FEASIBILITY OF GRAVITY GRADIENT TECHNOLOGY FOR FIGHTER AIRCRAFT

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Abstract

This paper documents the approach for investigation of potential applications of a gravitational gradiometer to fighter aircraft control functions. It includes a discussion of the specific requirements for using real-time gravity gradient measurements to estimate terrain features from a fighter aircraft platform, specifically the F-16. Then the manner in which these gravitational gradients can be determined and used in a gravitational tensor to yield information which can be correlated with terrain variations is discussed. Also, the technique employed by the gradiometer to measure the gradients used in the gravitational gradient tensor is discussed. The requirements for the F-16 control functions and operating environment and their impact on characteristics of the gravity gradiometer are explored. Expected tailoring of the gradiometer for application to the F-16 control functions is summarized.

Background

Because of contemporary advances in gravitational field sensing devices, new avenues of mission enhancements may be possible for modern fighter aircraft. In particular, recent advanced technological breakthroughs in a device known as a gravitational gradiometer, which can measure gravitational gradient anomalies associated with local topography, have opened the door to potential fighter aircraft applications. Gravity gradiometer development to date has been primarily applied to naval operations. In the naval application, comparisons were made of bathymetric profiles obtained from precision sonar measurements to information developed from sensed gravity gradients which correlate with ocean floor shape and contours. However, this application used devices too large and heavy for tactical aircraft applications. In addition, the time required to obtain an estimate of the sea floor contour would be prohibitive for an aircraft flying at speeds significantly faster than a submarine. The challenge is to determine whether the technology can provide a device of small size with the sensitivity required for airborne applications which can achieve near real-time terrain estimation capability from gravity gradient measures.

The investigative program plan for extending this proven naval application of gravity gradient technology to the airborne regime involves exploration of potential applications to automated fighter aircraft control functions, i.e., terrain following (TF), collision avoidance (CA), and terrain referenced navigation (TRN). The planned investigative program is a part of the Advanced Fighter Technology Integration (AFTI)/F-16 Close Air Support (CAS) Program currently on contract between Lockheed Martin Tactical Aircraft Systems and USAF Integration Division, Wright Laboratory. This program is a phased approach, with applicability assessments as an output of each phase. The first phase involves examination of the requirements that would be imposed on the gravity gradiometer in order to support the described fighter

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aircraft control functions such as detection thresholds, detection ranges, vibration and maneuver acceleration environment, and installation and integration constraints. Using the defined requirements, an assessment is then made of the requirements that would be imposed on the gravitational gradiometer by the sensed data requirements of the aircraft control functions. The second phase involves a comparison of the sensing capabilities of gravity gradient technology to the imposed fighter aircraft environment and control function requirements, followed by tailoring and application of the gradiometric information to the candidate fighter aircraft control functions.

Two specific applications are to be considered in the investigative program. The first is the use of a gravity gradient instrument as a stand-alone terrain sensor and the second is the fusion of measurements from such an instrument with information from a digital terrain database to yield a covert and safe TF, CA, and TRN system.

Approach

This paper addresses the initial investigative task which primarily concerns the requirements that the control functions and the F-16 maneuver and acceleration environment place on the gravitational gradiometer. From these requirements and the current state of the art in gravity gradient technology, together with some specific packaging, processing, and integration considerations, a feasibility assessment can be obtained. Figure 1 is an illustration of the investigative program approach.

In Figure 1, the TF, CA and TRN control functions have specific requirements for data related to terrain features in terms of minimum detection thresholds, detection ranges, and data rates which, with the vibration, acceleration, size, weight, power, and processing constraints of the F-16, impose requirements on the gravitational gradiometer in terms of sensitivity, packaging and processing. Assuming that the required gradiometer characteristics are attainable, a tailored development for the F-16 then follows. For a radar sensor, both transmitter

① DETERMINE CONTROL FUNCTION REQUIREMENTS

- Detection Threshold
- Detection Ranges
- Data Rates

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② EVALUATE EQUIPMENT REQUIREMENTS OF F-16

- Vibration
- Installation
- Integration

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③ COMPARE GRADIOMETER CHARACTERISTICS

- Sensing Capability
- Packaging
- Processing Constraints

↓

④ TAILOR AND APPLY TO F-16 CONTROL FUNCTIONS

- Analytical/Simulation
- Laboratory
- Flight Test Demo

Figure 1. Approach to F-16 Gradiometer Feasibility Assessment

power and receiver sensitivity can be varied to meet detection range requirements. In the case of a system based on a gravity gradiometer, the signal level is proportional to the mass of the terrain divided by the cube of the distance. The proposed program will define the signal level from a gravity gradiometer necessary to provide control function capability to a fighter aircraft. The process will first determine required detection ranges to function safely in a fighter aircraft. The distance can be correlated to terrain mass size, as depicted in Figure 2, and then to terrain shape and factored into the required control function parameters.

