Research Relative to the Development of a

Cryogenic Microwave Cavity Gradiometer for Orbital Use

NASA Grant NAG5-338

Semiannual Report No. 3

For the period 1 July 1984 through 31 December 1984

Principal Investigator

Dr. Mario D. Grossi

December 1984

Prepared for
National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland 20771

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
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The NASA Technical Officer for this Grant is
Mr. Jean E. Welker, Code 921, Earth Survey
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(NASA-CR-174249) RESEARCH RELATIVE TO THE DEVELOPMENT OF A CRYOGENIC MICROWAVE CAVITY GRADIOMETER FOR ORBITAL USE Semiannual Report, 1 Jul. - 31 Dec. 1984 (Smithsonian Astrophysical Observatory) 34 p

N85-16095

Unclas

G3/35 13040

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ACKNOWLEDGEMENTS

This report has been written by Dr. Enrico Lorenzini and by Dr. Mario D. Grossi.

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Summary

We have continued the investigation of the non-cryogenic, single-axis, gravity gradiometer characterized by a sensitivity of the order of 10^{-2} Eövös Units in a few sec integration time. We have expanded our initial analysis of the feasibility of the testing of the prototype of this gradiometer on the earth surface by the method of free-fall in vacuo.

We have inspected an existing free-fall tower facility available at NASA-MSFC and we have studied the possibility of adding inside the falling elevator-cabin an air-tight, sealed, cylindrical container with inside pressure $\lesssim 10^{-3}$ Torr. The gradiometer can thus be tested in free-fall conditions inside this evacuated container. Earth's gravity anomalies can be simulated with masses of suitable shape, weight, and location. The attitude of the falling gradiometer can be monitored by a three-axis gyro package mounted on the instrument package. Residual components due to the combined effect of rotation and fabrication errors can be compensated by post-test data processing.

We have concluded that the free-fall testing of the gradiometer is both feasible and practical, and should be carried out under a separate contractual support.

1.0 Introduction

In our previous report (Semiannual Report #2 dated July 1984, on NASA Grant NAG5-338), we pointed out that a non-cryogenic gradiometer with sensitivity of $\sim 10^{-2}$ EU in a few seconds integration time (see Section 2.7 of Semiannual Report #2) was the most practical approach to satisfy an orbital requirement of imminent formulation: the measurement of the gradiometric noise on-board the second demonstration flight of the Tethered Satellite System (TSS). This second mission is presently scheduled for Summer 1989. In the same report (see Section 2.9) we also outlined a free-fall testing approach, as a method that could be quickly implemented (thus, be compatible with the schedule of the TSS opportunity) and that, potentially, was offering adequate sensitivity for a meaningful verification, to be conducted on the ground, of the instrument sensitivity. The championing by our Observatory of the non-cryogenic instrument as the most attractive sensor for a first orbital testing of a gravity gradiometer is not a recently acquired posture.

At the Workshop on Spaceborne Gravity Gradiometers held at NASA-GSFC, 28 February - 2 March 1983[1], SAO and IFSI-CNR recommended, in fact, to invest a developmental effort on non-cryogenic instruments, initially single-axis mechanizations, with sensitivity of the order of 10^{-2} EU with a few second integration time, using a displacement sensor consisting of a condenser probe followed by a low-noise FET preamplifier. One of the rationales for this recommendation was that non-cryogenic instruments are the only ones capable to fly on board a potentially suitable, and already approved space mission such as the second Demonstration Flight of the Tethered Satellite System (TSS), scheduled to be launched in 1989. By installing the gradiometer in a tethered subsatellite deployed downward from the Shuttle, the observing height can be made as low as 120 km, with consequent ability, for an instrument with sensitivity of the order of 10^{-2} EU (assuming that the tether-induced dynamic noise can be kept under check), to detect and measure gravity anomalies having an intensity of ~ 1 milligal[2,3,4] (resolution ~ 111 km, sampling rate 1 measurement/sec). Another rationale for the SAO/IFSI position at the Workshop was that the recommended initial step above would be an effective beginning for a development activity that would lead logically to instruments with sensitivity of the order of 10^{-4} to 10^{-5} EU, by cooling down the sensor to liquid helium temperatures, and by replacing the condenser probe/FET preamplifier with a superconducting microwave cavity. In the almost two years that have passed since the Workshop held in Spring 1983, several developments have taken place that have reinforced the SAO/IFSI posture. These developments are:

1) It has been decided by NASA that the dynamic noise induced by the tether on a tethered subsatellite will be measured starting from the first demonstration flight of the TSS missions, now scheduled for December 1987. In this first flight, accelerometric noise on board the subsatellite will be determined with three linear accelerometers and three gyros, which are part of the so-called CORE instrumentation provided by NASA/PSN to the selected investigators. Although the sensitivity of these instruments is insufficient to establish whether or not the tethered subsatellite environment is benign enough to be suitable for gravity gradient measurements (even at the 10^{-2} to 10^{-3} EU level), they will provide important information to design dynamic dampers/filters for the tethered systems of later flights, in order to minimize this induced noise. The second demonstration flight will be the first opportunity to measure

directly (after this damping/filtering) the induced gradiometric noise, with a gravity gradiometer. The non-cryogenic model investigated in the course of our study on contract NAG5-338 should be the instrument that flies in this second TSS mission. A proposal to this effect[5] has been already submitted in response to TSS AO OSSA-1-84;

2) IFSI-CNR has started in early 1984 the construction of the mechanical subsystems, of the condenser probe, of the balancing bridge, and of the FET low-noise preamplifier, aiming at a non-cryogenic, single-axis instrument with 10^{-2} EU sensitivity with a few seconds integration time. In September 1984 they had already completed this development and had started its testing in their laboratory, with promising results;

3) At SAO, while working on NASA Grant NAG5-338 during FY 84, the PI for this Grant (M.D. Grossi) proposed the use of a free fall approach for the measurement, on the Earth surface, of the sensitivity of a gravity gradiometer, at least at a level of 10^{-2} EU $\tau^{-1/2}$ (where τ is the integration time), but possibly even at more ambitious sensitivity levels. The Semiannual Report #2 on the above mentioned Grant, dated July 1984, gave in Section 2.9 (pages 43-51) the preliminary analytical proof of the measurement's feasibility[6]. The value of the method resides on the possibility of eliminating to a great extent the effect of vibrations and seismic oscillations on the instrument under testing (the resonant frequency of the instrument can be easily filtered out). These results were presented to NASA-OSSA-Geodynamics Programs, by the project team, on 8/16/84[7];

4) At the suggestion of Mr. Thomas Fischetti, SAO searched for the possible existence of a suitable free-fall facility at various NASA Centers. A 380′ drop-tower that looked suitable from preliminary information, was identified at NASA-MSFC. On September 25, 1984 a group from SAO Central Engineering also including Dr. Enrico Lorenzini visited the facility at MSFC. SAO found that the MSFC drop-tower is close to what is required (see Appendix I). The most relevant addition that we need is to install inside the falling elevator-cabin an air-tight cylindrical container (with inside pressure $\leq 10^{-3}$ Torr), complete with the related vacuum equipment (most of which is available already at MSFC). Most of the radio link units necessary to establish a wireless connection between the falling gradiometer and the "receiving/recording station" are already available at the MSFC drop-tower facility.

