[redacted]

NASA Technical Memorandum

NASA TM- 4091

SUPERCONDUCTING GRAVITY GRADIOMETER MISSION

Volume I: Study Team Executive Summary

Edited by Samuel H. Morgan
Program Development Directorate
Marshall Space Flight Center

Ho Jung Paik
University of Maryland
College Park, Maryland

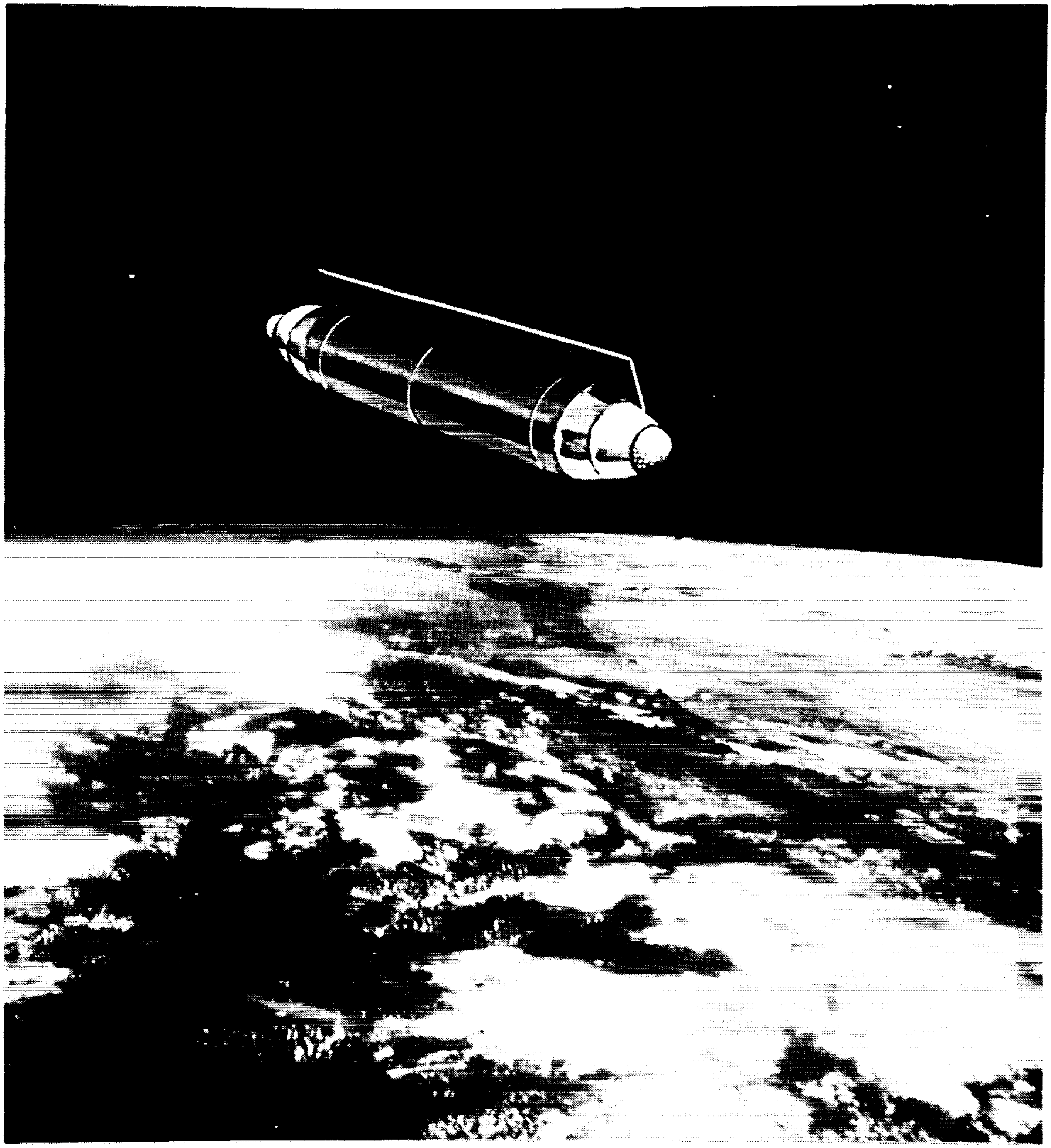
August 1989

(NASA-TM-4091-Vol-1) SUPERCONDUCTING GRAVITY GRADIOMETER MISSION. VOLUME 1: STUDY TEAM EXECUTIVE SUMMARY (NASA) 42 p CSCL 08G N90-15545

Unclas
H1/46 0234008

National Aeronautics and
Space Administration

George C. Marshall Space Flight Center



ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

FOREWORD

Accurate knowledge of the Earth's gravity field is fundamental to geophysics, oceanography, and geodesy. Since 1958, NASA has used artificial satellites and space platforms to measure and map the Earth's gravity. Currently the gravity field is derived indirectly through global measurement of satellite perturbations or over the oceans by means of satellite altimetry. Each of these techniques has severe limitations in obtaining the required resolution and accuracy needed to address important scientific problems.

During the past two decades, serious efforts have been made to develop moving-base gradiometers. Spaceborne gradiometers will permit dense, precise, and direct global measurements of gravity. An advanced gradiometer, utilizing superconducting technology, has been under development for the past several years through NASA, Air Force, and Army sponsorship. The Superconducting Gravity Gradiometer (SGG) promises to meet the science and applications requirements for the 1990's in both measurement accuracy (a few mgal) and spatial resolution (50 km). In addition, the SGG can be applied to tests of fundamental laws of physics and navigation. Recent advances at the very frontier of physics, the unification of the fundamental forces of Nature into one grand law, predict a departure from Newton's inverse square law of gravitation. A test of the gravitational inverse square law of unprecedented precision could be made utilizing a spaceborne SGG.

In 1985 the various federal and university activities involved with the development of the SGG were brought together under a study team to develop a total system concept for a space qualified three-axis SGG integrated with a six-axis accelerometer. This report is an Executive Summary of a companion volume, "Volume II: Study Team Technical Report." Volume II includes detailed discusssions of the science and applications objectives of the SGG Mission (SGGM), the instrument requirements and design, preliminary mission concepts, an analysis of a flight test program, and the study team's recommendations and proposed plan for achieving a SGG satellite mission.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SUPERCONDUCTING GRAVITY GRADIOMETER STUDY TEAM

Dr. Samuel H. Morgan	Marshall Space Flight Center	Study Manager
Dr. Ho Jung Paik	University of Maryland	Instrument PI
Dr. Rudolf Decher	Marshall Space Flight Center	
Mr. Tom Fischetti	Technology Management Consultants, Inc.	
Mr. Seymor Kant	Goddard Space Flight Center	
Dr. Andrew Lazarewicz	Air Force Geophysics Laboratory	
Dr. Marcia McNutt	Massachusetts Institute of Technology	
Dr. M. Vol Moody	University of Maryland	
Dr. David Sonnabend	Jet Propulsion Laboratory	
Dr. Eugene Urban	Marshall Space Flight Center	

Former Study Team Members

Dr. H. Baussus von Luetzow	U.S. Army Engineer Topographic Laboratories
Dr. H. Anthony Chan	University of Maryland
Mr. Charles J. Finley	NASA Headquarters
Capt. Terry J. Fundak	Air Force Geophysics Laboratory
Dr. Werner D. Kahn	Goddard Space Flight Center
Dr. Jurn-Sun Leung	University of Maryland
Mr. Joe Parker	Marshall Space Flight Center

GEOPHYSICS SCIENCE RATIONALE

The Geophysics Science Rationale in this report was obtained from a Science Workshop held at the Air Force Academy, Colorado Springs, Colorado, during February 8–9, 1987. The complete workshop report is published separately [1]. The workshop participants were:

Dr. Marcia McNutt, Chairperson	Massachusetts Institute of Technology
Dr. John Apel	APL, Johns Hopkins University
Dr. Lindrith Cordell	U.S. Geological Survey
Mr. Charles J. Finley	NASA Headquarters
Mr. Thomas Fischetti	Technology Management Consultants, Inc.
Dr. Edward A. Flinn	NASA Headquarters
Dr. Bradford Hager	California Institute of Technology
Dr. Albert Hsui	Air Force Geophysics Laboratory
Dr. Andrew Lazarewicz	Air Force Geophysics Laboratory
Dr. Ho Jung Paik	University of Maryland
Dr. David Sandwell	University of Texas
Dr. David Smith	Goddard Space Flight Center
Dr. David Sonnabend	Jet Propulsion Laboratory
Dr. Louis Walter	Goddard Space Flight Center

ACKNOWLEDGMENT

The study team wishes to thank the following individuals for their contributions to the work summarized in this report:

NASA Headquarters

Dr. Edward A. Flinn, Chief of NASA's Geodynamics Branch, provided overall review and guidance.[1]

Marshall Space Flight Center

The Engineering Study Team in the Preliminary Design Office of the Program Development Directorate. Mr. Joe Parker was the lead engineer for this study team.

Mr. M.E. Nein, Payload and Orbital Systems Office, assisted in the Conceptual Design of Option I-B.

Ms. J. Martz, Program Planning Office, developed cost estimates presented in Section 7.

Dr. G.S. Nurre and Dr. Michael E. Polites, System Dynamics Laboratory, provided contributions on the analysis of the Attitude Control System.

Ms. Gail Ralls, Payload and Orbital Systems Office, typed the draft of this report.

Jet Propulsion Laboratory

Dr. Emanuel Tward provided portions of the data on Instrument Cooling.

Goddard Space Flight Center

Mr. Tom Keating of the GSFC Advanced Mission Analysis Office provided contributions related to the GRM spacecraft and systems.

Other University and Industrial Contributors

Dr. Huseyin Iz (ST Systems Corporation) and Dr. Richard H. Rapp (Ohio State University) made major contributions on error analysis for satellite gradiometry.

Dr. John R. Glaese, Ms. Karen A. Bishop, and Mr. Thomas G. Howsman (Control Dynamics Company) performed the control system simulation.

---

1. NASA's Geology Program and the Geodynamics Branch have recently been combined within the Earth Science and Applications Division to establish a Solid Earth Sciences organization.

TECHNICAL MEMORANDUM

SUPERCONDUCTING GRAVITY GRADIOMETER MISSION

Volume I: Study Team Executive Summary

1.0 INTRODUCTION

During the past three decades measurements and observations from space have stimulated a major revolution in Earth Science. Fundamental new knowledge of the Earth, its continents, oceans, atmosphere, biosphere, and ice covers has revealed a complex and dynamic Earth system that could only have been imagined before the era of space observations. This scientific revolution has in turn increased the need for new and more accurate observations and data in order to understand this complex system. Fundamental to Earth Science is knowledge of the Earth's gravitational and magnetic fields.

Within NASA, the Solid Earth Sciences Program, the Oceanic Processes Program, and the Solar System Exploration Program require accurate gravity field measurements. In addition, NASA's Astrophysics Program has requirements for gravity measurements that relate to tests of General Relativity and other fundamental laws of physics. The Department of Defense (DOD) has interests in gravity field measurements and associated technology development for application to positioning and guidance.

Among the goals of NASA's Solid Earth Sciences Program is to further understand the solid Earth and ocean dynamics. This includes analysis of existing data to produce models of gravity and magnetic fields, scientific interpretations of the models, and the development of instruments and missions that collect better data, improve the models, and advance geophysics. Because of the vital importance of this area, the National Academy of Sciences (NAS) has recommended that "...the determination of an improved gravitational field through space measurements should be an objective of the highest priority ..."[2].

Since 1958 data from over 20 artificial satellites have been utilized to map the gravity field of the Earth [3]. Among the Earth satellite missions being considered by NASA in the near future is a joint gradiometer mission with the European Space Agency (ESA). This mission is designed to measure spatial variations in the Earth's gravity over the entire globe to a resolution of 100 km and utilizes the French Gradio gradiometer. This mission, if approved, could occur in late 1995.

During the late 1990's and into the next century, investigations in geodynamics will require even greater sensitivity and resolution than the Gradio would provide. Advanced instrument development has been underway during the past several years to exploit the full advantage the space environment offers for making extremely sensitive gravity measurements. Among the instruments proposed, gravity gradiometers show great promise. The success of the Bell Aerospace/ Textron gravity gradiometer, as a navigation aid and as a moving base gravity mapping system, has shown that the measurement of gravity gradients[1] is possible even in the very "noisy" environment of ships, aircraft, and land vehicles [4]. Therefore, a gradiometer-based mapping mission is the next logical step in providing the scientific community with more accurate, high-resolution geophysics data. A survey of gravity gradiometers for space applications is given in the report of a Spaceborne Gravity Gradiometer Workshop held in 1983 [5]. The gradiometer that holds the greatest predicted performance, both for geophysics and other science and applications areas, is the Superconducting Gravity Gradiometer (SGG).

An SGG with a sensitivity of 10^{-4} E $Hz^{-1/2}$ is under development to meet the gravity field measurement objectives discussed in the next section. The Superconducting Gravity Gradiometer Mission (SGGM) will include a three-axis SGG integrated with a Superconducting Six-Axis Accelerometer (SSA) to map the Earth's gravitational field. Another promising orbital application of the SGG is to test fundamental laws of physics. For example, the SGGM would provide an excellent opportunity to carry out a much desired test of the Newtonian gravitational inverse square law with high precision on the distance scale of 10 to 10^4 km. Tests of the General Theory of Relativity, Einstein's theory of gravity, could also be made with an SGG instrument of sufficient sensitivity. In particular, it appears possible to detect the Lense-Thirring term in gravity gradient that is produced by the angular momentum of the Earth. In addition to these orbital applications, there are also a number of other applications for both the accelerometer alone and the integrated gradiometer/accelerometer system.

