# Design to Improve the Productivity and Execution of Gravity Surveys

Evan Demick, Kyle Luukkonen, Sadeep Nonis, Yuri Zhylenko

*Abstract*— **The National Oceanic and Atmospheric Administration (NOAA) is responsible for conducting gravity surveys which are used to measure the variations in the pull of gravity of the earth's surface. Gravity surveys are vital for the country's safety (e.g. creation of flood plain maps and evacuation routes) and the economy (e.g. used for detecting petroleum and natural gas). The current set of gravity measurements known as the North American Vertical Datum of 1988 (NAVD 88') are outdated and lack complete coverage of the United States and its territories (e.g. Alaska has minimal data coverage). To improve accuracy, NOAA has begun a new survey, named GRAV-D, to combine existing ground (high definition) and satellite data (low definition) along with new aerial data (taken from aircraft) to establish the new datum. There is a complex logistical process in conducting the aerial surveys that are subject to large uncertainties due to weather, vehicle and personnel availability, and equipment failures. This paper describes the design of a logistics process to reduce the variation in the standard survey block from 24.59 to 15.11 days/survey. This is required to meet a Congressional mandate stipulating that the survey be completed by 2022. Analysis of factors affecting the completion of block surveys indicates high variability in aircraft maintenance, equipment repair, and weather related delays. Analysis using a decision-support tool designed to assist planners in managing the process by identifying elements that contribute to schedule risk, and advising mitigating strategies, indicates improved contingency planning through: (i) additional spares, (ii) additional support personnel, (iii) weather forecasting, and (iv) improved coordination among contractors would significantly reduce delays in the execution of the plans.**

## I. Introduction

### A. Background

Gravity surveys play a vital role in the nation's regional safety and economic sustainability. Gravity surveys are used in creating flood plain maps and evacuation routes, they can be used to monitor changes in crustal movement over time to help predict earthquakes and water flow, and detect various natural resources underneath the earth's surface [5].

Gravity Surveys are a collection of measurements of the acceleration of gravity around the earth [8]. The acceleration measurements are then used to create a model of the Earth's geoid. According to NOAA and the National Geodetic Survey, a geoid is "the equipotential surface of the Earth's gravity field which best fits, in a least squares sense, global mean sea level" [6]. Essentially, the geoid model can be used to measure and evaluate elevations of the Earth's surface.

### B. Measurement Types

Measurements are taken using a variety of methods. Ground measurements are collected through the use of geodetic leveling, a process in which a self leveling instrument and two calibrated staffs are used to find the difference between the staffs, which represents the difference in elevation [10]. Ground leveling is a very effective and highly accurate way of determining elevations above mean sea level.

Satellite altimetry is another method used to construct gravity surveys [9]. The measurements taken by satellites can be thought of as a low definition image of the Earth's gravity field. They capture only large differences in the gravity field (mountain ranges and valleys) and cannot see small variations in the gravity field [8].

Airborne measurements represent the balance between satellite and ground measurements. While not as detailed as ground measurements, they provide a more continuous representation of the Earth's gravity field [9]. Airborne survey missions also allow for measurements to be taken along coastlines and beyond the shoreline where humans cannot venture and satellite imagery cannot reach [8].

### C. Mission to Update the Gravity Survey

The current set of gravity measurements is known as the North American Vertical Datum of 1988 (NAVD 88') [8]. These measurements were collected over several decades by many sources outside of NOAA with varying accuracy. Data in certain areas (e.g. Alaska and U.S. territories) is sparse. Coastlines (up to 100km offshore) are missing data altogether because geodetic leveling is not possible in water, boats cannot venture into shallow depths, and satellites struggle to provide accurate measurements in shallow waters.

The current set of gravity measurements (NAVD 88') has gradually become inaccurate because of crustal movement, erosion, and regional development. A slight tilt (Southeast to Northwest) is also present in current data. Throughout NAVD '88, there are measurements that are inaccurate up to

Manuscript received April 1, 2013. This project was sponsored by the National Oceanic and Atmospheric Administration (NOAA). All authors are students at the Volgenau School of Engineering, Dept. of Systems Engineering and Operations Research, George Mason University, Fairfax, VA 22030 USA.

