May 2016

THE

MINUTEMAN GEODETIC AND GEOPHYSICAL (G&G)

ERROR BUDGET

-SOME HISTORICAL COMMENTS-

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PREFACE

The Air Force Aeronautical Chart and Information Center (ACIC) and its successor organization, the Defense Mapping Agency Aerospace Center (DMAAC), contributed significantly to the winning of the Cold War that existed between the United States (US) and the Union of Soviet Socialist Republics (USSR) from the mid 1940s to the early 1990s. The USSR was the initiator of the Cold War and through continued confrontational actions prolonged it for approximately 46 years. The Department of Defense (DoD) officially recognizes the dates of 2 September 1945 and 26 December 1991 as the beginning and end of the Cold War, respectively. The first date marks the surrender of Japan at the end of World War II, and the second is the date of the formal dissolution of the Soviet Union.

To counter the USSR threat, and serve as a defensive deterrent, the Air Force developed a series of Inter-Continental Ballistic Missiles (ICBMs); in particular, Minuteman I, II, and III. ICBM (Minuteman) Research and Development (R&D) carried an Air Force Precedence Rating of 1-1 and a DoD Force Activity Designator of 1. Since both are the absolute highest rankings in their respective priority schemes, nothing was more important to the National Defense than the development, flight testing, and field deployment of Minuteman. Therefore, the Minuteman Geodetic and Geophysical (G&G) data support roles of ACIC and the Air Force Geodetic Survey Squadron (GSS) were the most important activities of those two organizations. (Specifically, their role was to provide the G&G data required by Minuteman to traverse intercontinental distances from launch-to-target, impacting the latter within a specified accuracy.)

Prior to the development of the ICBM, ACIC’s DoD mission was primarily to provide support for Air Force aircraft. This support took the form of the production of Aeronautical Charts (for navigation purposes) and other aircraft-related flight information products. The development of ICBMs by the Air Force (Minuteman, in particular) drastically increased and changed ACIC’s weapon system support activities. What had heretofore largely been a cartographic operation by ACIC, with some photogrammetry and air navigation data involved, must now be supplemented with support for ICBMs. More specifically, ACIC also now had the responsibility for producing G&G products in support of ICBM testing, field deployment, and potential wartime launch.

The purpose of this paper is to:

+ Call attention to ACIC’s significant but little known contribution to winning the Cold War via the Center’s extensive support of Minuteman. Even within ACIC, there was only limited awareness that various Center projects were Minuteman related. This was due largely to the SECRET Security Classification of Minuteman and its G&G Error Budget and adherence to the associated “need-to-know” dictum of such a security designation.

+ Highlight and discuss the Minuteman G&G Error Budget as the basic document from which there emanated an identification of the various instrumentation development and data acquisition programs that were pursued by ACIC in satisfying Minuteman requirements.

+ Record for historical purposes the reason for much of ACIC’s activities during the 1960s through the 1980s, approximately. This time period coincided roughly with the Golden Age of Geodesy\*, which ACIC helped create by virtue of these ICBM G&G data support activities.

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\*The Golden Age of Geodesy is defined here as the period between the launch by the USSR of the Sputnik Satellite on 4 October 1957, and April 1995, when the Navigation Satellite Timing and Ranging Global Positioning System (NAVSTAR GPS) constellation of 24 satellites was declared by the Air Force Space Command to be fully operational.

THE

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ERROR BUDGET

-SOME HISTORICAL COMMENTS-

The development of the V-1 and V-2 rockets by Germany during World War II (WW II) and their use against England had a significant effect on the psyche of those responsible for planning for potential future conflicts. It was apparent that via appropriate research and development (R&D) programs it would be possible to develop a missile having intercontinental range. Further, it was apparent that the in-use products (maps and charts) required by conventional armed forces were not appropriate for Inter-Continental Ballistic Missile (ICBM) support. Early analyses revealed that geodetic and geophysical (G&G) data would be needed at the ICBM launch site, along the missile trajectory, and at the potential target. As a result, the natural Earth would need to be globally\* modeled from a geometric, geodetic, and gravitational standpoint.

Prior to the appearance of the concept of an ICBM, each nation for a variety of reasons, principally to promote commerce and in the interest of national security, prepared maps of their territory. This activity created the need for two national reference systems in which the nation’s natural and cultural features could be systematically positioned horizontally and vertically. These horizontal and vertical positioning entities were normally referred to as Horizontal Datums and Vertical Datums. In the geodetic literature, the term Datum sees usage as in Geodetic Datum, Horizontal Geodetic Datum, Vertical Datum, Local Geodetic Datum, Regional Geodetic Datum, and National Geodetic Datum. Additionally, the word datum may be (is often) replaced by the word system except in the case of Horizontal Datum and Vertical Datum.

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\*Since the Department of Defense (DoD) must be prepared to operate worldwide.

Early Local Geodetic Systems on the same land mass could be (and were usually) combined into a single National Geodetic System of larger areal extent. A country’s National Geodetic System (National Geodetic Datum) is comprised of more than one component. There’s an ellipsoid ideally chosen (hopefully) to best fit geometrically the region of the Earth within the National Geodetic System boundary. The National Geodetic System also has a rectangular X,Y,Z - Coordinate System. The origin and axes of the National Geodetic System are coincident with those of the selected ellipsoid. Formulas exist for transforming the X,Y,Z – Coordinates of a site to geodetic latitude, geodetic longitude, and geodetic height. In addition, the National Geodetic System has an initial point (a geodetic origin), to which all other geodetic (latitude and longitude) points that form the system are connected. An early National Geodetic System might have an astrogeodetic geoid as a component depending on the availability of astrogeodetic data of sufficient quantity and appropriate geographic coverage. Further, Local and National Geodetic Systems did not have as a component an Ellipsoid Gravity Formula or an Earth Gravitational Model.

The transformation of the coordinates of a site in one Geodetic System to its coordinates in another is discussed in [1; Chap. 7] [2; Chap. 7]. The key elements in the transformation are coordinates for the site that are known in both geodetic systems. The coordinate differences, expressed in either rectangular coordinate (delta X, delta Y, delta Z) or geodetic coordinate (delta phi, delta lamda, delta H) form are known as datum shifts. The other two parts of the datum transformation process are usually not included in the conversion. This neglect occurs because the difference (angular) in orientation of the two geodetic systems, and the difference in their scale, is not generally known.

In considering geodetic or gravitational applications involving the Earth, one or more of its following three figures (“surfaces”) may be involved:

+The Earth’s natural or physical surface with its topographic and marine features, familiar to a lesser or greater extent to everyone.

+A geometric or mathematical figure. Prior geodetic studies revealed that the best geometric representation of the sphere-like Earth is an ellipsoid. (The figure of an ellipsoid can be realized by rotating an ellipse either from left-to-right or right-to-left about its minor axis through 180 degrees.) With geodesy in mind, a left-to-right rotation seems preferable. For an ellipse with its minor axis pointing north, a left-to-right rotation is in keeping with the west-to-east rotation of the actual Earth.

+The geoid, which is defined as the equipotential surface of the Earth’s gravity field that coincides with mean sea level over the oceans and extends hypothetically beneath the land. The solid figure geoid approximates the solid figure ellipsoid; the smooth undulating surface of the geoid sometimes lies outside and sometimes within the ellipsoid. The geoid may also serve as the vertical datum (reference surface) to which elevation data is referred. During the 1960s and continues, ACIC used the World Geodetic System (WGS) geoids to obtain height-above-mean-sea-level values at sites in areas where such elevation data was not available. Use of the WGS 84 Geoid as a global vertical datum is mentioned in [1; p. 6-14]. Paradoxically, the WGS 84 Ellipsoid is also mentioned there as a candidate reference surface for elevation data (heights above mean sea level). If this were to occur, geodetic coordinates and elevation data would be referenced to the same surface. This would eliminate the dichotomy that currently exists, 2016, with the former referenced to the ellipsoid and the latter referenced to mean sea level, approximated by the geoid.

Before proceeding, it should be mentioned that various electronic instrumentation and techniques were available in the mid-to-late 1940s [3] to perform geodetic surveys\*. Reference [4] explores how widely separated disparate geodetic systems, including isolated islands, can be related via geodetic connection (ties). This was to be (was) accomplished by using the preceding electronic approaches and/or data acquired through ground-based tracking of geodetic satellites by camera.

Distances and directions between two sites on the same Local or National Geodetic System can be accurately calculated using available data. However, this is impossible when the two sites, located on different continents separated by an ocean, are positioned in different geodetic systems based on different ellipsoids and having different geodetic references (datum origins). Background information pertaining to this unsatisfactory situation is found in [4]. It was recognized as early as January 1947 [5; p. 367] that the solution to this problem was to combine all existing Local and National Geodetic Systems, thereby forming a single WGS. This (need-for-a-WGS recognition) date pertained to a Headquarters Army Air Forces letter to the Office of the Chief of Engineers/Intelligence Division, and then transferred to the US Army Map Service (AMS) for action on its contents; the WGS-related actions beginning in January 1947 in support of “guided missiles” (ICBMs)\*\*. (AMS was created in 1942 as a field office of the Army Corps of Engineers.) The AMS astrogeodetic (and minor gravimetric) activities continued for the next decade, with their extensive research results consolidated and presented as the Army’s World Geodetic System 1958 (WGS 58).

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\*Radio Detection and Ranging (Radar), Short Range Navigation (Shoran), and High-Precision Shoran (Hiran) are the methodologies of interest here.

\*\*Other individuals, committees, or organizations may also have suggested in the mid-to-late 1940s or early 1950s the need for a WGS and its creation.

