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Study on the Characteristics of Surface Layer's Currents around the Mouth of Isahaya Bay

Akihide TADA[1], Takehiro NAKAMURA[2], Shin'ichi SAKAI[3],
Michihiro MIZUNUMA[4] and Kenta TAKENOUCHI[5]

[1]*Department of Civil Engineering, Faculty of Engineering, Nagasaki University,
Bunkyo-machi 14-1, Nagasaki 852-8521, Japan*
[2]*Faculty of Environmental Studies, Nagasaki University,
Bunkyo-machi 14-1, Nagasaki 852-8521, Japan*
[3]*Central Research Institute of Electric Power Industry,
1646, Abiko 270-1194, Japan*
[4]*West Japan Engineering Consultants Inc.,
1-1-1, Watanabe-dori, Fukuoka 810-0004, Japan*
[5]*Japan Water Agency,
241, Aho, Iga 518-0294, Japan*

Abstract—This study deals with the field observations on surface layer's currents by means of Digital Beam Forming marine radar (Its abbreviation is DBF ocean radar.), Acoustic Doppler Current Profilers (Its abbreviation is ADCP.) and floating buoys in order to realize the flow characteristic in the center of Ariake Sound. As a result, it is obvious that tidal current along the north coastline of the Shimabara Peninsula is dominant during flood tide and that there is outflow into Ariake Sound from Isahaya Bay near Takezaki Island in the best part of one tidal cycle at spring tide. Furthermore, it is found out that the maximum current velocity of flood tide measured using DBF ocean radar branches off to both Isahaya Bay and the head of Ariake Sound significantly. It is also obvious that the flow velocity vector observed by DBF ocean radar accords with the one obtained by ADCP. That is to say, DBF ocean radar is one of the powerful remote sensing tools to measure surface layer's currents from the land widely and continuously without being affected by weather conditions.

Keywords: field observation, Ariake Sound, Ishahaya Bay, surface layer's currents, ADCP, DBF ocean radar

1. INTRODUCTION

Ariake Sound located in a western part of Japan, Kyusyu Island, has some distinguishing features in the physical environment such as the great tidal range with about 6 meters at its maximum and the huge tidal flats which is famous for laver cultivation. Moreover, a big project in Isahaya Bay that consists of the construction of sea-dike and reclamation by drainage has finished in November, 2007. A regulation pond of Isahaya has been constructed after completion of the sea-dike in 1997. These caused several environmental issues such as a change in currents, eutrophication, oxygen

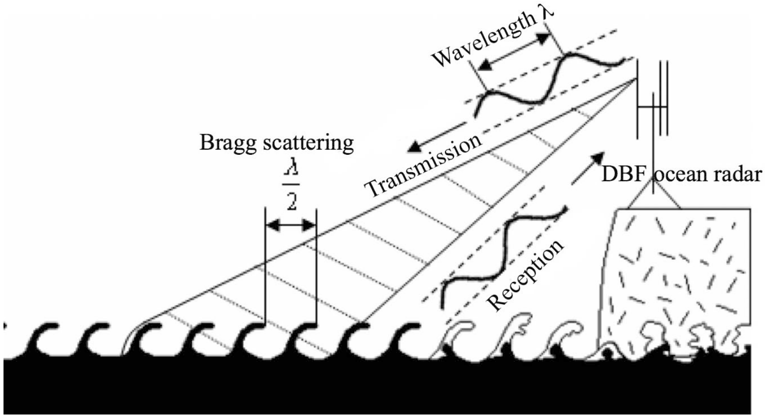


Fig. 1. How ocean radar works as observation instrument.

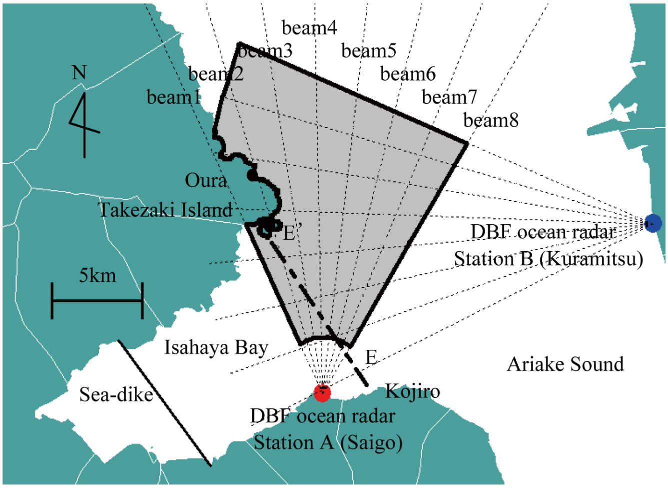
depression and so on. In particular, extensive generations of red tide during winter season from November in 2000 to February in 2001 retarded the growth of a cultured laver. As a result, production of the laver has gone down and environmental issues in Ariake Sound rose to the surface. In order to reveal characteristics of coastal currents after the construction of the sea-dike, the authors have been carrying out the current observations using Acoustic Doppler Current Profilers (Its abbreviation is ADCP.) near the mouth of Isahaya Bay (Nakamura et al., 2002, 2003; Tada et al., 2004, 2005).

