Detailed Current Structures in the Eastern Channel of the Tsushima Strait in Summer

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We discussed the detailed current structures in the Eastern Channel of the Tsushima Strait, using four sets of acoustic Doppler current profiler (ADCP) data, which were taken by the quadrirreciprocal method (Kato, 1988), for removing tidal currents, in summers of 1987–1989. In the Eastern Channel, diurnally averaged currents balanced almost geostrophically. In the upper layer of the deepest part of the Eastern Channel, there existed a current core which corresponded to one branch of the Tsushima Current. The current direction in this core was between NE and ENE in all observations, but the magnitude of velocity in 1987 differed largely from that in 1988. Another current core with lower velocities was found near the north coast of Kyushu. Near the bottom at the deepest part of the Eastern Channel, the velocity was more or less 0.3 kt (15 cm s⁻¹). Along the east coast of Tsushima and in waters northeast of it, countercurrents were observed. The continuity of these countercurrents was interpreted as follows: A part of the current flowing from the Western Channel of the Tsushima Strait into the Japan Sea turns clockwise in waters northeast of Tsushima, and flows southwestward along the east coast of Tsushima. The southwestward current along Tsushima was correlated with the northeastward current in the central part of the Eastern Channel. The transport through the Eastern Channel was between 0.59 and 1.30 Sv (1 Sv = 10⁶ m³ s⁻¹). The baroclinic component, which was defined as the transport based on calculations of geostrophic current with assuming zero velocity near the bottom, was very small.

1. Introduction

In the Eastern Channel of the Tsushima Strait, many current measurements were made up to now. Summarizing knowledges derived from previous current measurements, it is possible to point out two features of the current in the Eastern Channel as follows. i) A strong current with the direction between NE and E exists in the middle across the channel. ii) A countercurrent with the direction between SW and S exists along the east coast of Tsushima.

It is well known that the strong current, which is regarded as one branch of the Tsushima Current, exists in the middle of the Eastern Channel. The countercurrent along the east coast of Tsushima was reported by Tsujita (1954a, b), and its existence was recognized by current measurements (Shoji et al., 1971; Miita, 1976; Kato, 1988).

Nowadays, it is almost impossible to measure currents with mooring systems in the Eastern Channel mainly because of heavy trawl fishery. In the Eastern Channel, tidal currents are very strong, and thus it is necessary to remove tidal currents from observed currents in order to know averaged current structures. However, there are few cases when the tidally averaged currents are
calculated on the basis of GEK (geomagnetic electrokinetograph) or ADCP (acoustic Doppler current profiler) data. Therefore, observations for clarifying the detailed current structures in the Eastern Channel have hardly been carried out, and the horizontal and vertical structures of the strong current and the countercurrent have not been discussed yet, except for Miita (1976) and Kaneko et al. (1991).

In this paper, we discussed the detailed structures of the strong current and the countercurrent in the Eastern Channel on the basis of the ADCP measurements in summers in 1987–1989.

2. Observation Methods

Transects along which current measurements were made from 1987 to 1989 in the Eastern Channel are shown in Fig. 1. Positions of transect B are different between 1987 and 1988, and thus the position in 1988 is shown in Fig. 1. Current measurements were made with the R/V Yoko-Maru (499 ton, the Seikai National Fisheries Research Institute) and the R/V Kumamoto-Maru (380 ton, the Kumamoto Prefectural High School of Fisheries), and the installed ADCPs were CI-30 (used frequency, 130 kHz; Furuno Electric Company Ltd.) and JLN-612 (used frequency, 125 kHz; Japan Radio Company Ltd.), respectively.

In order to remove the components of tidal currents from observed currents, current measurements were carried out by the “quadrirreciprocal method”, which is a new method for measuring currents with plying four times along a same transect for 24 hours and 50 minutes (Katoh, 1988). Along transects except C, STD (AST-1000, Alec Electronics Company Ltd.) measurements were made at intervals of about 3.3 nautical miles (6.1 km). Procedures for ADCP

![Fig. 1. Transects for ADCP and STD measurements. ADCP and STD measurements were carried out as follows: along transect B on 4–7 June 1987 with the R/V Yoko-Maru, along transects A and B on 17–20 June 1988 with the R/V Kumamoto-Maru, along transect B on 1–2 August 1988 with the R/V Yoko-Maru and along transect C on 17–19 June 1989 with the R/V Kumamoto-Maru. STD measurements were lacked along transect C.](image-url)
and STD measurements were explained in Katoh (1993). It is possible to measure currents at three depths with each of the ADCPs. Thus the shallowest depth of measurement was fixed at 20 m (at 10 m in 1987), and the intermediate and deepest ones were adjusted according to the depth of the sea bottom.

