# Gravity and the Geoid in the Nepal Himalaya

IN-46-CR
58211
P-41

# NAGW-2704

Semi Annual Report to NASA Washington

1 January 1992

Roger Bilham
University of Colorado
Boulder CO 80309-0216
303 492 6189

(NASA-CR-189523) GRAVITY AND THE GEOID IN THE NEPAL HIMALAYA Semiannual Report (Colorado Univ.) 41 p CSCL 08E

N92-14560

Unclas
G3/46 0058217

## Uplift and erosion in the Himalaya

Materials within the Himalaya are rising due to convergence between India and Asia. If the rate of erosion is comparable to the rate of uplift the mean surface elevation will remain constant. Any slight imbalance in these two processes will lead to growth or attrition of the Himalaya.

The process of uplift of materials within the Himalaya coupled with surface erosion is similar to the advance of a glacier into a region of melting. If the melting rate exceeds the rate of downhill motion of the glacier then the terminus of the glacier will receed up-valley despite the downhill motion of the bulk of the glacier. Thus although buried rocks, minerals and surface control points in the Himalaya are undoubtably rising, the growth or collapse of the Himalaya depends on the erosion rate which is invisible to geodetic measurements.

Erosion rates are currently estimated from suspended sediment loads in rivers in the Himalaya. These typically underestimate the real erosion rate since bed-load is not measured during times of heavy flood, and it is difficult to integrate widely varying suspended load measurements over many years. An alternative way to measure erosion rate is to measure the rate of change of gravity in a region of uplift. If a control point moves vertically it should be accompanied by a reduction in gravity as the point moves away from the Earth's center of mass. There is a difference in the change of gravity between uplift with and without erosion corresponding to the difference between the free-air gradient and the gradient in the acceleration due to gravity caused by a corresponding thickness of rock. Essentially gravity should change precisely in accord with a change in elevation of the point in a free-air gradient if erosion equals uplift rate.

We were funded by NASA to undertake a measurement of absolute gravity simultaneously with measurements of GPS height within the Himalaya. Absolute gravity is estimated from the change in velocity per unit distance of a falling corner-cube in a vacuum.Time is measured with an atomic clock and the unit distance corresponds to the wavelength an iodine stabilised laser. Since both these are known in an absolute sense to 1 part in $10^{10}$ it is possible to estimate gravity with a precision of 0.1 μgal. Known systematic errors reduce the measurement to an absolute uncertainty of 6 μgal. The free air gradient at the point of measurement is typically about 3 μgals/cm. At Simikot where our experiment was conducted we determined a vertical gravity gradient of 4.4 μgals/cm.

The accompanying report records the experiment that we undertook in the Himalaya in 1991. The site description is provided together with a description of the instrument. The measured value of gravity at Nagarkot is 978494834.7±6.7 μgals. It is our intention to remeasure this point in 1993 or 1994.

Publications and reports:

Winester, D., J. Fried, B. Bernard, L. Shrestha, B. N. Shrestha, G. Adiga, R. Bilham and J. Faller (1990)) Absolute Gravity at Nagarkot Geodetic Observatory. pp.30. Archives of His Majesties Government of Nepal, Survey Department.

Jackson, M., S. Barrientos, J. Behr, B. Bernard, R. Bilham, P. Bodin, G. Chitrakar, R. DeConto, L. Denham, J. Faller, J. Fried, D. Kauffman, D. Kayastha, P. Molnar, J. Normandeau, G. Peter, B. Phuyal, T. Pradhananga, B. Sharma, B. Shrestha, K.Shrestha, F. Sigmundsson, B. Stephens, B. Washburn, Wang Wenying, D. Winister, Zhao Guogang, Trans-Himalayan Geodesy, (1991). *Eos Trans. Amer. Geophys. Un.* **72**, 44, 112

Adhikari, K , R Bilham, M Jackson, N Karki, Kayastha, B Phuyal, T Pradhananga, B Sharma, B Shrestha, K Shrestha (1991). Interseismic Himalayan Subsidense: Uplift of Everest, *Eos Trans. Amer. Geophys. Un.* **72**, 44, 497.

# ABSOLUTE GRAVITY

## Nagarkot Geodetic Observatory, Nepal

March/April 1991

## Observations, corrections and results.

## Gravity ties to Kathmandu and Simira airports.

Dan Winester, Jack Fried and Brent Bernard

National Geodetic Survey, Rockville Md

Laxman Shrestha, Buddhi N. Shrestha and Gajanan Adiga

HMG Survey Department, Dilli Bazar, Nepal

Roger Bilham and Jim Faller

University of Colorado, Boulder, CO, 80309

# ABSOLUTE GRAVITY, Nagarkot, Nepal 1991

NGS Rockville Md: Dan Winester, Jack Fried and Brent Bernard
Survey of Nepal: Laxman Shrestha and Gajanan Adiga
Coordinated by: Roger Bilham, Jim Faller and Buddhi N. Shrestha

*Summary of measurements*

The purpose of measuring absolute gravity in the Himalaya was to establish a reference datum for the local gravity network in Nepal and to establish points that may be remeasured to reveal changes of elevation in future years. The original plan was to measure absolute gravity at three locations: in the Greater Himalaya, in the Lesser Himalaya and in the Terrai bordering the northern plains of India. Each absolute gravity point was scheduled to be co-located with a GPS control point so that an independent estimate of vertical deformation might be possible.

The plan we adopted differed in three ways from the above:

1) One absolute-g site only was measured at Nagarkot (FAGS-1). The corrected value of the FAGS-1 indoor point at ground level for the period 3/30/91-4/2/91 is **978494834.7±6.7 μgal.** The gravity gradient at floor level (zero to 0.43m) was **4.4194 μgal/cm.**

2) Relative ties were made to three GPS points: Nagarkot, Kathmandu airport and Simira Airport. The relative differences from FAGS-1 to these points are listed on the next page.

The ties were undertaken using a pair of Model D LaCoste Romberg meters. For Nagarkot the GPS point is less than 10 m from the brick building where GPS measurements were made. The Kathmandu Airport tie was undertaken using road transport (multiple ties over the 33-km-long 1.5 hour road linking Nagarkot to the capital). The Simira tie was made by flying several times between Simira and Kathmandu. The Model D gravimeter has just sufficient range to accommodate the gravity variation associated with the vertical change in height between Nagarkot and Kathmandu, and also the latitude change and vertical range combination between Kathmandu and Simira.

3) The limited number of sites suitable for gravity measurements has resulted in no gravity measurements at points suspected to be rising in the Greater and Lesser Himalaya. Simira is south of the Lesser Himalaya and Kathmandu and Nagarkot lie between the Lesser and the Greater Himalaya. Future Model D or Model G gravimeter ties be made from Kathmandu airport to GPS points elsewhere in Nepal are needed to correct this limitation in the 1991 measurements.

A removal truck was used to meet the several hundred pounds of equipment from the plane and to store the packaging at Nagarkot. The power at Nagarkot was found to be unreliable for the gravity measurements as was the portable generator used to provide backup power. Measurements for this reason were spread over a longer period than is usual. Air conditioning was requested for the gravimeter but was found to be unnecessary in Nagarkot. A decision to occupy only one point "absolutely" and the other points using Model D gravimeters was made because:

a) the absolute gravimeter was damaged in transit to Kathmandu or on the road to Nagarkot and might have further been damaged by additional road transport.

b) suitable temperature control from air conditioners was unavailable at the other selected sites, and an air conditioner would have had to have been trucked in from India together with a 15 kw generator.

c) Power outages at Nagarkot reduced the time available for measurements at additional sites.

The new gravity base stations provide a framework for the local Nepal gravity network. It is anticipated that future gravity measurements will extend this network throughout the country. The absolute accuracy of the 1991 measurements is ±6 μgals or approximately ±1.5 cm in elevation.

Funding support for the measurements was provided by NASA grant NAGW-2704.

A description of the JILA absolute gravimeter follows the observational data.

**UNITED STATES DEPARTMENT OF COMMERCE**
**National Oceanic and Atmospheric Administration**
NATIONAL OCEAN SERVICE
~~OFFICE OF CHARTING AND GEODETIC SERVICES~~
ROCKVILLE, MARYLAND 20852

Coast and Geodetic Survey
11 June 1991

Dr. Roger Bilham
CIRES, Univ. of Colorado
Boulder, CO 80309

Dear Roger:

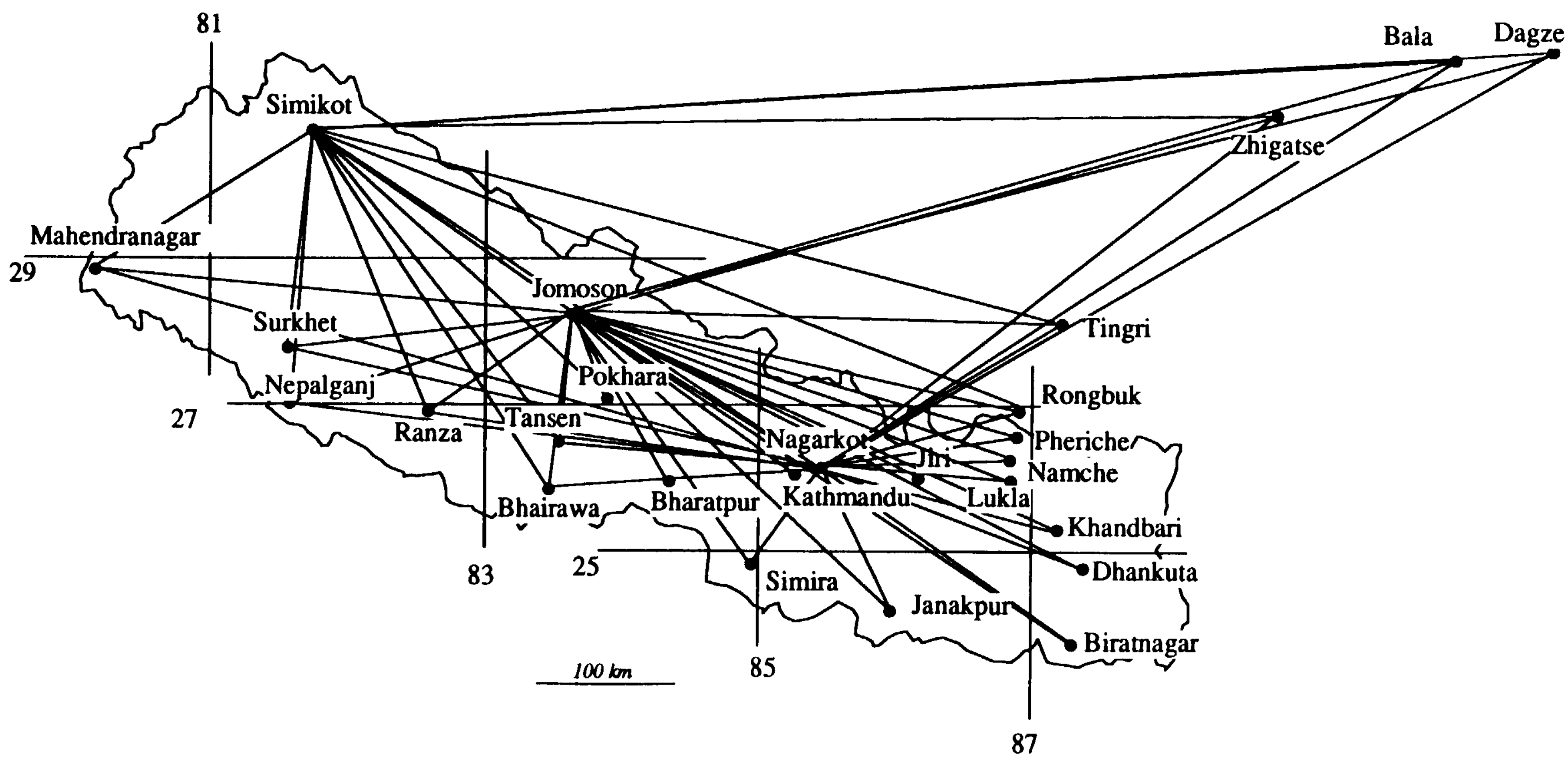
Enclosed are gravity base station descriptions for occupied sites in Nepal. A copy of these will be sent to Buddhi Shrestha. The NAGARKOT FAGS-1 absolute gravity value will be available from Dr. Peter. The gradients at NAGARKOT FAGS-1 from floor to 83 cm is 0.44194 mgal/m and from floor to 120 cm is 0.43923 mgal/m. Relative to the floor value at NAGARKOT FAGS-1 at the following gravity transfers:

| | |
|---|---|
| NAGARKOT GPS | - 0.691 ± 0.002 mgals |
| KATHMANDU J | +166.469 ± 0.005 |
| SIMARA J | +368.599 ± 0.017 |
| SIMARA GPS | +368.706 ± 0.013 |

