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GOING DEEP: A SYSTEM CONCEPT FOR DETECTING DEEPLY BURIED FACILITIES FROM SPACE

by

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Contents

Page

Illustrations

Chapter 1

Introduction

> *"Hard problems are those areas where there are particularly significant technical challenges, which, if solved, would counter a significant operational or strategic threat. Examples include: detecting and neutralizing hardened and deeply buried facilities..."*
>
> Hon. Edward "Pete" Aldridge
> Undersecretary of Defense for Acquisition Technology and Logistics
> Testimony before Congress, 2001

Finding deeply buried facilities stands out as one of the toughest technical challenges in the Air Force's efforts to find, fix, target, track, engage and assess targets of interest anywhere on earth. Use of deeply buried facilities is prevalent among potential enemies of the United States such as Iraq, Libya and North Korea because they realize they cannot confidently defend their airspace against United States airpower. Such nations have located potential high-value, high-interest targets such as weapons of mass destruction (WMD), WMD manufacturing plants and storage areas, missile garrisons, fuel storage areas and command and control nodes underground. All of these targets are critical to an enemy nation's ability to project power beyond its borders and threaten United States allies, friends and interests abroad.

Deeply buried facilities, whether they are bunkers buried under many meters of earth or tunnels dug into mountains, are hard find. In many cases only a door or an air vent reveal the presence of what could be a deeply buried facility with thousands of square meters of floor space. These small aboveground signatures can be easily masked from visible, infrared and other sensors making detection by existing intelligence assets very challenging. Furthermore, most deeply buried facilities of interest are located in denied areas, meaning any sensors must operate from standoff ranges beyond the reach of an adversary's armed forces.

There is no "silver bullet" intelligence solution to the problem of detecting deeply buried facilities. The solution comes from combining several sources of intelligence, including imagery intelligence, e.g. photographs from satellites or aircraft; measurement and signature intelligence, e.g. detecting heat, sound, vibration or chemical exhaust; signals intelligence, e.g. analyzing radio or radar signals, and human intelligence, the use of spies and informants, to locate and characterize a deeply buried facility. Effectively integrating these intelligence sources to find a deeply buried facility becomes easier when the approximate location of the targeted facility is known. Obtaining the approximate location of the facility requires an intelligence capability that can cover wide search areas, determine the rough location and size of a deeply buried facility from stand-off ranges and do so using technology that is difficult to mask or counter by an enemy. This capability could then be used to cue other intelligence assets to focus in on a specific area and collect more detailed information about the facility.

To find such a capability it is necessary to go outside the realm of traditional intelligence systems and look at ways that scientists or other specialists may use to understand what is going on beneath the surface of the earth. Geophysicists and geologists used gravity field measurements for over 100 years to analyze geologic structures beneath the earth's surface. Gravity field measurement is useful in understanding the types of soil, rocks and minerals beneath the earth because variations in the density of underground soil and mineral deposits cause minute but measurable variations in the force of gravity. Geologists, for example, can locate oil by looking for variations in gravity field strength caused by the low-density underground salt domes that contain oil. Similarly, it may be possible to detect deeply buried facilities by measuring the gravity field variations caused by the void created in the rock or soil where the facility is built. Intelligence officers could look for gravity field variations caused by deeply buried facilities that are less dense than the earth around them in the same way oil geologists look for salt domes that are less dense than the rock around them. Since it is very difficult to alter the earth's gravitational field, it would be equally difficult to mask the gravity field variations caused by a deeply buried facility, making gravity field measurement a reliable source of intelligence for deeply buried facility detection.

Gravity measurement technology in use for geophysics applications today could be advanced and integrated into an effective system for locating deeply buried facilities from space. Experience gained from current space borne, ship borne and airborne gravity field measurements, combined with ongoing research, provides a solid technical foundation to create a space system capable of deeply buried target detection. Data gathered by such a system could then cue other types of sensors to the targeted facility. Working together, these sensors would characterize the construction and functions of the facility in a manner that is very difficult to spoof. Information about the construction and functions of the facility will be necessary for those planning to destroy or neutralize the facility.

This paper will focus on the development and application of gravity field sensors for deeply buried target detection. It will begin with an explanation of what deeply buried facilities are and how their construction and use has evolved over the years. Next, the discussion will look at the weapons available today to counter deeply buried facilities and the intelligence information needed to make these weapons effective. The information needed to properly target these weapons will directly influence the capability of the sensors needed to detect and characterize deeply buried facilities. The focus of the paper will then shift to intelligence sources, starting with the intelligence capabilities available today and the ability of a potential enemy to counter those intelligence assets, then shift to exploring intelligence sources not in use today and their potential application in the hunt for deeply buried facilities. Finally, this paper will investigate gravity measurement technology to address the problem of deeply buried facility detection and characterization. The examination will include the history of gravity measurement technology, current uses for geology and earth science, ongoing laboratory developments and the applicability of this technology to the search of deeply buried targets. The discussion will conclude with desired system capabilities and potential system concepts.

Gravity field measurement has proven its worth in over 100 years of oil geology and earth science applications. It has enormous potential to help with the search for deeply buried targets. The effort to determine how much gravity field measurement can help in the search for deeply buried targets must start with understanding deeply buried targets themselves.

Chapter 2

Deeply Buried Facilities – Understanding the Threat

Deeply Buried Facilities are Not a New Idea

Going deep underground to gain a military advantage against the enemy is not new. Sappers dug tunnels under castle fortifications in Middle Ages to attack the walls of the enemy's structures. Once the tunnel was dug under the wall, a large fire would be lit under the wooden support beams that held up the tunnel ceiling. The fire would cause the beams to break, the ceiling would collapse and the ground under the fortification would give way, allowing attacking forces to exploit the resulting break in the fortification. This is where the word "undermine" came from.

Pennsylvania coal miners dug under the Confederate lines at Petersburg, Virginia during the Civil War and detonated 8,000 pounds of black powder to provide Union forces a breech in the Confederate lines.[1] In both these examples, what could be called the first generation of deeply buried facilities were used offensively to breech the enemy's defensive fortifications. Of important note is that these actions could be done out of sight of the enemy and out of the reach of the enemy's weapons. Digging tunnels to breech fortifications continued into World War I. Allied combat engineers tunneled under German lines on several occasions to create an opportunity for attack that otherwise would not have existed. The use of deeply buried facilities would escalate in future conflicts, in large part due to the increase in airpower capability.

The increased use of airpower in World War II was primarily responsible for changing deeply buried facilities from offensive to defensive in nature. The actions of Nazi German leadership during World War II provide ample evidence of the transformation in the use of deeply buried facilities. Adolph Hitler and his senior leaders had seen the destruction that their own Luftwaffe could bring upon enemy targets such as the Polish city of Warsaw in 1939. They took significant steps to protect themselves and critical war capabilities from Allied air attack. German Armaments Minister Albert Speer and Admiral Karl Doenitz, commander of German U-Boat forces, personally coordinated the construction of submarine pens along the French Atlantic coast.[2] These reinforced concrete structures were built into steep cliffs to protect the U-boat force that was vital to the war in the Atlantic. When Hitler gave the V-2 missile program his highest priority in 1943, the factory to build the V-2 was established in a system of caves in the Harz Mountains of Germany.[3] This cave system had been previously built for storage of chemicals vital to the war effort. Putting the V-2 factory in a deeply buried facility allowed production to be done in secret with protection from Allied air assault. In addition, senior German leaders took extraordinary measures to protect themselves from air attack. Many, like Hitler and Luftwaffe Chief Herman Goering, had multiple bunkers, each located near places they frequently visited. The thickness of the roofs of these bunkers increased as the size of the bombs used by the Allies increased until the roofs were 16.5 feet thick.[4] While these facilities did not turn the tide of war, they demonstrated that deeply buried facilities could provide an effective measure of defense against an enemy with air superiority.

North Korea realized the need for deeply buried facilities shortly after the start of what they call the “Fatherland Liberation War” in 1950. North Korea made a concerted effort to move critical war industries into secure locations in response to overwhelming United Nations air superiority.[5] For example, the 65th Arsenal at Pyongyang was moved 70 miles to an empty mine near Songchon. The process was 70 percent complete when United Nations forces overran the area.[6] Deeply buried facilities may have been of more benefit to the North Koreans if they had started preparing them before the war. Chinese Leader Mao Tse-Tung is reported to have told North Korean leader Kim Il-Sung that he could have won the war if he had built tunnels under the South Korean border to move his troops south in secrecy and without threat of air attack.[7]

The Cold War saw a dramatic increase in the construction of deeply buried facilities primarily in response to the deployment of nuclear weapons and the advent of strategies of deterrence. Both the United States and the Soviet Union sought to increase the survivability and thus the credibility of their nuclear deterrent capabilities by moving critical elements underground. Ballistic missile launch facilities, command and control centers and even emergency offices for senior government officials were moved into bunkers or into facilities dug deep into mountains. Many of these facilities remain today, including the U.S. facility at Cheyenne Mountain and the Russian facility at Kovinsky Mountain.

Other nations developed significant deeply buried fortifications for more conventional conflicts. United States forces in Vietnam encountered Viet Cong and North Vietnamese deeply buried facilities throughout the Vietnam War. The substantial Viet Cong tunnel complex in the Chu Chi region of South Vietnam was a prime example of the deeply buried facilities the United States faced during the Vietnam War. First discovered by United States forces in 1966, the complex consisted of multiple levels of concrete and steel reinforced tunnels and trenches capable of supporting an entire battalion.[8] These tunnels were heavily damaged by air strikes, but still provided significant support to the Tet Offensive in 1968.

Currently, North Korea, no doubt based on the lessons learned from the Korean War, has become the most fortified country in the world.[9] North Korea embarked on a fortification program in 1962 to put most of its critical military infrastructure underground. This effort included building an airbase into a granite mountain with room for an entire regiment of aircraft and its associated maintenance and support facilities.[10]

Two other examples of the numerous fortifications in North Korea are the North Korean Army tank tunnels, and tunnels under the demilitarized zone between North Korea and South Korea. The tank tunnels are designed to protect North Korean armor from air or ground attack by enemy forces prior to the start of a major battle. Each tunnel is 250 meters long, 5 meters high and 4 meters wide and capable of holding 29-30 T-54/T55 tanks along with their necessary support vehicles.[11] Alternatively, each tunnel could hold an entire regiment of FROG 5 short-range surface-to-surface missiles.[12] These tank tunnels were not easy to build. Each tunnel took 9-12 months to complete and required the removal of about 14,000 cubic meters of rock from the mountain into which it was built.[13] While these tunnels may not have the capability to be "buttoned up" to survive a nuclear or chemical weapons attack, they nonetheless provide substantial protection for North Korea's fielded forces. This protection could prove vital in shielding North Korean forces in the opening stages of a conflict and allow them to carry on the battle even after the United States and its allies had gained air superiority.

