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My Fifty Years of Adventures Measuring Gravity and Gravity Gradients at Sea, In Airplanes, and by Astronauts, on the Moon

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ABSTRACT

Gravity measurements that generally require an accuracy of 1 milligal for regional studies and often 0.1 milligal for commercial investigations in the presence of Earth's gravity of about 980,000 mgal are difficult to start with, even using apparatus placed on a fixed horizontal plane (1 milligal or mgal = .001cm/sec^2). Moving platforms at sea, because of their obvious instability pose additional large problems in measuring gravity. Those problems and their solution are the subjects of this paper, which discusses various methods of measuring gravity at sea. I also describe how a gravity measuring instrument was constructed for use by astronauts on the moon. A particular emphasis is placed on how the errors in measurements caused by horizontal accelerations on moving vehicles were determined and eliminated. Finally, an instrument for measuring gravity gradients in airplanes, and its application in a survey are described.

Key words: Gravity and Gravity gradients, Moving platforms, Gravity measuring instruments, horizontal accelerations

INTRODUCTION AND AUTHOR'S CONTRIBUTIONS

The main purpose of this paper is to follow the evolution of marine gravity measurements from measuring in shallow water by placing the gravimeter on a solid sea bottom, to measurements in a submarine and on to a surface ship. Building a gravity measuring system to be used on the moon and making measurements of gravity gradients in an airplane are also described. This is in part a personal journal and it describes the author's role both in making measurements in some cases and in other cases dealing with errors and constructing instrumentation to make the appropriate corrections. No gravity measurements are unique, and in this paper I subjectively describe and emphasize the role I played in making measurements and in devising instrumentation to correct instrumental errors. Thus, the measurements I made on a submarine were the last measurements made with the Vening Meinsz apparatus and the first in the Western Indian Ocean. I also developed the Cross Coupling computer to correct a serious error in the Graf Askania gravimeter and I was fortunate to be selected the Principal Investigator for the lunar gravity experiment. The airborne gravity gradiometer measurements on the San Andreas fault zone that I arranged are one of the very few gradiometer measurements to be in the public domain.

Gravity in Shallow Waters

My first introduction to measuring gravity in a marine environment was in 1956 off a fishing boat on the Bahama banks. The gravimeter was placed in a large housing and lowered down to the shallow bottom. The water was no deeper than a few tens of feet. The gravimeter was electrically connected to controls on the boat, which allowed the gravimeter to be levelled and the measurements made on the boat. Accurate readings could be obtained and the main limitation to the method was that observations could be made only in very shallow water, where the gravimeter could be place on the solid sea bottom. To the question "instead of controlling the gravimeter from the boat, why not simplify things by putting a person in the housing and have him take the readings", the answer was "if he is smart enough to operate the gravimeter, he would not be stupid enough to shut himself in the housing". The gravimeter measurements made in the Bahamas were an important part of my PhD thesis (Talwani et al., 1959).

The Vening Meinsz Pendulum Apparatus in Submarines and the Browne Correction

Vening Meinesz, one of the leading geophysicists of his time, was having trouble making pendulum observations to measure gravity because the ground was unstable in his native Holland, which caused errors in the measurements. So, he developed a pendulum apparatus to solve the problem and he was able to use a similar apparatus to make gravity measurements in submarines (Vening Meinesz, 1929). His was the first equipment that could be used to make measurements in deep water areas. Two innovations made these measurements possible. The first, which is the essential part of the Vening Meinesz pendulum apparatus, is that instead of using one pendulum, he used three, all

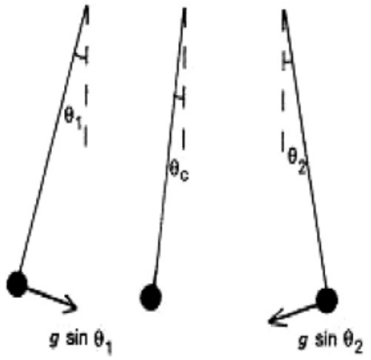


Figure 1. Instead of using the period of a single pendulum to obtain the value of gravity, *g*, Vening Meinesz suspended three pendulums from the same support. Only the two side pendulums were swung, and by obtaining the difference of motion between the side pendulums and the middle pendulum, he was able to eliminate the effect of disturbances on the side pendulums.

suspended from the same support and able to swing in the same plane. The middle pendulum in Figure 1 is not made to swing. It derives its motion from the motion of the support. The pendulums on either side are made to swing in opposite directions. By an elaborate mirror arrangement, the relative motion of the side pendulums with respect to the middle pendulum is recorded and the angular displacements $(\theta_1 - \theta_c)$ and $(\theta_2 - \theta_c)$ are averaged to obtain θ the familiar angular displacement in the equation of motion of a pendulum (Figure 1), which, as follows, is solved to obtain the period of the pendulum t and hence the value of gravity g.