Sincerely,

Daniel Winester
Daniel Winester, Geodesist
National Geodetic Survey, N/CG 161N

NEPAL/TIBET GPS Survey
Direct ties to base stations at Simikot, Jomoson and Nagarkot 25 March-12 April 1991



## DESCRIPTION

| DESCRIPTION | National Reference Base | KATHMANDU J |
|---|---|---|
| COUNTRY<br>Nepal | ZONE (ANCHAL)<br>Bagmati | CITY<br>Kathmandu |
| DISTRICT (ZILA)<br>Kathmandu | | QUAD<br>027274424 |
| LATITUDE<br>27° 41' 50" N | LONGITUDE<br>85° 21' 28" E | ELEVATION<br>1332.006 meters |
| GRAVITY STATION MARK<br>Benchmark Hub | AGENCY/SOURCE<br>HMG Survey Dept. | INSCRIPTION<br>-- |
| POSITION REFERENCE<br>GPS Position (unprocessed) | POSITION SOURCE<br>UNAVCO | SOURCE DESIGNATION<br>-- (4/1991) |
| ELEVATION REFERENCE<br>BM Elevation | ELEVATION SOURCE<br>HMG Survey Dept. | SOURCE DESIGNATION<br>-- (4/1991) |

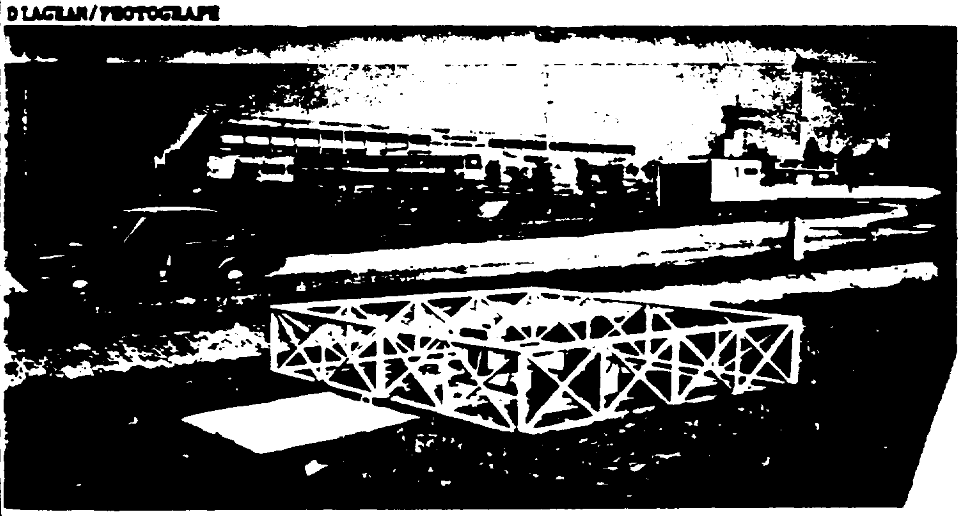
**POSITION/ELEVATION REMARKS** 1st order levels; Indian MSL; WGS 84

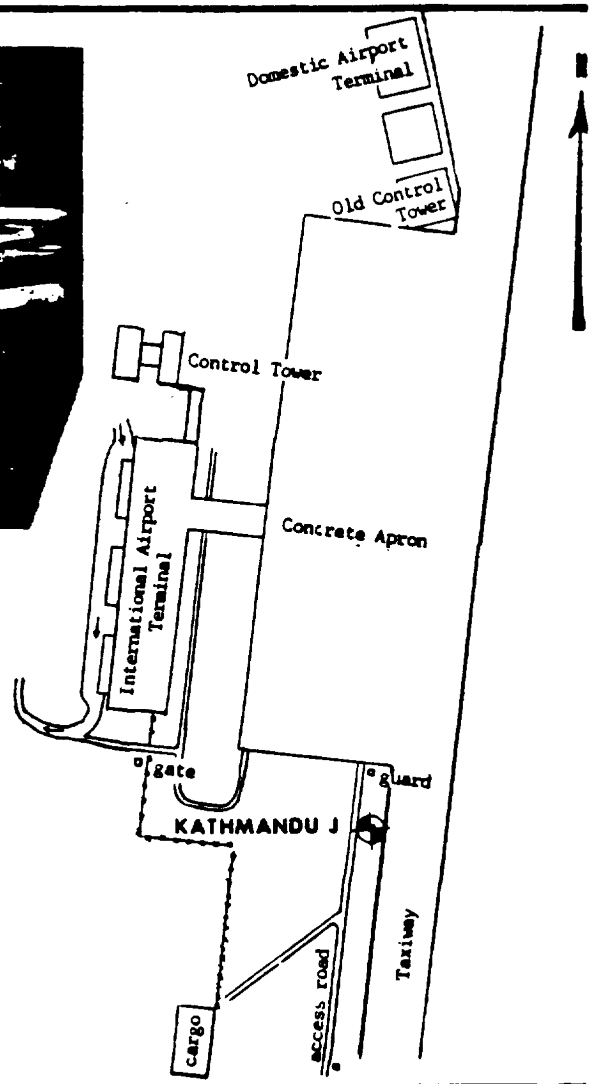
**GRAVITY VALUE** g = 978 661.22 ± 0.047 mgals (512 STRE,1984

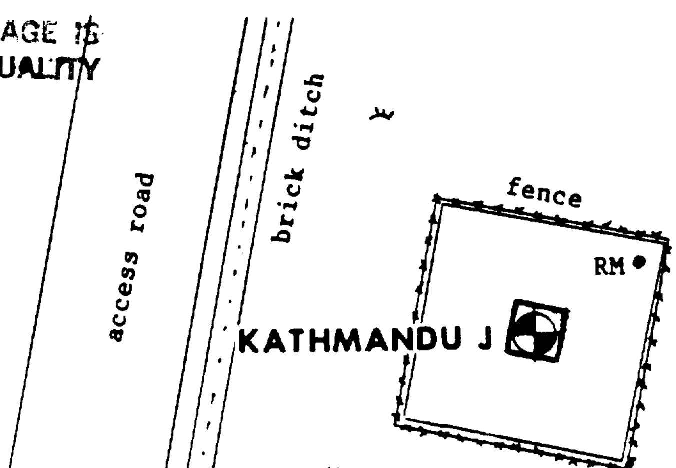
**DESCRIPTION** Station is at Kathmandu's Trebhuvan International Airport. Station is 3.8 km ESE of the Royal Palace. To access from the Tinkune (traffic triangle) on the east side of Kathmandu, go NNE on Meanmoven Road for 2.0 km. Turn east (right) into airport and go 0.3 km to Pass Office under control tower. Get field pass. Go south for 0.3 km, passed International Terminal, to gate to east and airfield. Go 0.2 km along jet parking apron to acce: road to SSW (right). Station is about 62 m SSW of apron, 16 m WNW of WNW edge of taxiway, 10.5 m ESE of center of access road and in the center of a 3 m by 3 m macadam area surrounded by a white fence. Station is in center of 0.70 m by 0.70 m by 0.36 m deep concrete pit and over 0.030 m wide by 0.025 m tall BM hub and 0.32 m SW of Reference Mark and 1.5 m ESE of witness sign.

**OTHER STATION DESIGNATIONS:** International Gravity Station

**DIAGRAM/PHOTOGRAPH**








**DATE OF PHOTO:** 5 Apr 1991

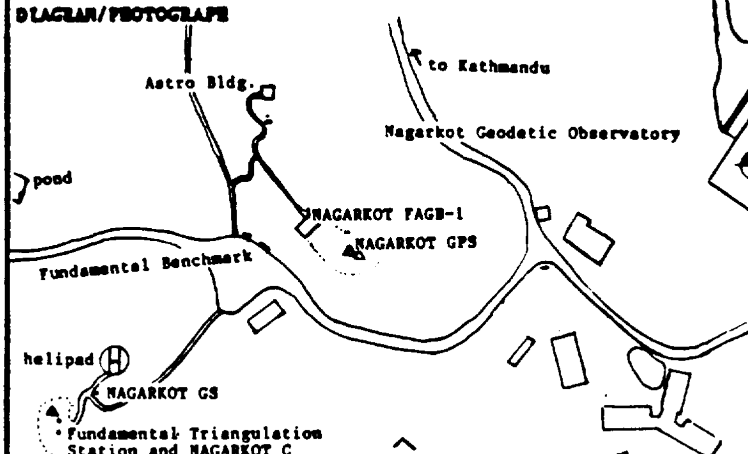
| DESCRIPTION BY | AGENCY | DATE |
|---|---|---|
| Bernard/Winester | NOAA/NOS/NGS | 7 April 1991 |

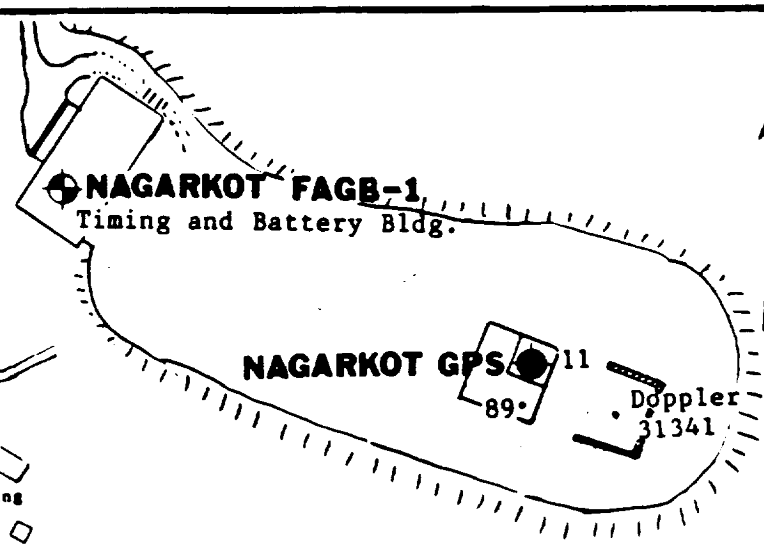
| DESCRIPTION | Absolute Site | NAGARGOT FAGB-1 |
|---|---|---|
| COUNTRY<br>Nepal | ZONE (ANCHAL)<br>Bagmati | CITY<br>Nagarkot |
| DISTRICT (ZILA)<br>Bhaktapur/Kabhre Palanchok | | QUAD<br>027274134 |
| LATITUDE<br>27° 41' 35" N | LONGITUDE<br>85° 31' 16" E | ELEVATION<br>2150.564 meters |
| GRAVITY STATION MARK<br>19 mm brass plug | AGENCY/SOURCE<br>NOAA/NGS | INSCRIPTION<br>NFAGB-1 1991 |
| POSITION REFERENCE<br>Scaled from GPS station | POSITION SOURCE<br>UNAVCO & NOAA/NGS | SOURCE DESIGNATION<br>-- (4/1991) |
| ELEVATION REFERENCE<br>Disk Elevation | ELEVATION SOURCE<br>HMG Survey Dept. | SOURCE DESIGNATION<br>-- (4/1991) |
| POSITION/ELEVATION REMARKS<br>1st order levels; Indian MSL; WGS 84 | GRAVITY VALUE | |

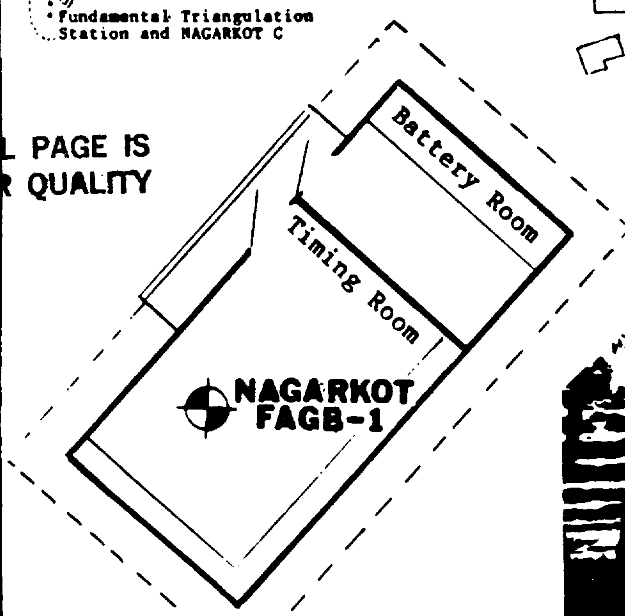
**DESCRIPTION** Station is at HMG Survey Department's Geodetical Observatory - Nagarkot. Station is 19.4 airline km east of the Royal Palace in Kathmandu. To access from the Tinkune (traffic triangle) on east side of Kathmandu, go easterly towards Bhaktapur for 4.7 km. Turn north (left) and go 0.4 km to second turn to east (right). Go easterly up a winding, bumpy road for about 20 km to second guard gate of Nagarkot Army Post. Bear left and go southeas for 2.7 km on dirt road to upper parking lot of Observatory. Station is uphill via footpat to NE in the Timing Room of the Timing and Battery Bldg.(3.7m by 7.5m). Station is 0.93 m SE of NW wall and 2.83 m SW of NE wall of room. Plug is epoxyed flush into the thin concre floor. Contact is Buddhi N. Shrestha, Director General, HMG Survey Dept. at 411-897 in Kathmandu. Site phone is 211-009. FAGB-1 stands for Fundamental Absolute Gravity Base - Number 1.

