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Cable Voltage Measurement using OKITAI and OLU Submarine Cables for Monitoring Ocean Transport

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Abstract

The OKITAI and OLU submarine cables cross the Kuroshio near the entrance into the East China Sea. They are old type co-axial copper cables and were retired from their commercial service in May 1997. For the scientific reuse of the cables, our cable voltage measurement was restarted in June 1998, after the settlement of the cable end facilities at the cable landing station, to monitor the variability of the ocean transport. This paper mainly describes the OKITAI and OLU cable facilities, the cable voltage measuring system and the cable data processing such as removing the effect of change in the geomagnetic field. Using the measured OKITAI cable voltage of about 3 years and half until the end of the year 2001, we try to estimate the Kuroshio transport crossing over the cable; [Cable estimated transp.(Sv)]= A_0 + A_1∗[Cable voltage(Volt)], where the offset A_0 = 20.87 (Sv, or $10^6 m^3 s^{-1}$) and the conversion factor A_1=53.69(Sv/Volt). The long-term variability of the estimated transport is basically consistent with that of the transport estimated by the sea-level difference (Ishigaki-Suao) at the entrance.

Keywords : submarine cable, cable voltage measurement, Kuroshio transport

Introduction

Observing the large-scale ocean transports is essentially important to understand the global ocean system that affects the climate change. In the recent years, there have been many efforts to observe the ocean transports under several international projects, such as GOOS (the Global Ocean Observing System). However, the direct field observation using current-moorings especially in the strong current sections is not so easy and is costly. We need various types of approach to observe ocean transports. The cable voltage

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*Current affiliation: Inspector General, Univ. of the Ryukyus, Okinawa 903-0213 Japan measurement will provide one approach. The ocean current through the geomagnetic field induces the ground voltage difference between the cable landing stations, which is basically proportional to the ocean transport crossing over the cable. The voltage difference at a great distance is measured with a voltmeter using the submarine cable as a long conducting wire. If a proper submarine cable crossing a strong current is available, we can estimate the ocean transport over the cable by measuring the voltage difference (cable voltage) as described in Larsen(1992). The cable voltages can be measured continuously in a long period only with a simple voltmeter.

There are two submarine cables near the entrance into the East China Sea crossing the Kuroshio as shown in Fig.1. The Okinawa-Taiwan submarine cable, abbreviated as

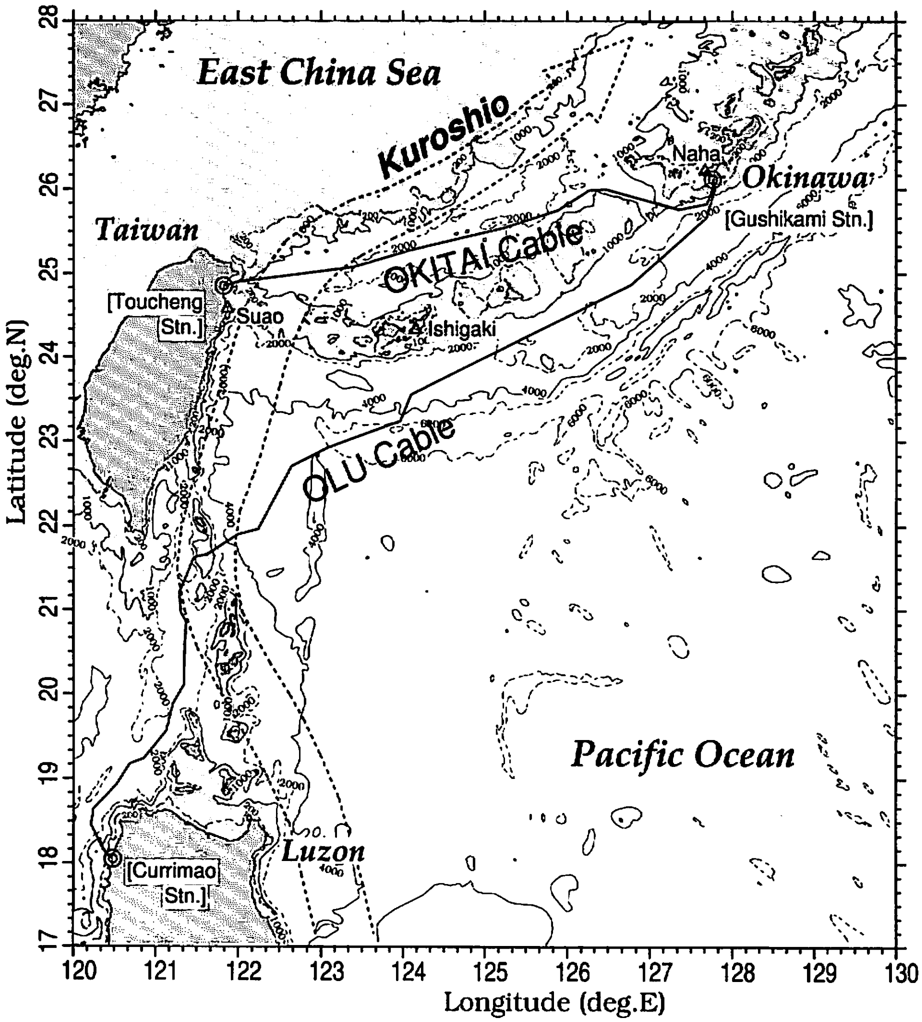

Fig.1 Map showing the position of OKITAI and OLU submarine cables in the beginning region of the Kuroshio. Tidal stations; Suao, Ishigaki, Naha used in the data analysis are also shown by triangle marks.

OKITAI cable, is located rather near the entrance than the Okinawa-Luzon submarine cable, abbreviated as OLU cable. Our preliminary voltage measurement using the OKITAI cable was carried out in the period, April 1995 - May 1997, while the OKITAI cable was still in-service with high voltages for the cable power supply. There was a difficulty to separate a small ocean-motion induced voltage from the measured high voltage. The result of the cable voltage measurement was reported in Koga *et al.*(1997) and Larsen *et al.*(1997).

Both the OKITAI and OLU cables are co-axial copper cables and were retired from their commercial service in May 1997. For the scientific reuse of these cables, the ownership of the cables was transferred from the international telephone companies to the related universities making the cable measurements. At the Gushikami, Okinawa cable landing station, the rearrangement of these cable facilities was made for a long-term scientific reuse. After completing the rearrangement, our new stage of the voltage measurement using both the OKITAI and OLU cables was started in June 1998, as a part of the NEAR-GOOS (North-East Asian Regional GOOS project). Preliminary report in the new stage of the measurement was given in Koga *et al.*(1998).