First order horizontal accelerations acting on the pendulum supports are removed by taking averages of swing angles

$$(\theta_1 - \theta_c) \text{ and } (\theta_2 - \theta_c)$$

If two pendulums of equal length are suspended from the same support and at any time have angular displacements of θ_1 and θ_2 , subtraction of the equations of motion gives

$$(d^2\theta_1{}^2/dt^2 - d^2\theta_2{}^2/dt^2)+(g/l)(\theta_1 - \theta_2)=0,$$

Which is solved to yield *t*, the time period of the so called fictitious pendulum, and is given by $\tau=2\pi\,(l/g)^{1/2}$, and *g* is thereby obtained.

His second innovation was to make the measurements on submarines rather than on surface ships. At sea, the water motions on the surface are greatly reduced at depth and therefore the disturbing motions that a submarine is subjected to are much smaller than the motions that a surface ship is subjected to. This makes it easier to make the gravity measurements on a submarine. Vening Meinesz was vastly successful in making measurements in many of the world's oceans. His measurement of the large negative gravity anomalies over the deep sea trenches in the Indonesian area was a fundamental discovery. But even great scientists sometimes make very simple mistakes, and Vening Meinesz overlooked a simple source of error. His apparatus was hung in a gimbal frame. This frame was firmly attached to the submarine's body and was subjected to the same motions as the submarine. These motions are small in a submarine but they still exist and the gimbal frame responds to them. It therefore hangs not vertically but in a direction that is the vector sum of gravity and the instantaneous horizontal accelerations. This vector sum is always positive and thus the derived value of gravity is always greater than the true value of gravity, which therefore has to be corrected. This correction is derived as follows.

The quantity measured in experiment is *t*, the time period of the fictitious pendulum, and is given by

$$t=2\pi\,(l/g)^{1/2}$$

But the total acceleration seen by the pendulums is not *g*, but is $(h^2+g^2)^{1/2}$, (where h is the horizontal acceleration) and, which can be rewritten as

$$g(1+h^2/g^2)^{1/2}, \text{ or}$$

$$g+h^2/2g+\ldots\ldots,$$

Thus $-h^2/2g$ is the Browne correction.

The correction requires the knowledge of the horizontal accelerations and Vening Meinsz added a horizontal accelerometer to his apparatus to measure horizontal accelerations. It was a young graduate student Ben Browne who pointed out this error and Vening Meinesz graciously acknowledged Ben Browne's correction as follows "*The writer (Vening Meinesz) wants to pay a sincere tribute to Mr B.C. Browne who discovered several effects of the second order of the ship's movements in the pendulum observations at sea, for which the results have to be corrected*". This was an exemplary communication from an eminent scientist to a young graduate student (Vening Meinesz, 1941).

I believe I was the last person to use the Vening Meinesz apparatus on a submarine. My measurements were made on a British submarine, the H.M.S. ACHERON. We sailed from Freetown, the capital of Sierra Leone, made measurements in the Eastern Atlantic, went around the Cape of Good Hope and made measurements in the

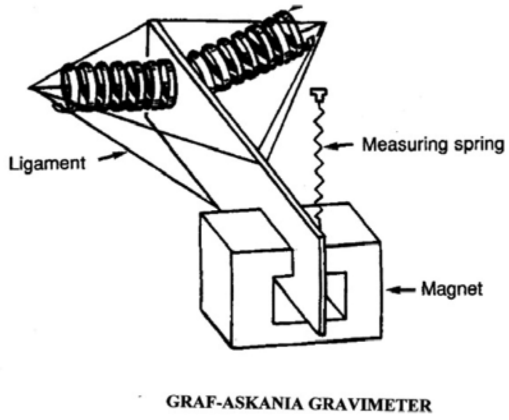


Figure 2. The beam of the Graf-Askania gravimeter is attached to a spring shown at the top of the figure, which allows it to move as gravity changes. The beam also lies in part within the pole pieces of a strong permanent magnet, which damps the motion caused by the periodic heave (vertical) accelerations, acting as a low pass filter.