Collection and analysis of current data were made according to Katoh (1988), and the outline is as follows. Velocity and direction were printed out at intervals of 5 minutes, in units of 0.1 kt (5 cm s\(^{-1}\)) and 0.1 degree, respectively. Each transect was divided into nine or eighteen "basic bins" with a length of about 3.3 nautical miles (6.1 km). Measured values were averaged at each basic bin, where eight preaveraged values were obtained for the four plying observation. The averaged value of these eight ones is the "diurnally averaged current", in other words, the current averaged in the diurnal tidal period of 24 hours and 50 minutes.

Measurement errors of shipboard ADCP come from various sources: i.e., 1) Sonic noise from ship, 2) Ship's pitching, 3) Ship's rolling, 4) Error of ship's position and 5) Error of compass direction (Nishida, 1991). In the Eastern Channel the velocity relative to the sea bottom can be measured, and thus the error 4) is unconsidered in this study. The error 3) is negligible since ship's speed in the direction of gunwales is very small (Nishida, 1991). Even though measured values with ADCP contain the errors 1), 2) and 5), it is possible to remove these errors considerably using the quadrireciprocal method.

In the next place, current data of the R/V Yoko-Maru were compared with those of the R/V Kumamoto-Maru on the basis of a trawl observation which was carried out with both vessels together in June 1989. As a result, differences of velocity between both vessels were not more than ±0.05 kt (2.5 cm s\(^{-1}\)) at 50% and not more than ±0.1 kt (5 cm s\(^{-1}\)) at 68% of all cases. As to direction, differences between both vessels were not more than ±10° at 43% and not more than ±20° at 64% of all cases (Katoh, 1990b). During the trawl observation, the distance between both vessels was relatively large (0.5–0.7 nautical miles, 0.9–1.3 km), and the depths at which current data were compared were different of 5 m between those. Therefore, actual differences of velocity and direction seem to be much smaller, and the measurement differences between both ADCPs were estimated to be not so large.

3. Results and Discussions

3.1 Diurnally averaged current on vertical sections

Diurnally averaged current vectors at three depths on each transect are shown in Fig. 2. As to transects A and B, distributions of temperature are shown together. In this paper, a part where northeastward current is relatively strong compared with surrounding parts on a transect is called the "current core".

On transect A in June 1988, a current core was situated near station A7, where the sea bottom was the deepest on the transect. The maximum velocity ranged from 0.4 kt (21 cm s\(^{-1}\), at 70 m depth) to 0.6 kt (31 cm s\(^{-1}\), at 20 m depth), and the direction was between NE and ENE.

On transect B, two current cores were observed at every measurement time in June 1987, June 1988 and August 1988. The offshore one was situated almost in the middle of the transect, where the sea bottom was deepest on the transect. The onshore one was situated near the north coast of Kyushu. The maximum velocity in the offshore current core was very different between 1987 and 1988. It ranged from 0.7 kt (36 cm s\(^{-1}\), at 60 m depth) to 1.0 kt (51 cm s\(^{-1}\), at 10 m depth) in 1987, while it was between 0.5 kt (26 cm s\(^{-1}\)) and 0.6 kt (31 cm s\(^{-1}\)) even at 20 m depth in 1988. The direction was between NE and ENE in all cases. On transects A and B, countercurrents were
observed near the coast of Tsushima.

On transect C, a current core was observed between stations C15 and C19. At the north end of the transect, the velocity was 0.9 kt (46 cm s\(^{-1}\)) at 20 m depth, while it was not more than 0.2 kt (10 cm s\(^{-1}\)) at 80 m depth. Another northeastward current weaker than that was observed between stations C1 and C4. This northeastward current seems to have connected with the offshore current core on transect B. Judging from the fact that the end of the offshore current core on transect B extended in waters shallower than 100 m, the center of this northeastward current on transect C seems to have been situated in the coastal side from station C1. Between these two northeastward currents, that is, between stations C4 and C15, a countercurrent existed. Its center was situated between stations C11 and C14. The velocity was from 0.4 to 0.5 kt (21 to 26 cm s\(^{-1}\)) at 20 m depth, while it was about 0.1 kt (5 cm s\(^{-1}\)) at 80 m depth.