Reference [2], which made its appearance in 1958, is believed to contain the first published discussion of how a global geocentric geodetic system could be developed using surface gravity data; the Gravimetric Method. (Also, see Appendices A and G.) Note again that Local and National Geodetic Systems of this era were (are) not geocentrically positioned. Additionally, these non-global geodetic systems do not have as a component a model of the Earth’s gravitational field. As a result, they are incapable of properly supporting ICBMs that travel in an astronomic, gravitational world. Thus, the advent of the ICBM created a requirement for the Earth’s first geocentric WGS.

The Gravimetric Method discussed in [2; pp. 299-310, principally] was used by ACIC in developing World Geodetic System 1959 (WGS 59). Not surprisingly, calculations using this method required the availability of surface point gravity data. The need for such data to support ICBMs was recognized quite early during the WGS conceptual phase. As a result, a program was initiated in the 1950s to collect surface point gravity values from any source having such data on file. An Air Force Cambridge Research Center (AFCRC) contract with The Ohio State University (OSU) located in Columbus, Ohio, was part of the DoD’s gravity collection effort. (The authors do not know with certainty whether OSU had any involvement with ACIC under the AFCRC contract to support the development of WGS 59 components except for providing surface gravity data.)

Having two WGSs within the DoD was impractical from a joint operations standpoint. Thus, neither the Army WGS 58 nor the Air Force WGS 59 were adopted by the DoD, leaving unfulfilled the DoD requirement for a single WGS capable of (suitable for) supporting Air Force ICBMs, and other Air Force systems and activities as well. Further, this single WGS must also be capable of supporting Army and Navy navigation and weapon systems. Unfortunately, the technical reports discussing WGS 58 and WGS 59 were never seen and thus not reviewable by the preparers of this paper.

To resolve this two-WGS dilemma, the DoD [5; p. 384] mandated that the key individuals involved in developing WGS 58 and WGS 59 meet, discuss the two systems keeping in mind the principal requirements for a WGS, and create the sorely needed single, DoD WGS before disassembling. A key AMS attendee of the successful meeting later commented [5; p. 384] that the newly created single, DoD WGS was formed by taking the arithmetic mean of the WGS 58 and WGS 59 components. He further stated that of these meaned components, the following were rounded as indicated here: datum shifts to the nearest meter, ellipsoid radii to the nearest five meters, and the equatorial gravity value of the Ellipsoid Gravity Formula to the nearest milligal. The attendee’s comments have been slightly modified from the original in the interest of clarity.

In January 1960, this hybrid WGS was designated as The Department of Defense World Geodetic System 1960, or when briefly written, DoD WGS 60. This geocentric WGS was published “in April 1960 as ACIC Technical Report Number 82 (Revised)” [5; p. 385]. A copy of this report was only seen once, and that briefly, by only one of the preparers of this paper. Therefore, they are not familiar with the components of DoD WGS 60. Fortunately, the system is described in [5; p. 385] as including a newly derived equatorial radius for the ellipsoid, an Ellipsoid Gravity Formula reflecting an ellipsoid flattening of 1/298.3, gravimetrically computed deflection of the vertical components and geoid heights, deflection and geoid height differences, positional errors, spherical errors (radial and relative), datum shifts in rectangular coordinate form, datum transformation formulas, geodetic coordinates, and positional relationships between the major datums. The preceding sentence has been extracted (with some modification) almost verbatim from [5; p. 385]. It is also noted there that WGS 60:

+Did not have an Earth Gravitational Model as a component, a serious deficiency. (There was not a sufficient amount of gravity data available at that time to form such a model.)

+Had a security classification of Secret originally, which was downgraded in 1970 to Confidential. In 1993, WGS 60 was Declassified [5; p. 385].

The AMS-developed astrogeodetic WGS 58 was a non-geocentric system and as such was unsuitable for supporting ICBMs. Therefore, it seems strange that a key AMS geodesist would express disgust [5; p. 385] because WGS 58 was not designated to be (selected en toto as) DoD WGS 60. It should be noted here that WGS 58 is prima-facie evidence that the term WGS, when appearing alone, does not implicitly imply that it is a geocentric WGS. Somewhat related, if the objective is to model the Earth from both a geometric and gravitational standpoint, the selected figure should be a geocentric equipotential ellipsoid of revolution. The terms ellipsoid or reference ellipsoid are applicable when the intent is only to model the Earth geometrically.

In the late 1950s to early 1960s, the Gravimetric Method was the only approach available for geocentrically positioning a geodetic system. Later, the availability of a variety of geodetic satellites including the ground based instrumentation needed to acquire satellite observational data, plus appropriate data processing and application techniques, made this earlier Gravimetric Method obsolete for developing a geocentric WGS. Due to an insufficient amount (or absence) of input data of a particular type and/or appropriate geographical coverage to support the development of WGS 58 and WGS 59, WGS 60 was by necessity a rudimentary WGS. Also, due to the process by which it was formed, WGS 60’s worthiness was somewhat unsettling from a scientific standpoint. (The reader with a historical interest in geodetic accomplishments achieved prior to DoD WGS 60 creation is referred to Appendix A.)

Succeeding geocentric geodetic systems, DoD WGS (66, 72, and 84) were developed by DoD Tri-Service (Army, Navy, Air Force) Committees, with an ACIC employee serving as the Chairman of each. Each later-date WGS was more accurate than its predecessor, and was required in order to achieve the accuracy objective of improved ICBMs as they were developed. For example, WGS 66 and WGS 72 were developed to support Minuteman II and Minuteman III, respectively. In the early 1980s, WGS 84 was created to support the development of the more accurate ICBMs being discussed at that time. Note also that, once available, the more accurate data provided by an improved WGS could be used to increase the accuracy of:

+Any predecessor missile(s) still field deployed.

+Other DoD navigation and weapon systems.

In 1960, the gravity data file assembled by OSU as part of the aforementioned AFCRC contract was transferred to ACIC, becoming the nucleus of the soon-to-be named ACIC Gravity Library. At approximately the same time, AMS also established a Gravity Library. In 1964, the DoD addressed this unsatisfactory two-library situation. The result was the creation of a single gravity depository to be located at ACIC, the DoD Gravity Library. The functions of the DoD Gravity Library were to:

+Continue the collection of surface gravity data (stored in files or resulting from new surveys) from all sources, domestic and foreign.

+Analyze the collected gravity data from a quality (accuracy) standpoint, apply any needed corrections that can be ascertained, and ensure that the data is referred to the same common gravity reference as the other on-file gravity data.

+Maintain the data in both point gravity value, point gravity anomaly\*, and mean gravity anomaly form for ready use.

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\*A point gravity anomaly is the difference in magnitude between two gravity values:

+One value measured at a point on the Earth’s surface and reduced along the vertical to mean sea level using an accepted gravity reduction method, the Free-Air Reduction.

+The other calculated on the surface of the ellipsoid, at the same geodetic latitude as the measured value, using the Ellipsoid Gravity Formula. (The Ellipsoid Gravity Formula has no dependence on geodetic longitude.)

The DoD mean gravity anomaly database is a highly important extensively used data set. A mean gravity anomaly is the average of the point gravity anomaly values available within an Earth surface element. The geodetic dimensions (e.g., 5’x5’, 15’x15’, etc.) of a surface element and its associated mean gravity anomaly are the same. The surface element dimension of the mean gravity anomalies selected for use in a calculation depends on the data requirements of the application involved.

During the 1960s and through the 1980s, ACIC’s Geosciences Branch made extensive use of the DoD Gravity Library’s mean gravity anomaly database. For example, the Geosciences Branch used the database:

+In performing Minuteman G&G Studies and trajectory analyses central to the development of the first and succeeding Minuteman G&G Error Budgets.

+In reducing Minuteman I, II, and III G&G CEP values.

+In conducting Minuteman trajectory analyses that proved the value of a Launch Region Gravity Model and identified its structure.

+In creating the DoD WGS (66, 72, and 84) Earth Gravitational Models and Geoids.

+In accomplishing G&G studies of:

-Peacekeeper, an improved follow-on of Minuteman.

-Various mobile options for ICBMs.

-Missiles having less than intercontinental range.

+In performing studies and calculations related to the use of gravity disturbance components to improve the positional output of:

-Inertial navigation systems used by aircraft and submarines.

-Inertial guidance systems used (not only by ICBMs but) by Navy Sea-Launched Ballistic Missiles (SLBMs).

The Air Force Space and Missile System Organization (SAMSO), located at Norton Air Force Base (AFB) near San Bernardino, California, had responsibility for the development, flight testing, and operational deployment of the Minuteman ICBM. As stated in the Preface, there were three versions of this land-based ICBM, Minuteman I, II, and III. Minuteman III was (is) the most accurate of the three weapon systems; Minuteman II was more accurate than Minuteman I. All three versions of Minuteman had solid fuel engines (motors) for propulsion and were equipped with an inertial guidance system. As inferred from [6], Minuteman I and II are no longer field deployed (2016).

The first SAMSO involvement with ACIC regarding Minuteman was the initiation in the early 1960s of a joint effort to develop a Minuteman G&G Error Budget. The individual, committee, or organization within SAMSO that originated the concept of a Weapon System G&G Error Budget is unknown (2016). This concept, as applied to Minuteman, required the determination of:

+The type of G&G data required at launch, during flight, and at target to support the flight testing and operational deployment of the ICBM.

