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V. FUTURE PLAN

V.1 SEA LEVEL MONITORING SYSTEM USING A SMALL MOBILE VLBI STATION

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ABSTRACT

The earth's environment has recently been taking a turn for the worse. In particular, earth warming is expected to seriously disrupt the environment, especially due to its direct effects on the level of the sea. If the sea level increases by 1 m, some parts of the world will lie under the sea. The monitoring of the sea level has now taken on new importance.

Our monitoring system uses tidal data (changes in sea level). It includes the periodic variations caused by the tide and the change in the atmospheric pressure. The periodic variation shorter than a month is removed by estimating the amplitudes and phase for each period, or by the average of the raw tidal data. The rate of long term change is obtained from the corrected tidal data. The rate includes the crustal movement of tide gauge stations. Since the crustal movement may be greater than the change in sea level for long term in Japan, the exact monitoring of sea level needs correction for this crustal movement. We have developed a mobile Very Long Baseline Interferometry (VLBI) station for monitoring the sea level which measures the crustal movements of tide gauge stations.

The equipment and subsystems developed for our mobile VLBI system consist of an antenna, a receiver, a frequency converter, VLBI acquisition terminals, frequency standard, phase calibration system, ionospheric correction system, and a weather measurements system. A K-4 recording system from the Communications Research Laboratory (CRL) or the Geographical Survey Institute (GSI) is used. The diameter of the antenna is 2.4 m, and the weight of the antenna and control system is less than 700 kg. The system is compact and will be transportable by a mobile unit in the future. The observation band is only X band (8 GHz), and the 16-channel video converters use a 2 MHz and/or 4 MHz video frequency band. The ionospheric delay will be corrected by equipment using Global Positioning System (GPS) data.

1. Introduction

The environment of the earth has been steadily getting worse in modern times. Significant themes are (1) earth warming, (2) destruction of ozone, (3) acid rain, (4) pollution of the ocean, (5) destruction of tropical forests, and (6) spread of the desert. These phenomena are considered to be closely related with each other, and earth warming itself introduces many of the other phenomena. Earth warming is caused by the green-house effect of carbon dioxide and methane gas. Modern industry and human labor require

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the combustion of oil, coal, gas and trees, thus discharging carbon dioxide and methane gas into the air. The green-house effect of these gases causes a rise in weather temperature which is potentially damaging to human life on this planet. Therefore, the discharge of carbon dioxide and methane gases should be controlled and countermeasures to earth warming should be studied by scholars of all fields.

A direct phenomena of earth warming is the rise in sea level. A rise in sea level can be a severe problem to the human life, causing lowlands to flood, islands to disappear, and in general causing much damage, especially in central Asia. If the sea level rises just 0.5 m, a land area of 7 million km^2, a population of 1.4 million, and property worth 14 trillion yen (about 100 billion US$) are estimated to lie below the mean water level in the world. If the sea level rises 10 m, about 10% of Japan is expected to be under the sea. However, specific information on the rate of rise in sea level is not extensive. For example, it was generally considered ten years ago that the earth was becoming colder and the sea level going down. Weather patterns change periodically between warming and cooling. The change in sea level does not depend on the change in weather in such a simple fashion. Close monitoring, analysis and forecast of changes in sea level are indispensable.

Figure 1 shows a chronological change in weather temperature and that in the density of methane and carbon dioxide gases measured in Antarctic ice(1). As can be seen, they correlate closely, strongly suggesting that carbon dioxide and methane gases cause earth warming.

