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PRECISE RELATIVE MEASUREMENTS OF GRAVITY IN KINKI DISTRICT, JAPAN

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Abstract Gravity measurements have repeatedly been carried out in the area around Lake Biwa since 1971 in order to detect the secular change of gravity. In addition, through the examination on characteristics of LaCoste & Romberg gravimeters, we proposed the method of measurement at the stations with almost equal gravity value in order to carry out the gravity measurement more accurately. And therefore, another precise gravity measurement has been carried out at stations where the gravity value is almost equal to that of reference station (Geophysical Institute of Kyoto University; 979.70775 gals), along the levelling route in the area covering Lake Biwa and the Kii Peninsula since 1972. Besides them, the precise gravity measurement has also been carried out at stations with the gravity value 979.686 gals in due consideration of their distribution.

The accuracy of the results was investigated in many points of view, and it was ascertained to be usually about 10 μgals in standard deviation.

The results obtained by the gravity measurements were compared with the results obtained by levelling surveys, by water level observations of the lake, by oceanic tidal observations, by underground water level observations and by geodetic control surveys. The gravity change was not in a good correlation with the vertical movement obtained from levelling surveys, but it was with the movements obtained from the observations of water level and oceanic tides. The precise gravity measurement is less accurate than the levelling survey when the vertical movement is to be obtained in a short distance. However, it is a very great advantage that the precise gravity measurement can directly connect two stations which are located far apart. The levelling survey cannot realize this advantage, while the observations of water level and oceanic tides have this advantage. The results of the present investigations may be ascribed to this advantage.

On the other hand, the gravity increase was found at the tip of the Kii Peninsula, and this may be partly explained by the areal contraction caused by the push of the Philippine Sea Plate.

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1. Introduction

The gravity value at a point on the earth depends on the followings;

a) attraction by the earth's mass including the ocean water and atmospheric gas,

b) centrifugal force by the rotation of the earth, and

c) attraction by the celestial bodies.

It had been thought for a long time that the gravity field on the earth is eternally unchanged with the lapse of time, but the advancement of gravity measurement changed its thought. When periodic variation such as tidal and atmospheric effects is not considered, the change of gravity value at a point on the earth can be produced by the followings;

a) change of the dimension and mass of the earth,

b) change of the rotation of the earth,

c) change of the gravitational constant,

d) change of mass distribution of the earth interior, as a whole,

e) redistribution of masses just under the earth surface, and

f) movement of the earth surface (the point of measurement).

In all cases mentioned above, the secular change of gravity can be substantially investigated by the absolute measurement of gravity. In fact, the accuracy of the absolute measurement of gravity recently reached at an order of μgals by an employment of the method of free-fall (*e. g.*, HAMMOND, 1978, FALLER *et al.*, 1982) or free rise and fall observation (*e. g.*, SAKUMA, 1973; OOE *et al.*, 1982) in order to examine non-tidal gravity change. SAKUMA (1973) found a change of gravity amounting to about 30 μgals by his absolute measurements between 1966 and 1972 at Sevrès. At the present time, however, it is not easy to carry out an accurate absolute measurement of gravity at many stations in the world. The hypothesis on the secular change of gravity field derived from the movement of earth core was introduced for its cause (VOGAL, 1968; BARTA, 1971; 1978), but either absolute measurement or worldwide relative measurement of gravity should be performed for such investigation.

On the other hand, relative measurement of gravity in local or regional area can be used only to investigate the last two cases mentioned above; *i. e.*, redistribution of masses just under the earth surface and movement (practically vertical movement) of the earth surface. However, such relative measurement of gravity is easier, more rapid and in a wider area to be carried out accurately at many stations than absolute measurement or worldwide relative measurement.

The vertical crustal movement can be measured by the levelling survey. When both the gravity measurement and the levelling survey are simultaneously carried out, we are able to obtain the information on mass redistribution or density change just under the earth surface. Levelling surveys usually take a great deal of labour and much time. On the contrary, a relative measurement of gravity can be carried out over a wider area, in a shorter period of time and at a cheaper cost than the levelling survey. It is therefore thought that repeated precise relative measurements of gravity may be one of the effective and economical methods for detecting the vertical crustal movement, though the gravity measurement is originally not a method to detect it, if their accuracy is comparable with that of levelling surveys. As a result, investigations on whether the secular change of gravity difference among some stations is detectable or not have recently been made in many regions of the world (*e. g.*, MORELLI and HONKASALO, 1975).

As it was impossible to obtain the high precision in gravity measurements, no substantial study on secular change of gravity appeared before 1950 except a few pioneer researches (*e. g.*, ISHIMOTO and TUZI, 1929).