E. Demick (edemick@gmu.edu), K. Luukkonen (kluukkon@gmu.edu), H. Nonis (hnonis@gmu.edu), and Y. Zhylenko (yzhylenk@gmu.edu).

two meters in numerous areas of the United States.

To improve upon the NAVD 88' data set, NOAA has begun a new survey known internally as GRAV-D. The new Gravity for the Redefinition of the American Vertical Datum (GRAV-D) project aims to fill in the gaps from the NAVD 88' project to create a more comprehensive set of gravity data. Through the GRAV-D project, discrepancies between the satellite gravity measurements and the leveling measurements can be adjusted using data from airborne surveys.

### *D. Logistics Process*

Before embarking on a survey, the aircraft, measuring equipment and personnel must be transported to the base airport in which the survey will be operating from. Transporting equipment and personnel takes on average one or two days, but may take longer when transporting to farther destinations (Alaska or Hawaii).

Once the aircraft, equipment, and personnel have arrived at the base airport, survey preparations may begin. Measuring equipment is installed into the aircraft and calibrated. Several test flights are conducted to ensure functionality of the measuring equipment before conducting official survey flights.

Upon completing the equipment installation and test flights, official survey flights may commence. Aircraft depart from the base airport and fly to a pre-determined starting location based on a standard 400 by 500 nautical mile flight block. As shown in Figure 1, individual flights from one end of the survey block to the other end occur until the flight block has been completed.

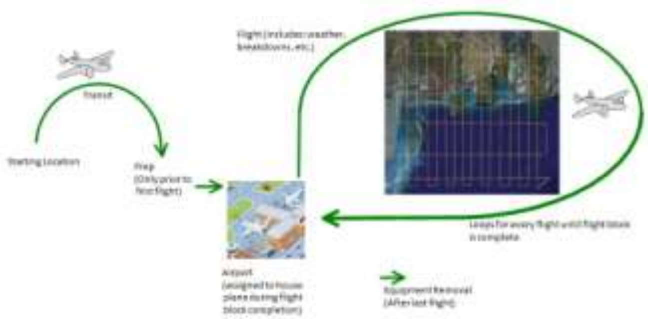

Fig 1. Logistics Diagram

Upon completing the survey, the measuring equipment is removed from the aircraft and each piece is returned to its home base.

The survey process is highly variable and is subject to several sources of disruption: (1) aircraft maintenance, (2) aircraft repair, (3) equipment repair, (4) weather delays, (5) personnel days.

To determine which steps in the process of completing gravitational surveys has the highest variability, a detailed analysis of historical data from nineteen surveys conducted from 2008 to 2012 has to be compiled to find its distribution.

The graph in Figure 2 represents the distribution for the number of days it took to accomplish all of the gravity surveys that have been completed to date. The Y-Axis represents the total amount of surveyed regions (nineteen in total) and the X-Axis represents the amount of days it took to complete the survey. The further right on the X-Axis indicates that more days were required to complete a survey. The distribution has a mean of 17.3 days and a standard deviation of 6.14 days.

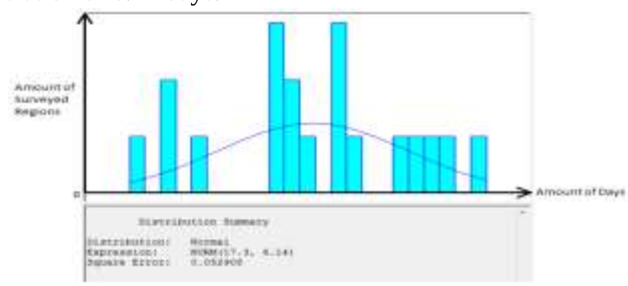

Fig 2. Distribution graph for Survey Days (Normal, $\mu = 17.3$, $\sigma = 6.34$)

Figure 3 represents the distribution for weather delays that impacted the GRAV-D project. The Y-Axis represents the amount of survey regions (nineteen in total) and the X-Axis represents the amount a survey was impacted by weather. The further right on the X-Axis means that more days were impacted by weather during a survey. There is an outlier on the far right where one of the surveys in Alaska faced severe weather delays.