Unlike the defensive tank tunnels, the tunnels under the Korean demilitarized zone were designed for purely offensive purposes, i.e. allowing North Korean troops to surprise their United States and South Korean opponents by quickly penetrating their lines at the beginning of a conflict. The effort to build tunnels under the Korean demilitarized zone began in 1974. An estimated 22 tunnels are under the 255-mile long demilitarized zone.[14] Only four tunnels have been found to date. It is interesting to note that none of these tunnels had an opening on the South Korean side. The apparent course of action for the North Korean army is to keep the tunnels closed on the South Korean side until needed and then use explosives to quickly create an opening to the south. An estimated 8,000 troops per hour, along with their support equipment, could move through these tunnels once they are opened.[15] While in the tunnels the troops would be concealed from detection and protected from United States airpower. It is believed that most of the estimated 22 tunnels still exist today. The North Korean tank tunnels and demilitarized zone tunnels are Cold War legacy fortifications that still pose a threat to United States forces. The threat of deeply buried facilities is made worse by newer, more sophisticated structures being added by America's enemies. These new facilities, combined with the Cold War legacy facilities described above, make for a potent 21st century deeply buried facility threat.

21st Century Threats

Today, those that oppose the United States have made significant investment in deeply buried facilities to counter United States airpower. Among those nations are Iraq, Iran and North Korea, labeled as the "Axis of Evil" by President George W. Bush in his 2002 State of the Union Address. These nations, and others such as Libya, use deeply buried facilities to protect assets that would become high value targets for air attack in the event of a conflict with the United States. These assets include command and control nodes, weapons of mass destruction (WMD) manufacturing and storage facilities, and ballistic missiles. Such assets are precisely the types of equipment a rogue nation would use to project power beyond its borders and threaten its neighbors and United States interests. Countering such capabilities is a high priority for the United States. A specific goal of the most recent United States National Security Strategy is to "prevent our enemies from threatening us, our allies and our friends with weapons of mass destruction."[16] Achieving this goal requires the United States to develop a robust capability to find and target deeply buried facilities.

To find and target deeply buried facilities effectively, it is necessary to understand how they are built. Understanding how deeply buried facilities are built provides valuable information for both detection, knowing what to look for, and targeting, knowing how to attack the facility. While there are numerous uses for deeply buried facilities, there are really only two types of construction methods used to create them, cut and cover facilities and tunnels.[17] Cut and cover facilities, as the name implies, are built by digging a large hole in the ground, building a reinforced concrete bunker and then covering the facility with soil and stone. These facilities are typically covered with 100 feet or so of rock and soil. The amount of material on top of the facility is known as the overburden.[18] The greater the overburden, the more protection the facility can provide. Tunnels are dug directly into mountains or other geologic features. They typically have more overburden than cut and cover facilities because of the nature of their construction. A tunnel into a mountain, for example, is usually built closer to the base than to the top of the mountain. This means it is likely to have much more than the 100 feet of overburden typically found in cut and cover facilities, and that overburden is usually solid rock as opposed to a mixture of soil and rock seen in cut and cover facilities. Each type of facility has advantages and disadvantages. Numerous factors must be taking into consideration when deciding between cut and cover facilities and tunnels to fulfill deeply buried facility requirements.

Key factors that influence the type of deeply buried facility built for a particular purpose are cost, local terrain and mission. These factors are not independent of each other. For example, cut and cover facilities are typically cheaper to build than tunnels. In some cases, however, a tunnel would be cheaper to build if there were an existing mine in the area that could be transformed into a deeply buried facility. Location and mission requirements may also influence each other. If the mission of the deeply buried facility is to provide a secure command and control location for national leadership it should ideally be located somewhere near a nation's capital, if not very close to the actual buildings which normally house the national leadership. Creating a tunnel-type facility for this purpose would be very difficult if there were no mountains close to a nation's capital. Modern tunneling machines make it possible to drill tunnels into flat ground as well, however, these tunnels would likely not have the same amount of overburden as tunnels into mountains, therefore providing less protection. Mission requirements also influence facility designs in other ways. Some facilities are used to house weapons and/or troops prior to battle. This means men and equipment must exit the facility to engage in battle, the North Korean Army tank tunnels being an example. Other facilities do not require the occupants to leave the facility to perform their missions. More complex facilities can "button up" and perform their missions protected from outside attack. Such facilities have systems to provide power, water and purified air for some period of time if they are cut-off from external utilities. Command and control bunkers and weapons of mass destruction manufacturing facilities are among these more complex facilities. Cost, location and mission requirements clearly influence deeply buried facility design. The type of deeply buried facility threats the United States faces in the future will likely be influenced by combat successes the United States achieved in Operation Desert Storm against Iraq.

Combat experience against United States airpower has significantly influenced the design and use of current deeply buried facilities. Many facilities have gone deeper underground as a result of lessons learned from Operation Desert Storm. Iraq and other nations took note of the United State's ability to defeat some deeply buried facilities such as the Taji command and control bunker near Baghdad. Al Qaeda and Talaban forces applied Desert Storm lessons together with their own experiences with Soviet airpower in Afghanistan when they chose to make their final stand in the Tora Bora cave complex during Operation Enduring Freedom. Our enemies clearly see the need to go deep underground to counter the asymmetric advantage of United States airpower. Countering an enemy's ability to do so requires gaining an understanding of facility construction and mission and then using that understanding to exploit potential weaknesses.

Countering Today's Threats

Countering today's threats starts with the intelligence process that turns data about things like facility location, construction and mission into vital information that can be used to exploit potential weaknesses in the underground facility. Intelligence helps airpower planners determine the best method to use in attacking a specific deeply buried facility. "Hard kill" and "functional kill" are the two methods used today to counter deeply buried facilities. Hard kill is the direct destruction of the facility, causing the walls, facility roof and/or tunnels to collapse. This is an effective method, but it is becoming harder and harder to accomplish as facilities go deeper underground. The alternative to a hard kill of a facility is a functional kill. A functional kill means that the facility is prevented from accomplishing its mission without actually being destroyed. The tactics used to accomplish a functional kill depend on the mission of the facility. For example, a North Korean tank tunnel will not be effective unless troops and equipment can leave the facility to enter the battlefield. Blocking the facility ingress and egress points with debris from a bomb attack, for example, means the forces in the tunnel cannot enter battle. This is a functional kill of the tank tunnel. More complex facilities require more complex tactics. Facilities designed to accomplish a mission while buttoned up are not directly impacted by attacks on their ingress and egress points since personnel do not have to leave the facility to accomplish their mission. A functional kill of these facilities means cutting their links to obtain resources from outside the facility such as air, power, water and communications connections that tie the facilities to the outside world.[19] A command and control facility, for example, is of no value if it loses its communications links. Likewise, most manned facilities can only operate for a short period of time if cut off from an external supply of air. Even advanced facilities with their own power generators and water storage cannot stay isolated from the outside world forever. Every facility has a weakness; the challenge is to find and exploit the weakness in time to positively influence the outcome of a conflict.

Neutralizing a facility requires proper intelligence to determine the weak points of the facility and the proper selection of weapons to attack those weak points. The type of weapon used depends on the method of attack. The primary weapon for hard kill of a facility is the GBU-28 "bunker buster" bomb developed during Operation Desert Storm. The GBU-28 is a 13-foot long, 4,700-pound laser guided bomb designed to penetrate up to 100 feet of soil or approximately 22 feet of reinforced concrete.[20] It was developed and used effectively against Iraqi deeply buried facilities in 1991. The GBU-28 is effective against most cut and cover facilities, but is not as effective against deeper targets because it cannot penetrate the substantial overburden associated with these facilities. There are several penetrator programs underway to counter the tendency to place critical facilities even deeper underground. Each of the services is building new penetrator weapons. The Air Force and the Navy are creating penetrators for the Joint Air Surface Stand-off Missile, and the Joint Stand-off Weapon respectively, and the Army is doing likewise for the Army Tactical Missile System.[21] There is also discussion of an advanced nuclear penetrating weapon as a follow-on to the current B61-11 penetrator deployed in 1997.[22] The most intriguing advanced concept, commonly called "Rods from God," would substitute hard steel penetrators for nuclear warheads on Intercontinental Ballistic Missiles. These solid steel penetrators would not explode, but would instead use the large amounts of kinetic energy imparted by the ballistic missile to damage or destroy deeply buried targets. The more kinetic energy imparted to the steel penetrator during its flight on a missile, the greater the destruction it will do when it hits the ground.

Each of these concepts has promises and drawbacks. In general, developing better and better penetrators will ultimately be unsuccessful because, as one expert put it, "you can always find a mountain that's going to go a lot deeper than the weapon".[23] It is easier for potential enemies to dig deeper than it is for the United States to develop a penetrator hard enough and fast enough to break through the facility overburden. Additionally, the use of intercontinental ballistic missiles and nuclear weapons may be extremely difficult to employ in the strategic context of the limited conflicts the United States will face in the future. Intercontinental ballistic missiles and nuclear weapons have always been considered as weapons of total war. Using such weapons in a limited conflict, such as removing Iraq's WMD capability, would likely face significant domestic and international political opposition. Use of such weapons in less than total war could also have the unwanted side effect of making them acceptable for other nations to use in limited conflicts, which is something the United States definitely does not want. All these limitations on hard kill weapons make it more likely that functional kill methods will be the chosen course of action against deeply buried facilities in the future.

A variety of weapons are available for use in functional kill attacks against deeply buried facilities. The most recent addition to the functional kill arsenal is the BLU-118/B thermobaric weapon, which is packaged as a GBU-24 laser guided bomb.[24] The weapon is designed to create a functional kill in deeply buried facilities where a hard kill may not be possible. Upon detonation inside the entrance to a tunnel, the thermobaric weapon creates significantly more heat and pressure than a conventional explosive. The resulting blast wave is effective against personnel and equipment even though it may do only limited damage to the structure of the facility itself.[25] The weapon was used against Al Qaeda and Taliban forces in the Shahi-Kot Valley of Afghanistan in March 2002.[26]

Functional kills of deeply buried facilities can also be achieved by using conventional precision weapons, such as the GPS-guided Joint Direct Attack Munition, against facility weaknesses including air shafts, ingress and egress points, power and communications links. Making effective functional kills against increasingly capable facilities requires improves intelligence to find the facilities and characterize them. A successful functional kill attack requires precise information on the location of the facility, its external links and ingress/egress points. This information is used to effectively target precision-guided munitions against the weak points of the facility. The problem is that this information is often difficult to obtain since deeply buried facility users often go to great lengths to protect or at least hide facility weak points from potential adversaries. Targeting information necessary to achieve a functional kill will become more important in the future as facilities go deeper and get tougher to attack via hard kill techniques. The rest of this paper will focus on meeting the challenges of finding and understanding the operations of deeply buried facilities.

Chapter 3

Locating Facilities and Understanding Their Uses

Deeply buried facilities are hard to find and once found are difficult to attack. Finding and targeting deeply buried facilities requires detecting the facility, pinpointing its exact location, determining the number, size and location of rooms in the facility, understanding the function of the facility and locating ingress and egress points and/or power, water, air and communications links with the outside world. Effectively targeting either cut-and-cover facilities or tunnels usually requires multiple sources of intelligence including imagery, signals, human and measurement and signature intelligence. The use of multiple sources is necessary because one source usually cannot provide all the information needed to effectively target a facility. Also, using multiple sources of intelligence makes the collection effort less susceptible to spoofing by the enemy. Effectively integrating intelligence assets in the hunt for deeply buried facilities requires understanding the strengths and weaknesses of each type of intelligence. Understanding the capabilities and limitations of each type of intelligence will allow analysts and mission planners to find and integrate the multiple signatures created by deeply buried facilities into a coherent picture of the facility. This coherent picture is the key to effectively targeting the facility. While any single intelligence source could hold the key to effective targeting of deeply buried facilities, the hunt usually begins with imagery.