The employment of a portable gravimeter of spring type enables the relative measurement of gravity to be carried out more easily and rapidly. Some detections of secular change of gravity were reported by means of Worden and North American gravimeters in Japan (*e. g.*, IIDA *et al.*, 1950; 1952; JITSUKAWA and TAJIMA, 1962; KUBOTERA and SUMITOMO, 1965).

In Kinki District, gravity measurements were carried out several times between 1950 and 1962. One gravity change amounting to 0.1～0.3 mgal was observed during the period of 1950～1953 (ICHINOHE, 1955), and the other amounting to 0.3～0.6 mgal was also observed during the period of 1952～1962 (ICHINOHE *et al.*, 1963). Both results show that gravity value increased on both shores of the southern part of Lake Biwa during the periods concerned.

The employment of LaCoste & Romberg gravimeter in the gravity measurements has enabled them more accurate, and investigations to detect time change of gravity difference have been made not only in Japan but also in many regions of the world. In Japan, time change of gravity by a LaCoste & Romberg gravimeter was first detected in Izu-Ooshima Island (FUJII *et al.*, 1964a), but it was achieved by comparing the result obtained by a LaCoste & Romberg gravimeter with that by a North American gravimeter. Another gravity measurement was carried out by a LaCoste & Romberg gravimeter in 1967 in Izu-Ooshima Island, and gravity decrease of 0.8～0.9 mgal was detected near the volcanic crater (INOUYE *et al.*, 1968).

Matsushiro Earthquake Swarm, which began in August 1965 in the central part of Japan, provided an appropriate test field to investigate the time change of gravity caused by seismic activity. A series of gravity measurements were carried out in the area of active crustal deformation by the Geographical Survey Institute (GEOGRAPHICAL SURVEY INSTITUTE, 1967; 1968), the Geological Survey of Japan (SEYA, 1968) and the

Earthquake Research Institute of the University of Tokyo (HAGIWARA and TAJIMA, 1973; TAJIMA and IZUTUYA, 1974). A dilatancy water diffusion model was applied to the Matsushiro Earthquake Swarm and it was discussed from the data of gravity measurements (FUJITA and FUJII, 1974; NUR, 1974; KISSLINGER, 1975).

The studies on time change of gravity were also reported by many overseas researchers (*e. g.*, BARNES, 1966; HUNT, 1970; SCHLEUSENER and TORGE, 1971; BOULANGER and SCHEGLOV, 1971).

Needless to say, a most accurate gravity measurement is highly required in order to detect the time change of gravity. Test measurements were carried out to check the accuracy of a LaCoste & Romberg gravimeter (FUJII *et al.*, 1964b). A special case to carry it was experimentally constructed to reduce the drift of the gravimeter (HAMILTON and BRULÉ, 1967).

On the other hand, theoretical studies were also made on the secular change of gravity as the result of crustal deformation and underground mass movement (*e. g.* FUJII, 1969; TAZIMA, 1970).

The International Association of Geodesy (IAG) recognized the importance of improving gravity measurements, and a Special Study Group on "Special Techniques of Gravity Measurements" was established at the General Assembly of the IAG held at Lucerne in 1967, and many researchers engaged in this study (HONKASALO, 1971).

Under these circumstances of researches on the precise gravity measurement and on the secular change of gravity in the world, we started the precise gravity measurements in about 1970.

2. Purpose of the Investigations

As we have mentioned in the Chapter **1**, to detect the time change of gravity has been one of the most important aims of investigation in gravimetry since 1960's, and many pioneer researches on time change of gravity have been carried out. The precision of the gravity measurement, however, has not always been sufficiently reliable to detect small gravity changes. We started an investigation for detecting the time change of gravity in the area near Kyoto in 1971. Two areas around Lake Biwa and in the Kii Peninsula were chosen in Kinki District to carry out precise gravity measurements.

We were interested in the area around Lake Biwa; first, it is close to Kyoto, and therefore the gravity measurements can be carried out easily, accurately and within a short time; secondly, in Kinki District including this area, gravity measurements had repeatedly been carried out between 1950 and 1962 by using North American and Worden gravimeters, and the results showed that gravity value had increased on the shore of Lake Biwa, but the results obtained by such gravimeters were not so accurate that they could not tell whether the gravity increase was real or not; thirdly, in this area two more precise gravity measurements were carried out in 1964 and 1967 by using LaCoste & Romberg gravimeters, but the methods of precise gravity measurements were not yet refined and such data had some questions on the accuracy to detect the secular change of gravity. We started the precise gravity measurements along the route around Lake Biwa in 1971 with LaCoste & Romberg gravimeter G-196 (NAKAGAWA *et al.*, 1972; SATOMURA and NAKAGAWA, 1972), and they have been carried out almost every year.