On the strength of these recent favorable developments, SAO has continued, with NASA concurrence, the investigation under the sponsorship of NAG5-338, of the 10^{-2} EU non-cryogenic gradiometer and of the free-fall, drop tower testing method. The latter compares favorably with other testing alternatives, such as a rocket flight (that would require a minimum of two and one half years effort and a budget in the several hundreds thousand dollars), or an orbital flight (that would require a minimum of 4 years effort and a budget in the few million dollar category). We expect that the ground-based free-fall testing approach can be made, with further efforts, capable of testing instruments in the 10^{-3} EU sensitivity class and possibly beyond. This would make it possible to concentrate the development work (even for the most ambitious gradiometers), to a low-cost ground-based activity, and to leave to the orbital flights the role and mission that truly belongs to them: the performance of scientifically useful global surveys, in our case the survey of the earth crust gravity anomalies.

2.0 Technical Discussion

2.1 General

The progress made recently by SAO and IFSI-CNR in their joint activity for gravity gradiometer development/testing has reached a point that we now see within reach the completion of the construction of a non-cryogenic 10^{-2} EU $\tau^{-1/2}$ prototype and its testing and calibration in an existing ground-based facility.

This substantial step forward is not only an important milestone toward cryogenic instruments of more ambitious sensitivity, but it represents also, in itself, an accomplishment that is immediately usable to satisfy a forthcoming orbital flight requirement. This is the measurement of the <u>gradiometric</u> <u>noise</u> on board the second T.S.S. demonstration flight, scheduled by NASA for Summer 1989. What is required in this flight is a simple, non-cryogenic instrument, either single-axis or multi-axis, suitable for system integration in the tethered subsatellite. The TSS subsatellite represents a modest accommodation facility and could not house any bulkier instrument. For instance, it can not accommodate a $\sim \frac{1}{2}$ m^3-to-1 m^3 cryostat, the container that would become necessary when operating a cryogenic gradiometer. The non-cryogenic instrument is the practical approach for achieving the following objective: determining the suitability of the tethered subsatellite (from the standpoint of the tether-induced dynamic noise) for the performance of gravity gradient measurements of scientific relevance, such as the detection and measurement of small-size anomalies in the earth crust. The scientific advantages of performing observations from an altitude as low as 120 km (as it is allowed, in principle, by the use of the tethered subsatellite) justify an effort aimed at the verification that the dynamic environment on board that subsatellite is sufficiently benign.

2.2 Evolutionary Approach to Gravity Gradiometer Development

The sensitivity gap between present-day instruments (with threshold of about 10^{-1} EU in a few seconds integration time) and the ultimate instrument for orbital use in a geodynamics mission (with required threshold of the order of 10^{-4} to 10^{-5} EU, again in a few seconds integration time) is clearly very wide. As we have mentioned in the previous sections of this report, there is the possibility that the requirement for the orbiting instrument's sensitivity might be relaxed if it will be experimentally verified that the dynamic noise on-board the tethered satellite of the TSS facility is low enough to make possible the conduct, from that platform, of high-sensitivity gravity gradiometer measurements. The fact is that the tethered satellite (if deployed downwards from the Shuttle, it could reach an altitude as low as 1[illegible] to 130 km) would relieve substantially the sensitivity requirement to be imposed on the instrument. However, until this proof is obtained, we must still consider as a requirement a sensitivity of the order of 10^{-4} to 10^{-5} EU in a few seconds integration time (when aiming at meeting all scientific objectives of NASA Geodynamics Program). It appears that starting from the development of a non-cryogenic, single-axis, instrument in the 10^{-2} EU range is a worthwhile beginning of an evolutionary approach that will ultimately lead to cryogenic, multi-axis, sensors at the upper end of the sensitivity scale under consideration. Table I shows a progression of instruments with the correspondent type of geometric displacement sensors that is required to achieve the indicated sensitivity in $EU\tau^{-1/2}$.

Table I

DESIGN PARAMETERS OF HIGH-SENSITIVITY GRADIOMETERS

Gradiometer Sensitivity (EU)	Integration Time (sec)	Temperature (K)	Proof Mass (g)	Baseline Length (cm)	Mechanical Q	Angular Resonance (rad sec^{-1})	Force Acting on oscill. (dyne)	Geometric Displacem. produced by force (cm)	Type of Displacement Sensor
10^{-2}	10	300	$5 \cdot 10^{2}$	100	10^{5}	20	$5 \cdot 10^{-7}$	$2 \cdot 10^{-12}$	condenser probe
10^{-2}	10	300	$5 \cdot 10^{4}$	100	10^{4}	200	$5 \cdot 10^{-5}$	$2 \cdot 10^{-14}$	" "
10^{-3}	10	4	10^{5}	200	10^{4}	100	$2 \cdot 10^{-5}$	10^{-14}	" "
10^{-4}	10	4	10^{5}	200	10^{4}	100	$2 \cdot 10^{-6}$	10^{-15}	microwave cavity
10^{-5}	10	4	10^{5}	200	10^{5}	100	$2 \cdot 10^{-7}$	10^{-16}	" "

To summarize, in a nutshell, the merits of the evolutionary approach, we can say the following:

a) if the tethered subsatellite will be proven useable for geodynamic surveys, we have already, from performing the first step, an instrument with sufficient sensitivity to meet the space mission requirements;

b) if the opposite turns out to be true, we can proceeds to develop more sophisticated instruments from the vantage point of having a non-cryogenic solution already worked out.

While developing sensors with greater and greater sensitivity, the free-fall approach could be correspondingly improved, in order to match the testing requirements. In the following sections we report on the recent investigations that we have carried out for the first step in this evolution: design and development of a 10^{-2} EU gradiometer and its free-fall testing in an existing drop-tower.