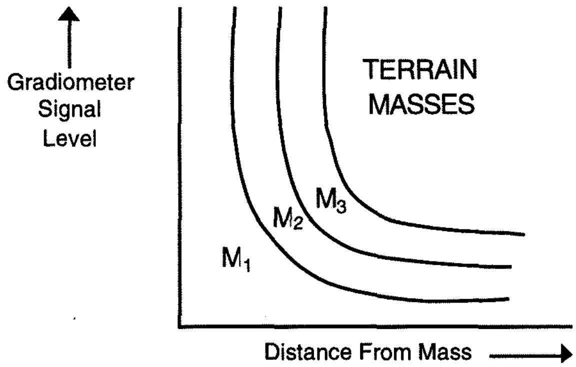

Figure 2. Gradiometer Signal Versus Range

In the comparison phase of the approach illustrated in Figure 1, the requirements for the gradiometer will be assessed from two different standpoints. One standpoint will be how the gradiometer compares to the current sensor complement used to perform the F-16 control functions, an active radar or a digital terrain system (DTS). The gradiometer feasibility will be assessed both in terms of complimenting or aiding the radar or DTS and in terms of its potential for autonomous operation instead of the radar or DTS.

Gravity Gradients

The manner in which minute variations in gravity caused by deviations from a homogeneous spheroidal earth, such as topography variations, can be used is related to the characteristics of those gravitational anomalies. Because of these anomalies, gravity at different locations differs from that expected for a uniform earth. The gravity vector, in general, will not be exactly vertical to the surface of the earth, since it is deflected by topography or subterranean density variations from the nominal upper crustal value of 2.67 gm/cm^3. The result of these variations is that there is a gravitational field gradient experienced for movement either vertically (z direction) or horizontally (x or y direction) with respect to the surface of the earth. This gradient is measured in Eotvos units (approximately 10^{-12}g/cm).

In Figure 3, the gravity measured in the z direction, g_z, at location A may be 1.00000000001g and g_z at location B which is 10 cm closer to a large lead deposit in the y direction (x direction is perpendicular to the paper) is 1.00000000002g. For this case, there exists a gradient in g_z of one Eotvos (10^{-11}g change over 10 cm change in y position). This gradient is the change in gravity in the z direction for movement in the y direction, τ_{zy}. τ_{zy} is a cross gradient in that the gradient is perpendicular to the direction of movement. Similarly, if g_z at A (1.00000000001g) changes to 1.00000000000g at C which is 10 cm higher in the z direction, the change in gravity in the z direction for movement in the z direction, τ_{zz}, would be one Eotvos. τ_{zz} is an inline gradient in that the gradient is in the same direction as the direction of movement.

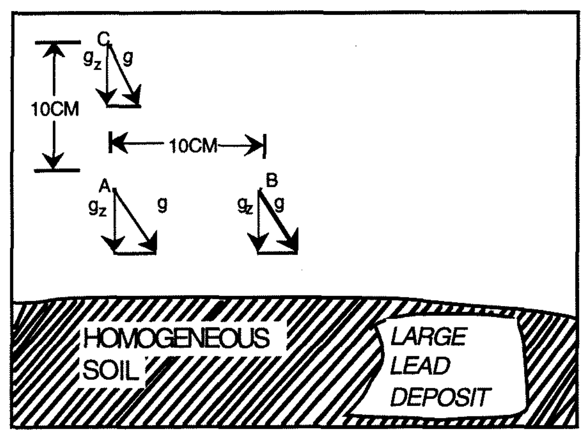

Figure 3. Variations in g_z

Considering g_x, g_y, and g_z it can be seen that there are nine possible gradients associated with inline and cross gravity gradients which can be expressed in a matrix called the gravitational gradient tensor. Each tensor element is a gradient, or slope, of one of the three orthogonal gravity vector components with respect to movement in one of three orthogonal directions. The tensor is as follows:

$$\begin{vmatrix} \tau_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \tau_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \tau_{zz} \end{vmatrix}$$

