Remote Sensing of Sea Surface Wind of Hurricane Michael by GPS Reflected Signals

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ABSTRACT In this paper, the propagating geometry and the waveform of the GPS reflected signals are expatiated in detail. Furthermore, the principle and the method of retrieving sea surface wind are presented. In order to test the feasibility of retrieval, the experiment data obtained by NASA in Hurricane Michael are used. The result shows that the retrieval accuracy of wind speed is about 2 m/s.

KEY WORDS GPS reflected signals; scattering zone; sea surface wind retrieval

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Introduction

It has been recognized that the GPS reflected signals have the potential use for various remote sensing purposes in recent years. Some of which are measurements of sea surface height, sea surface wind speed and direction, ocean significant wave height, ocean salinity, land soil moisture, sea ice thickness, eddy, tsunami, and so on. Over conventional remote sensing tools, the use of the GPS reflections has several advantages such as high temporal resolution and spatial resolution, no need of transmitters, abundance of GPS resources, simple receivers and so on.

Until recently, a great many of airborne and spaceborne experiments have been performed by America National Aeronautics and Space Administration (NASA), European Space Agency (ESA) and some other institutions. The airborne experiment results show that the estimated accuracy of sea surface height is about 3-5 cm, and the accuracy of wind speed and direction is about 2 m/s and 20° respectively. But in spaceborne case, the accuracy has not been confirmed.

The use of GPS reflections as a remote sensing tool has attracted attention since 1993 when a concept for GPS-based altimetry was first proposed and systematically described by Martin-Neira M[1]. The first published results demonstrated that the GPS signals reflected from sea surface were strong enough to be detected with conventional GPS navigation receivers, which resulted from an accidental discovery by Auber J C in July 1991 while testing a vehicle tracking system. NASA researchers Katzberg S J and Garrison J L developed a specialized GPS receiver called delay-mapping receiver (DMR) and began flight campaigns in 1996 to collect GPS reflections. They soon developed methods for GPS-based sea surface wind speed retrievals[2]. A little later, researchers Zavorotny V U and Voronovich A G gave a theoretical description of the retrieval technique[3]. In 2000, the University of Colorado proposed the SURGE (student reflected GPS experiment) satellite project partnered with the key reflection researchers in the USA[2]. Lowe S T presented the first spaceborne observation of GPS reflected signals in a short segment of Spaceborne Imaging Radar-C (SIR-C) calibration data[4]. In 2001, GeoFors-
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chungsZentrum Potsdam (GFZ) also published evidence of ocean reflected GPS signals measured by GPS/MET occultation satellite\(^2\). In addition, NASA performed GOLPE experiment (GPS occultation and passive reflection experiment) on SAC-C satellite which launched in November 2000\(^3\). In October 2003, a GPS reflection receiver was also added to UK-DMC satellite as a secondary payload\(^4\).

Hurricane Michael formed in the western Atlantic in the evening of October 16, 2000. The emergence of Hurricane Michael presented the first opportunity for NASA to traverse the core of a tropical cyclone on October 18, 2000. At the time of the aircraft penetration, the storm was moving at approximately 18 m/s\(^5\).

In this paper, the method for using GPS reflection to retrieve sea surface wind field is discussed in detail. Furthermore, the experiment data gathered in Hurricane Michael is processed. In order to test the retrieval method and the estimated accuracy of the result, the data segment of 13:35 on October 18, 2000 is processed and the retrieval result is shown. It is concluded that the retrieval wind speed shows an agreement about 2 m/s with the wind speed derived from Topex/Poseidon satellite. In addition, the data used in this paper can be downloaded from http://www-ccar.colorado.edu/~dmr.

1 Propagation geometry of GPS reflections

It is important to understand the propagation geometry of the GPS reflections. To accomplish this, we show the geometry in Fig. 1, where \(\theta\) is the receiver’s viewing angle; \(\epsilon\) is the GPS satellite’s elevation with respect to the specular point; \(R_{np}\), \(R_{np}\) are the distances from the GPS satellite and the receiver to the specular point respectively, \(R\) is the earth’s radius. It is convenient to center the Cartesian coordinate system at the nominal specular point on a spherical ocean surface with \(xy\) plane tangent to this surface, \(z\)-axis directed upward, and \(yz\) plane an incidence plane\(^6\). Therefore, given a random scattering point \(P(x, y, \zeta)\), where \(\zeta\) is the sea surface height of the point of \((x, y)\), we can obtain the following relations:

