PROPOSAL SUMMARY

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CO-INVESTIGATORS	Mike Lisowski, Hawaiian Volcano Obs. USGS Hazel Rymer, Open University, England
COLLABORATORS	Greg Lyzenga, Harvey Mudd College, CA Dan Johnson, Central Washington University, WA

PROPOSAL TITLE	Tracking magma migration and volatile content using continuous differential microgravity and continuous GPS
PROPOSAL COST	Yr1: $161.6K Yr2: $58.3K

Abstract

This proposal seeks to explore the ability of combined continuous microgravity and continuous GPS to track magma migration within a volcanic edifice, and to estimate the volatile fraction of that magma.

Since this is a new project rather than a renewal, there are no prior accomplishments to report.

We propose to install two LaCoste & Romberg gravimeters to record continuously in conjunction with two continuous GPS stations. By differencing the gravity recordings from the two sites, we should be able to significantly reduce the common mode local effects such as water table. Mass transfer from under one meter to under the other at depths less than the separation will have enhanced signatures in the difference. The combination of the gravity difference with the geometric deformation data from the GPS stations will allow the separation of the effects of height change and mass transfer and will permit estimation of the density of the magma. From the density, the fraction of volatile components can be estimated. On andesitic volcanos with more viscous magma, larger fractions of volatiles often imply higher explosivity.

1. RESEARCH OBJECTIVES

The primary goal of this project is to measure mass and volume transfer within Kilauea volcano, to better understand the process of magma transfer and emplacement. We presume that understanding this process will enable better prediction of eruptive activity.

This project will use continuous GPS and gravity data from co-located GPS receivers and gravimeters to track mass transfer within Kilauea volcano in Hawaii. Two continuous GPS sites will be instrumented with continuously recording gravimeters. GPS data by itself can monitor three dimensional displacements of the monument. Gravity measurements are sensitive to both changes in elevation and changes in mass distribution. The use of two gravimeters at sites separated by 10-30 km will allow common mode noise sources to be reduced through differencing. Mass transfer at depths less than the station separation will have enhanced signatures in the difference. Methods proposed here should result in measurement of relative gravity changes at periods of minutes to years with a resolution of 10 μgal or better. The combination of GPS and gravity will allow separation of the effects of change of height and change in mass. This will allow improved understanding of the migration and composition of magma within Kilauea volcano.

1.1. Previous Work

Gravity and deformation measurements have been used by several investigators to learn about magma migration in active volcanic regions. (eg Jachens & Eaton, 1980; Berrino et al 1992; Rymer 1989; Dzurisin et al. 1980; Johnson 1992; Rymer, 1994; Rymer, 1995;) Rymer (1994) summarizes the state of the art, and provides a review of the theoretical foundation upon which microgravimetric monitoring of volcanos is based. Temporal changes in gravity at active volcanos typically are in the range of 100-300 μgal per "event". As magma flows into the edifice of a volcano, either passively filling up existing voids, or forcing its way in under pressure, both the local gravity field, and the local surface deformation field are affected. As subsurface mass is increased by the addition of magma, assuming the height of the station does not change, the local acceleration of gravity is increased. As the edifice swells, and the station moves up, gravity is decreased according to the free air gradient (typical FAG = -308.0 μgal/m). The extent to which gravity and station elevation are affected, are dependent upon the quantity of magma flowing in (or out), the degree to which it is filling pre-existing voids, the relative densities of the country rock and magma, the location, size, and shape of the magma system, the geometry of the structure of the edifice, and the mechanical properties of the volcanic edifice.

Jachens & Eaton (1980), and Dzurisin et al (1980) investigated the 1975-1977 eruption of Kilauea using geodetic, gravity, seismic, tilt, and electrical potential data. The proposed a model in which magma is fed into a subsurface reservoir beneath Kilauea summit, which feeds a set of dikes to the eastern rift, where there may be other reservoirs, from which it is erupted to the surface. Jachens & Eaton (1980) used gravity and leveling data to estimate the amount (both volumetric and mass) of magma involved. Then comparing these estimates with likely magma densities they were able to argue that the magma must withdraw leaving voids within the volcano. They found that the gravity and leveling data were best satisfied with two such reservoirs under the crater of Kilauea to the south and southeast of Halemaumau. These reservoir locations coincided with reservoir areas identified by Fiske and Kinoshita (1969) on the basis of tilt and leveling data.