Next, we paid attention to the area in the Kii Peninsula. It is not far apart from Kyoto, and in this area there is much possibility to prove that a large gravity change accompanies a large scale of crustal movements. According to geophysical studies made so far, the ground gradually subsides at ordinary times, while an abrupt uplift occurs at the times of great earthquakes, in the Kii Peninsula (MIYABE, 1955). Therefore, it is highly expected to measure the gravity change of a large scale in this area. In general, the southern part of the Kii Peninsula has a high gravity anomaly, while the northern part has a low one. We could, therefore, find many gravity stations with a similar gravity value all over the area. The rectilinear distance between the two extreme stations was about 200 km in north and south. Gravity stations were specially chosen from the first order bench marks with small gravity differences in 1970, along the levelling route of the area covering Lake Biwa and the Kii Peninsula (NAKAGAWA and SATOMURA, 1973). Such measurements became the topic of conversations of researchers on gravimetry of those days in order to increase the accuracy in gravity measurements, because they were almost relieved from the irregularity of dial screw of the gravimeter, the determination error of scale values and others. We had tried to examine the validity of such measurements through performing the gravity measurements (NAKAGAWA and SATOMURA, 1971). Similar precise gravity measurements have been carried out in the Muroto Peninsula and in Tōkai District (SHICHI *et al.*, 1983) in Japan, and also in some overseas areas (*e. g.*, KIVINIEMI, 1974; GROTEN, 1975; ELSTNER *et al.*, 1978; HIPKIN, 1978).

The Geodetic Society of Japan organized a Working Group for Gravity Measurements and Precise Levelling, and held three symposia on "Gravity and Precise Levelling" in 1969, 1970 and 1971. Many reports were presented at the symposia (*e. g.*, WORKING GROUP FOR COMPARING THE GRAVIMETERS IN JAPAN, 1969; NAKAGAWA and SATOMURA, 1971). The necessity for making fundamental examinations to investigate the characteristics of LaCoste & Romberg gravimeters was emphasized at the symposia (NAKAGAWA, 1971).

After the symposia, we examined cooperatively the characteristics of LaCoste & Romberg gravimeters (model G) at Kakioka in 1973 (NAKAGAWA *et al.*, 1973) and at Mizusawa in 1974 (NAKAGAWA *et al.*, 1974). The following points were investigated for nine LaCoste & Romberg gravimeters;

a) scale values of the gravimeters,
b) effect by turning the measure screw of the gravimeters,
c) effect due to voltage change of the connected battery,
d) effect due to meteorological disturbances, and
e) influence due to vibration during the transportation.

Similar examinations were also carried out in many countries (*e. g.*, KIVINIEMI, 1974; DUCARME *et al.*, 1976; HIPKIN, 1978; GERSTNECKER, 1978; KANNGIESER, 1982).

We also carried out the precise gravity measurements cooperatively in East Hokkaidō (IZUTUYA *et al.*, 1976; OHKAWA *et al.*, 1976), in the Miura and Bōsō Peninsulas (TAJIMA *et al.*, 1976), in Tōkai District (ICHINOHE *et al.*, 1983) and in the Muroto Peninsula (TAJIMA, 1975); where large earthquakes periodically occur by interaction of oceanic and continental plates. Not only co-seismic gravity change but also inter-seismic one are expected in those regions (FUJII, 1972; FUJII and NAKANE, 1972). Large co-seismic change of gravity was observed during the Earthquake off Nemuro Peninsula of 1973 (M=7.4) (FUJITA *et al.*, 1975), but it was later found to be not co-seismic change but either after-seismic change or a measuring error (OHKAWA *et al.*, 1976). Izu Hantō-oki Earthquake (M=6.9) occurred in 1974. After this earthquake, the eastern part of Izu Peninsula became tectonically active, and some gravity changes were detected there (HAGIWARA *et al.*, 1976a; 1976b; 1977; 1978; 1980).

A gravity increase amounting to 0.1 mgal was reported on both shores of the southern part of Lake Biwa between 1964 and 1971 (NAKAGAWA *et al.*, 1972; SATOMURA and NAKAGAWA, 1972). Hypotheses that the basement rises and that the density of sediments increases by compaction, led to a conclusion that a viscosity of basement is 6×10^{20} poises (NAKAGAWA and SATOMURA, 1975b), but there are few geological evidences which support the hypotheses. The results obtained between 1971 and 1975 were consistent with the results of levelling surveys. They seem to support the view that repeated precise gravity measurements are substituted levelling survey as a more rapid and economical method (NAKAGAWA and SATOMURA, 1976; 1977).

We have also repeated the precise gravity measurements in volcanic regions; that is, Aso Volcano (KUBOTERA *et al.*, 1974; 1978; 1984; KUBOTERA and SATOMURA, 1985) and Iwaki Volcano (SATOMURA and ICHINOHE, 1975).