In this paper, we firstly describe the OKITAI and OLU cables, and the cable voltage measuring system. Next, we describe data processing showing several examples of the observed time series. Finally, using the OKITAI voltage data of about three years and half until the end of the year 2001, we try to estimate the Kuroshio transport and examine its variability.

Cable Voltage Measurement

OKITAI and OLU Cables

The location of the two submarine cables used in this study is shown in Fig.1. The OKITAI cable connects the Gushikami cable landing station (26° 07′ N, 127° 46′ E) in Okinawa to the Toucheng cable landing station (24° 51′ N, 121° 49′ E) in Taiwan through the East China Sea. The cable is about 650 km long and crosses the Kuroshio near the entrance into the East China Sea. The ocean depth along the cable is shown in Fig.2(a). Most of the cable route is along the Okinawa Trough of its typical depth 2000m. The OLU cable is a part of the original Okinawa-Luzon-Hongkong (OLUHO) submarine cable. The OLU cable is about 1390 km long and connects the Gushikami cable landing station in Okinawa to the Currimao cable landing station (18° 03′ N, 120° 29′ E) in Luzon, going along east of the Okinawa Islands and the deep Ryukyu Trench, finally through the Luzon Strait between Taiwan and Luzon, as shown in Fig.2(b). It also crosses the Kuroshio southeast of Taiwan, upstream side than the OKITAI cable.

Both the OKITAI and OLU co-axial copper cables were retired from their commercial service in May 1997. Our voltage measurement using these cables was restarted in June 1998, after resettling the cable end of the Gushikami station as described in the introduction part.

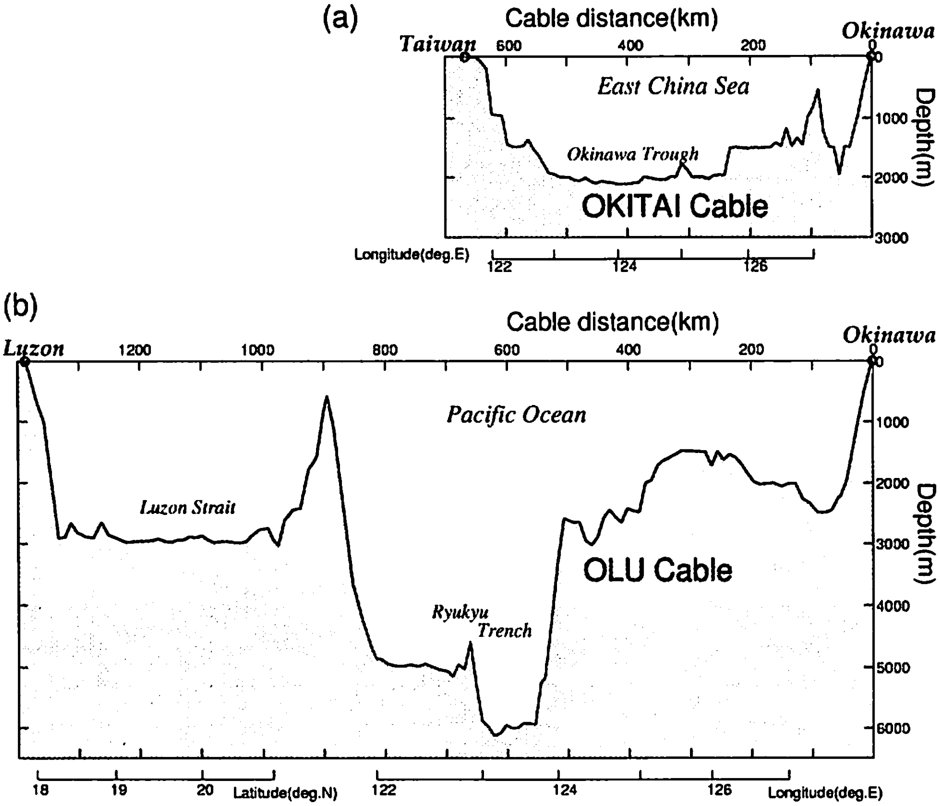

Fig.2 Ocean bottom topography along cable lines. (a) OKITAI cable in the East China Sea, (b) OLU cable south of the Ryukyu Islands and Taiwan.

Voltage measuring system

Figure 3(a) shows a schematic picture of the cable voltage measurement. The cable ends at Toucheng, Taiwan, for the OKITAI cable and at Currimao, Luzon, for the OLU cable are connected to sea-earth grounds. The cable voltages are measured at Gushikami, Okinawa. As these submarine cables are not in commercial service, there are no power supplies of high voltages. We can simply measure the ground voltage differences, between Taiwan and Okinawa and also between Luzon and Okinawa, by the cable voltage measurement. To examine the characteristics of our main OKITAI cable, the OKITAI cable voltage was measured with a fixed load resistance 5.105 k-ohm as shown in Fig.3(b) in the beginning period, July 1998 - March 2000.

The details of the voltage measuring system with digital voltmeters and personal computers (PCs) are shown in Fig.3(c). Both the cable voltages, channel 1 for OKITAI cable and Channel 2 for OLU cable, are measured by precision digital voltmeters through electric low-pass filters to avoid 60-Hz electric noise from a commercial AC power. The measured digital voltage values are stored in PCs through RS-232C interfaces. We have