A second representation of the gravitational gradient tensor gives the mathematical equivalent of each of the tensor terms. Since a gradient is the slope, or partial derivative, of a function with respect to a given direction, or variable, the tensor may be expressed in terms of the following partial derivatives:

$$\begin{vmatrix} \frac{\partial g_x}{\partial_x} & \frac{\partial g_x}{\partial_y} & \frac{\partial g_x}{\partial_z} \\ \frac{\partial g_y}{\partial_x} & \frac{\partial g_y}{\partial_y} & \frac{\partial g_y}{\partial_z} \\ \frac{\partial g_z}{\partial_x} & \frac{\partial g_z}{\partial_y} & \frac{\partial g_z}{\partial_z} \end{vmatrix}$$

Measurement of these tensor terms with a suitably sensitive device called a gravity gradiometer at different points over the earth's surface yields information which can be correlated with density variations and topography variations. Such work has been done with submarine-installed gradiometers which produced gradient data which correlated well with precision sonar maps of the ocean bottom so that the gradient map data, via a suitable transform model, could then be used to estimate the ocean bottom topography.

Gradient Correlation With Terrain Database

Since the F-16 has a DTS with stored digital map, it is envisioned that the digital map elevation data will be used in an algorithm to model terrain masses based on rectangular solid volumes with the nominal, upper-crustal value of 2.67 gm/cm^3 as depicted in Figure 4.

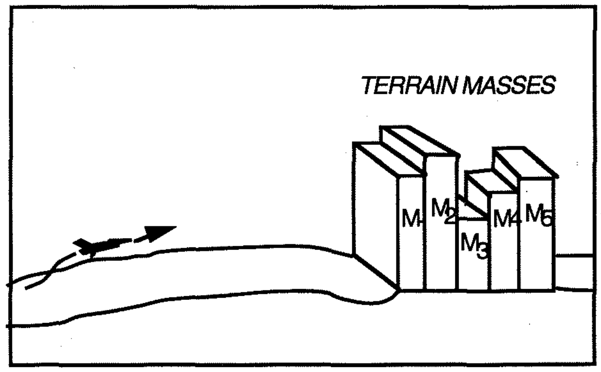

Figure 4. Terrain Mass Transform

The predicted gradient that should be experienced at the aircraft location due to the upcoming masses can then be computed continuously in the aircraft and compared to real-time gradient measurements by an on-board gradiometer. Based on the comparison of the real-time versus calculated gradients, the aircraft flight path can then be modified.

Figure 5 is a block diagram of how such a calculated versus measured gradient comparison could be implemented. In this particular implementation scheme, the gradiometer is used as an aid to DTS-based flight path control to modify the flight path as necessary when errors in the DTS data base might cause deviations from the desired flight path (modified DTS command in Figure 5) or, in the case of unsafe excessive deviations, trigger an automatic fly-up maneuver.

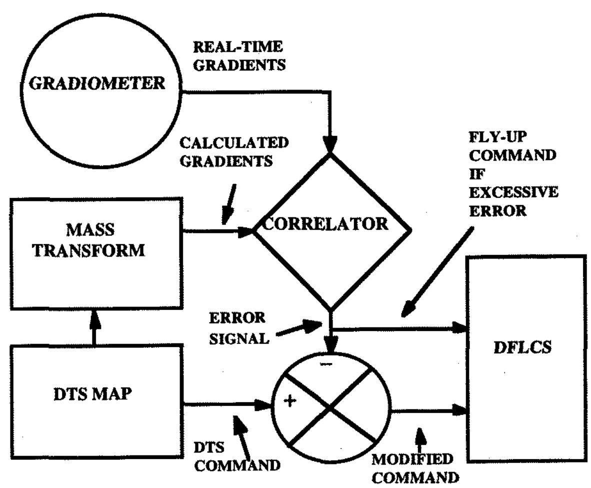

Figure 5. Gradiometer-Aided Flight

Also, the U.S. Defense Mapping Agency (DMA) creates gravity gradient maps from digital terrain elevation data (DTED). This DTED gradient data and real-time gradiometer measurements could conceivably be fused with an aircraft stored area gradient map to form a composite database for the various control function algorithms to use for trajectory computations. Only in the case where a real-time gradiometer measurement point was close enough to the aircraft and of a large enough magnitude would a fly-up be required.