We have confirmed the validity of precise gravity measurements in order to detect secular change of gravity, through our many performances of the gravity measurements. We recommended the method of the precise gravity measurements to the IAG (NAKAGAWA and SATOMURA, 1975a), presented the relation between gravity change and vertical movement obtained from the levelling surveys, and recommended to both the International Gravity Commission (IGC) and the IAG that such measurements were economical methods to detect the vertical movement. Through some recommendations including ours, the IAG recommended to develop the precise gravity measurements (NAKAGAWA, 1975), and many researchers started the studies on precise gravity measurement and on secular change of gravity in response to the recommendation. Of course, we have energetically continued to carry out the precise gravity measurements in the areas around Lake Biwa and in the Kii Peninsula.

We have successively published the results and discussed their interpretations. And now we collectively analyzed, in the present article, the total of our former data obtained by LaCoste & Romberg gravimeters around Lake Biwa and in the Kii Peninsula and new data not only of the measurements concerned but also scale values of the gravimeters employed; and discussed on the results of gravity change obtained in the areas concerned during the past decade, by comparing with some other data such as levelling surveys, oceanic tidal observations and so on.

3. Location of Stations and Method of Measurements

3–1. Around Lake Biwa

In the area around Lake Biwa, gravity measurements have repeatedly been carried out since 1950, but a North American gravimeter and a Worden one were employed in the measurements before 1956. These results are less accurate than those obtained by using LaCoste & Romberg gravimeters, so that we discuss only the results obtained by LaCoste & Romberg gravimeters in the present article. Only one LaCoste & Romberg gravimeter was used in these gravity measurements in 1964 and 1967. Measured stations were chosen mainly from the first order bench marks, while some stations were not bench marks but on the road near bench marks which could not be found, or on the stone steps of shrines or temples which, we judged, would remain intact. These stations are not suitable for the stations of repeated precise gravity measurements, because the gravity change measured cannot be told to result whether from the movement of measured station or from the underground mass redistribution.

We started a new series of precise gravity measurements in 1971 at the same stations as in 1964 and 1967, but some stations which were not bench marks were changed to the nearest bench marks. Location of the main measured stations is shown in Fig. 1, and their details are shown in both Table 1 and Note 1.

Table 1. Description of the stations in the area around Lake Biwa

	Latitude	Longitude	Height
Kyoto Univ.	35°01.′7 N	135°47.′2 E	59.86 m
B.M. 241	35 01.6	135 46.4	53.58
Keage	35 00.5	135 47.4	60.
B.M. 215.1	35 00.4	135 47.4	58.92
B.M. 215	34 59.6	135 48.2	63.16
Kyoto Col. Pharm.	34 59.2	135 48.8	55.
B.M. 213	35 00.1	135 52.4	90.47
Seta (Karahashi)	34 58.2	135 54.5	89.
B.M. 211.1	34 58.2	135 54.5	91.35
B.M. 210.1	34 59.2	135 56.6	109.49
Yasaka Shrine	34 59.2	135 56.0	100.
2nd Order B.M. 1330	35 01.2	135 55.9	86.95
Kusatsu JHS	35 00.7	135 58.0	95.
B.M. 209.1	35 00.9	135 57.8	97.07
Kusatsu (Dental)	35 00.8	135 57.7	97.
B.M. 209	35 01.7	135 58.5	93.86
B.M. 208.1 (former)	35 02.7	135 59.2	97.22
B.M. 207.1	35 03.6	136 01.4	99.27
B.M. 206	35 05.0	136 04.8	113.95
B.M. 205.1	35 05.6	136 05.9	99.59
B.M. 204.1	35 06.7	136 08.0	100.38
Higashioiso (Pass.)	35 07.8	136 10.0	103.
B.M. 203.1	35 07.8	136 10.0	104.55
Gokashō (Zenjū-ji)	35 09.2	136 12.0	108.
B.M. 202.1	35 09.2	136 11.9	107.99
B.M. 200	35 13.8	136 15.5	104.52
Hikone	35 16.4	136 15.6	95.
B.M. 198.1 (former)	35 16.5	136 17.1	102.80
B.M. 198.1 (new)	35 16.5	136 17.1	101.68
Emperor Meiji	35 18.7	136 19.0	118.
B.M. 197	35 18.8	136 19.2	114.79
Samegai	35 19.6	136 21.3	140.
Kashiwabara	35 20.5	136 24.5	177.
Sekigahara JHS	35 21.4	136 28.1	120.
B.M. 193	35 21.5	136 28.2	123.01
Sekigahara (Shrine)	35 21.6	136 28.3	122.
Ibuki	35 22.9	136 22.8	180.
B.M. 10495	35 24.7	136 20.1	131.13
Uchibo	35 25.6	136 17.9	113.
Kohoku	35 26.7	136 14.6	99.
B.M. 10500 (former)	35°27.′2 N	136°15.′8 E	101.21 m
Kinomoto	35 30.1	136 13.7	120.
B.M. 10506	35 32.5	136 12.5	147.45
Hannoura	35 30.0	136 11.4	140.
Yanokuma	35 30.7	136 09.1	105.
Sakaebashi (former)	35 30.1	136 08.1	90.
Sakaebashi (new)	35 30.1	136 08.1	90.
Ōura	35 29.2	136 07.6	95.
Kaizu (Fukuzen-ji)	35 27.6	136 04.6	90.
Kaizu (Saiei-ji)	35 27.6	136 04.4	90.
2nd Order B.M. 3851	35 27.2	136 04.0	87.30
Makino	35 27.7	136 02.6	105.
Kitashinpo	35 26.7	136 02.2	105.
Yū	35 24.2	135 59.4	140.
B.M. 1328	35 24.2	136 00.4	124.00
B.M. 1326	35 23.8	136 02.4	87.24
B.M. 1323	35 20.7	136 01.9	96.76
B.M. 1322	35 19.6	136 01.7	91.17
B.M. 1320	35 17.7	136 01.0	86.95
B.M. 1316	35 14.8	135 58.4	91.34
B.M. 1312	35 11.7	135 55.4	104.36
B.M. 1311	35 10.8	135 55.0	97.92
B.M. 1310	35 10.0	135 55.4	87.12
B.M. 1309	35 09.1	135 55.5	95.50
B.M. 1308	35 08.4	135 55.6	89.24
B.M. 1307	35 07.3	135 55.3	87.80
B.M. 1305	35 05.3	135 53.8	87.21
Karasaki (Shrine)	35 02.7	135 52.6	87.
B.M. 1302	35 02.7	135 52.5	86.36
B.M. B-2	35 09.3	135 54.4	230.
B.M. B-5	35 09.4	135 52.1	150.

