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# AIRBORNE GRAVITY GRADIOMETER SURVEY SYSTEM AIDED BY A HIGH-ACCURACY MASTER INERTIAL NAVIGATION SYSTEM

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One approach to the solution of the aircraft navigation and gradiometer platform stabilization requirements of an airborne Gravity Gradiometer Survey System (GGSS) involves the use of a high-accuracy inertial navigation system as a central element of the aircraft navigation facility. Currently available candidate systems for this application are identified and their inflight performance accuracy characteristics are discussed in relation to established survey mission requirements. Comments are provided on the potential utility of each of the candidate systems and on the applicability of aiding sensors and gravity disturbance compensation techniques to the improvement of system accuracy characteristics.

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# 1. INTRODUCTION

This report discusses available options for achieving the aircraft navigation and Gradiometer Stabilized Platform (GSP) stabilization requirements for an airborne Gravity Gradiometer Survey System (GGSS) through use of a high-accuracy Inertial Navigation System (INS) as a central element of the aircraft navigation facility. The GGSS navigation and stabilization requirements are summarized in Chapter 2 and the available high-accuracy inertial systems are identified in Chapter 3, together with descriptions of some of their salient characteristics. Chapter 4 is devoted to a discussion of GGSS navigation performance considerations and the responsiveness of the identified inertial systems to the GGSS mission requirements. Potential system navigation accuracy improvements obtainable through the use of gravity disturbance compensation techniques and aiding sensors on the aircraft are discussed and some observations on mechanization issues are presented. Chapter 5 summarizes the conclusions resulting from the study described in this report.

## 2. REQUIREMENTS

The navigation and GSP stabilization requirements for the airborne GGSS have been calculated elsewhere (Refs. 1 and 2) and are repeated here for convenient reference:

1. Navigation Errors:
   - Horizontal Position: $\leq$ 200 m CEP
   - Vertical Position: $\leq$ 200 m rms.
2. GSP Attitude Errors:
   - Tilt (about horizontal axes): $\leq$ 25 arc sec rms per axis
   - Azimuth: $\leq$ 50 arc min rms.

In the operational airborne survey system, the accuracy described above is to be achieved at a survey altitude of (approximately) 600 m above surface level during operations over land, ocean, and icecap areas. In addition, the chosen navigation/stabilization system must be capable of providing continuous operation to the above accuracies over survey runs of duration up to 12 hours with minimal impact on the scheduling of such runs.

## 3. AVAILABLE HIGH-ACCURACY INERTIAL SYSTEMS

Several inertial navigation systems have been produced that are intended to be responsive to the USAF high-accuracy INS position error rate specification of (better than) 0.3 nm/hr CEP. Systems which have been flight-tested by the USAF Central Inertial Guidance Test Facility (CIGTF) at Holloman AFB include:

- Honeywell SPN/GEANS (Gimballed Electrostatic Gyro Aircraft Navigation System)
- Litton LN-37 DECI-NAV (Gimballed System utilizing dry-tuned gyros)
- Delco CAROUSEL IVA and IVE: (Gimballed systems utilizing single-degree-of-freedom, floated gyros)
- Autonetics (RI) N-73: (Strapdown system employing wide-angle-readout electrostatically supported rotor gyros)
- Singer-Kearfott Division SKN-2440 (gimballed system utilizing dry-tuned gyros).

Of these systems, the SPN/GEANS is a production system currently installed in B-52 aircraft; the LN-37 DECI-NAV, CAROUSEL IVA, and SKN-2440 are "tuned-up" versions of production systems; the CAROUSEL IVE system is a modified (slower platform rotation rate and more precise azimuth readout subassembly) production system; and the N-73 is derived from a system which never achieved full-scale production status.

A distinction should be made between the established (by CIGTF flight test in a transport-type aircraft) navigation performance of the SPN/GEANS and that of the other inertial navigation systems in this list. Over flights of typical duration seven to eight hours, the SPN/GEANS exhibits a capability for a navigation CEP rate of 200 m/hr for the first three hours of flight followed by an essentially constant navigation error over the next four to five hours. If measured at a time seven hours into the flight and computed from a straight line passing through zero, the SPN/GEANS CEP growth rate is 110 m/hr. This is considerably better than the essentially linear CEP growth rate of 400 m/hr exhibited by the LN-37, CAROUSEL IVE, N-73, and SKN-2440 systems over similar flights and the 500 m/hr CEP growth rate of the CAROUSEL IVA.

