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The University of Hawaii lunar ranging experiment geodetic–geophysics support programme†

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Secular changes in the geocentric positions of lunar laser ranging stations will include components due to local and regional crustal deformations and tectonic plane movements.

Terrestrial geodetic and geophysical methods appear to be the most timely and economical approach to determining local and regional effects.

The University of Hawaii expects to implement a comprehensive geodetic–geophysical programme in support of its lunar ranging programme in mid-1976. Measurements will include (*a*) repeated geodetic surveys between the observatory and selected points on the island of Maui and neighbouring islands, (*b*) repeated level surveys on the island tied to ocean tide gauges, (*c*) tilt meter monitoring of changes in the local vertical, (*d*) gravimetric Earth tidal measurements, and (*e*) seismic monitoring of crustal activity.

A similar programme is also being undertaken by the University of Texas in support of their MacDonald Observatory lunar ranging programme.

Introduction

The University of Hawaii Institute for Astronomy has constructed and is operating a lunar laser ranging observatory at the summit of Mt Haleakala, on the island of Maui. The facilities have been described in detail by Carter & Williams (1973). Although the Lurescope, the receive telescope, has not yet been completed by J. E. Faller and his co-workers at Joint Institute for Laboratory Astrophysics, National Bureau of Standards and the University of Colorado, successful range measurements have been made using the nearby Advanced Research Project Agency 1.25 m telescope as a receiver. It is presently anticipated that the Lurescope will be completed and installed during the first half of 1976 and that the completed system will become fully operational by the year's end.

Hawaii was selected as the site of the second permanent United States lunar ranging installation primarily for two reasons: (1) the separation between MacDonald Observatory, Texas, and Hawaii is sufficient to provide a reasonable geometry for the determination of both components of polar motion, (2) Hawaii is located on the Pacific tectonic plate whereas MacDonald Observatory is located on the North American plate, providing an opportunity for verifying and measuring any plate motions.

Selection of a specific site within Hawaii was greatly limited by prevailing atmospheric conditions, assessibility, and developed support facilities. The geologically older islands do not have points of sufficient elevation to rise above the extensive rain cloud formations that form daily throughout most of the year. Only the islands of Maui and Hawaii have extensive areas

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with elevations of more than 3000 m: Mt Haleakala, Maui, and Mauna Kea and Mauna Loa, Hawaii. The Institute for Astronomy had established observatories on Haleakala and Mauna Kea, but the Haleakala site was chosen as it is more accessible and, because it is older and more distant from the present centre of volcanic activity, is presumably more stable. Before the tectonic plate motion can be extracted from the lunar ranging data, any local or regional motions must be measured and accounted for.

The University of Hawaii Institute of Geophysics and Institute for Astronomy presently have a joint grant from N.A.S.A. to study the problem of determining the local and regional stability of the Observatory, and to detail a suitable operational programme. It is anticipated that the programme will be instituted about mid-year 1976.

Tectonic setting

Haleakala is one of a long chain of volcanoes that stretches from the Aleutian Trench through the submerged Emperor Seamount, the Midway Islands, and the Hawaiian Archipelago to the Island of Hawaii, the present centre of volcanic activity, a total distance of approximately 6000 km. The oldest volcano of the chain is estimated to be about 70 million years old. It has been suggested that the line of volcanoes has formed as the Pacific plate has drifted across a huge column of upwelling lava, called a 'plume', which lies fixed beneath the plate. An alternative theory suggests the propagation of a crack, due to internal plate stresses that are generated by the plate's motion with respect to the equatorial bulge. The rate of drift is thought to be approximately 10 cm per year.

Haleakala was built up by many eruptions, beginning at the ocean floor 5400 m below sea level and reaching a maximum elevation of approximately 3000 m above sea level. The volcanic activity ceased for a period, during which time erosive processes dominated. Two streams cut large amphitheatre-like basins near the summit. Eventually the two basins met, creating a long erosional depression. Subsequent volcanic activity poured lava down the stream-cut valleys, nearly filling them. Cinders, ash, volcanic bombs, and spatter blown from vents formed multi-coloured symmetrical cones within the erosional basin. Today the partially filled water-carved depression superficially resembles a true volcanic crater. No volcanic activity has occurred within the crater for the past few hundred years, but there has been activity on the flanks of the volcano, in the form of lava flows, as recently as 1790. The mountain is still seismically active, and further eruptive activity is certainly possible. (Reference U.S. Department of the Interior, National Park Service, pamphlet *Haleakala*.)

The centre of volcanic activity is now on the island of Hawaii, approximately 150 km from the L.U.R.E. Observatory. The U.S. Geological Survey operates a very active observatory on Hawaii. An extensive array of seismometers and tilt meters is used to monitor the inflation and deflation of the volcano as it passes through cycles of buildup, eruption, and subsidence. The U.S.G.S. has also established an elaborate trilateration network which is reobserved regularly to determine surface strain, faulting, and displacements. A recent eruptive episode prior to the magnitude 7.3 (November 1975) earthquake resulted in the horizontal displacement of some stations by more than a metre.