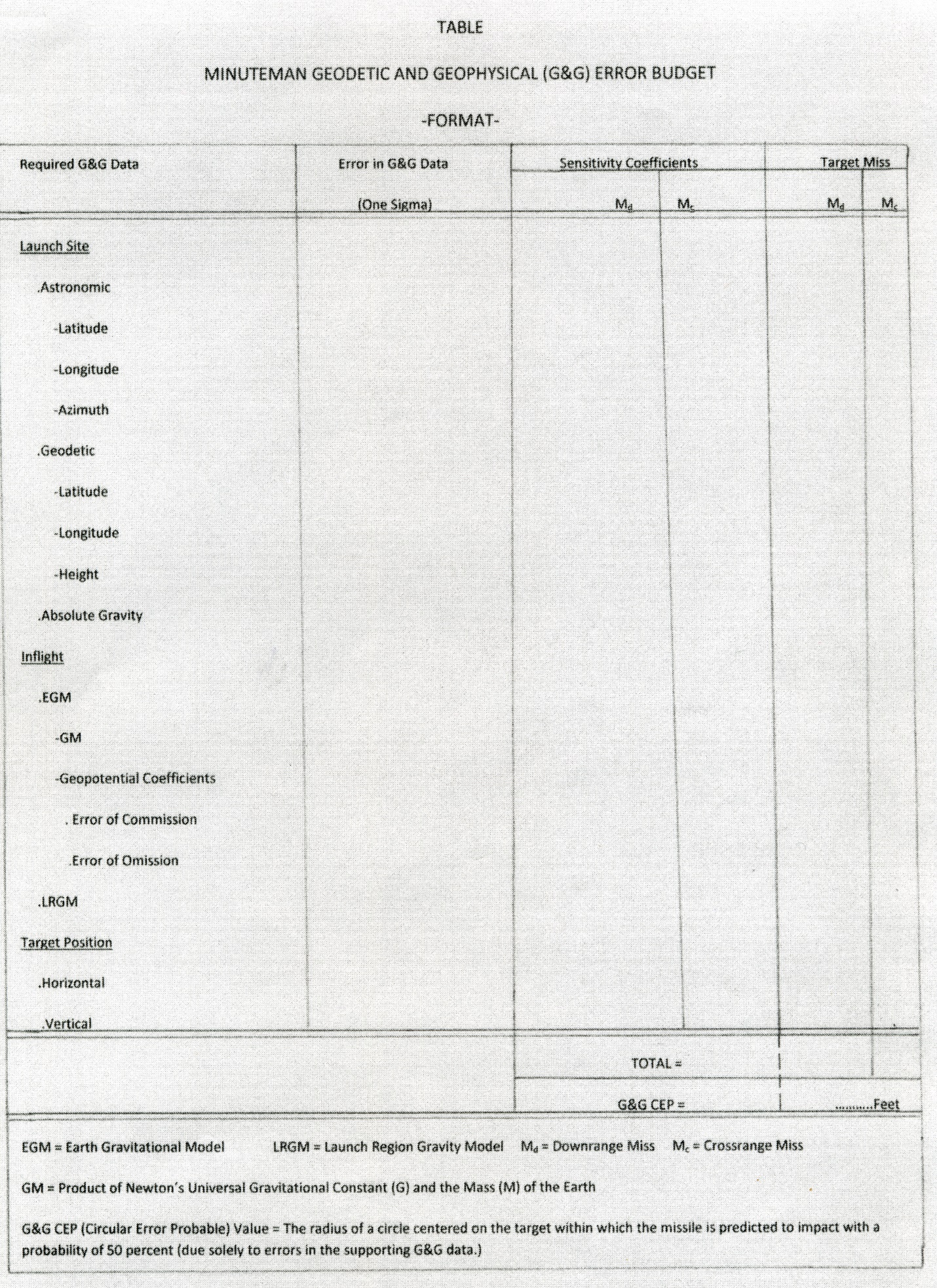
+The uncertainty present in the existing (on-hand) required G&G data.

+The trajectory downrange and crossrange target impact error, and ICBM G&G CEP (Circular Error Probable) value, resulting from (due to) uncertainties in the required G&G support data.

The findings from these SAMSO/ACIC studies and trajectory analyses were then recorded in a Minuteman G&G Error Budget having a jointly agreed-on format\* and numerical values.

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\*The Minuteman G&G Error Budget Format is shown in the enclosed Table.



Much time, effort, and thought were expended by ACIC (Geosciences Branch) personnel in conducting G&G Studies and trajectory analyses leading to creation of the Minuteman G&G Error Budget. The preceding is believed to have been true for SAMSO and their G&G Contractors\* as well. The SAMSO and ACIC investigations were conducted separately and independently. However, technical presentation meetings were held frequently throughout the error budget generation cycle to discuss investigative results. At times, these meetings would become contentious because of disagreement between the SAMSO G&G contractors and ACIC personnel on a G&G technical issue. Significantly, no error budget entry was accepted until there was agreement between the two groups on the contested element or its numerical value.

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\*See Appendix B.

Results from these joint SAMSO/ACIC ICBM G&G investigations were used collectively to form the first Minuteman G&G Error Budget\*. The error budget with its numerical values had a National Security Classification of Secret and, therefore, is not included here. However, the format of the Minuteman G&G Error Budget, presented in the enclosed Table, was (is) Unclassified.

The CEP value in the Minuteman G&G Error Budget reflects at a given time the predicted Minuteman target impact error due solely to the uncertainties present in the in-use supporting G&G data. This error budget was the Standard Minuteman G&G Error Budget kept by SAMSO for the Air Force, with a copy maintained at ACIC.

Two additional error sources, missile hardware (principally the inertial guidance system) and software also degrade Minuteman target impact accuracy. Somewhere within the Air Force, the missile CEPs resulting from these two error sources were combined with the G&G CEP to obtain the (total) CEP for the field deployed Minuteman Force. As a result of the “need-to-know” security dictum, it is believed that no one within ACIC ever knew the predicted Total Error Budget CEP Value for Minuteman. Note: Irrespective of the Minuteman G&G Error Budget discussions in this paper, it is assumed that the Air Force maintains (has) a Minuteman Error Budget with a Total CEP Value reflective of the target impact scoring of actual test range flights.

As time progressed, it became possible to develop a more accurate Minuteman ICBM. This was due to the technological advances made in many areas. For example, improvements in:

+Inertial guidance systems – They became smaller in size, lighter in weight, and more accurate.

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\*No G&G Error Budgets are believed to have been generated for earlier Air Force ICBMs: the Atlas D, E, and F; and Titan I and II. An excellent discussion of the development, deployment, and deactivation of these ICBMs is provided in [8]. The earlier Atlases (A, B, and C) were ICBM “proof of concept configurations” [8; p. 8], flight tested near the end of the 1950s. Therefore, as prototypes, these three systems were not part of any field deployment plans.

+Computers – They became smaller in size, lighter in weight, faster computationally, and had a larger data storage capacity.

+Survey instruments (astronomic, geodetic, gravity) – They became more accurate, faster in operation, and some were capable of collecting a new type of data.

With the preceding advancements either available or underway, weapon system planners were assured that the successful development of a more accurate Minuteman ICBM, Minuteman II, was possible.

The first step in the development of Minuteman II was the selection of a design CEP. The Minuteman II design CEP was, of course, smaller than the CEP for the deployed Minuteman I. Comparison of the two CEP values revealed the magnitude of the reduction in the missile impact error that was to be achieved. As customary, it was accepted that one-third of the error reduction was to come from improvements to be made in missile system G&G support data. This quantity then became the first entry in the Minuteman II G&G Error Budget, the G&G CEP Value to be pursued as a technical objective.

As with Minuteman I, creation of the Minuteman II G&G Error Budget was a joint SAMSO/ACIC effort initiated by SAMSO. In this process, SAMSO (and their G&G contractors) and ACIC, again working separately and independently, reviewed each G&G data element in the Minuteman II G&G Error Budget, except for those pertaining to Target Position. (The error budgets had the same format until the Launch Region Gravity Model became a reality.) Various technical studies and trajectory analyses were performed, as necessary, to ascertain:

+The potential for accuracy improvement of each launch site and inflight data element, and by how much\*.

+The amount of reduction in the trajectory downrange and crossrange miss at target due to use of that particular improved G&G element.

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\*The potential for improving the positional accuracy of potential targets was not addressed as part of this joint SAMSO/ACIC error budget activity. Another ACIC element provided the sought after horizontal and vertical target position data for the G&G Error Budget.

+The technical difficulty involved in achieving the improvement, and the time needed to do so.

+The cost of improving a data element versus the amount of improvement (reduction) in the Minuteman G&G CEP value that this data improvement would make.

The above information was then used by ACIC to identify the G&G-related programs needed to achieve the Minuteman II G&G Design CEP. It was important that the more accurate G&G data identified in the Minuteman II G&G Error Budget be available to support the first flight test and operational deployment of that system. The above discussion of the creation of the Minuteman II G&G Error Budget is (was) also applicable to the generation of the Minuteman III G&G Error Budget. Therefore, discussion of the development of the latter is not further pursued here.

Two Air Force organizations, ACIC and the Geodetic Survey Squadron (GSS), had responsibility for providing G&G data in support of ICBMs. The GSS, located at F. E. Warren Air Force Base (AFB), near Cheyenne, Wyoming (see Appendix C), was responsible for obtaining and furnishing the G&G data required at the Minuteman Wings and Test Range missile launch sites. The first column of the enclosed Table lists the type of launch site G&G support data required.