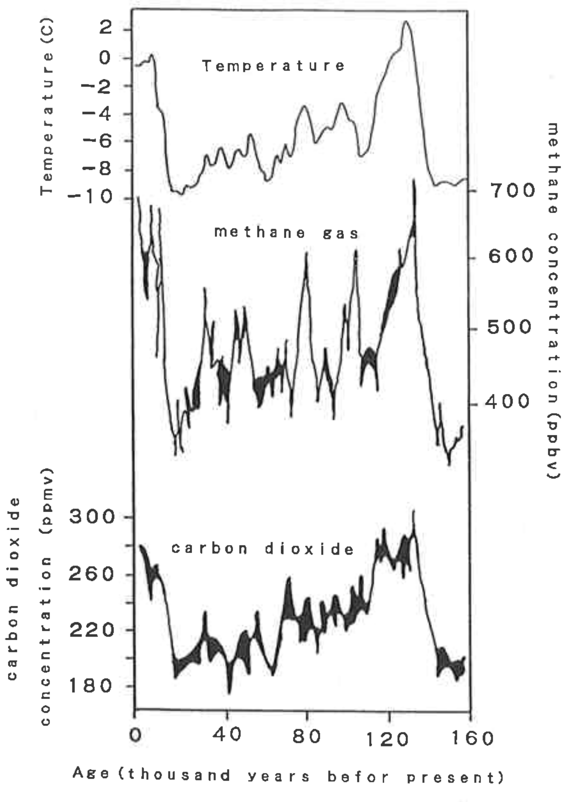

Fig. 1 Change of temperature, density of methane gas and carbon dioxide for the past 160000 years ago. (density including in the ice sheet of the Antarctica).

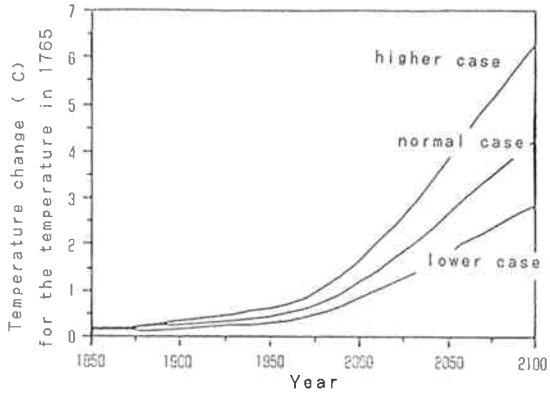

Fig. 2 Forecast of temperature without the control of carbon dioxide and methane gases (unit: C). (the reference is the temperature in 1765).

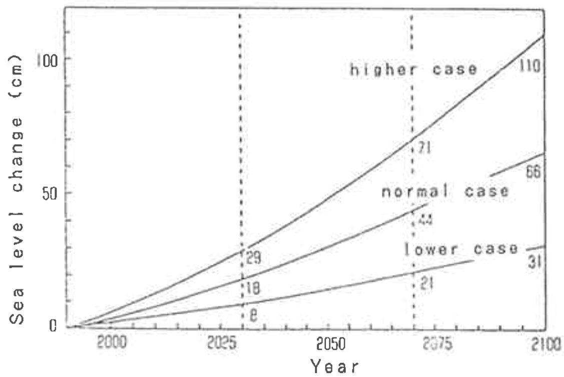

Fig. 3 Estimation of the sea level change with the forecast of temperature change (unit: cm).

The temperature has risen 0.3–0.6 degrees during the last 100 years. Figure 2 shows a forecast of the weather temperature assuming no control of carbon dioxide and methane gases discharge(1). The forecast shows that the temperature will rise 1 degree by 2025 and 3 degrees by 2100 by the best estimation. Forecasting change in sea level is difficult, but Figure 3 shows a rough estimation based on the temperature forecast(1). The sea level will rise 10–30 cm by 2030, and 30–110 cm by 2100. The expansion of the sea water contributes to the rise in sea level about 50%, the melting of glaciers about 40%, and the melting of the ice sheet in Greenland and Antarctica about 10%. The rate of the rise in sea level in the next century is forecasted to be about 6 mm/year, much higher than the current rate, due, for example, to increase combustion of fuel.