Visible Signature

Looking for signs of a deeply buried facility from imagery satellites or aerial reconnaissance is usually the first step in facility detection. Imagery intelligence can detect signs of a deeply buried facility in the visible, infrared and hyperspectral frequency ranges. Visible imagery gathers data in the same optical wavelength as the human eye. Infrared imagery, as the name implies, collects data in the infrared spectrum. This usually involves looking for sources of heat such as that created by generators, machinery or engines. Hyperspectral imagery is collected at frequencies beyond the visible and infrared bandwidths. Hyperspectral images can help reveal information not obtainable through other forms of imagery intelligence such as the moisture content of soil. This data can also help distinguish camouflage netting from natural foliage. Each of these types of imagery intelligence has its own capabilities and limitations.

Ideally, visible imagery assets would detect the facility while it is under construction. Cut and cover facilities in particular would have large signatures because of the very large holes and large piles of turned earth created by their construction. Once found, the construction progress could be monitored and assessments made as to the vulnerability of the facility. In practice this is difficult because the large areas of land that need to be covered by a limited set of imagery intelligence assets. For example, Iraq alone is slightly more than twice the size of Idaho, 437,072 square kilometers.[27] Searching these large areas for signs of deeply buried facilities has to compete with many other collection requirements placed on the same limited assets.

Further, facility construction can also be masked from imagery intelligence identification. There are two primary methods of masking facility construction and/or operations, which apply to visible imagery and other sources imagery intelligence, simulation and dissimulation. Simulation is making something look like the target the enemy wants to see when it really is not the target. For example, a construction crew could dig a large hole to attract attention the of intelligence assets to the presence of a potential deeply buried facility. Meanwhile the actual facility is being built at another location, unbeknownst to the intelligence assets that are focused on the deception created by the large hole in the ground. Dissimulation or camouflage, on the other hand, is making an actual target appear to be something else to an opponent's intelligence assets. This would entail making the actual construction and operation of a deeply buried facility appear to be something else. One such technique for dissimulation is to combine the construction of the deeply buried facility with construction of an openly acknowledged above ground building. Consider the example of the large bunker built to protect members of Congress from nuclear attack during the Cold War. This substantial construction effort was accomplished as part of an addition to the Green Briar resort in West Virginia. Detecting tunnel construction is even harder because the only visible signature of a tunnel construction site comes from the entrance and perhaps large amounts of rock and dirt removed during construction. Neither is easy to spot. Even if spotted they could easily be confused with legitimate commercial mining efforts. Once built, tunnel entrances and openings such as exhaust ports can be camouflaged, further adding to the detection problem.

Infrared imagery provides an alternative to visible imagery by looking for heat sources emitted by deeply buried facilities. Infrared sensors look for heat such as exhaust vents and entrances. Infrared imagery could provide information about facility operations. For example, the level of heat coming from a facility is a key indicator of the activity going on inside. As with visible imagery, the techniques of simulation and dissimulation can be applied to thwart infrared intelligence assets. Dissimulation of infrared signatures involves masking the facility's thermal output by using some method to cool the air prior to leaving the facility. This creates an artificially small infrared signature. Simulation uses false thermal sources in other locations to make infrared sensors think they have actually found a thermal source related to the deeply buried facility, when in fact they have not. This would be easy to do, especially if the facility was located near an area with many of above ground buildings to provide alternate heat sources.

Hyperspectral sensors provide another alternative to visible and infrared imagery intelligence. Hyperspectral sensors work in multiple frequency bands beyond the visible and infrared spectrum so they provide the potential for detecting deeply buried facility signatures that cannot be detected by visible or infrared imagery intelligence assets. For example, hyperspectral sensors could be used to detect information about a facility's operation by examining exhaust gases or water discharge from a deeply buried facility, especially facilities manufacturing chemical or biological weapons. As infrared sensors look for sources of heat, hyperspectral sensors could look for signatures in air or water associated with particular chemicals. However, these sensors also have their drawbacks. First, it is not possible to detect every type of chemical or material of interest using hyperspectral sensors. Second, deeply buried facility users could use commercially available air and water pollution control devices, like those used in the commercial chemical industry, to reduce the amount of certain materials in their air or water exhaust, thus hampering hyperspectral detection methods.

One additional imagery intelligence source capable of producing both images and sets of digital data describing terrain features is radar. Radar imagery systems use electromagnetic beams reflected off the earth's surface to produce images and digital models of the earth's surface. The information contained in these digital models is known as Digital Terrain Elevation Data (DTED). DTED models contain a series of latitude and longitude points on the surface of the earth, with each point having a terrain height value associated with it. Integrating large numbers of DTED points together can create detailed computer models of the earth's surface. This data comes from space radar missions including the Shuttle Radar Topography Mission (SRTM) in 1998 and the Canadian RADARSAT spacecraft. Since DTED provides very precise elevation measurements at certain locations on the ground, it could be used to detect activities associated with the construction or operation of deeply buried facilities. A minor change in elevation at a specific location on the ground could be the result of deeply buried facility construction. Large debris piles from cut and cover facility or tunnel construction could register as changes in terrain when examining DTED data from the same location over a period of time. Imagery intelligence in general provides multiple potential methods for detecting the signature of deeply buried facilities. Each of these methods can, however, can be deceived by a potential adversary. Successfully using imagery intelligence to detect deeply buried facilities requires combining it with other intelligence sources to reduce the vulnerability of one method of detection.

Other Detection Methods

Imagery intelligence may be the most recognized source of information about deeply buried facilities, but other sources are also critical to the search for deeply buried facilities. Signals intelligence and human intelligence are two valuable sources of data. Signals intelligence intercepts of radio and telephone communications could provide information on facility location and operations. Defectors associated with the construction or operation of deeply buried facilities could provide human intelligence. Information provided by defectors helped lead to the discovery of the first of an estimated 22 North Korean tunnels under the Korean Demilitarized Zone.[28] Concentration camp laborers were used in V-2 production during World War II in part because they had little communication with the outside world and, therefore, were less likely to become sources of human intelligence on the location and operation of the deeply buried V-2 production facility.

A variety of other detection methods can be placed under the heading of Measurement and Signatures Intelligence (MASINT). The use of MASINT for detection focuses on a variety of different signatures created by the construction and use of the facilities. For example, acoustic or seismic sensors could be used to detect the sound or vibrations associated with the operations of deeply buried facilities. Magnetometers could be used to detect large metal objects underground such as key pieces of equipment located in a deeply buried manufacturing facility.[29] Magnetometers are extremely sensitive versions of the metal detectors used by airport security screeners. The United States Navy uses magnetometers on low-flying aircraft to search for submarines by looking for the magnetic signatures of the large metal submarines that stand out from the ambient magnetic field of the ocean. The common problem with each of these sensors, however, is that they need to be placed fairly close to the facility to gather the data effectively. Acoustic, seismic and magnetic sensors could also be confused by nearby signatures not associated with the deeply buried facility. Imagine trying to detect the acoustic signature of a suspected deeply buried facility that is located beneath a noisy industrial area in a large city. The background noise would most likely mask the signature of the facility. Like imagery intelligence, MASINT can contribute to the hunt for deeply buried facilities, but each source has its limitations.

One additional method for facility detection involves combining cues from multiple sources of intelligence like those mentioned previously, then finding the facility the old fashioned way by digging for it. United States forces in Korea used this method to locate four Demilitarized Zone tunnels. Drilling teams used cues from other intelligence sources to drill survey holes and lower sensors to find the tunnels. This method is very time consuming, however. It has led to the discovery of only 4 of a suspected 22 tunnels in 18 years of work.[30] These drilling surveys also required the 43-person search team to have unrestricted access to the area around the suspected deeply buried facility. This is not likely in many locations other than the Korean Demilitarized Zone.

What's Left?

All of the previously mentioned capabilities could contribute to deeply buried facility detection and characterization. However, as such facilities become strategically more important and harder to find, other methods must be considered. One method that deserves further investigation is detecting deeply buried facilities through variations in the earth's gravitational field. While very small, these variations are detectable. Gravity field measurement offers the potential to detect deeply buried facilities in a manner that is very difficult to spoof or confuse. The remainder of this paper will look at methods of gravity field measurement and how they can be applied in the search for deeply buried facilities.

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Chapter 4

Gravity Measurement

Isaac Newton first postulated the existence of gravity in his Second Law that states every object in the universe is attracted to every other object. The force of that attraction is a function of the mass of the respective objects and the distance between them. Since the earth has a substantially larger mass than any object on or near the surface of the earth, the attraction of individual objects to the earth overwhelms any attraction between two separate objects on or near the surface of the earth. Gravity is the force of attraction between objects on or near the surface of the earth and the earth itself. The force of gravity is represented in the equation:

$$F_g = G \frac{(m_1 \text{ x } m_2)}{r^2}$$

F_g is the force of gravity, G is the universal gravity constant, m_1 is the mass of the earth, m_2 is the mass of the other object attracted to the earth, and r is the distance between the two objects.

The accepted value F_g on the surface of the earth is 9.81 meters per second squared (m/s^2). This, however, is the *average* value of gravity on the surface of the earth. The actual value of gravity varies from point to point on the surface of the earth because the actual mass of the earth, m_1, varies from point to point. This point-to-point variation occurs because the earth is not homogeneous. The earth is made up of water and wide variety of rocks, soils and minerals each with varying mass. Therefore, the mass of the earth at any given point is a function of the types of material present below the surface of the earth at that point. For example, the value of F_g on top of a granite mountain will be greater than value of F_g on a sand-covered beach because granite has more mass than sand. If you could precisely measure F_g at any given point on or near the surface of the earth you could gain insight into what lies beneath the surface of the earth because the mass of the earth will vary depending on what materials lie beneath the surface. Taking this idea one step further, it is possible to detect a deficiency of mass beneath the surface of the earth that shows subsurface material was removed to construct a deeply buried facility. Gravity field measurements could be used to help detect deeply buried facilities if the gravity field can be measured accurately enough.

Gravity Measurement Concepts

The challenge with gravity measurement is that variations in the force of gravity are very small. Variations of the force of gravity on the earth's surface are on the order of 10^{-6} of the average value of 9.81 m/s^2.[1] That means characterizing materials or voids below the surface of the earth requires an instrument that is capable of measuring variations in the force of gravity that are less than one one millionth of the force that caused the apple to fall on Sir Isaac Newton's head. To be of value in the search for deeply buried facilities, a method of gravity field measurement must be found that is accurate enough, yet also portable, easy to use, and capable of operating at standoff range. Range is particularly important since deeply buried facilities will most likely be located in denied areas. Gravity field strength is a function of the distance from the surface of the earth. The distance r appears in the force of gravity equation as $1/r^2$, therefore an increasing in range will have a significant decrease in the force of gravity, making stand-off gravity field measurements very challenging.

There are two ways to measure the force of gravity at any point on the surface of the earth. The first is direct measurement of the force of gravity using a device known as a gravity meter or gravimeter. A gravimeter uses a proof mass, which is a fancy way of saying a block of material whose mass is precisely known and does not change over time, and suspend it from a spring. The stronger the force of gravity, the further the mass stretches the spring. Figure 1 shows the basic layout of a gravimeter.