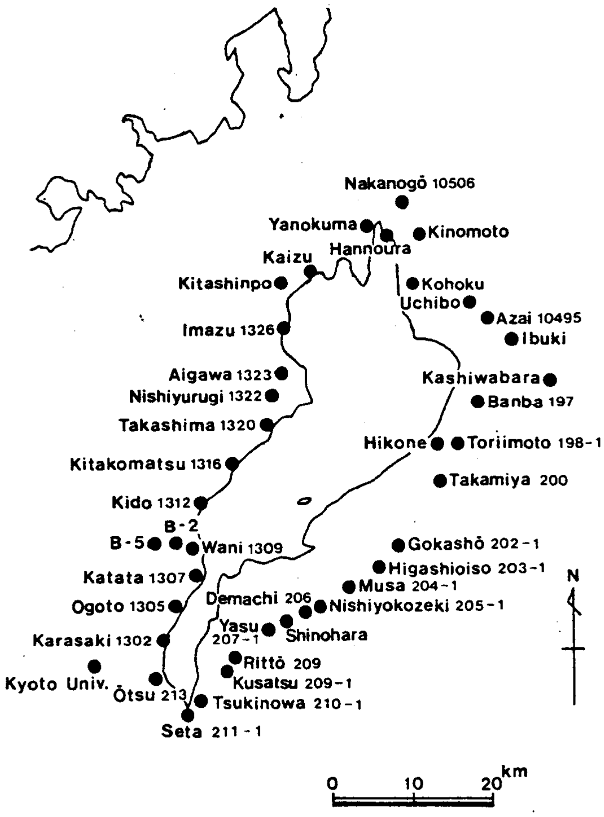

Fig. 1. Location of the main measured stations in the area around Lake Biwa.

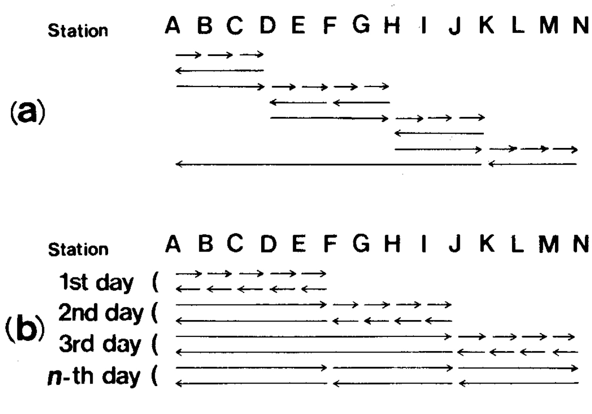

Fig. 2. Schemes of the measured order of the stations.
(a) One-way measurements making the small loops.
(b) Going and returning measurements.