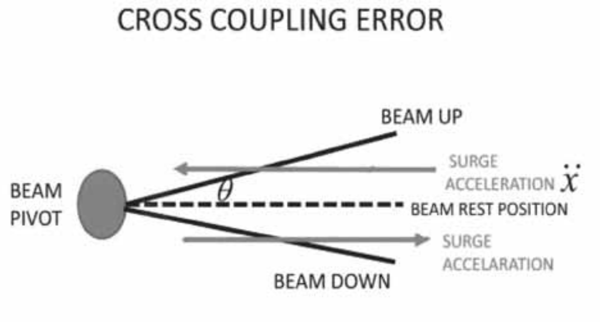


Figure 3. The worst case for the Cross Coupling error occurs when the surge acceleration and the beam motion are in phase or are 180 degrees out of phase.

Mozambique Channel and over the Carlsberg Ridge in the Indian Ocean to disembark in Karachi (Talwani, 1962). In a period of four months, the total number of measurements was 39. It was not a very efficient exercise.

Surface Ship Gravimeters and the Cross Coupling Conundrum

In the early 1960s two surface ship gravimeters were developed, the Graf meter by Anton Graf in Germany, and the Lacoste meter by Lucian LaCoste in the USA. My colleagues and I used the Graf meter at the Lamont Doherty observatory. It is a spring gravimeter as shown in a schematic in Figure 2. The main spring at the top of the schematic is attached near the pivot point of the aluminum beam. Changes in gravity move the beam up or down. The beam motion is optically recorded and changes in beam motion yield the value of gravity.

But the beam is not only subjected to the pull of gravity, it is also subjected to vertical periodic accelerations (heave). By placing the beam between the pole pieces of a permanent magnet the motion caused by the vertical accelerations is greatly attenuated. The Graf Meter is placed on a gyro stabilized horizontal platform. It therefore stays in a horizontal position and does not swing in a gimbal frame and no Browne correction is necessary.

The LaCoste meter in its early incarnation was not placed on a gyro stabilized platform, but was hung in a gimbal frame in the same manner as the Vening Meinsz pendulum apparatus. A Browne correction was therefore necessary. LaCoste was able to obtain the magnitude of the horizontal accelerations necessary for calculating the Browne correction by measuring the angle between the vertical and the appropriate direction in the gimbal frame. An accurate vertical reference was necessary for the purpose.

In 1960, J.C. Harrison, a collaborator with Lacoste, published a paper (Harrison, 1960), in which he stated " In the case of a beam gravimeter on a gyro stabilized platform, the Cross Coupling effect can contribute an error of 500 milligal, depending on the phase difference between the oscillations of the gravimeter beam and the horizontal accelerations". This was alarming news for our group at Lamont Observatory working with the Graf (later the Graf Askania) gravimeter, and we needed to examine the situation.

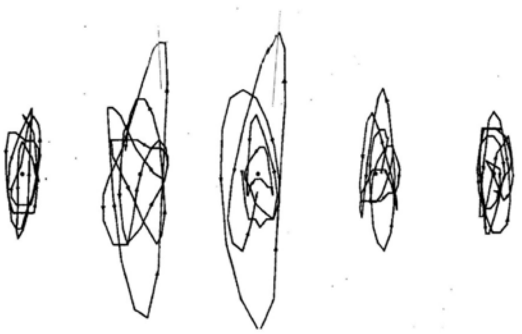


Figure 4. The phase difference between heave and surge is shown in an actual case by constructing hodographs (plots of the two accelerations plotted against each other over a number of wave cycles).