Gradiometer

Since this paper is focused on the approach to the first phase which is to assess the requirements imposed by the F-16 TF, CA, and TRN control functions on the gradiometer, an in-depth discussion of the gradiometer technique will not be given. However, the basic gravity gradiometer device planned for F-16 application uses rotating planar arrays of accelerometers.[1,2] The accelerometers are arranged with their measurement axes tangential to the perimeter of circular discs in such a way that summation of the differences of measured accelerations of opposing pairs cancels the common contributions, leaving only the gravitational difference across the diameter of the disc, which is a gravitational gradient as opposed to a gravity measurement. Inline and cross gravitational gradients can be measured in the plane of the disc by taking the differences between a_1 and a_2 or a_3 and a_4 divided by the disc diameter as illustrated in Figure 6. The measured gradients in Eotvos, due to geologic and local disturbances, become successively more steep as a local disturbance (e.g., a hill) is approached. Consequently, a given Eotvos detection threshold can be exceeded as the range to a hill decreases to some minimum range. The rotating gradiometer disc modulates the signal frequency of the electrically-sensed gradients, which is chosen to be at a frequency different from the platform normal operational maneuver regime and vibration environment. Filtering is then used on the gradient signals to reject platform acceleration contributions.

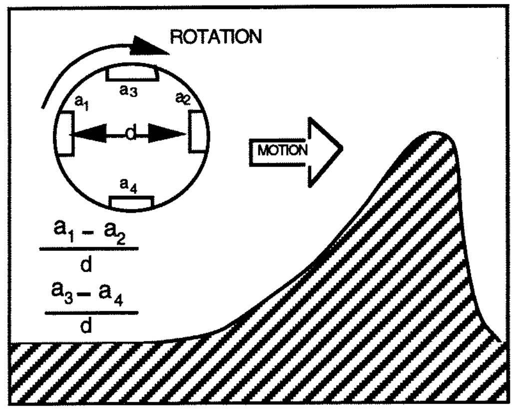

Figure 6. Rotating Gradiometer Disc

The contributions of significant subterranean geologic variations in density can hopefully also be rejected. If the geologic gradient effects are due to fields that are physically large compared to topography variation dimensions (longer wavelength gradient signal contribution), then the geologic, as well as the platform contribution to the gradient signals, can be filtered out.

F-16 Control Functions

The control functions consist of TF, CA, and TRN. TF, as depicted in Figure 7, is a low-level terrain profiling function to maximize survivability from surface-to-air weaponry via terrain masking. CA is a terrain-clobber avoidance function and involves shorter-range higher-g maneuvers than TF. Figure 8 illustrates a CA maneuver. Figure 9 illustrates TRN which is a navigation function utilizing the DTS terrain data base with a radar altimeter to register location in the data base by matching radar altitude profiles with data base topography.

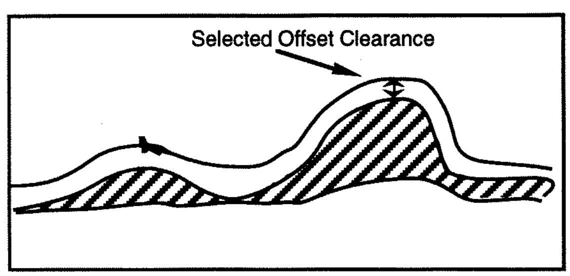

Figure 7. Terrain Following

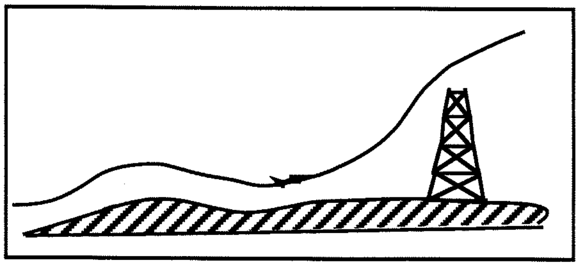

Figure 8. Collision Avoidance

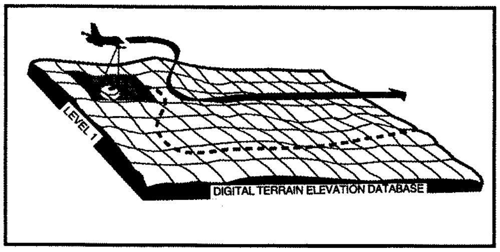

Figure 9. Terrain Referenced Navigation

F-16 Requirements

The general function requirements in terms of typical expected values for detection range, data rates, and typical maneuver accelerations are listed in Table 1.