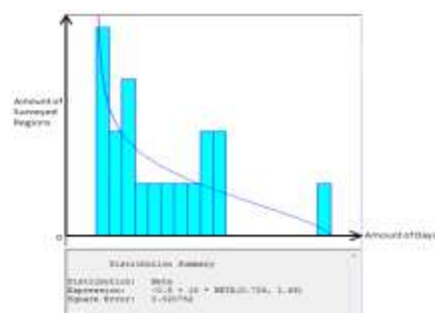

Fig 3. Distribution graph for Weather Delays (Beta, $\mu = 4.98$, $\sigma = 4$)

The same process was used to calculate the distribution for other processes as shown in Table 1.

| Factors | Type of Distribution | Mean (days) | Standard Deviation (days) | Square Error |
|---|---|---|---|---|
| Aircraft Maintenance | Beta | 5.57 | 8.18 | 0.036 |
| Aircraft Repair | Beta | 3.85 | 6.77 | 0.025 |
| Equipment Repair | Beta | 2.14 | 3.80 | 0.035 |
| Weather Delay | Beta | 4.98 | 4.00 | 0.021 |
| Personnel Day | Gamma | 3.06 | 1.84 | 0.005 |

Table 1. Data from analysis of each parameter.

These results indicate the contributions of each of these factors in delays in the survey blocks. Aircraft Maintenance represents the highest mean delay (5.57 days) as well as the largest variation (8.18 days). Aircraft repair ($\mu$=3.85, $\sigma$=6.77), weather delays ($\mu$=4.98, $\sigma$=4) and equipment repair ($\mu$=2.14, $\sigma$=3.8) exhibited high variance.

To meet program target completion goals these delays must be reduced. They key is to reduce the variance.

## II. Stakeholder Analysis

### *A. National Oceanic and Atmospheric Administration*

The National Oceanic and Atmospheric Administration is a federal agency within the Department of Commerce with the mission to monitor the world's oceans and atmosphere. NOAA plays a key role in our everyday life as they monitor daily storm threats, track climate change, support the maritime industry, and restore coastal environments. For the GRAV-D project, NOAA acts as the primary stakeholder responsible for logistics planning and project execution.

### *B. Federal Emergency Management Agency*

The Federal Emergency Management Agency relies heavily on gravity data from NOAA to implement flood zones for the National Flood Insurance Program. FEMA currently uses and requires NAVD 88' data for the distribution of flood control certificates. New GRAV-D supplied data will be implemented by FEMA for floodplain maps, which are used in creating building code requirements and in land-use decisions.

### *C. Department of Commerce*

The Department of Commerce funds the GRAV-D project through federal mandate 80-373 and has set forth a completion deadline of fiscal year 2022. Additional support may be given to NOAA to compress the project schedule.

### *D. Airplane Contractors*

Several airplane contractors are utilized by NOAA to complete the GRAV-D project. The airplane contractors provide aircraft and pilots to the project. Each contractor has a different set of constraints that can greatly impact the success of the project (e.g., Navy aircraft cannot fly near Cuban coastline).

### *E. Pilots and Support Crews*

The pilots and support crews active on each gravity survey play a vital role in the outcome of the GRAV-D project. Pilots are supplied by each airplane contractor while the support crews (individuals that operate gravity measuring equipment) are NOAA employees. Support crews also encompass maintenance personnel that are generally provided by the airplane's contractor. In extreme circumstances, maintenance may be contracted out to maintenance personnel at on site airports in order to return the aircraft to the air as quickly as possible.

### *F. Stakeholder Tensions*

The National Oceanic and Atmospheric Administration must operate the GRAV-D project on a given budget from the Department of Commerce and must meet annual target goals. NOAA is also limited by the amount of time and area that the aircraft can fly depending on the airplane contractor.

## III. Problem and need statements

### *A. Problem Statement*

NOAA has to reach 8% geographic area coverage annually to meet the federal mandate. A plan to reduce variability within the gravitational survey is needed to maximize coverage within budget before the Fiscal Year 2022.