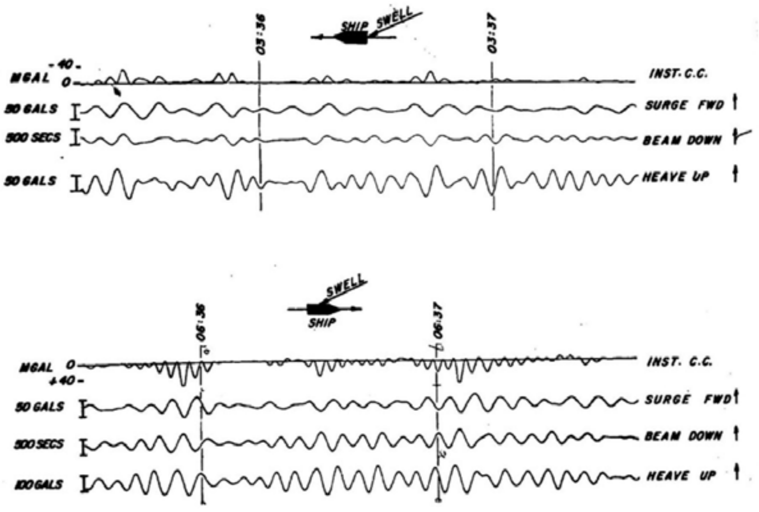


Figure 5. The phase difference between heave and surge can also be seen by simultaneously, but separately, plotting the two accelerations for the same time interval. Also shown are beam motions and the instantaneous Cross Coupling. Top, in a following sea, bottom, sailing into the sea.

First, what is the Cross Coupling effect? And how can it be corrected for? With the help of Figures 3 through 7, we explain this effect and show how it can be dealt with. In Figure 3 we explain the effect in a special idealized case. In Figures 4 and 5, we show the relationships between the relevant quantities that give rise to the Cross Coupling effect in actual cases. In Figure 6 we show how an analog Cross Coupling computer works, and in Figure 7 we show how the computed Cross Coupling is used to correct the recorded gravity signal.

As seen in Figure 3 The gravimeter beam moves in response to changes in gravity, but it also moves in response to heave (vertical) accelerations. Because of heavy damping, the beam motion lags heave by 90 degrees in phase. If there is a phase difference of 90 degrees between the heave accelerations and the accelerations in the fore and aft directions (surge), the beam motions will be in phase or 180 degrees out of phase with the surge accelerations. The component of the surge accelerations at right angles to the beam will then consistently move the beam in the same direction throughout the cycle of the accelerations, giving rise to the Cross Coupling effect.

Figure 4 (Wall et al, 1966) shows the phase difference between heave and surge in actual cases by constructing hodographs (plots of the two accelerations plotted against each other over a number of wave cycles). A sample, when the ship was headed into the sea is seen in this figure. The heave accelerations are several times larger than the surge accelerations, and the elliptical nature of the hodograph shows that the phase difference between the two is indeed close to ninety degrees.

A second way to consider the phase difference between heave and surge is to simultaneously, but separately, plot the two accelerations for the same time interval (Figure 5). Consider the bottom plot. The phase difference is a little difficult to see, but it is present. This plot also shows the beam motion which, because of the large damping, lags heave by ninety degrees and consequently is 180 degrees out of phase with surge. The Cross coupling error, which is basically the product of beam motions and surge is,

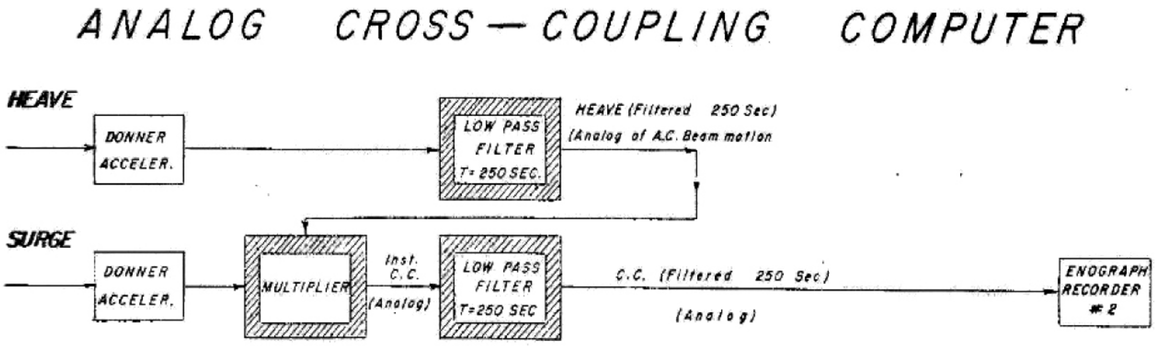


Figure 6. A simplified sketch of the Cross Coupling computer.