**OTHER STATION DESIGNATIONS:**

**DIAGRAM/PHOTOGRAPH**






**DATE OF PHOTO:** 3 Apr 1991

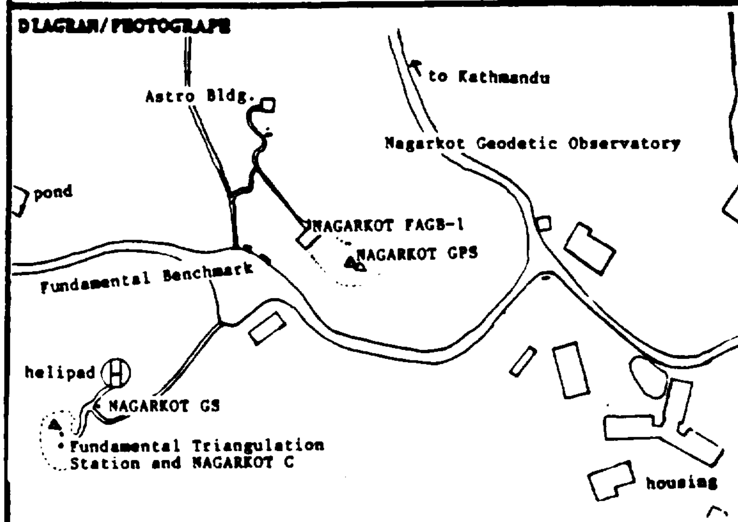
| DESCRIPTION BY | AGENCY | DATE |
|---|---|---|
| Bernard/Winester | NOAA/NOS/NGS | 7 April 1991 |

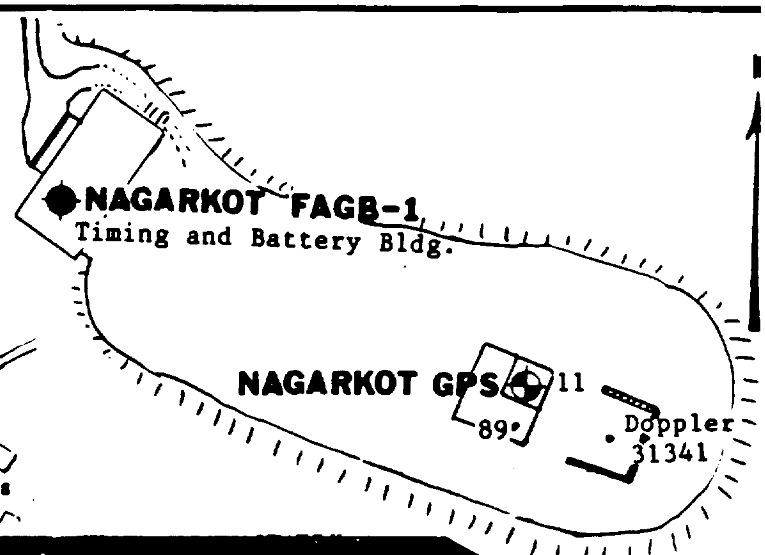
| **DESCRIPTION** | Absolute Excenter | NAGARKOT GPS |
|---|---|---|
| **COUNTRY** Nepal | **ZONE (ANCHAL)** Bagmati | **CITY** Nagarkot |
| **DISTRICT (ZILA)** Bhaktapur/Kabhre Palanchok | | **QUAD** 027274134 |
| **LATITUDE** 27° 41' 34" N | **LONGITUDE** 85° 31' 16" E | **ELEVATION** 2152.789 meters |
| **GRAVITY STATION MARK** Vertical Rod in Pier | **AGENCY/SOURCE** UNAVCO | **INSCRIPTION** 11 |
| **POSITION REFERENCE** GPS position (unprocessed) | **POSITION SOURCE** UNAVCO | **SOURCE DESIGNATION** -- (4/1991) |
| **ELEVATION REFERENCE** Disk Elevation | **ELEVATION SOURCE** HMG Survey Dept. | **SOURCE DESIGNATION** -- (4/1991) |
| **POSITION/ELEVATION REMARKS** 1st order levels, Indian MSL; WGS-84 | **GRAVITY VALUE** | |

**DESCRIPTION** Station is at HMG Survey Department's Geodetical Observatory - Nagarkot. Station is 19.4 airline km east of the Royal Palace in Kathmandu. To access from the Tinkune (traffic triangle) on east side of Kathmandu, go easterly towards Bhaktapur for 4.7 km. Turn north (left) and go 0.4 km to second turn to east (right). Go easterly up a winding, bumpy road for about 20 km to second guard gate of Nagarkot Army Post. Bear left and go southeas for 2.7 km on dirt road to upper parking lot of Observatory. Station is uphill via footpat to northeast, 18.5 m SE of Battery & Timing Bldg's east corner, 4.2 m NW of Doppler station 2.0 m NNE of GPS point 89, in east quadrant of 3.3 m squared concrete pad and in center of 1 m square, isolated, concrete pier inscribed GPS Main Station Nagarkot 1991. Pier goes down about 1 m to weathered rock. Rod goes down 0.3 m and then angles to side. Arrow on pier points north.

**OTHER STATION DESIGNATIONS:**

**DIAGRAM/PHOTOGRAPH**






**DATE OF PHOTO:** 3 Apr 1991

| **DESCRIPTION BY** | **AGENCY** | **DATE** |
|---|---|---|
| Bernard/Wiriester | NOAA/NOS/NGS | 7 April 1991 |

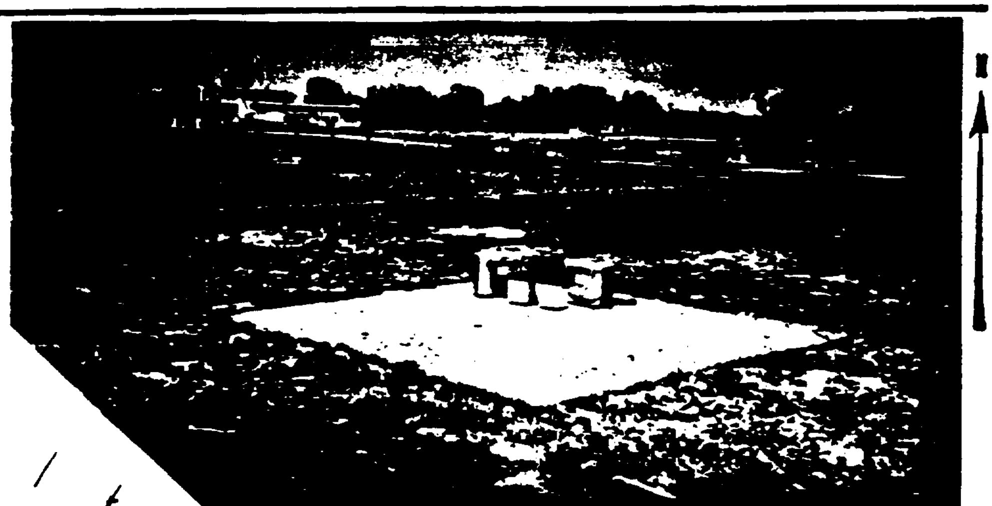
# DESCRIPTION

| DESCRIPTION | Base Station | SIMARA GPS |
|---|---|---|
| COUNTRY: Nepal | ZONE (ANCHAL): Nara Yani | CITY: Simara |
| DISTRICT (ZILA): Bara | | QUAD: 027275112 |
| LATITUDE: 27° 09' 45" N | LONGITUDE: 84° 58' 54" E | ELEVATION: 132.5 meters |
| GRAVITY STATION MARK: Vertical Rod in Pier | AGENCY/SOURCE: UNAVCO | INSCRIPTION: 34 SIMR |
| POSITION REFERENCE: GPS Position (unprocessed) | POSITION SOURCE: UNAVCO | SOURCE DESIGNATION: -- (4/1991) |
| ELEVATION REFERENCE: Estimated from BM | ELEVATION SOURCE: NOAA/NGS & HMG Survey Dept. | SOURCE DESIGNATION: -- |
| POSITION/ELEVATION REMARKS: Indian MSL; WGS 84 | GRAVITY VALUE: | |

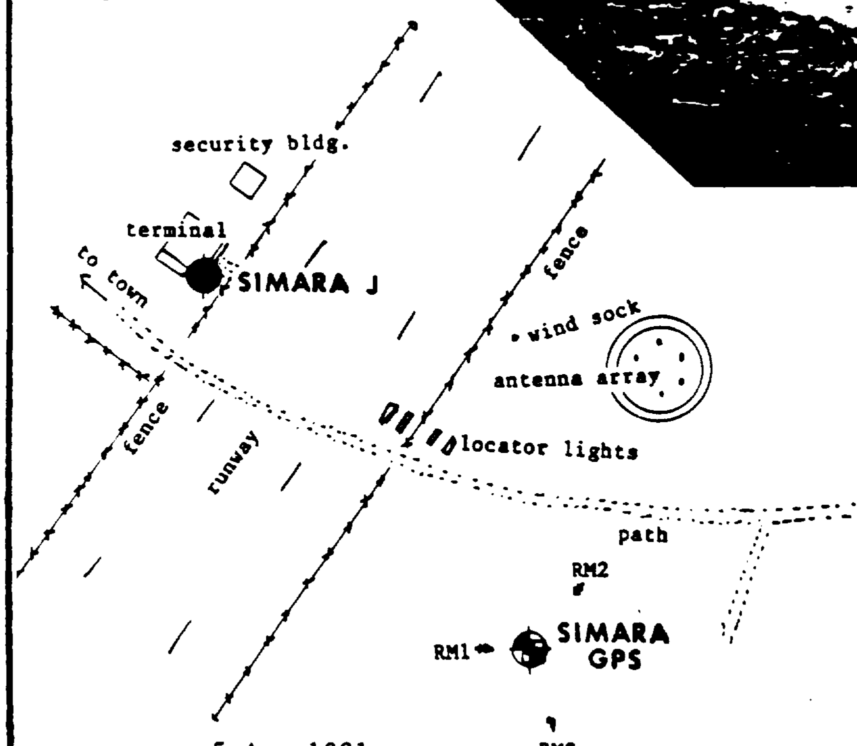
**DESCRIPTION** Station is on the Simara Airport grounds, Simara, Nepal. Airport is on east side of Simara and 20 km NNE of Birganj. Station is on SW side of grass runway, near center of old, abandoned east-west runway, 125.3 m S10E of wind sock, 74.8 m S30E of aircraft locator lights, 104 m north of D. Shamser's house, 17.35 m east of RM 1 on old runway marker, 30.68 m S62W of RM 2 on old runway marker and 30.90 m N16W of RM 3 on 0.3 m squared concrete post Station is in center of 1 m squared concrete pier at NW corner of 3.3 m concrete pad. Pier is 2.0 m deep and belled at bottom and set into soft, sandy soil. Steel rod goes down 0.3 in concrete and then angles to the side.

