Geostrophic current estimation using altimetric cross-track method in northwest Pacific

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Abstract. Geostrophic current contributes a large part of ocean current, which plays an important role in global climate change. Based on classic oceanography, geostrophic current can be derived from pressure gradient. Assuming water density to be constant, we can estimate geostrophic current from Absolute Dynamic Topography (ADT). In this paper, we use ADT data obtained from multi-satellite altimeter to extract sea surface tilt along track at ground track crossover points. The calculated tilt along these two tracks can be converted into orthogonal directions and are used to estimate geostrophic current. In northwest Pacific, geostrophic current velocities computed above are evaluated using Argos data, a global Lagrangian drifter program. 771 precisely temporal and spatial coherent Argos data with estimated geostrophic velocity data are used for evaluating. Effect of different threshold length of the low pass filter applied to ADT is discussed. A threshold length of 75 km is most suitable for the study area. The estimated geostrophic velocity and the Argos measurement agree well with each other, with correlation coefficient R equals 0.867 for zonal component, and 0.734 for meridional component. A relationship between the estimated geostrophic velocity and Argos measurement is drawn.

1. Introduction
Ocean circulation is one of the most important forces that driving global mass and heat transportation, plays an important role in global climate change, and have a significant impact on human society. Large scale ocean current in deep ocean away from land, if we ignore the forces of sea surface wind, can be considered as horizontal and quasi-stable flow, and controlled by the gradient of pressure and Coriolis force, which is called geostrophic current. Geostrophic current is the main part of the deep ocean circulation, hence attracting much attention from various disciplines, such as oceanography, climatology, environmental monitoring, ship navigation, etc.

Currently, observation of ocean geostrophic currents with adequate temporal and spatial resolution can only be expected from altimetry. The observation of ocean circulation globally begins with the application of SEASAT, Geosat and ERS altimeter data [1-3]. Different methods have been proposed and excellent works have been done to improve the accuracy of retrieval algorithm. As the launch of Topex/Poseidon (T/P) satellite, the observing of ocean circulation has been forwarded to a new level. However, it is recognized that a single satellite will not be sufficient to resolve the mesoscale...
phenomenon. The overlapped operation period of T/P, Envisat, Geosat Follow On (GFO), Jason-1/2 altimeter provides new opportunity to resolve the problem using multiple satellite altimetry measurements. The combination of these data achieves denser temporal and spatial coverage and reduces errors[4, 5]. Estimates of the geostrophic surface flow field from altimetry derived Absolute Dynamic Height (ADT) can be achieved through three methods: gridded geostrophic velocity estimation using space-time optimal interpolation of ADT [4], which is referred as optimal interpolation method; geostrophic velocity estimation at crossovers of ascending and descending tracks [6], which is referred as cross-track method; and geostrophic velocity estimation utilizing two altimeters operated in two identical orbits with a small zonal offset [7], which is referred as parallel track method. In this paper, we focus on the estimation of geostrophic current in the way of cross-track method using multiple satellite data in northwest Pacific. A set of configuration of the method will be discussed hereafter.

2. Materials and Methods
According to physical oceanography theory, in a local Cartesian coordinate with \(x\) axis pointing east, \(y\) axis pointing north and \(z\) axis pointing to the opposite direction of gravity, the zonal and meridional geostrophic velocity \((u, v)\) can be derived from the following equations assuming water density to be constant,

\[
\begin{align*}
    u &= -\frac{1}{\rho f} \frac{\partial p}{\partial y} = -\frac{g}{f} \frac{\partial h}{\partial y}, \\
    v &= \frac{1}{\rho f} \frac{\partial p}{\partial x} = \frac{g}{f} \frac{\partial h}{\partial x},
\end{align*}
\]

in which, \(g\) is gravitational constant, \(\rho\) is density of water, \(p\) is pressure, the Coriolis parameter \(f=2\Omega \sin\phi\), \(\Omega\) is angular velocity of earth rotation, \(\phi\) is latitude, \(h\) is ADT obtained from altimeter. In the follow context, we denote \(D_1=\partial h/\partial y\) and \(D_2=\partial h/\partial x\). \(D_x\) and \(D_y\) represent the orthogonal components of sea surface tilt along north-south and east-west directions.