Some studies of the change in sea level have been previously reported. Figure 4 shows the change in sea level according to Barnett (1988)(2). The mean rising rate is 1.2 mm/year for the 100-year period. Other reported results are similar. Recently, the slope of the change in sea level has steepened, with a rate

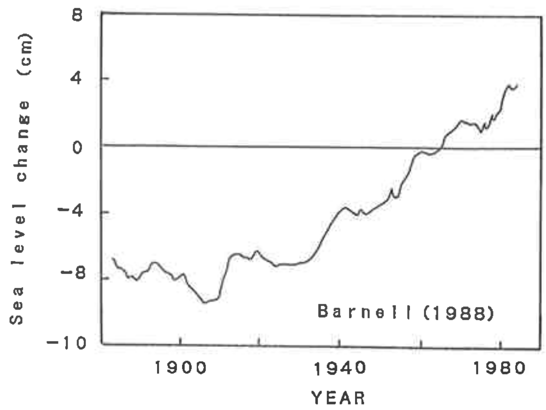

Fig. 4 Change in the global mean sea level (unit: cm).

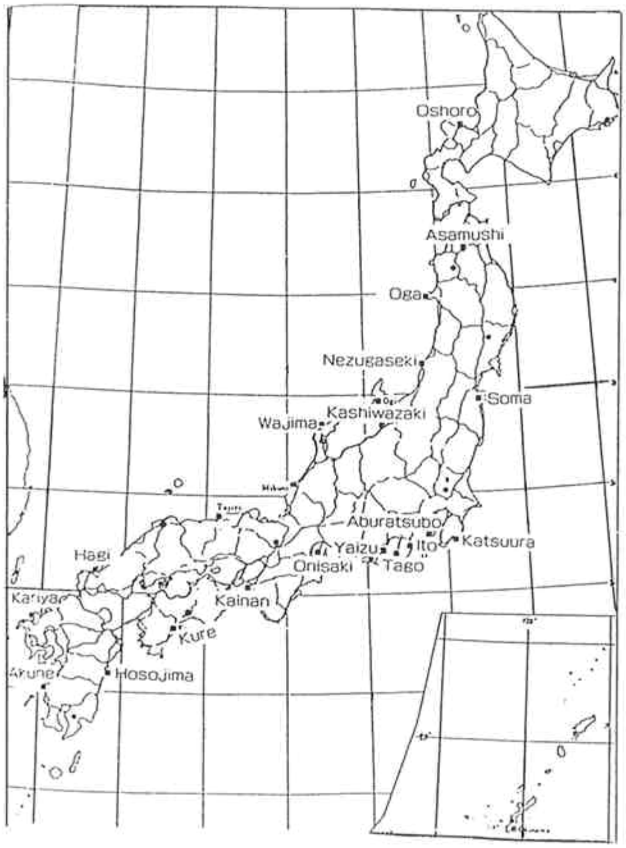

Fig. 5 Location of tide gauge stations of GSI.

of about 2 ~ 3 mm/year for the last 30 years. There are regional differences in the change in sea level[3]. The change in sea level in Europe and Africa is very similar to that on the west coast of North America, in Central and South America, and of the Indian Ocean. However, the change in sea level on the east coast of North American is steeper than changes in other regions, and there is a peculiar change in the Far East. Since the rise in sea level by earth warming is not a local change but a global one, worldwide tidal data from many stations are necessary for monitoring the sea level.

Tidal data includes not only actual change in sea level, but also the deformation of the earth and crustal deformation of the local area. The rate of change in sea level is a few mm/year, so that the crustal movements of the tide gauge station should be measured and corrected for tidal data. New geodetic space techniques such as VLBI, Satellite Laser Ranging (SLR) and GPS are available to measure positions with high precision within 10 cm. The precision of VLBI is the best among these techniques (within 3 cm) and does not depend on baseline length. Consequently, VLBI is the most desirable for measuring on baselines greater than 500 km. The movement of a tide gauge station as measured by VLBI is necessary for monitoring the sea level. The International Earth Rotation Service (IERS) are using VLBI, SLR and GPS to establish and maintain a global geocentric coordinate system. This coordinate system is necessary for absolute sea level monitoring, that is, the effect of earth deformation on the change in sea level.