Although it is predicted that the behaviour of tidal currents in Isahaya Bay has a great influence on both advection and diffusion of red tide, anoxic bottom water and a flush from the regulation pond of Isahaya, the hydrodynamic mechanism related to these phenomena is not understood yet. Therefore, this study deals with the field observations on coastal currents by means of Digital Beam Forming marine radar (Its abbreviation is DBF ocean radar.), ADCP and floating buoys in order to reveal the flow characteristics in the center of Ariake Sound. Through comparison of flow velocity vector's data measured by both DBF ocean radar and ADCP, the basic performance of the DBF ocean radar is also evaluated.

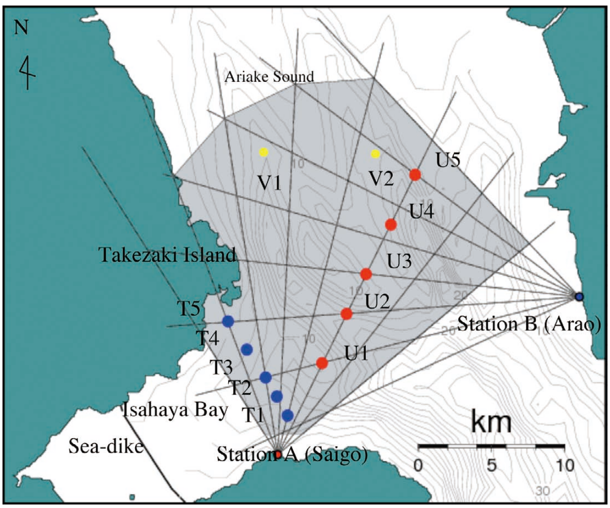
2. ADVANTAGES OF DBF OCEAN RADAR

DBF ocean radar transmits radio waves from the land toward the ocean and receives back the radio energy reflected by ocean waves (Bragg scattering as shown in Fig. 1). By analyzing Bragg scattering, the system provides data on directions, velocities and wave height of surface currents.

Conventional ocean surveys have conducted by hanging a current meter from a ship into the sea or mooring it in the sea in order to directly measure current directions and velocities at multiple observation spots. With this method, measurements were not possible under adverse weather conditions. Another drawback to it was errors resulting from spatial interpolations of point specific data or different measurement



(a) An observational period from the 30th of August in 2005 to the 7th of December in 2006.



(b) An observational period from the 27th of April in 2007 to the 25th of February in 2008.

Fig. 2. Observation area in Ariake Sound.

times at individual measurement points. In contrast, DBF ocean radar allows remote surveys from the land, that is to say, measurements are possible any time regardless of weather conditions. In addition, it can monitor ocean currents over a wide area simultaneously in a short period of time.

Table 1. Comparison of ocean radars.

Item	HF radar	VHF radar	DBF ocean radar
Center frequency	24.515 MHz	41.9 MHz	41.9 MHz
Frequency sweep width	100 kHz	300 kHz	300 kHz
Transmission output	100 W	50 W	100 W
Receiving beam width	15°	20°	13–17°
Observation range	1.5–50 km	0.5–25 km	0.5–25 km
Distance resolution	1.5 km	0.5 km	0.5 km
Velocity resolution	4.78 cm/s	2.89 cm/s	2.13 cm/s
Measureing time	2 hours	1 hour	15 minutes
Installation area	66 m × 6 m	15 m × 15 m	40 m × 7 m

*DBF ocean radar developed by Central Research Institute of Electric Power Industry provides high distance and velocity resolutions and features a short measuring time interval.

3. OUTLINE OF FIELD OBSERVATIONS

Figure 2a shows the observation area, the locations of measurement line (a dash line as shown in Fig. 2a) and DBF ocean radar stations in Isahaya Bay. Field observations carried out during autumn in 2005 consist of two observations, namely 1) the successive observation on surface currents over a wide area by the DBF ocean radar in the center of Ariake Sound and 2) the current observation using ADCP along the E–E′ Line.