Johnson (1992) examined the dynamics of magma transfer within Kilauea during the 1981, and 1983 intrusions and eruptions, and reviewed the probable locations of reservoirs from previous events. He found that the center of subsidence and inflation migrated around within the summit crater and the upper rift zone, and argued that it is not necessary to have voids within the volcanic edifice but that the data could be modeled using realistic magma compressibilities.

Ohminato et al. (1998) inverted broadband seismic data to deduce that the magma is transported from the summit reservoir to the east rift of Kilauea in pulses along a subhorizontal crack. In their model the crack is filled over a 1-3 minute period and is then emptied in 5-10 seconds.

J. M. Goodkind operated a superconducting gravimeter for a time at HVO on top of Kilauea (Goodkind & Young, 1990). Their main conclusion was that environmental effects must be identified and measured, particularly ground water. This study hopes to address this issue by 1) running two instruments and looking at the differential gravity, and 2) measuring precipitation and ground water.

Most of the work to date on measuring microgravity variations around volcanos has been done with portable instruments visiting multiple sites multiple times in episodic surveys. This mode of operation yields good spatial coverage, but very limited temporal coverage. Jachens & Eaton (1980) noticed that gravity changed during the first part of a survey following the onset of eruption at Kilauea in 1975. Rymer (1984) also reported variations of gravity during a survey of Poas Volcano in Costa Rica. This study would be complementary in that it examines the temporal changes much more closely at two sites on an active volcano. The gravity signatures of deformation events lasting hours to days have never been investigated at Kilauea, and very little has been done in this frequency band at other volcanos.

1.2. Why this work should be done at Kilauea

This experiment is best done at Kilauea Volcano in Hawaii for several reasons. First and foremost, we know quite a bit about the magma migration paths in Kilauea already. This knowledge will be essential for selecting the positions of the two stations. The width of a gravity signal from an intruding dike is about the same as the depth. The signal will fall off rapidly outside this area. Since there are only two gravity stations proposed due to cost, their placement is critical to the success of the project.

Collaboration with researchers at the Hawaiian Volcano Observatory (HVO) will greatly simplify logistics and reduce cost. We also anticipate being able to share helicopter time with other geologists conducting field work out at the East Rift. Estimates generated by other researchers of volume of lava moved through the volcanic edifice "plumbing" and erupted will be used for comparison with the results of this study. We anticipate that permitting of the East Rift site will be handled by the personnel at HVO.

There is a growing network of continuous GPS sites being installed by several research groups. Mike Lisowski, one of the co-investigators on this project is heavily involved with the installation of these continuous GPS sites, and with the analysis of the data from them. The two continuous GPS sites at our two gravimeter sites are obviously essential to the success of this project. The other sites on Kilauea will also be useful for illuminating the deformation field over a wider area.

The gravity changes reported in the past over Kilauea by Jachens & Eaton (1980) and Dzurisin et al. (1980) are in the range of 140-240 μgal. Given that we anticipate achieving 10 μgal precision, we should be able to resolve details of the change in our time series. The fact that Kilauea has basaltic flows, with relatively smaller amounts of volatiles implies that the gravity signal is likely to be smaller than at other types of volcano where there is a greater density contrast between the magma and the country rock.

We chose Kilauea volcano over Mauna Loa because this is an initial experiment to determine the feasibility of an approach. In such a case, it is desirable to have the instruments operate in an environment that is as well known as possible, with multiple comparisons available. In view of the experimental nature of the technique, it is also desirable to have the instruments relatively accessible. Indeed, we plan that regular visits will be made to each site in order to maintain a gravity tie between the two continuously recording meters. Kilauea is much more accessible than is Mauna Loa. When the technique has been successfully demonstrated, then other experiments might be run on other volcanos. Such experiments will have a much greater degree of confidence in the implementation, and interpretation after gaining experience at Kilauea.