In 1964 and 1967, one-way measurements making the small loops were carried out as shown in Fig. 2 (a). These measurements were completed at all stations in a few days. To be concrete, we measured in 1964 as follows;

first day : Kyoto – 1 station – Ōtsu – Seta – Ōtsu – 1 station – Kyoto – Seta – 4 stations – Shinohara – 1 station – Seta – Kyoto,

second day : Kyoto – Seta – 1 station – Shionohara – 4 stations – Gokashō – 1 station – Shinohara – Gokashō – 2 stations – Hikone – 1 station – Gokashō – Hikone,

third day : Hikone – 2 stations – Kashiwabara – Hikone – Kashiwabara – 3 stations – Kinomoto – Kashiwabara – Kinomoto – 5 stations – Imazu – Kinomoto – Imazu, and

fourth day : Imazu – 4 stations – Kitakomatsu – 1 station – Imazu – Kitakomatsu – 5 stations – Ogoto – 1 station – Kitakomatsu – Ogoto – 1 station – Ōtsu – 1 station – Ogoto – Kyoto,

In 1967 we measured as follows;

first day : Kyoto – 1 station – Ōtsu – 10 stations – Gokashō – 3 stations – Kyoto,

second day : Kyoto – 1 station – Gokashō – 9 stations – Uchibo – Gokashō,

third day : Uchibo – 5 stations – Kinomoto – 3 stations – Imazu – Kitashinpo – 1 station – Kinomoto – Uchibo,

fourth day : Kinomoto – 1 station – Kitashinpo – Imazu – 11 stations – Ōtsu – 2 stations – Imazu, and

fifth day : Imazu – 4 stations – Ōtsu – Kyoto.

After 1971, a going and returning measurement was adopted as shown in Fig. 2 (b); the connection was made directly from the reference station (Geophysical Institute of Kyoto University) every day in order to determine gravity values at the measured stations as accurately as possible. Every measurement included at least three so-called "connective stations"; *i. e.*, the reference station, the first station and the last station of that day. Another measurement only at the connective stations was also carried out. For example, in 1977 we measured as follows;

first day : Kyoto – Ōtsu – 10 stations – Hikone (twice) – 10 stations – Ōtsu – Kyoto,

second day : Kyoto – Hikone – 8 stations – Kinomoto(twice) – 8 stations – Hikone – Kyoto,

third day : Kyoto – Ōtsu – Hikone – Kinomoto – Imazu(twice) – Kinomoto – Hikone – Ōtsu – Kyoto,

fourth day : Kyoto – Imazu – 8 stations – Kinomoto(twice) – 8 stations – Imazu – Kyoto, and

fifth day : Kyoto – Ōtsu – 9 stations – Imazu (twice) – 9 stations – Ōtsu – Kyoto.

Since 1971, we had measured almost in the same way as this; some other measurements were added to these measurements when some troubles took place. Almost all measurements were carried out by means of a single gravimeter; namely, G-83 in 1964, G-29 in 1967, G-196 in 1971 ~1977 and July 1980, and two gravimeters G-196 and G-534 after 1979 except July 1980.

3–2. In Kinki District

When we started the precise gravity measurements in 1971, we had never carried out precise calibrations on scale values of LaCoste & Romberg gravimeters, so the obtained results contained uncertainty of an order of 10^{-4} on the scale values. As for gravity measurements in Kinki District, we had to select the gravity stations where the gravity difference was less than about 1 mgal in order to obtain the gravity difference from a reference station with the accuracy of 10 μgals or better by avoiding the irregularity of dial screw of the gravimeter, the determination error of scale values and others.

As mentioned in the Chapter **2**, we could find gravity stations with a similar gravity value all over the Kinki District. Along the levelling route of the area covering Lake Biwa and the Kii

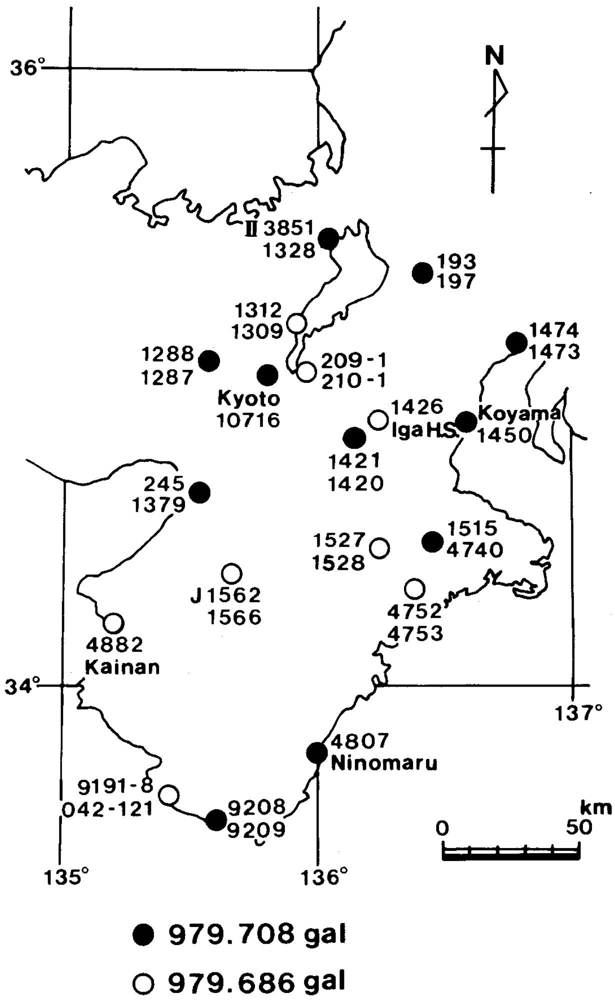

Fig. 3. Distribution of the iso-gravity stations in Kinki District.