Table 1. Function Requirements

	RANGE (Nmi)	UPDATE (Hz)	G (Inc.)
TF	1-6	.4-1	+2 to -1Vert.
CA	0.5-1	.4-1	+4 Vert.
TRN	0.25-10	Contin-uous	Not Applicable

The F-16 has limited room and would have to have a consolidation of other avionic elements to accommodate a gradiometer. One possibility is an integrated INS (Inertial Navigation System) and gradiometer. Another possibility is a combined GPS (Global Positioning System), INS, and gradiometer. In any case, the available volume freed up by such combinations is probably on the order of one to two cubic feet. A weight of about 100 to 200 pounds and power consumption of up to 200 watts is also a reasonable preliminary estimate for the F-16. Information from manufacturers indicate that achievement of installation constraints on this order may be possible.

The vibration environment for the F-16 is documented for frequencies above 15 Hz. Vibration data in the 0.1 Hz to 15 Hz range will have to be generated for the F-16 if typical (0.25 Hz) rotational frequencies presently employed by advanced gradiometer manufacturers such as Bell Textron are used.

It is probable that the velocity regime associated with a fighter aircraft, such as the F-16, will necessitate additional filter cutoff and integration time changes for application to F-16 control functions.

The detection thresholds for the F-16 control functions depend on the masses which the gradiometer will have to detect. Since the normal minimum altitude for these control functions is 200 feet above ground level, a reasonable assumption would be that the mass would have to be at least 150 feet tall and, assuming various square base dimensions for a pyramid shape, and a density of 2.67 gm/cm^3, the Table 2 data in Eotvos threshold levels for τ_{yy} are obtained for various ranges to the mass center.

Table 2. Detection Threshold Versus Range

Base (Feet) Height = 150 Feet	5 Eotvos Threshold Range (Feet)	10 Eotvos Threshold Range (Feet)
16000 x 16000	9600	7600
8000 x 8000	6000	4800
4000 x 4000	3800	3000

Gradiometer Requirements

The resultant gradiometer requirements imposed by the Table 1 F-16 control function requirements then mean that, for a stand-alone system, (1) the detection ranges from Table 2 imply that the gradiometer would need at least a 5 Eotvos sensitivity in the direction of flight to achieve TF over hills 150 feet tall with a square base of at least 8000 feet on a side. Though the maximum TF range listed in Table 1 is 6 Nmi for extremely large abrupt elevation changes, most commands occur in the one to two Nmi range. So the values in Table 2 appear promising for TF. For hills with smaller bases, a greater sensitivity would be required, perhaps 1 Eotvos or less. Further studies of actual hills encountered during typical TF runs would be needed to better quantify the needed detection threshold for TF. In a fused system, long-range information for trajectory determination is provided by the database. The gradiometer would only provide close-in corrections. So TF with a fused system may be possible even if it proves not to be feasible for a stand-alone system. For CA, the 5 Eotvos threshold covers all the hills of Table 2, but again, smaller hills would require a lower detection threshold. The TRN function, in particular since it is not flight critical (insufficient detection capability will not result in potential loss of the aircraft as for autonomous TF or CA), appears to be covered by a 5 Eotvos along-track detection threshold.

The update frame rates of Table 1 require TF and CA refresh every 1 to 2.5 seconds. TRN, though shown as continuous because the current radar altimeter can provide continuous ground track correlation, probably does not require continuous gradiometer updates since it also utilizes INS data. Updates on the order of the other function updates are probably adequate.

The typical G environment imposed on the gradiometer is about -1g to +4g vertical and ± 2g horizontal for the functions. However, the F-16 pilot can override commands and frequently executes higher-g lateral maneuvers, interspersed with these functions. Consequently, the gradiometer will have to withstand a 9-g maneuver environment and still provide required performance within lesser acceleration limits, typically those listed in Table 1.

The vibration environment will have to be determined after the appropriate rotational frequency and filter cutoff values for the F-16 application are determined. These and other parameters will be determined in the planned investigative approach.

Recommendations

It is recommended that application of the gravitational gradiometer to fighter aircraft applications be pursued and the necessary gradiometer parameters be further analyzed and refined. In addition, simulation modeling to evaluate control function performance using gradiometer derived data needs to be accomplished to fully ascertain the feasibility of utilizing gravity gradient technology for fighter aircraft applications.

Conclusion

From the initial assessment, it appears that gravity gradient technology is applicable to fighter aircraft control functions. It is also concluded that much additional work is required to fully define the requirements and then to properly define the design criteria for a gradiometer system compatible with the F-16. Then the investigative program should continue into the actual test and demonstration phase to achieve successful integration of gravity gradient technology into the F-16.

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