Orthogonal component of sea surface tilt can be estimated from two intersected altimetric tracks. However, additional uncertainty is introduced by the fact that the intersected tracks are usually not orthogonal. The relationship between the orthogonal component of true sea surface tilt and tilt along the two intersected tracks are

\[
\begin{align*}
    D_1 &= D_x \sin \theta_1 + D_y \cos \theta_1, \\
    D_2 &= -D_x \sin \theta_2 + D_y \cos \theta_2,
\end{align*}
\]

where \(\theta_1\) and \(\theta_2\) are angles between ground tracks and north meridian, \(\theta_1\) is defined positive if it is clockwise from north meridian, and \(\theta_2\) is defined positive if it is counterclockwise from north meridian. \(D_1\) and \(D_2\) are sea surface tilt along track 1 and track 2 respectively, both defined positive in northward direction. From equation (2a) and (2b), orthogonal component of sea surface tilt can be derived from along track sea surface tilt. Consequently, Geostrophic velocity can be obtained by substituting \(D_x\) and \(D_y\) in to equation (1a) and (1b) with the relationship

\[
\begin{align*}
    u &= -\frac{g}{f} D_y = -\frac{g}{f} \frac{\sin \theta_1 D_1 + \sin \theta_2 D_2}{\sin(\theta_1 + \theta_2)}, \\
    v &= \frac{g}{f} D_x = \frac{g}{f} \frac{\cos \theta_1 D_1 - \cos \theta_2 D_2}{\sin(\theta_1 + \theta_2)}.
\end{align*}
\]

Assuming the error variances for sea surface tilt along tracks \((D_1 \text{ and } D_2)\) are uncorrelated and equal, given by \(\sigma^2_{\text{tilt}}\) according to the error propagation law, the error variances for the geostrophic velocity components \((u \text{ and } v)\) are
The error variances for the geostrophic velocity components will be sufficiently large when angle between the two ground tracks is small or at low latitude. In this paper, angle between ground tracks larger than 45° are necessary for selecting qualified crossovers. The latitudinal restriction of crossovers refers to previous studies[8-10] are suggested to 5°-55°.

Sea surface tilt is obtained from deviation of ADT, which is quite sensitive to errors in ADT data cause by various sources. Filtering is an effective approach to eliminate these errors. In this paper, a low pass filter with different threshold length is applied to the ADT data before calculating the sea surface tilt.

![Figure 1. Illustration of altimeter satellite ground tracks at crossover.](image)

2.1. Altimeter Data
This study uses along track ADT dataset derived from T/P, Jason-1/2, Envisat, GFO satellite altimeters. The products are distributed by Archiving Validation and Interpretation of Satellite Data in Oceanography (AVISO) in France. Multi-mission cross-calibration process is applied, ensuring that data from all satellites provide consistent and accurate information. It removes residual orbit error, long wavelength error, and large scale biases and discrepancies between various data sources[11]. The altimeter data used in this study is sorted into five categories, each of which occupies a unique ground track. The five categories are: TPJ for regular tracks of T/P and Jason-1/2 altimeter; TPJN for interleaved tracks of T/P and Jason-1 altimeter; EN for regular tracks of Envisat altimeter; ENN for interleaved tracks of Envisat altimeter; GFO for tracks of GFO altimeter. The time span of each ground track category is illustrated in figure 2.

ADT data from 1992-2011 are collected in northwest Pacific (118°E-160°E, 10°N-45°N). In the region where sea water depth less than 100 m, sea surface height can significantly be impacted by tide, equation (3a) and (3b) are not suited in these regions. For the area near shore (less than 20 km), altimetric echoes could be contaminated by land, sea surface height can not be retrieved properly. In this research, crossovers of ground tracks in the region where water depth less than 100 m, or offshore distance less than 20 km, are omitted. Figure 3 shows the coverage of altimeter data in the study area. The combination of multiple altimeter satellite greatly enhances the spatial resolution. Each of the

\[
\sigma_u^2 = \left(\frac{g}{f}\right)^2 \sin^2 \theta_2 + \frac{\sin^2 \theta_1}{\sin^2 (\theta_1 + \theta_2)} \sigma_{\text{tilt}}^2, \quad (4a)
\]

\[
\sigma_v^2 = \left(\frac{g}{f}\right)^2 \cos^2 \theta_2 + \frac{\cos^2 \theta_1}{\sin^2 (\theta_1 + \theta_2)} \sigma_{\text{tilt}}^2, \quad (4b)
\]

\[
\sigma_u^2 + \sigma_v^2 = \left(\frac{g}{f}\right)^2 \frac{2}{\sin^2 (\theta_1 + \theta_2)} \sigma_{\text{tilt}}^2 \approx \frac{10^{10}}{\sin^2 (\theta_1 + \theta_2) \sin^2 \varphi} \sigma_{\text{tilt}}^2 \quad (4c)
\]
crossovers between two ground tracks could be a potential location for estimation of geostrophic velocity, if the observation time lag of the two tracks is acceptable.