### *B. Need Statement*

NOAA needs to complete the 8% annual quota but receives limited funding from the Department of Commerce. Making the gravity survey reduce variability will remove the tension with the Department of Commerce on NOAA's need for more financial backing by decreasing the time needed to complete a survey block. By allocating resources NOAA can reduce the variability in the time it takes do aircraft maintenance and aircraft repair. NOAA can also reduce the variability in personnel days and time spent down due to weather. The best combination of reduced variability will give NOAA the best results in decreasing time to complete survey blocks.

## IV. Design Alternatives

The focus of the project is to provide recommendations and design a planning support tool, which will assist in planning and executing gravitational surveys in order to cover all United States territories by year 2022. Due to limited budget and high variability in different aspects of the project, there has been excessive downtime in the past. After analyzing NOAA's historical data, each major process was fit to a distribution (see Table 1). The team has determined that the goal is to reduce uncertainty in controllable variables. There are couple alternatives that may improve the existing logistics process.

The first alternative is to focus on performance to improve the execution of gravitational surveys and reduce variance in several variables that cause extra delays and unnecessary downtime. Improving performance may significantly reduce the amount of delays in a survey. The key is to determine which of the factors has the biggest impact in reducing duration variability of a survey. One example is having more aircraft maintenance to reduce future breakdowns. Certain conditions cannot be controlled, such as downtime due to bad weather.

The second alternative is to acquire additional resources such as aircraft, equipment suites, or personnel. Currently, NOAA only operates with six aircraft, 4 teams, and two equipment packages (equipment packages include a gravimeter, IMU, and GPS base stations). By having only a few resources, NOAA is severely limited by the number of surveys they can complete during a fiscal year. Focusing on availability may provide the needed resources to meet the target goal of 8% annual coverage. Additional assets will cost more money, but will speed up the process by allowing multiple surveys to be done at the same time and may be more beneficial in the long run.

The third alternative is to use a combination of the first two alternatives if the budget allows. By improving the variables with the greatest impact on performance and increasing the availability of the most limiting resources, the gravity surveys may be completed in the fastest possible time. It would take a lot from the budget to implement this alternative and may not be feasible.

## V. METHOD OF ANALYSIS

### A. *Simulation*

After performing analysis on the data of the previous surveys, the major processes were fit to distributions based on the amount of days that the process took (Table 1). The Grav-D survey logistics process was modeled as shown in Figure 4. One of the assumptions was process independence so there is no correlation between variables.

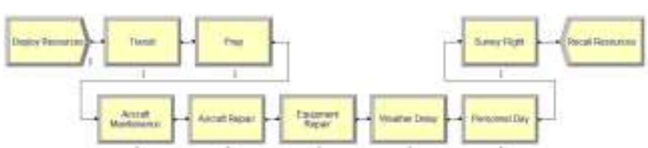


Fig 4. Simulation represented in Arena Modeling Software

There are 10 independent processes in series to reflect the logistics procedure. The simulation begins at the "Deploy Resources" block where an entity is generated. This is the entity that represents the necessary resources to complete a gravity survey. Each process block adds days based on the calculated distributions that the entity spends in the system. There are several decision blocks where the simulated survey may face delays.

To verify that the model is correct, the simulation data was compared to the historical data. The average amount of days that a survey takes using this simulation is 44.01 days. This number is fairly close to the actual survey average calculated from the past data which is 41.63 days. The worst case scenario of the simulation was 110.45 days which is fairly reasonable. From historical data, the worst survey took 76 days and when taking the worst values from each process then it took 130 days.

Calculating the correlation between different processes further supports the model as shown in Table 2. The relationship is symmetric so only half the table is shown. The value determines the magnitude of the correlation and the sign determines the relationship whether it's positive or negative. There is little correlation between some of the comparable variables, like aircraft maintenance and aircraft repair. Some of the parameters are considered coincidental because they would not make sense in a real world application.

| | Weather Delay | Aircraft Maintenance | Aircraft Repair | Equipment Repair | Personnel Day |
|---|---|---|---|---|---|
| **Weather Delay** | 1 | -0.21 | -0.066 | 0.49 | 0.17 |
| **Aircraft Maintenance** | | 1 | -0.0055 | -0.16 | 0.62 |
| **Aircraft Repair** | | | 1 | -0.029 | -0.24 |
| **Equipment Repair** | | | | 1 | 0.33 |
| **Personnel Day** | | | | | 1 |

Table 2. Table represents the correlation between different processes based on historical data.