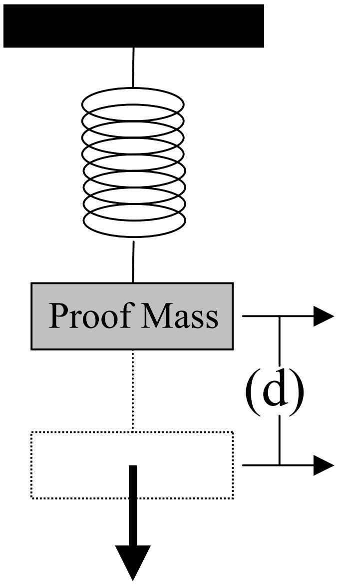

Figure 1. Gravimeter [2]

The basic unit of gravimetric measure is a milligal. One milligal is equal to a gravitational force of 10 micrometers per second per second, or slightly more than one one millionth of the force of gravity experienced by a person standing on the surface of the earth.[3] Since a gravimeter measures the force of gravity in such extremely small units, it is very susceptible to motion. Gravimeters cannot distinguish between the force of gravity and acceleration due to motion of the instrument itself. Therefore, gravimeters are not suitable for use from moving vehicles since even the slightest acceleration, such as that of a car hitting a bump in a road or an airplane experiencing turbulence, tends to overwhelm the gravity measurement results.[4]

The second method of gravity measurement is to measure the change in gravity from one location to another. The change in the force of gravity over a certain distance is known as the gravity gradient. The device used to measure the gravity gradient is a gravity gradiometer. Figure 2 shows the first gravity gradiometer known as a torsion balance.

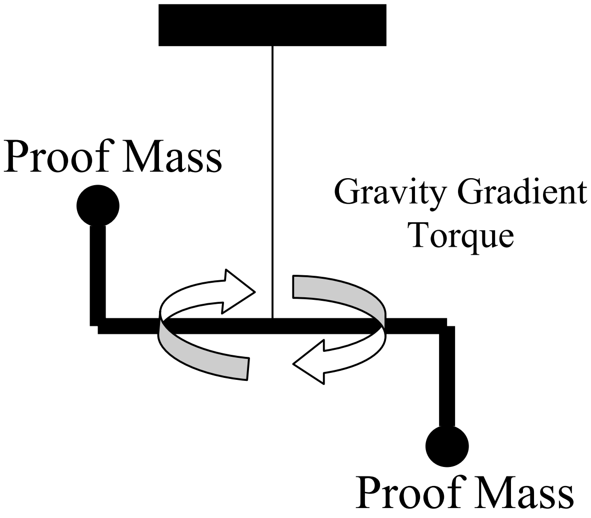

Figure 2. Torsion Balance[5]

The torsion balance consists of a beam suspended on a thin fiber. At either end of the beam are proof masses, each suspended at different heights from the end of the beam. Because the gravity field is not uniform, there is a slight difference in the force of gravity acting on each of the two masses. This difference causes the torsion balance to twist. The unit of gradiometric measurement is the Eotvos (pronounced *Eht-vosh*). The unit is named for Hungarian physicist Baron Roland von Eotvos who developed the torsion balance in 1890.[6] One Eotvos or one E equals 10^{-9} ms^{-2}/m or $10^{-9}/s^{2}$.[7] One E is a change in the force of gravity of $10^{9}m/s^{2}$ for every meter traveled. One E is the equivalent to an adult taking one step and during that step experiencing a change in the force of gravity equivalent to one one billionth of the normal force of gravity he or she experiences standing on the surface of the earth. Though this is an extremely small unit of measure, it is possible to develop a map of variations in the strength of the gravity gradient over a particular area by measuring the amount of twist in the torsion balance at various locations. A strong gravity gradient means a large change in gravity force. A large change in gravity force, or a large value of E, is caused by a change in the type or amount of material below the surface. For example, a large gravity gradient could indicate a deposit of low-density rock surrounded by high-density rock. A large gravity gradient could also indicate a large void in high-density rock that could be an indication of a deeply buried facility.

A gradiometer measures very small forces, but unlike a gravimeter, it can be used from a moving vehicle, as long as the vehicle is moving in a straight line. This is possible because a gradiometer uses multiple sensors to measure gravity field strength. In the case of the torsion balance, the use of two proof masses makes it possible to cancel out common accelerations due to vibrations of the vehicle because both proof masses will experience the same acceleration. Straight line motion is necessary because lateral accelerations caused by turns will impact each sensor differently causing the instrument to be overwhelmed by acceleration in the same manner as the gravimeter. While the torsion balance itself is not ideally designed for use in a moving vehicle, the basic concept of using multiple sensors to measure the gravity field makes a gradiometer superior to a gravimeter for measurements from a moving vehicle, a critical factor if the device is to be used to search large areas for deeply buried facilities.

The ability to make measurements from a moving vehicle makes gravity gradiometry the clear method of choice to help locate deeply buried facilities. The challenge is to find a gravity gradiometer that meets the previously established requirements of accuracy, portability, ease of use and standoff range. To find the right gravity gradiometer to fulfill the deeply buried target detection mission, it is worthwhile to look at the history of gravity gradiometer development, including its past and current applications.

History of Gravity Gradiometry

Baron von Eotvos successfully demonstrated his torsion balance in 1901 when he used it on a frozen lake to attempt to survey the contours of the lakebed. He took measurements at multiple sites on the ice. The results of his survey compared very well to earlier soundings of the lakebed taken with line and sinker, the "state of the art" measurement device of the day.[8] This successful demonstration was confirmed by other geologic surveys of the area that demonstrated the effectiveness of the torsion balance.

After World War I, American geologists used the torsion balance in the search for oil.[9] The geologists hoped the torsion balance would detect the presence of underground salt domes that often had large oil and gas deposits around them. Salt domes had been very hard to find because they hardly ever reached to the surface of the earth. American oil geologists believed that since salt domes are less dense than the rocks surrounding them, the change in density between the salt domes and the surrounding rock should be indicated by gravity gradient measurements. They turned out to be correct. Geologists of the Amerada Hess Corporation using a torsion balance made the first discovery of a major oil deposit in the state of Texas in 1924.[10] This success and others like it caused more geologists to use the torsion balance in their search for oil. By 1935 the torsion balance was used routinely in oil exploration.

The initial success of the torsion balance did not guarantee its long-term use, however. The device was extremely cumbersome to use in the field. To make a measurement, geologists first had to clear a 100-meter long swath in eight directions from the point where the balance was to be set up. This clearing was necessary to prevent the mass of nearby trees and large rocks from interfering with the measurements of the torsion balance. Recall that Newton's second law said all objects in the universe were attracted to each other. The forces measured by the torsion balance were so small that is was possible to confuse the attraction of the proof masses to the earth with the attraction of the proof masses to large, above ground objects nearby. A small building to house the torsion balance had to be setup once the area was cleared. This building protected the torsion balance from wind and temperature changes. Even with these precautions, the torsion balance could still be thrown off by nearby power lines or by large belt buckles worn by the geologists.[11] Data collected by gradiometer surveys was also difficult to interpret which sometimes lead to false conclusions being drawn from the gradiometer surveys. Gravimeters, on the other hand, did not have the same operating problems, as did gradiometers. Gravimeters did not require the extensive site preparation like that needed for the gradiometer. The data produced by gravimeters was also easier to interpret since it was a straight measurement of the force of gravity rather than a measure of the change in the force of gravity over a certain distance produced by gravity gradiometers. Theoretically, the gradiometer had an advantage over the gravimeter because it could be used from a moving vehicle. However, in practice the sensitive torsion balances used for oil exploration were not well suited for operation from a moving vehicle. The lack of a clear advantage of gravity gradiometers over gravimeters, combined with the problems of using gravity gradiometers, led to an increased investment in gravimeter technology. This technology investment made gravimeters an even more attractive choice over gravity gradiometers for oil exploration. The result of all this was that by the 1950's, gravimeters had replaced gravity gradiometers in most gravity field measurement applications.[12]

Gravity gradiometers may have languished in geophysics obscurity were it not for the discovery of an operational military need to make gravity field measurements from a moving vehicle. U.S. and Russian scientists both realized the importance of gravity field measurement to inertial guidance systems in the 1970s.[13] Knowing the gravity field strength at the point of launch of the missile helped improve the accuracy of the missile's inertial guidance system. The local gravity field could be easily measured at fixed launch sites using existing gravimeters. It was more difficult, however, to measure the strength of the gravity field at the numerous potential launch sites for mobile launch systems such as ballistic missile submarines. The United States Navy contracted with what is now Lockheed Martin Bell Laboratories (Bell) in Buffalo, New York to develop a system that could measure the gravity field around a submarine. The system had to be accurate enough to provide reference data for the inertial guidance systems of the submarines missiles and to help the submarine navigate itself by sensing minute variations in gravity caused by underwater ridges and mountains.[14] A total of $400 million was spent on the project.[15] The Navy's system significantly advanced the technology of gravity gradiometry to the point where it was possible to accurately measure the gravity gradient without encountering the operations or data analysis problems seen with the Eotvos torsion balance. Instead of proof masses, rods and strings used in the Eotvos balance, the Navy system used accelerometers. Accelerometers are small devices, usually only a few inches long, which contain their own small proof masses. The accelerometer measures the forces acting on the proof mass from a particular direction and converts that force measurement into an electric current value. The most common application of accelerometers is to trigger the deployment of automobile air bags during a car crash. The system developed by Bell for ballistic missile submarines used eight accelerometers to measure the force of gravity in the each of the three axes: x, y and z. Having two accelerometers to measure the force of gravity in a particular direction at the same time canceled out the effects of vehicle motion in the same manner as the

Eotvos torsion balance theoretically would have done by having two proof masses. Twentieth century technology thus addressed many of the shortfalls the 19th century torsion balance. Bell created a sensitive gradiometer that was easy to use and could work from a moving vehicle. This technology remained classified, however, until the end of the Cold War because of the important role it played in America's nuclear deterrent. Post-Cold War relaxation of some security restrictions in the 1990's brought the Navy technology to the attention of oil geologists. The military advancements in gravity gradient measurement technology made the gravity gradiometer attractive again for use in the search for oil almost 100 years after Eotvos developed his first torsion balance.

Current Applications

Oil geologists sought to apply the new gravity gradiometer technology to improve the effectiveness of their searches for new oil and gas deposits. The dwindling reserves in known oil and gas deposits, combined the cost of exploration, made the modern gravity gradiometer extremely attractive. The concept of using gravity gradiometers to locate salt domes with their associated oil and gas deposits had been proven 70 years earlier. The advancements made by Bell removed many of the problems encountered with the torsion balance and made relatively fast gravity field measurements from a moving vehicle possible. This combination of proven concept and dramatically improved technology made gravity gradiometry an ideal place to invest some of the $5 billion oil companies spend annually searching for oil and gas deposits.

Efforts began in Australia and the United States in the 1990s to apply the Bell technology for oil and mineral exploration. The Australian company BHP sought to field an airborne gravity measurement capability to address a need for more cost effective (read faster) oil and mineral exploration in the vast areas of the Australian outback. Airborne gravity surveys were long considered the “holy grail” of geophysics because of the capability to quickly survey large areas.[16] Airborne gravity surveys were extremely difficult in the past because aircraft motion overwhelmed the gravimeters used for the survey. BHP successfully deployed a version of the Bell gravity gradiometer on a single-engine Cessna Grand Caravan aircraft in October of 1999. The BHP system called Falcon used a Bell gravity gradiometer that measured the gravity gradient in a single vertical. Measurements were made by flying the aircraft at about 100 meters above ground level and collecting data in a 200-meter grid pattern.[17] BHP has successfully deployed other systems in Australia, Canada and South Africa since 1999.