Figure 2. Time span of ground track categories. Yellow dotted bars indicate the period when there is an altimeter satellite on orbit. The solid bars indicate the period in which altimeter data is collected in this study, with the satellite name labelled.

Figure 3. Study area and spatial coverage of altimeter data. Crossovers of ground tracks in the region where water depth is less than 100 m or offshore distance less than 20 km are not considered, illustrated as grey in the figure. TPJ, EN, GFO, TPJN, ENN are five ground track categories defined in the paper.

Figure 4. Argos drifter trace in September to November (1992-2011). The flow represented by the dense drifter trace at the west boundary of Pacific is Kuroshio.

2.2. Drifter Data
Satellite tracked drifting buoys in the program of Argos are collected for validation of the estimation of geostrophic velocity in the study area. The Argos program maintained by NOAA’s Atlantic Oceanographic and Meteorological Laboratory (AOML) is responsible for the collecting, processing and distributing of global Lagrangian drifter data. The datum of Argos program includes 24 million ocean surface current data from more than 10,000 drifters globally from 1979 to 2012. Each data represents 5m depth current velocity at certain location interpolated to regular 6-hour interval. The Argos data collected in this paper corresponds to the ADT data temporally and spatially.
3. Results and Analysis

Low pass filter applied to the ADT data is crucial to the estimation. Different filter threshold length can lead to quite different results. A comparison of the effect of different filter threshold lengths is listed in Table 1. The correlation coefficient for both components reaches its maximum when a low pass filter with threshold length of 75 km is applied.

| Threshold length/km | R for zonal component | R for meridional component |
|---------------------|------------------------|---------------------------|
| 0                   | 0.65                   | 0.24                      |
| 25                  | 0.83                   | 0.54                      |
| 50                  | 0.87                   | 0.72                      |
| 75                  | 0.87                   | 0.73                      |
| 100                 | 0.84                   | 0.68                      |
| 125                 | 0.82                   | 0.62                      |
| 150                 | 0.82                   | 0.59                      |
| 175                 | 0.80                   | 0.56                      |
| 200                 | 0.78                   | 0.55                      |

Geostrophic velocities at qualified crossover points are calculated using ADT data from multiple satellite data. To eliminate the error induced by time difference between intersected ground tracks, a maximum time lag of 24 hours is selected to qualify the crossovers used in the study. In order to evaluate the accuracy of the estimation method, a comparison between the estimated geostrophic velocity and Argos drifter data is conducted. The Argos drifter data is selected with criteria in two folds: (i) the distance between the location of the drifter measurement and the crossover must be less than 2 km, according to a correlation analysis of the Argos dataset; (ii) the time gap between the drifter measurement and any of the two altimeters passing the crossover should be less than 24 hours. The criteria ensure the synchronization of the comparison pairs. 771 pairs of velocity are selected according to the criteria. The comparison result is shown in Figure 5, in which the left part represents the zonal component and the right part represents the meridional component. The estimation of the geostrophic velocity shows a good agreement with the Argos measurement, especially for the zonal component. The correlation coefficient reaches 0.867 for zonal component, and 0.734 for meridional component.

![Figure 5. Comparison of estimated geostrophic velocity and Argos measurement (low pass filter threshold length is 75 km). The x-axis for each scatter plot is velocity from Argos, and y-axis is velocity estimated from altimeter data. The lines in both plots are linear fit of the comparison.](image-url)
The relationship between the estimated geostrophic velocity \((u_{\text{geo}}, v_{\text{geo}})\) and Argos measurement \((u_{\text{Argos}}, v_{\text{Argos}})\) can be expressed as equation (5a) and (5b).

\[
\begin{align*}
u_{\text{Argos}} &= 1.398 v_{\text{geo}} + 1.096, \\
\end{align*}
\]

\[
\begin{align*}
u_{\text{Argos}} &= 1.138 u_{\text{geo}} - 2.658. \\
\end{align*}
\]

4. Conclusions
Geostrophic current in northwest Pacific is estimated from altimeter ADT data. Argos data is collected to validate the estimation result. Strict criteria are selected to ensure the synchronization of altimeter data used to estimate geostrophic velocity and Argos data temporally and spatially. A 75 km threshold length of low pass filter is suggested for the estimation in northwest Pacific. The estimated geostrophic velocity and the Argos measurement agree well with each other, with a correlation coefficient of 0.867 for zonal component, and 0.734 for meridional component. The relationship between the estimated geostrophic velocity and Argos measurement is drawn, which provides an approach for estimates of sea surface current using altimeter data.

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