The Japan Archipelago exhibits complex crustal deformation. GSI in cooperation with CRL, has 23 tide gauge stations through-out the Japan Archipelago, as shown in Figure 5. These stations have been supplying good tidal data. GSI has made an analysis of the tidal data, and the vertical crustal movements in the Japan Archipelago were obtained on the assumption that the annual mean sea level along the coast of the Japan Sea is stable[4]. It was found that most parts of Japan Archipelago tend to subside –2 ~ –10 mm/year, which is greater than the current rate of change in sea level, and that the movements have complex regional differences. However, the assumption that the annual mean sea level of the Japan Sea is stable must be examined. It is necessary to measure the movements of tide gauge stations for several years by the new space geodetic techniques in addition to collections tidal data. Our monitoring system for sea level and the application of this system are described in this paper.

2. Sea Level Monitoring System

Our sea level monitoring system consists of three components as follows:

(1) tidal data analysis software;

(2) a mobile VLBI station for measuring positions of the tide gauge stations;

(3) GPS nets for the local area and continuous data.

Both CRL and GSI will develop analysis software for tidal data. In GSI, the tidal data are averaged over the long term. In CRL, each component (amplitude and phase) of short periodic tidal variation in sea level is estimated and removed from monthly tidal data. The average of corrected data is calculated every month and errors due to large tidal variations are removed. The change in sea level caused by atmospheric pressure is adjusted for in the tidal data before tide analysis. Long periodic variation and the slope of change are estimated from the adjusted tidal data for every month. After the movements of tidal stations obtained by VLBI or GPS are adjusted for in the long term variation of sea level, the real change in sea level is obtained.

The tidal analysis software "BAYTAP" has already been prepared by National Astronomy Observatory (NAO)[5][6]. Figure 6 shows tidal data at Kashima from June to August 1981 and the analysis results by "BAYTAP". The upper figure is raw data, the middle figure is data after correcting for the short periodic variation, and the lower figure is the variation after correcting for the atmospheric pressure. The final

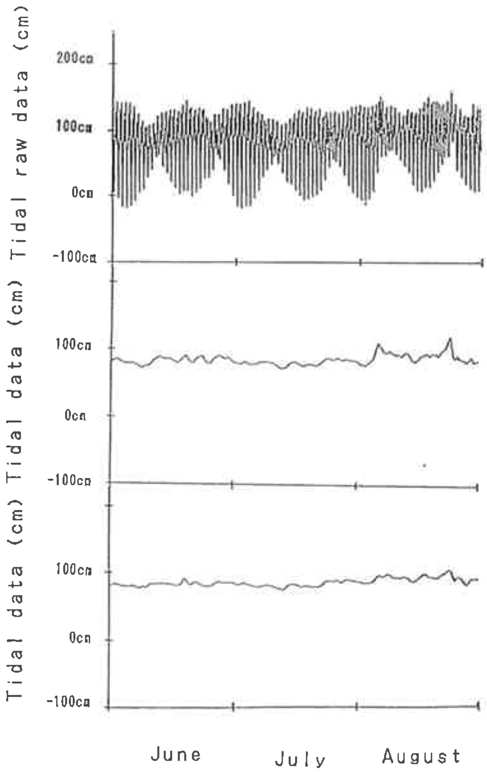

Fig. 6 Tide data at Kashima from June to August in 1981. (Upper figure: the raw tide data, Middle figure: the tide data after the correction of the short periodic variation, Lower figure: the tide data after the correction of the atmospheric pressure).

variation is about 6 cm and r.m.s. is about 2 cm. If the long periodic variation in tidal data is adjusted for the rate of change in tidal data is obtained within a few mm/year for a period over three years. CRL will prepare analysis software on the basis of "BAYTAP".

Together with GSI, we have developed a mobile VLBI station for our system as described in section 3. GSI and CRL have several GPS systems for precise positioning, which can be operated automatically. We use a GPS system for continuous data and data in a narrow area within 100 km instead of VLBI.