Consequently, it was clarified that a current core existed in each of middle parts of transects A and B. The direction in the current core was always between NE and ENE, while the velocity was very different between 1987 and 1988. The width of the current core was estimated at about
15 nautical miles (28 km) on transect A and at about 20 nautical miles (37 km) on transect B (Fig. 2). Another current core weaker than it was observed near the north coast of Kyushu on transect B. On the other hand, countercurrents existed near the east coast of Tsushima on transects A and B, and in the middle of transect C.

3.2 Extent of geostrophic balance of diurnally averaged currents

In order to examine the extent of geostrophic balance of diurnally averaged currents, the velocity components of diurnally averaged currents and those derived from calculations of geostrophic current, which are both perpendicular to the sections of ADCP measurements, are shown in Fig. 3. At the time of calculating geostrophic current, the velocity measured with ADCP at the intermediate depth was regarded as the basic value.

On transects A and B in June 1988 and on transect B in August 1988, the distribution patterns of geostrophic currents were significantly similar to those of diurnally averaged currents as to the current core and the countercurrent. On transect B in June 1987, not only distribution pattern but also velocity of geostrophic currents were remarkably similar to those of diurnally averaged currents. Therefore, we can conclude that the diurnally averaged currents balanced almost geostrophically in the Eastern Channel.

Fig. 3. Vertical sections of velocity components (in kt) perpendicular to transects A and B. The velocity components in the left and right panels were derived from ADCP measurements and calculations of geostrophic current, respectively. Shadow areas indicate southwestward countercurrents.
3.3 Vertical sections of diurnally averaged velocities perpendicular to the transects

Vertical sections of diurnally averaged velocities perpendicular to transects A and B, derived from ADCP measurements and calculations of geostrophic current together, are shown in Fig. 4. The method of estimating surface and bottom velocities (Katoh, 1993), is as follows. After subtracting geostrophic velocity from ADCP velocity at the shallowest depth of ADCP measurement, the remainder was added to geostrophic velocity at the surface. The sum was regarded as the surface velocity. The calculated remainder at the deepest depth of ADCP measurement by the same method was regarded as the bottom velocity.

As shown in Fig. 4, the center of the current core in the middle of the Eastern Channel was situated closely at 20 m depth on transect B in June 1987 and August 1988, while it was situated near the surface on transects A and B in June 1988. At every measurement, the area where the velocity was larger than 0.3 kt (15 cm s\(^{-1}\)) extended deeper than 100 m depth, and the current with velocities of about 0.3 kt (15 cm s\(^{-1}\)) existed even near the bottom at the deepest part. Miita (1976) reported that the current with velocities of 0.2 to 0.4 kt (10 to 21 cm s\(^{-1}\)) existed near the bottom.

Fig. 4. Vertical sections of velocity components (in kt) perpendicular to transects A and B. The velocity components were derived from ADCP measurements and calculations of geostrophic current together. Shadow areas indicate southwestward countercurrents.
at the deepest part of the Eastern Channel, and that the velocity at the deepest part between Tsushima and Iki was more than 0.6 kt (31 cm s⁻¹). Thus it is natural to think that the velocity is more or less 0.3 kt (15 cm s⁻¹) near the bottom at the deepest part of the Eastern Channel.

On transect A, a countercurrent was observed in a limited part near Tsushima. On transect B, however, the countercurrent extended near the bottom in June 1987 and June 1988, and it extended at 80 m depth even in August 1988. The countercurrent shown in Miita (1976) extended near the bottom, too. Therefore, we can conclude that the countercurrent near the east coast of Tsushima reaches to a deep level.