Bell Geospace (not part of Lockheed Martin Bell Laboratories) in Houston began using a three-axis Bell gravity gradiometer on a ship to search for oil in the Gulf of Mexico. By 1998, seven oil companies were using gravity gradiometry to search for oil in the Gulf of Mexico. Modern gravity gradiometry proved more effective in mapping salt domes than previous seismic or other survey methods.[18] The Bell gravity gradiometer technology proved to be deployable on both aircraft and ships. The challenge for applying this technology to deeply buried facility detection is to determine if the device is sensitive enough to detect facilities at the standoff ranges necessary to conduct searches of denied areas. The Bell gradiometer proved effective at locating underground structures such as salt domes that are a kilometer or more in diameter. Deeply buried facilities are much smaller, with many being 10 meters or less in diameter, a hundred times smaller than the geological features found with the Bell gradiometer. Also, the airborne surveys done by BHP and others were done at altitudes of only 100 meters above ground level. Doing any kind of aerial survey only 100 meters over denied enemy territory would be extremely difficult. To be effective in the search for deeply buried facilities a gravity gradiometer needs to be able to operate beyond the range of most surface to air missile systems.

Sensitivity and range are the two key issues that must be addressed to successfully deploy a gravity gradiometer in the search for deeply buried facilities. While it may be possible to improve the current performance of the Bell gravity gradiometer, there are other promising gradiometer technologies that must also be investigated.

A variety of other technologies for gravity gradient measurement are being developed. Each technology effort attempts to solve the challenges of making sensitive measurements in a slightly different way. As expected, each application has its own capabilities and limitations. Some of these other devices are based on the use of Superconducting Quantum Interference Devices (SQUID). SQUIDs measure the disturbance caused by the movement of a proof mass within a magnetic field much like an airport metal detector reacts to a person with a large metal belt buckle walking through it. The difference is that SQUIDs can detect much smaller disturbances in the magnetic field than airport metal detectors and thus measure very small movements of their proof masses. The SQUIDs are capable of sensing movement in their proof masses as small as 10^{-13} centimeters.[19] This is about a million times smaller than the length of the average dust mite. One SQUID-based gradiometer is made of two very high performance gravimeters. This device measures the gravity gradient by determining the difference in the readings between the two SQUID gravimeters. Each gravimeter is setup like the gravimeter in Figure 1. In this device, however, the proof mass and spring are immersed in liquid helium, cooled to 4 Kelvin and surrounded by a reference magnetic field.[20] Movement of the proof mass caused by the force of gravity causes a disturbance in the reference magnetic field that is detected by the SQUIDs. Other SQUID-based devices use the movement of a thin string or measure the torsional displacement of two perpendicular blocks to obtain measurements of the gravity gradient.[21]

All these SQUID-based devices have proven workable in the laboratory, but they face significant problems when deploying to the field. The need to maintain cryogenic temperatures means these systems require bulky cooling devices and a sufficient supply of liquid helium. SQUIDs have also been shown to be overly sensitive to vibration because they are so precise and able to measure the slightest motion. This combination of cryogenic cooling requirements and sensitivity to vibration creates significant challenges in deploying SQUID-based gradiometers on the same type of platforms as the Bell gradiometer. It will be challenging to deploy SQUID-based devices in the field unless more advancements are made in their construction and operation.

Other advancements in gravity gradiometry have been driven by the desire of geophysicists to more accurately model our planet. Geophysicists need two types of data to construct a comprehensive physical model of earth: geometric measurement of the earth's surface and a detailed gravity field map.[22] Significant progress has been made on the geometric measurement yet little progress has been made on the gravity field map. To address this need, a space-based gravity gradiometry project was launched.

The $145 million Gravity Recovery and Climate Experiment (GRACE) is a joint mission between the NASA Jet Propulsion Laboratory and the German Aerospace Research Center. GRACE is a space-based gravity gradiometry survey mission. GRACE performs gravity gradient measurements in a unique manner. The mission consists of two 950-pound satellites flying in formation at a 311-mile altitude, 89-degree inclination orbit, with one satellite trailing the other by 200 miles.[23] The satellites use K and Ka band radar range finders to measure the distance between them to an accuracy of less than 10 microns. The satellites measure gravity by detecting how the distance between them changes as they pass over the earth. The change in distance between satellites happens when one satellite experiences a force of gravity, F_g, different than the other satellite. This causes the speed of one satellite to change relative the other satellite. The change in F_g is caused by variations in the mass of the earth below the satellite, which can be linked to variations in the types of material beneath the surface of the earth. The GRACE mission collects gravity gradient data by measuring the changing distance between the satellites and the time and place in the orbit at which the change occurred. This data can then be translated into a gravity gradient model of the earth. The GRACE satellites are capable of mapping the entire earth every 30 days using the process described earlier. They will map the earth 60 times during their 5-year mission that began in March 2002.[24] The result of the mission will be both a static map showing the average gravitational field of the earth and a dynamic map showing how the gravitational field fluctuates with movements of large ocean currents and magma beneath the surface of the earth.

The GRACE mission is capable of resolving a geologic feature 300 kilometers across and one centimeter thick using gravity gradient data.[25] This is helpful for geologists and geophysicists, but probably not helpful to those seeking deeply buried targets. GRACE does, however, provide the worldwide coverage and standoff range desired for deeply buried facility search system.

What is the Next Step?

Each of the current gravity gradient measurement technologies has some, but not all the desired characteristics of a system capable of searching for deeply buried targets. None of the current gradiometer technologies discussed, including the Bell gradiometer, the SQUID-based gradiometers and the GRACE space mission have, to date, demonstrated the required sensitivity at stand-off range needed to detect deeply-buried facilities from space. Creating an effective gravity gradiometer to go deep and hunt for deeply buried facilities requires examining both current and future gravity gradiometer technologies in more detail to determine their applicability to the mission. The next chapter will focus on this task.

Chapter 5

Applying Gravity Gradiometry to the Search for Deeply Buried Facilities

Gravity gradiometers need to be deployable and provide strategically or tactically useful resolution from a sufficient standoff range to be helpful in the hunt for deeply buried facilities. The search for the right technology for such a device needs to start by examining current technology solutions. Current technologies include the Bell gradiometer originally developed for the U.S. Navy, the SQUID-based gradiometers using various configurations of proof masses and the GRACE tandem-satellite system. Future technologies should also be examined. Future technologies now in concept development or initial laboratory research include an improvement to the GRACE satellite concept using laser range finders and a gradiometer that uses atoms as proof masses. Each of these technologies must be examined and their performance compared to estimates of the resolution needed to go deep and find deeply buried facilities.

Bell Gradiometer

The Bell gravity gradiometer was successfully used in military and civilian missions in a variety of configurations while operated from moving vehicles. The question is how will it work in the search for deeply buried facilities? The Defense Threat Reduction Agency (DTRA) sponsored an experiment in 1997 to investigate this issue. Conducted by the Air Force Research Laboratory (AFRL), the experiment used a Lockheed Martin Bell Laboratories Arms Control Verification Gravity Gradiometer to examine a known deeply buried facility. The device is essentially the same as that used by the Australian Falcon airborne survey system and was originally developed to distinguish nuclear-armed cruise missiles from conventionally armed cruise missiles during treaty verification inspections.[26]

The target of the experiment was a Missile Alert Facility at Vandenberg AFB, California. The facility is identical to others deployed across the strategic missile fields of the United States. Each Missile Alert Facility has two underground structures or capsules that are linked to each other and to the surface. One capsule is the launch control center, which houses the two-person missile crew, and the crew's command, control and missile launch equipment. The second capsule is the Launch Equipment Building which houses support equipment such as air conditioners and back-up diesel generators. The Vandenberg site was selected because good information was available about the depth of the facility and the size of the void created by the facility. This information was needed to validate measurements made by the gravity gradiometer.

The Vandenberg missile alert facility is a cut and cover type of structure. A large hole was dug, the reinforced concrete structure of the capsules was built and then the entire facility was covered over with the excavated earth. The Launch Control Center capsule is 4.7 meters in diameter and the adjacent Launch Control Equipment Building capsule is 3.5 meters in diameter, with the entire facility is located 12.2 meters below the surface. This configuration provides a good representative example of the types of facilities that could be deployed by adversaries of the United States. Successfully characterizing this facility would provide a firm foundation for future deeply buried facility detection systems.

The survey of the Vandenberg site was conducted in a manner similar to the airborne gravity gradient surveys done in Australia mentioned earlier. The Bell gradiometer collected data in a grid pattern mapped out on the ground above the facility; a total of 55 measurements were taking of the Launch Control Center, with 41 measurements made of the Launch Control Equipment Building.[27] Two members of the survey team physically moved the Bell gradiometer from point to point on the grid, with the entire survey being completed in a "few days."[28] This was a vast improvement compared with the ground clearing and facility construction problems associated with the oil field gravity gradiometer measurements made with a torsion balance.

Figure 3 shows the results of the gravity gradient measurements of the Launch Control Center. The results clearly indicate the presence of the capsule beneath the surface as evidenced by the strong gradient measurement near the zero value on the cross axis scale. The strong gradient is expected since the zero value on the cross axis scale marks the center of the capsule and thus marks the largest part of the underground void created by the capsule. The largest part of the underground void is expected to create the largest gravity gradient measurement because that is the point of greatest difference in gravity field strength between the capsule the surrounding earth. Figure 3 shows how gravity gradient measurements can be of value in detecting a deeply buried facility.

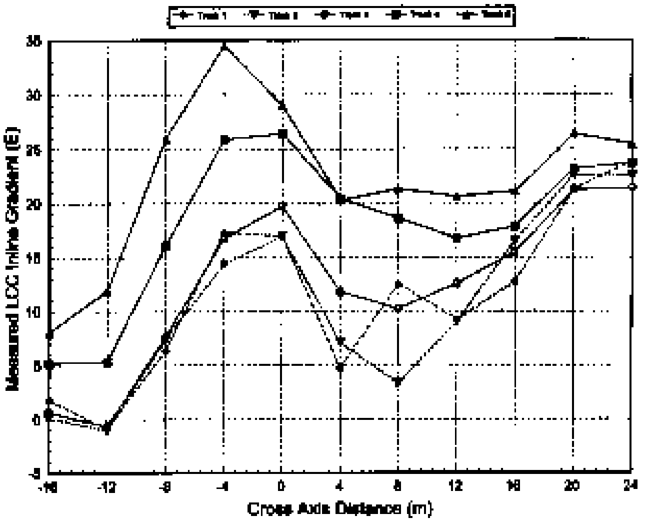

Figure 3. Inline Gradient Measurements of Launch Control Center[29]

Figure 4 shows the results of the gravity gradient measurements of the Launch Control Equipment Building. They are not as conclusive as the results of the Launch Control Center survey because only one of the four data sets gives the strong gravity gradient measurement shown by all five data sets in the Launch Control Center survey in Figure 3. It is not possible to absolutely determine the presence of the Launch Control Equipment Building based on this data though it is possible to argue that the strong results of the one data set would lead analysts to investigate the area further if this were an actual search for an enemy deeply buried facility. One possible reason for the inconclusive results is that the Launch Control Equipment Building is 30 percent smaller than the Launch Control Center, resulting in a weaker gravity gradient signal that was more difficult for the gravity gradiometer to detect. Another possibility is that the Launch Control Equipment Building signal was masked by subsurface clutter around it such as water tanks, blast valve ducts and air intake pipes.[30] The results of the Vandenberg Missile Alert Facility survey show that it is indeed possible to detect a deeply buried facility using gravity gradiometry. However, the effectiveness of the gravity gradiometry survey is very much a function of the sensitivity of the gradiometer and the size and configuration of the facility.