Equally important, the GSS also geocentrically positioned test range instrumentation (radars, cameras) at both the Air Force Eastern and Western Test Ranges. The Eastern Test Range (ETR) originated at Patrick AFB, Cape Canaveral, Florida, and included missile impact areas near various islands in the South Atlantic (e.g., Ascension Island) and in Broad Ocean Areas (BOAs). When a Minuteman missile, launched from Patrick AFB came into view of test range instrumentation, observations were collected and used to determine its target impact accuracy. Reference [10] discusses Air Force attempts to determine Minuteman accuracy via ETR flight tests and ascertain what portion of the impact error was due to use of an imperfect model of the Earth’s gravitational field. No GSS or ACIC G&G personnel were involved in the analysis of the Minuteman ETR flight test results. The latter were only vaguely aware, if at all, of these early flight tests.

The Air Force Western Test Range begins at Vandenberg AFB near Lompoc, California, and extends southwestward some 4250 nautical miles to the Kwajalein Atoll impact area in the South Pacific Ocean. Minuteman Flight Tests were also made to impact areas near other South Pacific islands and to BOAs. As with ETR flight tests, no GSS or ACIC personnel were involved in the WTR missile impact scoring. Since surface ships, hydrophones, etc., were (are) required to support BOA missile flight test impact scoring, and land/lagoon instrumentation cannot do so, missile/BOA activities are not further mentioned here.

In addition, with the advent in the late 1960s or early 1970s of the Launch Region Gravity Model (LRGM) supporting Minuteman, the GSS performed the point gravity densification surveys required. These surveys provided the additional surface point gravity observations needed in support of LRGM generation for the Minuteman Wings, ETR, and WTR. However, at this point in time, the additional gravity data acquired in the vicinity of the ETR was principally in support of Navy activities.

There were six Minuteman wings. Each wing consisted of three squadrons of 50 missiles each. A wing’s 150 missile silos were scattered throughout the countryside, separated from each other by several miles. Minuteman wings were located at Whiteman AFB (Knob Noster, Missouri), Ellsworth AFB (Rapid City, South Dakota), Grand Forks AFB (Grand Forks, North Dakota), Minot AFB (Minot, North Dakota), Malmstrom AFB (Great Falls, Montana), and F. E. Warren AFB (Cheyenne, Wyoming).

Today (2016), due to Arms Reduction Agreements between the United States and Russia, the nation’s ICBM Force has been reduced to 450 Minuteman III ICBMs. These missiles [6] are deployed in Montana, North Dakota (Minot AFB) and Wyoming under the control of the Air Force Global Strike Command.

The best surveying instrumentation and techniques available at a given time were used by the GSS in obtaining Minuteman Launch Site G&G data. This G&G data was then stored on a Missile Launch Site Data (MLSD) computer tape and made available to the appropriate Air Force organization. The launch sites were positioned geocentrically within the WGS in-use with Minuteman at the time of the survey. New and improved survey instrumentation and G&G data reduction techniques were developed, as needed, to satisfy the launch site data requirements of the new, more accurate, Minuteman missiles as they were developed.

The GSS was a quality organization well led by its military officers and having senior civilian employees well versed in their G&G areas of responsibility. The performance of their G&G survey mission did not appear to suffer despite sometimes having to operate with limited resources and being somewhat isolated geographically from larger centers of geodetic activity.

ACIC had a significant role in contributing to the attainment of the Minuteman G&G CEP level. In the Minuteman G&G Error Budget Format (enclosed Table), listed under the Inflight and Target Position Headings, are the types of G&G data produced or provided by ACIC.

Stated somewhat succinctly, ACIC’s main responsibilities in support of Minuteman were:

+Forming, in conjunction with AMS, DoD WGS 60, the first DoD WGS. This task was accomplished by ACIC/AMS prior to the joint development by SAMSO and ACIC of the Minuteman I G&G Error Budget.

+Developing as a key component of later WGSs an Earth Gravitational Model (EGM) for use with Minuteman. Due to the scarcity of gravity observations, DoD WGS 60, unlike later systems, did not have (as mentioned earlier) an EGM as a component. However, WGS 60 did have as a component an Ellipsoid Gravity Formula (also as mentioned earlier). Unfortunately, such ellipsoidal formulas are only capable of providing theoretical gravity values on the surface of the ellipsoid, and are therefore unable to satisfy Minuteman’s EGM requirement.

+Participating with SAMSO and their G&G Contractor (Geodynamics Corporation) in the trajectory analyses leading to the selection of the form of the LRGM and the providing (by ACIC) of the mean gravity anomaly input data for its generation\*. The LRGM was not a Minuteman G&G Error Budget entry until its development and use with Minuteman in the late 1960s or early 1970s. Further information on ACIC’s LRGM participatory efforts is provided in Appendix D.

+Developing instrumentation and techniques for determining within the in-use WGS the geocentric position (to the required accuracy) of potential targets anywhere in the world, in particular those in politically inaccessible areas.

In further explanation, the ACIC programs supporting Minuteman through the years had a major impact on Center workload and activities. For example, some ACIC actions in support of the missile while in flight (see Minuteman G&G Error Budget Format) were:

+Participation (in a very minor sense) in the establishment of a global network of Absolute Gravity Stations [11] to which all gravity data in the DoD Gravity Library, maintained by ACIC, is referenced. The official name of this worldwide absolute gravity reference system is The International Gravity Standardization Net 1971 (IGSN 71) [12]. It was developed under the

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\*Major L. Bruce Thompson of SAMSO was the originator of the concept of an LRGM (an innovative and laudable idea). The purpose of the LRGM was (is) to more accurately model the Earth’s gravitational effect on Minuteman during the early portion of its flight when it is traveling relatively low and slow. The LRGM consists of a set of fictitious point masses generated from mean gravity anomalies that reflect actual point gravity measurements made on the Earth’s physical surface. The point masses, mathematically placed inside the Earth, are capable of providing computed gravimetric values at missile trajectory points that agree with similar quantities calculated using the mean gravity anomalies from which they (the point masses) were formed. The LRGM Point Mass Method resulted from approximately nine months of SAMSO-sponsored research by Geodynamics Corporation.

auspices of the International Association of Geodesy and approved as an international reference by the XV General Assembly of the International Union of Geodesy and Geophysics at Moscow, USSR, in August 1971. The need for such an absolute gravity network was recognized as early as the mid-1940s. It represents the efforts of various international organizations, universities, and scientists working somewhat sporadically over several decades. AFCRC and its successor organization, the Air Force Cambridge Research Laboratory (AFCRL) were major contributors to IGSN 71 development. (AFCRC, AFCRL, and the latter’s successor, the Air Force Geophysics Laboratory, AFGL, were each located during their existence period at Hanscom AFB near Bedford, Massachusetts.) The GSS was also a substantial contributor to the finalization of IGSN 71.

+Supporting (in a very minor sense) R&D efforts to develop improved instrumentation for measuring Absolute Gravity (first, pendulums, and later, “falling sphere” apparatuses).\* These instrumentation development programs were conducted by AFCRL.

+Collection by the DoD Gravity Library of surface point gravity values from a variety of sources such as other government organizations (domestic and foreign), oil and geophysical exploration companies, universities, US Navy oceanic gravity surveys, etc.

+Providing geographical boundaries and density specifications for surface point gravity surveys to be accomplished by the GSS.

+Acquisition, processing, and utilization of data from non-DMA satellite radar altimetry satellites [Geodetic Earth Orbiting Satellite-3 (GEOS-3), Sea Satellite (SEASAT), TOPEX/Poseidon, etc.] to obtain oceanic geoid heights. (The acronym TOPEX stands for Topographic Experiment.)

+Development of improved techniques for calculating mean gravity anomalies from point gravity anomalies alone or in conjunction with other geophysical data.

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\*Relevant also to the GSS since that organization had responsibility for providing Absolute Gravity values at Minuteman Wing and Test Range Sites. This was done by making a relative gravity tie of the launch site to an Absolute Gravity Station within (forming) IGSN 71. Additional explanatory material is provided in Appendix E.

+Development of techniques, data weighting schemes, and computer software for determining the coefficients for the EGM from a combination of surface mean gravity anomalies and ground-based satellite tracking data (Doppler, Laser) to the best accuracy\* achievable at a given time. The Doppler data set used in WGS 84 EGM development was prepared by the Naval Surface Weapons Center located at Dahlgren, Virginia. The laser satellite data set was prepared by the Aerospace Engineering Department of the University of Texas (Austin, Texas) under a Defense Mapping Agency (DMA) Contract.

+LRGM development (with an update needed to support an improved version of Minuteman) and associated trajectory analyses to determine the gravity station density required, the surface geodetic element sizes (5’x5’, 15’x15’, etc.) of the mean gravity anomalies used to develop the LRGM. Some LRGM particulars that cannot be remembered at this time (2016) are:

-The size of the geographical region contained within the outer boundary of the LRGM.

-The size of the area containing the 5’x5’ mean gravity anomalies.

-The outer extent of the areas containing progressively larger size surface elements with their associated mean gravity anomalies (e.g., 15’x15’, etc.).

-The largest size surface element with its associated mean gravity anomalies used in developing the LRGM.

-The altitude of the point along the missile trajectory where the calculated gravitational contribution of the LRGM becomes negligible and computations can be discontinued.

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\*Forming the data sets used to generate the EGM coefficients was (is) a very slow, tedious, and non-glamorous process.

+Identification and support of R&D programs designed to develop instrumentation and/or systems capable of rapidly acquiring gravity data\* in gravimetrically unsurveyed areas of the world; for example, the Inertial Positioning System (IPS) and a Gravity Gradiometer to be used in mobile modes. It should be noted that in the late 1950s, AFCRC developed and flight tested an Airborne Gravity Measurement System (AGMS). Unfortunately, the geographical area selected for aircraft overflights was not suitable for evaluating the AGMS. The region was topographically rugged and did not have a sufficient amount of surface gravity values to form a “ground truth” gravity data set. The AGMS-acquired data was evaluated by ACIC. However, due to the reasons stated above, no conclusion could be reached from the data evaluation regarding the feasibility of airborne gravimetry. Despite this setback, efforts continued in an unsuccessful attempt to obtain financial support for the development of an AGMS. (Some West Coast G&G contractor personnel were not supportive of an AGMS development program.)