4. CURRENT OBSERVATION USING DBF OCEAN RADAR

Long-term successive observation on surface layer's currents in the center of Ariake Sound was enabled by using the DBF ocean radar which Central Research Institute of Electric Power Industry has developed (Sakai et al., 2003). Two DBF ocean radars were set at both Station-A (Saigo, Unzen City) and Station-B (Arao, Arao City) from the 17th of September in 2005 to the 25th of February 2008. Each station installed one transmission antenna, eight reception antennas and an observation data processing container.

The DBF ocean radar receives radio waves from all directions within the observation range simultaneously and forms waves from particular directions in the signal processing process through use of the digital beam forming (DBF) method. This method reduces measuring time to about 15 minutes, a quarter of the time with conventional ocean radars. Furthermore, the predominant frequency of the DBF ocean radar is 41.9 MHz (VHF band), a range-direction resolution 500 m, the maximum reach 25 km, an azimuthal resolution 13–17° and a velocity resolution 2.13 cm/s (see Table 1).

5. CURRENT OBSERVATION USING ADCP

In order to reveal a three-dimensional structure of tidal current in the mouth of Isahaya Bay, field observation using ADCP (RD Instruments Workhorse-ADCP

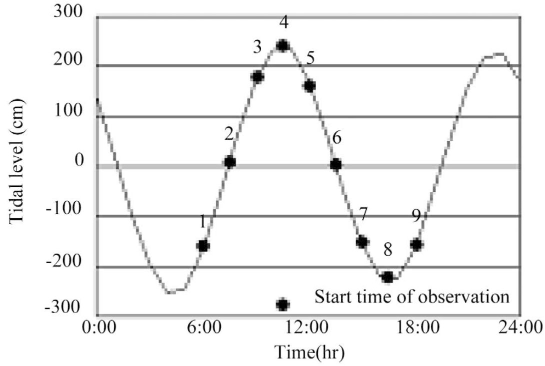


Fig. 3. Change of tidal level at Oura on the 20th of September in 2005.

1,200 kHz) was performed on the 20th of September in 2005, the 12th of August in 2007 and the 26th of October in 2007. The E–E′ Line (about 9 km in length) was adopted as a measurement line. ADCP was mounted over the side of a fishing boat. Current measurements were collected 9 times during one tidal cycle beginning from 2 meter below the water surface to 2 meters above the seabed at intervals of 1 m. The fishing boat's speed was almost constant at about 3.0 m/s. The sampling time was about 120 seconds. Figure 3 shows a change of tide level at Oura (Saga Prefecture) on the 20th of September in 2005 (the Meteorological Agency 2005). That day's tidal range was about 4.8 m because of spring tide.

6. LAGRANGIAN OBSERVATION USING DRIFTING BUOY

The Lagrangian observation on surface layer's currents was executed by a drifting buoy. Namely, we cast three drifting buoys mounted with GPS (GARMIN Company) in the center of Ariake Sound from 8:15 a.m. to 3:00 p.m. on the 25th of October in 2007. The drifting buoy with no drogues consists of both a floating piece and a resistible element. The former composes of a column type of 300 mm in the diameter and 50 mm in height and possesses the dome of a hemisphere type of 100 mm in diameter for keeping GPS. The latter combines four boards made of the vinyl chloride of the 225 mm in width, and 450 mm in height with the cross as shown in Photo 1. The positioning information (latitude and longitude) was recorded in GPS's memory every 30 seconds. Two buoys (Buoy-1, Buoy-2) were set at the point V1 and another (Buoy-3) at the point V2 as shown in Fig. 2b.

7. RESULTS AND DISCUSSION

Horizontal distribution on velocity vectors of tidal currents in surface layer

Figure 4 shows the horizontal distribution on surface layer's currents pattern (0.3 m below the water surface) detected by DBF ocean radar at both flood tide and ebb tide on the 20th of September (spring tide) in 2005. In particular, Fig. 4a is the