On transect B, another countercurrent was observed at the surface near station B4 in June 1987 and August 1988, but it was not observed in June 1988. On the other hand, the current core near the north coast of Kyushu, pointed out in Subsection 3.1, was clearly recognized as the area with velocities of more than 0.3 kt (15 cm s⁻¹). In the previous measurements, a countercurrent was mainly observed near the north coast of Kyushu (Seventh Regional Maritime Safety Headquarters, 1962; Oceanographical Section, Nagasaki Marine Observatory, 1965; Miita, 1976). Above all in Miita (1976), a countercurrent existed widely near the north coast of Kyushu, and a northeastward or an east-northeastward current was not observed widely. Accordingly, we can conclude that the current pattern near the north coast of Kyushu is very changeable, and that only a northeastward or an east-northeastward current appears in a case, but in another case, a countercurrent is distributed widely.

3.4 Horizontal distributions of diurnally averaged current vectors

In order to examine the continuity of currents in the Tsushima Strait, horizontal distributions of diurnally averaged current vectors at 20 m depth (10 m depth in 1987) are shown in Fig. 5.

According to Tsujita (1954a, b), a current was separated from the main stream of the Tsushima Current in the Eastern Channel and flows toward Tsushima across the channel to form a topographically generated cyclonic eddy near “Kamishima”, the northern part of Tsushima (see Fig. 1). Consequently, a countercurrent seems to occur near the east coast of Kamishima, coming off the coast near the south end of Kamishima. As shown in Fig. 5, however, the current distributions suggesting the separation of the main stream of the Tsushima Current were not recognized in June 1987 and June 1988 at all, except in August 1988. Moreover, the fact that the countercurrent was observed on transect A near “Shimoshiba”, the southern part of Tsushima, shows the countercurrent extends southward even near the south end of Shimoshima, without coming off at the south end of Kamishima. Therefore, it is not reasonable to regard the countercurrent near the east coast of Tsushima as the current which was separated from the main stream of the Tsushima Current as shown in Tsujita (1954a, b).

In this study, a countercurrent was observed in the middle of transect C. There are many reports about the current distribution on a transect between Kawajiri and Ulsan (see Fig. 1), which is closely located at the same place as transect C, based on calculations of geostrophic current (Suda, 1938; Miyazaki, 1952; Yi, 1966; Tawara et al., 1984) and current measurements (Miita, 1976). All reports showed a very weak northeastward current or a countercurrent in the middle between Kawajiri and Ulsan in summer. Thus a countercurrent must exist near the middle of transect C (near station C10 shown in Fig. 1) almost steadily in summer. Moreover, Fig. 5 suggests that a part of the current flowing into the Japan Sea from the Western Channel separates clockwise near transect C, returning to the Eastern Channel.

By the way, it is well known that the low salinity water flows into the Japan Sea from the East China Sea almost in June and July (Ogawa et al., 1977; Takahashi, 1987). However, the
inflow of the low salinity water does not start at the same time in both channels, and in many cases, the time of inflow in the Western Channel is earlier than that in the Eastern Channel (Katoh, 1990a). Therefore, salinities in June and July are often different between both channels, and so it is possible to distinguish easily the water originated from the Western Channel from that of the Eastern Channel.

Now, it was examined whether the current from the Western Channel actually flows into the Eastern Channel as mentioned above, on the basis of salinity distributions at 10 m depth in June and July from 1987 to 1989. As a result, there was no difference in salinity between both channels in June and July 1988. In July 1987 and June 1989, however, salinity in the Western Channel was significantly different from that of the Eastern Channel (Fig. 6). In July 1987, water of salinity lower than 34 was distributed in the Western Channel, and a part of it was extended along the east coast of Tsushima. On the other hand, salinity was higher than 34 in the part where the current core existed on transect B (Fig. 5). In June 1989, salinity in the center of the Eastern Channel was higher than 34.3, while salinity was lower than 34.3 from the part where the countercurrent was observed on transect C (Fig. 5) to the east coast of Tsushima. Especially in the Western Channel, water of salinity lower than 34 was distributed. Consequently, the countercurrent seems to be connected with the current through the Western Channel, as shown in the schematic map of surface currents drawn by Kawai (1991) on the basis of the data of diurnally averaged currents calculated by Katoh (1990b).

Tsujita (1954a, b) suggested that a topographically generated eddy was formed in waters northeast of Tsushima as well as along the east coast of it. Isoda (1989) showed that a warm water mass was formed near the exit of the Western Channel. These facts suggest that the current
flowing through the Western Channel returns to the Eastern Channel to make a large anticyclonic gyre.