1.3. Why two gravimeters are required

Two gravimeters are required for this experiment because we are interested in tracking the migration of magma. With one gravimeter, we could tell that magma came into or went out of a given reservoir under the station, but could say nothing about where it came from or where it went. With two gravimeters in the right locations, we can demonstrate that as one area is losing mass, another is gaining a similar mass.

Another reason to require two gravimeters is that we wish to look at the spatial gradient of gravity. This requires two instruments. We wish to look at gradients because we anticipate that the signals of interest will be larger in the gradient than in the individual point measurements from one gravimeter.

2. RELEVANCE OF PROPOSED WORK

This proposal addresses item IV-2 of NRA-98-OES-13, Thermal and Geothermal Hazards: Volcanic Hazards, in that it seeds to apply "geodetic techniques to understand ... the nature and dynamics of magmatic plumbing systems". It also addresses the Pacific Disaster Center Volcanic Activity Information Products - Physical Model objectives.

The combination of GPS and gravity data will allow an estimate of the density if the magma, and hence the volatile content.

The experience and capabilities developed in this project can be applied to other volcanos around the world. As mentioned earlier, volcanos with larger contrasts between country rock and magma (such as andesitic volcanos around the Pacific Rim) would be expected to have larger gravity signatures. Since we anticipate being able to estimate the volatile fraction of the magma, we should be able to estimate the explosivity of a potential eruption for an andesitic volcano. This capability could greatly benefit the Pacific Disaster Center which has many such volcanos around the pacific rim under its jurisdiction.

Over the years, many events at the volcano have had an impact on the local populace. For example, in the last 25 years a town on the east coast was destroyed by lava flows, s M=7.2 earthquake initiated an eruptive sequence lasting 2 years, and a lava flow from Mauna Loa flowed down the side of the mountain toward Hilo, but stopped before reaching the outskirts of the city. As the area becomes more and more populated, there is greater and greater risk from such events. Improved understanding of the "plumbing" of the volcano can allow mitigation of such hazards.

3. EXPECTED RESULTS

This proposal seeds to first demonstrate that it is possible to measure differential microgravity variations in time using continuously recording LaCoste & Romberg gravimeters.

Assuming the first goal is met, we will then obtain one year of continuous microgravity and continuous GPS deformation on Kilauea volcano.

This data will be interpreted in terms of mass and volume change and used to refine models of the "plumbing" of Kilauea, and to predict eruption volume and magma composition.

4. DETAILED WORK PLAN

The overall task of measuring gravity and deformation changes at Kilauea can be broken down into several sub-tasks In broad view, the tasks to be accomplished are to 1) obtain two suitable gravimeters 2) characterize the relative drift rates 3) design a measurement schedule 4) design and build a gravity station next to a GPS station 5) install the gravity meters and atmospheric pressure gauges 6) have the FG5 absolute gravimeter based at NOAA in Boulder Colorado visit both sites at least twice per year. 7) interpret measured gravity changes and deformation from GPS in terms of tectonics of the volcano and magma composition.

4.1. Obtain two suitable gravimeters

The budget allocates money to purchase one new Portable Earth Tide (PET) LaCoste & Romberg gravimeter. This newly available model (introduced in 1996) is chosen over the more familiar D or G models because it is designed for continuous recording of small gravity signals. It uses a double oven design, making it less subject to varying environmental temperatures

A second gravimeter, a model G meter which can be used for the two year duration of the project, belongs to Harvey Mudd College. This gravimeter must be returned to the factory for servicing and for fitting with an electronic feedback unit, a double oven, electronic levels, and variable damping to make it suitable for this project. Given that the cost of a new unit is about $45K, and the cost of servicing and retrofitting the existing one is about $15K, this represents a significant cost savings. In addition, older instruments typically have lower drift rates than new instruments, so it would be better suited to our needs.

4.2. Characterize the relative drift rates

In order to make relative gravity measurements between the two continuously recording gravimeters, it is necessary to remove the relative instrumental drift. An individual meter may have a drift rate of several tens of μgal per day (Mark Holiday, LaCoste & Romberg pers. comm.). The drift will be removed by periodic comparison between the two locations using a third gravimeter. There are two LaCoste & Romberg gravimeters which can be used for this purpose already at the Hawaiian Volcano Observatory. In addition, the two stations will be visited twice per year by the FG5 absolute gravity machine based at NOAA in Boulder Colorado. These two visits will remove long-term, common-mode apparent gravity changes at the two sites.