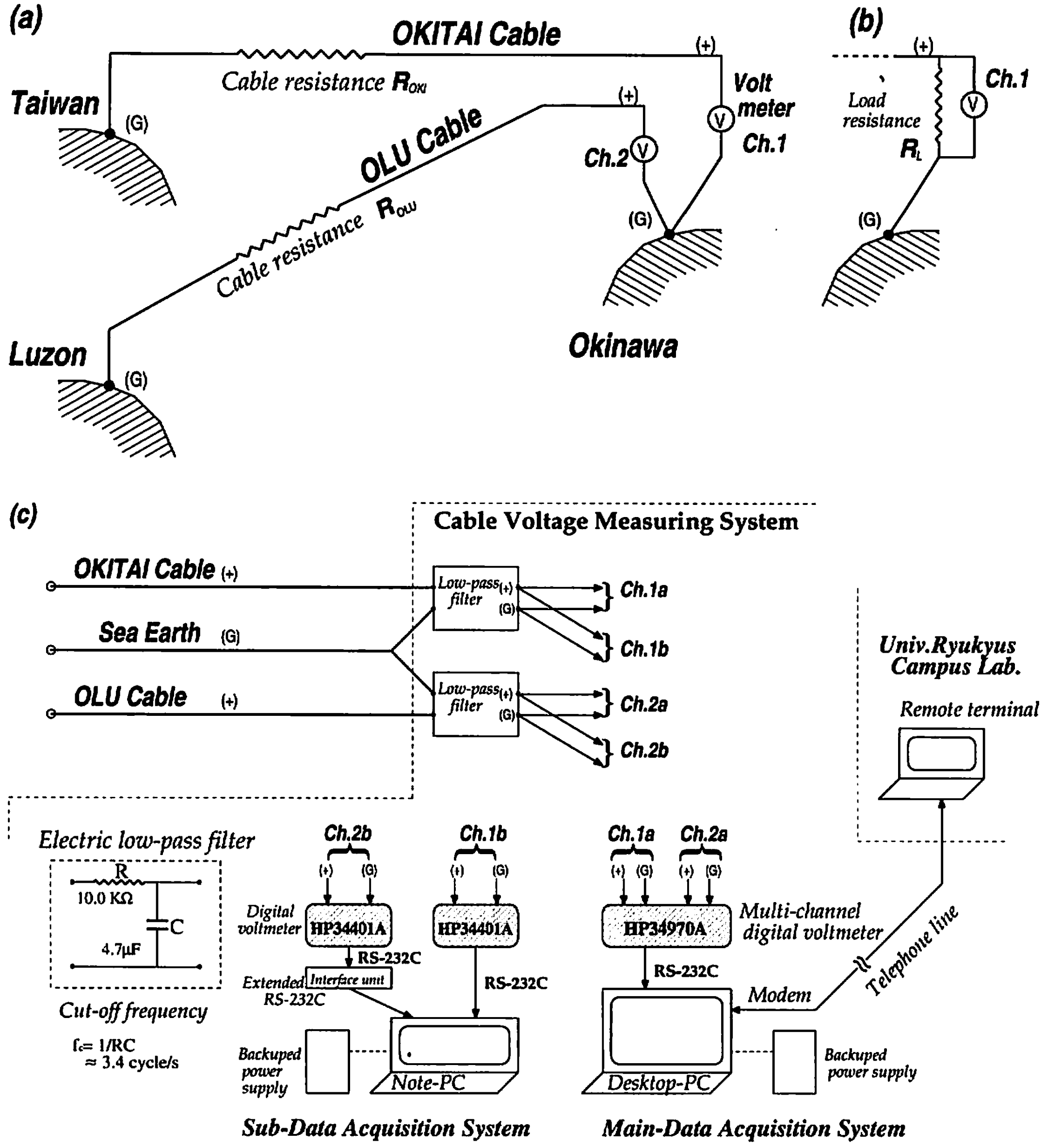

Fig.3 Schematic picture of cable voltage measurement. (a) The OKITAI cable end at Taiwan side and the OLU cable end at Luzon side are connected to the sea-earths marked with (G). Each cable voltage is directly measured at Okinawa side using accurate voltmeters. (b) OKITAI cable voltage measurement with a load resistance R_L from June 1998 to March 2000. (c) Cable voltage measuring system with accurate voltmeters and PCs. There are double measuring systems; Main-data acquisition system and Sub-data acquisition system.

two PC systems for the data storing; the main desktop PC with a multi-channel digital voltmeter (HP type-34970A) and the sub note PC with two single-channel digital voltmeter (HP type-34401A). For the main PC, a mean value of 10 sampled data in several seconds for each channel is stored at every minute. We access the main PC through a commercial telephone line from the campus laboratory, Univ. of the Ryukyus, about 20 km far from the Gushikami cable station for the data acquisition and the system maintenance. The sub PC for the data backup stores mean values at every 2 minutes. The pictures of the cables and the PC systems are shown in the Appendix A; Fig.A(a)-(f).

Cable data processing

The time series for two days of the measured cable voltages, on September 15-16, 2000 is shown in Fig.4. For the first step, the intermediate data set of 10-minutes mean is prepared using the original 1-minute interval data. The time series of the 10-minutes mean (thick solid line) is not so much different from that of original 1-minute interval data (thin solid line) as seen in Fig.4(a) for OKITAI cable and in Fig.4(b) for OLU cable. Finally, we calculate 1-hour means from the 10-minutes means to prepare basic data sets for our data analysis, which are also shown in the figures by dashed lines with circle marks. Figures 5(a), (b) show the hourly time series of the cable voltage (thin solid lines) for one month in September 2000. There are significant diurnal and semidiurnal fluctuations due to the time varying geomagnetic field (Fig.5(c)) and the ocean tides (Figs.

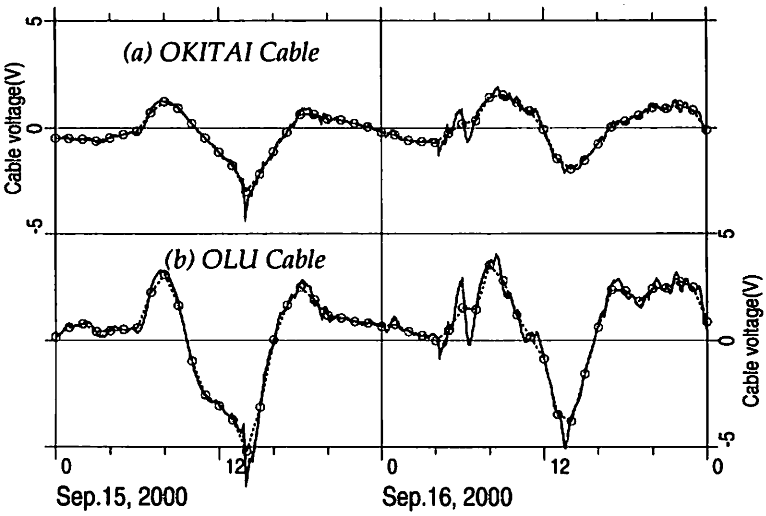

Fig.4 Example of the measured cable voltage of two days, Sep.15-16, 2000. (a) OKITAI cable. (b) OLU cable. Original voltages of 1-minute interval is shown by thin solid lines. 10-minutes means and hourly means are shown by thick solid lines and dashed lines with circles, respectively.

5(d), (e)). Since our main interest is a long-term voltage variation induced by a large-scale ocean current like the Kuroshio, these fluctuations will be removed. Daily mean (25-hours running mean) is also shown by a thick solid line in each panel of Fig.5.