Cryogenic technology is essential for obtaining very sensitive gravity measurements because of the very weak nature of the gravitational interaction. Superconducting technologies at liquid helium temperatures are very important in realizing highly sensitive and stable gravity sensors in addition to the obvious reduction of thermal noise in the system. Moreover, the properties of superfluid helium and superconductors can be utilized to obtain the very quiet thermal, mechanical, and electromagnetic environments required for the operation of such sensitive instruments.

The superconducting gravity gradiometer and ancillary technologies now under development will permit a space mission with a gravity measurement accuracy of a few mgal (1 gal = 1 cm sec^{-2}) and a spatial resolution goal of 50 km for the global gravity map of the Earth, and of achieving a resolution of 10^{-10} for the inverse square law test. An orbital lifetime of six months to a year at a nominal altitude of 160 to 200 km in polar orbit is desirable. The cryostat will be kept at a fixed temperature around 1.5 K to take advantage of the properties of superfluid helium.

The measurement precision dictates platform requirements for very low disturbance levels, precise pointing and control, and isolation from internal and external disturbances that are more severe than most other satellite missions. The required instrument sensitivity makes it impossible to verify the instrument performance unambiguously in Earth-based laboratories. Therefore, critical technologies must be integrated in a precursor flight test to verify that the key elements of the science payload will meet the mission requirements, and to insure that the risk level is acceptable for the full-duration science mission.

1. Gravity gradient has units of s^{-2}. However, this unit is too large for real gradients. A more useful unit, the Eötvös (1 Eötvös = 1 E = 10^{-9} s^{-2}), has been defined.

The development of a spaceborne SGG and a related SSA at the University of Maryland under joint funding by the National Aeronautics and Space Administration (NASA), the Air Force Geophysics Laboratory (AGFL), and the U.S. Army Engineer Topographic Laboratories (ETL) has been underway since 1980. Related work (funded by NASA) dealing with gravity-field science requirements and with methods for acquisition and analysis of gradiometer data is being conducted by the Goddard Space Flight Center (GSFC). The Jet Propulsion Laboratory (JPL) is studying SGG isolation and in-flight measurements of the SGG parameters.

During the fall of 1985, at the direction of NASA Headquarters, and through the cooperation of other agencies, the various federal and university activities were brought together under a Gradiometer Study Team directed by the Marshall Space Flight Center (MSFC). The objectives of the Study Team are:

- To develop a total system concept for a space qualified three-axis SGG integrated with an SSA

- To examine and recommend methods for flight test of the gravity gradiometer package in space

- To examine methods for the acquisition, processing, and analysis of space-derived gravity gradiometer data

- To develop a detailed plan for an initial spaceborne cryogenic gravity gradiometer flight test in the early 1990's.

This report is a summary of the plans and progress made thus far by the Study Team in accomplishing these objectives. A detailed Study Team report has been published in a companion report [6].

Recommendations for future Earth Science missions have recently been published in a Space Science Board Report. The scientific objectives of the SGG flight mission are twofold: (1) the primary mission objective is to make dense and very acccurate measurements of the Earth's gravity field for geophysical studies, and (2) the secondary mission objectives are to carry out tests of fundamental laws of physics. The latter objectives, although considered as secondary for this mission, relate to our fundamental understanding of Nature, and are no less scientifically important than the primary mission goals.

Figure 1 illustrates the incremental steps of the SGGM program, the accomplishments to date, and future plans. The laboratory development and tests required to produce a space quality SGG instrument and associated systems will proceed in parallel with the development of the flight test of the Experiment Module. (It is anticipated that an upgraded version of the laboratory SGG will be used in the flight test.) After the space performance of the instrument has been verified through the flight test, a total system including Experiment Module and Spacecraft will proceed toward development.

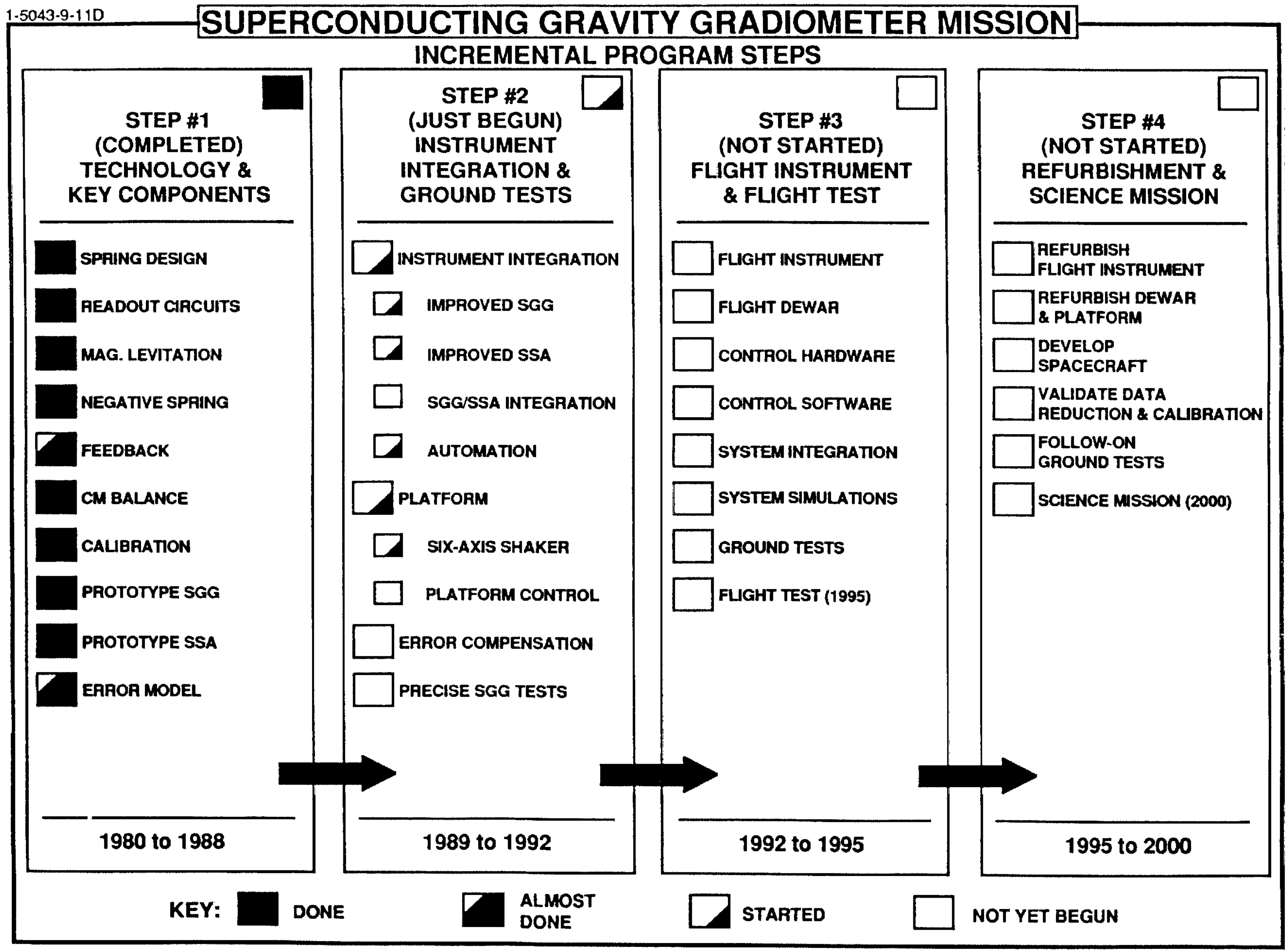


Figure 1. Superconducting Gravity Gradiometer Mission – incremental program steps.

The next two sections of this report present a synopsis of the Science and Applications Rationale and Gradiometer Instrument Requirements, respectively. This is followed by a discussion of the instrument design, status, and an outline of the ground test requirements. The preliminary mission analysis and alternative spacecraft concepts are included in Section 4. Section 5 includes options for a proposed flight test program. Section 6 outlines future technology advances that might benefit the SGGM. The next section includes preliminary schedules and cost estimated for the program. The final section includes the Recommendations and Conclusions of the Study Team.

2.0 SCIENCE AND APPLICATIONS OBJECTIVES

2.1 Geophysics

Advancement of the geosciences is the primary rationale for this mission; however, the SGGM also provides an excellent opportunity to investigate fundamental laws of physics. Geophysical instrumentation and experimental techniques have improved to the extent that geophysical research can no longer be considered as being limited to the geosciences. Instead, one is now required to have intimate knowledge and understanding of the physical laws on which instruments and techniques are based. Scientifically, this mission represents, and takes advantage of, the tremendous advances in geophysics.

The requirements for global gravity data for geophysics investigations to complement other data sources generally fall into two general scientific categories: geodynamics and oceanography. The importance of gravity data to both of these areas was highlighted by the following: In 1982, the NAS published a report in which "...the accuracy and scope of the measurements [that would lead to] the greatest scientific advances..." in the Earth sciences were identified [2]. In solid Earth dynamics, the NAS concluded that the measurement of the gravitational field is, by itself, the third primary science objective for the 1980's. Since the measurement of the Earth's gravitational field is a primary objective for both solid Earth and ocean dynamics, and a secondary objective for continental geology, the NAS determined that a major improvement in both the accuracy and resolution of the global gravity field is "...an objective of the highest priority for the 1980's."

The geophysical and physical rationale summarized here is excerpted and condensed from a NASA workshop report [1]. This workshop, held in the Spring of 1987, combined the talents of a diverse team of geoscientists to define the advancement of the various geosciences resulting from improved knowledge of the Earth's gravitational field. The goals were set by scientific need, without regard to practical experimental constraints. These goals were merged with the capabilities of the SGGM, described in Reference 6, and summarized here.

The description of the gravity field is one of the most important data sets required to gain a comprehensive understanding of the Earth as it reflects a broad spectrum of phenomena over a broad range of spatial scales. For example, on a global scale, the gravity field is affected by the structure and dynamics of the core-mantle boundary and long-range variations in the mantle and lithosphere. On the continental scale, gravity data provides information on mantle convection and large vertical isostatic adjustments, while on the regional scale, gravity data are necessary for understanding the process of mountain building.

It is clear that the geophysical models which must be created cannot be developed using only one type of observation. The need to consider a phenomenon from several observational aspects is an integral part of the scientific method. An important aspect of the gravity field is that it reflects, and can be related to, parameters which are derived by many other disciplines. For example, the gravity field integrates the effects of variable bulk modulus observed in seismology, the variations in rock density and inferred composition observed in geochemistry, and lithospheric stresses observed in tectonics. Gravity-field data thus serve an important function in the model development through integration of other independent data. Furthermore, such models have been extremely useful in the development of our concepts of the structure, composition and evolution of other planets and the Moon; in turn, helping us learn more about the Earth.

Detailed surface gravity data have been acquired in many geophysically important areas of the Earth. With the advent of the space-borne measurements, global data sets with increasingly improving spatial resolution have become available. Now, the improved technical capabilities of the SGG, forming the heart of this mission, presents the possibility of providing precise global gravity data with high spatial resolution which will yield much advanced geophysical information essential to gaining fundamental understanding of the solid Earth. Our knowledge of mantle processes, the continental and oceanic lithosphere, and oceanography will all step forward from analysis of these data. Detailed discussions can be found in References 1 and 6. Figure 2 presents an overview of the many and diverse geophysical phenomena which are measurable through this mission. Although some important phenomena with shorter wavelengths cannot be observed, a major advancement in the global understanding of many diverse geophysical phenomena to within 50 to 100 km is within reach.

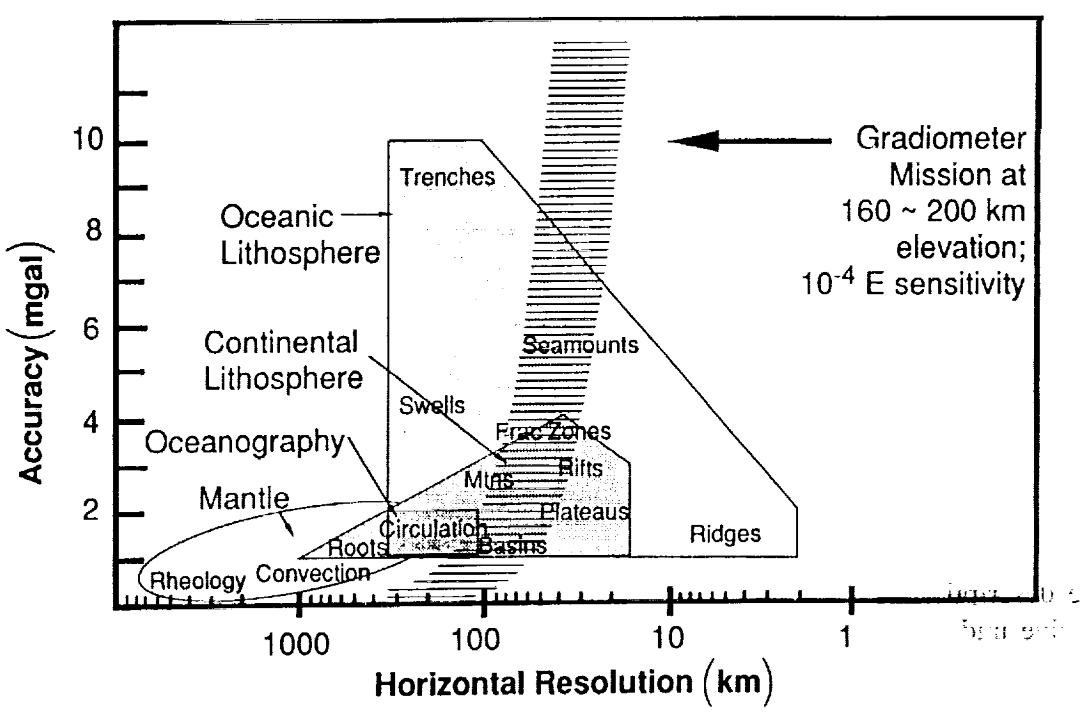


Figure 2. Summary of requirements for gravity measurement accuracy as a function of spatial resolution.