3.5 Correlation between countercurrent along the east coast of Tsushima and current core in the middle of the Eastern Channel

Kawai (1992) discussed the fluctuation patterns of difference in water level across the Eastern and Western Channels, and he pointed out that the northeastward current in the middle of the Eastern Channel was probably strengthened without any increase of the difference in water level across the Eastern Channel, also, when the countercurrent along the east coast of Tsushima was strengthened. Now, it will be examined whether or not the velocity distributions are different between two cases when the differences in water level across the Eastern Channel are almost alike.

At first, the distribution of water level was calculated as follows.

The positive $y$ axis is taken along transect $B$ in the direction from station B1 to B19, and the positive $x$ axis is taken in the direction making the right angle clockwise from the positive $y$ axis. The positive $z$ axis and water level $\eta$ are taken vertically upward. The difference in water level between two stations of $B_{i-1}$ and $B_i (i = 1, 2, ..., 18)$ is $\Delta \eta_i$, and $x$ component of surface velocity
is $u_i$. If the geostrophic balance is presumed, we can write

$$fu_i = -g \frac{\Delta \eta_i}{\Delta y_i} \quad (i = 1, 2, \ldots, 18),$$

where $\Delta y_i$ denotes the length between two stations of $B_{i-1}$ and $B_i$, $f$ is the Coriolis parameter ($8.2 \times 10^{-5}$ s$^{-1}$), $g$ is the acceleration of gravity ($9.8 \times 10^2$ cm s$^{-1}$), and $\Delta y_i$ is constant (6.12 km). As the velocity from the surface to 20 m depth is nearly uniform as shown in Fig. 4, the velocity at 20 m depth (10 m depth in 1987) is used as $u_i$. According to Eq. (1), $\Delta \eta_i$ is calculated at every bin.

The distribution of water level between stations B1 and B19 at each measurement time is shown in Fig. 7. In this figure, water level at station B19 is conveniently set at 0 cm. Figure 7 shows the differences in water level between stations B1 and B19 changed every measurement time; about 12.0 cm in June 1987, while about 7.0 cm in June 1988 and about 9.7 cm in August 1988. The actual differences in water level between Hakata and Izuura, which were calculated from data taken by the Seventh Regional Maritime Safety Headquarters, were 3.6 cm in June 1987 and 2.0 cm in August 1988. In this case, the water levels were corrected with atmospheric pressures at the sea surface, while the difference between Hakata and Izuura in datum line height was not considered. During the period when the observations were carried out in June 1988, water level was not measured at Izuura. Subtracting the actual difference of water level in August 1988 from that in June 1987 gives 1.6 cm, which is almost equal to the water level difference of 2.3 cm calculated with Eq. (1). This fact supports the result in Subsection 3.2 that diurnally averaged currents in the Eastern Channel balances almost geostrophically.

![Fig. 7. Geostrophically estimated profiles of water level between stations B1 and B19 shown in Fig. 1. The water level at B19 was conveniently set at 0 cm.](image-url)
It is difficult to discuss the hypothesis proposed by Kawai (1992) on the basis of water levels between stations B1 and B19, since the water levels at station B1 were different among the three measurement times. However, it is possible to discuss the velocity distributions between stations B13 and B19 in June 1987 and August 1988, because the water levels at station B13 are similar in both cases (Fig. 7). Though the difference in water level was between 0.5 cm and 1.0 cm in both cases, the velocity distributions were fairly different (Fig. 4); the maximum northeastward velocity was more than 0.8 kt (41 cm s\(^{-1}\)) in June 1987, while it was at most 0.4 kt (21 cm s\(^{-1}\)) in August 1988. The southwestward current with velocities of more than 0.2 kt (10 cm s\(^{-1}\)) was distributed widely in the former case, while it was distributed in a limited part (B17–B18) near the surface in the latter case. Consequently, both northeastward and southwestward currents were stronger in June 1987 than those in August 1988. This fact is an actual example to support the hypothesis proposed by Kawai (1992).