Another way the drift might be dealt with would be to periodically swap the meters. This would allow us to do the experiment with only 2 gravimeters,but would have a drawback in that the meters would need to be disturbed at each move. Since a third gravimeter is available, we prefer to use it to tie between the two stationary gravimeters.

A major issue which must be settled is to determine the required frequency of the periodic tie between the two stations using the third gravimeter. If it is not done frequently enough it will not be possible to meet the goal of 10 μgal accuracy. The required frequency will be determined by the linearity of the relative drift of the two meters, and is impossible to predict accurately beforehand.

To determine the required frequency of the tie, the two gravimeters will be run side by side for a period of 2 to 3 months prior to being deployed to their respective stations. The two resulting time series will be subtracted, and the required tie interval will be determined from inspection of the spectra of the differenced series.

We anticipate that this task will take 3 to 4 months after we have both gravimeters in hand.

4.3. Design a tie measurement schedule

Armed with a knowledge of the spectra of the differenced series, a frequency of repetition of the tie will be chosen such that the relative instrumental drift can be characterized by a linear polynomial in time. The interval must be short enough that the second and higher order terms contribute less than 1-3 μgal between tie measurements.

Another issue is the possibility of a change in the calibration (gain) of the gravimeters while they are recording at their separate locations in Hawaii. Sudden calibration changes of up to 0.1% have been observed in a LaCoste & Romberg model G meter (Carbone, 1999). If the calibration of one of the instruments changes, then a given change in gravity will be measured differently at the two stations. Given the size of the expected changes in gravity (150-300 μgal) and our anticipated resolution (10 μgal), a 0.1% change in calibration should not produce a noticeable effect (0.1% of 300 μgal = 0.3 μgal; 30 times less than the resolution we plan to achieve.) If a calibration change large enough to be noticed in our data were to occur, we should be able to detect it as a change in the amplitude of the gravity tide. In addition, the program of tie measurements using a third gravimeter left to run for a few days at each site, and also the twice yearly visit from the absolute G machine should help detect and minimize the effect of calibration changes in our time series. The third meter will be periodically calibrated against the stations visited by the absolute G machine.

4.4. Design and build a gravity station next to a GPS station

This project will use existing or planned continuous GPS stations to provide the deformation data. This will both avoid the costs of installing the GPS stations, and will make it easier to get through the permitting process with the National Park Service. One station will be placed near the parking lot near Halemaumau. The other station will be built adjacent to a planned continuous GPS station that will be installed near the western end of the east rift. A pier, shelter, and source of power will have to be installed for this station. Power will come from solar cells and batteries. Communication will be via free-wave modem which will be shared with the GPS station. The station must be built such that the absolute gravity machine can visit it.

An important noise source for microgravity measurement is often the local water table. A well for monitoring the water table height has already been drilled near the Kilauea site. In addition, local rainfall and runoff measurements will be made to infer the water table level. The fact that there will be two gravimeters may ameliorate the rainfall problem. To the extent that the water table fluctuation is the same at both instruments, the rainfall signal will be diminished in the gravity difference between the two stations. The climate and annual rainfall vary rapidly over a very short distance near the summit of Kilauea. We will attempt to site the two stations in areas where we think the rainfall and watertable may be similar.

It also may be possible to do something a little more clever than straight differencing of the gravity series. If for example the water table variation at one site maintains a constant amplitude and phase relation to the water table at the other site, it will be possible to perform a filtering operation on the first series before subtracting in order to remove the water table signal more completely.

We anticipate placing the two gravimeters inside sealed, insulated boxes with as low humidity as possible. There is some indication that humidity may be an important contributor to instrumental drifts (Michael van Ruymbeke, Obs. Royal de Belgique, pers comm. 1996).

This task can happen in parallel with the previous tasks, such that the station is ready to receive the gravimeter as soon as the drift rate comparison is finished.

4.5. Install gravimeters and atmospheric pressure gauges

When the gravimeters are installed in their respective stations, an atmospheric pressure gauge and both instrument and outside air temperature gauges will be installed. The data from these gauges will be used to reduce the environmental effects on the data.