**OTHER STATION DESIGNATIONS:**

**DIAGRAM/PHOTOGRAPH**






**DATE OF PHOTO:** 5 Apr 1991

| DESCRIPTION BY | AGENCY | DATE |
|---|---|---|
| Bernard/Winester | NOAA/NOS/NGS | 7 April 1991 |

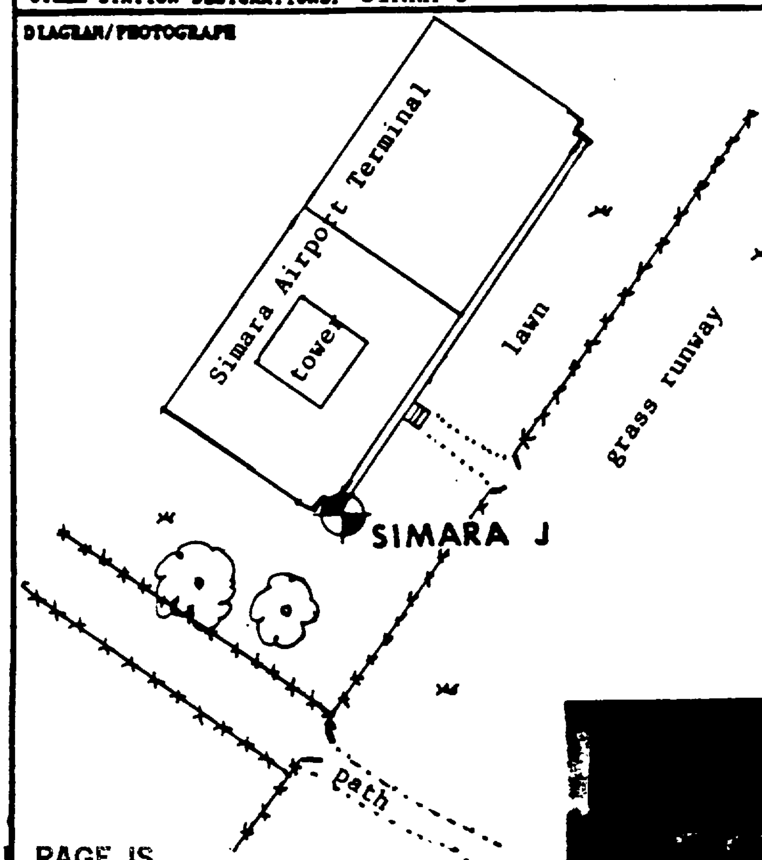
| DESCRIPTION | Base Station | SIMARA J |
|---|---|---|
| COUNTRY<br>Nepal | ZONE (ANCHAL)<br>Nari Yani | CITY<br>Simara |
| DISTRICT (ZILA)<br>Bara | | QUAD |
| LATITUDE<br>27° 09' 49" N | LONGITUDE<br>84° 59' 49" E | ELEVATION<br>131.739 meters |
| GRAVITY STATION MARK<br>Benchmark Hub | AGENCY/SOURCE<br>HMG Survey Dept. | INSCRIPTION<br>-- |
| POSITION REFERENCE<br>Topo Map 1:50,000 | POSITION SOURCE<br>Surveyor General of India | SOURCE DESIGNATION<br>Panchayat $72\frac{A}{T6}$ (c.1945) |
| ELEVATION REFERENCE<br>Disk Elevation | ELEVATION SOURCE<br>HMG Survey Dept. | SOURCE DESIGNATION<br>-- (1989) |

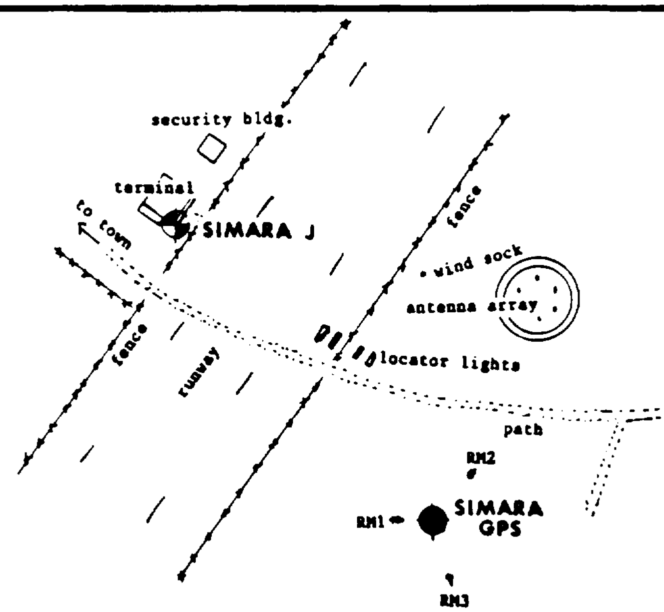
| POSITION/ELEVATION REMARKS | GRAVITY VALUE |
|---|---|
| 1st order levels; Indian MSL ; adj. to WGS 84 | g = 978 863.32 ± 0.070 mgals (512 STRE, 198 |

**DESCRIPTION** Station is at the Simara Airport Terminal, Simara, Nepal. Airport is on east sid f Simara and 20 km NNE of Birganj. Station is at SSE corner (field side) of terminal bldg. over brass hub set into concrete sidewalk at ground level. Station is about 0.7 m away frc terminal wall and is below concrete walkway along ESE side of terminal.

**OTHER STATION DESIGNATIONS:** SIMRA J

**DIAGRAM/PHOTOGRAPH**




ORIGINAL PAGE IS OF POOR QUALITY

**DATE OF PHOTO:** 5 Apr 1991

| DESCRIPTION BY | AGENCY | DATE |
|---|---|---|
| Bernard/Winester | NOAA/NOS/NGS | 7 April 1991 |

# Systems Check Log

NEPAL

**SERIAL NUMBERS** (Sheet of )

| | | | | | |
|---|---|---|---|---|---|
| DROP CHAMBER | N4 | LASER HEAD | | DROP CONTROL | DC5 |
| SUPER SPRING | N4 | LASER CONTROL | | SPRING CONTROL | 552 |
| INTERFEROMETER | N4 | SCALER-COUNTER | N4 | COMPUTER | |
| RUBIDIUM STD | 8501 | UTIC | 2332A00433 | DISC DRIVE | |
| AVALANCHE DIODE | | ZERO CROSS DET | N4 | PRINTER | |
| ION PUMP | | ALTIMETER "W&T" | 45FF04217 | | |

**EQUIPMENT CHECKS**

| DATE (UT) | TIME -5:40 (UT) | DROP CHAMBER BEAM VERT | TRAV | MARK | SPRING LEVELS END | SIDE | LAS. CUR. (A) | ION CUR (mA) | COMP CK | TEMP (°C) | PRES (inHg) | CART HT. (mm) | REF HT. (mm) | AV SIG. (mV) | OBS | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3/30 | 0920 | ✓ | ✓ | ✓ | ✓ | ✓ | Not Locked | .300 | ✓ | 23.1 | — | — | 1007 | — | JF/BB | INITIAL CHECK |
| 3/30 | 1245 | ✓ | ✓ | ✓ | ✓ | ✓ | .309B | .300 | ✓ | 20.5 | 784 | 27 | 1007 | 170 | BB | Sets begun |
| 3/31 | 0000 | ✓ | ✓ | ✓ | ✓ | ✓ | .274B | .300 | ✓ | 19.9 | 784 | 29 | 1006 | 185 | BB | SEE Comments |
| 3/31 | 0625 | ✓ | ✓ | ✓ | ✓ | ✓ | .217R | .250 | ✓ | 21.6 | 785 | 27 | 1006 | 185 | BB | Lost POWER * |
| 4/1 | 1300 | ✓* | ✓ | ✓ | ✓ | ✓ | .282 | .200 | ✓ | 18.0 | 782 | 25 | 1006 | 180 | BB | 2 reflected spots, 1 stationary |
| 4/2 | 0100 | * | ✓ | ✓ | ✓ | ✓ | .162R | .250 | ✓ | 19.9 | 784 | 27 | 1006 | 185 | BB | 1 Diam to 7:00 - Adj |
| 4/2 | 0649 | ✓ | ✓ | ✓ | ✓ | ✓ | .056B | .275 | ✓ | 23.2 | 785 | — | 1006 | — | BB/JF | 21 sets - sys shutdown |

**ADDITIONAL COMMENTS**

| DATE | TIME | ADDITIONAL COMMENTS |
|---|---|---|
| 3/31 | 0625 | Relocked SS, LASER — LASER Locked @ .217 amps — SEE Comments |
| 4/2 | 0100 | Temp prob on Recorder Reading 2°C higher than actual. |
| 4/2 | 0649 | System shut down as Room temp becoming unstable — Laser Ready to Unlock |

JILA #4

# ABSOLUTE GRAVITY DETERMINATION

Site: [illegible] AA    Start date: [illegible]    End date: [illegible]

LAT: [illegible]    LON: [illegible] 274 [illegible] 43 [illegible]    Elevation: 2151 m

| | |
|---|---|
| Number of drop sequences . | : [illegible] |
| Drops per sequence . . | : 250 |
| Sequences using red laser. | : 10 |
| Sequences using blue laser | : 7 |

| | | GRAVITY (mean) | STD. DEV. |
|---|---|---|---|
| Observed gravity from meter . . . . | | : | : |
| Add 3 sigma rejections . . . . | 2 | : 410.4 | : [illegible] |
| Add grav. tide program corrections | 1 | : 978 4[illegible] 410.9 | : 5.5 |
| Add local atmosphere corrections . | 3 | : 411.5 | : 5.[illegible] |
| Add synoptic. atm. corrections . . | | : | : |
| Add ocean loading corrections . . | 4 | : [illegible] | : 5.[illegible] |
| Add water table correction . . . . | | : [illegible] | |
| Add polar motion correction . . . . | | : [illegible] | |
| Add laser drift correction . . . . | | : [illegible] | |
| Add laser-head temp. correction . | | : 0 | |
| Gravity determination . . . . . . | | : 417.0 | : 5.[illegible] |

Average std. dev. of observation . . . . . . . : 11.7 ugals
Difference between means of the two laser settings : 19.4 ugals

Grav. gradient est. by relative meters : [illegible] ugal/cm    : [illegible]
Weighted mean instrument height . . : [illegible] cm

| | | |
|---|---|---|
| Gravity reduced to one meter height | : 394.1 | : 6.4 |
| Gravity reduced to ground level . | : 978 494 834.7 | : 6.7 |

Comments : System response correction was +4.3 ugal.
[illegible] spot on left [illegible] interferometer [illegible]
[illegible] to [illegible] The [illegible]
[illegible] bias due to beam [illegible]
[illegible] to the floor and [illegible] values.
Large scatter in set means was due to interferometer alignment problems.

ORIGINAL PAGE IS OF POOR QUALITY

COMMENTS Katmandu, Nepal
HMG Survey Nagrakot Observatory (NAGARKOT)
March 30, 1991 1251Z

Nagrakot GPS site Position 25m to West
27° 41' 34.24" N = 27.6928N
85 31' 16.30" E = -85.5212 E
Elevation 2131 meters (height above WGS84 ellipsoid)

Where to begin? Equipment arrived and took 5 days to clear customs. Dropper/SS/Keithly pallet split up and both chamber cases had bent metal and were laying on side. Another container had a puncture - you get the picture. 2 1/2 hour ride on potholed road to observatory. Pumpdown initiated @ 1900 local. Ion pump on @ 0830 local. 200 uamps. Equip set up was wrot with problems. #1 optical mount for Pinhole jarred loose and required repair. This went ok although reflected interferometer spot seems to show more interference by getting larger/fuzzy. This has been resolved and reflected spot looks good. #2 Superspring malfunction indicated by rapid dampening (no ringdown) plus an apparent coupling to floor through support structure. First investigation was of level bubbles being misadjusted. We could not correct problem by diddling levels in various combinations in an attempt to let mass hang freely. So we removed cannister to look for loose parts when it

Prepared By Bernard/Fried/Winester
Organization NOAA/NOS/NGS

COMMENTS

became apparent that the springs main stainless steel tube (connected to flexures) had been mistreated. The safety devices which were installed last spring have 4 set screws with a 4mil gap to the steel tube protecting the spring and what it looked like was that the spring had been bounded a number of times resulting in a slight bend of the tube so that now it contacted the set screws. We proceeded to back the screws out another 4mils and tested the unit to satisfaction. #3 Power here is a nightmare. Just about anything thats turned on causes the ~~SS~~ Elgar to lose lock on the voltage and frequency. We have overcome this short of an all out power failure which apparently can occur. We will watch this carefully! #4 Grounding: Building has an open ground. Last night while setting up just about everything I touched gave me a jolt including the Balzer Turbo Pump which is ungrounded. Fixed this by stripping the paint on a 2inch feed pipe for wiring and connected a grounding belt between pipe and Electronic chassis. #5 Radio Telephone! The ~~[illegible]~~ CHARLOTTESVILLE mystery is solved! When Radio telephone transmitting dropper is out of control. To solve this we said no more calls and turned the amplifier off! Nice guysch? #6 Heat? what heat. we have a generator a heater but no adapter to go from a US

Prepared By Bernard/Fried/Winester

Organization · NOAA/NOS/NGS

COMMENTS

Extension cord to a german plug. Solution will arrive tomorrow morning from katmandu. Building is a very solid brick timing House on a bare mica schist. 12" concrete floor w/ a metal door and last night the temp only varied 2°C. So for tonight I will check the equip @ 02:00 Local to make sure all is ok. #6 All three of us have got the stomach bug but are copping.

March 30, 1991 1300Z First set begun - monitoring drop on scope but every time a drop Trigger's the Elgar loses lock! Turned scope off. Residuals look very reasonable. # Looks good so far. SS Looks stable. Vacuum and feedthrough holding up. Cummulative effect of 3 pumpdowns without heat tape is that the average vacuum pressure has risen. Still well within operational limits but will require heat possibly in Hawaii. Wind outside has picked up and we will submit wx records which they collect 50m from the station to submit with the data.
Distrubance seen approximately 2/3rds through first set caused by the Nepalese gaurd next door opening and closing the heavy metal door which doesn't close to smoothly to check if I was still there. otherwise set looks excellent.