Peninsula, such first order bench marks were chosen in 1970, as gravity stations, as gravity differences from the Gravity Station of Geophysical Institute of Kyoto University (reference station in the present study and its gravity value is 979.708 gals) are smaller than 4 mgals (later, we narrowed down to smaller than 1 mgal) – hereinafter, referred to as "the iso-gravity station" in the present article – (NAKAGAWA and SATOMURA, 1971). Besides them, the first order bench marks with the gravity value of 979.686 gals±1 mgal were added to the iso-gravity stations in due consideration of their distribution, in 1973. In another words, two sets of the iso-gravity networks were established in the area covering Lake Biwa and the Kii Peninsula. One more first

Table 2. Description of the iso-gravity stations

	Latitude	Longitude	Height		Latitude	Longitude	Height
	N	E	m		N	E	m
11.0.	35°01.′7	135°47.′2	59.86	33.1.	34°17.′2	136°22.′7	158.36
11.1.	35 00. 5	135 47. 4	60.	33.2.	34 17. 3	136 22. 8	155.
11.2.	35 00. 4	135 47. 4	58.92	33.3.	34 17. 2	136 22. 9	157.86
11.3.	34 59. 6	135 48. 2	63.13	33.4.	34 17. 1	136 22. 4	161.73
11.4.	34 59. 2	135 48. 8	55.	33.5.	34 16. 9	136 22. 4	160.
11.5.	34 57. 1	135 49. 3	50.	33.6.	34 16. 6	136 22. 0	169.12
11.6.	34 56. 6	135 49. 2	31.81				
				15.1.	33 45. 4	136 01. 6	8.77
12.1.	34 45. 8	136 07. 8	147.94	15.2.	33 45. 4	136 01. 6	13.
12.2.	34 45. 9	136 07. 6	145.	15.3.	33 48. 1	136 02. 5	40.
12.3.	34 45. 7	136 07. 5	140.	15.4.	33 43. 6	135 59. 7	40.
12.4.	34 45. 8	136 08. 2	150.	15.5.	33 42. 8	136 00. 0	30.
12.5.	34 45. 7	136 08. 3	150.	15.6.	33 42. 0	135 59. 5	35.64
12.6.	34 46. 4	136 08. 5	141.94				
				16.1.	33 30. 2	135 35. 8	7.34
31.1.	34 48. 9	136 12. 1	177.	16.2.	33 30. 2	135 35. 5	15.
31.2.	34 48. 5	136 12. 5	180.	16.3.	33 30. 3	135 35. 8	20.84
31.3.	34 47. 6	136 12. 7	195.	16.4.	33 30. 2	135 36. 1	15.
31.4.	34 46. 4	136 13. 2	220.	16.5.	33 30. 4	135 35. 0	5.
31.5.	34 49. 1	136 12. 8	185.	16.6.	33 30. 5	135 34. 8	6.07
31.6.	34 49. 5	136 13. 2	188.76				
				34.1.	33 34. 3	135 25. 9	7.78
13.1.	34 49. 1	136 34. 9	1.49	34.2.	33 34. 1	135 26. 1	5.
13.2.	34 48. 9	136 34. 7	2.73	34.3.	33 34. 0	135 26. 0	5.
13.3.	34 48. 8	136 34. 4	1.10	34.4.	33 35. 3	135 27. 0	15.
13.4.	34 48. 8	136 33. 7	5.	34.5.	33 35. 6	135 27. 2	15.
13.5.	34 48. 6	136 34. 2	3.	34.6.	33 34. 4	135 25. 8	12.98
13.6.	34 48. 5	136 34. 1	1.32				
				35.1.	34 05. 7	135 07. 3	5.
14.1.	34 24. 6	136 27. 9	72.34	35.2.	34 06. 2	135 09. 2	15.
14.2.	34 24. 4	136 27. 7	75.	35.3.	34 06. 6	135 09. 5	6.56
14.3.	34 24. 6	136 28. 0	70.20	35.4.	34 07. 0	135 09. 2	20.
14.4.	34 24. 8	136 28. 4	68.33	35.5.	34 08. 5	135 11. 6	2.69
14.5.	34 26. 9	136 26. 4	100.	35.6.	34 10. 0	135 12. 6	7.72
14.6.	34 27. 0	136 26. 5	95.73	35.7.	34 09. 1	135 12. 7	2.40
14.7.	34 27. 0	136 24. 0	115.				
				36.1.	34 18. 8	135 36. 5	84.57
32.1.	34 24. 7	136 14. 3	209.42	36.2.	34 18. 9	135 37. 3	88.51
32.2.	34 24. 9	136 14. 4	208.	36.3.	34 18. 9	135 37. 6	93.68
32.3.	34 24. 6	136 14. 3	210.	36.4.	34 22. 2	135 44. 8	138.01
32.4.	34 24. 5	136 14. 0	210.	36.5.	34 21. 2	135 42. 6	120.
32.5.	34 24. 4	136 13. 8	215.	36.6.	34 20. 8	135 41. 9	105.
32.6.	34 24. 3	136 13. 5	217.04	36.7.	34 20. 8	135 41. 9	104.00