Another high-accuracy navigation system which merits consideration is produced by Northrop Electronics Division under the designation NAS-26. It is a stellar-inertial system based on a gimballed inertial platform, employing Singer-Kearfott Gyroflex Mod. II dry-tuned gyros and Model 2401 accelerometers, on which is mounted a star tracker capable of elevation and azimuth training (relative to the inertial platform) and 24-hour per day worldwide operation. This system is the latest member of a family of astroninertial systems produced (recently in development quantities only) for aircraft or cruise missile applications. Van testing at CIGTF indicates that, when operating to its full potential, this system's positional navigation error behavior, at least in the rather active gravity anomaly area of Holloman AFB, is dominated by local vertical deflection errors. That is, the star-tracking system bounds the components of position error attributable to gyro drift to levels that are small compared with those attributable to (uncompensated) vertical deflection errors over the Holloman AFB van test track. As of late 1983, this system had not been flight tested at CIGTF, although Northrop reported some limited "private venture" flight testing without providing detailed quantitative results.

For completeness, mention should be made of the Advanced Inertial Reference Sphere (AIRS) currently in production by Northrop Electronics Division as the inertial guidance system for the Peacekeeper missile. This system, while undoubtedly representing state-of-the-art in terms of sensor design for high-accuracy performance in its designated role, was not originally intended for cruise vehicle applications. As a result, it employs costly components, notably pendulous integrating gyro accelerometers (PIGAs), that are chosen for performance attributes which are largely irrelevant to navigation accuracy in an aircraft environment. In addition to cost in its present configuration (which is higher than that of all the other systems listed, probably by at least an order of magnitude in the case of a near-production configuration system like the CAROUSEL IVA), this system would require an extensive engineering effort to adapt it for use in survey aircraft. The other systems listed were originally designed for and used in airborne applications and can be expected to require much less adaptation for use in the airborne gravity survey mission. For these reasons, the AIRS guidance system is not considered a good candidate for the role of high-accuracy Master Inertial System in the airborne GGSS aircraft.

# 4. NAVIGATION PERFORMANCE CONSIDERATIONS

## 4.1 FREE-INERTIAL AND ASTROINERTIAL SYSTEMS

The dominant performance constraint in choosing a Master INS for the airborne GGSS mission is imposed by the navigation position error requirement of 200 m CEP in the horizontal plane. Before discussing the implications of this requirement, consideration is given to the roles played by the aircraft altitude error and gradiometer stabilized platform attitude error requirements in the selection of a Master INS.

### 4.1.1 Altitude Error

Since inertial systems exhibit unstable error growth characteristics in their vertical position solutions (altitude above a defined reference ellipsoid), it is necessary to employ an external source of aircraft altitude data to meet the rms vertical position error requirement of (less than) 200 m. Whatever this source is (barometric altimeter, GPS receiver, or radar altimeter with a suitable digital terrain altitude map), its error characteristics will dominate the vertical position accuracy achievable by the resulting navigation system. In addition, in the event of failure or temporary outage of the external altitude source during a mission, no inertial system can be relied on to provide suitably accurate altitude data for more than a few minutes with an unaided vertical channel. Thus, the vertical position accuracy requirement is not a factor in the selection of a Master INS for the survey aircraft.

### 4.1.2 Gradiometer Stabilized Platform Attitude Errors

Once the concept of a separate, high-accuracy Master INS is accepted, that INS can be regarded as a potential source of precise information on the orientation of geodetic axes (normal to the reference ellipsoid and true North/East) at the location of the survey aircraft. As such, it constitutes a source of attitude reference data that can be exploited in aligning other stabilization systems in the aircraft to geodetic axes. In particular, data from the Master INS can be used to maintain the Gradiometer Stabilized Platform aligned to geodetic axes. To obviate problems associated with airframe flexure and with the transmission of precise angular attitude information across axes of rotational freedom (gimbal axes), high-precision mechanizations of this "Transfer Alignment" process are usually based on a concept wherein the slave system is also configured as an inertial navigation system (carrying accelerometers and gyros on a stabilized platform) and misalignments between the slave platform and the Master INS platform are detected through differences in navigation (usually velocity) outputs from the two systems. The differences are used, through suitable control functions, to align the slave platform to the Master INS platform, which is by definition, the best representation of geodetic directions within the aircraft.