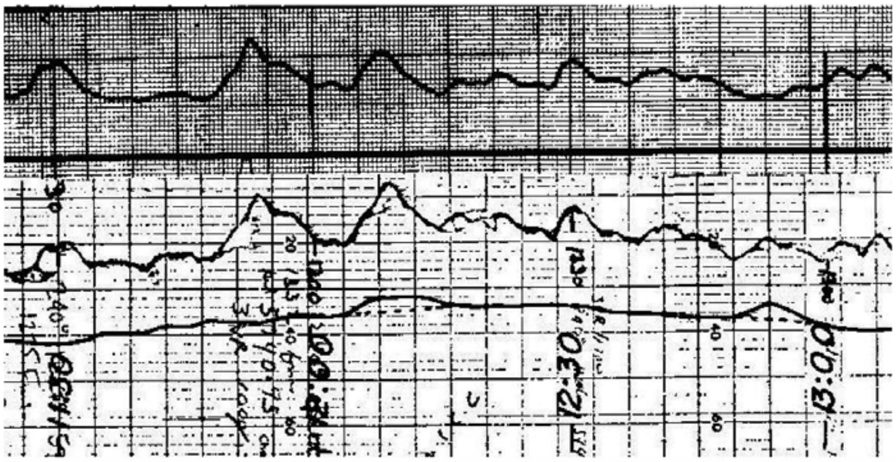


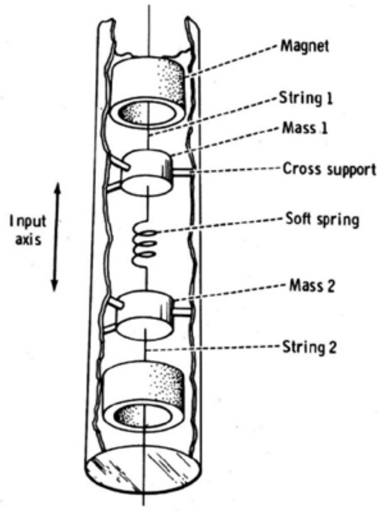
Figure 7. Plotted time record shows how the computed Cross Coupling (top trace) when applied to the raw gravity (middle trace) can make the required correction (bottom trace).

then, continuously negative. If, on the other hand, the ship is in a following sea, the phase difference between heave and surge is reversed and the Cross Coupling error is continuously positive (top plot).

The finite magnitude of the Cross Coupling error in Figure 5 made it necessary to construct an analog Cross Coupling computer to determine the error in real time, and, to apply the corresponding correction. I proceeded to design and build it (Talwani et al, 1966). A simplified sketch of this computer is shown in (Figure 6). Two commercial accelerometers were used to obtain the heave and surge accelerations. The output of the heave acceleration is passed through a low pass filter (T=250 seconds) to mimic the gravimeter beam motions and then multiplied by the surge accelerations. The resultant output after being passed through the low pass filter obtains the Cross Coupling error, which can be subtracted from the raw gravity record in real time to obtain a gravity recording corrected for cross coupling. This is shown in Figure 7. The middle trace is the raw gravity record plotted against time on the moving ship (and hence against distance). The top trace is the Cross Coupling error computed by the analog computer. The very close resemblance between the two speaks to the fidelity of the Cross Coupling correction. The bottom trace is the gravity trace corrected for Cross Coupling.

To sum up, Harrison was correct in pointing out the importance of the Cross Coupling error. But though he was incorrect in estimating its magnitude, it still became necessary to construct a Cross Coupling computer to apply the correction. It is interesting to note that LaCoste gave up the practice of hanging his gravimeter in a gimbal frame and started mounting his instruments also on a gyro stabilized platform and correcting for Cross Coupling.

Cross Coupling can be avoided in a number of other ways. Askania has altered its gravimeter so that the motion of the mass is only in the vertical direction and is not affected by horizontal accelerations. The "Force Balance" method is used in the Bell instrument manufactured by Bell Aerospace company, which restores the pendulum in the instrument by passing current through a coil mounted on the pendulum and placed in a magnetic field such that the current in the coil moves it to its null position. The current then gives the value of changes in the gravity field. The vibrating string method involves the measurement of



$$\Delta f = k_0 + k_1 g + k_2 g^2 + k_3 g^3 + ...$$

Figure 8. A sketch of the Bosch-Arma vibrating string instrument. The frequency difference between the two strings depends on the value of gravity, *g*, and on a number of constants, k_1, k_2, etc.