2.3 Development of the Non-Cryogenic Instrument with Sensitivity in the 10^{-2} EU Class

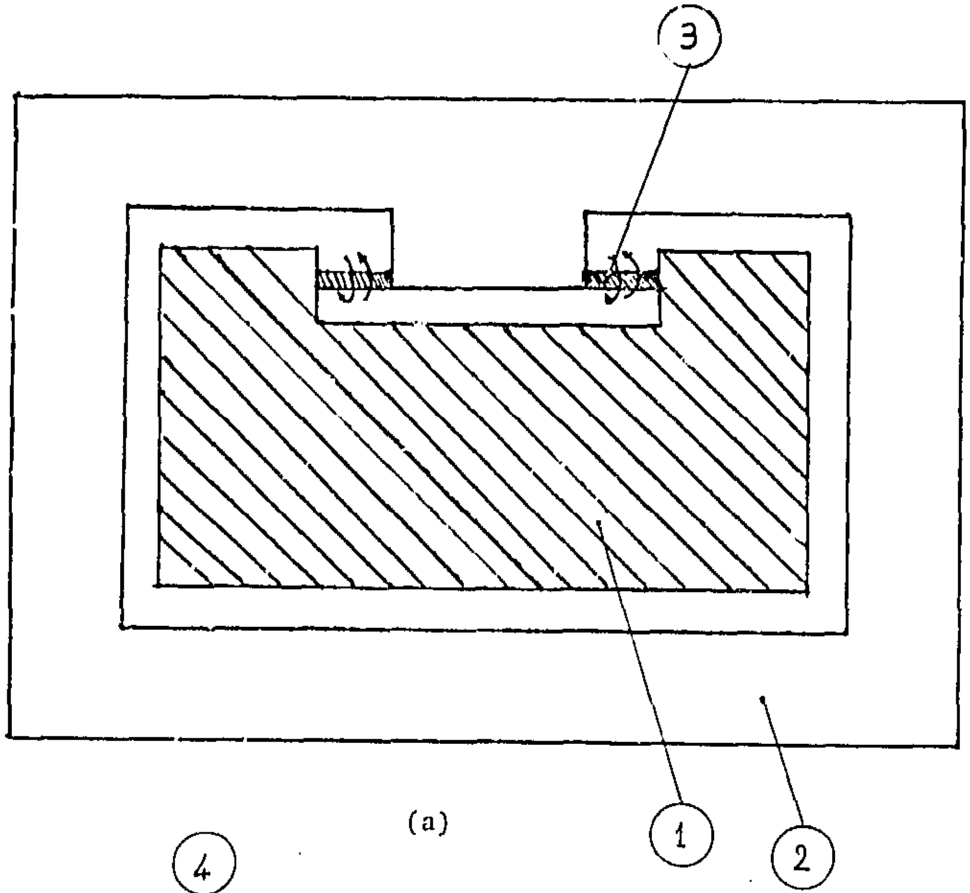
This is a joint effort of SAO and IFSI-CNR, Frascati, Italy. In Frascati, IFSI-CNR has initiated in Spring 1984 the construction and laboratory testing of the non-cryogenic, single-axis, gravity gradiometer with sensitivity goal 10^{-2} EU in a few seconds integration time. This gradiometer uses a condenser probe as displacement sensor. This consists of a rectangular plate attached to a rigid frame by crank-shaped suspensions, all machined from a single block (see Figure 2.1). Forces acting on the device cause accelerations of the proof mass corresponding to torsion of the suspension. In this way low resonance frequency and high

1 - Sensing Mass

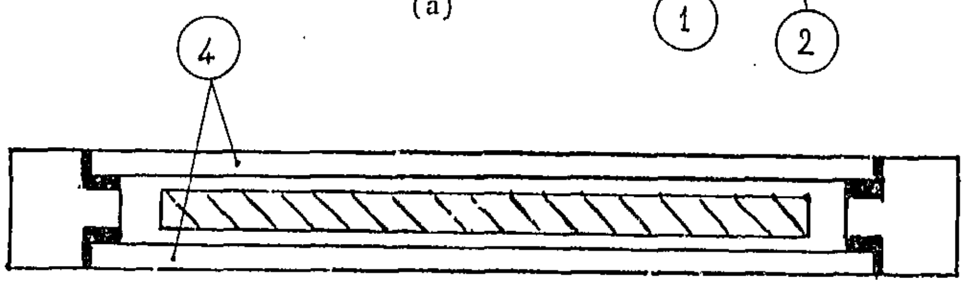
2 - Cage

3 - Suspension

4 - Cover



(a)



(b)

Figure 2.1
Condenser Probe Conceptual Design
(a) Plan View; (b) Front View

mechanical Q are both possible. As displacement sensor, two series capacitors are used, of which the moving mass constitutes the common plate. The other two plates are mounted on opposite sides and are attached to the rigid frame. The spacing between successive plates is approximately 30 μm. The gravity-gradient signal-frequencies of interest are around 0.1 Hz. We expect that at these low frequencies the noise temperature of the amplifier (FET) is as high as a few degrees K, almost two orders of magnitude higher than at acoustic frequencies. To avoid this problem and to keep the amplifier noise at its lowest value, the capacitive probe is used as a branch in a AC bridge which has the source in one diagonal and the signal pick-up on the other (Figure 2.2). The frequency of the pump is around 1 kHz. Noise due to phase and amplitude fluctuations of the source is not very critical since these fluctuations, as past experience has shown, give a contribution in terms of voltage noise of the order of $1 nV/\sqrt{Hz}$ which is further reduced by at least 100 db by balancing the bridge. The double-face configuration of the capacitive sensor will, on the other hand, compensate for the back-action due to the resulting current fluctuations in the four branches of the bridge. With a mass of the sensor of 0.5 kg and a resonance circular frequency $\omega_o = 20\ sec^{-1}$, the expected sensitivity is of the order of 10^{-2} EU in 10 second integration time and with a baseline length of 1 m. To enhance the dynamic range of the system and to finely-tune to each other the scale factor of the accelerometer, the fixed plates of the probe are split in two mutually isolated parts, one serving as probe, the second as part of a feedback loop through which a proper dc voltage, i.e. a force, is supplied. In this way accelerations of the order of 10^{-1} g can be tolerated. The feedback loop is driven by the output signal from the bridge and is also used to short-circuit the system when the acceleration is so strong to bring the plates of the capacitor in