In this type of mechanization, it is important to note that the inertial sensors carried by the (slave) gyro stabilized platform do not have to be of quality comparable to those of the Master INS. In fact, a cost-effective design would probably involve apportionment of the resulting GSP attitude errors among three major sources:

(1) Imperfections in the GSP inertial sensors which would be chosen accordingly.

(2) Errors associated with the actual mechanization of the transfer alignment algorithm.

(3) Errors in the Master INS knowledge of the directions of geodetic axes.

The last of these quantities is of particular interest in the process of selecting a Master INS. Assuming an error budget consisting of three equal contributions to GSP attitude errors from the sources listed above, the achievement of the 25 arc sec rms per axis GSP attitude error requirement would demand that Master INS per channel tilt errors not exceed $25/\sqrt{3}$, i.e. 14.4 arc sec rms over the duration of a survey mission. However, the Master INS is required, by the positional navigation specification, to provide information allowing either a real-time or post-flight reconstructed* horizontal position CEP of less than 200 m. Assuming equal contributions from both horiontal navigation channels, this specification will not allow Master INS platform tilt uncertainties to exceed 5.5 arc sec rms per axis.

In short, if the selected Master INS is capable of meeting the GGSS positional navigation requirement of 200 m CEP, it will automatically satisfy the requirements imposed on it as a source of attitude reference data for transfer alignment of the GSP about both horizontal axes. The azimuth alignment requirement for the GSP of 50 arc min rms is so easily obtained that it is not a major consideration in this discussion. Thus, the achievement of GSP attitude error requirements is not a determining factor in the selection of a Master INS.

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*Note: The option of post-flight data processing to improve Master INS position estimates over a completed survey mission is discussed later in this chapter.

### 4.1.3 Navigational Position CEP

The achievement of a 200 m horizontal position CEP throughout the duration of a survey mission using an inertial navigation system raises several interesting issues. In survey areas where gravity disturbances are typical of the world-wide average, no purely inertial system will meet the 200 m CEP requirement throughout the duration of the mission without some form of compensation for those gravity disturbances. In fact, the typical error growth pattern of an otherwise perfect inertial-only system operating without gravity disturbance compensation in such areas can be approximated by:

$$\mathrm{CEP}(t) = 200\sqrt{t} \text{ (in meters)} \qquad (4.1\text{-}1)$$

where t is the time of unaided inertial operation in hours. From Eq. 4.1-1 it is evident that the GGSS horizontal position specification would be violated after one hour of flight, even if the inertial system were perfectly mechanized. The same observation holds true for a "perfect" astroinertial system, since the errors generated by gravity disturbances are not observable in (and therefore not correctable by) the star sightings.

Ignoring for the time being solutions to this problem that may be afforded by the use of additional sensors (such as Doppler radar velocity measurement systems and radio navigation receivers on the aircraft), two approaches can be identified for the reduction of the components of position error attributable to the local gravity disturbance field:

(1) Use of existing gravity map grid-point data, together with some appropriate interpolation technique, for the compensation of the effects of vertical deflection on the navigation system outputs.

(2) Use of gradiometer data collected during a survey mission for the same purpose.

Because the construction of a suitable map presupposes the existence of a gravity data base of sufficient surface densification to support accurate upward continuation, the map option conflicts with the original survey mission rationale. Thus, for a high-accuracy master inertial system mechanization, use of the gradiometer to provide vertical deflection compensation would be necessary. Further discussion of the mechanization of gradiometer-derived compensation is presented later.

The main question of interest is the positional navigation performance which could be expected from the use of this gradiometrically measured vertical deflection technique in conjunction with the high-accuracy navigation systems identified in Chapter 3 of this report. The answer depends on the type of inertial (or astroninertial) system employed and comes in three parts:

(1) LN-37, CAROUSEL, N-73, and SKN-2440 Inertial Systems: No significant improvement of position navigation capability is expected. The CIGTF flight test evidence indicates that error sources other than vertical deflections dominate the behavior of these systems for periods of navigation greater than about 0.5 to 1.0 hour (depending on the system tested). Providing compensation for vertical deflection effects would make no material difference to horizontal position error for flight durations of greater length.