By the way, a change in sea level also affects the earth rotation speed. As the sea level rises, the inertial moment of the earth becomes larger and the earth rotation becomes slower because of the preservation of the total angular momentum. The monitoring of earth rotation is also important in the study of the change in sea level. CRL has been conducting international VLBI experiments in the IERS network with NAO every month. CRL will also monitor the change in sea level by using the earth rotation data.

3. Development of a Mobile VLBI System

CRL has helped in developing a mobile VLBI system for our sea level monitoring system. This system will be used to measure the position of about ten tide gauge stations selected from among those of GSI. The measurements will be continued for 5 ~ 10 years. Cutting down on transportation costs is an important factor when visiting the tide gauge stations every year for sea level monitoring. Therefore it is desirable that the system be transportable by a mobile unit. Although good results have been obtained for a mobile VLBI experiment using a CRL 3 m antenna system(7), the experiment concerned a CRL project, such as for the Western Pacific VLBI Network. Consequently, we felt it be better to develop a special system for monitoring the sea level.

3.1 Mobile System

The antenna for our special system is developed for easy and inexpensive transportation, and can ride on a mobile unit. The main features of this system are in Table 1. The system has only an X band receiver to make it compact and lower the cost. A new technique called "GTR2" has been developed to measure Total Electron Content (TEC) using GPS(8). Correction for ionospheric delay in our system is obtained by GTR2. Our system is used for a domestic area less than 1000 km and the difference in ionospheric delay between two stations is small. The correction of ionospheric delay by GTR2 will have a precision better than 0.1 ns r.m.s.

Table 1 Main features of mobile VLBI station.

Antenna	Diameter 2.4 m X band (7860–8600 MHz) Efficiency 55%
Reciever	LNA (90 K) (120° K System Noise Temperature)
Acquisition Terminal	K-4 video converter 4 MHz/channel. 16 channels
Recorder	K-4 Recorder (CRL or GSI)
Ionospheric Correction	GTR2 (TEC meater) using GPS
Frequency Standard	Transportable H-maser or Cesium & Crystal
Generator	Power supply for Mobile VLBI station

The diameter of the antenna for the mobile VLBI system is calculated based on overall design specifications of the antenna. The 34 m antenna at Kashima(9) will be used as a partner in our system. The performance of this antenna in X band is 70 K in system temperature, 70% in efficiency. The mobile VLBI performance is 120 K in system temperature and 55% in efficiency. In usual VLBI experiments, more than 20 sources are necessary for a precise station position since the range of source declination is related to the precision. There are more than 20 sources whose correlated flux is more than 1.5 Jy on a short baseline(10). The lower limit of the observable correlated flux is set to 1.5 Jy. In this case, SNR is calculated