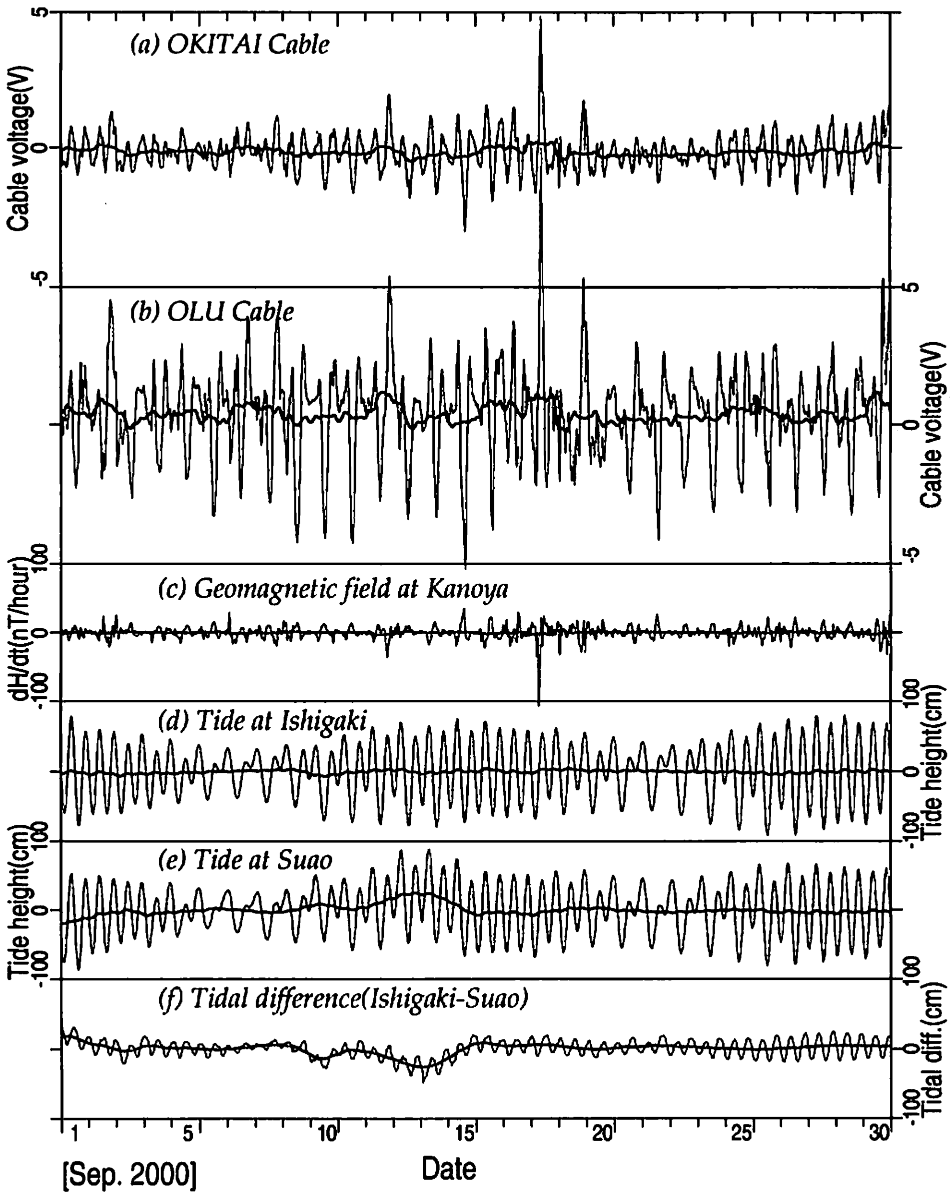

Fig.5 Time series of the measured cable voltage of one month, Sep. 2000. (a) OKITAI cable, (b) OLU cable. Thin solid line and thick solid line show hourly mean data plot and daily mean data plot, respectively. Related time series are also shown; (c) Rate of time change of the horizontal component of the geomagnetic field at Kanoya,Kyushu, (d) Tide at Ishigaki, (e) Tide at Suao, (f) Tidal difference between the two tidal stations. Both tidal data are corrected with the barometric pressure.

In the observation period of about 3 years and half from June 1998 to December 2001, we had an abrupt voltage change in the OKITAI cable in late July 1998, as shown in Fig.6(a). We had no abrupt voltage change in the OLU cable (Fig.6(b)). Figure 6(c) is a correlation diagram between OKITAI and OLU voltages using daily mean voltages in two months around the abrupt voltage change. The split of the correlation indicates that the change occurred in 2 days with about +0.035 V level shift. Considering that the abrupt change is not caused by the variation of ocean currents, the time series before and after the change are connected smoothly adding a necessary bias.

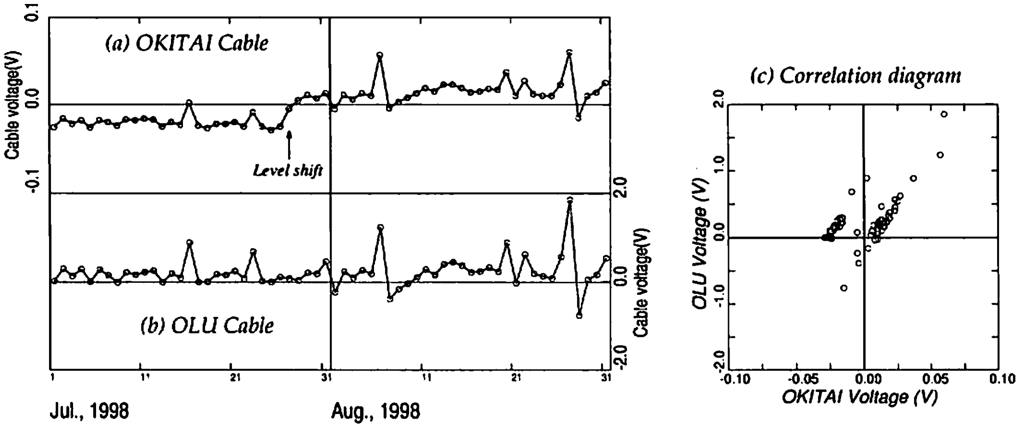

Fig.6 Abrupt voltage change in the cable data. (a) An abrupt voltage change in OKITAI cable data, marked by 'level shift', in July 1998. (b) OLU cable data with no abrupt voltage change. (c) Correlation diagram between OKITAI and OLU voltages using daily mean voltages in two months around the abrupt voltage change.

The OKITAI cable voltage was measured with a load resistance as shown in Fig.3(b) in the beginning period, July 1998 - March 2000. For a successive time series, the cable voltage measured with the load resistance is converted. The daily mean OKITAI voltages have rather good correlation with those of OLU as seen in Fig.6(c). Assuming the correlations are similar before and after the change of the measuring system with and without the load resistance, the conversion coefficient is estimated. The converted full cable voltage is expressed by the following formula; V(converted)= 9.689 $*$ V(measured with the load resistance), (See the Appendix B).