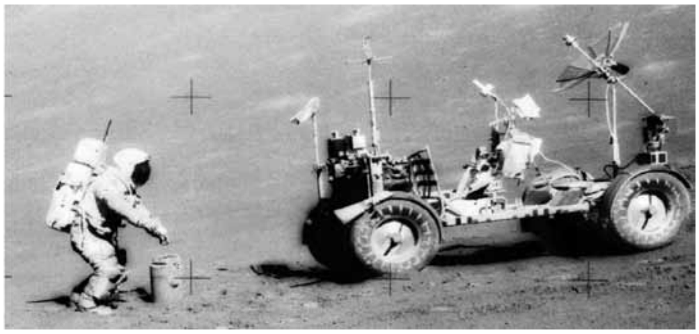


Figure 9. The astronaut about to take a gravity reading on the moon.

the frequency of a vibrating string, which depends on the value of gravity. These methods are discussed by Talwani (1971). The use of a vibrating string to measure gravity on the moon is discussed in the next section.

Since the gyro stabilized platforms cannot be perfectly horizontal, an error similar to the cross coupling error can occur. It can be minimized by minimizing the deviation of the platform from horizontal and by designing the vertical reference to avoid objectionable phase differences between the horizontal accelerations and the off leveling angles.

Vibrating String Gravimeter to Measure Gravity on the Moon

The following description is excerpted in part from my article in the journal "The Leading Edge" (Talwani, 2003). The specific objectives for the experiment on the Moon were to make an Earth Moon gravity tie and to investigate the buried structure of the Taurus Littrow valley, the Apollo17 landing site. NASA experiments are carried out by teams. I was the Principal Investigator of the team with members from various institutions of what came to be known as the "Traverse Gravity Experiment (or TGE)". Sheldon Buck of MIT's Draper lab supervised the instrumentation and the astronauts Gene Cernan and Jack Schmitt made the measurements on the moon.

For the TGE the Bosch-Arma double stringed instrument (Figure 8) was utilized. By taking the difference frequency between the two strings, the values of the constants in the higher order terms (which bring about non linear effects) are reduced. The values of the constants are all determined before the mission, but they can shift. To get the correct value of k_0 (the most significant constant) at the mission, the instrument is inverted and the frequency Δf_i is obtained

$$\Delta fn = k_0 + k_1 g + k_2 g^2 + k_3 g^3$$

$$\Delta f_i = - k_0 + k_1 g + k_2 g^2 - k_3 g^3,$$

where Δfn is the frequency difference between the two strings in the normal vertical position and Δf_i in

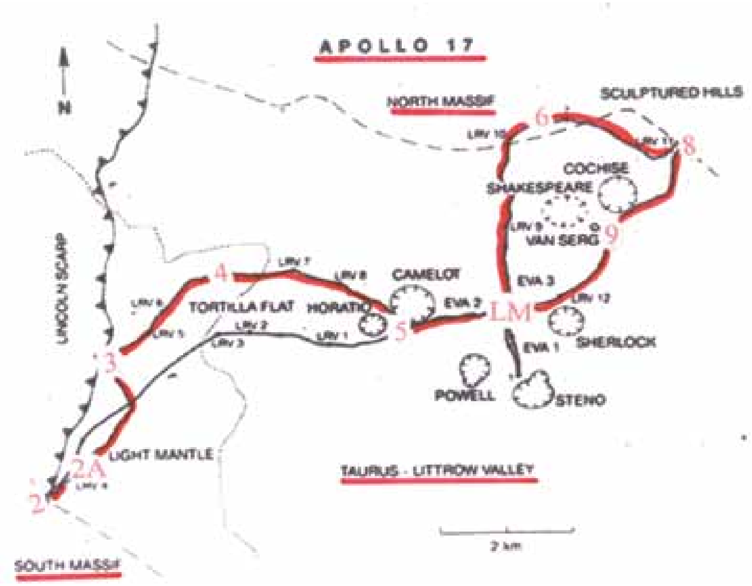


Figure 10. The traverse across the Taurus Littrow valley between the South and the North massifs along which gravity readings were taken at stations indicated in red.

the inverted configuration and the k's are instrument constants. By subtracting Δf_i from Δfn, the value of k_0 can be obtained, provided k_2 does not shift.

The Bosch-Arma instrument was very temperature sensitive and in view of the large differences between day and night temperatures on the moon, keeping it at a constant temperature was a very serious issue and was a serious hurdle that had to be overcome in getting the instrument operational on the moon.

Figure 9 is a picture of an astronaut about to use the instrument to use a gravity reading, Also in the picture is the Rover on which the gravimeter was carried.

An Earth Moon gravity tie was made to obtain a value of 162694.5+/- 5 mgals. It was obtained for the floor of the Taurus- Littrow valley. This is the first gravity value ever obtained on an extra terrestrial body.