2.2 Fundamental Laws of Physics

A secondary, but nevertheless very important, objective of this mission is to directly test the validity of the gravitational inverse square law and to provide a platform for testing the current models of General Relativity. Demonstrating the nonvalidity of the inverse square law, currently in heated debate among geophysicists and physicists, has far-reaching consequences in physics and geophysics. Possible variations of the Gravitational Constant (G) of up to 1 to 2 percent between the laboratory and astronomical scales have been reported in the literature. A 1-percent error in G translates directly to a 1-percent error in the determination of the mass of the Earth. Figure 3 shows the expected improvement in this field with this mission. In the (non-Newtonian force) range of 10 to 10,000 km, the detection threshold is improved by several orders of magnitude.

Einstein's General Theory of Relativity is widely accepted as the correct theory of gravity. Unlike Newton's theory, Einstein's theory contains a velocity-dependent term in gravitational interaction, analogous to the magnetic field in electrodynamics. This results in dragging of local inertial frames, the so-called Lense-Thirring effect. This dynamical aspect of General Relativity has never been tested although the static feature of the theory has been checked repeatedly by such classical tests as the perihelion shift of Mercury and light bending experiments. The Gravity Probe-B (GP-B) mission is an attempt to detect the Lense-Thirring effect by measuring the precession of superconducting gyros in Earth orbit. A highly sensitive superconducting gravity gradiometer in Earth orbit may provide another way to check the dynamical prediction of General Relativity [7]. If this experiment could be performed with a resolution comparable to that expected of GP-B, it would provide a highly desirable independant check of the GP-B results.

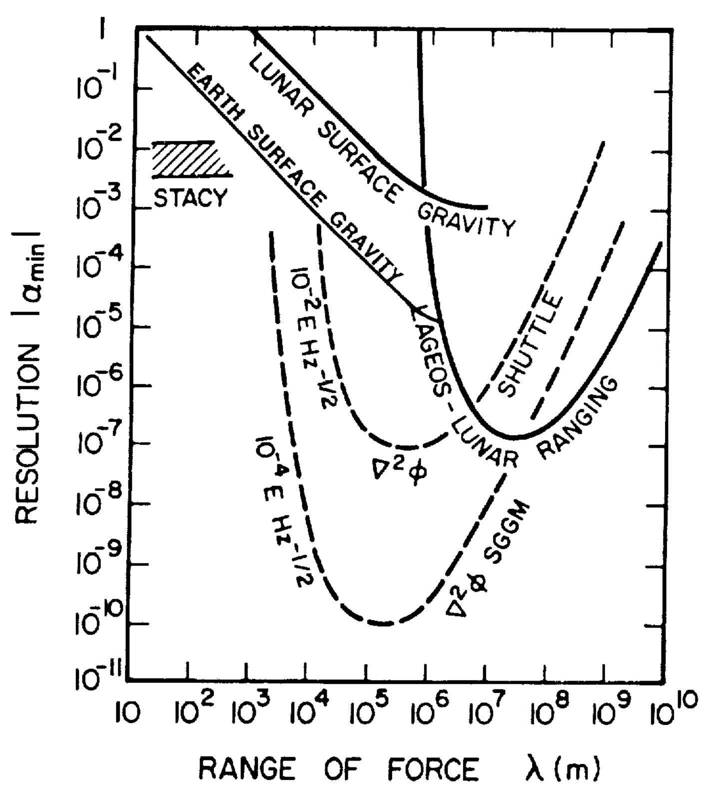


Figure 3. Expected resolution of α as a function of λ for $\nabla^2\Phi$ experiments in Earth orbit (dotted lines).

Finally, long-range objectives for, and spinoffs from, this mission are in improving inertial navigation systems, orbit determinations, greatly improved sensors and techniques for planetary missions, and clearly identifiable applications for Earth rotation, seismology, and mineral exploration. All these stem from an instrument design which advances the ability to measure acceleration fields by several orders of magnitude.

This is a scientifically exciting program, not only from the point of view of improved gravity determination, but especially from the exceptionally broad range of geophysical and physical problems that will be addressed with this mission. It is the depth and diversity of scientific applications which gives this project the imperative to move ahead and provide us with a rich source of new and unique data.

3.0 SUPERCONDUCTING GRAVITY GRADIOMETER INSTRUMENT (Fig. 4)

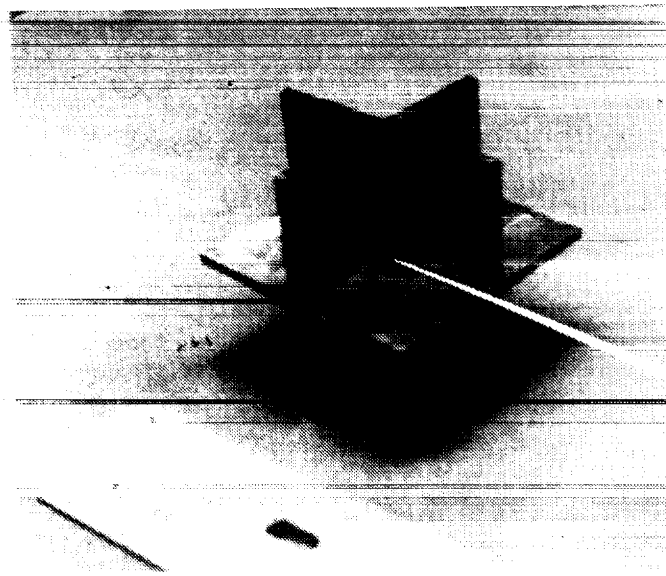
Although an orbiting satellite is under a free fall, the gravity gradient can be measured by monitoring the relative motions between two proof masses inside a spacecraft. For example, two masses separated by 20 cm horizontally are accelerated toward each other by 3×10^{-8} g due to the Earth's gravity gradient. The science objective of the SGGM corresponds to resolution of this acceleration to one part in 10^7, or measurement of a relative acceleration of 3×10^{-15} g! Such an acceleration, though incredibly small, could be detected in principle by utilizing superconducting technologies, provided that dynamical disturbances of the platform and other interferences could be kept to sufficiently low levels.

3.1 Instrument and Platform Requirements

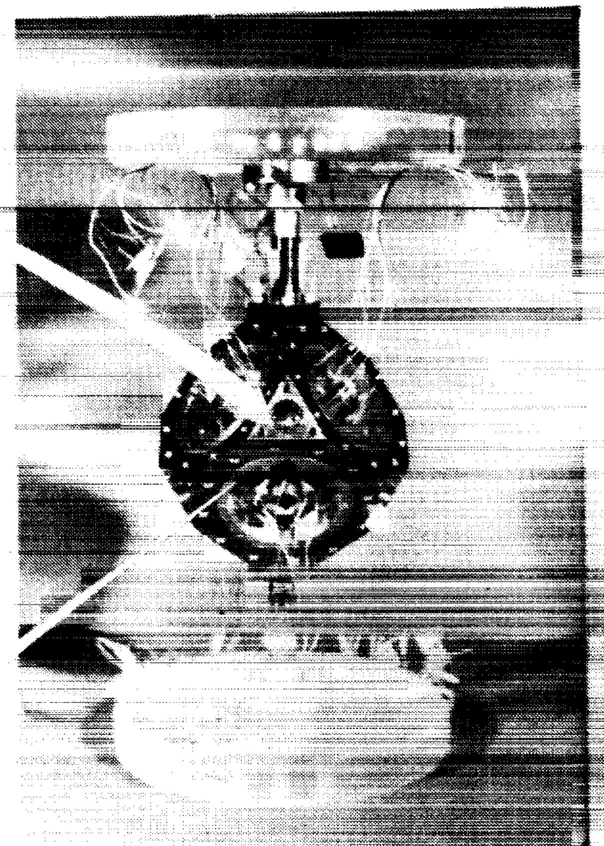
The instrument and platform requirements for SGGM depend critically on the satellite altitude since the spectral density of the gravity gradient is a sensitive function of the altitude. For the spherical harmonic of degree $\ell = 400$, which corresponds to a horizontal resolution of 50 km, the gravity gradient is reduced by an order of magnitude for every 37 km of altitude increase. Thus, a low altitude orbit is essential for a sensitive gravity mission.

Many geophysics objectives enumerated in Section 2.1 call for a resolution of 2 to 3 mgal at a wavelength of 100 km, or a spatial resolution of 50 km (Fig. 2). Studies have indicated that such a resolution could be achieved with a 10^{-4} E gradiometer in six months at 160 km altitude. For a signal bandwidth of 0.1 Hz, the spectral density requirement of the instrument is then 3×10^{-4} E $Hz^{-1/2}$. It is desirable to extend this sensitivity down to 10^{-3} Hz in order to satisfy the objectives for seismic tomography and temporal variation of the Earth's gravity field.

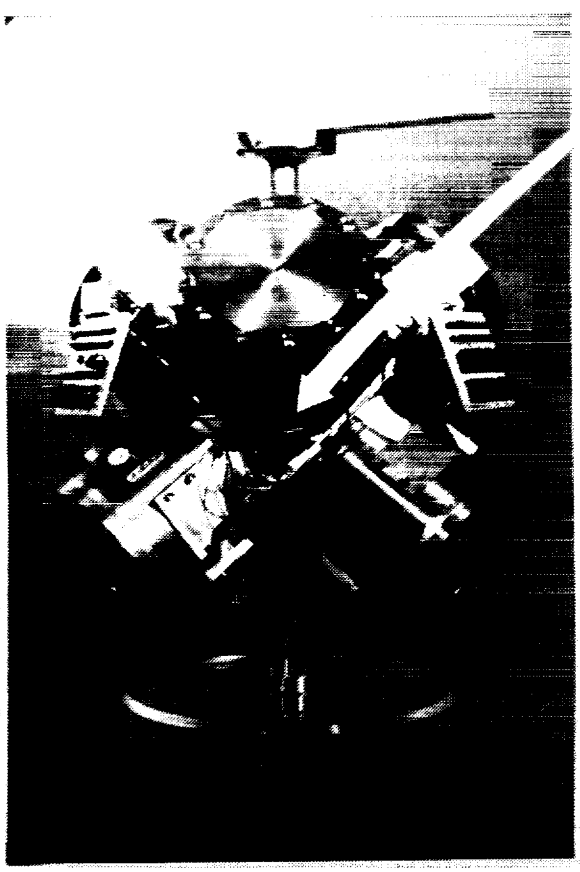
Operation of such a sensitive gravity gradiometer instrument presupposes developing a platform with demanding requirements. For a 10^{-4} E $Hz^{-1/2}$ gradiometer, the linear and angular vibration levels of the platform must be kept below 2×10^{-8} g $Hz^{-1/2}$ and 2×10^{-3} arcsec sec^{-2} $Hz^{-1/2}$, respectively. Fluctuations in self-gravity must be minimized by designing the spacecraft with few moving parts and preventing sloshing motions of the propellants and the liquid helium.



ACCELEROMETER NIOBIUM PROOF MASS



SUPERCONDUCTING 6-AXIS ACCELEROMETER



PROTOTYPE 3-AXIS SGG

Figure 4. Superconducting Gravity Gradiometer.

The fundamental physics experiments, the secondary mission objectives, require an instrument sensitivity of 10^{-5} E $Hz^{-1/2}$ and a more demanding attitude control. Since the physics experiments do not require as low an altitude as gravity mapping, the optimum configuration of the physics mission may be different from that of the geophysics mission. Studies are continuing to examine the feasibility of the fundamental physics experiments.

3.2 Instrument Design

Superconducting Gravity Gradiometer (SGG): A single-axis SGG is composed of two superconducting proof masses that are coupled by means of persistent currents to a Superconducting Quantum Interference Device (SQUID), a highly sensitive magnetic field detector. The proof masses are confined by mechanical springs to move along the line-of-sight between them. "Superconducting negative springs" also act on the proof masses to cancel the stiffness of the mechanical springs and thus make the gradiometer effectively a "free-mass" system along the sensitive axis. Reduction of thermal noise by cooling, the high sensitivity of the SQUID, and further sensitivity enhancement by the superconducting negative spring permit construction of a 10^{-4} E $Hz^{-1/2}$ gradiometer with a baseline of 10 cm [8].

In the SGG, common mode acceleration is rejected by adjusting the persistent currents which determine the scale factors of the component accelerometers. The "flux quantization" in superconducting loops assures the stability of the scale factors and of the common-mode balance in the SGG.

A three-axis gravity gradiometer is an assembly of three sets of single-axis units in three orthogonal directions. Although harmonic coefficients of the Earth's gravity can be determined from the global data set of a single component of the gravity gradient tensor, the three-axis diagonal component device allows removal of centrifugal effects and provides desired redundancy in the data. Further, the physics objectives require simultaneous detection of three orthogonal gravity gradients. Thus a three-axis SGG is proposed for the mission.

Superconducting Six-Axis Accelerometer (SSA): In order to measure the linear and angular accelerations of the platform to the required precision, an SSA will be provided. The SSA senses the rigid body motion in all six degrees-of-freedom of a single, levitated superconducting proof mass. The accelerometer sensing is accomplished by using 24 superconducting "pancake" coils organized as six inductance bridges, coupled to a single SQUID. A linear sensitivity of 10^{-13} g $Hz^{-1/2}$ and an angular sensitivity of 10^{-6} arcsec sec^{-2} $Hz^{-1/2}$ are expected. The device occupies a 10.2 cm cube.

Figure 4 shows the laboratory models of the SSA and the three-axis SGG. The SSA proof mass occupies the center of the cubic accelerometer housing on which the six accelerometers of the SGG are mounted. In order to calibrate these instruments and stabilize the gradiometer platform, the integrated package of the SGG and SSA will be mounted on a six-axis shaker, which resembles gyro gimbals. The entire assembly will weigh 60 kg and fit in a 50 cm diameter sphere.