To remove the significant diurnal and semidiurnal fluctuations due to the time varying geomagnetic field, Larsen(1989)'s robust method is used. This method tries to estimate the geomagnetic induced cable voltage referring the observed geomagnetic time series near the cable. The magnetotelluric transfer function is calculated with the robust least-squares technique by comparing the observed cable voltage with the observed geomagnetic field data. As a proper continuous hourly time series of the geomagnetic field data just near the OKITAI and OLU cables is not available, we used the time series of geomagnetic field (X,Y) components at Kanoya (31° 25′ N, 130° 53′ E), Kagoshima, about 650 km northeast from Okinawa, about 1150 km from Taiwan, for our calculation. Figure 7(c), thin solid line, is an example of the hourly time series of the OKITAI cable voltage for three months from July to September 2000, after removing the fluctuations due to the geomagnetic field change using the robust method. Comparing with the original hourly plot (Fig. 7(b) thin solid line), the diurnal and semidiurnal fluctuations due to the geomagnetic field change are largely removed. There are four geomagnetic storms clearly seen in Fig.7(a), geomagnetic field X (east-west) component, as strong downward spikes. In the storm periods, however, some effects of the geomagnetic change seem to be still left even in the processed time series Fig.7(c). The daily means (25-hours running mean) are also shown by thick solid lines in Figs.7(b),(c). The OLU cable voltages are similarly processed referring the geomagnetic field data at Kanoya. The 10-days mean time series of the above processed cable voltages are shown in Fig.8 to show the long-term variation in three years and half. For the OKITAI cable, the converted voltage until March 17, 2000 is shown with a thin solid line. The OKITAI cable data in the period, October 20-December 11, 1999 is not available because of the measuring system trouble. The interpolated voltages referring the OLU cable voltage is shown with a dashed line.

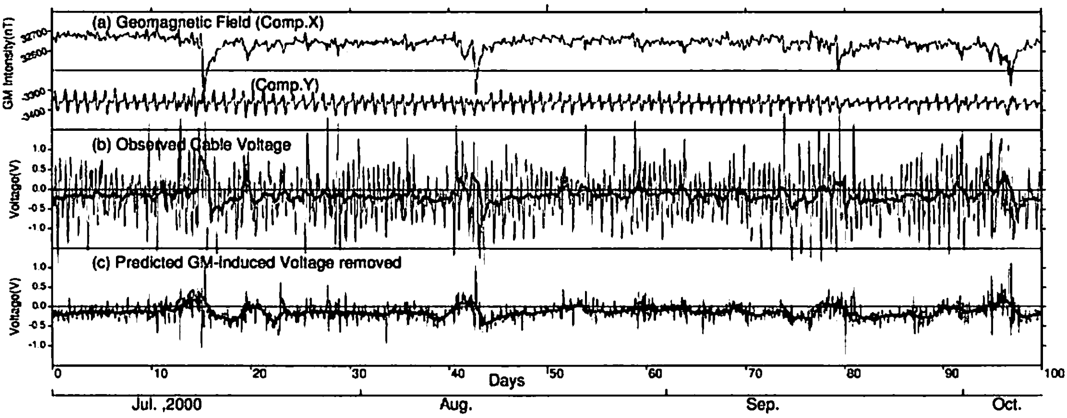

Fig.7 Geomagnetic field and the corrected cable voltage of about three months, Jul.-Sep. 2000. (a) Hourly plot of the geomagnetic field at Kanoya. Component X (east-west), component Y (north-south). (b) Observed OKITAI cable voltage. Hourly plot (thin solid line) and daily mean plot (thick solid line) (c) Corrected OKITAI cable voltage by removing the predicted time-variable geomagnetic induced voltage with Larsen's robust method. Hourly plot (thin solid line) and daily mean plot (thick solid line).

Estimation of the Kuroshio Transport

The main ocean current crossing the OKITAI and OLU submarine cables is the Kuroshio as shown in Fig.1. We can expect most of the long-term variation in the cable voltage is caused by the variation of the Kuroshio. The cable voltage induced by an ocean current flowing over it is basically proportional to the ocean transport with some offset as described in Larsen(1992). The proportionality constant (conversion factor) and the offset are the functions of the vertical geomagnetic field and the electric conductivity of the ocean floor around the cable etc. These constant and offset must be determined comparing the observed cable voltage with the directly observed ocean transport. Though there are few continuous direct observations of the Kuroshio transport in the beginning region of the Kuroshio, the recent result by Yang *et al.*(2001) will be useful. It shows that the directly observed Kuroshio transport using the WOCE PCM-1 moored current meter (observation period 1994-1996) is well related to the sea level difference between Ishigaki and Suao tidal stations (see also Fig.1) at the entrance into the East China Sea. They used 10-days mean values of the observed transport and the sea level difference to have a better correlation between them. They proposed an equation to estimate the Kuroshio transport using the sea level difference (Isigaki-Suao).

Here, we try to examine the possibility of the Kuroshio transport monitoring near the entrance into the East China Sea using the OKITAI cable. The 10-days mean voltages of the OKITAI and OLU cables in Fig.8 still have some linear drifts with time as indicated by thin strait lines in the figure, which may be due to the change of the cable conditions rather than the variation of the Kuroshio. After removing the linear drifts, the cable voltage anomalies are compared with the sea level difference (Ishigaki-Suao) anomaly in Fig.9. The long-term variation of the OKITAI voltage (Fig.9(b)) is basically similar to that

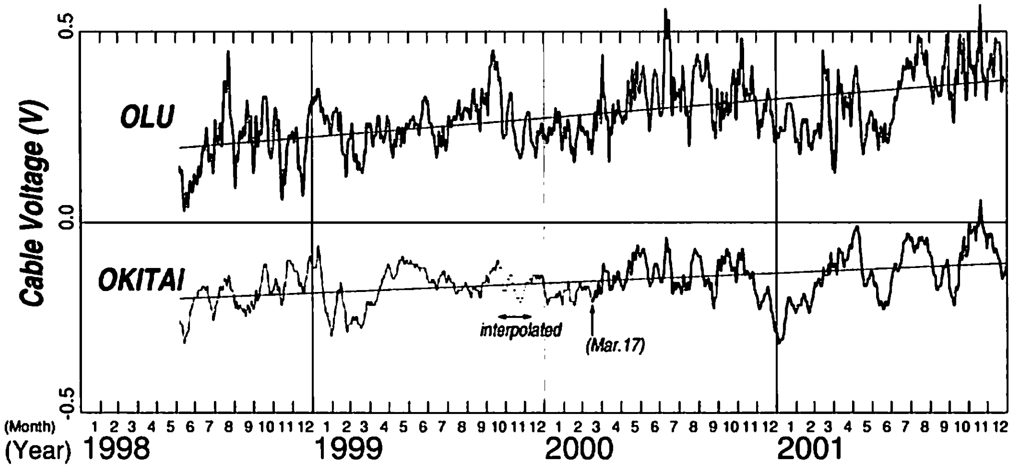

Fig.8 10-days means of the cable voltage in the observation period, Jun.1998-Dec.2001. The predicted time-variable geomagnetic induced voltage is removed. (a) OLU cable voltage, (b) OKITAI cable voltage. In the observation period with the load resistance until Mar.17, 2000, the converted voltage is shown with a thin solid line. In the period, Oct.20 - Dec.11, 1999, there was data lack. The interpolated cable voltage is shown by a dashed line. Thin straight lines are the fitted linear trends.