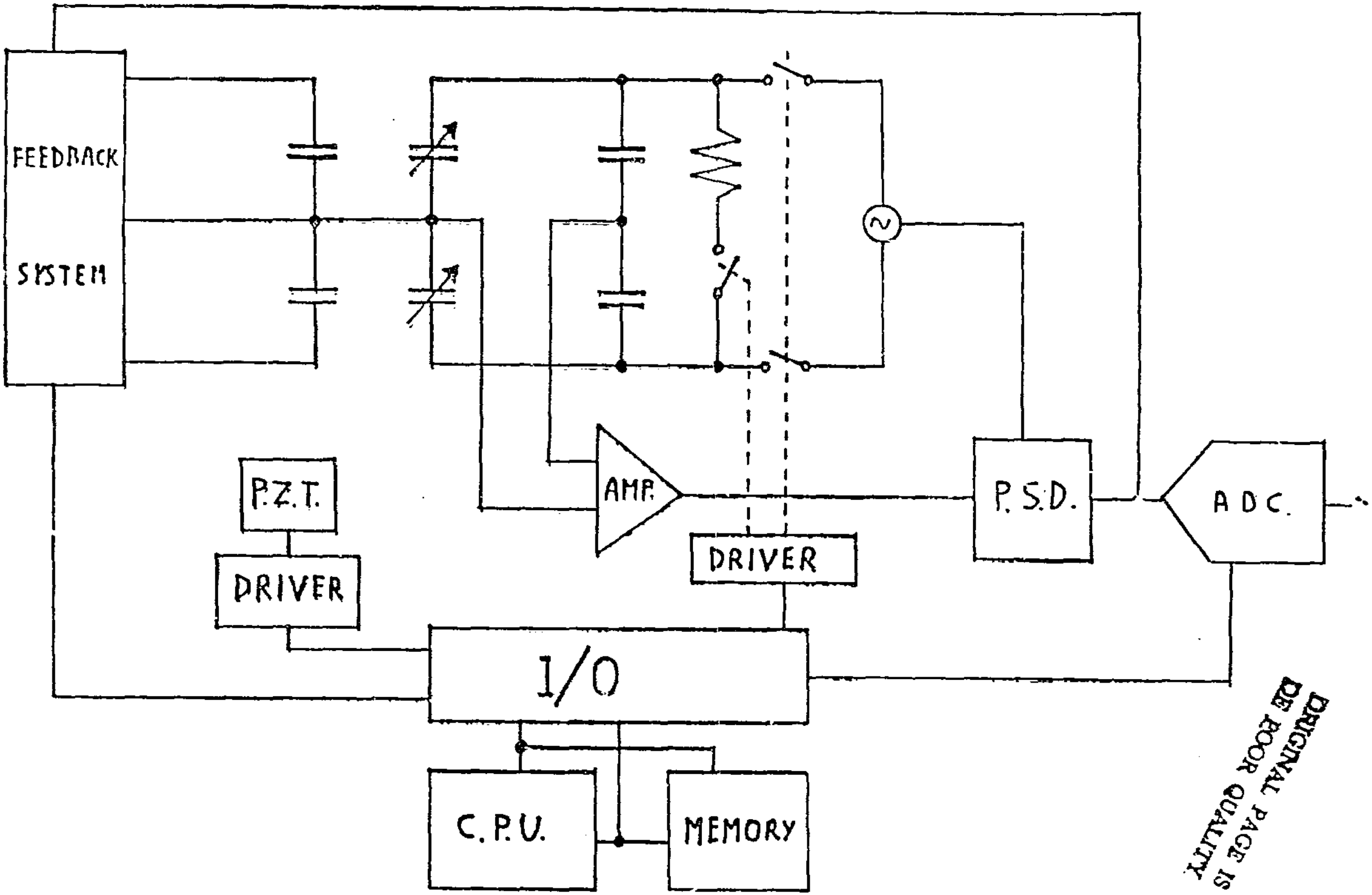


Figure 2.2

contact. A possible configuration of the gradiometer in the satellite is to mount the accelerometers on a baseline parallel to the z axis (vertical) with sensitive axis normal to it (say along y axis), that is to measure the Γ_{zy} component of the gradient. These have the advantage to strongly reduce problems due to the gradient of the spherical earth, and those due to steady rotation of the spacecraft mainly considering the dynamic range of the instrument.

During September 1984, the development at IFSI-CNR of the single-axis instrument was completed. Laboratory tests have already shown that high Q and low resonance frequency have been indeed achieved. The output of the amplifier that followed the FET low-noise preamp is of the order of millivolts, on an impedance of 600 ohm. We require therefore further amplification and signal conditioning, in order to match the input signal requirements of the modulator/transmitter available at the drop-tower facility of NASA-MSFC. The completion of the required subsystems will be performed at SAO.

The plan that we have developed calls for complementing at SAO the single-axis gravity gradiometer provided by IFSI with the following subsystems: a) A container package to accommodate the gradiometer and the relevant instrumentation; b) A power amplifier to feed the modulator/transmitter; c) A gyro package to measure the angles and the angular rates of the instrument package during the free-fall tests, that we expect to perform at the drop-tower facility of NASA-MSFC.

The container package is a rigid metal structure capable of accommodating the instrument in the middle. The overall external dimensions will not exceed 1 m x 0.7 m x 0.7 m (height x width x length).

It will be well balanced in the sense that the c.g. of the instrument package will be as close as possible to the instrument c.g. and it will be symmetrically located with respect to the instrument package supports touching the ground. Preliminary estimation of the effects of balancing and fabrication errors are given in Appendix II.

The power amplifier is required to complete the interface between the FET amplifier and the modulator/transmitter already available at the drop tower facility of MSFC. A three axis gyro package, mounted on the instrument package, is necessary to monitor the attitude and the angular rates of the instrument during the fall.

The instrument has a good geometrical rejection of the centrifugal acceleration because the two sensing masses are radially mounted (tangential sensitive axis) and therefore theoretically insensitive to radial acceleration. Nevertheless, due to parallelism errors and to the alignment errors of the sensing masses with respect to the instrument package c.g., unbalanced components of spurious tangential accelerations are produced by a non zero angular rate.

The attitude of the instrument must be also monitored. A departure from the vertical alignment through a pitch and a roll (or vice versa) rotation makes the instrument to measure a component of the vertical gravity gradient due to the Earth (for further details on these issues see Appendix II). Attitude and angular rates must therefore be known with an accuracy (per each axis) that has been preliminary estimated as follows:

- Angular rates	better than	0.01 DEG/SEC	
- Angles	better than	0.05 DEG	(2.1)

The dynamic range is limited to few degrees per sec. The measurement time is limited to few seconds so that drift problems are irrelevant. The gyro package has moreover the advantage to operate in a very low-g environment so that g-dependent errors are canceled out. Gyros produce however small amplitude high frequency disturbances because of unbalances of the spinning mass. The resulting accelerations are however at a frequency far away from the measurement frequency range and can be easily abated by a visco-elastic suspension. Note also that the common mode rejection of the instrument, as presently designed, is of the order of 1/60000. The gyros provide an inertial attitude measurement and the output should be therefore corrected by the Earth rotation. With a measurement time of 4 sec the swept angle is around 0.01 DEG at the latitude of Huntsville, AL. Data from the gyros will be time correlated to the data of the gradiometer. Correction of errors due to attitude variations will be performed in the post-test analysis of the data.