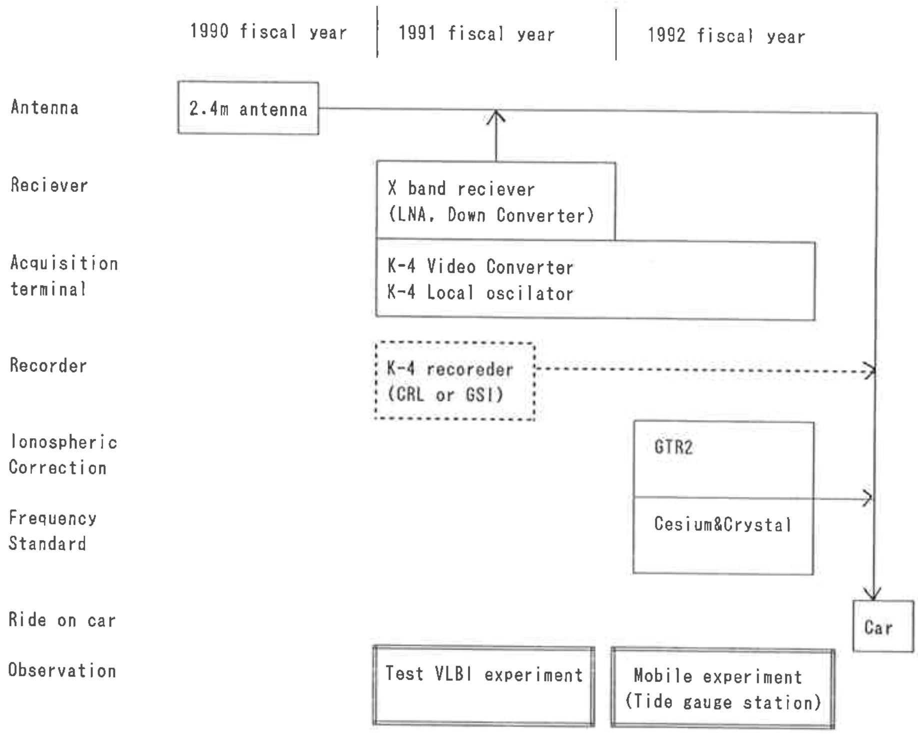

Fig. 7 Plan of the developments of the mobile VLBI station.

as follows:

$$SNR = 0.884 \times 10^{-4} \cdot D \cdot \sqrt{nBT} \cdot L \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where D is antenna diameter of mobile system, L is coherence factor, n is the channel number of the bandwidth synthesis, B is the video bandwidth of each channel, and T is the effective integration time in correlation processing.

The video converters will be of a K-4 system type[12]. Since the receiver is only X band, all video-converter channels are used for X band only ($n = 16$). Although the K-4 system can accommodate both a 2 MHz and 4 MHz video bandwidth, our system will use just the 4 MHz video bandwidth ($B = 4$ MHz). As for a frequency standard, the integration time of a hydrogen maser can be longer than 400 sec and its coherence loss very small. However its cost is very expensive and transportability is poor. We will begin by using a cesium & crystal system[11], which is transportable and already in possession by CRL. The coherence loss is 20% ($L = 0.8$) and a suitable integration time for correlation is 120 sec ($T = 120$ sec). Since the correlation is detectable for SNR greater than 10, the lower limit of SNR is set to 10. In a cesium & crystal frequency standard, antenna diameter should be greater than 1.6 m. If our system includes a transportable hydrogen maser, the diameter of the antenna can be 80 cm.

SNR is proportional to antenna diameter. Since the error estimated by SNR is the main error in measurements in small antenna system, the diameter should be as large as possible. On the other hand,

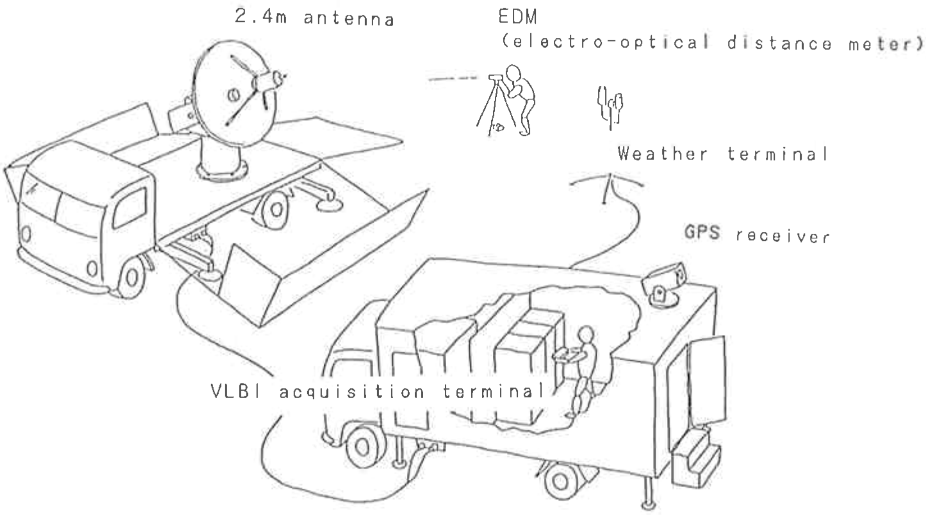

Fig. 8 Mobile VLBI station on the car in future.