\[
\begin{align*}
\Theta &= \frac{\pi}{2} + a - \theta - \epsilon \\
R_{np}'^2 + L^2 - 2LR_{np}\cos\theta &= R^2 \\
R_{np}'^2 + R^2 + 2R_{np}\sin\epsilon &= L^2 \\
R_{np}'^2 + R^2 + 2R_{np}\sin\epsilon &= G^2 \\
R^2 + G^2 - 2RG\cos\alpha &= R_{np}'^2 \\
R_{np}'^2 &= R_{np}'^2 \left(1 - 2\frac{\frac{\cos\theta}{R_{np}} - \frac{\zeta\sin\epsilon}{R_{np}} + \frac{x^2 + y^2 + \zeta^2}{R_{np}^2}}{R_{np}}\right) \\
R_{np}'^2 &= R_{np}'^2 \left(1 + 2\frac{\frac{\cos\theta}{R_{np}} - \frac{\zeta\sin\epsilon}{R_{np}} + \frac{x^2 + y^2 + \zeta^2}{R_{np}^2}}{R_{np}}\right)
\end{align*}
\]

(1)

Given \(L\), \(G\), \(\theta\), we can derive \(R_{np}\), \(R_{np}\), \(\epsilon\), \(a\) and \(\Theta\).

2 GPS reflections waveform

With a theoretical view of rigorous electromagnetic wave, when GPS signals touch the ocean surface it will arouse conductive electrical current in the surface, and the ocean surface becomes a secondary emissive resource. It can be assumed that the ocean surface is comprised of many small facets and each facet can be considered a secondary emissive resource, therefore, the received GPS reflections can be regarded as the accumulation of the signals trans-
mitted by all of the secondary emissive resources. There are two classes of GPS signals emanating from the ocean surface. One is purely specular and the effect is mirror-like if the ocean surface is perfectly smooth with respect to GPS carrier wave length. The other is diffuse, with radiation coming from angles other than from the expected specular direction. In real case, the ocean surface is relatively coarse with respect to GPS carrier wave length, so the received GPS reflections come really from a glistening zone area around the specular point. The shape and the size of the glistening zone are dominated by the roughness of the ocean surface, GPS satellite elevation and receiver height.

Using the Kirchhoff approximation theory, the waveform of GPS reflected signals can be given by\[^3\]

\[
\langle |Y(\tau,f_d)|^2 \rangle = T^2 \int \int G(x,y) |\mathcal{R}(x,y)|^2 q^2(x,y) \times A^2 \left[ \frac{R-x-R+y}{c} \right] 
\times P_i \left( -\frac{q_x}{q_y} - \frac{q_y}{q_x} \right) \cdot S \left[ f_d(x,y) - f_c \right] ^2 \text{d}x \text{d}y
\]

where \( \langle |Y(\tau,f_d)|^2 \rangle \) is the reflected power for any delay time \( \tau \) and Doppler offset \( f_d \); \( (x,y) \) is a random scattering point around the specular point; \( T \) is the integration time; \( G \) is the antenna gain; \( \mathcal{R} \) is Fresnel reflection coefficient; \( q \) is a scattering vector; \( q_x, q_y \) are the \( x, y \), \( z \) component of the \( q \); \( A \) is the correlation function of the GPS C/A code or P code; \( S \) is the Doppler sync function; \( c \) is the velocity of light; \( f_d \) is the Doppler shift at the specular point; \( R_x, R_y \) are the distances from the GPS satellite and the receiver to some scattering point respectively; \( \mathcal{P} \) is the probability density function (PDF) of the surface slopes. In this paper the distribution of the 2D slope is assumed to be accorded with Gaussian model whose expression is

\[
P_i(s_x,s_y) = \frac{1}{2\pi\sigma_u\sigma_v} \times \exp \left[ -\frac{1}{2(1-b_{xy}^2)} \left( \frac{s_x^2}{\sigma_u^2} - 2b_{xy}s_x s_y + \frac{s_y^2}{\sigma_v^2} \right) \right]
\]

where \( s_x, s_y \) are the components of sea surface slopes along the \( x \) and \( y \) axes respectively; \( \sigma_u, \sigma_v \) are the mean square slope (MSS) along the \( x \) and \( y \) axes respectively; \( b_{xy} \) is the correlation of the random variables \( s_x \) and \( s_y \). These slopes variances and correlations are wind-dependent and can be derived from sea surface elevation spectrum \( \phi(k_x,k_y) \), the relations are:

\[
\sigma_u^2 = \langle s_x^2 \rangle = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} k_x^2 \phi(k_x,k_y) \text{d}k_x \text{d}k_y
\]

\[
b_{xy} = \langle s_x s_y \rangle / \sigma_u \sigma_v
\]

\[
\langle s_x s_y \rangle = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} k_x k_y \phi(k_x,k_y) \text{d}k_x \text{d}k_y
\]