The atmospheric gauge could also be used in conjunction with the GPS data for estimating the precipitable water from the GPS estimates for tropospheric delay.

This task should require a few days of dedicated work as soon as the relative drift rates are known, and the sites prepared.

4.6. Arrange visits by absolute gravimeter

The FG5 absolute gravimeter based at NOAA in Boulder Colorado is available (Sasagawa & Bilham, 1994) and will be brought to Hawaii twice per year to allow removal of long period instrument calibration variations. This gravimeter is available for scientific research for the cost of the air freight to bring it to Hawaii plus the airfare and perdiem of the operator. The salary of the operator does not need to be paid by this project.

Due to the active geology of Hawaii, a stable gravity reference is difficult to attain. The absolute gravimeter will allow the relative measurements made with the LaCoste and Romberg instruments to be tied to an absolute reference and will thus permit the removal of long period instrumental drifts.

It is anticipated that 4 to 5 sites will be visited by the absolute gravimeter: the two stations in this proposal, plus two or three others for purposes of calibration of the third (and other) gravimeters.

The absolute G machine should arrive in Hawaii after the sites have been prepared.

4.7. Interpret gravity and deformation measurements

The continuous GPS measurements and gravity measurements will be modeled with volumetric and mass changes within the volcano. Previous studies interpreting microgravity changes at volcanos have calculated volumetric change of the volcano using only elevation change data (e.g. Rymer, 1989, Jachens & Eaton 1980) assuming that station displacements were straight up. This assumption was necessitated by the fact that these studies used leveling data which was not sensitive to horizontal station displacements. GPS will provide all 3 components for each station.

5. ROLE of PI, CO-I, COLLABORATORS AND OTHER PERSONNEL

Kenneth Hurst will serve as principal investigator for the proposal. He will have overall responsibility for the direction of the work. He has worked for several years on the development of the GIPSY-OASIS II GPS analysis software.

Mike Lisowski of the Hawaiian Volcano Observatory will provide detailed background knowledge about the deformation of Kilauea. He will also act as a liaison between the project and the National Park Service and be responsible for submitting the request for permitting the required construction within the National Park to the Park Service. His role as Deformation Specialist at HVO will facilitate crucial access to the required deformation data to allow interpretation of the gravity data. He will also arrange to have local personnel carry out the required gravity ties at regular intervals. This represents a huge contribution to the project since if we had to pay someone to do all this, the overall budget could easily double.

Hazel Rymer of the Open University in the United Kingdom, has had considerable experience applying microgravity and deformation measurements to understanding volcanos. In 1989 she reported the first unambiguous microgravity precursor to a volcanic eruption at Poas volcano in Costa Rica. She will collaborate in the data interpretation and will also assist with the design of the the experiment.

Greg Lyzenga of Harvey Mudd College in Claremont California and the Jet Propulsion Laboratory in Pasadena California, has worked on viscoelastic deformation modeling and using finite element methods to model tectonic deformation. He will assist with interpretation of the data.

We anticipate and hope that an undergraduate student from Harvey Mudd College in Claremont California, and a graduate student from Open University in England may become involved in the project. Support for these individuals has not been included in the budget since the individuals have not as yet been identified. When and if such students emerge, the budget will be rearranged slightly to provide logistical support for both when in the field, and some financial support for the Harvey Mudd student. It is anticipated that the Open University student will have alternative sources of support for their salary and compensation.

Dan Johnson of Central Washington University, has had experience measuring and interpreting gravity surveys over Kilauea Volcano. He will assist with choosing the locations for the two gravimeter sites and will contribute to the interpretation of the data.

6. DATA REQUIREMENTS

This proposal will require timely access to the precise GPS orbits and clocks which are produced at JPL and to GPS data from the continuous GPS networks in Kilauea. Access to the orbits should be easy since they are available routinely via anonymous FTP. In addition, Hurst is involved in the generation and distribution of these orbits. Lisowski, in his role as Deformation Specialist at HVO, has access to the GPS data in Hawaii, as he is already responsible for downloading the data from the receivers. Hence, although the GPS receivers are being installed by other teams, and we are sensitive to data ownership, we do not anticipate a problem with data availability.