The gradiometer platform will be isolated from the vibrations and jitter of the dewar by feeding back the SSA outputs to the six-axis shaker. The signals from the SSA can also be used to effect the drag free and attitude control of the spacecraft.

3.3 Status of Instrument Development

An SGG capable of satisfying the instrument requirements for the SGGM has been under development since 1980, at the University of Maryland with support from NASA's Geodynamics Program. The development of an SSA began in 1985 at the same institution under an Air Force contract. The instrument research and development has demonstrated that superconducting technology not only can be utilized to lower the intrinsic noise of the instrument, but also can meet many of the practical challenges of operating a sensitive gravity measuring instrument in a noisy environment.

Based on the experience obtained with the early instruments (Model I and Model II SGG, Model I SSA), advanced designs of the three-axis SGG (Model III) and SSA (Model II) were produced. The assembly of the Model III SGG and Model II SSA will be completed in 1989. The instrument development schedule is shown in Figure 12. It is expected that the basic laboratory tests and automation of the new instrument will be completed by the end of 1991.

Table 1 summarizes the past accomplishments for the development of the instrument. No technical difficulty is expected in demonstrating the instrument and associated hardware. However, it appears that a major new effort must be devoted to the automation and error compensation of the instrument in the next few years. With adequate support of all of these efforts, the flight test program could be initiated in FY92 with an orbital flight test in 1995.

The SGGM flight hardware is expected to be a modification of the laboratory prototype instrument under assembly. Since extensive experience will be obtained with the prototype instrument prior to the construction of the flight instrument, the ground test of the flight instrument should be relatively straightforward.

TABLE 1. MAJOR INSTRUMENT RESEARCH TASKS ACHIEVED

- **PROTOTYPE SINGLE-AXIS SGG (MODEL I)**
  - COMMON MODE REJECTION, CALIBRATION DEMONSTRATED
  - NOISE SPECTRUM MEASURED
  - MAJOR ERROR SOURCES IDENTIFIED
  - INVERSE SQUARE LAW EXPERIMENT CARRIED OUT
- **IMPROVED THREE-AXIS SGG (MODEL II)**
  - TEMPERATURE COMPENSATION INCORPORATED
  - THREE-AXIS RESIDUAL BALANCE INCORPORATED
  - HARDWARE CONSTRUCTION COMPLETED
  - PARTIAL TESTS OBTAINED
- **FURTHER IMPROVED THREE-AXIS SGG (MODEL III)**
  - SUPERCONDUCTING NEGATIVE SPRING DEMONSTRATED
  - SINGLE-AXIS PORTION CONSTRUCTED
- **INSTRUMENT ERROR MODELING**
  - DYNAMIC ERROR ANALYSIS OBTAINED
  - PLATFORM REQUIREMENTS GENERATED
  - SSA (MODEL I) CONSTRUCTED AND TESTED

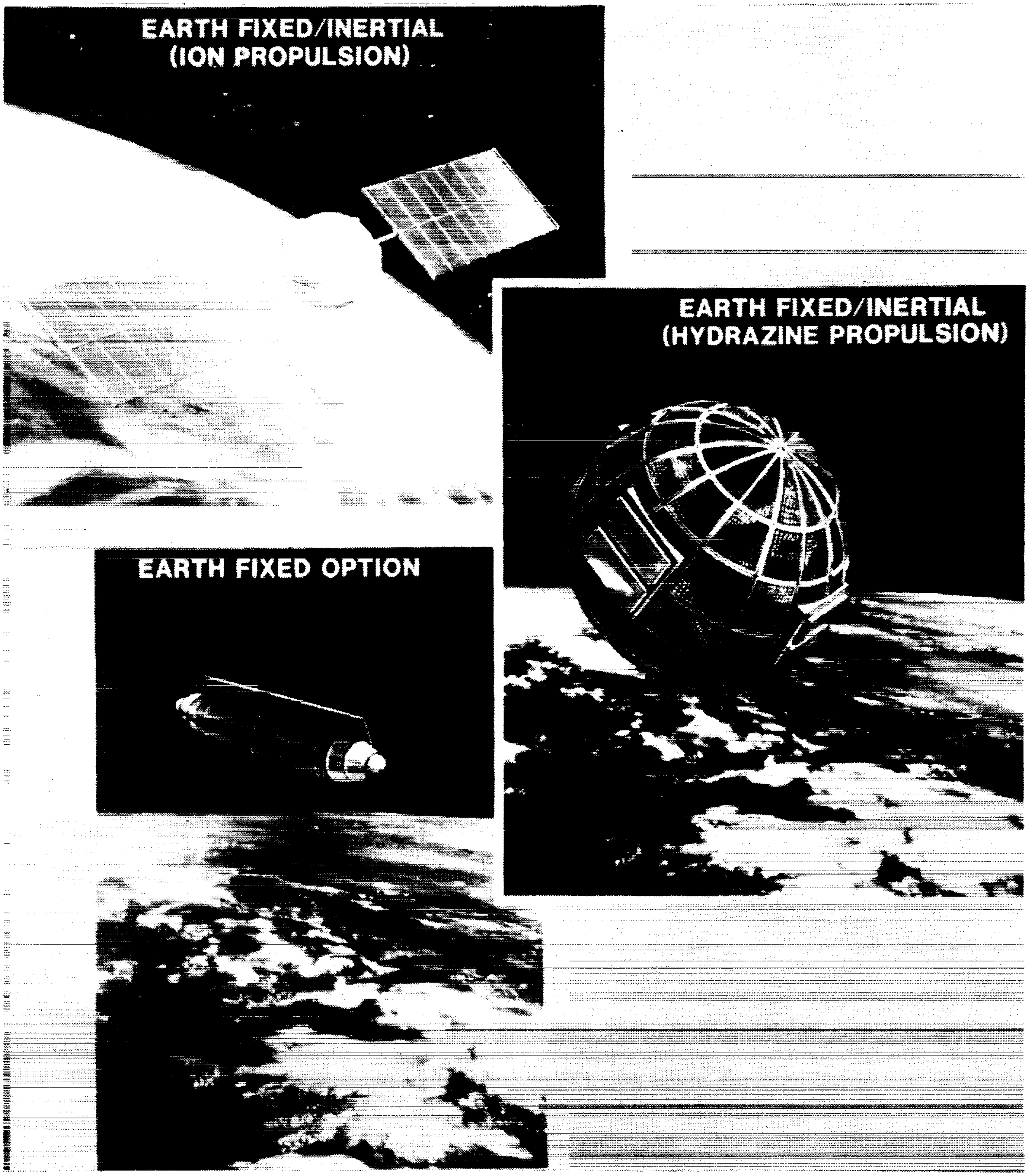


Figure 5. SGGM alternative spacecraft concepts.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

4.0 MISSION AND SPACECRAFT CONCEPTS (Fig. 5)

In order to establish references against which mission requirements and various trades could be examined, four alternative spacecraft concepts were analyzed. These concepts included two major configurations, a spherical spacecraft design, and a long cylindrical concept. The spherical configuration was further divided into an ion propulsion option and an option that would utilize a hydrazine propulsion system. The cylindrical configuration was also divided into two separate options, a new spacecraft design and a modification of the design for the previously planned Geopotential Research Mission (GRM) spacecraft. Other potential carriers such as the space station, the Earth Observing System (EOS) platform, and the Tethered Satellite System (TSS) were also briefly examined.

Requirements such as spacecraft control and gradiometer scale factors as well as instrument sensitivity are more severe for the inverse square law test than for geophysics applications. The gravitomagnetic field experiment would also require attitude control and instrument sensitivity similar to the inverse square law test. Thus, the physics experiments could require a separate mission if the implementation of the more stringent requirements proves too costly or too advanced. In a separate mission, the spacecraft and orbit would be optimized to suit the low frequency nature of the physics experiments. Spacecraft concepts were included in this study that would accommodate both the geophysics and physics objectives.

The major tasks of this study were to establish mission feasibility and to identify critical systems. The most critical element identified thus far is control of the spacecraft. While the Attitude Control System (ACS) was analyzed in this study, a deeper study is needed. Many of the subsystems are within the state-of-the-art. Recommendations for further study are identified in Section 8.

4.1 Orbit and Spacecraft Orientation

Even though the SGG will be an extremely sensitive instrument, a low altitude orbit must be selected to provide the desired measurement accuracy. For a gradiometer precision of 10^{-4} E, a 160 km orbit appears to provide a gravity anomaly uncertainty of 1 to 4 mgal for 0.5-degree x 0.5-degree blocks. For the same instrument precision, a 200 km orbit is estimated to provide a total anomaly uncertainty of about 4 to 7 mgal for 0.5-degree x 0.5-degree blocks and about 0.8 to 2 mgal for 1-degree x 1-degree blocks. Although this does not yield the desired 2 to 3 mgal uncertainty for the 0.5-degree x 0.5-degree block, the maximum resolvable harmonic degree does approach 400, which corresponds to the desired 50 km horizontal resolution. Therefore, an orbital altitude of 200 km was selected for this study.

The gravity anomaly uncertainty depends fairly strongly on orbit position error. It was postulated in this study that the Global Positioning System will be able to adequately provide the required orbit position knowledge during the time frame in which the SGGM is expected to be operational (~2000).

A Sun-synchronous orbit (inclination 96.3 degrees) will provide the desired Earth coverage and maximize the time the spacecraft is in full sunlight. This would provide efficient power production and aid in minimizing thermal cycling (and thus induced thermal-mechanical vibrations) of the spacecraft. However, it remains to be determined whether the loss of coverage within a few degrees of the poles would be acceptable for the geophysics investigations. This should be expanded in future trade studies.

Because the primary and secondary mission objectives may prefer different spacecraft orientations, the studies included an examination of spacecraft concepts that can be: (1) either inertial or Earth-fixed (a spherical configuration) utilizing a single spacecraft design or (2) Earth-fixed only (long, cylindrical configurations, similiar to GRM, with the axis of the cylinder parallel to the direction of flight).

An Earth-fixed mode is preferred for the null test of the inverse square law as well as for the tests of General Relativity. On the other hand, the requirements for control or knowledge of attitude rate are in general several orders of magnitude more severe for the Earth-fixed mode. Fortunately, the centrifugal acceleration errors can be removed to the first order by using the gradiometer itself for the primary (geophysics) mission objective. Therefore, for geophysics applications, either orientation would be acceptable.

4.2 Cryogenics and Experiment Module

Providing a cryogenic environment ($T \leq 1.5$ K) for the SGG during the six-month mission is a common element of all spacecraft concepts studied. The core technology exists through actual space flight experience for superfluid helium instrument cooling. The most notable mission of this type was the Infrared Astronomy Satellite (IRAS), in which a 0.6-m diameter infrared telescope performed an all-sky survey over the mission's 10-month lifetime. Another promising design is the Cosmic Background Explorer (COBE) dewar which is currently scheduled to be flown in 1989.

After carefully examining all potential candidates, the COBE dewar was found to be capable of meeting the SGGM requirements. However, the COBE dewar is actually larger than necessary to meet the SGGM requirements. Since the dewar diameter is a driver for the spacecraft diameter, the dewar diameter should be kept as small as possible to reduce drag. The development of a suitable dewar does not appear to be a major cost or technology driver. Therefore, a new dewar based on the COBE design is recommended.

A conceptual design of the SGGM Experiment Module is shown in Figure 6. Electronics packages, a sensor to align the SGG and external navigation base, star trackers, remote interface units and rate gyros are elements that could be mounted to the external shell of the dewar. The Experiment Module is estimated to weigh approximately 467 kg.

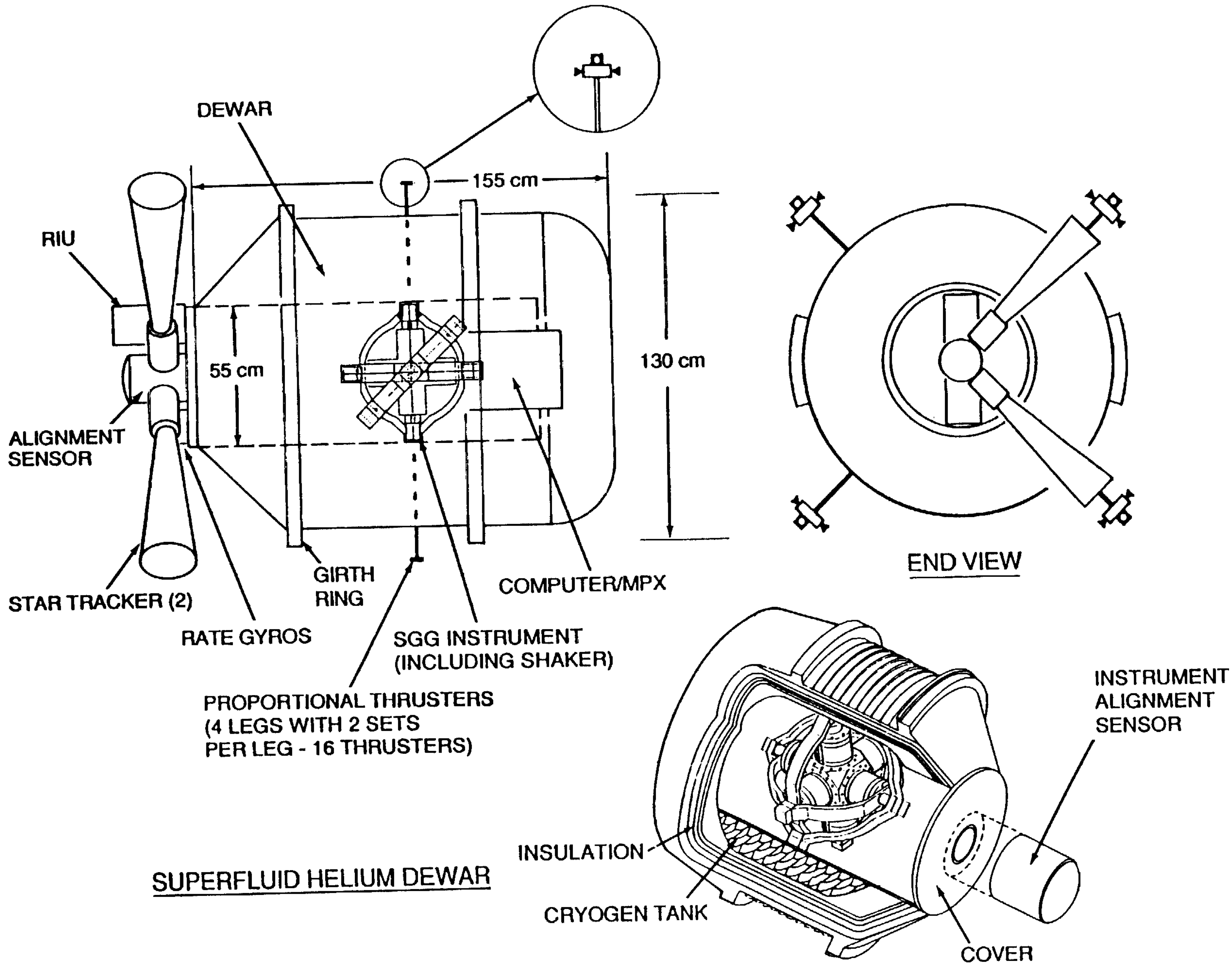


Figure 6. SGG Experiment Module concept.