(2) SPN/GEANS: The CIGTF flight test data appear to indicate that the position error contributions of uncompensated vertical deflections and error sources internal to the inertial system are equal at about 1.75 hours into flight after a complete inertial system ground alignment process. Subsequently,

the system internal error sources (which appear to have the characteristics of uncompensated gyro bias drifts) exert the major influence on system horizontal position error, although for longer (six to seven hours) times of flight, the diurnal bounding of drift-originated error effects makes it difficult to determine what is the major contributor to position errors. Nevertheless, based on observed CIGTF behavior of SPN/GEANS, error sources internal to the INS can be expected to produce a CEP of approximately 240 m after 1.75 hours of flight. If it is assumed that the positional errors due to internal INS error sources propagate linearly with time of flight, a SPN/GEANS system perfectly compensated for the effects of vertical deflection errors still violates the survey mission CEP requirement after 1.5 hours of flight from a perfectly known initial position.

(3) NAS-26 Astroinertial System: Van tests conducted at CIGTF indicate that the CEP of this aided-inertial system over a four-hour mission is dominated by uncompensated vertical deflections. In other words, the major error sources internal to the inertial system appear to be of the nature of gyro drifts and their effects on horizontal position errors. In the navigate mode these errors are observed and corrected by the star tracker. Gravity disturbance compensation derived from a 3 arc min x 3 arc min grid of vertical deflection values over the van test track via a three-dimensional interpolation algorithm are reported to have reduced the system CEP to approximately 20 percent of the uncompensated value. If this factor of improvement could be achieved in an area possessing worldwide average gravity disturbance characteristics, it would result in a navigation system whose CEP would grow as $50 \sqrt{t}$ meters, where t is in hours. In theory, this would allow 16 hours of continuous operation before accumulated position error exceeded the airborne survey system requirement.

However, some caution is required in extrapolating the statistical result of this limited series of van tests to the operational airborne context. A "typical" data plot from one run of the series does substantiate the 80 percent CEP reduction, on average, but this plot also exhibits peaks in the corrected CEP that exceed 20 percent of the uncorrected CEP at several points during the four-hour test run. In fact, the corrected CEP marginally exceeds 200 m at the end of the test run, although no evidence of continued growth is apparent at this point. Furthermore, it is reported that the improvement in system CEP obtained during Northrop-sponsored flight tests did not match that observed during van testing at CIGTF. The flight testing indicated 40 percent improvement over uncompensated system performance. The causes of this degradation have not yet been determined. If they are found to be attributable to the "cruder" set of gravity data used in the compensation algorithm during flight tests, then the system will retain considerable navigational potential in the context of an airborne GGSS that employs gravity data collected during the survey mission for navigational compensation purposes. If on the other hand, the flight test degradation is found to be due to astroinertial system errors attributable to the flight environment, then the prospects for satisfactory system performance in airborne survey missions are less promising.

## 4.2 AIDED-INERTIAL SYSTEMS

It is already known that a navigation system responsive to the airborne GGSS mission requirements can be designed on the basis of a Global Positioning System (GPS)-inertial mechanization. The only operational limitation of this type of system is set by the availability of sufficient GPS satellites in view of the survey aircraft antenna to provide adquate radio navigation coverage during the various phases of a survey mission. The utility of an accurate inertial system in this configuration is marginal at best. Its major contribution would be to extend the periods over which survey operations could continue in the absence of radio-navigation coverage from tens of minutes to about 1.5 hours maximum (for the SPN/GEANS). This extension would be achieved at considerable increases in system cost and complexity, since mechanizations which employ the Gradiometer Stabilized Platform and its inertial sensors as the inertial element of the GPS-inertial system are quite capable of performing satisfactorily and of providing up to ten minutes of operation during GPS outages.

Other sensors, apart from star trackers, that could be employed in aided-inertial configurations all suffer from accuracy or operational limitations. Doppler radar velocity measurement sets are available for installation on aircraft but are very limited in the navigational accuracy improvement that they provide when used in conjunction with high-accuracy inertial systems, even over terrain having favorable scattering properties. Over water (particularly ocean areas) and over icecaps, their performance characteristics degrade even further, to the point of uselessness in the current context. Hyperbolic radio navigation systems are either too limited in coverage area or are too inaccurate compared with gradiometry survey mission requirements to be of any significant benefit. Finally, correlation sensors such as TERCOM or SITAN are useful only over terrain with suitable profile characteristics for which relief maps have been previously prepared.