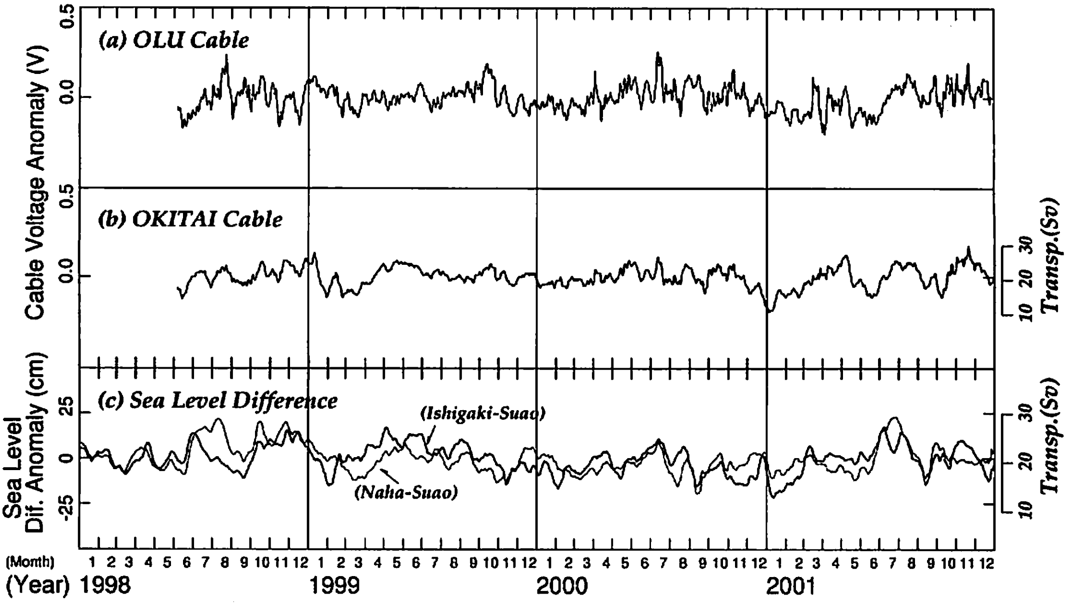

Fig.9 Anomalies of the 10-days mean cable voltage in the observation period, Jun.1998-Dec.2001. Fitted linear trends removed. (a) OLU cable voltage, (b) OKITAI cable voltage. Related anomalies of the 10-days mean sea level differences are also shown in (c), thick line: difference/ Isigaki-Suao, thin line: difference/ Naha-Suao. Right vertical axes for (b) and (c) indicate ranges of the Kuroshio transports estimated.

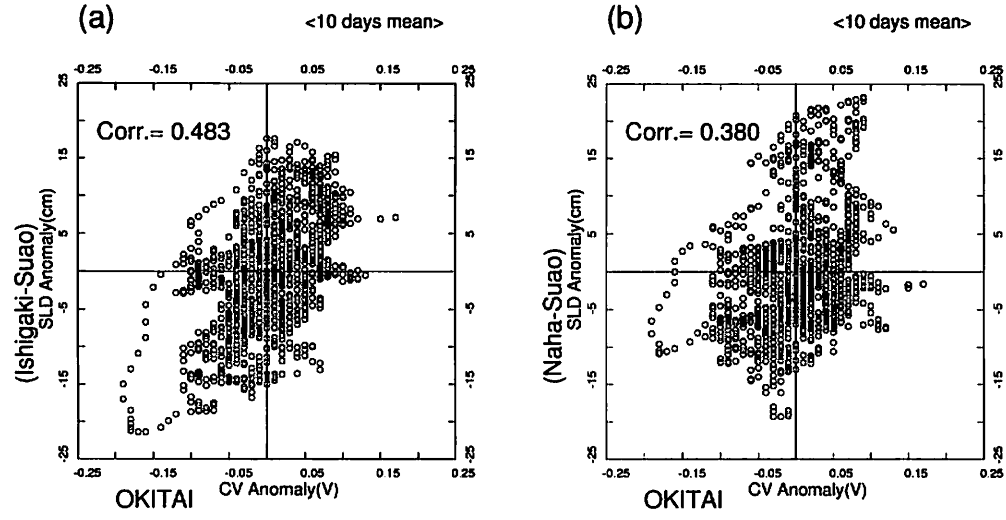

Fig.10 Scatter plots between the OKITAI cable voltage and the sea level differences. (a) Plot between the cable voltage and the sea level difference (Ishigaki-Suao), with the correlation coefficient 0.483. (b) Plot between the cable voltage and the sea level difference (Naha-Suao), with the correlation coefficient 0.380. The plots are shown using 10-days mean data.

of the sea level difference (Fig.9(c)). The scatter plot between them is shown in Fig.10(a) with the correlation coefficient 0.483. The scatter plot between the cable voltage and the sea level difference (Naha-Suao) rather along the cable is also shown in Fig.10(b) with less correlation coefficient 0.380. The formula to estimate the Kuroshio transport based on the 10-days mean OKITAI cable voltage anomaly is derived, assuming the standard deviation of the OKITAI cable estimated transport is equal to that of the sea level difference estimated transport.

[Cable estimated transp.(Sv)]= $A_0 + A_1 *$[Cable voltage(Volt)],
where the offset $A_0 = 20.87$ (Sv) and the conversion factor $A_1 = 53.69$(Sv/Volt).

The unit 'Sv' means transport of $10^6\ m^3s^{-1}$. The estimation is indicated by the vertical axis on the right side in Fig.9.

Discussion

There have been several problems must be examined in the series of our cable voltage measurement. We had an abrupt voltage change as shown in Fig.6(a) in the OKITAI cable voltage measurement. Such an abrupt change seems to be inevitable in the cable voltage measurement. Larsen and Sanford (1985) also reported several abrupt voltage changes in their cable measurement for monitoring the Florida Current transport. They inferred that the changes were most likely caused by the switching of the cable-seawater contact by corrosion and so on. The change of the contact of the many repeaters within the cable may also give some affect. In addition, we have cable voltage drifts in the processed time series, both for OKITAI and OLU cables, as seen in Fig.8 (linear trend lines). These drifts may also be caused by the change of cable conditions with long years. Since the reason of the drifts is no necessarily clear, we must be careful in discussing the cable-estimated ocean transport especially in the low frequency range more than one year.