4.3 Experiment Module Isolation

The inherent sensitivity of gravity gradiometers to disturbances translates into very demanding spacecraft requirements. For example, external disturbances, such as aerodynamic drag, must be compensated for through the spacecraft propulsion/control systems. Likewise internal disturbance sources such as self gravity, thermal-mechanical noise, reaction wheel disturbances, bearing noise, thruster noise, gimbal motion, solar array motion, liquid helium boiloff and slosh, and propellant motion or unbalance must be eliminated, greatly reduced, or in some cases, accurately known. Vibration is also an important concern since it is a coupling mechanism between instrument errors and instrument performance. Vibration can also cause attitude errors. These problems combine to make the design of the spacecraft a particularly demanding task.

A drag free spacecraft, like GP-B, has a proof mass shielded from external forces so that it follows a true gravitational orbit, with the spacecraft forced to follow the proof mass. The SGGM does not require a drag free orbit because the gravity gradient is measured in situ by a single instrument without referring to the orbital characteristics. However, the severe restrictions on acceptable acceleration levels make the isolation of the SGG an area of concern and a system similar to a drag free system (discussed later) may offer a solution.

The GP-B spacecraft utilizes helium boiloff gas from the cryogenic system to provide propulsion for drag compensation and spacecraft control. Thrust levels utilizing this approach would not be adequate for SGGM because the much higher drag forces experienced at the lower SGGM altitude cannot be counteracted using helium boiloff alone. However, drag compensation of just the free floating Experiment Module and utilizing an additional spacecraft propulsion system may be possible. Proportional thrusters similar to those of GP-B would function as a vernier control system to maintain precise control of the Experiment Module within the spacecraft cavity.

Using this technique, the Experiment Module would be shielded from the relatively high drag forces by the surrounding spacecraft surfaces. The SSA would serve as the proof mass and provide signals for control. Two star trackers would be mounted on the Experiment Module for attitude determination, and an alignment system would be required to determine the alignment between the external base (star trackers/external Experiment Module structure) and the SGG located within the dewar.

4.4 Alternative Concepts

The four alternative spacecraft concepts considered in this report are summarized in Figure 7 where the major characteristics of each are listed. In addition to the SGGM concepts analyzed, data for the GRM and GP-B spacecraft are shown for reference in the last two columns of the figure. These latter two concepts are included as examples of spacecraft designs that have sensors which, like SGGM, impose demanding platform requirements.

1–803–7

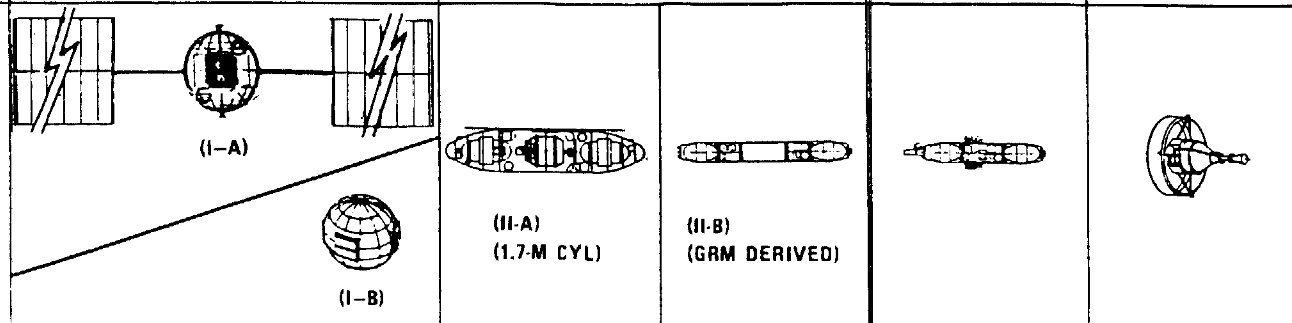
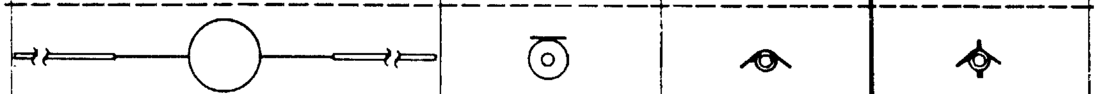
OPTION	(I) 3–M SPHERE	MINIMUM DRAG CONFIGURATIONS		(FOR REFERENCE ONLY) GRM	(FOR REFERENCE ONLY) GP–B
CONFIGURATION	 (I–A) (I–B)	(II-A) (1.7-M CYL)	(II-B) (GRM DERIVED)		
CROSS SECTION					N/A
FEATURE					
ATTITUDE	EARTH FIXED OR INERTIAL	EARTH FIXED	EARTH FIXED	EARTH FIXED	INERTIAL
MINIMUM DURATION (MO)	6	6	6	6	24
ORBIT: ALTITUDE (km) INCLINATION (DEG)	200 96.3	200 96.3	200 96.3	160 90 ± 0.1	650 90
TOTAL WEIGHT (kg)	2,524 / 3,727	4,072	3,377	2,734	1500
PROPELLANT WEIGHT (kg)	99 (XENON) / 1525 (HYDRAZINE)	1400 (HYDRAZINE)	1400 (HYDRAZINE)	1400 (HYDRAZINE)	296 (HELIUM BOILOFF)
DIMENSIONS (LENGTH X DIAM.) (m)	3.05 (DIAM.) 20 W/SOLAR AR. / 3.05 (DIAM.)	8.2 X 1.7	7.9 X 1.04	5.7 X 1.04 (10.1 X 1.04 m / MAG. BOOM)	4.3 X 4.3
POWER (W) (CONTINUOUS)	4,340 / 740	740	740	400	168
DATA HANDLING (kb/s)	43	43	43	4.6 34 (PLAYBACK)	0.256
CONTROL SYSTEM REQ. -POINTING STAB (rad $Hz^{-1/2}$) -ATTITUDE RATE (rad s^{-1} $Hz^{-1/4}$) GEOPHYSICS– PHYSICS– –LINEAR ACCEL (g $Hz^{-1/2}$)	EARTH FIXED: 3×10^{-6} 3×10^{-7} 4×10^{-11} 2×10^{-8} INERTIAL: 2×10^{-8} 3×10^{-7} – 2×10^{-8}	3×10^{-6} 3×10^{-7} 4×10^{-11} 2×10^{-8}	3×10^{-6} 3×10^{-7} 4×10^{-11} 2×10^{-8}	8.7×10^{-4} rad 5.2×10^{-5} rad s^{-1} –	ANG DISPL ERRORS BETWEEN TELESCOPE & INSTR. $\sim 4.8 \times 10^{-10}$ rad 1×10^{-10} AVG.

Figure 7. Comparison of SGGM spacecraft concepts.

Spherical Configuration: A spherical configuration was chosen as Option I so that either an inertial or Earth-fixed orientation would produce nearly the same atmospheric drag. This option was further divided into Option I-A, which utilized ion propulsion, and I-B, where monopropellant hydrazine was assumed. Ion propulsion, while it offers high performance, and lesser propulsion system weight and volume, requires large amounts of electrical power. This in turn necessitates large solar arrays which create additional drag, and possible perturbing mechanical vibrations.

The spacecraft cross sections for Options I-A and I-B are quite different, resulting in vastly different atmospheric drag forces, even when the solar arrays in Option I-A are flown "edge-on." This problem, and the potential for vibrations from the large solar arrays, make the ion propulsion concept Option I-A less attractive. For Option I-B to be considered as a viable candidate, more detailed analyses must be done to demonstrate that the hydrazine propulsion system can meet the SGGM requirements. If this problem is favorably resolved, then it would appear that Option I-B is the best approach to a spherical spacecraft configuration.

Cylindrical Configuration: Option II-A would rely heavily on GRM-type spacecraft subsystems. Like GRM, it has a long cylindrical envelope and produces less drag than Option I, however, it is limited to an Earth-fixed attitude. The GRM propulsion system would have to be modified, as well as portions of the ACS and the Data Management System.

Option II-B started with the GRM spacecraft design, and required that modifications to the GRM design be held to a minimum. To accomplish this, the SGGM Experiment Module must fit within the 1.04-m diameter of the GRM spacecraft and would replace the Disturbance Compensation System (DISCOS) hardware. There are major problems involved in the design of the dewar within the constraints imposed by this particular spacecraft configuration and this option is not viable.

Option II-A is shown in Figure 8. This cross section has an average atmospheric drag about a factor of 3 lower than Option I-A. The configuration shown in the figure includes a schematic representation of the instrument isolation technique, utilizing the free floating Experiment Module. The major concern in this configuration, like that of Option I, is the ACS. The thermal, power, and C&DH designs are straightforward and no problems in developing these subsystems are anticipated.

For geophysics applications either an Earth-fixed or inertial orientation would be acceptable, and Option II-A appears to be a viable option, if the Earth-fixed orientation is selected. Like GRM, the cylindrical cross section, which is based on the diameter of the Experiment Module, offers a low drag profile. Isolation of the SGG by free floating the Experiment Module, in conjunction with utilizing the helium boiloff gas for vernier control of the Experiment Module, and using the six-axis accelerometer to control the spacecraft, is the leading candidate evolving from this study.

Critical spacecraft subsystems that need further study include the ACS and the hydrazine Reaction Control System (RCS). Isolation of the Experiment Module must also be studied in more detail. Detailed analyses, including a high-fidelity simulation of the control system, should be initiated. Since the spacecraft attitude rate and acceleration, attitude stability, pointing stability, and linear acceleration must all be satisfied simultaneously, a simulation is a critical element in assessing overall mission feasibility.