a small diameter is more desirable considering cost and transportability. Consequently, we have chosen an antenna diameter of 2.4 m since this diameter is common and the limit in car width is 2.5 m by Japanese law. Thus, for a 2.4 m antenna and a transportable hydrogen maser, the lower limit of the correlated flux becomes 0.5 Jy, or the partner in our system can be an 11 m antenna.

The Environment Agency has approved and budgeted our monitoring system, and its development plan is shown in Figure 7. The antenna itself will be developed in the 1990 fiscal year. In the following year, the receiver and part of the acquisition terminal, such as the K-4 video converters, will be installed. In the third year, the nest of the acquisition terminal will be installed, such as the GTR2 for ionospheric correction and the frequency standard system. The recorder system will be a K-4 recorder(13) from CRL or GSI. If possible, all of the system will ride on the mobile unit to make it more transportable. Figure 8 illustrates the basic design for our system. The system can be moved to several tide gauge stations in Jápan Archipelago and to conduct VLBI experiments with foreign stations.

3.2 Precision of Vertical Movements

The vertical movements of tide gauge stations are necessary for monitoring the sea level. The precision of vertical movement in our system is estimated as follows. The error (x_i) in each estimation parameter is calculated by using a differential matrix A and the r.m.s. of the residuals after the estimation σ, that is, the error in each data item:

$$\left(\varepsilon_{ij}\right)=\left({}^{T}AA\right)^{-1}$$
$$x_i=\sqrt{\varepsilon_{ij}}\,\sigma. \qquad (2)$$

SNR is greater than 15 for a 2.4 m antenna and a source flux greater than 1.5 Jy. The noise error estimated by SNR is less than 0.07 ns in usual bandwidth. In addition to this type of error, there are also those errors caused by atmospheric scintillation, the error in correcting ionospheric delay, the clock estimation error and analysis error. The final error σ is considered to be about 0.15 ns (5 cm) for the hydrogen maser, and about 0.25 ns (8 cm) for the cesium & crystal frequency standard.

The observation directions are uniform for the baseline vector and the elevation distribution is also uniform in the geodetic VLBI so as to obtain precise positions. We assume that the observations are completely uniform as our system will be used mainly near Japan with a baseline less than 1000 km. The mutual visibility is not limited, that is, both VLBI stations can observe the same sources at all times. Although a detailed discussion needs a schedule, a rough estimation of error is possible by making some reasonable assumptions. The errors in estimation are calculated as a function of the mean latitude of both stations, range of declinations, and elevation cutoff (limit of low elevation).

The error in estimating the vertical movement is calculated for a mean latitude of about 35° near Japan and for 300 observations. In addition, the error is calculated in the case of a hydrogen maser. If a cesium & crystal frequency standard is used, the error will be twice as much.

If the estimation of vertical movement is independent of other estimation parameters, the error in vertical movement is $(1.6/\sqrt{\mathrm{N}})\sigma = 4$ mm. However, this assumption is not completely realistic, as the estimation of vertical movement is affected by estimations of the clock, atmospheric delay and north-south movement. The error in vertical movement thus becomes $(2.5/\sqrt{\mathrm{N}})\sigma = 6$ mm if we consider the estimation of north-south movement without the estimation of atmospheric delay. The estimation of vertical movements is almost independent of the estimation of east-west movement.

The estimation of atmospheric delay strongly affects the estimation of vertical movement. The error in vertical movement is $(9.8/\sqrt{\mathrm{N}})\sigma = 25$ mm at 10° elevation cutoff, and $(7.3/\sqrt{\mathrm{N}})\sigma = 19$ mm at 6° elevation cutoff. The 2.4 m antenna of our system will be able to observe sources in the range of declination from −30° to 80°, and for a low elevation less than 6°. The final error in vertical movement will be about 2 cm for the hydrogen maser, and about 4 cm for the cesium & crystal frequency standard.