We have tried to remove the significant diurnal and semidiurnal fluctuations due to the time varying geomagnetic field using Larsen (1989)'s robust method. The robust method basically works well removing the fluctuations as shown in Fig.7(c). Some fluctuations, however, seem to be left not well removed. There will be three reasons. First, the geomagnetic field data near the cables are not available in this study. Second, the ocean-tide induced cable voltages of the almost similar diurnal and semidiurnal frequencies overlap each other and make the separation difficult. Some part of the ocean-tide induced voltage variation may be also removed by this method. Third, an unexpected geomagnetic storm generates very large spike-like voltage variations that are difficult to remove properly even using the well-designed robust method. The long-term OLU cable voltage (Fig.8 upper panel) shows more irregular variation than the OKITAI cable (lower panel).

It may show the signal removal for the OLU cable does not work as well as for OKITAI cable. The more details of the OKITAI and OLU voltages in the diurnal and semidiurnal periods remain to be solved.

The long-term OKITAI cable voltage (and also the estimated Kuroshio transport) variation is basically similar to that of the sea level difference between Ishigaki and Suao as shown in Fig.9. The voltage variation, however, must be examined more detail in some viewpoints. First, the voltage variation sometimes differs from that of the sea level difference. Considering that the sea level difference is rather a good indicator of the surface geostrophic current, we can expect that the cable voltage reflecting a total ocean transport from surface to bottom over the cable route does not necessarily behave in a similar way to the sea level difference. The variability in several months period seems to be not simple. Using satellite altimetry data, Ichikawa(2001) showed that the meso-scale eddies with the several months period are very active around the entrance into the East China Sea. Zhang *et al.*(2001) also showed the dominant 100-day timescale variation of the Kuroshio transport at the entrance is strongly affected by the westward propagating meso-scale eddies from the interior Pacific Ocean. Such an effect of the eddies was examined by Yang and Liu(2003). These effect of meso-scale eddies on the cable voltage variation must be analyzed further.

Second, the line connecting two tidal stations, Naha-Suao, fits on the OKITAI cable route (Fig.1) better than the line, Ishigaki-Suao (see Fig.1). But, the correlation between the OKITAI cable voltage and the sea level difference (Naha-Suao) is 0.38 that is less than the correlation 0.48 for the sea level difference (Ishigaki-Suao). This may partly due to the fact that the Kuroshio crosses the OKITAI cable nearer to the line, Ishigaki-Suao. As Naha is far from Suao, the meso-scale variability may also make the correlation low.

Third, the OLU cable voltage (Fig.9(a)) seems to have much irregular variation than the OKITAI cable voltage (Fig.9(b)). One reason may be the inadequate data processing to remove the diurnal and semidiurnal fluctuations due to the time varying geomagnetic field, as discussed above. The other reason may come from the fact that there may be other current contribution, like the current between Taiwan and Luzon, for the widely spreading OLU cable than the OKITAI cable. Getting more available current information from the OLU cable along with the OKITAI cable will be our further topic.

We had 4 days' ship-boarded ADCP (Acoustic Doppler Current Profiler) observation crossing the Kuroshio near the entrance into the East China Sea using R/V Hakuho-maru in Sep. 2000 (KH-00-4 cruise). The observations were 1 round along the OKITAI cable and 3 rounds of the shortest Kuroshio cross section at the entrance. The observed currents are integrated from the sea surface to the depth 500m (substantial maximum depth of our ADCP observation) to estimate the transport. The result of our ADCP observations will be reported in another paper including the examination of the availability of the estimated formula for the Kuroshio transport.

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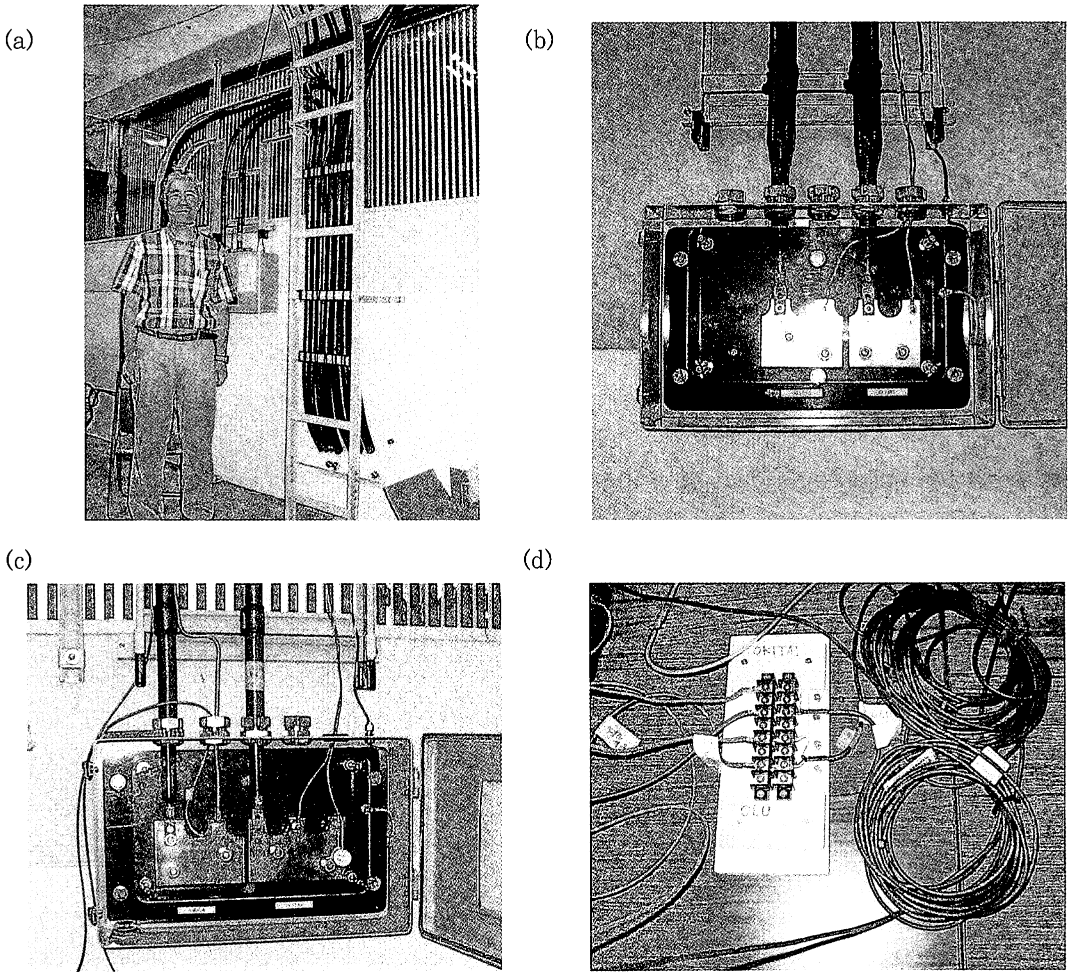
Appendix A