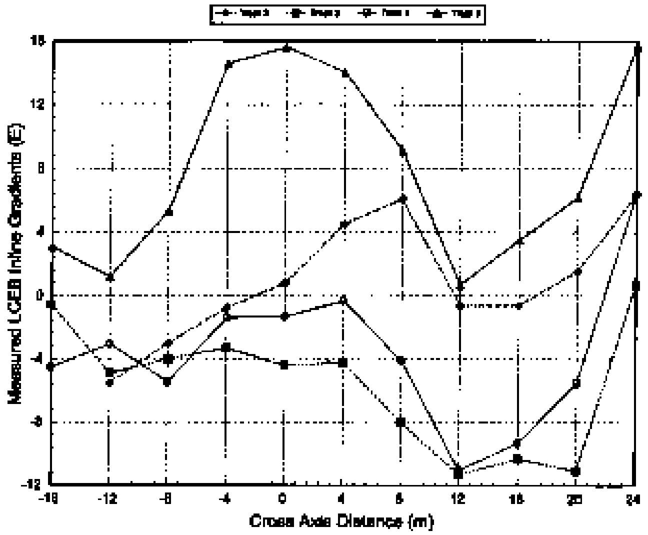

Figure 4. Inline Gradient Measurements of Launch Control Equipment Building[31]

The Vandenberg experiment also included efforts to determine the dimensions of the Missile Alert Facility using the data collected from the gravity gradiometer survey. The results of this portion of the experiment were fairly successful for the Launch Control Center. The gradiometer data estimated the Launch Control Center diameter to be 7 meters; the actual inner diameter of the capsule was 4.7 meters, not including the thickness of the reinforced concrete around the capsule. The depth of the Launch Control Center was estimated to be 8 meters when the actual depth was 12.2 meters.[32] Though not perfect, these results demonstrate the ability of a gravity gradiometer to be used as a “trip wire” sensor to initially detect and characterize a deeply buried facility and then cue other sensors to examine the facility in more detail. Similar estimates for the Launch Control Equipment Building were inconclusive. This again is not a failure of the experiment, but rather a demonstration of the impact that gradiometer sensitivity and facility size have on deeply buried facility detection using gravity gradient measurements.

The same AFRL-Lockheed Martin team conducted a similar characterization experiment with the same gravity gradiometer on the Low-Energy Booster tunnel of the Superconducting Super Collider in Waxahachie, Texas. The Low-Energy Booster is a reinforced concrete tunnel built in an area surrounded by limestone. The objective of this experiment was to characterize the dimensions of the facility and the direction in which the tunnel was going relative to the survey area. Four separate sections of the tunnel were surveyed for this experiment. As with the Vandenberg Launch Control Center capsule, the tunnel dimensions predicted by the gradiometer closely approximated the actual tunnel dimensions. For example, in one of the four sections the tunnel goes from 6.45 meters to 10.47 meters in depth. The gravity gradiometer data predicted a tunnel depth of 6.25 meters to 8.75 meters.[33] The direction of the tunnel relative to the survey area was also estimated with good accuracy. The difference between the actual value and the predicted value of the direction of the tunnel was between 2 and 5 degrees.[34] In an operational application, this means that it could be possible for a gravity gradiometer to show which direction a tunnel leads from an enemy's deeply buried facility, thus allowing other intelligence sensors to find facility ingress or egress points and effectively target them.

The results of both experiments show that gravity gradiometry in general and the Bell gradiometer in particular is capable of both locating and determining the basic dimensions of deeply buried facilities. However, all these experiments were performed on the surface of the earth and took days to accomplish. This particular process would not lend itself to quickly locating a deeply buried facility in denied enemy territory. An actual survey of enemy territory would need to be done in minutes or hours not days, and accomplished from standoff range. Significantly increased sensitivity would be needed to conduct surveys at standoff ranges with devices like the Bell Gravity Gradiometer.

SQUID-based Gradiometer

The extreme sensitivity that SQUID based gradiometers demonstrated in the laboratory makes this technology a potential candidate for detecting deeply buried targets. One device was so sensitive that it could detect motion of a human fist from 50 cm away.[35] The problem is being able to deploy these very sensitive instruments to the field. The need to keep the devices supercooled means there will be constant need for bulky liquid helium cryogen coolers. These coolers would significantly increase the mass of the system as well as limit the mission duration because the system would not work after all the liquid helium had been expended. Cryocooling would have its biggest impact on a space system. It would greatly increase the weight and, therefore, the cost to build and launch a space-based deeply buried target detection system. If a space system were built with a SQUID-based gradiometer it would likely have a mission duration of less than 18 months compared with the GRACE mission duration of five years. It is difficult to make a case for a $145 million investment like that made for the five year GRACE mission for a SQUID-based gradiometer mission that is planned to last less than two years if everything goes well. More field experience is needed before SQUID-based gradiometers can be considered for deeply buried facility detection and characterization.

Current GRACE System

The current GRACE system provides the foundation for space-based gravity gradiometry though it may not provide the resolution needed for deeply buried facility detection. The GRACE satellites are currently going through instrument calibration on orbit.[36] The system is expected to be able to resolve objects on the order of hundreds kilometers. This is good for geophysicists and geologists looking for oil deposits and studying ocean currents, but not for people searching for deeply buried facilities. GRACE can, however, provide a wealth of foundation data and experience conducting gravity gradiometry from space. This data and experience will be valuable if and when a more sensitive system is deployed to search for deeply buried facilities.

One potential step to improving space-based gravity gradiometry beyond the current GRACE capability is to look at improvements to the GRACE system for follow-on missions. There are plans for a potential follow-on system to GRACE that would use lasers, instead of K and Ka band transmitters to measure the distance between the satellites. This improved system would be able to measure changes in distance between the satellites in nanometers (10^{-9} meters) versus microns (10^{-6} meters), which is the capability of the current system. This improved measurement capability could improve gravity field measurement sensitivity to tens of kilometers rather then the hundreds of kilometers of the current system.[37] This resolution is still not good enough to hunt for deeply buried targets, but like the current GRACE system, an improved GRACE system could provide valuable experience and gravity field background data to support a future system focused on deeply buried target detection.

Quantum Gravity Gradiometer

Perhaps the most promising technology for increasing the performance of space-based gravity gradiometry beyond the current GRACE mission is the quantum gravity gradiometer. This technology is still in the laboratory, but already shows significant promise for making effective gravity gradient measurements from space. Like the original Eotvos torsion balance, the quantum gravity gradiometer makes gravity gradient measurements by detecting the difference in gravitational force acting on different proof masses. What makes the quantum gravity gradiometer unique is that the proof masses are individual Cesium atoms.[38] The challenge here is to determine a way to precisely measure the influence of gravity on something as small as an atom.

To understand how a quantum gravity gradiometer is possible, imagine a small cork floating in a bucket of water. Imagine the cork constantly bobs up and down, which causes a pattern of ripples to form on the surface of the water in the bucket. As the force of gravity acting on the cork changes, the pattern of those ripples will change. Measuring the change in the pattern of the ripples will allow you to measure the force of gravity acting on the cork. This is essentially how the quantum gravity gradiometer works. Quantum mechanics states that atoms behave as waves.[39] Since atoms behave as waves in the same manner as light, it is possible to measure those waves using an interferometer similar to those used to characterize laser beams. A laser interferometer takes the laser beam, splits it into two separate beams, and then recombines the beams to form an image. The image created is a pattern that results when the two beams recombine and interfere with each other, hence the name interferometer. The wave nature of an atom makes it possible to construct a device to perform interferometric measurements on a group of atoms the same way as could be done to characterize a laser beam. What makes this whole process sensitive to gravity is that while an atom behaves as a wave, it also behaves as matter with a finite mass. The finite mass of an atom makes it very sensitive to changes in the force of gravity.[40] Being sensitive to gravity means the interference pattern created by the atoms flowing through the interferometer will change as a result of the local gravitational force. Thus this gravity gradiometer concept is possible because of the quantum nature of atoms. The finite mass of the atom makes it sensitive to changes in the force of gravity and the wave nature of the atom makes it possible to precisely measure the influence of gravity on the atom using an interferometer.

While this may sound exotic, the quantum gradiometer described previously is actually an extension of proven atomic clock technology. An atomic clock measures changes in atomic waves over time rather than the spatial changes measured in a quantum gravity gradiometer.[41] Atomic clocks have flown in space for years as the heart of the Global Positioning System (GPS). Each GPS spacecraft has four atomic clocks on board, each of which operates for years at a time. The quantum gravity gradiometer itself is categorized as Technology Readiness Level (TRL) of 2/3 on the NASA TRL scale of 1-9(9 being most mature, 1 being least mature technology), which means research to prove the viability of the concept has been substantially completed.[42] While there is a firm scientific and technical foundation behind the quantum gradiometer, the system is still challenging to develop and operate.

There are several challenges associated with the quantum gravity gradiometer. One is that under normal circumstances an atom moves too fast to be measured using an interferometer. The atoms themselves must be cooled to the point where their wavelength is comparable with that of light so that the atoms can be measured with an interferometer.[43] This cooling process is done using lasers that emit photons at a specific frequency, which then collide with the Cesium atoms. The Cesium atom absorbs the photon it collides with, then emits another photon. The motion of the atom is slowed by the net effect of many such collisions thus causing the cooling effect. This process has been proven in the development and manufacture of atomic clocks but is nonetheless challenging and adds complexity to the system. Taking any science from the basic research stage, to proven technology and then to something that can be manufactured economically requires significant effort. The other key challenge is that the atoms need to be “falling” or floating above the surface of the earth to measure the impact of gravity on them. This is challenging in a laboratory environment on the ground. For a quantum gravity gradiometer to work on earth the atoms used must be lifted some distance off the surface and then allowed to fall. The "lifting" of the atoms is done using a device called a Magneto Optical Trap, which essentially traps the atoms in a magnetic field, raises them up like a water fountain lifting a small pebble out the water and then allows them to fall.[44] Measurements can only be taken during the brief period of time, measured in fractions of a second, when the atoms are falling. This situation adds complexity on the ground but actually makes the system perform better in the microgravity of low-earth orbit. In orbit there is no need for a Magneto Optical Trap, since the atoms will naturally be falling toward the earth at all times. Operating a quantum gradiometer in space would allow measurements for tens of seconds instead of the fraction of a second allowed on the ground. This situation allows measurements to be taken over much longer periods of time in space leading to significant increases in the sensitivity of the quantum gravity gradiometer.