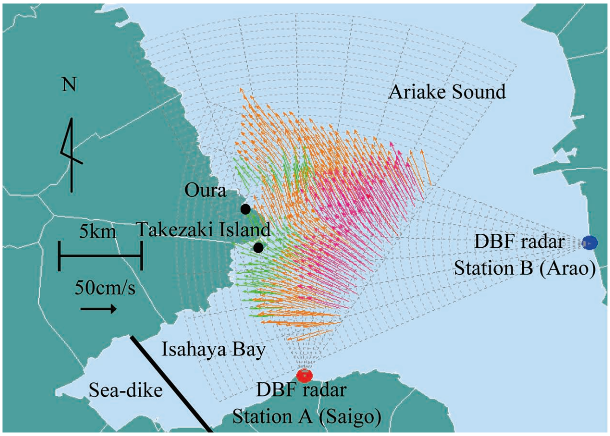
Photo 1. Drifting buoy (Miyata et al., 2006).

spatial variations of tidal currents when the flood current becomes the maximum. According to Fig. 4a, it is found that the flood current at its maximum branches off to both Isahaya Bay and the head of Ariake Sound significantly.

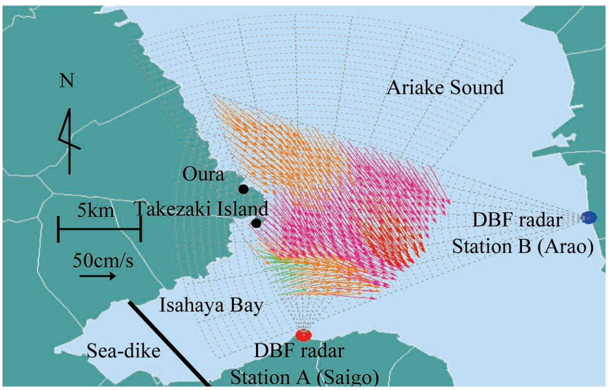
Figure 5 also shows the horizontal distributions on velocity vectors of tidal currents in surface layer (2 m below the water surface) measured by ADCP. Figure 5b indicates the spatial variations of the maximum ebb current. It is obvious that the maximum of a current velocity vector along the E–E′ Line occurs near an offshore where is about 2 km out from Kojiro (Pt. E as shown in Fig. 2a). Tada et al. (2005) have obtained the same results on the maximum velocity of tidal current in the summer season’s field observation at neap tide in 2004. From the facts mentioned above, the characteristic of surface layer’s flows in Isahaya Bay has the predominant tidal currents along the north coastline of the Shimabara Peninsula. Bringing the northern side of the E–E′ Line into focus, there are outflow into Ariake Sound from Isahaya Bay near Takezaki Island and the current pattern can be explained by the combination of the cavity flow and the potential flow, which was proposed by Matsuno and Nakata (2004).

Vertical structure of tidal currents along E-E′ Lines;

Figures 6a and b show the vertical structure of velocity vectors at elevation of 1 m intervals along the E–E′ Line. The former is at the maximum flood current and the latter is at the maximum ebb current. The outflow into Ariake Sound occurred in the northern part of the E-E’ Line (as shown in Fig. 5) is reconfirmed in Fig. 6. The vertical structures of the maximum ebb current are similar to the observation results not only in October 2001 but also in August 2002 (Nakamura et al., 2002, 2003).



(a) At the maximum velocity of flood tide.



(b) At the maximum velocity of ebb tide.

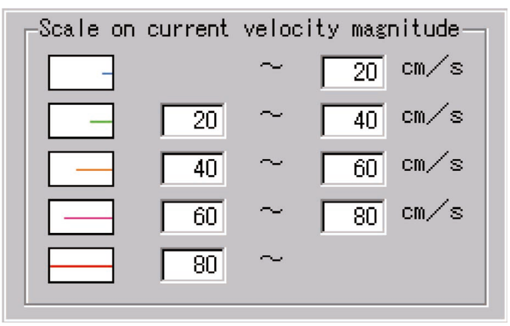
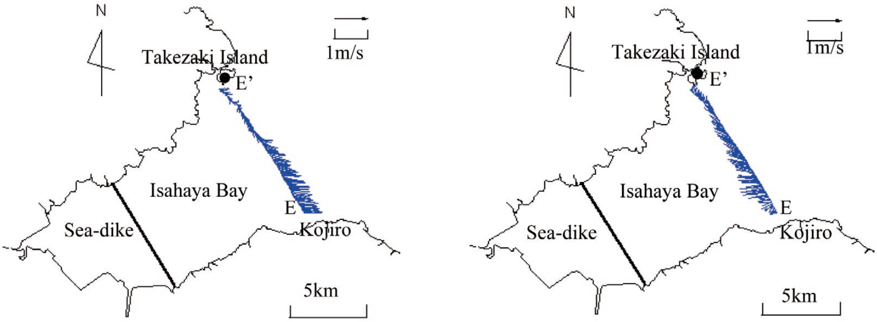


Fig. 4. Velocity vectors of tidal currents measured by DBF ocean radar on the 20th of September in 2005.