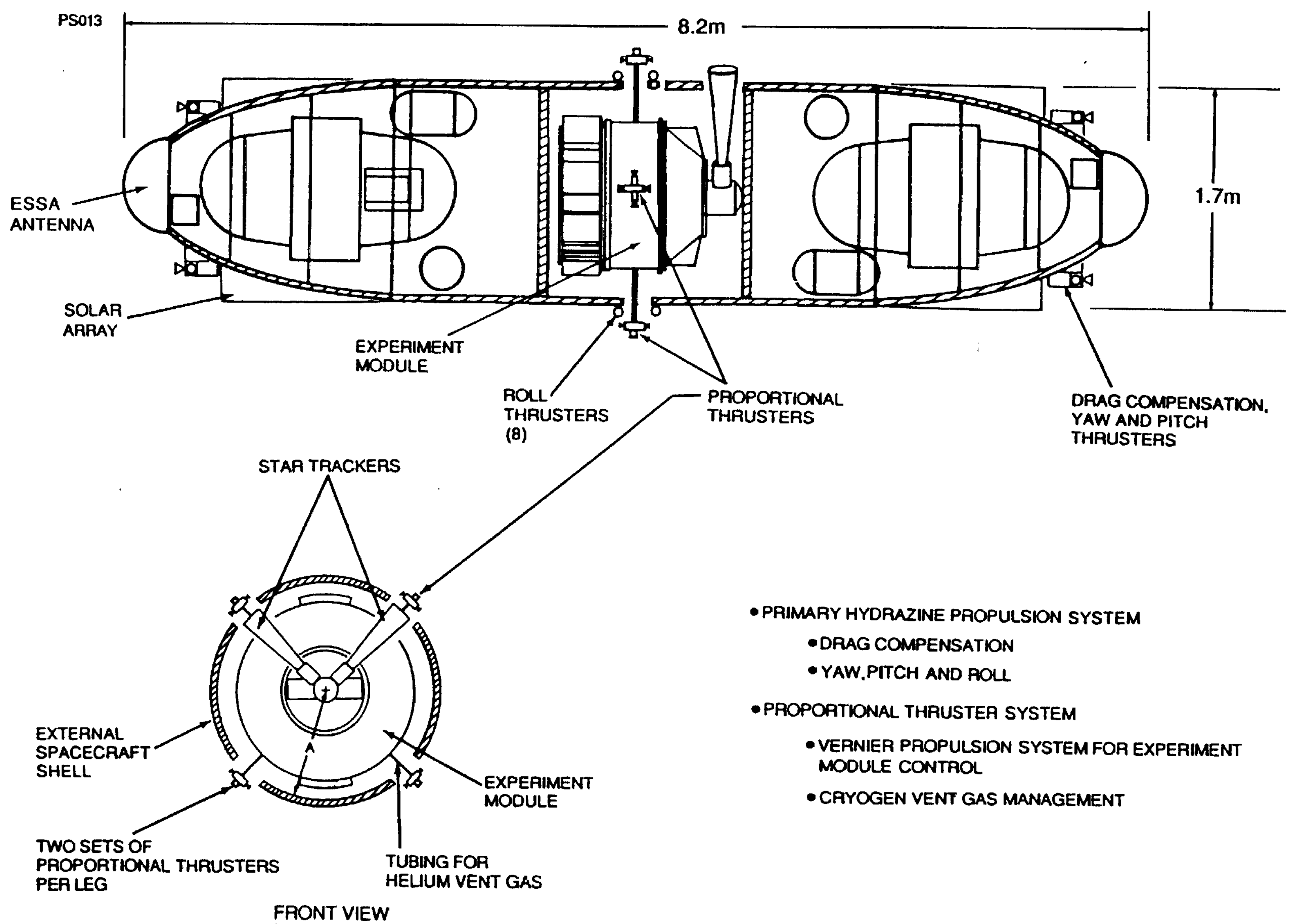
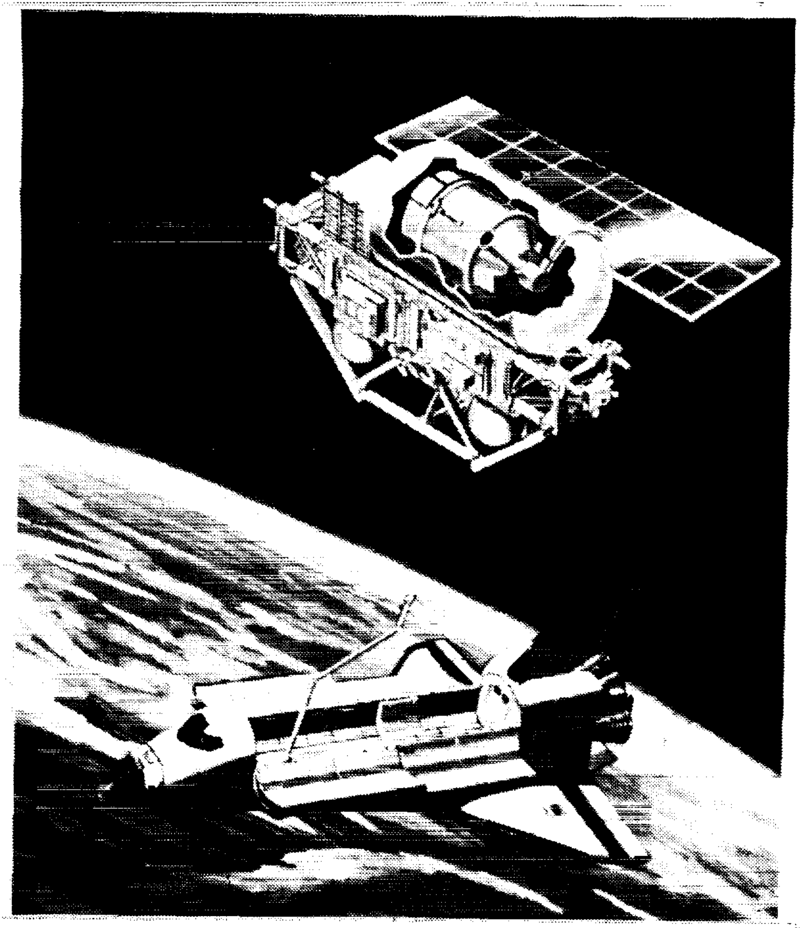
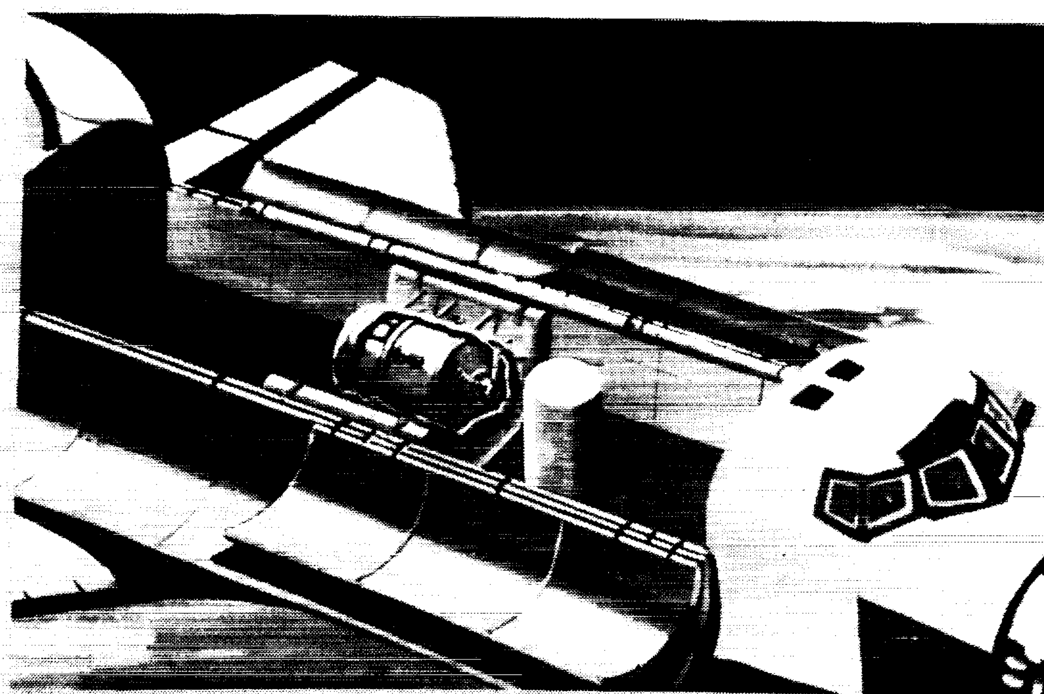


Figure 8. Option II-A (Earth-fixed only) spacecraft configuration.



DETACHED (FREE FLYING) MODE



SHUTTLE ATTACHED MODE

Figure 9. SGG Flight Test modes.

5.0 FLIGHT TEST PROGRAM (Fig. 9)

The SGGM requires a very sensitive instrument and demanding spacecraft performance to meet the scientific objectives. With a very sensitive instrument like the SGG, it is virtually impossible to verify the instrument flight performance unambiguously, under the full gravitational acceleration and ambient disturbances existing in an Earth laboratory. There are also unknowns concerning the effects of the orbital and platform environments on the instrument performance that can only be determined through an orbital test. Therefore, it is recommended that an orbital test be performed prior to the full duration science mission.

To establish the lowest baseline cost, an option was analyzed that would utilize the existing space qualified hardware to the greatest extent possible. An option to "soft-mount" the Experiment Module in the Shuttle's cargo bay was also analyzed. Finally, placing the Experiment Module on a carrier, setting it free from the Shuttle, and then recovering it, was considered.

5.1 Flight Test Objectives

The objectives of the Flight Test are listed below in roughly descending order of importance. However, many of the objectives are interrelated and all are considered vital to the program.

- Validate the flight performance of the SGG instrument
- Validate the design and operation of the Experiment
- Validate alignment and attitude control of the Experiment Module
- Determine the noise spectrum of the carrier
- Validate the analytic predictions of the instrument error model
- Assess the performance of automated instrument control
- Validate the techniques for processing the data.

5.2 Shuttle Attached Options

During data taking, other Orbiter activities must be curtailed. This would limit SGG operations to either a dedicated Shuttle flight, flights which deploy satellites, or dedicated portions of shared flights. The Shuttle environment is relatively severe for an instrument that is very sensitive to linear and angular accelerations. A major question to be resolved is whether the SGG can be adequately isolated from Orbiter disturbances.

Overall Shuttle acceleration levels of 10^{-3} to 10^{-4} g are common. Acceleration levels at very low frequencies seem to reach 10^{-6} g or better during unpredictable periods. However, this region has been very difficult to measure and no assurance can be made for low frequency disturbances at this time. Moreover, the attitude may be uncertain to the order of arc minutes.

Pointing is also an important consideration. For Orbiter payloads, pointing and stabilization are limited by the Orbiter ACS, by Orbiter structural distortions, and misalignments between the Inertial Measuring Unit (IMU) and the instrument. By providing attitude sensors between the Orbiter and SGG, absolute pointing accuracy can be improved.

Available Hardware Approach: The approach requiring the minimum of new developments (and lowest cost) would be to utilize available flight hardware where possible and existing standard Orbiter and Spacelab accommodations. The dewar, helium control system, structures, and pumps from the Spacelab Infrared Telescope mission could be used. A new cryostat to accommodate the SGG and attitude measuring equipment would be added. The experiment assembly would be mounted on a standard ESA pallet near the Orbiter center of mass. Power and data requirements could be easily met by standard Spacelab subsystems.

This option, utilizing previously flown hardware, is straightforward and no obstacles to its development were identified. However, a separate development and integration for the SGG science mission, with the exception of the SGG instrument package, would be required. Moreover, it is unlikely that the full SGG instrument performance could be validated with this concept.

Soft Mounted Mode: Studies have been made of a Suspended Experiment Mount (SEM) to provide some isolation from accelerations and to stabilize the viewing direction of Shuttle attached payloads. A flexible suspension system has been considered which would be rigidly locked for ascent and descent. Analysis has shown that about an order of magnitude attenuation of the disturbances can be expected from a fairly straightforward SEM design. In general, the suspended mount is better than hard-mounting the instrument, but probably not good enough to demonstrate the full instrument performance.

Freely Floating Mode: A possible instrument isolation approach would be to float the Experiment Module in zero-g and essentially operate the Shuttle as a drag free satellite. An experiment provided drag free package would control the Shuttle's vernier thrusters to provide drag compensation. This approach, however, does not appear feasible since it would relinquish control of the Shuttle to the experiment. Moreover the Shuttle's RCS is probably too coarse to provide the precise control needed to compensate for drag levels around 10^{-6} g. Therefore, this approach was not considered further. However, a related approach would use magnetic suspension or the helium boiloff to actively position the instrument assembly, as discussed in Section 4.3 (Fig. 10).

5.3 Shuttle Detached Options

This option would accommodate the Experiment Module on a carrier in the Shuttle cargo bay and be deployed from the Shuttle. The SGG experiment would then be a nearly autonomous, subsatellite of the Shuttle. Alternatively, the flight experiment could be left in orbit and retrieved during a later Shuttle mission.

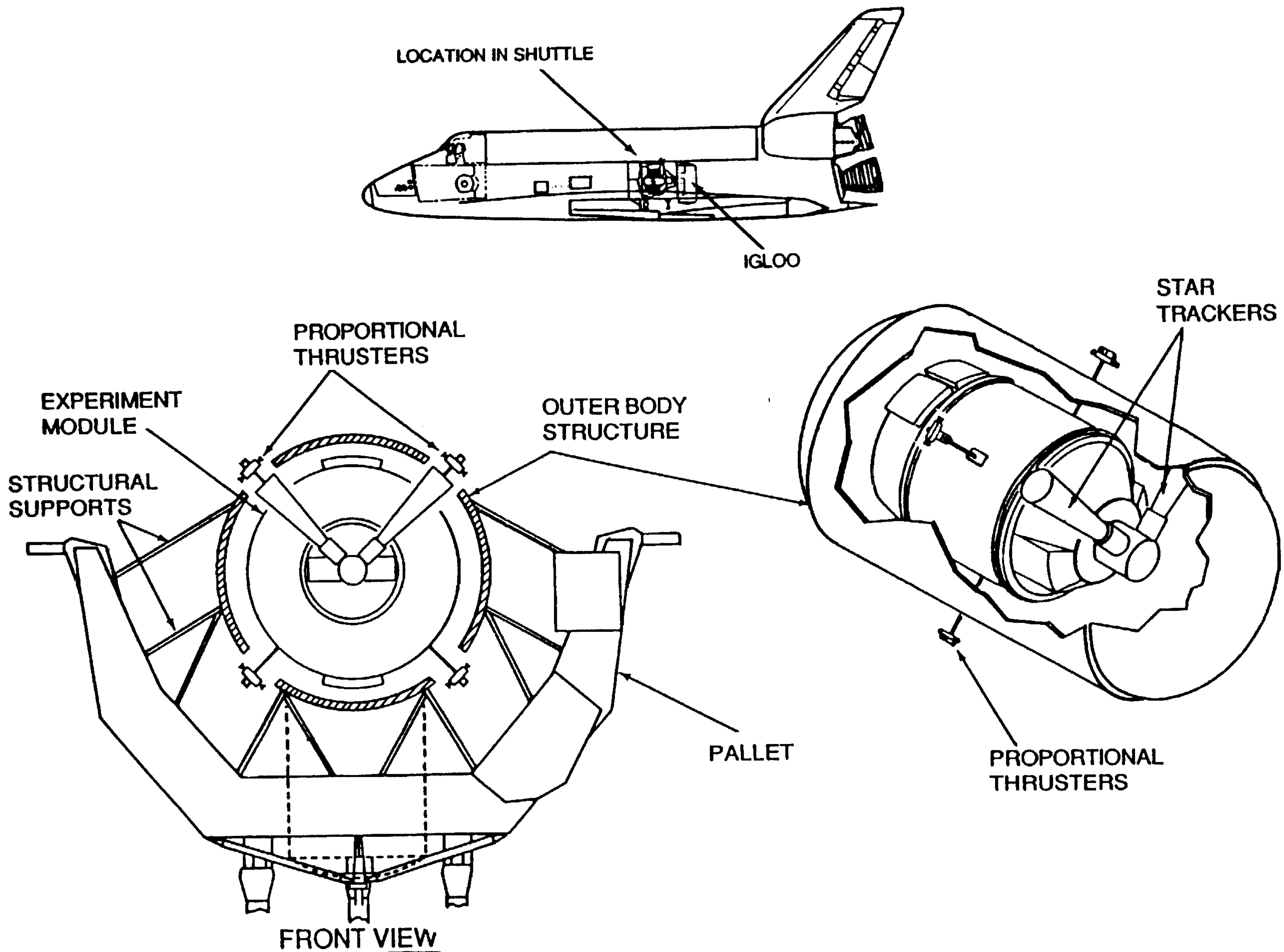


Figure 10. SGG Flight Test – free-floating mode concept.