A Helicopter Gravity Measurement System (HGMS), developed by a private company, was flight tested during the 1980s. An analysis of the HGMS-acquired flight test data was conducted by DMAAC and DMAHTC\*\*. The DMAAC Analysis revealed that the HGMS data was capable of providing 10x10 mean gravity anomalies of sufficient accuracy to satisfy DoD requirements. This finding (conclusion), viewed by DMAAC as a significant accomplishment, was presented to Headquarters DMA in a briefing. However, DMAHTC maintained that the HGMS had demonstrated a more accurate gravity measurement capability than that presented by DMAAC. (The DMAHTC claim was adjudged to be overly optimistic.) Any follow-on actions involving the HGMS that may have been taken are unknown (2016) to the authors.

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\*Sufficiently accurate to satisfy Minuteman accuracy requirements (and that of other DoD weapon and navigation systems).

\*\*DMAAC = Defense Mapping Agency Aerospace Center; DMAHTC = Defense Mapping Agency Hydrographic/Topographic Center. Also, see Appendix F for additional information on organizations.

As part of ACIC’s support of Minuteman, various actions were taken to further validate the error values recorded in the Minuteman G&G Error Budget for the G&G data. The following are examples of these error verification activities:

-Using a different type of instrumentation to measure or observe a quantity.

-Performing calculations when possible or applicable using different types of data and/or different formulas.

-Using the in-use WGS EGM to calculate a point gravity value at a launch site and compare it with the gravity magnitude provided at the same location by the GSS. This is the most stringent test that can be applied to an EGM. Due to the lack of sufficiently dense surface gravity data worldwide, EGMs developed during the 1960s and through the 1980s were incapable of producing a point gravity value as accurate as a GSS-determined quantity. (Thus, this comparison, at the time, was done only to satisfy curiosity.)

-Using an entirely different approach to determine a quantity.

As an example of the latter, DMAAC recommended that gravity be measured directly at various altitudes using balloon-borne gravimetric instrumentation. The objective was to obtain gravity values at spatial points that could be compared with EGM/LRGM gravity magnitudes computed at the same locations. This research project\* was undertaken by AFGL with balloon-borne gravimetric instrumentation flights conducted at Holloman AFB near Alamogordo, New Mexico. The authors are not aware of the results from these balloon flights. However, it is believed that initial efforts were not pursued to fruition, perhaps because of lack of funding or personnel changes.

During this same time period, the late 1980s, an alternate approach was sometimes proffered for obtaining measured gravity values at spatial points. The idea broached was to use a gravimeter to make measurements:

-In stairwells, elevators, and on tops of tall buildings or observation decks near their summits.

-On tall towers, preferably isolated and in areas of level terrain.

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\*Approved and partially funded by Headquarters DMA.

During the 1988 time period, AFGL made gravimeter measurements at intervals along a tall tower [13][14]. Unfortunately, it appears that the surface gravity data representing ground truth in this endeavor was woefully inadequate in both density and geographic coverage. This ground truth deficiency is believed to have led AFGL investigators to arrive at a conclusion that may be viewed as too-hasty. (This investigation should be reinitiated, but with adequate ground truth data available.) Perhaps a dirigible or an aerial hovercraft would also be a good platform for making at-altitude gravity observations.

The genesis of one of the more interesting ACIC G&G studies in support of Minuteman was a telephone call from a Minuteman Wing Air Force Officer to the Center’s Geosciences Branch. A coal company was contemplating the surface excavation of coal not far distant from a Minuteman silo. Some mining site particulars were verbally conveyed. The basic question arising from this situation was: If this surface coal mining operation were to occur, would it modify the Earth’s gravity field near the silo enough to require any missile gravity-related corrective action? The verbal preliminary response by ACIC to this question was:

- Any effect on the missile would be negligible since gravity is a weak force\*.

-A G&G study is needed to obtain numerical values and verify the preliminary conclusion.

-A letter would be needed from the caller to ACIC requesting the G&G study be made and providing salient excavation area data such as size, depth, silo distance, etc..

The appropriate letter was received by ACIC and the G&G study was performed. Results from the study showed that the change in the local gravity field due to the coal removal would be negligible, and thus have no discernible effect on the deployed Minuteman. These findings from the ACIC Study were forwarded to the Minuteman Wing.

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\*As an aside, recall from physics that there are four fundamental forces: electromagnetism, the strong nuclear force, the weak nuclear force, and gravitation. Particles of gravitation, gravitons, unlike particles of light, photons, have not yet been detected. However, astronomers have recently detected gravitational waves deep in the Universe.

ACIC activities in support of the Target Position Portion of the Minuteman G&G Error Budget were extensive and technically challenging. Determining the horizontal and vertical positions of targets in politically inaccessible areas to the accuracy levels listed in the error budget was not a mundane task. Many investigative studies and much analytical thought, innovation, and perseverance (plus R&D programs to develop various instrumentation and spaceborne sensors) were needed in order to successfully complete this target positioning task. For example, some of the Center activities were:

+Development via contract of the computer software programs, SOAP (Satellite Orbit Analysis Program) and MOREG (Multiple Orbit Regression Ephemeris Generation).

+Development of spaceborne instrumentation such as NAVPAC (Navigation Package) and GPSPAC (GPS Package) via R&D programs.

+Initiation of and/or participation in R&D programs to develop:

-Spaceborne cameras of improved resolution.

-Various new spaceborne sensors designed to acquire imagery in other than the visible portion of the electromagnetic spectrum.

+Determining the geocentric location of cameras and other sensors in space within the in-use WGS; plus determining their orientation with respect to the vertical.

+Developing techniques for utilizing in combination the imagery acquired by different types of spaceborne sensors.

+Processing (exploiting) the spaceborne camera and sensor-acquired imagery within the in-use WGS to obtain the horizontal and vertical positions of identified potential targets.

For completeness, it should also be mentioned that DMA was involved in R&D programs to develop the Geoceiver (Geodetic Receiver) and GPS Receiver, including improved astronomic survey instrumentation; e.g., an astrolabe. These instruments were used by the GSS in obtaining launch site data in support of the Minuteman G&G Error Budget. The Geoceiver and GPS Receiver were used to acquire ground-based tracking data from Navy Navigation Satellite System satellites and GPS satellites, respectively. The GSS then used this data to obtain site geodetic coordinates within the in-use WGS. The T4 Theodolite was used by the GSS to obtain launch site astronomic data. In later years, the R&D-developed astrolabe also became available to perform this service.

In actuality, there were two versions of the SAMSO/ACIC Minuteman G&G Error Budget:

-The existing one that reflected the available and in-use G&G data supporting the operational Force.

-A second budget, in preparation, to support an improved Minuteman missile being developed.

It is noted here, with absolutely no hint of rancor, that ACIC was never tasked to participate in the development of a Minuteman G&G Error Budget, per se, for either test range. Additionally, ACIC was never asked to participate in the scoring of a test range re-entry vehicle (R/V) impact resulting from an actual Minuteman Flight Test. However, the G&G data required by the test ranges to support Minuteman Flight Tests were available, either from ACIC support of the operational Force or provided by GSS Surveys.

When invited, ACIC attended west coast meetings where Western Test Range G&G data to support Minuteman Flight Tests was discussed. Occasionally, a question would arise regarding the accuracy of the ACIC-supplied G&G data. Whenever this occurred, the ACIC response was in three parts:

+One – The detailed structure of the Earth’s gravitational field is inadequately modeled in the test range area.

+Two – This inaccurate modeling is due to the lack of an adequate number of point gravity observations in most of the test range area.

+Three – Surface gravity surveys are needed to obtain the additional point gravity observations needed to solve this problem.

Unfortunately, only limited funds were made available during the 1960s through the 1980s to correct this deficiency of surface gravity measurements. Despite the shortage of resources, the GSS conducted surface land gravity surveys of limited areal extent in the uprange portions of both the ETR and WTR. The latter gravity survey was made in support of the development of an improved LRGM for the WTR. It is not known by the authors if an LRGM was ever developed for the ETR.

Ideally, the contribution of uncertainties in the G&G data to missile impact error should be reduced to near zero if possible. This reduces the number of contributing error sources thereby simplifying impact scoring. As a result, it permits attention to be largely focused directly on reducing the impact error caused by an imperfect inertial guidance system.

From the preceding, it is apparent that the Air Force Minuteman G&G Error Budget was the basis (the origin) for much of ACIC’s activities throughout the 1960-1980 time period. As such, this error budget was one of the most important products produced (with SAMSO) by ACIC and its successor organization, the Defense Mapping Agency Aerospace Center (DMAAC).

However, only a few ACIC employees were ever present at a briefing on the error budget or knew of its existence as a Center product. Information about the Minuteman G&G Error Budget was not disseminated to an employee unless there was a “need-to-know”.

Many G&G data acquisition systems or G&G data collection programs were initiated and completed without reference being made to the DoD weapon or navigation system(s) being supported. Thus, it was possible for ACIC employees to accomplish meaningful G&G tasks for years in support of Minuteman without knowing the end purpose of their contribution.

Importantly, some of the G&G data and/or products generated to support Minuteman were available to support other DoD weapon and navigation systems: e.g., Sea-Launched Ballistic Missiles (SLBMs), naval vessels, aircraft, cruise missiles, drones, and GPS.