(a) At the maximum velocity of ebb tide. (b) At the maximum velocity of flood tide.

Fig. 5. Velocity vectors of tidal currents measured by ADCP on the 20th of September in 2005.

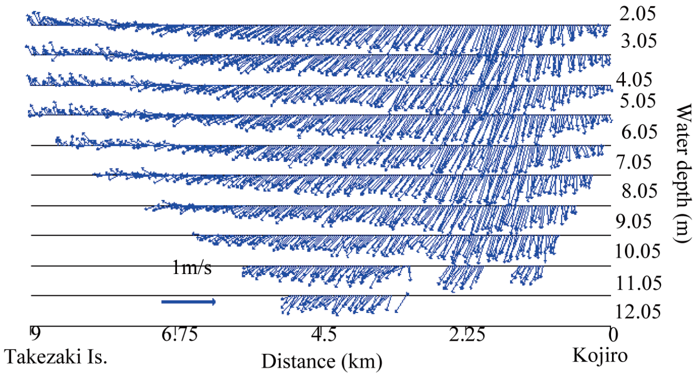
Precision of DBF ocean radar compared with ADCP

Figure 7 show the scattering plot of the surface velocity by the DBF ocean radar and by the ADCP classified into current speed and its direction. In these figure, the circle symbol (○) and the triangle one (▲) indicate the data measured at T1–T5 and U1–U5, respectively. By the way, the velocity of the ADCP is at the depth of about 1.0 m below the sea surface. And the representative depth of the velocity by DBF ocean radar is about 0.3 m below the sea surface if the vertical current profile changes linearly. *R*, *a*, *b* and *STE* mentioned in Fig. 7 are the correlation coefficient, the gradient, the intercept of the regression line and the standard error respectively. Totally the correlation coefficient of current speed is 0.866 with the standard error 9.17 cm/s and those of current direction are 0.963 and 27.3°. Considering the difference of both the measuring water depth and the measuring interval time between both instruments, the DBF ocean radar can grasp the surface layer's current with the same precision as common current meters.

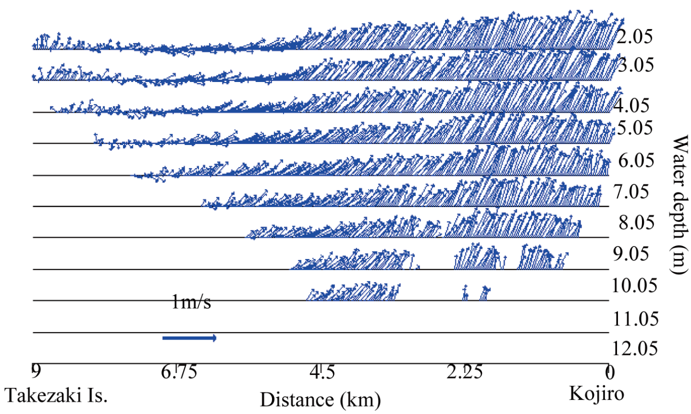
Precision of DBF ocean radar compared with drifting buoy

Figure 8 shows trajectories of drifting buoys and Fig. 9 indicates change of tidal level at Oura in the 25th of October in 2007. The drifting buoys were threw in at just about high tide. Buoy-1 and Buoy-2 went south about 10 km, afterward the tide was flooding, they went north. Similarly, Buoy-3 went south about 12.7 km, and moved north.

Figure 10 is time series of the zonal and meridional surface current components interpreted by the movement of the drifting buoy, one of the three buoys, and by the DBF ocean radar measurement with a time interval of 15 minutes. The values of DBF ocean radar were adopted at the nearest point of the drifting buoy trajectory every time step. The tendency of the current variability derived from the DBF ocean radar agrees



(a) At the maximum velocity of flood tide

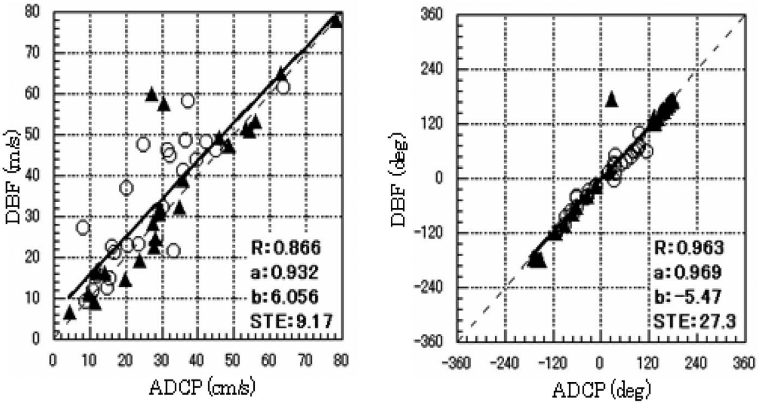


(b) At the maximum velocity of ebb tide.