One concept studied was to use the Spartan as the carrier. The Spartan is an experiment carrier that is placed in the cargo bay on a modified Multipurpose Experiment Support Structure carrier and released from the Shuttle during an orbital mission. The primary emphases are simplicity, low cost, and reusability. The baseline Spartan program included three separate configurations and enhancements to the basic Spartan capabilities have been proposed. However, the current Spartan carrier would not adequately accommodate the SGG Flight Test.

Possible future Spartan enhancements include solar arrays, a momentum exchange system, and possibly RF uplink and/or downlink capability. If the Spartan carrier is indeed enhanced as proposed, then it should be examined further as a potential carrier. Other possible carriers include the European Retrieval Carrier (EURECA) which has been designed for micro-g applications. If the enhanced Spartan or EURECA could be utilized, a significant reduction in program cost could likely be realized.

6.0 ADVANCED TECHNOLOGY DEVELOPMENT

Advances in technology development in several areas could benefit the SGGM. Included among these are developments associated with guidance, navigation and control (GNC); instrument cooling; high-temperature superconductivity; and spacecraft auxiliary propulsion systems.

Modern GNC systems utilizing digital control techniques greatly enhance the stability and accuracy of present day spacecraft. Primarily, the control system will be governed by the sensors and forcing elements. Based on the requirements for SGGM, only star trackers and the superconducting accelerometer have the required accuracy. The most accurate existing solid-state trackers are in the arcsec range, with a projected accuracy near 0.1 arcsec within five years. One method of stabilizing the Experiment Module consists of proportional thrusters being developed for the GP-B spacecraft. If this technology is perfected for GP-B, it could be used for vernier control of the Experiment Module.

Stored liquid helium coolers are state-of-the-art and have been considered for this mission. A superfluid helium dewar would provide the necessary thermal and vibration-free environment for the required mission life. A closed-loop superfluid helium refrigeration system, which could offer several advantages for the SGGM, will probably not be practical for some time to come. The use of solid cryogens would offer distinct advantages over liquid systems. However, the operating temperature is too high for SGGM, the lowest projected operating range being 8.3 to 13.8 K with solid hydrogen.

The recent discovery of new superconducting materials with high transition temperatures (T_c) adds a completely new outlook for the application of SGG technology. Oxide superconductors with T_c's in excess of 90 K and 120 K have been obtained. Although it may take a decade or two to successfully apply these materials in measuring devices, a high-T_c SGG would make future gravity missions to other planets much more feasible. The spacecraft could carry a liquid nitrogen dewar, which can have a hold-time of many years in space, or radiation cooling might be sufficient to keep the sensors in the superconducting state.

Monopropellant hydrazine is the current standard for spacecraft auxiliary propulsion. Since this type of system has been state-of-the-art for a good number of years, improvements are becoming more difficult. Ion propulsion is ideally suited for missions like SGGM, which demand low acceleration levels. Ion thrusters have been flown as experiments, and the critical technology component program for the baseline 30 cm ion technology was developed for missions such as a proposed Comet Rendezvous Mission. Ion propulsion is power limited, since the performance depends on the available electric power. Current technology efforts are directed toward an increase in performance, higher reliabilty, and reduction in cost.

7.0 COST ESTIMATES AND SCHEDULES

7.1 Preliminary Cost Estimates

Preliminary cost projections were made for the SGGM Program using parametric cost estimating techniques. This method uses mathematical analyses and historical data to obtain relationships between the cost and physical or performance variables (such as subsystem weight, power, or data rates).

The cost estimates given in this section were based on the SGGM Phase A results [6]. Therefore, since the phase A study developed only preliminary concepts of the SGGM systems, cost estimates should be considered as very preliminary at this stage of the study efforts. The following ground rules and assumptions were used in estimating the costs presented in this section:

- All costs are in constant FY89 dollars.
- Costs are for phase C/D.
- A protoflight approach was assumed.
- Costs were estimated at the subsystem level.
- Estimates include all system-level costs (system test operations, ground support equipment, systems engineering and integration, program management) and wraparound costs (i.e., 12-percent fee, 4-percent program support, and 30-percent contingency).
- The SGGM dewar cost estimate was based on a modification of the COBE dewar design.
- Costs for the electrical power, command and data handling, and a portion of the attitude control system were estimated by assuming a modification of the Multimission Modular Spacecraft systems. Costs for all remaining subsystems were estimated with the MSFC Protoflight Unmanned Spacecraft Cost Model.
- The SGG Instrument costs were estimated using an instrument cost estimating relationship developed by GSFC which is based on the database of the Scientific Instrument Cost Model developed for NASA.

Costs were estimated for a SGGM Science Mission only (without a precursor Flight Test Mission). Table 2 gives the cost details of the SGGM Science Mission and Figure 11 shows the program funding schedule, assuming a new start in FY96 and a launch in 2000.

Cost estimates for the Flight Test Mission depend on the carrier used (i.e. Shuttle attached, existing carrier, or a carrier specifically developed for the flight test). Thus the cost estimate of the Flight Test Program must await the completion of the Flight Test Accommodations Study. Moreover, the elements associated with the Flight Test and the Science Missions are interrelated. For example, the Experiment Module and SGG Instrument would be developed as part of the Flight Test Program, refurbished and flown on the Science Mission. In addition, some of the elements of the ground support equipment, systems engineering and integration, and systems test operations will likely be applicable to both the Flight Test and the Science Missions. The program management costs are likewise not independent for the two programs. Therefore, the only estimates that can be given for the Flight Test Mission at this time are for the design, development and the flight hardware costs associated with the Experiment Module and SGG Instrument.

7.2 Program Schedules

Program schedules were developed for both the Flight Test and the SGGM Science Mission. The Flight Test Program schedule is shown in Figure 12. For the Flight Test, an FY92 New Start was assumed leading to a flight in 1995. The development schedule for the laboratory instrument is also included. Figure 13 shows the total program schedule.

TABLE 2. SGGM COST ESTIMATES – SCIENCE MISSION ONLY (IN MILLIONS OF 1989 DOLLARS)

	DESIGN & DEVELOPMENT	FLIGHT UNIT
OUTER SPACECRAFT	45	42
EXPERIMENT MODULE	22	19
SGG INSTRUMENT	12	5
SUBTOTAL	79	66

SCIENCE MISSION TOTALS

DESIGN & DEVELOPMENT	79
PROTOFLIGHT HARDWARE	66
GSE	8
SYSTEMS TEST OPERATIONS	4
SYSTEMS ENG & INTEGRATION	22
PROGRAM MANAGEMENT	19
PROGRAM FEE (12%)	24
PROGRAM SUPPORT (4%)	9
CONTINGENCY (30%)	69
TOTAL	300

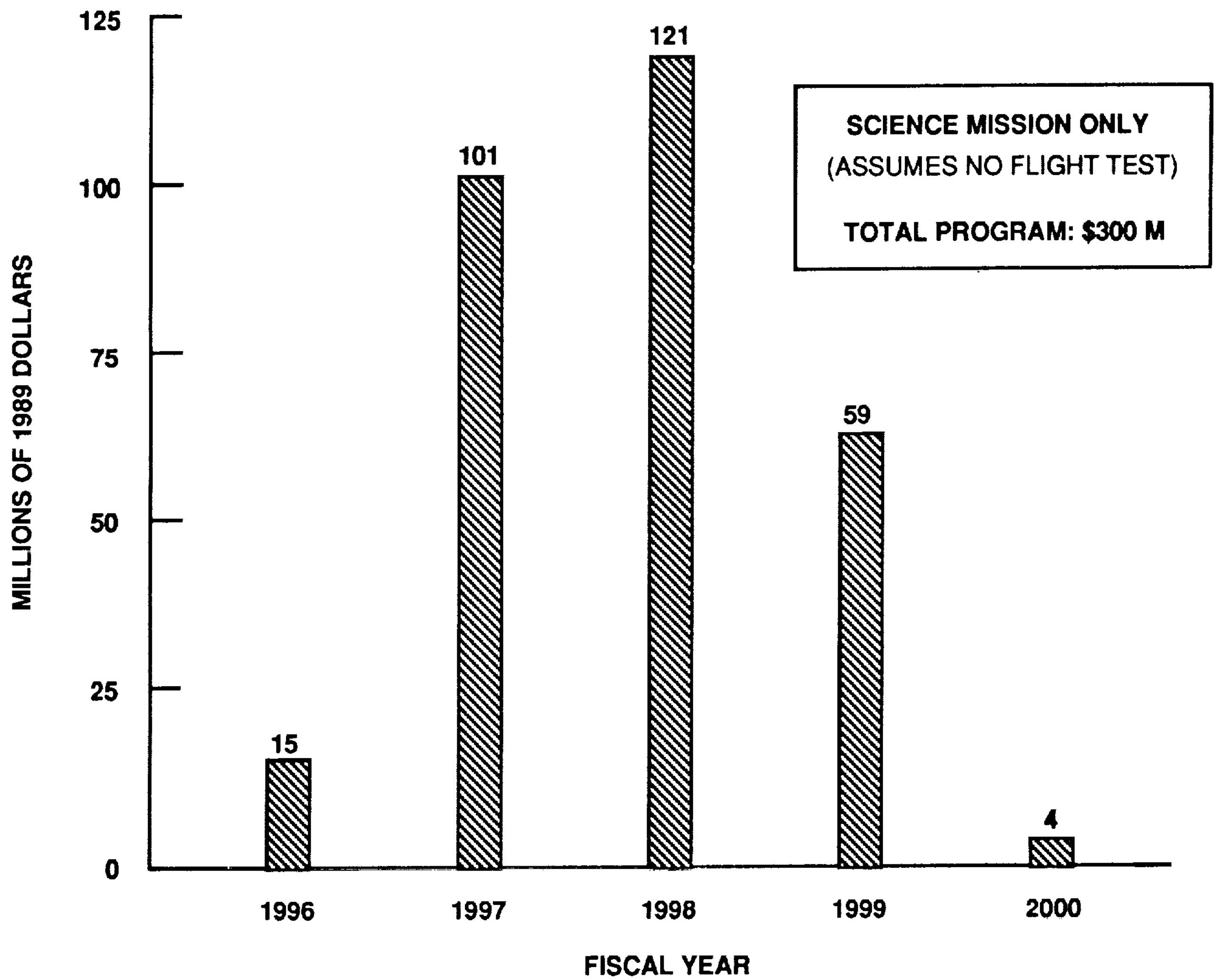


Figure 11. SGGM funding schedule.

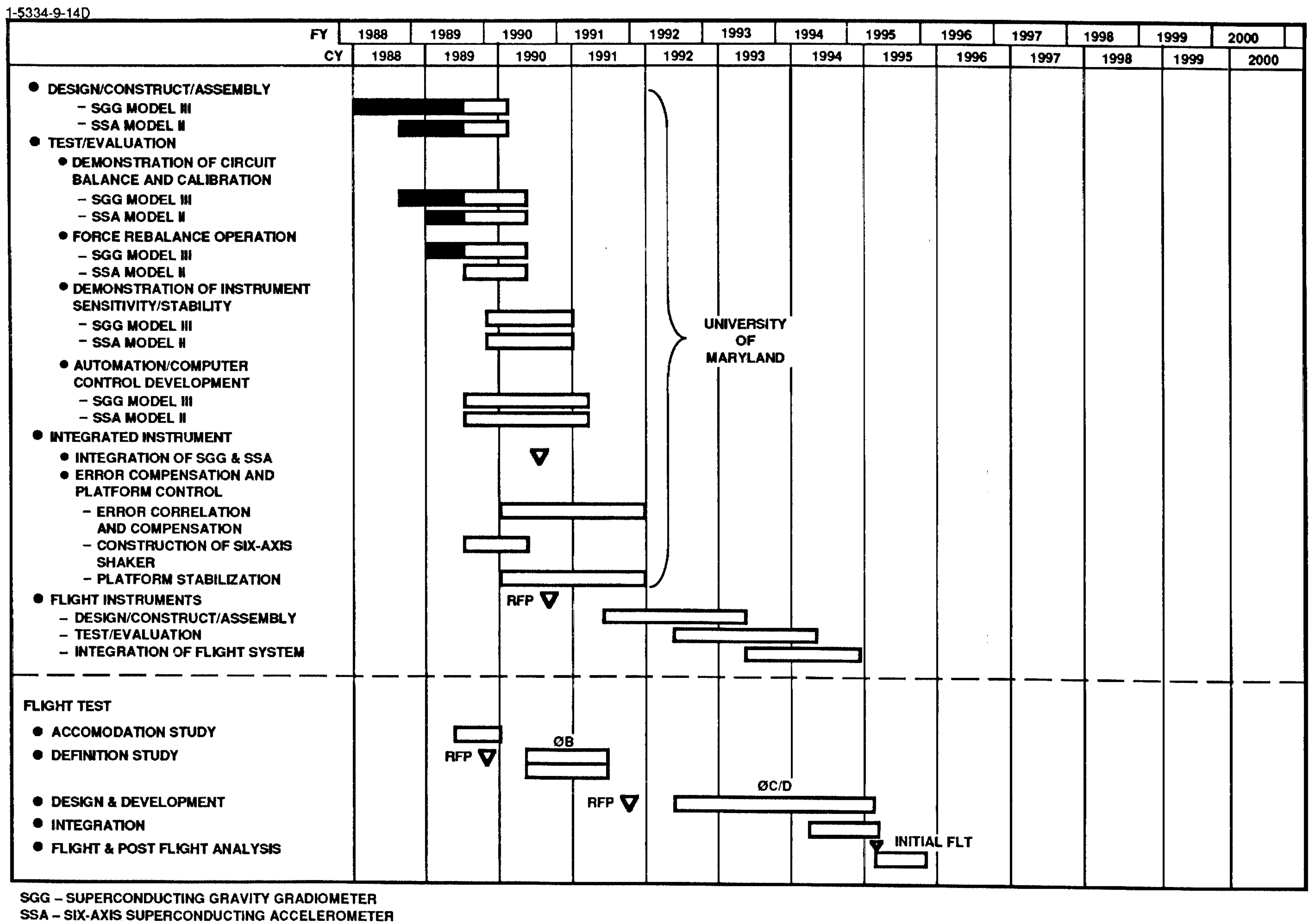


Figure 12. SGGM Instrument Development and Flight Test schedules.