2.4 Free-Fall Testing of the Gravity Gradiometer at the NASA/MSFC Drop-Tower Facility

As mentioned in the introduction, SAO has looked for, and found, an already existing and operating drop-tower to perform free-fall experiments. Such drop-tower is located at the NASA Marshall Space Flight Center (MSFC) in Huntsville, AL. A more detailed description of the tower is given in Appendix I. In summary, the tower consists of an elevator, drag shielded and accelerated by thrusters, falling along two vertical rails. The free-fall drop is 293.8 feet long that corresponds to a time of 4.3 sec available to collect data. At the bottom, the elevator is decelerated in the last 20 feet by a sort of air piston. The tower is equipped (see Appendix I) with everything necessary for the experiment: power supply, batteries, data transmitter and receiver, data storage devices. Two high speed movie cameras are also available to monitor the package's attitude during the free fall. These cameras are located inside the elevator. We think however that, owing to the random vibration of the elevator cabin during the fall, attitude measurement accuracy required by our instrument cannot be provided by these cameras. The gyro package mounted on the instrument package provides, on the contrary, an adequate inertial attitude measurement.

The elevator cabin is not air tight. Since we want to reduce as far as possible the external dynamic noise, we require an additional air-tight cylinder with an available internal space of 48 in. diameter x 60 in. height. This cylinder will be fixed to the elevator cabin. It will be easily accessible (from the top) and replaceable, in order to allow operations on the gravity gradiometer between different tests. The cylinder will be evacuated, before initiating the test, to a residual pressure that is presently estimated to be 10^{-3} torr. The required pumps are available at the tower and, if necessary, even better pumps can be provided by MSFC.

Signals from the output of the gyros, gradiometer data and other housekeeping functions (battery voltage/current, temperature etc.) must be transmitted by wireless radio link from the instrument package to the data collection system via an intermediate relay station, located on the cylinder shell.

The initial tests at the MSFC drop-tower facility will be performed with a scaled down version of the TSS instrument above that was illustrated in Section 2.3. However, while tests do progress, the performance of the gradiometer prototype will be enhanced toward the TSS model. The initial prototype, to be tested at MSFC, will be characterized by the following design parameters:

- Baseline $\ell = 50$ cm
- Resonance Frequency $f_o = 20$ Hz ($\omega_o = 125.66\ \text{sec}^{-1}$)
- Operating Temperature $T = 300^oK$
- Noise Temperature of FET Amplifier $T_n = 0.1^oK$
- Quality Factor $Q = 10^5$
- Sensor Mass $m = 3 \times 10^2$ gr
- Ratio $\frac{\Delta f}{\omega_s}$

  $\left(= \frac{\text{measurement bandwidth}}{2\pi\text{signal frequency}}\right) \quad \frac{\Delta f}{\omega_s} = 1$
- Integration Time $t_{int} = 0.1$ sec
- Measurement Bandwidth

  $\Delta f = \frac{1}{t_{int}}, \quad \Delta f = 10$ Hz
- Signal Frequency

  $f_s = \frac{\omega_s}{2\pi} = \frac{\Delta f}{2\pi}, \quad f_s = \frac{10}{2\pi} = 1.59$ Hz

With this initial design parameters for the gradiometer prototype, the sensitivity will be:

$$\Gamma = 7.6 \times 10^{-1} \text{ EU in 0.1 sec integration time.}$$

The most effective way of improving on this score will consist of lowering the resonance frequency f_o of the instrument by the use of an electric feedback acting as a negative spring between the condenser plates. The prototype for ground testing is of a smaller size because of the limited space available, it has a higher resonance frequency in order to increase the dynamic range, and has a much shorter integration time.

We expect that it will be possible to improve the instrument sensitivity toward the goal of $\sim 10^{-1}$ EU in 0.1 sec integration time. This instrument will therefore be potentially suitable, as it is, to conduct tests in the TSS to a level of sensitivity of $\sim 4.7 \times 10^{-2}$ EU in approximately 1.6 sec integration time.

Concerning the temperature control of the instrument, we have reached the initial conclusion that, should this become a serious issue, an active control of the temperature around the instrument or other means of uniforming it can be worked out and added to the instrument package.

Another problem that we have examined is the tower's gradiometric noise. The free-fall tower has a complicated structure. Basically, the elevator travels through 12 metallic floors with intersecting beams that support the elevator's rails. The space between two sequential floors is free of massive structures. Qualitatively speaking, the beams that support the elevator's rails are symmetrically distributed with respect to the vertical center line of the elevator. Therefore, their horizontal gravity gradient component is expected to be of low amplitude. However, quantitative evaluation of the gradiometric noise produced by the tower is possible only after a number of repetitive tests with the actual gradiometer. After having learned and measured the gradiometric noise as a function of the gradiometer's attitude, a perturbing mass producing the desired horizontal gravity gradient will be located outside the elevator.

A possible location could be in between two floors where the gradiometric noise of the tower is expected to be lower. Another possibility is to have a much smaller mass, properly shaped, rotating, at a frequency consistent with the drop time (e.g. f = 0.5 Hz) around the air-tight cylinder in the gap between the elevator shell and the cylinder itself (the gradiometer and the mass falls together). The mass will have a shape that makes the signal insensitive to the vertical position of the instrument within at least 0.5 m (the instrument could move vertically of this amount during the drop). The main advantage of this option is to narrow the signal bandwidth and therefore to improve the sensitivity. Both options must be investigated and traded off.

3.0 Conclusions and Recommendations

In these past six months, further elaborations have been performed of the non-cryogenic gravity gradiometer concept, inclusive of the instrument's free-fall testing at the NASA-MSFC drop-tower facility. This concept was introduced in our last Semiannual Report on NAG5-338, dated July 1984. Substantial progress has been made towards the analytical feasibility proof and the full definition of the instrument as well as of the testing approach. Under separate sponsorship, that is sought at present by SAO, the project team (SAO and IFSI-CNR) plans to construct and to test (at the MSFC drop-tower facility) an initial prototype characterized by a configuration that is close to the non-cryogenic instrument expected to fly in the second demonstration mission of the TSS Tethered Satellite Facility.

The remaining period of contractual performance on NAG5-338 (1/1/85 through 6/30/85) will be devoted to the further definition of the non-cryogenic, FET-amplifier, gradiometer, and of its free-fall testing at the NASA/MSFC drop-tower facility. We expect that by the end of the next reporting period, we will have learned enough about this approach to be ready for its implementation and drop-tower testing. A SAO proposal to perform these tests was submitted to NASA-Geodynamics Programs on 6 December 1984.