Prepared By Bernard/Fried/Winester
Organization NOAA/NOS/NGS

COMMENTS Nagrokot Observatory, Nepal

Adjusted SS Levels after Set # 1. Each bubble had drifted almost 1 diameter:

March 31, 1991 0530 Local first 6 sets complete. Temperature surprisingly stable. Light ~~rain~~ Rain and fog outside. - 0023 Z serious cloud burst overhead w/ 1 mean lightning bolt. Not even a brown out of power surprisingly. System ✓ was perfect. Change in Ref. Ht. must be due to bad tape Reading. No adjustment to tripod was made. Temperature probe Reading 1.5°C higher than calibrated thermometer. Yesterday the Radio transmitter signal was also affecting the thermocouple by causing erratic Readings. Correction should be uniform for first 6 sets. We will continue to update.

Gravity readings from last night are excellent 4 sigma's for sets 3-6 below 10 microgals. Set #9 Temp. starting to fluctuate within observation tolerances (10:49 Local). Skies starting to clear. Sets proceeding without incident.

1055 Local - Complete power out - Transfered frequency / Volt meter to Topaz's to watch power drain. Will shut down and save data and equipment if necessary. UPS voltage @ 1055 117VAC @ 11:10 113 VAC on UPS power to system. 1 UPS for Ion pump only. Well that was it 11:12 Local the whole system crashed. I turned off everything. UPS to pump still running. Got to go.

Next Page

Prepared By Bernard/Fried/Winester

Organization NOAA/NOS/NGS

COMMENTS Nagrokot Observatory Cont'n

0645Z 1225 Local March 31, 1991

Re-initiallized system. Saved DDT Data for set #10 (approx 190 drops) to file called "Nag". System ✓ was good but temperature has risen as clouds are breaking. Because of this I believe that the laser has locked at a lower heater current and rather than cycle it up to .300 amps as we did long ago before the 10-12 hr stabilizing period I will leave it alone. The reason being that it was off only 1 hour and its temp is already stable – the decreased current is the expected response to the increase in temp. Will begin next set on original observation schedule. Set #11 Power failure again while Rodger & I were attempting to wire up and start the generator in the event of a power failure. To late Naton! System down again. Generator now running, systems powered up waiting to relock spring and laser: Generator will require refulling every 2 to 3 hours. Current PLAN is to operate until we have 18 sets (19) as the data looks good – very good and the problems are many.

Generator Refueling schedule: 5:30P

8:00P

1 liter carosen / hr 10:30P

5 liter capacity 01:00A

03:30A

0600A

Next Page 0830A

Prepared By Bernard/Fried/Winester

Organization NOAA/NOS/NGS

COMMENTS Nagrakot Observatory

March 31, 1991 Started Set # 13 @ ~ 1006 Z
on generator power. LASER is not appreciating
this on off activity relocking @ .220 A and
drifting down to .187 A after 70 drops. This
generator they've supplied us with is a
piece of shit and almost dies every 10 minutes
causing the ehc. to switch off and since
the topaz's haven't recharged from this
morning there not likely to hold the
system for long. Also the generator is
injecting a lot of noise into the data which
in my opinion is very undesirable. The power
has been off for over an hour now and if
it doesn't come back on soon I'll be pissed.
The First Blue set run w/ the generator on had
a considerably higher sigma of 60 microgals but
still a very reasonable value considering other
sites we've visited during this trip.
1106 Z Generator Died and UPS unable to maintain
system. Everything shut off. Restarted it to
recharge UPS but it died again. Thunderstorm
has moved in and were calling it quits until
the main power is returned. Unplugged unit
& ground to safeguard equipment. Setting up
battery to run ion pump as were uncertain
as to how long the UPS will run the pump.

Prepared By Bernard/Fried/Winester
Organization NOAA/NOS/NGS

COMMENTS Nagrokot Observatory cont'n

April 1, 1991 1400Z Began the 3rd restart. Spent all day recharging batteries to keep the Ion pump and GPS receivers up while the power remained out. Power came up around 1800 local and I was able to begin obs. Power capability at this site is at the very edge of operational requirements. Example - Turn the scope on to fix the fringe signal and the current draw w/ everything on causes the UPS to trigger as the power to the Elgar drops out. Fun and games.

0100Z ~~March~~ April 2, 1991 Last 6 sets showed a offset of ≈ 10 microgals from earlier sets which following a 1 diameter adjustment of the Interferometer verticallity raised the red value by 7 microgals. Difficulty in leveling the interferometer is I believe related to the pinhole objective lens collumnation which was upset during cargo transport. Last nights initial check revealed 2 reflected spots and one stationary. I chose the brightest spot to collumnate but this morning that spot had drifted. Sorry the data's not perfectly streamline but I think that explains it.

0500Z Room temperature rising to high. Inside 24°C outside 19°C - opened door.

0600 Set - Telephone Transmitter was left connected by accident and seriously affected a number of Drops on the 9th set (last 12 sets). Temperature is also very high and the laser is at the edge of unlocking. More activity than during the previous 20 sets is

Prepared By Bernard/Fried/Winester

Organization NOAA/NOS/NGS

COMMENTS Nagrakot Observatory Cont'n
apparent on the SS trace marked by spikes.
only 3 more sets to go. Jack & I decided to
shut system down w/ 21 sets under our belt.
The temperature became abnormally high and
the laser was about to unlock.

System ✓ OK – still 1 Extra reflected spot in the
alcohol pool. Must check this with Glenn when
we arrive in Hawaii and do a quick check
of the collumnation.