(continued to the next page)

Table 2. (continued)

	Latitude	Longitude	Height		Latitude	Longitude	Height
	° ′ N	° ′ E	m		° ′ N	° ′ E	m
17.1.	34°34′.6	135°28′.9	5.	38.1.	35°11′.7	135°55′.4	104.36
17.2.	34 35. 0	135 29. 1	2.95	38.2.	35 10. 8	135 55. 0	97.92
17.3.	34 36. 1	135 29. 5	2.09	38.3.	35 10. 0	135 55. 4	87.12
17.4.	34 35. 4	135 30. 5	10.	38.4.	35 09. 1	135 55. 5	95.50
17.5.	34 35. 5	135 31. 9	10.	38.5.	35 08. 4	135 55. 6	89.24
17.6.	34 34. 8	135 31. 8	13.	38.6.	35 07. 3	135 55. 3	87.80
17.7.	34 34. 4	135 31. 9	14.74				
				20.1.	35 02. 2	135 33. 1	98.69
37.1.	34 59. 2	135 56. 6	109.49	20.2.	35 02. 6	135 34. 5	100.
37.2.	34 59. 2	135 56. 0	100.	20.3.	35 01. 2	135 35. 6	100.
37.3.	35 01. 2	135 55. 9	86.95	20.4.	35 00. 9	135 31. 7	150.
37.4.	35 00. 7	135 58. 0	95.	20.5.	35 01. 4	135 32. 6	130.
37.5.	35 00. 9	135 57. 8	97.07	20.6.	35 02. 6	135 32. 8	100.50
37.6.	35 01. 7	135 58. 5	93.86				
				21.1.	35 06. 0	136 46. 9	−0.54
18.1.	35 18. 8	136 19. 2	114.79	21.2.	35 06. 3	136 46. 1	−0.5
18.2.	35 18. 7	136 19. 0	118.	21.3.	35 05. 9	136 46. 5	−0.5
18.3.	35 19. 6	136 21. 3	140.	21.4.	35 05. 2	136 46. 6	−0.5
18.4.	35 21. 4	136 28. 1	120.	21.5.	35 04. 8	136 47. 2	−0.5
18.5.	35 21. 6	136 28. 3	122.	21.6.	35 05. 7	136 45. 6	−0.49
18.6.	35 21. 5	136 28. 2	123.01				
19.1.	35 27. 2	136 04. 0	87.30				
19.2.	35 27. 6	136 04. 4	90.				
19.3.	35 27. 6	136 04. 6	90.				
19.4.	35 27. 7	136 02. 6	105.				
19.5.	35 24. 2	135 59. 4	140.				
19.6.	35 24. 2	136 00. 4	124.00				

order bench mark and four or five sub-stations were subjointly established near each bench mark in 1973, in order to keep the stations as long as possible and also to confirm the accuracy of gravity change measured (NAKAGAWA and SATOMURA, 1973; 1975a). The distribution of the stations thus established is shown in Fig. 3, and their detailed descriptions are shown in both Table 2 and Note 2. In Fig. 3, each circle consists of six or seven gravity stations; namely, two bench marks (we call them "main stations") and four or five sub-stations.

Gravity measurements at the main stations along the route of Kyoto—the Kii Peninsula—Kyoto were carried out both clockwise and counter-clockwise by means of three LaCoste & Romberg gravimeters G-34, G-196 and G-210 during the period of three days on either way in 1972 (NAKAGAWA and SATOMURA, 1972). Similar measurements were repeatedly carried out by means of two or three LaCoste & Romberg gravimeters in 1974 (G-34, 196 and 210), 1975 (G-34, 196 and 210), 1978 (G-118, 196 and 210), 1980 (G-196, 534 and D-36) and 1981 (G-196 and 534) at the main stations