The Keller well at the summit of Kilauea is available measuring the ground water level.

We have already discussed the gravity data requirements at some length.

7. SUPPORTING FACILITIES

Greg Lyzenga, of Harvey Mudd College is contributing the loan of a LaCoste and Romberg model G gravimeter. This receiver will require servicing and installation of an electronic feedback unit and other options to make is capable of carrying out the measurements we need to make. We have included $15K in the budget for returning it to the factory to get these upgrades.

We have budgeted for the purchase of one Portable Earth Tide LaCoste and Romberg gravimeter. This meter will cost considerably more than refurbishing an older unit, but we have been unsuccessful in attempting to find an unused second meter.

We have discussed the use of a piece of a gravity pier at Table Mountain Gravity Observatory with Doug Robertson from TMGO. He has indicated a willingness to allow us to use the facilities at TMGO for the purposes of running the two gravimeters side by side for 2-3 months. (see memo of cooperation) TMGO is a good place for this because it is known to be a quiet site, and there are other gravimeters there including at least one superconducting gravimeter which records continuously.

Lisowski has been involved in the installation, maintenance, data collection, and analysis of continuous GPS stations around Kilauea. Several existing stations appear as possible candidates for having a gravity station constructed adjacent to them. In addition, other stations continue to be installed, and there is the possibility that one or two of them could be sited with the gravity experiment in mind.

Hawaiian Volcano Observatory typically has a few volunteers assisting with field work of various kinds. Either they, or HVO staff plan to make a very large contribution by carrying out the gravity ties between the continuous sites at regular intervals using a third existing gravimeter belonging to HVO.

Adequate computer resources for this project exist at JPL, HVO, and Open University.

8. REFERENCES

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9. INVESTIGATOR RESUMES

9.1. Kenneth J. Hurst - Principal Investigator

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EDUCATION:

Columbia University, New York, New York Title of thesis: "The Measurement of Vertical Crustal Deformation"	PhD Geology, October, 1987
Columbia University, New York, New York	MPh Geology, 1987 MA Geology, 1982
Earlham College, Richmond Indiana	BA Geology, 1980 BA Physics, 1980

AWARDS:

Co-recipient of runner-up award in NASA software of the year competition 1995.

Co-recipient of NASA Group Achievement award for Global Positioning System Geodesy Development, Jet Propulsion Laboratory, 1994.

Co-recipient of NASA Group Achievement award for development of the GIPSY-OASIS GPS analysis software Jet Propulsion Laboratory 1992.

Departmental honors in Geology, Earlham College 1980.

All college honors, Earlham College 1980.

Recipient of Anna Hubbard Grave, Thomas Clarkson Grave honorary scholarship for graduate work in science, Earlham College 1980.

EMPLOYMENT EXPERIENCES:

- 1997 to present - Senior Member of the Engineering Staff - Jet Propulsion Laboratory
- January 1990 to 1996 - Member of the Technical Staff - Jet Propulsion Laboratory

  Principal Investigator of Parkfield Rapid Static GPS experiment under sponsorship of NASA-DOSE program.

  Member of a team to generate automated analysis methods for the SCIGN (Southern California Integrated Geodetic Network) array.

  Organizer of conversion/rewrite of GIPSY-OASIS II GPS analysis software to run under UNIX, and general release of the software to other research institutions.

  Co-organizer and designer of the first class on the theory and use of GIPSY-OASIS II.

  Part of a team to design and implement an automated processing system for analysis of data from a network of 800-1000 GPS stations installed for the Geographical Survey Institute of Japan.

  One of the organizers of the Landers 1992 and Northridge 1994 JPL earthquake response,

  Analysis of Rapid Static Survey GPS data collected following the October 1989 Loma Prieta earthquake, and modeling of the measured post-seismic deformation.

  Member of the CONAN receiver software development team. This software is used in Rogue and TurboRogue GPS receivers for communication and remote operation.

- June 1992 to Dec 1994 - Independent Consultant

  Analysis of 1988 and 1989 Aegean GPS data sets.

- August 1988 to December 1989 - Post-doctoral Research Scientist - LDGO, Columbia University

  Co-leader of 1989 Northern Aegean GPS survey.

