) SESAME ESA Special Workshop, ESA SP-1080, Ising, FRG, March 1986
- 2) Benz, R. et al., ARISTOTELES Phase A Study, Final Report, Dornier-System GmbH, Friedrichshafen, FRG, 1988.