Prepared By Bernard/Fried/Winester
Organization NOAA/NOS/NGS

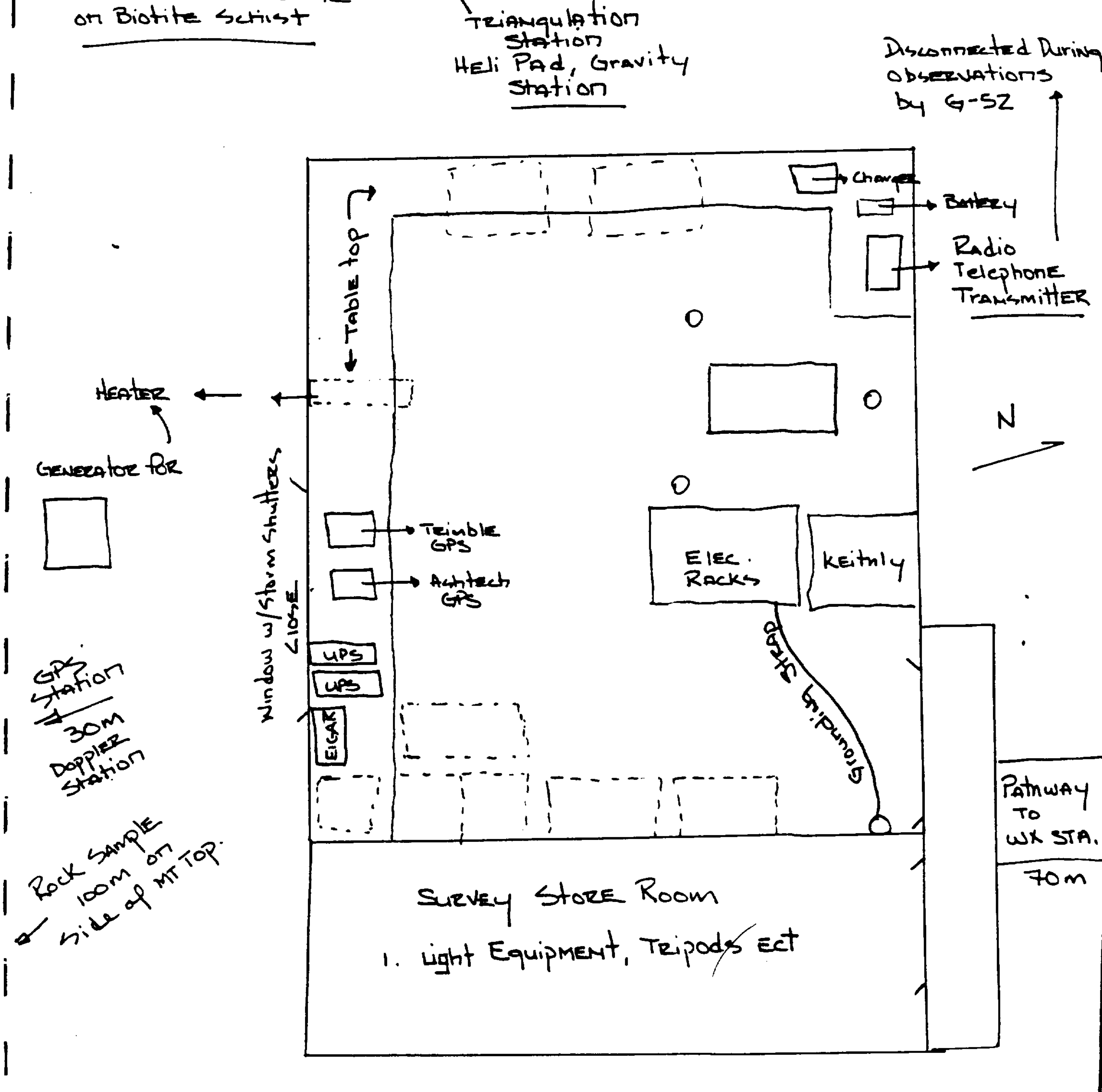
## ABSOLUTE GRAVITY STATION ORIENTATION DIAGRAM

STATION: Nagrokot, Nepal DATE: March 31, 1991

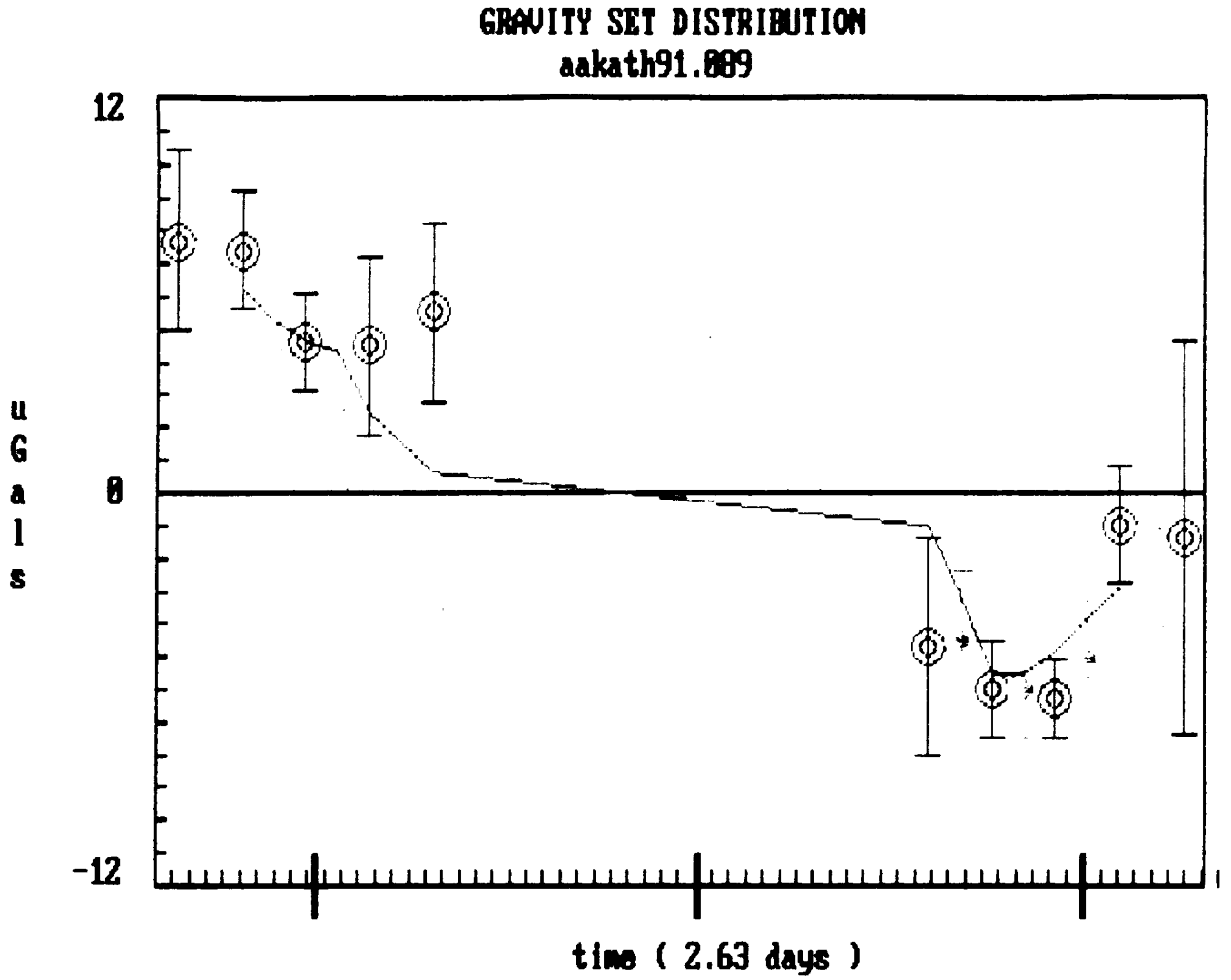
HMG Survey Dept, Nagrokot Observatory

Timing & Radio Room

Brick Building
12 inch concrete Pad
on Biotite Schist



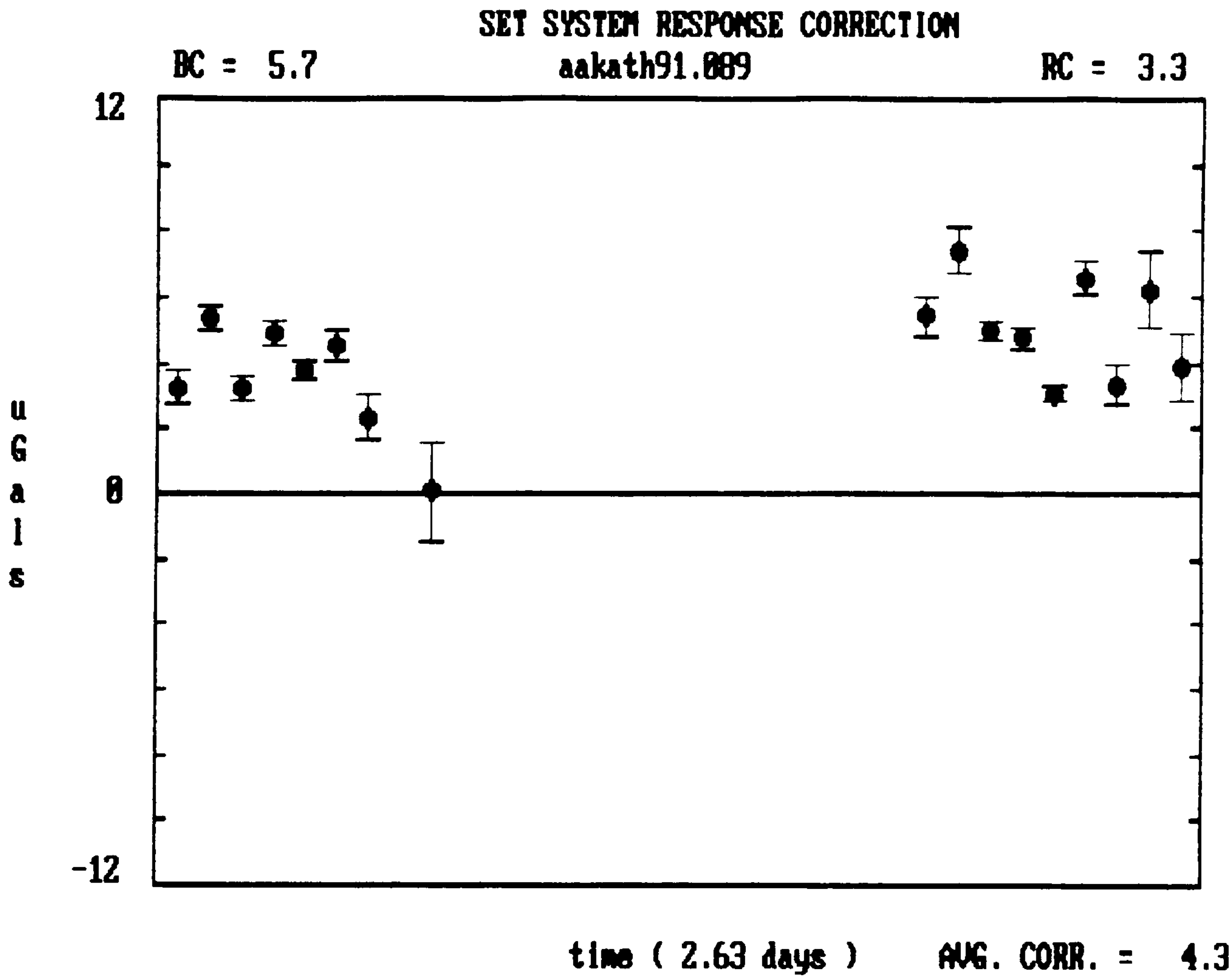

STATION CONTACT: Mr. Buddhi N. Shrestha 977 1 411 847
Director General HMG Survey Dept



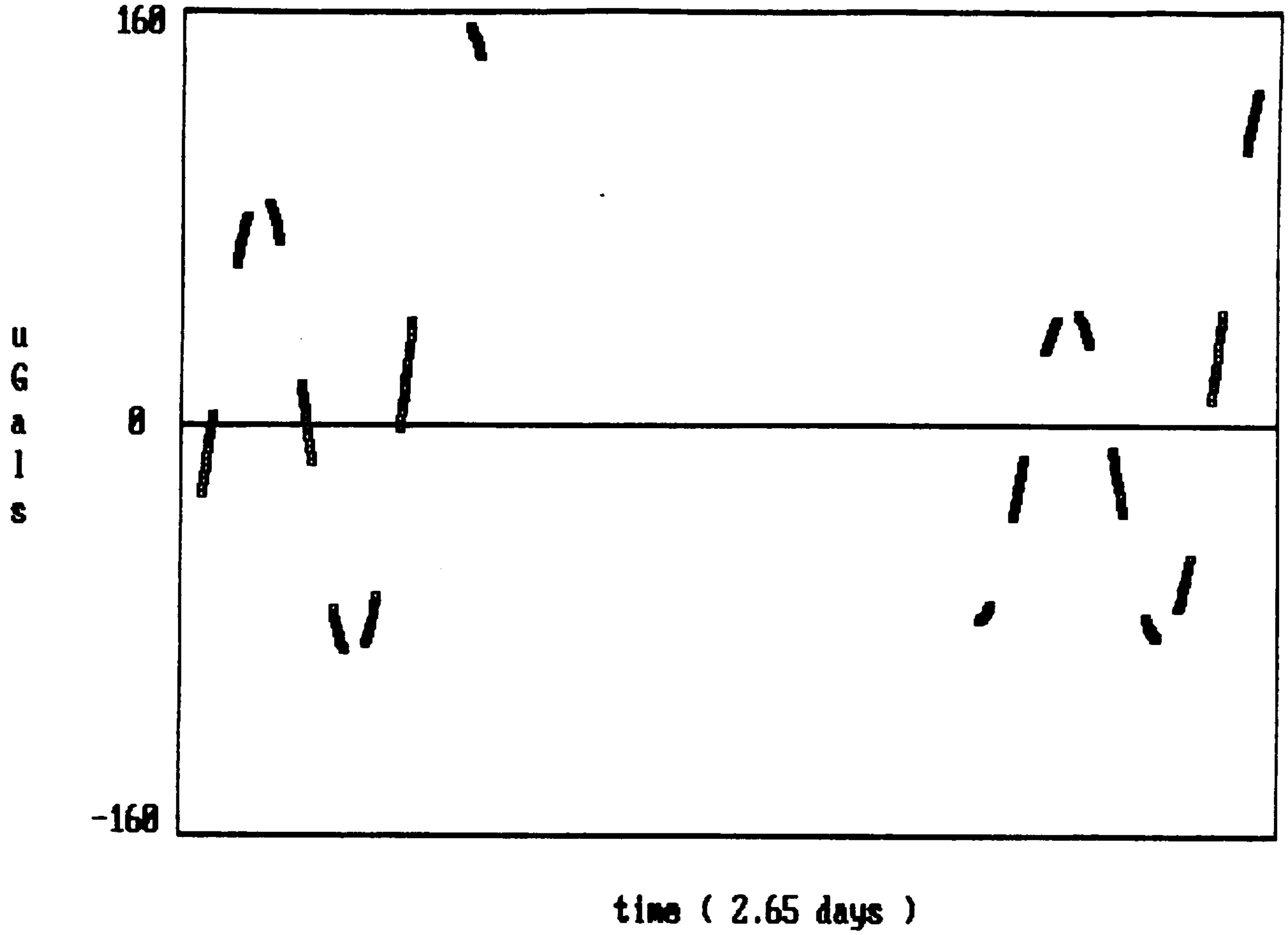

Final Processed set means.