  Planning, organization, and analysis of 1988 Southern Aegean GPS survey.

• June 1988 to August 1988 - Research Assistant - LDGO, Columbia University
  Planning for 1988 Southern Aegean GPS survey.
• October 1987 to April 1988 - Research Associate - University of Colorado
  Analysis of the effect of atmospheric water vapor on the vertical accuracy of GPS.
• July 1987 to September 1987 - Professional Research Assistant - University of Colorado
  Assisted with organization of the first South Iceland GPS survey.
• 1983 to 1987 - Graduate Research Assistant (Seismology) - Columbia University
  Analysis of the effect of atmospheric water vapor on the vertical accuracy of GPS
  Spirit leveling field work and analysis, design and installation of, and analysis of data from, sea-level gauges in the Shumagin Islands, Alaska to monitor vertical crustal deformation.
  Development of a hydrostatic leveling system for high speed precision leveling without slope-dependent errors.
  Installation and analysis of data from extensometers across the Babojan fault, People's Republic of China.
  Subsurface radar profiling in the Adirondack region in N.Y. to look for lake bottom sediment structures related to earthquakes.

PROFESSIONAL AFFILIATIONS:
Geological Society of America
American Geophysical Union
Seismological Society of America
National Association of Geoscience Teachers

PUBLICATIONS LIST

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9.2. Hazel Rymer - Co-Investigator

9.3. Michael Lisowski - Co-Investigator

PRINCIPAL INVESTIGATOR CURRENT AND PENDING SUPPORT

STATUS: pending

TITLE: Tracking magma migration and volatile content using continuous differential microgravity and continuous GPS

SOURCE OF SUPPORT: NASA

PRINCIPAL INVESTIGATOR: Kenneth Hurst

AWARD AMOUNT AND PERIOD OF PERFORMANCE:

PERSON-MONTHS of SUPPORT: YR1 2 YR2 2

9.4. Hazel Rymer

9.5. Mike Lisowski

10. DETAILED BUDGETARY INFORMATION AND EXPLANATIONS

quantity	description	$K each	$K
	1st Year Budget		
	Supplies and Equipment		
1	LaCoste and Romberg model PET gravimeter	45	45
1	retrofit of existing L&R G meter SN 407		
	MVR electronic feedback	3.6	
	Liquid Electronic Levels	2.5	
	G-Meter long term service	1.5	
	Add double oven	3.5	
	Variable Damping	4	
	TOTAL retrofit		15.1
2	Laptop computers and software for data logging	4	8
2	Paroscientific absolute pressure atm gauge	1	2
2	water level gauge	1	2
1	freewave modem	1	1
1	solar cell/battery system	5	5
2	materials for gravity piers/buildings	2	4
	Transportation		
4	Hours Helicopter	1	4
7	round trip to Hawaii (air+car+perdiem@64/day)		17.4
3	PI+Co-Is to investigators meeting	1	3.2
2	PI to TMGO in Boulder	1	2
	Freight		
1	1663 lbs airfreight for Absolute G machine	4	4
1	freight for instruments and supplies	2	2
	Salary		
2	months PI salary (burdened)	9	18
1	month assistant (burdened)	6	6
	2nd Year Budget		
	Supplies and Equipment		
1	misc repair parts		1
	Transportation		
2	Hours Helicopter	1	2
4	Round trip to Hawaii (air+car+perdiem@64/day)		9.0
3	PI+Co-Is to investigators meeting	1	3.2
	Freight		
2	1663 lbs airfreight for Absolute G machine	4	8
	Salary		
2	months salary (burdened)	9	18

The supplies and equipment list has, I believe, been justified within the body of the proposal and does not require further justification here.

We anticipate that there will be about 20 minutes of helicopter time per trip to the site on the East Rift. Anticipating 6 trips for building the station, 2 trips to get the gravimeter and other instrumentation and telemetry installed and operating correctly, and 1.5 trips/month after recording starts (4 trips total) yields 12 trips = 4 hours of helicopter time.

The absolute G machine and ancillary equipment weigh 755 kg. The budget contains funds to send it air freight to Hilo Hawaii and back to Boulder. The other equipment and supplies which we need to ship to Hawaii can mostly go by surface freight and hence is cheaper.