Fig. 6. Vertical structures of the maximum current along the E–E′ Line measured by ADCP on the 20th of September in 2005.

well with that by the drifting buoy though the range of the drifting buoy movement is a little large.

Figure 11 shows the comparison of a pursuit result of trajectories between the drifting buoy and the imaginary particle moved by the velocity of DBF ocean radar every 15 minutes. Both trajectories show the same moving pattern qualitatively, however the discrepancy of the horizontal distance is about 1000 m at the maximum. This discrepancy occurs due to the accumulation of the velocity error between the interpretation of the drifting buoy and that of the DBF ocean radar.



(a) Current speed (b) Current direction

Fig. 7. Scatter plots between ADCP and DBF ocean radar.

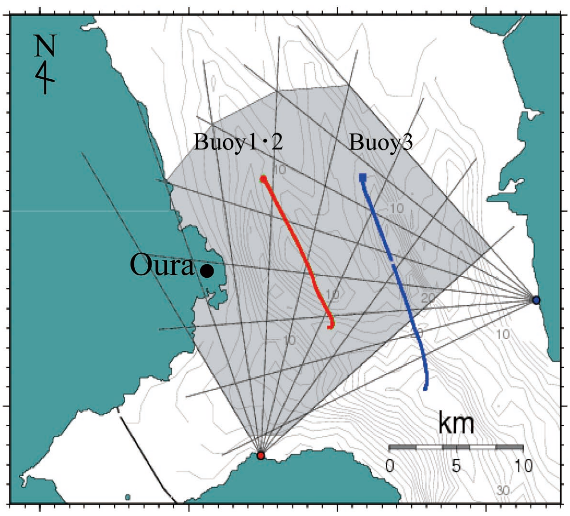


Fig. 8. Trajectories of drifting buoys in the center of Ariake Sound.

Daily average current vectors detected by DBF ocean radar

Figure 12 shows daily average current vector detected by the DBF ocean radar on the 20th of September in 2005. Generally speaking, the number of valid data acquired (hereafter, data acquisition) by DBF ocean radar varies temporally and

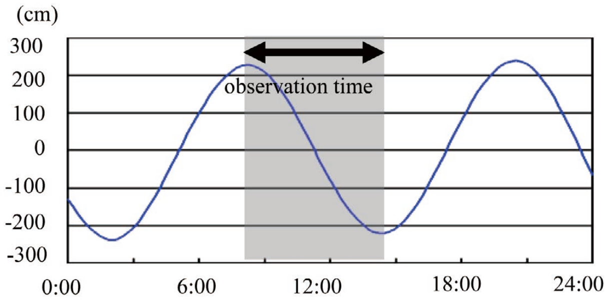


Fig. 9. Change of tidal level at Oura on the 25th of October in 2007.

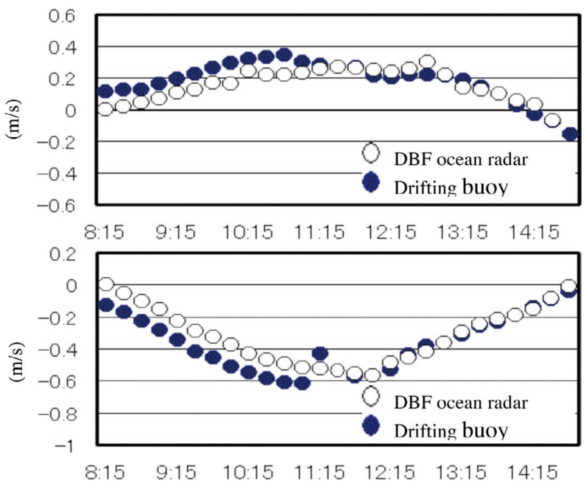


Fig. 10. Time series of surface layer's currents derived by a drifting buoy (Buoy-1) and DBF ocean radar. The upper figure is an E–W component of currents velocity and the lower one is a N–S component.

spatially. Here, the daily average current vector is calculated for the grid points where their data acquisition is more than 80%. According to meteorological observation data at Station-A, wind speed on the observation day is less than 1.0 m/s, and amount of the rainfall for ten days in the past is less than 1.0 mm. Figure 12 is a typical average current pattern for one day when the tidal (spring tide) is the predominant factor in Ariake Sound.