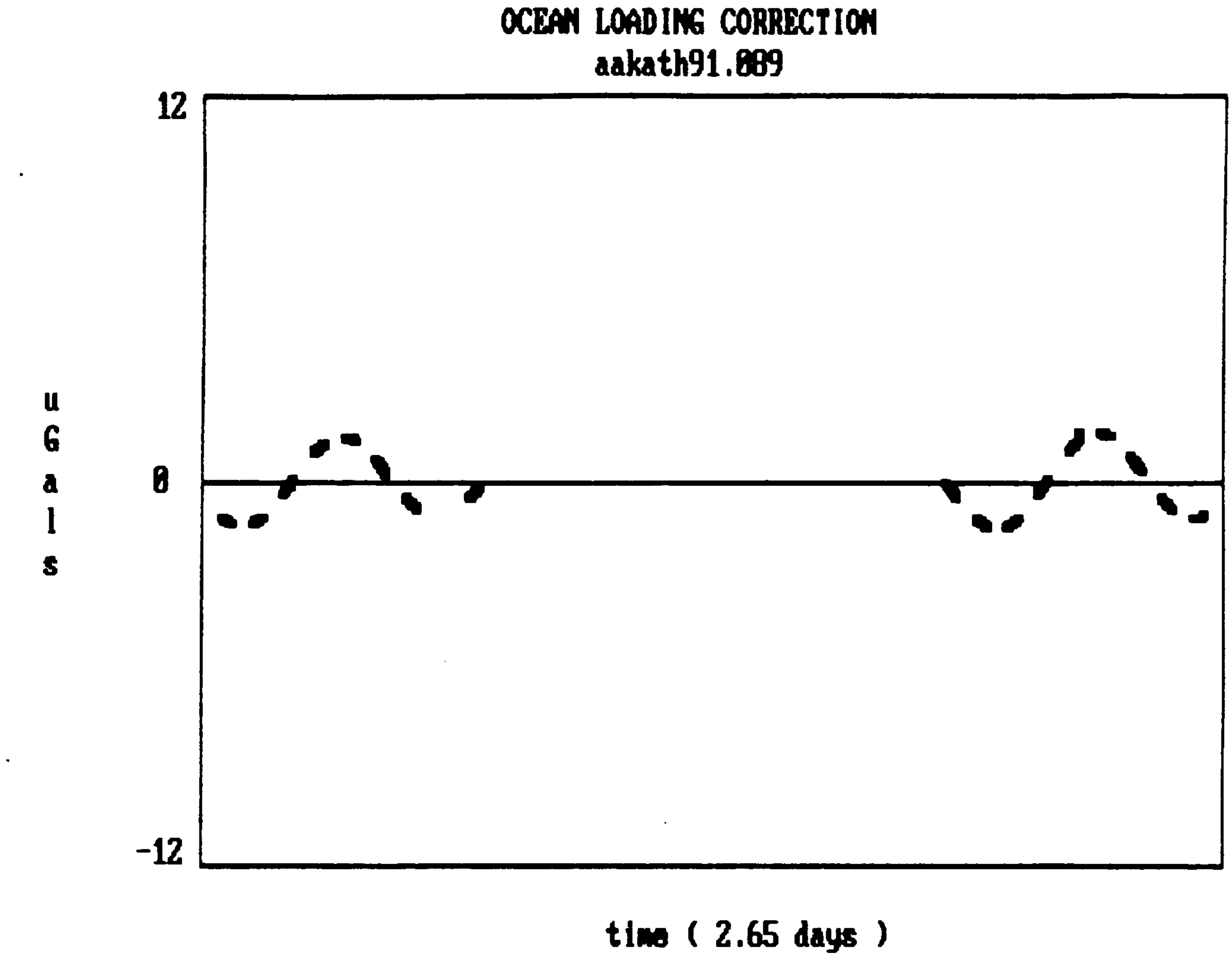
3 STD errors For error bars

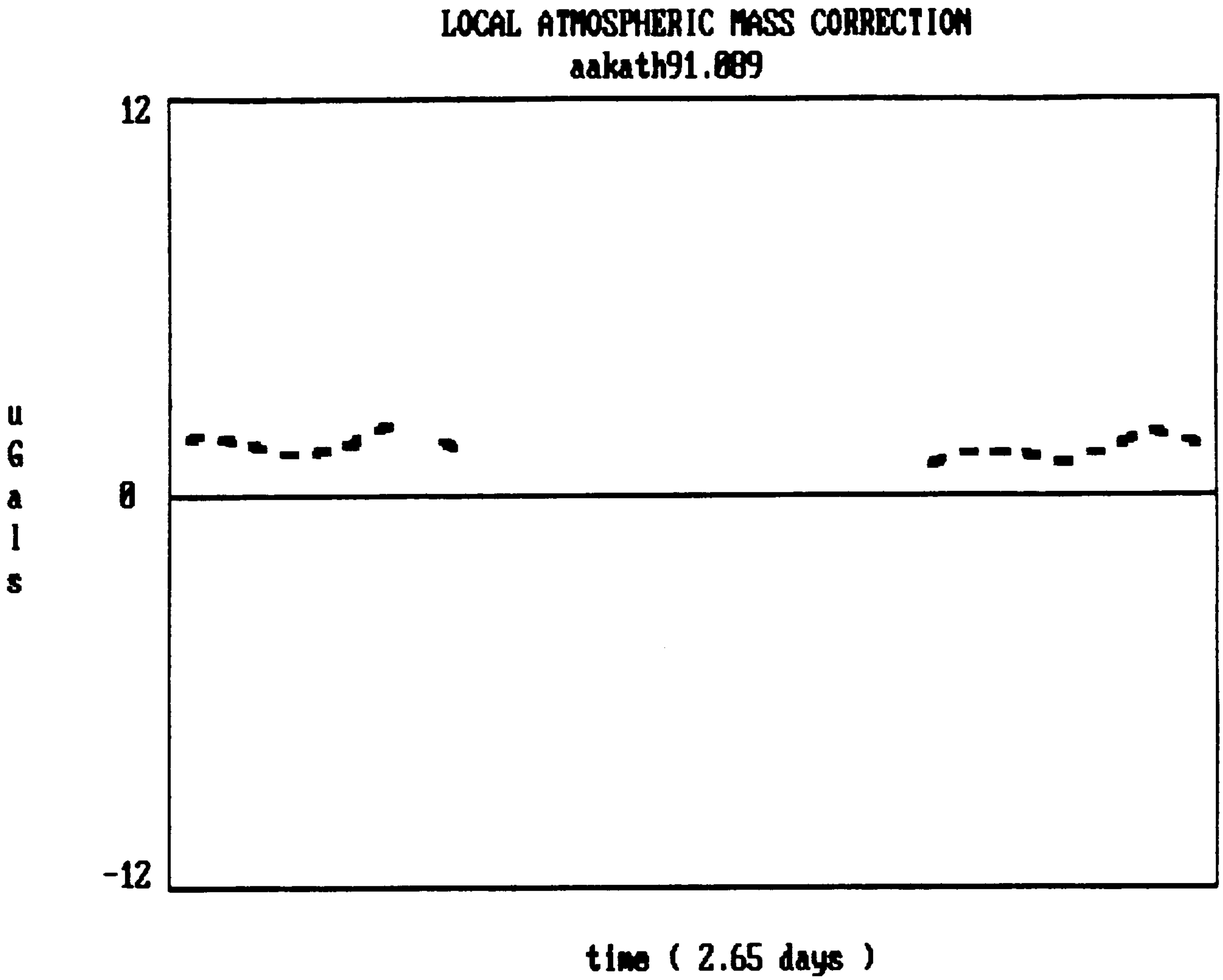
Scatter due to Field operators have Trouble setting system correctly with damaged interferometer.


SET SYSTEM RESPONSE CORRECTION
BC = 5.7
aakath91.009
RC = 3.3
12
0
-12
uGals
time ( 2.63 days )
AVG. CORR. = 4.3

LUNAR-SOLAR TIDE CORRECTION
aakath91.009




OCEAN LOADING CORRECTION
aakath91.089
12
0
-12
uGals
time ( 2.65 days )


LOCAL ATMOSPHERIC MASS CORRECTION
aakath91.009
12
0
-12
uGals
time ( 2.65 days )

NGS ABSOLUTE GRAVITY OBSERVATIONS From aakath91.089

This drop set has been previously processed for:
three sigma acceptance limit
gravitational tide correction

DROP SET MEANS SUMMARY

| drop set | num of drops | laser mode | mean date/time | mean grav (ugal) | sd mean (ugal) | sd obs (ugal) |
|---|---|---|---|---|---|---|
| # 1 | 250 | RED | 910330152056 | 978 494 428.8 | .9 | 14.6 |
| # 2 | 247 | BLUE | 910330172055 | 978 494 409.3 | .5 | 8.6 |
| # 3 | 249 | RED | 910330192056 | 978 494 427.7 | .6 | 9.0 |
| # 4 | 248 | BLUE | 910330212101 | 978 494 404.1 | .5 | 8.1 |
| # 5 | 249 | RED | 910330232055 | 978 494 423.6 | .5 | 8.0 |
| # 6 | 246 | BLUE | 910331012055 | 978 494 402.7 | .6 | 9.7 |
| # 7 | 248 | RED | 910331032056 | 978 494 424.7 | .9 | 13.7 |
| # 8 | 234 | RED | 910331072101 | 978 494 425.9 | .9 | 13.6 |
| # 9 | 234 | RED | 910401142106 | 978 494 416.2 | 1.1 | 16.1 |
| # 10 | 237 | BLUE | 910401162101 | 978 494 397.7 | .7 | 10.2 |
| # 11 | 250 | RED | 910401182100 | 978 494 415.6 | .5 | 8.2 |
| # 12 | 248 | BLUE | 910401202055 | 978 494 395.1 | .5 | 8.3 |
| # 13 | 247 | RED | 910401222055 | 978 494 413.2 | .4 | 6.8 |
| # 14 | 236 | BLUE | 910402002100 | 978 494 394.3 | .6 | 8.9 |
| # 15 | 242 | RED | 910402022055 | 978 494 418.4 | .6 | 9.7 |
| # 16 | 246 | BLUE | 910402042110 | 978 494 399.9 | 1.0 | 16.2 |
| # 17 | 215 | RED | 910402062136 | 978 494 419.8 | 2.0 | 28.6 |

10 dropsets weighted mean of red mode observations = 4 420.1 5.7
7 dropsets weighted mean of blue mode observations = 4 400.7 5.3
average of weighted red and blue means = 4 410.4 5.5

average standard deviation of observation = 11.7

NGS ABSOLUTE GRAVITY OBSERVATIONS From aakath91.089

This drop set has been previously processed for:
three sigma acceptance limit
gravitational tide correction

DROP SET MEANS SUMMARY
OFFSET CORRECTED

| drop set | num of drops | laser mode | mean date/time | mean grav (ugal) | residual (ugal) |
|---|---|---|---|---|---|
| # 1 | 250 | RED | 910330152056 | 978 494 419.1 | 8.7 |
| # 2 | 247 | BLUE | 910330172055 | 978 494 418.9 | 8.6 |
| # 3 | 249 | RED | 910330192056 | 978 494 418.1 | 7.7 |
| # 4 | 248 | BLUE | 910330212101 | 978 494 413.8 | 3.4 |
| # 5 | 249 | RED | 910330232055 | 978 494 413.9 | 3.5 |
| # 6 | 246 | BLUE | 910331012055 | 978 494 412.4 | 2.0 |
| # 7 | 248 | RED | 910331032056 | 978 494 415.1 | 4.7 |
| # 8 | 234 | RED | 910331072101 | 978 494 416.3 | 5.9 |
| # 9 | 234 | RED | 910401142106 | 978 494 406.5 | -3.9 |
| # 10 | 237 | BLUE | 910401162101 | 978 494 407.4 | -3.0 |
| # 11 | 250 | RED | 910401182100 | 978 494 405.9 | -4.5 |
| # 12 | 248 | BLUE | 910401202055 | 978 494 404.8 | -5.6 |
| # 13 | 247 | RED | 910401222055 | 978 494 403.5 | -6.9 |
| # 14 | 236 | BLUE | 910402002100 | 978 494 404.0 | -6.4 |
| # 15 | 242 | RED | 910402022055 | 978 494 408.7 | -1.7 |
| # 16 | 246 | BLUE | 910402042110 | 978 494 409.6 | -.8 |
| # 17 | 215 | RED | 910402062136 | 978 494 410.1 | -.3 |

average of weighted red and blue means = 4 410.4 s.d. mean = 5.5

average standard deviation of observation = 11.7

NGS ABSOLUTE GRAVITY OBSERVATIONS From aakath91.089

This drop set has been previously processed for:

gravitational tide correction

DROP SET MEANS SUMMARY

OFFSET CORRECTED

| drop set | num of drops | laser mode | mean date/time | mean grav (ugal) | residual (ugal) |
|---|---|---|---|---|---|
| # 1 | 250 | RED | 910330152056 | 978 494 419.7 | 8.8 |
| # 2 | 250 | BLUE | 910330172055 | 978 494 418.7 | 7.8 |
| # 3 | 250 | RED | 910330192056 | 978 494 418.6 | 7.7 |
| # 4 | 250 | BLUE | 910330212101 | 978 494 413.4 | 2.6 |
| # 5 | 250 | RED | 910330232055 | 978 494 414.4 | 3.6 |
| # 6 | 250 | BLUE | 910331012055 | 978 494 411.8 | 1.0 |
| # 7 | 250 | RED | 910331032056 | 978 494 415.7 | 4.9 |
| # 8 | 250 | RED | 910331072101 | 978 494 416.1 | 5.2 |
| # 9 | 250 | RED | 910401142106 | 978 494 403.9 | -6.9 |
| # 10 | 250 | BLUE | 910401162101 | 978 494 406.9 | -4.0 |
| # 11 | 250 | RED | 910401182100 | 978 494 406.5 | -4.3 |
| # 12 | 250 | BLUE | 910401202055 | 978 494 404.5 | -6.4 |
| # 13 | 250 | RED | 910401222055 | 978 494 403.8 | -7.0 |
| # 14 | 250 | BLUE | 910402002100 | 978 494 403.2 | -7.6 |
| # 15 | 250 | RED | 910402022055 | 978 494 408.8 | -2.0 |
| # 16 | 250 | BLUE | 910402042110 | 978 494 410.1 | -.8 |
| # 17 | 250 | RED | 910402062136 | 978 494 411.8 | .9 |

average of weighted red and blue means = 4 410.9 s.d. mean = 5.8

average standard deviation of observation = 20.1

NGS ABSOLUTE GRAVITY OBSERVATIONS From aakath91.089

This drop set has been previously processed for:

three sigma acceptance limit
gravitational tide correction
local atmospheric pressure correction

## DROP SET MEANS SUMMARY

| drop set | num of drops | laser mode | mean date/time | mean grav (ugal) | sd mean (ugal) | sd obs (ugal) |
|---|---|---|---|---|---|---|
| # 1 | 250 | RED | 910330152056 | 978 494 430.6 | .9 | 14.6 |
| # 2 | 247 | BLUE | 910330172055 | 978 494 411.0 | .5 | 8.6 |
| # 3 | 249 | RED | 910330192056 | 978 494 429.3 | .6 | 9.0 |
| # 4 | 248 | BLUE | 910330212101 | 978 494 405.4 | .5 | 8.1 |
| # 5 | 249 | RED | 910330232055 | 978 494 425.0 | .5 | 8.0 |
| # 6 | 246 | BLUE | 910331012055 | 978 494 404.4 | .6 | 9.7 |
| # 7 | 248 | RED | 910331032056 | 978 494 426.8 | .9 | 13.7 |
| # 8 | 234 | RED | 910331072101 | 978 494 427.6 | .9 | 13.6 |
| # 9 | 234 | RED | 910401142106 | 978 494 417.2 | 1.1 | 16.1 |
| # 10 | 237 | BLUE | 910401162101 | 978 494 399.0 | .7 | 10.2 |
| # 11 | 250 | RED | 910401182100 | 978 494 416.9 | .5 | 8.2 |
| # 12 | 248 | BLUE | 910401202055 | 978 494 396.3 | .5 | 8.3 |
| # 13 | 247 | RED | 910401222055 | 978 494 414.2 | .4 | 6.8 |
| # 14 | 236 | BLUE | 910402002100 | 978 494 395.6 | .6 | 8.9 |
| # 15 | 242 | RED | 910402022055 | 978 494 420.1 | .6 | 9.7 |
| # 16 | 246 | BLUE | 910402042110 | 978 494 401.8 | 1.0 | 16.2 |
| # 17 | 215 | RED | 910402062136 | 978 494 421.4 | 2.0 | 28.6 |

| | | |
|---|---|---|
| 10 dropsets weighted mean of red mode observations | = 4 421.5 | 5.9 |
| 7 dropsets weighted mean of blue mode observations | = 4 402.1 | 5.5 |
| average of weighted red and blue means | = 4 411.8 | 5.7 |

average standard deviation of observation = 11.7

NGS ABSOLUTE GRAVITY OBSERVATIONS From aakath91.089

This drop set has been previously processed for:
three sigma acceptance limit
gravitational tide correction
local atmospheric pressure correction