All of the recorded seismic activity in the Hawaiian Islands does not originate from the volcanic processes on the island of Hawaii. There is a major fault known as the Molokai fracture zone which passes between Maui and Molokai and extends beyond Oahu that is also seismically active.

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Unfortunately, to date most of the effort has been directed toward recording and investigating the activities from volcanic origins. However, recent recordings of several events located along the fault near Oahu have generated increased interest in monitoring such activity. Activity along faults is of greatest concern to the lunar ranging experiment because it may be accompanied by displacements of surface features.

In summary then: the L.U.R.E. Observatory is located at the summit of a dormant volcano, more than 8000 m above the surrounding ocean floor and within 150 km of present extensive volcanic activity, and the entire plate is believed to be drifting at a rate of approximately 10 cm per year. It is not unlikely that additional significant local and regional motions may also exist.

Geodetic control

The University of Hawaii L.U.R.E. Observatory is located less than 25 m east of the first-order triangulation station Kole-Kole, originally established in 1876 in the Hawaiian Government Survey network. It was reoccupied in 1950 by the U.S. Coast and Geodetic Survey and the coordinates were determined on the Old Hawaiian Datum. Astronomic latitude, longitude, and azimuth observations were also made in 1961.

More recently, an offset station was established for BC-4 stellar camera observations, and the U.S. Defense Mapping Agency has occupied the station for geodetic doppler satellite observations.

During the fall of 1975 the U.S. Geodetic Survey tied the L.U.R.E. transmitter and receiver to Kole-Kole. The survey consisted of electronic distance measurements, triangulation, and levelling. Additionally, the Smithsonian Astrophysical Observatory has an observatory located less than 200 m west of station Kole-Kole. Both laser ranging and Baker-Nunn camera observations have been made from that site.

The L.U.R.E. Observatory is obviously in an excellent location for direct comparison between its position as derived from lunar ranging and that derived from artificial satellite techniques. The initial range measurements were in close agreement with the range predicted using the geocentric coordinates derived from the BC-4 network.

Comparison of L.U.R.E. measurements with v.l.b.i. measurements may prove more difficult. It is likely that v.l.b.i. measurements will be made on Kauai, approximately 400 km from Haleakala. The sites may be tied together by terrestrial e.d.m. methods or satellite methods, or by visitations of the transportable lunar ranging system, now under construction at the University of Texas.

E.d.m. network

A network of stations will be established and observed periodically using electronic distance measuring (e.d.m) techniques, to determine local and regional motions.

'Local motion' refers to motion of areas on the scale of the mountain area of Haleakala. A relatively dense network of stations will be established on the summit area and slopes of Haleakala. The line lengths in this network will generally be a few kilometres in length and e.d.m. techniques should allow the detection of motions smaller than 1 cm. Several existing bench marks will be used and several new stations will be established.

'Regional motion' refers to motion between distant parts of Maui and other islands of the chain. A trilateration network will be developed extending at least to the islands of Hawaii and Oahu, and perhaps to Kauai. The line lengths will be tens of kilometres, and a few may be as long as a 100 km or more. In order for the regional network to be very useful the internal consistency and repeatability of the measurements will have to be a few parts in 10^7 or better. Achieving the desired consistency of measurements will depend largely upon the accuracy of the atmospheric correction applied. National Geodetic Survey tests (Meade 1969) indicate that the refractive index can be determined to a few parts in 10^7 by using an aircraft to fly temperature and humidity sensors along the atmospheric path during e.d.m. operations. Simo Laurila (1976), University of Hawaii, has suggested another technique that utilizes a number of surface station measurements of atmospheric parameters to model the atmosphere simultaneously with the laser measurements and compute the refractive index along the line of measurement. It is likely that comparative tests of the two techniques will be made.

Another approach to the problem is to directly measure the index of refraction along the path by the use of multi-wavelength systems. Such systems determine the index by measuring its dispersion. The theory has been worked out in detail for two- and three-wavelength systems and indeed multiple wavelength instruments have been successfully demonstrated. Huggett & Slater (1974), report that they have achieved standard deviations of about 5×10^{-8} for short-term measurements and 1.3×10^{-7} for long-term measurements over a 10 km path. It now appears feasible to build a three-wavelength instrument with an accuracy of a few parts in 10^8 and a range of 30–50 km. Such an instrument would be very useful in determining the local and regional motions effecting lunar-ranging observatories.

Ocean tide gauges and levelling surveys

Tide gauge records from Kauai, Oahu (Honolulu), Maui, and Hawaii indicate a downward tilt of the ridge toward Hawaii with a relative average subsidence of 4 mm per year to Hilo (Hawaii) with respect to Honolulu, when averaged over a 20-year period. However much larger fluctuations lasting several years are present. It therefore is important to monitor such fluctuations more precisely since they exceed the planned lunar ranging accuracy of a few centimetres.