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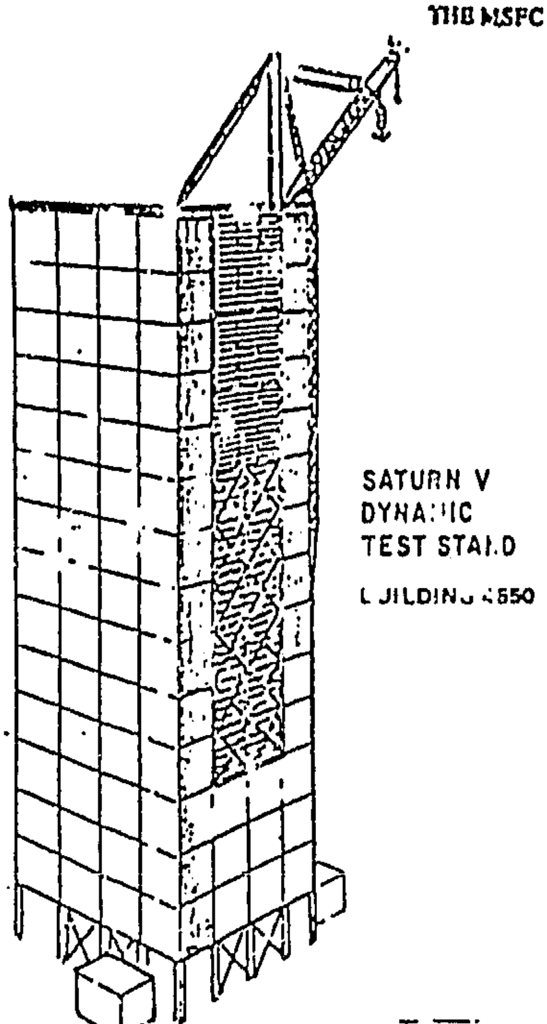
Appendix I - The Free-Fall, Drop-Tower, Facility at NASA/MSFC

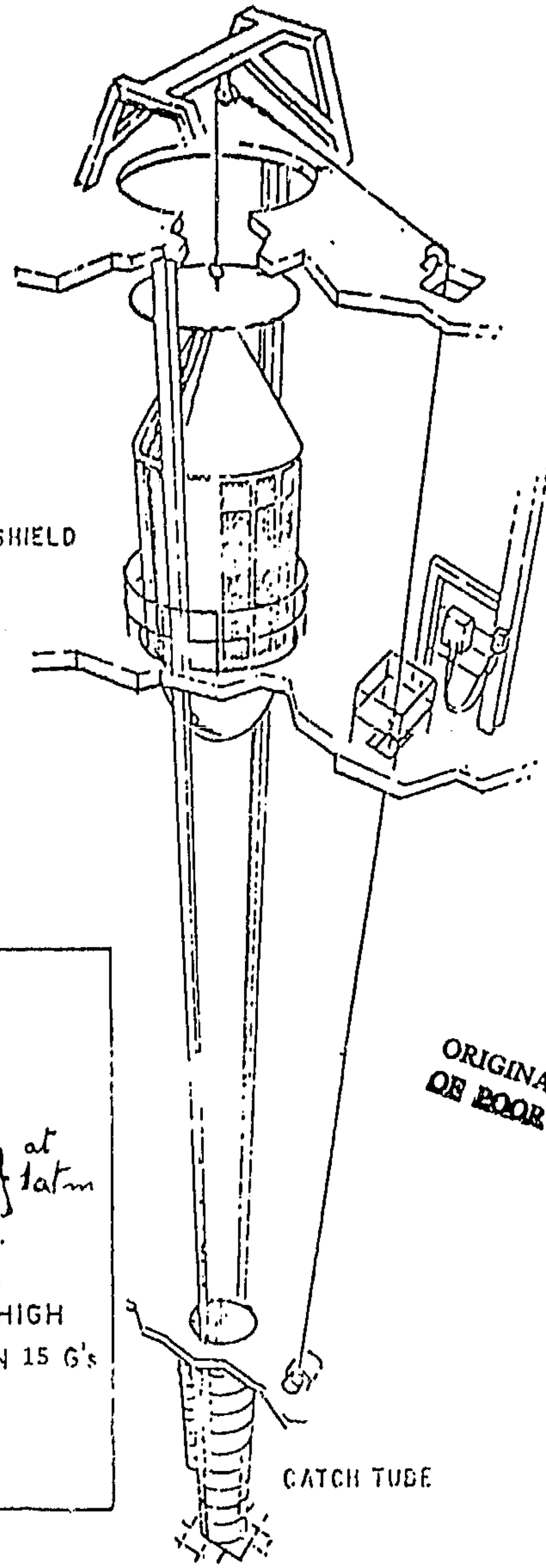
On September 24, 1984, SAO personnel visited NASA/MSFC and inspected there the drop-tower facility usable in free-fall tests.

The facility consists of a metallic tower, 380 feet tall, that was originally built for vibrational tests. The free-fall testing facility is located on one side of the tower. Two vertical rails guide a properly shaped elevator cabin where the instrument package is accommodated. The elevator cabin is lifted by a winch, and, when released, is accelerated by thrusters in order to overcompensate the drag and frictional forces. The available space inside the elevator cabin is a cylinder 9 feet tall and 7 feet in diameter. The elevator cabin is not air tight.

Other relevant characteristics of the facility are illustrated in Figures A-I-1 and A-I-2. It is important to point out that the free-fall length is actually 293.8 feet with a free-fall time of 4.31 sec. This is the time available for data collection. The maximum actual deceleration seems to be 15g, but this information still lacks corroboration. Since the system cannot be operated from a shorter height because all the disconnecting mechanisms are located at the top, the deceleration of the elevator cabin is a fixed value. Power is available via cable before release, and via a battery pack (supplying 20 Amp hour at 28 VDC) after release. Two movie cameras are available to monitor the instrument package's attitude during free-fall while the monitoring radio link consists of 5 channels for experiment data plus 4 channels for auxiliary monitoring. THe system has one power line at 28 VDC providing 20 Amp hour. Bubble memories will be installed directly available (maybe they will be installed in the near future).