In the interest of completeness, it’s important to note the tremendous positive effect an early ACIC decision had on the Center’s ability to successfully provide G&G support for Minuteman. In the late 1950s, ACIC management recognized that addressing the more complicated issues associated with ICBM G&G support would require employees trained in a variety of disciplines such as geodesy, photogrammetry, astronomy, celestial mechanics, computer science, and later, remote sensing. Since jobs in the public domain requiring these disciplines were (are) quite scarce, university students majoring in these fields were (are) rare. Thus, there was almost no one available in the job market with such skills. To lessen this problem, ACIC initiated a university one-year\* graduate school, Long Term Full Time Training (LTFTT) Program for training new and existing employees in the new skills required for ICBM support.

The first group of ACIC employees selected to receive such training began graduate school studies in geodesy for 12 months at The Ohio State University (OSU) Columbus, Ohio, in the fall of 1958. Half of this 50-member group was to return to ACIC at the end of six months of

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\*Later, however, a two-year graduate school program of study in a particular discipline would occasionally be approved for a selected individual when deemed to be in the Center’s best interest.

academic study. Individuals with the lowest grade point average (and perhaps some having an acceptable non-academic rationale) were the returnees. In the fall of 1959, a second group of 19 ACIC employees also began (and completed) a 12-month period of graduate school study in geodesy at OSU. At the same time, the Air Force Institute of Technology (AFIT), located at Wright-Patterson AFB near Dayton, Ohio, was sending a number of Air Force officers for training at civilian universities, (including OSU in Geodetic Science). Some of these officers later served at ACIC and DMA.

Through the years a more limited number of Center employees were also selected to receive graduate school LTFTT in various disciplines (including geodesy) at selected universities. For example:

+Three individuals were selected in 1960 to study astronomy at the University of Cincinnati (Cincinnati, Ohio).

+Eight individuals were selected in 1960 to study astronomy at Yale University (New Haven, Connecticut).

Due to its demonstrated value, this LTFTT Program has survived throughout the years, existing today (2016) under a different name within the successor organization, NGA\*.

It should be noted that all G&G data prepared by the Chart Research Division (Geosciences Branch) and provided to Air Force users was subjected to a quality assurance review by one or more Air Force G&G contractors. It’s believed that no other ACIC-produced products underwent (undergo) such a stringent accuracy review. Such verification is important since accurate G&G data is essential for the accurate assessment of missile flight test results, for successful operation (if the need ever arose), and for the security of the Nation.

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\*National Geospatial-Intelligence Agency.

Due to their importance, ACIC Technical Director, Thomas C. Finnie, took a keen interest in guiding the Minuteman G&G Error Budget actions being accomplished by ACIC. Finnie’s interest continued from ACIC’s first involvement with ICBM G&G studies/support in the late 1950s until his departure in 1972 for Headquarters DMA (Washington, DC) to accept the position of Deputy Director of Management and Technology\*. Due to his close contact with Minuteman G&G Error Budget activities, Finnie had first-hand knowledge of the supporting projects that ACIC needed to pursue in order to satisfy the increasingly more stringent Minuteman accuracy objectives. His knowledge and guidance were paramount in determining and acquiring the Center resources needed to successfully complete these projects.

Other high level ACIC (later DMAAC) Staff who took a strong contributory interest in Center G&G activities were Air Force Colonel James H. St Clair, DMAAC Director from 1975 to 1979 and Dr. Mark M. Macomber, DMAAC Technical Director from 1979 to 19??. Both had strong geodetic backgrounds, having studied geodesy at OSU (and received advanced degrees from there in that discipline).

The authors hope that this paper will be of interest and value to current and retired DoD personnel, and perhaps to others as well. Its preparation has been an enjoyable period of recollection of some of the people and organizations leading up to and through the Minuteman era addressed herein (1960 through the 1980s).

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NOTE:

Appendix G is included for the reader interested in additional information about the creator of the Gravimetric Method and the AFCRC funding support provided OSU/MCRL, and later the OSU/Department of Geodetic Science. This sponsorship of OSU research in geodesy also continued under AFCRC successor organizations (AFCRL and AFGL).

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\*The Defense Mapping Agency (DMA) was created 1 July 1972.

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**APPENDIX A**

Major Geodetic and Gravimetric Accomplishments

Achieved Prior to DoD WGS 60 Creation

A discussion of the beginning and early history of geodesy is not germane to the basic purpose of this paper. However, several significant geodetic and gravity-related accomplishments occurred from 1900 through the mid-1950s that influenced directly or indirectly the support of Minuteman. Significant among them was the creation of early World Geodetic Systems (WGSs):

-WGS 58, the first non-geocentric WGS.

-WGS 59, the first geocentric WGS.

-WGS 60, the first DoD geocentric WGS, formed via a merger/modification of WGS 58 and WGS 59 components.

Other major early geodetic accomplishments were the completion of:

-North American Datum 1927 (NAD 27).

-European Datum 1950 (ED 50).

-Provisional South American Datum 1956 (PSAD 56).

-North American Vertical Datum 1929 (NAVD 29).

Also, worthy of mention is:

-The development and exploitation of electronic surveying instrumentation and techniques to perform geodetic ties.

-The expansion of the use of astrogeodetic techniques.

-The determination of various:

+Ellipsoids (with values for their semimajor axes and flattenings) [2; p.230].

+Ellipsoid Gravity Formulas [2; p. 78].

The major early gravimetric accomplishments were:

-The development and dissemination of physical (gravimetric) geodesy principles and techniques.

-The development of new pendulums and their use to establish absolute gravity measurements at additional sites.

-The development of portable light-weight gravimeters for making relative gravity measurements.

-The establishment of:

+National Gravity Base Stations [2; p. 86] and their connection.

+World Gravity Base Stations [2; p. 121] and their connection.

(Some of these relative gravity connections involved aircraft flights [2; p. 121].

-Formulation of the Gravimetric Method of WGS development.

-Initiating the systematic worldwide collection of on-file gravity data for use with the Gravimetric Method.

-The development of various gravity reduction techniques for referring gravity data from the point of measurement to a corresponding point on the geoid [2; Chap. 6, Chap. 7].

-Using the Stokes Formula of 1849 [7; pp. 92, 100] to compute various gravimetric geoids: Tanni, Hirvonen [2; p. 282]; Rice, Bomford [2; p. 291]; and the OSU/MCRL Columbus Geoid [2; p. 289].

-Using the Vening Meinesz Formulas of 1928 [2; Chap. 8] [7; p.111] to compute gravimetric north/south and east/west deflection of the vertical components.

The development of early WGSs and the above mentioned major geodetic and gravimetric accomplishments provided a foundation for post-1960 geodesy.

**APPENDIX B**

Some SAMSO G&G Contractors/Personnel

SAMSO G&G contractors and personnel remembered (in 2016) as being involved periodically in Air Force ICBM G&G activities during the early-to-late 1960s were:

* Aerospace Corporation: Roger Gore, Lem Wong, George A . Reams, Dr. Anthony Gregory, Dr. Leander DeWitt, Paul …, and “Nick” … .
* TRW Systems: Dan Scalley, Richard Westlake, and Duane Olinger.
* Geodynamics Corporation: George A. Reams\*, Dr. Anthony A. Gregory\*, Morris M. Bennett, P. W. Davis, and Charles Ford.
* Logicon Corporation: (Unable to recall the names of any employees.)

However, after Geodynamics Corporation was formed in the late 1960s, and had acquired a small group of individuals technically capable of performing missile system G&G analyses, that organization then became SAMSO’s main G&G contractor, and remained so in subsequent years.

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\*In either 1967 or 1968, George A. Reams and Dr. Anthony Gregory left their employment at the Aerospace Corporation and formed Geodynamics Corporation. (However, Dr. Gregory left Geodynamics Corporation approximately one year later, returning to his earlier employer, the Aerospace Corporation.)

**APPENDIX C**

**Our Air Force Ground Geodetic Survey Brethren**

**And**

**The Fluidity of Their Organizational Structure [9]**

For the first 14 years of their existence, the ground geodetic surveyors were part of the Air Force’s photomapping community and were assigned to photomapping units. Because they didn’t have an aerial mission, never rose above the Squadron organizational level, and were nearly always geographically separated from their parent organization, they were largely underrecognized and underappreciated. This, in spite of the fact that they once numbered over 460 people, were headed by a Colonel, had Detachments spread over the United States, and for the most part worked on programs and projects with as high or higher priorities than the flying units. They carried a higher Unit Precedence Rating than any other Photomapping unit.

The history of the ground geodetic surveyors is an interesting one and much of it can be found on the Aerial Survey and Photomapping History Website ([www.1370th.org](http://www.1370th.org)) under the Geodetic Survey Squadron button. However, some of the very early years have not been covered. This article briefly covers the entire 14 years mentioned above in the hope that a reader will find it informative, if not interesting.

The ground geodetic survey era began in the early 1950s when the United States Air Force (USAF) began development of their nuclear intercontinental ballistic missiles (ICBMs). In order to assure target destruction and yet, at the same time, limit collateral damage, the Air Force needed missile systems with the highest attainable accuracy. They realized that unknowns at the target end would largely monopolize the error budget of these systems, so error sources at the launch site would have to be minimized. Key to doing this would be knowing the precise geodetic and astronomic coordinates, the gravity value, and precise azimuth orientation for the inertial measurement unit of each missile at each launch site. An elevation value was also determined for each launch site. In addition, enough accurate gravity data (its intensity, geodetic position, and elevation) would have to be acquired in the areas surrounding the launch sites to support the development of a sufficiently accurate Launch Region Gravity Model (LRGM) with which to better determine the trajectory of the missiles during the launch phase while they are low and slow.