Photographs of the cable ends and the voltage measuring system at Gushikami cable landing station;



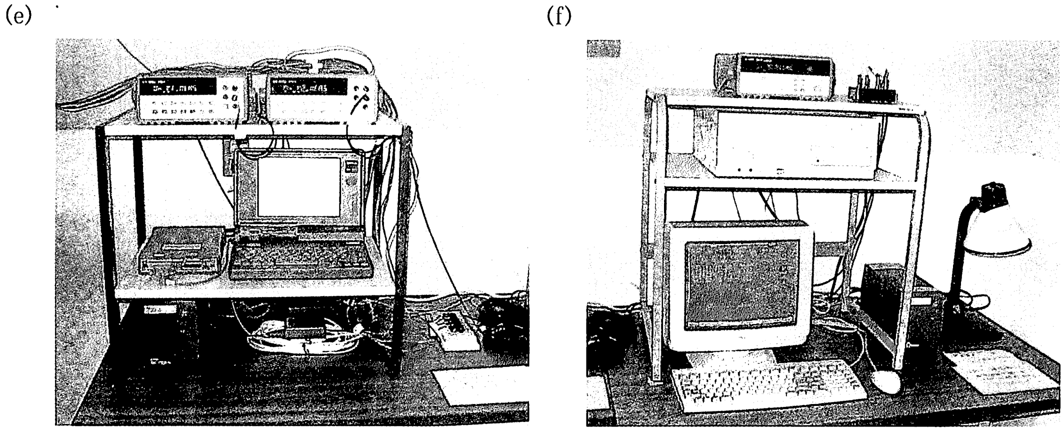


Fig.A Photographs of the cable ends and the voltage measuring system at Gushikami cable landing station. (a) Co-axial submarine cable lines brought in the measuring room. (b) Cable ends (Left:OKITAI, Right:OLU). (c) Sea-earth end used in the voltage measurement (Right terminal). The initial sea-earth facility settled at the shoreline near the cable station, specially designed for OKITAI and OLU cables, is used. (d) Cable signal lines are separated into main and sub lines with electric low-pass filters for each channel (see Fig3(c)). (e) Sub-data acquisition system consists of two digital voltmeters and a Note-PC. (f) Main-data acquisition system consists of a multi-channel digital voltmeter and a Desktop PC.

Appendix B

Converting the measured OKITAI cable voltage with a load resistance to a full cable voltage; Figure B(b) is the correlation diagram after the system change, using about 7 months' daily means (Mar.18 – Oct.23, 2000). The fitted linear line is;

$$[\text{Full OLU voltage(Volt)}] = a_0 * [\text{Full OKITAI voltage(Volt)}] + b_0,$$
$$\text{where } a_0 = 2.316,\ b_0 = 0.652.$$

Figure B(a) is the correlation diagram before the system change using about 3 months' daily means (Dec.13, 1999 - Mar.16, 2000). Assuming the same bias b_0, the fitted linear line is;

$$[\text{Full OLU voltage(Volt)}] = a_1 * [\text{OKITAI voltage with the load resistance(Volt)}] + b_0,$$
$$\text{where } a_1 = 22.44.$$

Then the conversion formula to estimate the full OKITAI cable voltage is;

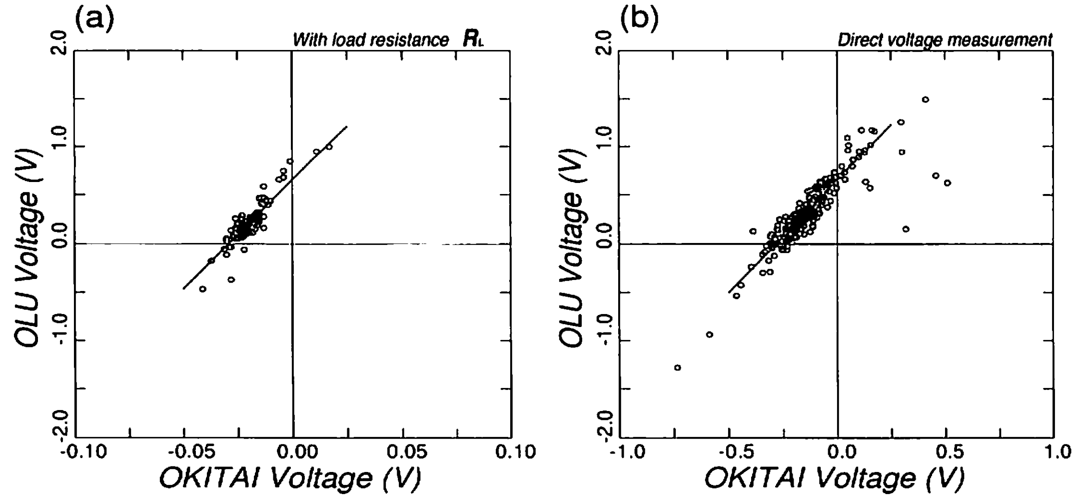


Fig.B Correlation diagrams between the OKITAI and OLU cable voltages. Daily mean voltages before removing the predicted time-variable geomagnetic induced voltage are used. (a) The correlation diagram in the observation period, Dec. 13, 1999-Mar. 16, 2000, while the OKITAI cable voltage measurement with the load resistance. (b) The correlation diagram in the observation period, Mar. 18- Oct. 23, 2000, after the measuring system change without the load resistance (direct voltage measurement).

[Full OKITAI voltage(Volt)]= (a_1/a_0)*[OKITAI voltage with the load resistance(Volt)]
=9.689*[OKITAI voltage with the load resistance(Volt)].

Noting that the OKITAI voltage with the load resistance R_L is a part of the full voltage, given by the ratio $R_L/(R_{oki}+R_L)$, we can estimate R_{oki} by the equation; $R_{oki} = R_L/(R_{oki}+R_L)= (a_1/a_0)$, where R_L = 5.105 k-ohm. Finally, the estimated R_{oki} = 44.40 k-ohm. This cable resistance R_{oki} will be an overall resistance including both the complicated 44 repeaters installed within the cable lines and the sea-earth segments.

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