The instrument was also used on three EVAs (Extra Vehicular activities) which, taken together, constituted a traverse across the valley between the Northern and Southern Highlands (Figure 10). A gravity high of about 30 mgal was found over the valley. The high was attributed to a one km thick basalt layer underlying the valley (Figure 11) which has a higher density than the material constituting the highlands. This is in contrast to terrestrial valleys, being floored by sediments have negative gravity values.

Lockheed Martin GGI Gradiometer and the Survey Over the San Andreas Fault Drill Hole

Lockheed Martin's GGI gradiometer (Figure 12) consists of two pairs of carefully matched accelerometers (of the pendulous force balance type) on a rotating plate (Hofmeyerand Affleck, 1993, Talwani, 2011).

The sensitive axes of the accelerometers are along directions shown in Fig. 12. By having the input axes of oppositely positioned accelerometers point in opposite directions, the linear accelerations of the plate cancel out. In addition to the four accelerometers, a second set placed in between the first set at 45 degrees is also shown in Fig. 12. The signals from these accelerometers can then be summed to obtain gradients in the plane of the plate, if the rotating plate is in a horizontal plane. The gradients recovered are g_{xx} - g_{yy} and g_{xy}., which can be used to derive all the individual components, g_{xx}, g_{yy} etc .

The first development and utilization of this gradiometer in an airborne configuration was made in a joint program by Lockheed Martin and BHP Billiton, a mineral company (Van Leeuwen, 2000). Diamonds are often located in kimberlite pipes, which have a negative gravity or gravity gradient signature. Since the structures are generally shallow, a gradiometer is preferred for locating them.

Airborne gravity gradiometers are being extensively utilized commercially for mineral exploration but there are very few surveys where the results can be publicly available. The survey described in the next section was jointly funded by the U.S. National science foundation, a number of energy companies and by the state of Texas. I was able to design the plan of this survey, and more excitingly, I was able to sit in the co-pilot seat of the Grand Caravan airplane which flew the survey.

A survey covering an approximately 10 Km x 10 Km area that was centered on the proposed San Andreas Fault drill site (Figure 13). The azimuth of the survey lines was chosen to be approximately parallel or perpendicular to the San Andreas fault. The survey was carried out with 40 lines, the lines being spaced 200m apart in a NW SE

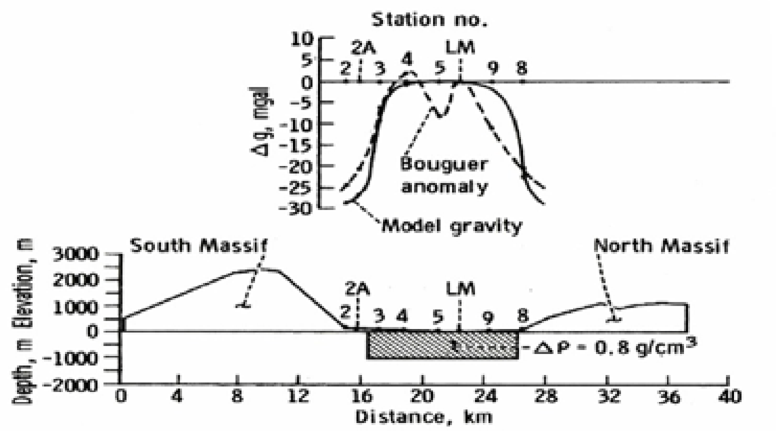


Figure 11. The 30 mgal gravity high over the Taurus Littrow valley was attributed to a one km thick layer of basalt which layered the valley.

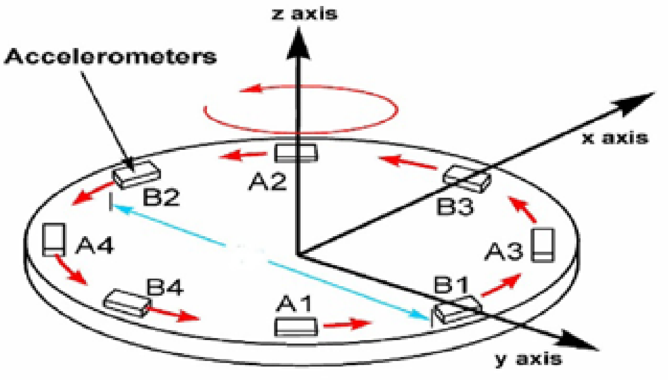


Figure 12. Eight matched accelerometer on a rotating plate constitute the basis of the Lockheed Martin GGI gradiometer.