At that time, the Air Force did not have an internal organization with the organic resources needed to accomplish the necessary surveys. To rectify this situation, the Air Force assigned to the Air Photographic and Charting Service (APCS) the responsibility to develop the necessary

capabilities and accomplish the surveys. The following chronology identifies how the surveyors were integrated organizationally into and then phased out of the Photomapping lineage:

1 May 1954: Headquarters (Hq) Air Force assigns USAF Photo-Mapping and Aerial Electronic Surveying responsibilities to the Air Photographic and Charting Service (APCS) located at Orlando Air Force Base (AFB), Florida.

February 1956: Hq Air Force assigns missile site Ground Surveys to APCS. Because of the lack of geodesists and geodetic surveyors in the Air Force, APCS contracts with the United States Coast and Geodetic Survey (USCGS) to perform the missile site surveys.

27 March 1958: As the number of missile sites increases and the organic Air Force capabilities expand, Operating Location 1 (OL-1) of the 1370th Photo-Mapping Group is established at Orlando AFB, Florida, to assume day-to-day responsibility for the surveys. The Ground Surveyors enter the Photo-Mapping lineage.

September 1958: OL-1 of the 1370th Photo-Mapping Group is inactivated and replaced by OL-1 of the 1373rd Mapping and Charting Squadron under the 1370th Photo-Mapping Group.

Early 1959 : The 1370th Photo-Mapping Group is moved from Palm Beach AFB, Florida, to Turner AFB, Georgia.

1 July 1959: The expanding workload and increasing complexity of the required ground surveys leads to the establishment of a unit dedicated solely to the geodetic, astronomic, and gravity missile site surveys worldwide. This new unit is designated the 1381st Geodetic Survey Squadron (Missile), still under the 1370th Photo-Mapping Group.

1 January 1960: Due to expansion of its mission, the 1370th Photo-Mapping Group is redesignated the 1370th Photo-Mapping Wing (PMW). It takes with it the responsibilities for the missile site surveys.

1 April 1960: Detachment 1 of the 1381st Geodetic Survey Squadron (Missile) is activated at Vandenberg AFB, California.

1 October 1962: Five more Detachments of the 1381st are formed at Minuteman Bases.

January 1964: As the mission of the 1381st becomes more diversified, the word missile is dropped from its name, and the Squadron becomes the 1381st Geodetic Survey Squadron.

1 October 1965: The 1370th Photo-Mapping Wing is detached from APCS and assigned directly under Hq Military Air Transport Service (MATS). The 1381st GSS moves to F. E. Warren AFB, Wyoming, still under the 1370th PMW.

July 1967: The 1370th PMW is inactivated at Turner AFB, Georgia. Photomapping resources are reactivated at Forbes AFB, Kansas, as the Aerospace Cartographic and Geodetic Service (ACGS), one of the Technical Services of the Military Airlift Command (MAC). The Ground Survey resources are assigned to ACGS as the 1381st Geodetic Survey Squadron.

Fall 1968: The 1381st Geodetic Survey Squadron is redesignated the 1st Geodetic Survey Squadron.

1 July 1972: The Geodetic Survey assets split from the Photomapping lineage as the Defense Mapping Agency (DMA) is formed and these assets are assigned to the DMA Aerospace Center (DMAAC) as the Geodetic Survey Squadron (GSS).

August 1976: The Geodetic Survey assets of the Military Services are consolidated at F. E. Warren AFB and then reassigned from DMAAC to the DMA Topographic Center (DMATC).

September 1978: The DMA Hydrographic Center is merged with the DMA Topographic Center. The Geodetic Survey Squadron is assigned to the new DMA Hydrographic/Topographic Center (DMAHTC) at the Division Level.

April 1980: The Geodetic Survey Squadron is elevated from Division to Department Level within DMAHTC.

1989: The organizational status of the Geodetic Survey Squadron is elevated once more when they are redesignated as the Geodetic Survey Group within DMAHTC.

October 1993: With the Cold War at an end (the official DoD date is 26 December 1991), the Geodetic Survey Group is deactivated and the Air Force drops Geodetic Surveying as a career field. Responsibility for geodetic surveys was then transferred (assigned) to the DMAAC Office of Geodesy and Geophysics.

Later: When DMA was inactivated on 1 October 1996, the new National Imagery and Mapping Agency (NIMA) assumed responsibility for Geodetic Surveying within the DoD. On 24 November 2003, NIMA was renamed the National Geospatial-Intelligence Agency (NGA), and they have retained the Geodetic Surveying mission since then.

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Note: In this Appendix, and in the context of GSS responsibilities, the meaning of the word geodetic in Geodetic Survey and Ground Geodetic Surveyor has been expanded, and is understood, to include astronomic and gravity surveys and surveyors.

**APPENDIX D**

ACIC

Minuteman LRGM Development Activities

As mentioned in the text, the development of a Launch Region Gravity Model (LRGM) in the late 1960s was a joint SAMSO/ACIC effort. The SAMSO G&G contractor participating with ACIC in this endeavor was Geodynamics Corporation.

Investigations leading to the identification of the mathematical structure of the LRGM, and its associated computational process, was estimated by SAMSO to take six months. The criteria for the sought LRGM were computational speed (as fast as possible) and high accuracy for the calculated gravimetric values.

Being familiar with the geodetic literature, ACIC chose to investigate for LRGM suitability the following three methods appearing there: the Hirvonen/Moritz Method [1] [2], the Poisson Integral Method [2], and the Orlin Coating Method [2] [3]. (These three references are identified at the end of this Appendix.) Since these were the only in-print approaches with the possibility to become the LRGM formulation, Geodynamics Corporation by necessity was relegated to investigate the Point Mass Method or develop some other technique.

The Point Mass Method was not generally known throughout the G&G community and had not previously been investigated in depth, if at all. Further, an internationally known American gravimetric geodesist viewed with skepticism the idea that a viable Point Mass Model could be created, stating that if it were possible someone would already have done so.

Investigative calculations utilizing trajectories over a wide range of azimuths were made by ACIC using the three above mentioned candidate methods. Also, as part of ACIC’s LRGM research, investigations were conducted to determine if the usual distance between points along the trajectory where gravimetric calculations were usually made could be increased. Investigative results revealed that an increased distance between trajectory points could be used with negligible effect on where the missile would impact. This reduced the computer time required for an LRGM calculation.

At the end of six months, ACIC had completed their analyses of the three candidate LRGM Methods they had selected to investigate. They concluded that the Hirvonen/Moritz Method using a speeded-up computation scheme was the best formulation for the LRGM. In addition,

ACIC had also created a well-tested surface geometric framework for the mean gravity anomaly input data required for an LRGM computation. This included determination of:

-The density of surface gravity observations required.

-The surface geodetic element sizes (5’x5’, 15’x15’, etc.) of the mean gravity anomalies.

-The size of the geographical region contained within the outer boundary of the LRGM.

-The size of the area containing the 5’x5’ mean gravity anomalies.

-The outer extent of the area containing progressively larger size surface elements with their associated mean gravity anomalies (e.g., 15’x15’, etc.).

-The largest size surface element with its associated mean gravity anomalies used in developing the LRGM.

-The altitude of the point along the missile trajectory where the calculated gravitational contribution of the LRGM becomes negligible and computations can be discontinued.

Since Geodynamics Corporation had been unsuccessful after six months of investigations in developing the Point Mass Method, SAMSO extended their on-going contract for another six months. After approximately three more months, Geodynamics Corporation was successful in proving that the Point Mass Method was a viable technique for generating a Point Mass Model that could be viewed synonymously as an LRGM. This was an outstanding geodetic/gravimetric achievement by Geodynamics Corporation. With general knowledge now available regarding the point mass generation procedure, ACIC was able to verify the validity of Geodynamics Corporation research results within two weeks.

The Point Mass Model uses less computer time than the Hirvonen/Moritz Method (Expedited) to perform an LRGM computation at a trajectory point. Therefore, the former was selected by SAMSO as the LRGM for Minuteman, with the latter available as a backup technique and quality control check for the former.

During the LRGM investigations, ACIC made a surprising discovery when analyzing the contours of a computer-generated graphic. The closer spacing of the contours rearward of the launch site indicated that gravity data in that area, over which the missile did not fly, had a greater effect on the missile than the downrange gravity data over which the missile would fly. Since this arrangement of contours appeared to violate common sense, the immediate thought was that there must be an error in the computer program. However, it quickly dawned on the ACIC geodesists that the depicted results were correct and showed what should have been expected all along. A mass behind the launch site has a rearward gravitational attraction on

the missile as it proceeds downrange. This gravitational attraction acts in the same direction (rearward) from the time the missile is launched until it impacts downrange. However, a mass located downrange of the launch site has a forward gravitational pull on the missile as it approaches; then after the missile passes by and continues downrange, the gravitational attraction switches to a rearward direction. This reduces the gravitational effect on the missile of a mass located forward of the launch site. This finding, the requirement for a greater densification of gravity observations rearward of the launch site, was incorporated into the specifications for the Minuteman LRGM Gravity Surveys performed by the GSS.

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**APPENDIX E**

Absolute and Relative Gravity Measurements

Clarification is needed regarding the Launch Site Absolute Gravity\* entry in the Minuteman G&G Error Budget Format. Without further explanation, the reader would logically conclude that an absolute gravity measurement had been made at the launch site. However, that is not the case.