To determine which extraneous variable has the biggest impact on the duration of the survey, the variance of each distribution was reduced gradually from 5% to 25% in increments of 5%. After each change the simulation ran for 10,000 replications and was compared with the data from the original run.

### B. *Design of Experiment*

A Monte Carlo simulation was performed with 10,000 replications per run, with each replication representing a single survey.

The simulation provided the results after each variance reduction step. The given data included minimum, maximum, and mean values of days to complete a single survey. From this data the 10%, 50%, and 90% confidence intervals were calculated and recorded in a table. Each confidence interval represents the likelihood chance for the amount of time to complete a survey block. The following equations were used for interval calculation.

$$(10\%\ interval) = (\mu - min) * 0.2 + min \quad (1)$$

$$(50\%\ interval) = \mu \quad (2)$$

$$(90\%\ interval) = (max - \mu) * 0.8 + \mu \quad (3)$$

## VI. RESULTS

The 90% confidence interval showed the greatest change. The difference from the original data was calculated and graphed as shown in Figure 5.

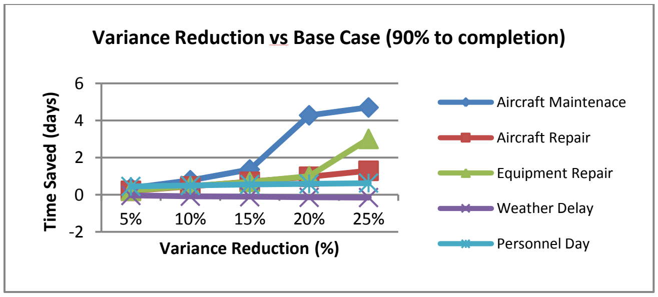


Fig 5. Graph that shows the number of days that could be saved per survey as the variance of each process was reduced.

Based on the results from this chart, the variables with the biggest impact on the length of the survey as well as their magnitude were identified. The rank of each process variability and the possible mitigation strategies are shown in Table 3.

| Factors | Rank in Variability | Max Delay Reduction (days) | Mitigation Strategies |
|---|---|---|---|
| Aircraft Maintenance | 1 | 4.70 | Additional maintenance personnel. Preventative maintenance. |
| Aircraft Repair | 3 | 1.29 | Improved maintenance. Available spare parts. |
| Equipment Repair | 2 | 3.01 | Back up equipment. |
| Weather Delay | 5 | -0.15 | Weather analysis from regional historical data. |
| Personnel Day | 4 | 0.63 | Schedule days off around other delays. |

Table 3. Parameter variability rank with mitigation strategies.

Table 3 ranks each factor in terms of their variability and the order in which the survey planners should focus their energy and resources.

Aircraft Maintenance shows the greatest reduction in survey days among each factor (4.70 days). It is feasible to see this reduction through several different mitigation strategies. Additional onsite maintenance personnel can help minimize service downtime for the aircraft and preventative maintenance can help prevent future breakdowns.

Weather Delays showed no reduction in survey days and instead showed an increase. This factor has lowest priority since weather is uncontrollable. However, survey planners can analyze historic weather patterns from potential survey regions to determine when to schedule surveys.

## VII. Recommendations & Conclusion

Based on the analysis and the results on the execution of gravity surveys, it is recommended that NOAA focuses on the performance of the surveys by allocating any available budget towards improving parameters with the highest variability which will reduce the time to conduct an average survey by 3 - 9 days resulting in more surveys being complete in 44 days or less. Reducing the amount of days will reduce the time that resources are deployed thus resulting in less spending and staying within the budget constraints. Saving up to 47.4 days of survey time annually, will result in conducting another survey or more resources being available for the next fiscal year. This method will avoid some of the major delays in the future and allow more surveys to be completed such that there is enough area covered to reach the project deadline of FY2022.

## Acknowledgment

We would like to thank the project planning team from NOAA for all of the information they provided us, and specifically, Sandra Preaux for acting as the project's sponsor. We would also like to thank the instructors: Dr. Lance Sherry (lsherry@gmu.edu), Mrs. Paula Lewis, and Mr. Juan Mantilla for their feedback and support.

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