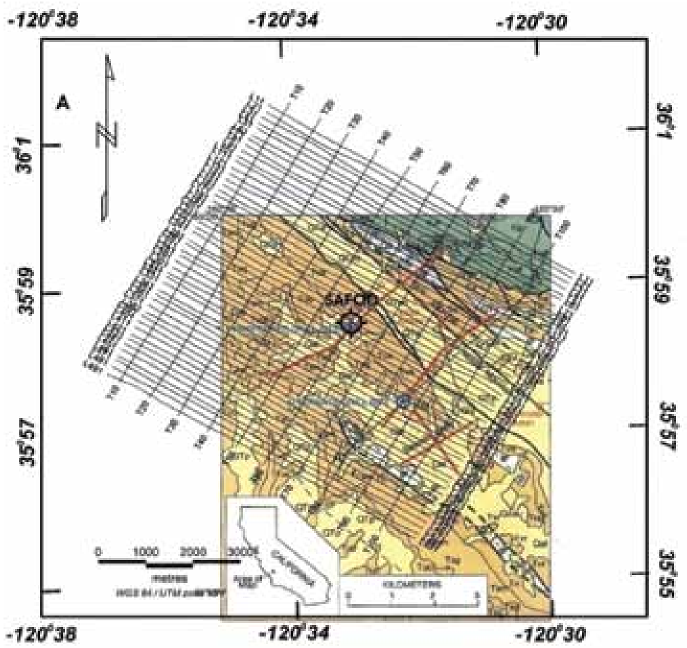


Figure 13. Site of the San Andreas fault drill hole.

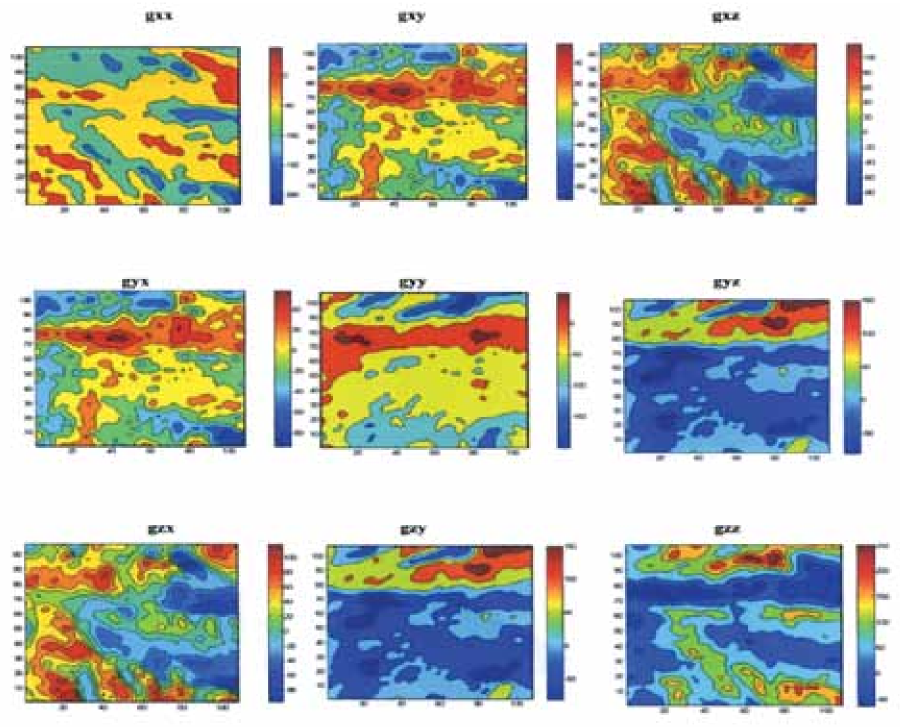


Figure 14. Measured gradients gxx, gxy, gyy etc.

configuration, as well as ten cross lines spaced one km apart in a NE SW configuration. All the lines were to be flown at a nominal elevation of 200m over the terrain. The terrain was not flat and a suitable "drape" surface was chosen for the plane to fly.

The various gradients obtained for the symmetric gradient tensor are shown in Figure 14. The data are at present being interpreted.

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Compliance with Ethical Standards

The author declares that he has no conflict of interest and adheres to copyright norms.

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