## 4.3 MECHANIZATION ISSUES

Two GGSS mechanizations are briefly discussed in this section of the report. The <u>first</u> is depicted in Fig. 4.3-1 and is the current baseline system employing an onboard GPS receiver as the basic source of aircraft navigation data.

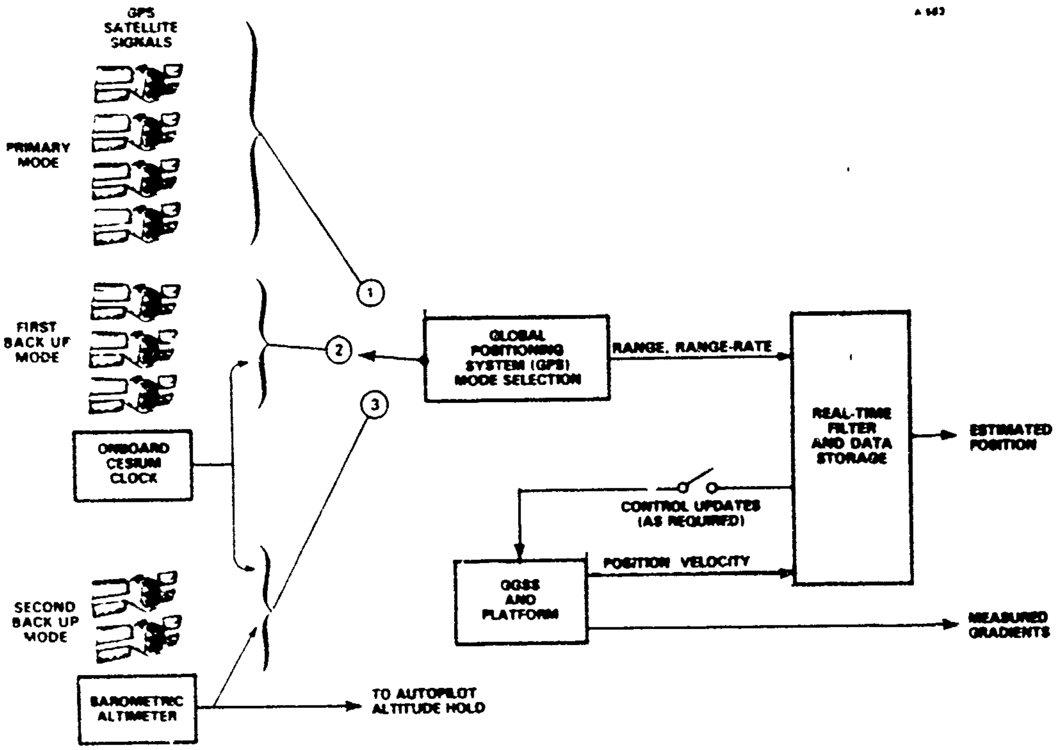

Figure 4.3-1 GGSS/GPS Mechanization

No separate inertial navigation function is provided in this mechanization; instead, the Gradiometer Stabilized Platform is equipped with inertial sensors (accelerometers and gyroscopes) of reasonably high quality and acts as an interim navigation facility during periods of inadequate GPS data availability. GPS position inputs are also used, when available, to provide control of the Gradiometer Stabilized Platform attitude relative to geodetic axes. Aircraft altitude is determined (and controlled during survey legs) by a barometric altimeter which, together with an onboard cesium clock, allows survey operations to continue when only two GPS satellite signals are being received and processed. The cesium clock alone provides a back-up mode of survey operation when three GPS channels are receiving and processing satellite transmissions.

The second mechanization, depicted in Fig. 4.3-2. is based on the use of a high-accuracy astroinertial system to provide the required aircraft navigation and gradiometer stabilized platform attitude control data. The configuration shown uses real-time computation of vertical deflection values