Measurement will be performed for N years and two experiments will be conducted every year. The rate of change in vertical movement in the long term is $\sqrt{(6/(\mathrm{N}\cdot(\mathrm{N}^2-1)))}$ × (estimation error for each experiment). If the error in vertical movement is about 2 cm and N = 5 years, then the rate of change in vertical movement is measured with a 4 mm/year precision. Since the current rate of change in sea level is considered to be 2 ~ 3 mm/year, the precision is of the same order. It is desired that the measurements be continued for more than 10 years to detect whether the change in sea level is the same as the current change.

4. Application of the Mobile VLBI System

Our system can measure changes in sea level near the Japan Archipelago precisely. Although only vertical movements of tide gauge stations are necessary for monitoring the sea level, precise horizontal and vertical movements of the tide gauge stations are obtained at the same time in VLBI experiments. Such data are useful for certain applications as follows.

4.1 Crustal Deformation of the Japan Archipelago

Data on tide gauge station positions throughout Japan can be obtained by our system and used to measure the crustal deformation of the Japan Archipelago. Up to now, such information with a precise of a few cm has been little.

Earthquakes near Japan are sometimes caused by the crustal deformation and plate motion. Precise information on these phenomena is obtained by VLBI or SLR. VLBI provides data with the highest precision among geodetic equipments, and is especially useful for long baselines. However, it is difficult to obtain continuous data at many stations, since the cost of VLBI experiments is expensive and operation and correlation processing need larger labors. In addition, the results of VLBI are not obtained in real time. Forecasting earthquakes requires continuous data from many points in real time. GPS is suitable for this purpose. The precision of GPS, however, is worse than VLBI for distances, above 100 km. Consequently some points in the GPS net can be measured by VLBI, and GPS data can be calibrated by the VLBI data. Our system is useful for this application.

4.2 Reference Points for GPS and Land Surveying

The tide gauge stations throughout Japan can be used as reference positions to estimate a GPS orbit precisely. These reference stations can also be used as reference points in land surveying.

4.3 Collocation of VLBI, SLR and GPS

Collocation is the measurement of the same point by several techniques. The collocation of VLBI, SLR and GPS data is important in geodesy analysis. However, since GPS is much more transportable than VLBI and SLR, mobile VLBI and SLR stations are desired for collocations. Our system is especially applicable to collocations.

4.4 Crustal Deformation in East Asia

Precise measurements of positions in East Asia by VLBI or SLR are few except in Japan and China. Data on crustal deformation in East Asia, however, is very important to the study of tectonics. Mobile stations such as the one described here can be used for measurements at points in East Asia which lack adequate VLBI antennas and SLR equipment.

5. Conclusion

A system for monitoring the sea level has been under development since the 1990 fiscal year with support of the Environment Agency. Some studies have indicated a change in sea level of about 2 mm/year at present which should increase with time. However, the precise change in sea level is not well known. Crustal deformation and deformation of the earth may be greater than the current rate of change in the sea level, and it is necessary to correct for these effects when measuring changes in the sea level. CRL has developed a sea level monitoring system in cooperation with GSI which can adjust for crustal movements. Our system is a mobile VLBI station consisting of a 2.4 m antenna, an X-band receiver, VLBI acquisition units (video converters), and equipment for ionospheric correction. The mobile system will be transported to tide gauge stations of GSI and positions measured precisely. The analysis software for tide data will also be developed.

Obviously, position data of tide gauge stations throughout Japan are useful for monitoring the sea level. They are also useful for monitoring the deformation of the Japan Archipelago. Still more, a mobile VLBI system can be used in diverse applications, such as the forecast of earthquakes with GPS data and the collocation of VLBI, SLR and GPS data.

Acknowledgement

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