The improvement in measurement sensitivity as a function of measurement time is substantial. Laboratory measurements using a quantum gravity gradiometer, with a measurement time of 60 milliseconds yielded a gravity gradient sensitivity of 10 $E/hz^{1/2}$.[45] In space, measurement times of many seconds are possible. Assuming a measurement time of 10 seconds, it is theoretically possible to achieve a sensitivity of 0.001 $E/hz^{1/2}$.[46] This number could be significantly improved with enhancements in device performance and even longer measurement times.[47] Compare these estimates with current gravity gradiometers that have a measurement sensitivity of 1 $E/hz^{1/2}$ and it is possible to see the potential associated with quantum gravity gradiometers. The real question will be whether the potential improvement in sensitivity with the quantum gravity gradiometer will be offset by locating the device in space 200-300 kilometers from the target as opposed to 10-15 meters from the target, which was the case for the previously mentioned AFRL experiments. Recall that the force of gravity F_g is a function of the inverse square of the distance between an object and the earth; therefore, increasing the distance of the gradiometer from the surface of the earth means the sensitivity of the instrument must increase substantially. Answering the question of how sensitive a space-based gravity gradiometer needs to be will take time and research and will most likely require a space experiment for definitive proof. A space experiment will be necessary to prove whether or not the theoretical predictions made in the laboratory are actually feasible in space. The substantial potential of quantum gravity gradiometry combined with the growing threat posed by deeply buried facilities make this investment worthwhile.

Notes

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[3] Ibid., 1.

[4] Ibid.

[5] Ibid., 2.

[6] Bell, Robin E. “Gravity Gradiometry”, originally published in *Scientific American*, Vol 278, Issue 6, 8 Oct 99, on-line, Internet, 22 October 2002, available from http://plinks.epnet.com/citation.asp, 76.

[7] Gravity Gradiometry, 8 Oct 99, on-line, Internet, 22 October 2002, http://www.geocities.com/CapeCanaveral/4764/gradiometry.

[8] Bell, 2.

[9] Ibid.

[10] Ibid.

[11] Ibid.

[12] van Leeuwen, 2.

[13] Frasier.

[14] Bell, 1.

[15] Van Leeuwen, 3.

[16] Ibid.

[17] Ibid., 4.

[18] Bell, 4.

[19] Ibid.

[20] Fraser, 4.

[21] Ibid., 4-6.

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[24] Ibid.

[25] Ibid.

Notes

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[27] Romaides, Anestis J. *et al*, "A Comparison fo gravimetric techniques for measuring subsurface void signals", *Journal of Physics D – Applied Physics*, Vol. 34, 2001, 439.

[28] Ibid., 443.

[29] Ibid., 440.

[30] Ibid., 441.

[31] Ibid.

[32] Ibid.

[33] Romaides – Draft Report, 2.

[34] Ibid., 6.

[35] Fraser, 4.

[36] Grace Newsletter #1 – 1 August 2002, on-line, Internet, 9 November 2002, available from http://www.csr.utexas.edu/grace/newsletter/2002/august2002.html

[37] Morring, 58.

[38] Yu, 1.

[39] Ibid.

[40] Ibid., 2.

[41] Kulikov, Igor K., "Gradiometry", Quantum Computing Technologies, on-line, Internet, 4 Nov 02, available from http://cs.jpl.nasa.gov/qct/qct/grad.html.

[42] Quantum Technology, slide 15 from Earth Science Enterprise Technology Planning Workshop – Innovative Technology, 23-24 Jan 01, on-line, Internet, 9 November 2002, available from http://nmp.nasa.gov/workshop-eo4/proceedings/ESE_Wkshp_Innovative_Tech.pdf - On the NASA TRL scale 2 means "Technology concept and/or application formulated", Level 3 means Analytical and experimental critical function and/or characteristic proof of concept".

[43] Morring, 58.

[44] Yu, 1.

[45] Ibid., 3.

[46] Ibid. 12.

[47] Quantum Technology slide includes an estimate that measurements of 0.000001 $E/hz^{1/2}$ are theoretically possible, though there was no such statement in the material directly produced by the scientists working on the experiment.

Chapter 6

Operational Concept – Going Deep with Gravity Gradiometry

Space is the best location for a gravity gradiometer and the quantum gravity gradiometer is the most promising technology for detecting deeply buried targets from space. A space-based system allows coverage of the entire surface of the earth, even areas that may be denied to aircraft because of sophisticated enemy air defense systems. The repeating nature of the satellite orbit allows a space-based gravity gradiometer to easily revisit the same area many times allowing analysts to look for changes in gravity gradients over time which could be an indicator of deeply buried facility construction. Repeated visits to the same location by an airborne system could make it vulnerable to enemy attack and also potentially give away the target of the aerial surveillance. A space-based gravity gradiometer provides the best platform for repeated gravity gradient measurements of large areas of denied enemy territory.

Employment Concept

Successfully employing quantum gravity gradiometer technology in the hunt for deeply buried facilities first requires getting the technology to the point where it can be taken out of the laboratory and deployed in space. The goal for this effort should be to achieve a Level 7 “System Prototype Demonstration in a Space Environment” on the NASA technology readiness level scale. Level 7 means the technology has been proven in the laboratory and proven in space. NASA, through the Jet Propulsion Laboratory (JPL), is currently spending $400,000 per year on a three-year program to advance quantum gravity gradiometer technology to the point where it can ready to fly in space, though no specific plans have been made for the flight.[1] The focus of the quantum gravity gradiometer effort to date has been to improve on the ability to collect data for geophysics purposes, essentially a follow-on to the GRACE mission. Making the quantum gravity gradiometer viable for deeply buried target detection will likely require more resources to be added to the program. The first step to obtaining these needed resources is to make the current gradiometer development effort a joint NASA/DoD project. Joint space science projects have proven successful and cost effective in the past. The Chemical Release Radiation Effects Satellite, launched in 1990, was a joint effort between NASA's Marshall Spaceflight Center and the Department of Defense Space Test Program. This joint mission allowed both organizations to achieve complimentary mission objectives to examine the effect of the space environment on microelectronic circuits, for less cost than if each organization had pursued individual missions. Similar success could be achieved for a quantum gravity gradiometer mission. Both the DoD and NASA are in search of global gravity gradient data of increased resolution versus the data collected by the GRACE mission; the main difference between the organizations' objectives is in what they want to do with the data after it has been collected and in their ultimate accuracy goals.

DoD involvement in the quantum gravity gradiometer development must focus on supporting the current geophysics goals of the device, while providing additional resources to address unique DoD requirements. The military need for deeply buried target detection will likely place more stressing demands on a gradiometer than the geophysics need to detect underground mineral deposits and ocean currents. Caution must be exercised that any changes to the instrument to address DoD needs are not so extensive as to threaten the original geophysics mission or drive up costs to the point where a joint effort is not cost effective. An additional option to help reduce the cost of the system is to seek investment from oil and mineral mining companies in return for sharing results of the data collected by the space mission. If the gradiometer can be shown to improve the speed and effectiveness of a commercial company's search for oil and/or minerals, partnering with NASA and DoD for the mission could be an attractive option for the company.

Determining the best opportunity for spaceflight of the gravity gradiometer will be the next step after agreement is reached on joint gradiometer development. Spaceflight options could include flying the gradiometer as a secondary payload on the space shuttle, flying the gradiometer as a secondary payload on a large free-flying spacecraft or building a separate free flying satellite for the gradiometer mission. Each approach has strengths and weaknesses. The space shuttle flight may be the lowest cost option if the gradiometer can fit into one of the existing shuttle secondary payload containers such as the Get Away Special or GaS canister. Another advantage of the space shuttle is that the instrument can be returned to earth so any problems encountered during the flight could be fixed and the instrument re-flown on subsequent flights as necessary. However, the short duration of each shuttle flight means that only a few days worth of data can be collected at a time. Collecting all the necessary data would require several shuttle flights which may negate the cost savings of flying as a secondary payload. By way of reference, the GRACE experiment spent four months on orbit calibrating its systems before it started to collect data. Such a timeline would not be possible with shuttle missions. A final downside to shuttle flight is that the space shuttle is limited to equatorial orbits, which means the instrument would not fly over the entire surface of the earth. Both NASA and DoD customers want gravity field maps of the entire planet; this requires placing the quantum gravity gradiometer into a polar orbit similar to that of the GRACE mission. The limitations of a space shuttle flight significantly outweigh its potential lower cost and make it an unlikely candidate for spaceflight of the quantum gravity gradiometer.

Flying the gradiometer as a secondary payload on a larger spacecraft offers the chance for cost savings without many of the mission impacts of flying on the shuttle. Flying as a secondary payload would mean the gradiometer could stay in space for years, not days as would be the case with the space shuttle. Mission planners could also select a host satellite that was already planned for polar orbit, which means the instrument would be able to collect gravity gradient data over the entire surface of the earth. The downside is that flying as a secondary payload means finding a host spacecraft that has extra weight, space, power, data storage, and communications capacity to allocate to the gradiometer. There is unlikely to be such a host spacecraft given the fact that a quantum gravity gradiometer that could weigh 100 pounds or more and would require a large host spacecraft. There are few large scientific spacecraft planned for polar orbit launch in the next decade so this option would be very problematic. The size and mission requirements of the quantum gravity gradiometer make it unlikely that a large enough host spacecraft could be found to host it as a secondary payload. This leaves a dedicated free-flying spacecraft as the only real option for spaceflight of the quantum gravity gradiometer.

A spacecraft necessary to fly the quantum gravity gradiometer will be similar in size and performance to each of the GRACE spacecraft, with one or two distinct differences. The quantum gravity gradiometer spacecraft would likely be slightly larger than one of the 950 pound GRACE satellites. A spacecraft with a mass of 1200 pounds would probably be adequate to support the quantum gravity gradiometer payload. The distinguishing feature of this satellite will be the way in which the quantum gravity gradiometer is integrated into the vehicle. Like the Bell gradiometer, the quantum gravity gradiometer is made up of accelerometers, in this case two, each of which is a matter-wave interferometer like that described earlier. Each of these devices independently measures the force of gravity and thus cancels out the impact of spacecraft motion on data collection. To be effective, these accelerometers would need to be separated from each other by a certain distance in order to obtain proper gravity gradient measurements. In laboratory experiments, 10 feet separated the devices.[2] Applying a similar requirement on orbit would likely mean one of the matter-wave interferometer devices would need to be placed on a deployable boom that would be extended after launch. This step would be necessary to keep the satellite small enough to fit into the payload fairing of existing launch vehicles capable of launching 1200-pound satellites into polar orbit.[3] Placing one of the matter-wave interferometers on a deployable boom would also have the advantage of allowing experimenters to vary the distance between the interferometers during the flight as necessary to study how the distance between the two interferometers impacts performance of the quantum gravity gradiometer. Flying the gradiometer on its own spacecraft would likely be the highest cost option, but would provide the most time for on-orbit operations and probably place the fewest limitations on experiment design. Mission needs clearly dictate that a dedicated spacecraft be developed for spaceflight of the quantum gravity gradiometer. The cost of such an effort, probably on the order of the $145 million spent on the GRACE mission, could be mitigated by sharing it between NASA, DoD, commercial partners and potential overseas organizations such as the German Aerospace Research Center that was a joint partner on the GRACE mission. The value of high accuracy gravity gradient data to many government and commercial customers make a dedicated space mission viable for the quantum gravity gradiometer.