DROP SET MEANS SUMMARY
OFFSET CORRECTED

| drop set | num of drops | laser mode | mean date/time | mean grav (ugal) | residual (ugal) |
|---|---|---|---|---|---|
| # 1 | 250 | RED | 910330152056 | 978 494 420.9 | 9.1 |
| # 2 | 247 | BLUE | 910330172055 | 978 494 420.7 | 8.9 |
| # 3 | 249 | RED | 910330192056 | 978 494 419.6 | 7.8 |
| # 4 | 248 | BLUE | 910330212101 | 978 494 415.1 | 3.3 |
| # 5 | 249 | RED | 910330232055 | 978 494 415.3 | 3.5 |
| # 6 | 246 | BLUE | 910331012055 | 978 494 414.0 | 2.2 |
| # 7 | 248 | RED | 910331032056 | 978 494 417.2 | 5.4 |
| # 8 | 234 | RED | 910331072101 | 978 494 417.9 | 6.1 |
| # 9 | 234 | RED | 910401142106 | 978 494 407.5 | -4.3 |
| # 10 | 237 | BLUE | 910401162101 | 978 494 408.6 | -3.2 |
| # 11 | 250 | RED | 910401182100 | 978 494 407.2 | -4.6 |
| # 12 | 248 | BLUE | 910401202055 | 978 494 406.0 | -5.8 |
| # 13 | 247 | RED | 910401222055 | 978 494 404.5 | -7.3 |
| # 14 | 236 | BLUE | 910402002100 | 978 494 405.3 | -6.6 |
| # 15 | 242 | RED | 910402022055 | 978 494 410.4 | -1.4 |
| # 16 | 246 | BLUE | 910402042110 | 978 494 411.5 | -.3 |
| # 17 | 215 | RED | 910402062136 | 978 494 411.8 | .0 |

average of weighted red and blue means = 4 411.8 s.d. mean = 5.7

average standard deviation of observation = 11.7

NGS ABSOLUTE GRAVITY OBSERVATIONS From aakath91.089

This drop set has been previously processed for:
- three sigma acceptance limit
- gravitational tide correction
- local atmospheric pressure correction
- ocean loading correction

DROP SET MEANS SUMMARY
OFFSET CORRECTED

| drop set | num of drops | laser mode | mean date/time | mean grav (ugal) | residual (ugal) |
|---|---|---|---|---|---|
| # 1 | 250 | RED | 910330152056 | 978 494 419.6 | 7.7 |
| # 2 | 247 | BLUE | 910330172055 | 978 494 419.5 | 7.6 |
| # 3 | 249 | RED | 910330192056 | 978 494 419.4 | 7.4 |
| # 4 | 248 | BLUE | 910330212101 | 978 494 416.2 | 4.3 |
| # 5 | 249 | RED | 910330232055 | 978 494 416.6 | 4.6 |
| # 6 | 246 | BLUE | 910331012055 | 978 494 414.6 | 2.6 |
| # 7 | 248 | RED | 910331032056 | 978 494 416.5 | 4.5 |
| # 8 | 234 | RED | 910331072101 | 978 494 417.5 | 5.5 |
| # 9 | 234 | RED | 910401142106 | 978 494 407.2 | -4.7 |
| # 10 | 237 | BLUE | 910401162101 | 978 494 407.4 | -4.5 |
| # 11 | 250 | RED | 910401182100 | 978 494 405.9 | -6.0 |
| # 12 | 248 | BLUE | 910401202055 | 978 494 406.0 | -6.0 |
| # 13 | 247 | RED | 910401222055 | 978 494 405.7 | -6.3 |
| # 14 | 236 | BLUE | 910402002100 | 978 494 406.8 | -5.1 |
| # 15 | 242 | RED | 910402022055 | 978 494 411.0 | -1.0 |
| # 16 | 246 | BLUE | 910402042110 | 978 494 410.9 | -1.1 |
| # 17 | 215 | RED | 910402062136 | 978 494 410.6 | -1.4 |

average of weighted red and blue means = 4 412.0 s.d. mean = 5.5

average standard deviation of observation = 11.7

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 91, NO. B9, PAGES 9145-9149, AUGUST 10, 1986

# ABSOLUTE GRAVITY: A RECONNAISSANCE TOOL FOR STUDYING VERTICAL CRUSTAL MOTIONS

T. M. Niebauer, J. K. Hoskins,[1] and J. E. Faller

Joint Institute for Laboratory Astrophysics, National Bureau of Standards
and University of Colorado, Boulder

Abstract. A major effort is under way to develop highly portable absolute gravimeters having an ultimate accuracy of 3-5 μGal, an accuracy which translates into a height sensitivity of several centimeters. We are just finishing the construction of six such units. Measurements at the Joint Institute for Laboratory Astrophysics with one of these new instruments agree well with the earlier measurements made in 1981 and 1982 with a previous generation instrument. Recent measurements at the International Bureau of Weights and Measures in Sevres, France, as a part of an international intercomparison of absolute gravimeters, also show good agreement with the other instruments.

Measurement of the absolute value of the free-fall acceleration "g" has long been a matter of scientific interest. Present-day methods of measuring the absolute value of g employ ballistic systems involving either direct free-fall or symmetrical rise-and-fall methods. The earliest such measurements employed the direct free-fall method and geometrical optics to determine the position of the dropped object as a function of time. More recently, laser interferometry has been used almost exclusively.

A major effort to develop a new generation of high-precision absolute gravimeters is in the final stages at the Joint Institute for Laboratory Astrophysics (JILA) located at the University of Colorado in Boulder, Colorado. These gravimeters interferometrically measure the position of a free-falling object as a function of time and thereby permit the determination of the free-fall acceleration. This paper will discuss the use of absolute gravity for the study of vertical motions, the status of the JILA absolute gravity instruments, and the advantages and near-term prospects of using them for this purpose.

Traditionally, vertical height information has been derived mainly from leveling data. However, even using automated leveling systems, the cost per kilometer is high, from $350/km to rerun an existing line to between $500 and $600/km to run a new line (G. J. Mitchell, private communication, 1986). A number of extraterrestrial techniques and systems also exist for measuring vertical movements of the earth's surface such as laser satellite ranging, very long baseline interferometry, and using ground receivers together with the NAVSTAR global positioning system satellites. These methods are now capable of achieving the interesting accuracies of between 1 and 3 cm and are therefore likely to play an increasingly important role in determining vertical motions. Their costs are still high; but these costs, particularly those associated with the global positioning satellite system approach, should soon be lowered.

Gravity measurements, both relative and absolute, given sufficient measurement precision, provide a comparatively inexpensive way to look for vertical crustal movements. A 1-cm vertical crustal motion would result in a gravity change of approximately 3 μGal were no change in the local mass distribution to occur. The actual change in gravity observed in connection with a 1-cm vertical displacement will generally be 2-3 μGal but can be outside this range for some crustal movement mechanisms [Jachens, 1978a,b]. To differentiate, however, between subsurface density changes and vertical height changes, one must use one of the geometrical geodetic systems. Gravity does, however, provide an excellent and low cost reconnaissance tool with which to gather large amounts of preliminary data which then, for those areas in which gravity changes are occurring, can be checked and interpreted in combination with the other (geometrical) vertical data. If vertical motions are subsequently confirmed by other means, the observed gravity changes can help to determine the mechanism responsible for the motions.

In using gravity measurements as a reconnaissance tool to look for vertical movements, absolute gravity measurements have a number of advantages over relative gravity measurements: the most important of these being that absolute gravity is a "point technique." A single measurement produces a gravity value, in some sense a measure of the distance from the center of the earth, which depends only on the basic standards of length and time. Relative gravity measurements (as well as conventional leveling techniques) must necessarily be tied to a (presumed) stable external reference point which complicates the measurement process and inevitably raises questions about the stability of that reference point over the appropriate time frame. In a relative gravimeter (see, for example Clark [1984]), the spring, whose length is essentially the measured parameter, displays secular creep as well as episodic changes in its length. Vibrations encountered while transporting these devices and stresses due to clamping only serve to exacerbate these problems. In addition, nonlinearities in the adjusting screw and its associated lever reduction mechanism have to be carefully calibrated if their effects are to be removed. In practice, the measurement precision depends on the par-

[1]Now at Northrup Corporation, Hawthorne, California.



Paper number 5B5687.
0148-0227/86/005B-5687$05.00

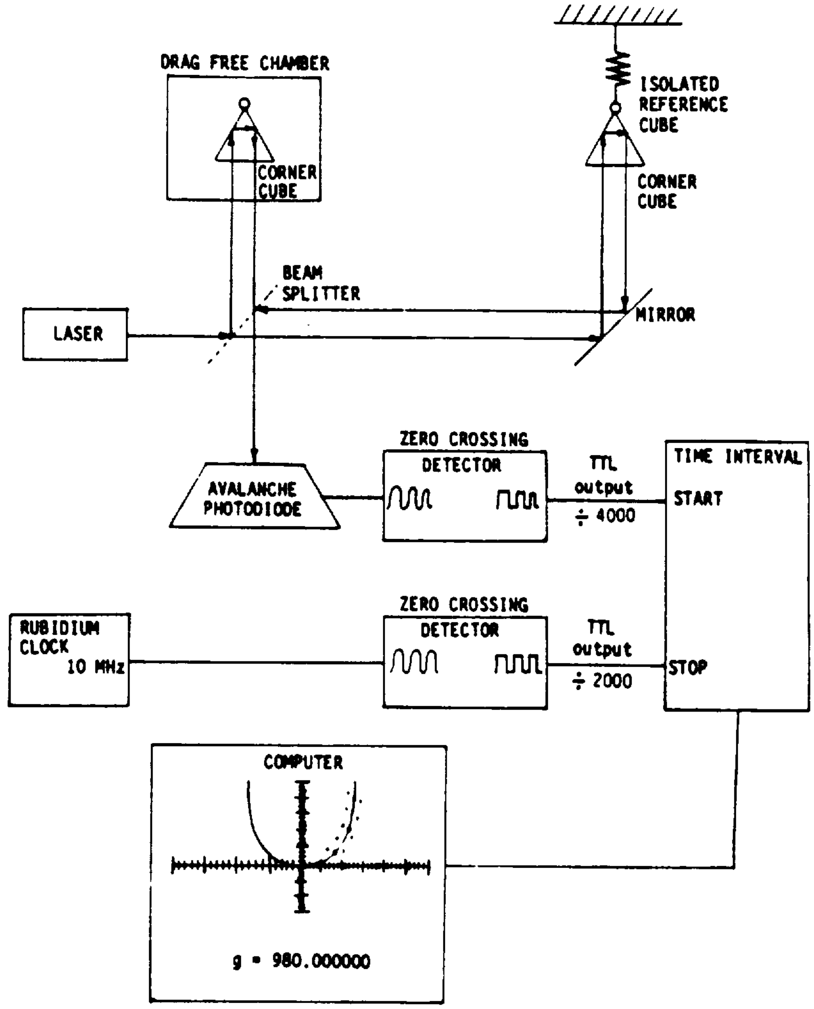



Fig. 1. Block diagram of free-fall method.

ticular instrument used, the station-to-station distance, and also on the gravity difference. Without special precautions, relative gravimeters typically reach precisions of between ±30 and ±100 μGal for a single measurement of a given difference in gravity. Extreme care is required to reduce this error to the ±5 to ±10 μGal range [Torge, 1985].

By contrast, the accuracy of absolute free-fall instruments depends mainly on the reproducibility of the basic standards of length and time, and a stabilized laser provides the length standard and an atomic (rubidium) clock provides the time standard. The absolute wavelength of the laser and the frequency of the atomic clock can easily be measured directly in the laboratory. The drifts in these "standards" are low enough so that they can be used for months with negligible error contributions at the parts in $10^9$ level of accuracy. Further, these "standards" are less subject to the ordinary vibration in transit, environmental temperature, etc., problems which have proven difficult with traditional relative gravimeters at the microGal level of sensitivity.

Modern-day absolute gravity instruments have been developed and improved over the past 30 years through the utilization of available technology. In practice, they all measure the position of a freely falling mass as a function of time (with exquisite sensitivity) and from that motion determine the value of g (Figure 1). Two types of free-fall instruments have been developed: the first utilizes simple free fall, and the second uses an up-and-down trajectory [Faller and Sakuma, 1986]. In each case, g is determined by fitting a quadratic expression to the measured trajectory. In practice, a Michelson-type laser interferometer is used to sense the position of the falling object during its fall. The dropped object contains a cube corner (a special type of optical mirror that reflects the laser directly back, independent of the cube's exact orientation). The occurrence times of the zero crossing of the fringes then provide the necessary information with which to calculate g.

The first laser interferometric g measurements were made in 1962 by J. E. Faller using an early commercially available He-Ne laser in what had been designed as a white-light-fringe g apparatus. The first portable laser interferometer absolute gravimeter was developed by J. A. Hammond and J. E. Faller at JILA and Wesleyan University with support from the Air Force Geophysics Laboratory (AFGL). With this apparatus, which had an accuracy of 50 μGal, data were taken at eight