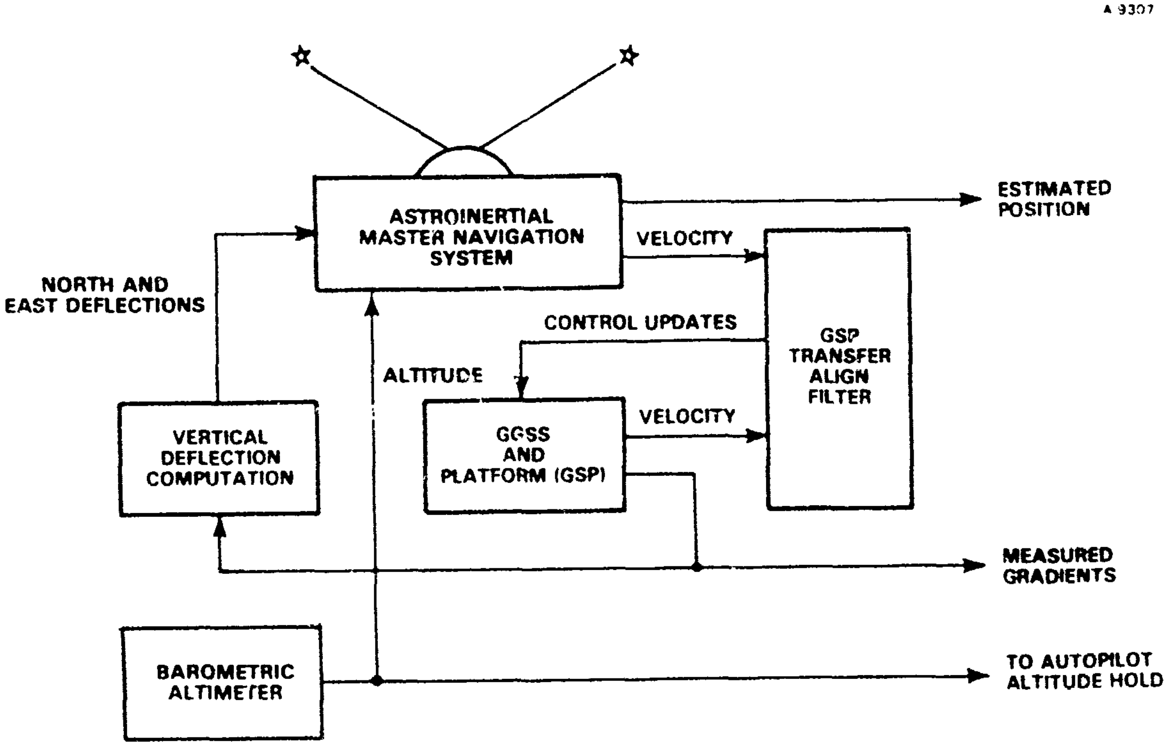

Figure 4.3-2 GGSS/Master Inertial System Mechanization

from the gradiometer outputs and applies those values to provide vertical deflection compensation at the outputs of the master navigator accelerometers. In theory, better results should be obtainable by deleting this design feature and resorting to post-survey processing of the gradient and position/time data. This processing exploits the advantages of batch data smoothers over real-time filters in the derivation of vertical deflection values for correction of the Master INS position outputs. In practice, considerations relating to operation over active gravity disturbance areas and the effect of Master INS platform tilt errors that ensue on GSP attitude errors and distortion of the gradiometer outputs must also be factored into the solution. The optimum practical mechanization in this area has not yet been fully investigated and may well include elements of both real-time and post-mission compensation for the effects of deflections of the vertical. In any case, the information needed to provide adequate compensation should exist in the data gathered during the mission.

# 5. SUMMARY AND CONCLUSIONS

At the present time it appears that the only inertially based high-accuracy navigation system possessing the potential for meeting GGSS survey requirements (excluding the currently baselined GPS-inertial configuration) is an adaptation of the Northrop NAS-26 astroinertial system. This adaptation would also require the implementation of a scheme for compensation of the Master INS for gravity disturbance propagation effects using gravity gradiometer data taken during the survey mission, either on a real-time basis, through post-mission data processing, or a combination of both. A major penalty associated with the adoption of such a master navigation system is the need to configure the survey aircraft with a stellar viewing aperture in its upper fuselage surface. The acceptability of this type of system is still conditional on proof of its applicability to airborne use through further flight testing and isolation/remedy of the causes of residual errors experienced in past flight testing. The operational limitations of this type of system are determined by the incidence of cloud cover above the survey aircraft altitude over the intended regions of operation. Finally, the development of a gradiometer-aided mechanization of the NAS-26 and the conduct of sufficient flight testing to ensure performance at GGSS accuracy requirement levels represents a substantial program in its own right.

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