(4)

where \( k_x \) and \( k_y \) are wave numbers along the \( x \) and \( y \) axes respectively; \( k_x = 2\pi \text{sin}(3\lambda) \) is scale dividing parameter (\( \lambda = 0.19 \) m). If the spectrum is symmetrical with respect to a wind direction, then \( b_{xy} = 0 \), otherwise, \( b_{xy} \neq 0 \). If \( \phi_0 \) is the angle between the wind direction and \( y \) axis, then \( \sigma_u, \sigma_v \) and \( b_{xy} \) can be expressed as:

\[
\begin{align*}
\sigma_u^2 &= \cos^2 \phi_0 - \sin^2 \phi_0 \\
\sigma_v^2 &= \sin^2 \phi_0 \\
b_{xy} &= \frac{\cos \phi_0 \sin \phi_0}{\sigma_u^2} \cdot \begin{bmatrix} \sigma_u^2 & 0 \\ 0 & \sigma_v^2 \end{bmatrix}
\end{align*}
\]

(5)

where \( \sigma_u^2 \) and \( \sigma_v^2 \) are the MSS in up and cross wind direction respectively. In order to simplify the problem, assuming that the sea surface elevation spectrum \( \phi(k_x,k_y) \) is dominated by the sea surface wind, so the Elfouhaily spectral model can be used for \( \phi(k_x,k_y) \). Therefore, the relationship between the GPS reflection waveform and the ocean wind can be concluded.

In Eq. (2), the expression of \( A \) and \( S \) are:

\[
\begin{align*}
A(\delta \tau) &= \frac{1}{\sqrt{1 - b_{xy}^2}} \\
S(\delta f) &= \frac{\sin(\pi \delta f T_e)}{\pi \delta f T_e} \exp(-\pi i \delta f T_e)
\end{align*}
\]

(6)

where \( \tau \) is the GPS chip (C/A code or P code) duration. And the scattering vector can be expressed as:

\[
q = -K \nabla (R_x + R_y) = K(R_e - R_l) \equiv K(l - m)
\]

(7)

where \( \hat{R} \) and \( m \) are the unit vector of the incident wave; \( \hat{R}_l \) and \( l \) are the unit vector of the scattered wave; \( K \) is the wave number of the GPS carrier. As shown in Fig. 1, the coordinates of the GPS satellite and receiver can be deter-
mined respectively by the vectors \((0, R_x \cos \theta, R_x \sin \theta)\) and \((0, -R_y \cos \theta, R_y \sin \theta)\). Neglecting the effect of the sea surface height, the scattering vector's components at any scattering point \((x, y, 0)\) can be given by:

\[
q_x = -Kx \left( \frac{1}{R_x}, \frac{1}{R_y} \right), \quad q_x = K \left( \frac{R_x}{R_z}, \frac{R_y}{R_z} \right) \sin \theta
\]

\[
q_y = K \left( -\frac{R_x}{R_z}, \frac{R_y}{R_z} \right) \cos \theta - Ky \left( \frac{1}{R_x}, \frac{1}{R_y} \right)
\]

Further more, the effect of the reflection on the polarization of the GPS signals must be taken into account. The transmitted GPS signal is right-hand circular polarization (RHCP), and the GPS reflection changes gradually to left hand circular polarization (LHCP) at higher GPS satellite elevation after an interaction with the ocean surface. Assuming that GPS reflection is predominant LHCP, therefore, the Fresnel coefficient can be expressed through vertical and horizontal linear polarizations:

\[
R = R_H = (\beta_H - \beta_v) / 2
\]

where \(R_H\) and \(R_v\) are the Fresnel coefficients of vertical and horizontal linear polarization respectively, whose expressions are:

\[
\beta_H = \frac{\sin \theta - \sqrt{e' - \cos^2 \theta}}{\sin \theta + \sqrt{e' - \cos^2 \theta}}
\]

\[
\beta_v = \frac{\epsilon_v \sin \theta - \sqrt{e' - \cos^2 \theta}}{\epsilon_v \sin \theta + \sqrt{e' - \cos^2 \theta}}
\]

where \(e'\) is the complex dielectric constant of seawater, which is the function of sea surface temperature and salinity and the GPS wavelength. A typical value \(e' = 73.0 + i57.5\) is chosen for GPS L1 carrier.