THE MSFC 300 FOOT DROP TOWER



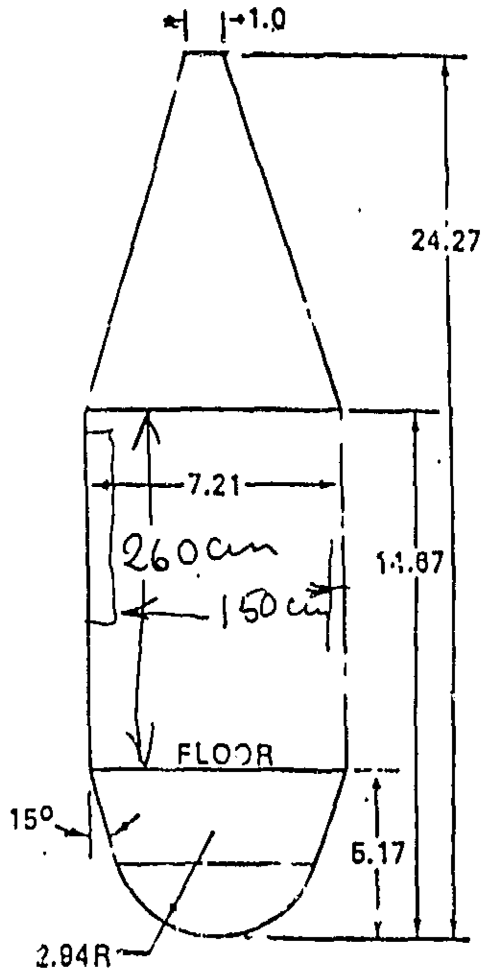


CAPABILITIES

PAYLOAD	
PRESENT	450 LBS.
FUTURE	1000 LBS.
LOW GRAVITY TEST RANGE	
MINIMUM	10^{-5} Go } at 1atm
MAXIMUM	4×10^{-2} Go } at 1atm
DROP TIME (294')	4.135 SEC.
TOTAL DROP WEIGHT	4000 LBS.
MAXIMUM TEST PACKAGE	3' DIA. X 3' HIGH
DECELERATION	LESS THAN 15 G's
INSTRUMENTATION CHANNELS	6
NON-DESTRUCTIVE TESTING	
ZERO TURN-AROUND TIME	

Figure A-I.1

The 300' drop tower at NASA-MSFC



DRAG SHIELD

TOTAL DROP HEIGHT	332.8 FT
FREE FALL HEIGHT	293.8 FT
DRAG SHIELD FREE FALL TIME	4.31 SEC
DRAG SHIELD DECELERATION	15 G

DRAG SHIELD DIMENSIONS:

- LENGTH 24' 3¼"
- DIA. 7' 2½"
- WT. 3620 POUNDS
- TEST AREA 6' X 8'

TEST PACKAGE SIZE:

- HEIGHT 4 FT
- WIDTH 3 FT
- LENGTH 3 FT

MAX TEST PACKAGE WT 450 LBS

LOW GRAVITY RANGE:

- MAX 2.5×10^{-2}G
- MIN 1×10^{-6}G

AUX DRAG SHIELD THRUST 75 LBS

Figure A-I.2

Zero-g Facility at NASA-MSFC

The elevator is operated in such a way that the instrument package, sitting on the floor before the test starts, goes upwards with respect to the elevator cabin, floating a couple of feet above the floor. When the system is decelerated the package sits on the floor again. Attempts at operating the system by releasing the instrument package from the elevator ceiling have failed and the instruments have crashed against the floor.

No problems have ever been experienced with instruments attitude as long as the package is well balanced. It would appear at present that the drop tower is suitable for SAO needs. A problem that must be solved comes from the strong deceleration that the instrument package is going to experience. The modifications required appear to be the addition of an air tight cylinder to be placed inside the elevator cabin. The cylinder will be evacuated before the tests and it should be easily accessible to remove the instrument package when necessary. Pumps are provided by MSFC and all that is additionally required is only a connector and a valve.

Appendix II

Preliminary Evaluation of Attitude Measurement Accuracy of the Instrument Package

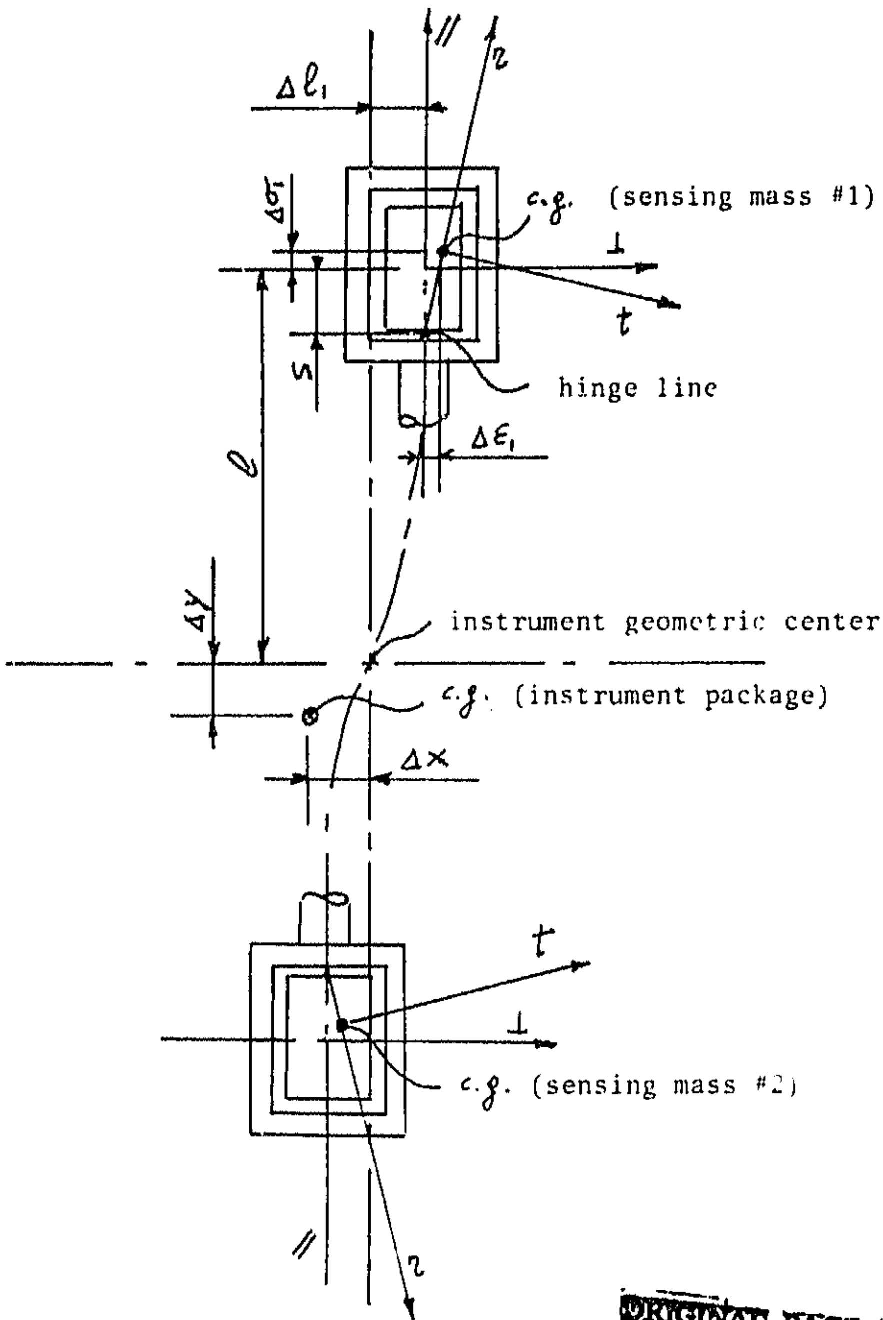
The IFSI/SAO single axis gravity gradiometer is characterized by a good cancellation of the centrifugal acceleration because of the instrument geometry. The sensing masses are symmetrically and radially mounted with respect to the instrument c.g. (it coincides with the instrument geometric center). In a ideal situation, the centrifugal acceleration is completely rejected if the sensing masses are exactly aligned with the radial line through the instrument package's c.g. In an actual situation, as two-dimensionally shown in Figure A-II.1, there are parallelism errors of the two sensors, non-perfect alignment of the sensing mass c.g. with the hinge line, instrument package c.g. mismatches, etc. In Figure A-II.1, Δx and Δy are the components of the mismatch between the gradiometer geometrical center and the instrument package c.g.; $\Delta\varepsilon$, $\Delta\sigma$ are the error components of the sensing mass c.g.; Δ is the distortion of the bar connecting the two condenser probes. An angular velocity ω perpendicular to the plane of the figure produces radial and tangential acceleration components given by:

$$a_{1\perp} = \omega^2 (\Delta x + \Delta\varepsilon_1 + \Delta\ell_1)$$

$$a_{1//} = \omega^2 (\ell + \Delta y + \Delta\sigma_1)$$

$$a_{2\perp} = \omega^2 (\Delta x + \Delta\varepsilon_2 + \Delta\ell_2)$$

$$a_{2//} = \omega^2 (\ell - \Delta y + \Delta\varepsilon_2) \qquad \text{(A.II-1)}$$



(t) is the instrument sensitive axis.

The design is not to scale.

2ℓ is the instrument baseline.

Figure A-II.1

Fabrication and Mounting Errors of the Single Axis Gravity Gradiometer (Two-Dimensional Case)

By projecting these acceleration components in the sensor reference frame (r, t) and by considering that the radial component (r) is fully rejected by the instrument itself, we obtain:

$$a_{1t} = a_{1\perp} - a_{1//} \left(\frac{\Delta\varepsilon_1}{s} + \frac{\Delta\ell_1}{\ell}\right) = \omega^2 \left[(\Delta x+\Delta\varepsilon_1+\Delta\ell_1)-(\ell+\Delta y+\Delta\sigma_1)\right] \left(\frac{\Delta\varepsilon_1}{s} + \frac{\Delta\ell_1}{\ell}\right) \quad \text{(A}$$

$$a_{2t} = a_{2\perp} - a_{2//} \left(\frac{\Delta\varepsilon_2}{s} + \frac{\Delta\ell_2}{\ell}\right) = \omega^2 \left[(\Delta x+\Delta\varepsilon_2+\Delta\ell_2)-(\ell-\Delta y+\Delta\sigma_2)\right] \left(\frac{\Delta\varepsilon_2}{s} + \frac{\Delta\ell_2}{\ell}\right)$$

A compensation bridge can be always arranged in order to have an output linearly proportional to the difference of the condenser outputs on the same side. Such arrangement rejects the common mode acceleration (as desired) and it provides an output proportional to the differential component. However, the uneven terms in (A-II.2) produce an error signal, superimposed to the gradiometric signal. This is given by:

$$N_\omega \,\alpha\, (a_{1t} - a_{2t}) \simeq \omega^2 (s-\ell - \Delta y) \left[(\Delta\varepsilon_1-\Delta\varepsilon_2)/\ell + (\Delta\ell_1-\Delta\ell_2)/\ell\right] \quad \text{(A-II.3)}$$

In A-II.3 the symbol α means "proportional to," while the higher order terms have been neglected. The ratio R_ω that has in the numerator the right side terms of (A-II.3) and in the denominator the difference of the centrifugal acceleration at the opposite ends, can be considered a geometrical common mode rejection factor of the centrifugal acceleration and it is given by (remember that 2 is the instrument baseline):

$$R_\omega = \left|\frac{1}{2}\,(s/\ell - \Delta y/\ell -1)\left[(\Delta\varepsilon_1-\Delta\varepsilon_2)/\ell - (\Delta\ell_1-\Delta\ell_2)/\ell\right]\right| \quad \text{(A-II.4)}$$

If $X = S/N_{\omega}$ is the ratio between the gradiometric signal and the rotational dynamics noise, we can derive an expression for the angular speed as follows:

$$\omega = \{ S/X\ R_{\omega} \}^{1/2} \tag{A-II.5}$$

We adopt the following values for the gradiometer's basic parameters:

$\ell = 0.25;$ $\quad s = 0.033m;$

and we assume that fabrication errors and signal/noise ratio are as follows

$\Delta\varepsilon_1 = -\Delta\varepsilon_2 = 1x10^{-6}m$; $\Delta y = -1x10^{-3}m$; $\Delta\ell_1 = -\Delta\ell_2 = 1x10^{-4}m$

$X = 10.$; $S = 4.7x10^{-2}$ EU (flight instrument sensitivity)

Under these circumstances, we obtain:

$$\omega = 0.01 \text{ deg/sec} \tag{A-II.6}$$

This provides a preliminary estimate of the angular rate measurement accuracy required to filter out from the signal (with a post-test filtering) the angular-rate-dependent components down to 10% of the instrument sensitivity.

Another major issue is the instrument attitude. When departing from the local vertical alignment through a roll and pitch rotation, the gradiometer measures a component of the Earth gravity gradient. This component is comparatively greater than any other effect due to mass distribution in the vicinity of the gradiometer.

For a preliminary evaluation we can equate the noise produced by the Earth gradient to the signal that we want to detect, through the signal to noise ration X:

$$\sin\theta \sin\phi = \frac{S}{X\,|\mathrm{grad}\ g|} \qquad \text{(A-II.8)}$$

By assuming:

$$X = 10; \quad S = 4.7\mathrm{x}10^{-2}\ \mathrm{EU}; \quad |\mathrm{grad}\ g| = 3073.56\ \mathrm{EU}$$

we obtain:

$$\theta = 0.05\ \mathrm{deg} \qquad \text{(A-II.9)}$$

This provides an estimate of the attitude measurement accuracy required to filter out from the signal (by a post-test filtering) the Earth gravity gradient component down to 10% of the instrument sensitivity.