3.6 Transports through the Eastern Channel

A transport, \( T \), through a unit section where a diurnally averaged current was calculated is given by the following formula,

\[
T = \frac{d}{2} \left[ \frac{1}{(V_s + V_1)H_{s-1}} + \frac{1}{(V_1 + V_2)H_{1-2}} + \frac{1}{(V_2 + V_3)H_{2-3}} + \frac{1}{(V_3 + V_b)H_{3-b}} \right],
\]

where \( V_1, V_2 \) and \( V_3 \) are velocities at the shallowest, intermediate and deepest depths of ADCP measurements, respectively. \( V_s \) and \( V_b \) are velocities at the surface and bottom, respectively, which were estimated from ADCP measurements and calculations of geostrophic current together (Subsection 3.3). \( H_s, H_{1-2}, H_{2-3} \) and \( H_{3-b} \) are lengths between the surface and shallowest depth, between the shallowest and intermediate depths, between the intermediate and deepest depths and between the deepest depth and bottom, respectively. The quantity \( d \) is the width of the unit section. After transport \( T \) is calculated at each unit section, it is summed up along the transect.

Calculated transports are shown in Table 1, where transports based on calculations of geostrophic current with assuming zero velocity near the bottom are shown, too. The transports through transect B at the three measurement times were different from each other; it was 1.30 Sv (1 Sv = 10\(^6\) m\(^3\)s\(^{-1}\)) in June 1987, while at most 0.59 Sv in June 1988, which was 45% of that in the last year. There are some reports about the transports through the Eastern Channel which were

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calculated on the basis of direct current measurements (Miita, 1976; Kaneko et al., 1991). Miita (1976) estimated the transport in summer as 1.63 Sv using data derived from anchored measurements. Kaneko et al. (1991) estimated it at 0.7 Sv from ADCP data. These results show that the transport through the Eastern Channel in summer fluctuates considerably, ranging from about 0.5 Sv to more than 1.5 Sv.

In June 1988, the remainder after subtracting the transport through transect A from that through transect B is 0.04 Sv, which is regarded as the transport through the Iki Channel (between Iki and Kyushu). It is about 7% of all the transport through the Eastern Channel, and the ratio is nearly equal to the value of 5% evaluated by Miita (1976). Therefore, it is clarified that the transport through the Iki Channel is very small.

The calculations of geostrophic current with assuming zero velocity near the bottom give the baroclinic component of the total transport. Table 1 shows that the transport based on calculations of geostrophic current is very small (from -0.02 to 0.06 Sv), because isotherms from Kyushu to Tsushima repeated ascending and descending (Fig. 2). This fact means that it is impossible to estimate the total transport from calculations of geostrophic current.

4. Conclusions

Main conclusions obtained from this study are as follows.

1) Diurnally averaged currents in the Eastern Channel of the Tsushima Strait balanced almost geostrophically.

2) In the middle of the channel, there existed a current core which corresponded to one branch of the Tsushima Current. It was centered between the surface and 20 m depth, and the maximum velocity was 0.5–1.0 kt (26–51 cm s\(^{-1}\)). Near the bottom at the deepest part of the channel, the velocity was more or less 0.3 kt (15 cm s\(^{-1}\)). Another current core with velocities of more than 0.3 kt (15 cm s\(^{-1}\)) was found near the north coast of Kyushu.

3) Along the east coast of Tsushima and in waters northeast of it, countercurrents were observed. The continuity of these countercurrents is thought as follows: A part of the current flowing from the Western Channel into the Japan Sea turns clockwise in waters northeast of Tsushima and then flows southwestward along the east coast of Tsushima. The southwestward current along Tsushima seems to be correlated with the northeastward current in the central part of the Eastern Channel.

4) Transport through the Eastern Channel was between 0.59 and 1.30 Sv (1 Sv = 10\(^6\) m\(^3\) s\(^{-1}\)), and its baroclinic component was very small.

In this study, the current structures in the Eastern Channel in summer were clarified. In summer, the velocity decreases gradually with depth (Subsection 3.3), but on the other hand, the velocity is almost uniform from the surface to the bottom in winter (Mizuno et al., 1989). For this reason, it is suggested that the current structures in winter are significantly different from those in summer. However, current measurements have been hardly carried out in winter mainly because of rough weather, and it is almost impossible to verify the suggestion. Therefore, current measurements in winter must be carried out to understand the current structures in the Eastern Channel of the Tsushima Strait.

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