Three ocean-tide gauges are planned, located at the vertices of a nearly equilateral triangle centred on the observatory. The array would allow detection of tilts to 0.1″ and relative uplift or subsidence of the island to a few millimetres. Levelling lines from the tide gauges to higher points inland will assure that any detected motion is not a purely local effect but representative of the surroundings. Also one of the gauges will be connected to the observatory by a first order levelling line.

Tilt measurements

Tilts (or changes in the local vertical) will be monitored in the immediate vicinity of the observatory by fluid level or pendulum instruments. One two-component fluid bubble tiltmeter (Autonetics SE 541 A) operates at present on the base of the Lunastat (transmitter) and provides a reference to point the laser beam. A second tiltmeter (of the same manufacture) has been temporarily installed on the base of the pier on which the Lurescope (receiver) will be mounted. Both units presently show tilts in phase with the diurnal temperature variations of the sensors. It is likely that one of the units or a pendulum will be placed in a borehole near the observatory. The resolution of the bubble-type tiltmeters is claimed to be less than 1.4×10^{-3}″ r.m.s. at 1 Hz and null repeatability better than 0.1″. However borehole tidal tiltmeters of the pendulum type would provide a better long-term stability.

Seismic network

Large historic earthquakes with magnitudes of 6.7–7.3 have occurred in or near the islands, one (6.7, in 1938) about 40 km north of Maui and one (7.3 in 1871) in the Molokai–Maui area. These are probably associated with the faults and fracture zones (figure 1) that are still seismically active. Vertical and horizontal displacements of several centimeters occur even at some distance from such shallow-focus events and it is therefore planned to install a small (4–5 stations) short-period seismic telemetry network to monitor such activity and determine direction and amount of motion. Special filter techniques are required to eliminate a large portion of the ocean-generated microseisms.

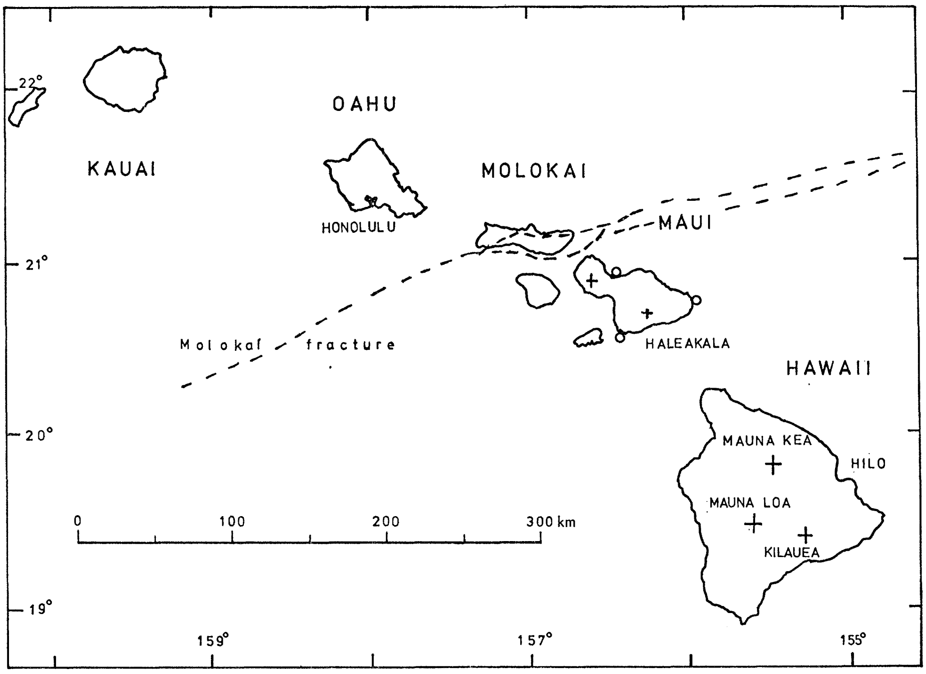

Figure 1

Gravimetric earth tidal measurements

The lunar range measurements contain a component resulting from solid earth tides and having an amplitude of about 40–50 cm, which must be taken into consideration. John Quo, Columbia University, has installed a tidal gravity meter at the observatory and plans to record the data for a period of a year or more.

The same instrument that it presently operating on Haleakala was previously installed at McDonald Observatory for a period of approximately one year. The data will provide a check on the model used to compute the earth-tide correction.

Conclusion

In order for the maximum information about plate motion to be derived from lunar laser ranging, it is necessary for any local or regional motions to be determined. In a volcanically active region, such as the Hawaiian Islands, this is considered to be particularly important. A long-term comprehensive well-documented programme of observation and analysis is required. Such programmes have been begun at both U.S. stations – MacDonald Observatory, Texas, and Haleakala L.U.R.E. Observatory, Hawaii. Hopefully, similar programmes will be instigated at other permanent lunar stations as they become operational.

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