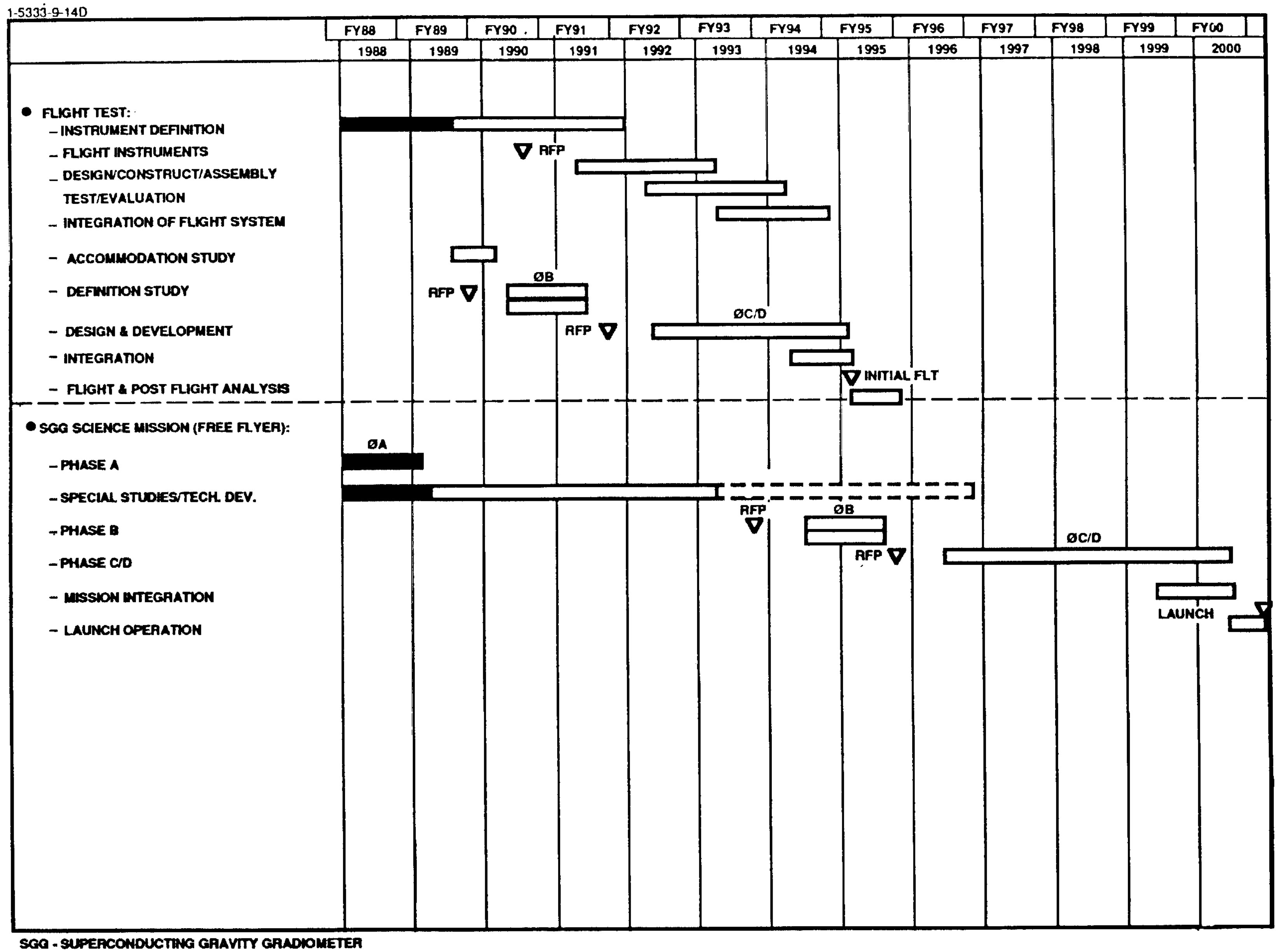


Figure 13. SGGM program schedule.

8.0 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

Program: The SGG is a substantial advance over present technology. Significant progress is being made in the development of the instrument, and no fundamental barriers to the delivery of an instrument with the required sensitivity were found. However, instruments of the SGG class present particular problems. For example, a more demanding instrument, but of the same general class, the GP-B, has been under development for more than 20 years. In general, instruments of the SGG class present quite long development times, and high technical risks. The SGGM program must take care to minimize these risks to the greatest extent possible.

While the primary (geophysics) and secondary (physics) mission objectives are not mutually exclusive from a mission standpoint, the more severe requirements for the secondary mission objectives indicate that a separate mission may be necessary to accomplish the physics experiments.

A precursor flight test of the SGG, while adding more expense to the program, is nevertheless vitally important in order to verify that the key elements of the science payload will meet the mission requirements, and to reduce overall mission risks.

Instrument: The SGG and the SSA under development at the University of Maryland should meet the sensitivity requirement for SGGM. While the SGG is the primary instrument which measures gravity signals, the SSA will also be a necessary component of the instrument since its outputs will likely be used to control the attitude of the Experiment Module and the spacecraft drag compensation system.

While the primary (geophysics) mission objective requires measurement of any single component of the gravity gradient, redundancy in measurement is desirable. The secondary (physics) mission objectives require measurement of three orthogonal in-line component gradients.

Common-mode acceleration balance of the gradiometer and attitude control of the instrument are among the most demanding requirements for SGGM. By isolating the Experiment Module from the spacecraft, one should be able to decouple the instrument from the expected high mechanical noise level of the carrier. Helium boiloff gas could be used to obtain fine control of the attitude and position of the Experiment Module within the outer spacecraft. Transmitting power and signals between the outer spacecraft and Experiment Module with minimum mechanical coupling needs further investigation.

Mission: For geophysics applications, either an Earth-fixed or inertial orientation appears acceptable at this time. Refined future analyses will determine which of the two orientations offers definitive advantages. Likewise, further studies are needed to decide which orientation will give best resolutions for tests of the laws of physics.

In these initial studies, an orbital altitude of 200 km is a reasonable compromise between desires for high resolution and minimum aerodynamic drag.

A Shuttle attached flight test, even with some type of soft mounting, probably will not meet all the desired objectives of the flight test. A free-flying mode would be ideal scientifically, but would likely be considerably more expensive unless an existing carrier can be utilized. A controlled, free-floating mode inside the Shuttle cargo bay may be an acceptable alternative.

Other potential carriers that were examined, i.e., Space Station, EOS platform, and TSS, are not viable options.

Spacecraft Systems: The limited analysis of the ACS performed thus far did not indicate any behaviors of the system that would preclude the feasibility of the SGGM. This conclusion, however, must be qualified by a listing of those potentially important effects which have not yet been investigated. Effects due to sensor noise or dynamic characteristics have not yet been included. Neither have self and mutual gravity effects. No sensor complement, which is necessary to define ways in which accelerometers, rate gyros, star trackers, and perhaps the GPS may be used together to control the system to the required levels of accuracy, has been established.

In order to provide the required gentle RCS for drag compensation, ion propulsion offers many advantages. However, serious disadvantages such as large power requirements and the attendant need for large solar arrays, make this approach less attractive. On the other hand, it is not clear that a hydrazine system can provide the thrust levels necessary to compensate for the drag imposed at the low mission altitude, and yet be gentle and controllable enough to meet the low instrument acceleration requirements. This area is closely related to instrument isolation. Primary RCS by helium boiloff, as utilized by GP-B, is not feasible. However, vernier control of the Experiment Module appears to be feasible.

Successful experience with cryogenic systems in space indicates that no barriers to the development of an acceptable superfluid helium dewar system should occur.

The SGGM power, thermal control, and C&DH system requirements can be met with state-of-the-art systems.

Modification of the GRM design to accommodate SGGM does not appear to be a viable option. A new spacecraft design, with some of the subsystems similiar to GRM, is required for the SGGM.

8.2 Recommendations

Program: A Phase A study of the flight test mission should be initiated as soon as possible to resolve issues beyond the scope of the current study, to further refine a preliminary design of the systems, and to provide schedules and cost estimates.

The physics experiments would provide important contributions to knowledge and should be actively pursued through the physics community and the NASA program organizations having responsibility for this area.

Instrument: Development of the SGG, SSA, and associated electronics should be accelerated. The operations of these instruments should be brought under computer control and be automated.

Instrument error analysis, including dynamic error analysis, should be continued. Error compensation techniques should be developed.

Details of ground test requirements should be formulated.

Mission: Analyses of the flight test mission in detail, including isolation techniques (attached, suspended, or free flyer); measurements required; calibration, alignment, and pointing techniques/requirements; time history in orbit; environmental monitoring, should be conducted. An upgraded version of the laboratory SGG should be considered as the flight test instrument.

A Phase B study of the SGGM should be initiated as soon as the availability of resources permit.

Detailed trade studies of the mission altitude, inclination, ground retrace pattern, and duration, versus science return should be made.

Simulation of the control system should be continued. This should include a high fidelity model of the vehicle dynamics, external and internal disturbances, and instrument noise, to generate power spectral densities for the various attitude and linear velocities and accelerations, orbit variations, and other disturbances. Controller effects such as sampling and quantization should also be included.

A detailed analysis of instrument isolation techniques should be made. This should include, among other possibilities, eddy current forcing and helium boiloff control of the floating Experiment Module, as well as various soft mounting approaches.

Total error analysis including the instrument, internal and external disturbances, and all spacecraft systems should be developed as soon as possible.

Techniques for utilizing and controlling helium boiloff should be investigated further. This technology, now being developed for GP-B, should be closely followed.

REFERENCES

1. McNutt, M.K. and Flinn, E.A. (editors): "Geophysics and Geodetic Requirements for Global Gravity Field Measurements 1987–2000, Report of a Gravity Workshop." NASA, Colorado Springs, CO, February 1987.

2. Committee on Earth Sciences: "A Strategy for Earth Science from Space in the 1980s; Part I: Solid Earth and Oceans." National Academy of Sciences, National Academy Press, Washington, DC, 1982.

3. Taylor, P.T., Keating, T., Kahn, W.D., Langel, R.A., Smith, D.E., and Schnetzler, C.C.: "GRM: Observing Terrestrial Gravity and Magnetic Fields in the 1990s." EOS, Vol. 64, No. 43, 1983, pp. 609–611.

4. Metzger, E.H. and Allen, D.R., Bell Aerospace Company Report 9500-92044, 1972.

5. Wells, W.C., (editor): "Spaceborne Gravity Gradiometers." NASA Conference Publication 2305, Greenbelt, MD, 1983.

6. Morgan, S.H. and Paik, H.J. (editors): "Superconducting Gravity Gradiometer Mission Volume II: Study Team Technical Report." NASA TM-4091, November 1988.

7. Paik, H.J.: "Tests of General Relativity in Earth Orbit Using a Superconducting Gravity Gradiometer." Advances in Space Research (in press).

8. Moody, M.V., Chan, H.A., and Paik, H.J.: "Superconducting Gravity Gradiometer for Space and Terrestrial Applications." Journal of Applied Physics, Vol. 60, No. 12, 1986, pp. 4308–4315.

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
NASA TM-4091		

4. TITLE AND SUBTITLE	5. REPORT DATE
Superconducting Gravity Gradiometer Mission - Volume I: Study Team Executive Summary	August 1989
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Edited by Samuel H. Morgan and Ho Jung Paik,*	8. PERFORMING ORGANIZATION REPORT #
9. PERFORMING ORGANIZATION NAME AND ADDRESS George C. Marshall Space Flight Center Marshall Space Flight Center, Alabama 35812	10. WORK UNIT NO. RTOP 676-59-33
	11. CONTRACT OR GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Office of Space Science and Applications National Aeronautics and Space Administration Washington, D.C. 20546	13. TYPE OF REPORT & PERIOD COVERED Technical Memorandum
	14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

Prepared by Program Development Office.
*Department of Physics and Astronomy, University of Maryland, College Park, MD 20742.

16. ABSTRACT

This report is an executive summary based upon the scientific and engineering studies and developments performed or directed by a Study Team composed of various Federal and University activities involved with the development of a three-axis Superconducting Gravity Gradiometer integrated with a six-axis superconducting accelerometer. This instrument is being developed for a future orbital mission to make precise global gravity measurements. The scientific justification and requirements for such a mission are discussed. This includes geophysics, the primary mission objective, as well as secondary objectives, such as navigation and tests of fundamental laws of physics, i.e., a null test of the inverse square law of gravitation and tests of general relativity. The instrument design and status along with mission analysis, engineering assessments, and preliminary spacecraft concepts are discussed. In addition, critical spacecraft systems and required technology advancements are examined. The mission requirements and an engineering assessment of a precursor flight test of the instrument are discussed.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
Geodesy, Geodynamics, Gravity, General Relativity, Gradiometers, Accelerometers, and Superconductivity	Unclassified – Unlimited Subject Category: 46

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified	44	NTIS

MSFC - Form 3292 (Rev. December 1972)

For sale by National Technical Information Service, Springfield, Virginia 22151