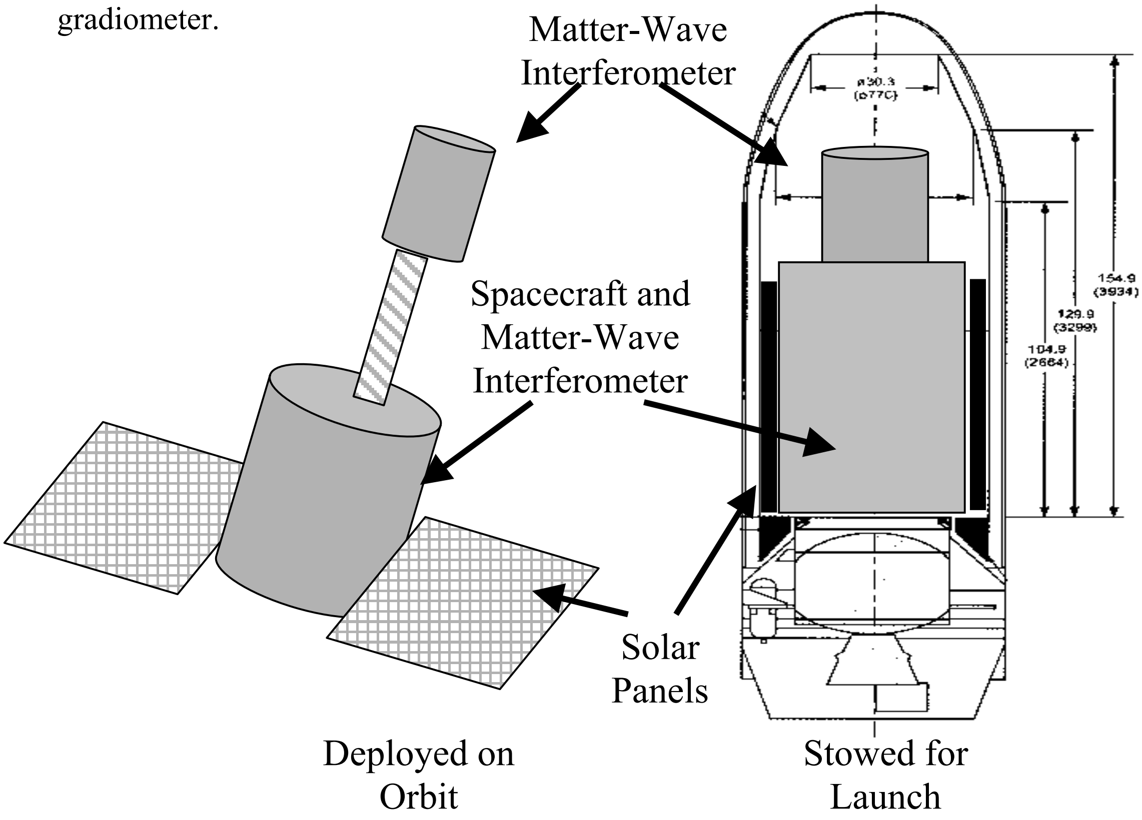

Figure 5: Notional Concept for Quantum Gravity Gradiometer Spacecraft[4]

Concept of Operations

Assuming joint development and spaceflight of the quantum gravity gradiometer is agreed upon, the next step in the mission planning process will be to determine how the system will be operated. Operations issues for the quantum gravity gradiometer mission include launch, on-orbit operations, data processing and dissemination and, most importantly, the use of the data in the hunt for deeply buried facilities. Selecting the right solution for each of these items involves balancing considerations of cost, mission need and numerous other factors. The launch requirement for the quantum gravity gradiometer spacecraft may be the most straightforward requirement to address. The spacecraft needs to be launched into a polar orbit so that the gradiometer can survey the entire surface of the earth. Launching a 1200-pound class spacecraft into a polar orbit requires a launch vehicle on the order of the Orbital Sciences Taurus launch vehicle or the Russo-European Rockot launch vehicle, which was used to launch the GRACE mission. Final selection of a launch vehicle will be based on consideration of cost and potentially the nature of the joint partnership formed to support the quantum gravity gradiometer mission. Significant European or Russian involvement in the mission could mean launch on a Rockot or similar vehicle would be provided as in-kind cost sharing by those countries. A United States focused team would likely use the Taurus launch vehicle. Either vehicle would meet mission requirements.

Selection of the ground station network to support the quantum gravity gradiometer mission has a significant impact on system design. The more stations in the ground station network, the more opportunities there are to downlink data and the lesser the need for on-orbit data storage. A larger ground station network also means more stations available to contact the spacecraft in the event of an on-orbit anomaly. The polar orbit of spacecraft also favors a ground station network that has multiple locations in the higher latitudes. More high-latitude locations increase the contact opportunities for the polar orbiting quantum gravity gradiometer spacecraft. Only the United States and Russia have satellite control networks that have multiple ground stations in the necessary locations. Since Russian participation in the gradiometer mission is not certain, the ground station selection process should focus on the networks operated and/or controlled by the United States. The two networks that could be used include the Air Force Satellite Control Network with eight stations located throughout the world and the NASA polar ground station network with five stations worldwide. Though smaller, the NASA polar ground station network is probably the best choice of the quantum gravity gradiometer mission because three of the four stations are located at higher latitudes, optimizing contact opportunities.[5] This network is successfully being used today to support the GRACE mission. By contrast, only one of the Air Force Satellite Control Network sites, Thule, Greenland, is located at high latitudes. There is the additional problem that research spacecraft such as the quantum gravity gradiometer mission may be out prioritized from time to time on the Air Force network due to the need for that network to support multiple operational Air Force space systems. Use of the NASA Polar Science network makes the most sense for the mission envisioned.

A critical step for any space mission is to determine how to get the data collected by the mission into the hands of the people who need to use it. The best, most accurate, most reliable data will be useless if it cannot be quickly delivered in the right format to the proper end users. A joint mission such as the quantum gravity gradiometer may have multiple data processing and dissemination sites depending on the needs of various users. Geophysics users may process their data through one of the potentially many participating agencies such as the German Aerospace Research Center, which does all the data processing for the GRACE mission. On the other hand, DoD users will most likely want a system where the gradiometer data can be processed and disseminated through existing DoD channels. Using existing National Imagery and Mapping Agency (NIMA) organizations and systems holds the most promise to meet the needs of DoD users. The NIMA Geospatial Sciences Division and its predecessor organizations have been maintaining gravity field models for over 50 years. Previous gravity measurement efforts have focused on gathering data mainly from fixed gravity measurement sites around the world and using it to support inertial navigation system use by aircraft, submarines and ICBMs. NIMA is also in the process of transforming from a maker of specific maps and map related products into an agency that maintains a variety of geospatial databases from which users can obtain the data they need for their own mission specific applications. Integrating data from the quantum gravity gradiometer mission into this environment is ideal to ensure people familiar with gravity measurement process make the data available to as broad a population of DoD, allied nation and coalition partner country users as possible. Another benefit of using NIMA is that the data collected from the quantum gradiometer mission can be used to support development and maintenance of inertial navigation systems throughout the DoD and the commercial community. Recall that gradiometry was revived in the 1970s for the purpose of supporting submarine navigation and that gravity field measurements have been made in support of navigation system development since the 1950s. A space-based quantum gradiometer sensor could provide valuable data to support military and commercial navigation systems. This data would come at a time when increased threats by terrorists and nation states to jam GPS receivers places a premium on the performance of the inertial navigation systems integrated with those receivers on military and commercial aircraft. NIMA's heritage combined with its current system initiatives make it the perfect choice for processing and dissemination of quantum gravity gradiometer data.

The final piece of the operational concept puzzle is to determine how to use the data once it has been processed and disseminated. As noted previously, the most important use of gravity gradiometer data in the hunt for deeply buried facilities is to be the first step or trip wire system for deeply buried facility detection. Such a system would cue other sensors and systems to help in the hunt for the facility. A detector that measures variations in the force of gravity is very difficult to spoof by means of simulation or dissimulation discussed earlier. A system such as the quantum gravity gradiometer may not always be able to always positively detect and characterize a deeply buried facility, but it has significant potential to be the system that first detects a possible deeply buried facility signature, then cross-cues other sensors to focus on a specific area. For example, a deeply buried facility may be masked from detection by optical and infrared imagery intelligence spacecraft due to measures taken by the builders of the facility. The presence of the facility would probably not be masked from detection by the quantum gravity gradiometer. This device could detect the presence of the facility then help other intelligence assets focus on the same area. Knowing where to look the second time may help intelligence systems operators defeat potential enemy deception techniques. In this manner, the quantum gravity gradiometer is not the silver bullet single solution for facility detection, but rather like the parachute flare that pierces the darkness of the nighttime battlefield and makes it possible for others to see things they could not see before. The quantum gravity gradiometer has the potential to counter the efforts of our potential enemies to go deep underground to protect their critical assets from attack by United States airpower.

Notes

[1] Morring, 58.

[2] Yu, 3.

[3] The payload space available within the basic fairing on the Orbital Sciences Corporation Taurus launch vehicle is 55 inches wide and 155 inches long. It would be difficult to build a spacecraft that had 10 feet of separation between the two matter-wave interferometers if the entire vehicle was on 13 feet long. Some kind of deployable boom is the most likely solution to this design problem.

[4] Line drawing for Taurus payload fairing taken from Taurus Payload Users Guide downloaded from www.orbital.com

[5] Grace Newsletter #1 –Three stations located in high latitudes include Poker Flat, Alaska, McMurdo, Antarctica, Spitzbergen, Norway.

Chapter 7

Conclusion

Deeply buried facilities pose an ever-increasing threat to the United States, our allies, our friends and our worldwide interests. Potential enemies of the United States realize the value deeply buried facilities offer to counter the asymmetric advantage held by United States airpower. These enemies are using everything from old caves to sophisticated underground operations centers to protect themselves and key military assets such as ballistic missiles and weapons of mass destruction. Countering such efforts requires an integration of intelligence resources including imagery intelligence, signals intelligence, human intelligence and MASINT to detect their facilities and identify weaknesses that could be exploited in a potential conflict. The builders and operators of the deeply buried facilities, however, could spoof many of these intelligence sources. Countering efforts to spoof our intelligence systems requires coordinating their use so that systems can be cross-cued by each other to get more effective coverage of an area of interest. This cross cuing becomes more effective if at least one intelligence source operates in a manner that is very difficult to spoof. Space–based gravity gradiometry sensors have the potential to serve as the “trip wire” system that could draw the attention of other intelligence assets to a previously undiscovered deeply buried facility. Gravity gradient measurements have been made for over 100 years and have proven successful in oil exploration, submarine navigation, ICBM guidance and geophysical sciences. Advances in technology have overcome the drawbacks of the early gravity gradiometers and have made robust operations from moving platforms possible.

The quantum gravity gradiometer has the potential to deliver the accuracy needed for deeply buried facility detection from space. It also has the advantage of performing better in space than it does on the ground. While the absolute effectiveness of the quantum gravity gradiometer is not known, the enormous potential of the instrument makes DoD investment worthwhile. The DoD should team with NASA to take the quantum gravity gradiometer out of the laboratory and fly it in space. A joint agency mission could serve the needs of geophysicists and military planners alike. Launch vehicles, ground station networks and data processing and dissemination networks exist today to support such a mission. It is time to make the modest investment necessary to add a new tool to the DoD's arsenal to counter the construction and operation of deeply buried facilities. The United States needs the quantum gravity gradiometer to help counter the abilities of our enemies to "go deep."

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