There are two types of gravity measurements, absolute and relative. As mentioned earlier in the text, early absolute gravity measurements were made using pendulums. Later, absolute measurements were made by accurately timing the free-fall of a spherical ball in a vacuum. A relative gravity measurement is made more rapidly by a simple, easily portable instrument called a gravimeter. Gravimeter measurements (after being processed to obtain gravity units) provide the difference in the value of gravity at two sites.

The GSS used gravimeters to obtain absolute gravity values at launch sites, but not directly. This is done indirectly by conducting relative gravity measurements (a tie) between an Absolute Gravity Station and a launch site. In fact, most of the 1854 Absolute Gravity Stations forming the in-use Absolute Gravity Network, (IGSN 71), were established via relative gravity ties using gravimeters.

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\*The term absolute gravity refers to the magnitude (numerical value) of gravity. However, other absolute gravity descriptors of equal merit appearing in print include “the intensity of gravity” and the “acceleration due to gravity”. The unit of acceleration used with gravity is the “gal” named in honor of Galileo Galilei. One gal equals an acceleration of 1 cm/sec2, with one milligal equaling an acceleration of 0.001 cm/sec2. For everyday usage, geodesists use the milligal unit, normally written as “mgal”. A rough approximation of the numerical value of gravity at a point on the Earth’s surface is 1000 gals. In the aerospace community, this numerical value is often referred to as “1 g”. The preceding units expressed more compactly, are:

1 gal = 1 cm/sec2

1 mgal = 0.001 cm/sec2

1000 gals = 1 g.

**APPENDIX F**

Some Mapping, Charting, and Geodetic (MC&G) Organizations

-Their Start-up Dates and Other Facts-

Over the years, the MC&G organizations relevant to this paper have undergone name changes, mergers, function changes, etc. The purpose of this Appendix is to provide some chronological coherence to this organizational evolution. Proceeding:

1940 – The United States (US) Army Air Corps creates a Map/Chart Section. The Map/Chart Section located in Washington, DC, later becomes known as the Aeronautical Chart and Information Service (ACIS).

1942 - The US Army Map Service (AMS) is created as a Field Office by the US Army Corps of Engineers.

1943 – The Aeronautical Chart Plant is created and located in St. Louis, Missouri.

20 September 1945 – The Cambridge Field Station (CFS) is created by the Air Technical Services of the US Army Air Forces and located in Bedford, Massachusetts. The CFS is charged with military research and development.

1947 – The United States Air Force (USAF) is created as a separate Military Service. It is formed by absorbing the US Army Air Forces (USAAF) of World War II (WW II). Organizations that provided aeronautical and geodetic support to the USAAF are also part of the USAAF-to-USAF transfer; this transfer occurring over time.

5 July 1949 – The CFS is redesignated the US Air Force Cambridge Research Laboratories (AFCRL). The AFCRL had responsibility for conducting geodetic research both in-house and via contract in support of Air Force requirements.

28 June 1951 – USAF AFCRL becomes the US Air Force Cambridge Research Center (AFCRC).

1952 – The USAF Aeronautical Chart and Information Center ( ACIC) is formed by transferring ACIS from Washington, DC, to St. Louis, Missouri, and merging it with the resident Aeronautical Chart Plant. (However, it appears from [5; p. 375] that ACIC may have been temporarily named the Aeronautical Chart Service.) The site occupied by ACIC is designated an Air Force Station\*.

1954 – The USAF is assigned “responsibility for America’s Major Missile Programs” [5; p. 381]. This, in effect, would limit over the years the geodetic role of AMS within the Department of Defense (DoD).

2 May 1960 – AFCRC is dissolved. Its Geophysical Division becomes Detachment 2 of Headquarters Air Force Research Division (a new Division).

1 August 1960 – Detachment 2, mentioned immediately above, becomes AFCRL (again).

1969 – AMS is integrated into the US ARMY Topographic Command.

1 July 1972 – The Defense Mapping Agency (DMA), a Tri-Service Organization, is formed with its Headquarters located on the US Naval Observatory grounds in Washington, DC. The agency elements consisted of the paper transfer and renaming of the following organizations:

+ AMS becomes the DMA Topographic Center (DMATC).

+ The US Navy Hydrographic Center (HC) becomes (DMAHC).

+ ACIC becomes the DMA Aerospace Center (DMAAC).

15 January 1976 – AFCRL is designated the Air Force Geophysics Laboratory (AFGL).

1978 – DMATC and DMAHC are merged to form (DMAHTC), the latter Center joining the former at its Bethesda, Maryland, location.

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\*An Air Force Station (AFS) and Air Force Base (AFB) differ in capability. An AFS is a facility that does not have a runway for supporting aircraft take-offs and landings.

1 October 1996 – The National Imagery and Mapping Agency (NIMA) is formed with:

+ NIMA East being a renamed DMAHTC.

+NIMA West being a renamed DMAAC.

24 November 2003 – The National Geospatial – Intelligence Agency (NGA) is formed with:

+NGA East being a renamed NIMA East.

+NGA West being a renamed NIMA West.

Note: The material contained herein was obtained primarily from [5], [15], and via personal communication with DoD retirees.

**APPENDIX G**

Heiskanen

-Gravimetric Geodesy and AFCRC\*/OSU Contracts-

It seems appropriate to identify Weikko A. Heiskanen as the creator of the Gravimetric Method. Without question, he was the main proponent for its use to create a geocentric WGS. Since this was the type of WGS required to support ICBMs, financial arrangements were made by the USAF for Heiskanen to come to America and assist in that endeavor. At that time (late 1940s), Heiskanen was the Director of the Finnish Geodetic Institute located at Helsinki, Finland.

Heiskanen relocated to Columbus, Ohio, in August 1950 and was ensconced in The Ohio State University (OSU) Mapping and Charting Research Laboratory (MCRL). The MCRL was an off-campus OSU element of the OSU Research Foundation (OSURF). The MCRL replaced the OSURF Mapping, Charting, and Reconnaissance Laboratory created earlier in 1947 [5; p. 376]. It is assumed that the reason the USAF selected OSU as the US destination for Heiskanen was because MCRL was already in existence and, perhaps equally or more importantly, was already providing mapping and charting support to the DoD via AFCRC/OSU contracts.

With the creation of the USAF in 1947, the responsibility for the AFCRC/OSU contracts shifted from the US Army to this new Service. Now, with Heiskanen available (1950) at the OSU/MCRL, the USAF, via continuation of the AFCRC/OSU contracts increased and expedited its gravity collection and gravimetric research efforts in support of WGS development. Under this AFCRC/OSU contractual arrangement, OSU [2; p. 294]:

-Collected on-file gravity data worldwide.

-Used the acquired gravity data and appropriate formulas to calculate:

+Gravimetric geoid heights and depict them graphically as a geoid height contour chart, the Columbus Geoid.

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\*For simplicity, only AFCRC is identified in the Appendix as being associated with OSU contracts. However, depending on the time interval involved, the reader is advised that AFCRC might have one of the following different designations: CFS (1945 – 1949), AFCRL (1949 – 1951), AFCRC (1951 -1960), AFCRL (1960 – 1976), and AFGL (1976 – 1985). (These acronyms are identified in Appendix F.)

+Gravimetric north/south and east/west deflection of the vertical (DOV) components and separately portray them in contour chart form.

These actions served to authenticate the Gravimetric Method as a valid approach to use in developing a geocentric WGS.

Soon after his arrival\* at OSU, Heiskanen created the off-campus OSU Institute for Geodesy, Photogrammetry, and Cartography which also contained an academic program in geodesy [5; p. 377]. Again, according to [5; p.377], the academic portion of the off-campus Institute became the on-campus OSU Department of Geodetic Science in 1961.

Occasionally, a Finnish Geodetic Institute colleague of Heiskanen’s would come to OSU to temporarily perform geodetic research and/or teach one or more courses in geodesy. The description and findings from any research performed were normally documented as an MCRL report or as a publication [3; e.g.] of the OSU Institute of Geodesy, Photogrammetry, and Cartography. The organizational and name changes occurring in 1960-1961, including timelines, are somewhat murky (2016) to the authors. However, with the 1961 formation of the Department of Geodetic Science, it seems appropriate to assume that OSU research in geodesy became vested in that Department at some specified time thereafter. In any case, OSU Department of Geodetic Science publications treating geodetic research began to appear quite regularly. The geodetic research leading to these publications was accomplished under AFCRC/OSU Contracts. (Beginning at an unremembered date, ACIC informally provided research ideas to AFCRC for consideration.)

Throughout the years, the OSU Department of Geodetic Science produced many, many dozens of publications. These publications documented the research sponsored by AFCRC and by the US National Aeronautics and Space Administration (NASA). The information contained in these reports were quite helpful to ACIC (and later DMAAC) personnel as they dealt with MC&G problems. Of special interest to Center G&G

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\*Two of Heiskanen’s graduate school students from the Finnish Geodetic Institute (Urho A. Uotila and Lassi Kivioja) emigrated to America (Columbus, Ohio) at approximately the same time. Uotila and Kivioja completed their Doctor of Philosophy Degrees in geodesy at OSU, the latter leaving at some point to join the Purdue University faculty at West Lafayette, Indiana. Uotila remained at OSU teaching geodesy and conducting geodetic research. He later became Chairman of the Department of Geodetic Science, serving in that capacity until his retirement.

personnel were publications containing the research performed by Dr. Helmut Moritz, when working during the summer at OSU as a research associate. Dr. Moritz was from the University of Graz (Graz, Austria) and could safely be described as the premier gravimetric geodesist of the western world. His 1967 Physical Geodesy textbook [7] (with Heiskanen as honorary co-author) serves to exemplify his talent.