Occupation of each mark by the absolute gravimeter requires 3 days, with one day to move between sites. If we occupy 5 sites (2 of our gravity stations, 1 at the coast, and 1 near the top of the road up Mauna Loa, and 1 intermediate point) we anticipate that it will take 20 days of measurements plus 2 days at the start and 2 days at the end for unpacking and repacking the equipment for a total of 24 days.

The table below gives the breakdown on travel funds for each trip, who will be taking the trip, and the purpose of the trip.

Number of days	Person	Purpose	$K
		1st year	
14	Hurst	Select two sites, Prepare Kilauea summit site	2.4
14	Rymer	Select two sites, Prepare Kilauea summit site	2.6
21	Hurst	Prepare East Rift site	3.0
21	undetermined	Prepare East Rift site	3.0
7	Hurst	Install meters, Initiate Absolute G measurements	1.4
7	Rymer	Install meters, Initiate Absolute G measurements	1.6
24	undetermined	Absolute G measurements	3.4
3	Hurst	Attend Investigators meeting	1
3	Rymer	Attend Investigators meeting	1.2
3	Lisowski	Attend Investigators meeting	1
		TOTAL 1st year	20.6
		2nd year	
4	Hurst	Maintenance & Collaboration	1.0
4	Rymer	Maintenance & Collaboration	1.2
24	undetermined	Absolute G measurements	3.4
24	undetermined	Absolute G measurements	3.4
3	Hurst	Attend Investigators meeting	1
3	Rymer	Attend Investigators meeting	1.2
3	Lisowski	Attend Investigators meeting	1
		TOTAL 2nd year	12.2

The salary included in the budget is best justified by describing the work to be done and the anticipated level of effort for each task.

Task	Description	Hours
	1st year	
1	Obtain 2 suitable gravimeters	8
2	Characterize the relative drift rates	30
3	Design a measurement schedule	10
4	Design and build a gravity station next to a GPS station	
	PI	80
	assistant	120
5	Install gravimeters	40
6	Coordinate visits by absolute gravimeter	30
7	Interpret gravity and deformation measurements	120
	2nd year	
7	Interpret gravity and deformation measurements	200

The first task, obtaining two suitable gravimeters and administering the proper configuration of them should require only a small amount of effort to carry out. Eight hours time should be adequate to accomplish this task.

The second task, characterizing the relative drifts, requires setting up the meters in a suitable environment, recording data for several months, and then calculating the spectrum of the differenced signal. A site with a stable temperature, easy access, a suitable and stable pier to set the meters on, and data logging capability are required. We plan to use a gravity pier at Table Mountain Gravity Observatory (TMGO), near Boulder Colorado for this test. We have estimated 30 hours of work to complete this task.

Task 3, designing a measurement schedule should be fairly quick once the spectrum from task 2 is in hand. We estimate that this should be accomplished with 10 hours of work.

Task 4, Design and build a gravity station next to a GPS station is expected to require a major effort. Since we will be trying to push the envelope to see what is possible, we must pay careful attention to the details of construction which could affect the data quality. The station must be designed such that the meter is solidly supported on the pier, yet isolated from temperature, humidity, and possibly pressure variations. There must be room for a second gravimeter, and accommodation for the absolute G machine. We have estimated 80 hours of work by the PI, and 120 hours of work by an assistant.

The fifth task, installing the meters, will involve both the physical installation of the meters, and checkout of the telemetry and data collection from the gravimeters and other gauges at each site. Typically these sorts of tasks require a small amount of trouble shooting at the beginning to get everything running smoothly together. We have estimated 20 hours effort for each of the two sites, or 40 hours total.

The sixth task (and last one for the first year) is to coordinate the visit by the absolute G machine. The PI plans to meet the machine in Hawaii for the initial measurements. Subsequent measurements will be supervised by co-investigator Lisowski from HVO. We have allocated 30 hours to accomplish this task.

The seventh task, interpreting the gravity and deformation measurements, will be started in the first year and will be the main task for the second year. We will have to understand all the features in the data as best we can, and try to model the data with migrating magma in the volcano. We have estimated that we will spend 120 hours in the first year and 200 hours (5 weeks) in the second year.