On the other hand, Fig. 13 shows daily average current vector detected by the DBF ocean radar on the 12th of August in 2007. It has not been raining for six days in the past. Moreover, south wind blew all day long and the wind speed was about

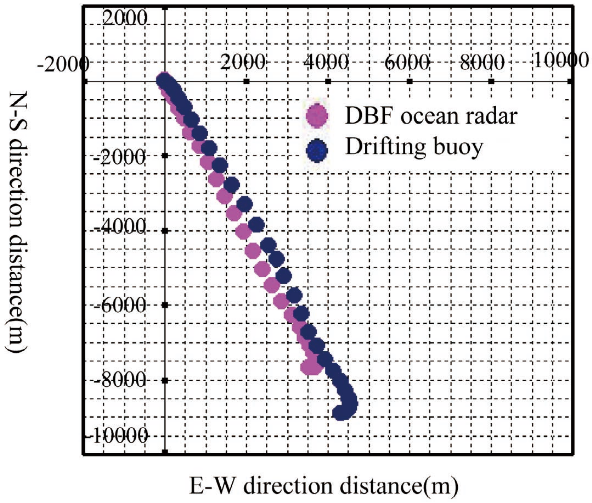


Fig. 11. Trajectories of a drifting buoy and an imaginary particle inferred from DBF ocean radar.

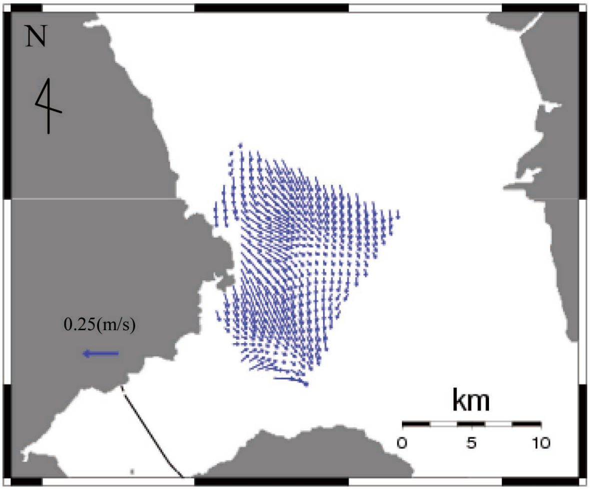


Fig. 12. Daily average current vectors detected by DBF ocean radar on the 20th of September in 2005.

3.4 m/s on the 12th of August in 2007. As a result, most of current vectors turn toward north-northeast around the mouth of Isahaya Bay. This is a typical wind-driven current pattern.

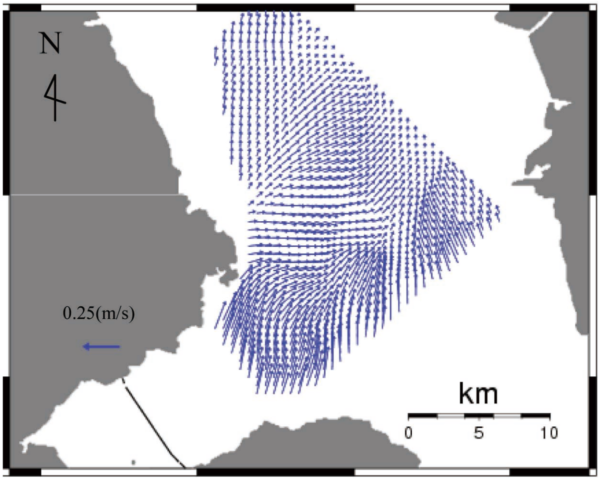


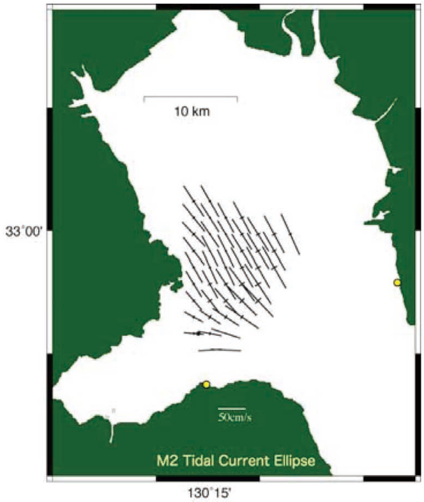
Fig. 13. Daily average current vectors detected by DBF ocean radar on the 12th of August in 2007.