### 3.1 Annulus zone

According to the Eq. (2) and Eq. (6), if \(|\tau - (R_x + R_y)/c| \geq \tau_i\), then \(|Y(\tau, f_D)|^2 = 0\). In other words, only the zone \(\tau - \tau_i \leq (R_x + R_y)/c \leq \tau + \tau_i\), makes contribution in Eq. (2). Introducing a variable \(\tau_0 = \tau - (R_x + R_y)/c\), it is obvious that the GPS reflections received at the time delay \(\tau_0\) are formed by only those GPS signals that could be scattered by points located on an ellipsoid of rotation which has the GPS satellite and receiver as its foci. Let \(\tau_0 = \tau_0/2\) \((i = 1, 2, 3, 4, \ldots)\), then we can draw a series of Fresnel zones around the specular point. According to the definition of the ellipsoid, the points defined by the equation of \((R_x + R_y)/c - (R_x + R_y)/c = \tau_0\) form a series of ellipsoids. These ellipsoids' equation is \(R_x + R_y = R_x + R_y + ik/2\), where \(k\) is the wavelength of the GPS pseudorandom code \((\lambda = 293.1\) m for C/A code). The intersections of these ellipsoids with the sea surface are ellipses, and a Fresnel zone is formed between the nearest two ellipses. Neglecting the effect of the sea surface height, and assuming that the intersections of the \(i\) th ellipse with the \(y\) and \(x\) axes are \((0, y_{i1}, 0, 0, y_{i2}, 0)\) and \((x_{i1}, 0, 0, x_{i2}, 0, 0)\), then we can gain the following expressions:

\[
y_{i1,2} = \left[ \pm \sqrt{\alpha (\alpha + 2L_y) / \sqrt{\alpha + 4L_y}} \sqrt{\alpha + 4L_y} \sqrt{\alpha + 16R_yR_\alpha \sin \theta} - \alpha \cos (R_x + R_y)(\alpha + 4L_y) \right] / 4(\alpha)^2 + 4\alpha L_y + 4L_y^2
\]

\[
x_{i1,2} = \pm \sqrt{\alpha \sqrt{(\alpha)^2 + 8(\alpha)^2 L_y + 16(\alpha)(L_y^2 + R_yR_\alpha) + 64R_yR_\alpha L_y}} / 4(\alpha)^2 + 4\alpha L_y + 4L_y^2
\]

where \(L_y = R_x + R_y\). From Eq. (11) the semi-major and semi-minor axes of the \(i\) th ellipse are \(a_i = (y_{i1} - y_{i2})/2\) and \(b_i = x_{i1} (-a_i/y_{i2})^{1/2}\) respectively, and the corresponding ellipse center \(O\) is \((0, (y_{i1} + y_{i2})/2, 0)\).

Assuming that the GPS satellite height is \(2000\) km, the earth's radius \(R\) is \(6371\) km, the receiver height is \(10\) km, and the GPS satellite's elevation \(\varepsilon = 30^\circ\), then we can obtain the geometry of the first ten Fresnel zones in Fig. 2.
(a) from Eq. (1) and Eq. (11), where the origin of the coordinate system is the specular point, \( a_i = 4.85 \text{ km} \), \( b_i = 2.56 \text{ km} \), \( O_i \) is \((0, 0, 0.52 \text{ km}, 0)\), and \( a_{i0} = 15.82 \text{ km} \), \( b_{i0} = 9.68 \text{ km} \), \( O_{i0} \) is \((0, 5.61 \text{ km}, 0)\); changing \( \varepsilon \) to 60° under the same conditions, then we can obtain the Fig. 2(b), where \( a_i = 2.13 \text{ km} \), \( b_i = 1.89 \text{ km} \), \( O_i \) is \((0, 0.10 \text{ km}, 0)\), and \( a_{i0} = 6.85 \text{ km} \), \( b_{i0} = 6.55 \text{ km} \), \( O_{i0} \) is \((0, 1.11 \text{ km}, 0)\); changing the receiver's height to 5 km and \( \varepsilon \) to 30°, then we can obtain the Fig. 2(c), where \( a_i = 3.45 \text{ km} \), \( b_i = 1.87 \text{ km} \), \( O_i \) is \((0, 0.53 \text{ km}, 0)\); with respect to LEO-receiver, we can assume that the receiver height is 700 km and keep \( \varepsilon \) unchangeable, and then we can obtain the Fig. 2(d), where \( a_i = 37.08 \text{ km} \), \( b_i = 18.65 \text{ km} \), \( O_i \) is \((0, 0.46 \text{ km}, 0)\). From the Fig. 2, we can conclude that the centroid of the ellipses moves along the direction of the major axes towards the GPS satellite, and the lower elevation \( \varepsilon \), the larger moving scope. Further more, we can conclude that the higher receiver height, the larger Fresnel zones and the smaller moving scope of the centroid with respect to specular point.