Coastal current characteristics in the middle west area of Ariake Sound

As the result of the harmonic analysis of the data for about 16 days, the spatial map of the tidal ellipse of the principle constituents M_2 and K_1, and of the residual current are shown in Figs. 14 and 15, respectively. The area that the acquisition ratio of the valid data less than 75% is depicted blank. M_2 constituent flows approximately northwestward to southeastward and the amplitude of the current in the long axis about 50 cm/s around the mouth of Isahaya Bay. It also seems that the exchange of seawater between Isahaya Bay and Ariake Siund occurs significantly in the south part of the mouth of Isahaya Bay. The main current direction of K_1 constituent is similar to M_2, however the figure of ellipse shows little difference and the magnitude is about a fifth to M_2. The residual currents flow southward to southeastward with those magnitude ranging from 5 cm/s to 10 cm/s. Among this period the averaged wind at Shimabara AMeDAS site near Unzen was less than 2.5 m/s from south-southeastward. Though both directions of the residual current and the wind are consistent, the tidal residual current due to the asymmetric topography can be inferred as the principal component to the residual current. The river runoff in the head of Ariake Sound also contributes to form the residual current. However, we do not prepare the data concerning with river runoff, we can't discuss in detail the effect of the density flow. In the northern area close to the coasts of Isahaya Bay's mouth, the weakness of the residual current seems to relate to the mechanism of occurrence of red tide.

8. CONCLUSION

In this study, field observations on surface layer's currents were carried out by means of the ADCP, the DBF ocean radar and floating buoys in order to realize the



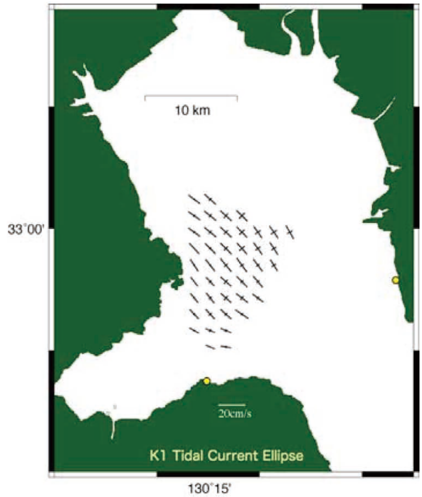


Fig. 14. Tidal current ellipse of M_2 (left hand side) and of K_1 (right hand side) detected by DBF ocean radar from the 20th of September to the 5th of October in 2005.

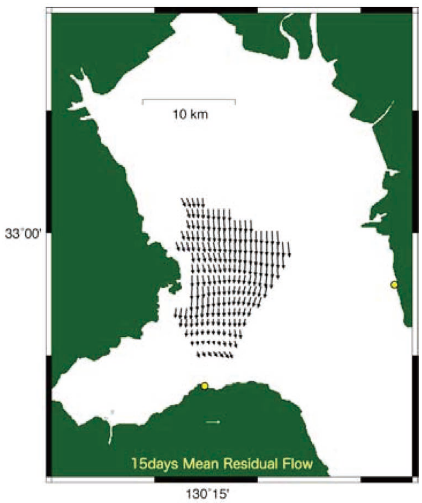


Fig. 15. Residual currents detected by DBF ocean radar from the 20th of September to the 5th of October in 2005.

characteristic of currents in the center of Ariake Sound.

The obtained results are as follows: 1) It is realized that tidal current along the north coastline of the Shimabara Peninsula is dominant at flood tide and that there is outflow into Ariake Sound from Isahaya Bay near Takezaki Island in the best part of one tidal cycle; 2) It is obvious that the DBF ocean radar can grasp the surface current with the same precision as common current meters; 3) The tendency of the current variability derived from the DBF ocean radar agrees well with that by the drifting buoy; 4) According to a daily average current vector, it realized that the meteorological conditions and tidal fluctuation had a great influence on the characteristics of surface layer's currents in the center of Ariake Sound.

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A. Tada (e-mail: atada@nagasaki-u.ac.jp), T. Nakamura, S. Sakai, M. Mizunuma and K. Takenouchi