Therefore, the GPS reflected signals received at time delay \( \tau = \frac{t_0}{2} \) come from the Fresnel zones between the \((i-2)\)th and the \((i+2)\)th (totally four Fresnel zones).

![Fig. 2 The geometry of Fresnel zones](image)

### 3.2 Glistening zone

As shown in Fig. 3, \( T, R \) and \( P \) correspond to the GPS satellite, receiver and scattering point respectively. \( PA \) is the bisector of the angle \( TPR \), and \( \beta \) is the angle between the \( PA \) and \( z \)-axis. Then we can define the glistening zone as the areas around the specular point with \( \beta \leq \beta_0 \), and \( \beta_0 \) is a constant used to describe roughness of sea surface whose definition is \( \beta_0 = \arctan \left( \frac{2\sigma}{L} \right) \), where \( \sigma \) is the standard deviation of the surface height distribution and \( L \) is the correlation length\(^\text{[2]}\). Therefore, the size of the glistening zone is determined by the function \( P \).

### 3.3 Doppler zone

It can be considered that the Doppler shift is compensated when \(|S|^2 \approx 1\). Therefore, we can define the zone with \(|S|^2 \approx 1\) as a Doppler zone. According to Eq. (6), it is obvious that the function \(|S(f - f_0)| \) is centered near \( f_0 = f \), and concentrated mostly within the area \(|f_0 - f| \leq 1/(2T)\). Assuming that the Doppler shift is mainly caused by the velocities of the GPS satellite and the receiver, then we can determine the Doppler zone on the sea surface by the function \(|S|\), and the boundaries of these zone can be
found from the following equation:

\[ f_c \pm 1/(2T_c) = (V_i \cdot m - V_r \cdot l)/\lambda \]  \hspace{1cm} (12)

where \( V_i \) and \( V_r \) are the velocities of the GPS satellite and the receiver respectively; \( m \) and \( l \) are the unit vectors of the incident wave and the scattered wave respectively. Assuming that the maximum of the Doppler shift in the glistening zone is \( f_{D,\text{max}} \), the maximum is \( f_{D,\text{min}} \), and the Doppler shift corresponding to the specular point is \( f_{D,\text{spec}} \). Therefore, the Doppler spreading scope with respect to the specular point is \([-\Delta f_{D-}, \Delta f_{D+}]\), where \( \Delta f_{D-} = f_{D,\text{min}} - f_{D,\text{spec}}, \Delta f_{D+} = f_{D,\text{max}} - f_{D,\text{spec}} \). From Eq. (6) we can conclude that the effect of the Doppler shift can be neglected when \( (\Delta f_{D+} - \Delta f_{D-}) \) is less than the bandwidth \( \Delta f = 1/(2T_c) \). In other words, if the glistening zone is less than the Doppler zone, then \( |S|^2 \approx 1 \) and the effect of the Doppler shift can be neglected.

4 Wind retrieval method

4.1 The relationship between the MSS and the ocean wind

According to Elfordhaily model\cite{ref6}, we can get the values of \( a'_2 \) and \( a'_1 \) in Eq. (5) with respect to different GPS satellite elevation, wind speed and direction as shown in Table 1. Therefore, the relationship between the MSS and the ocean wind can be determined.

4.2 Wind retrieval principle

According to Table 1 and numerical evaluation of Eq. (2), we can know that higher sea surface wind speed means larger MSS, lower peak and flatter trailing edge of the GPS reflected signal power waveform, and vice versa, as shown in Fig. 4. This phenomenon provides us a possibility of remote sensing the sea surface wind. The method of wind retrieval is to compare the experimental waveform with the modeled waveforms (theoretical waveforms) with respect to the corresponding receiver height and GPS satellite elevation. For the sake of simplicity, it is necessary to normalize the reflected waveform, and the normalization factor can be the total of the reflected power or the direct power\cite{ref10}.

3.4 Receiver antenna footprint

In order to simplify the problem, we assume the receiving antenna is omnidirectional and the antenna gain is \( G^2 = 1 \). Therefore, the whole glistening zone can be detected from the antenna.

### Table 1 Mean square slopes related to different ocean surface wind speed and GPS elevation

| GPS elevation | Wind speed/m \( \times \) s \(^{-1} \) | 30° | 45° | 60° | 90° |
|---------------|---------------------------------|-----|-----|-----|-----|
| 3             | 0.005 80, 0.002 37              | 0.006 68, 0.002 87 | 0.007 16, 0.003 15 | 0.007 47, 0.003 33 |
| 5             | 0.009 14, 0.004 66              | 0.010 02, 0.005 32 | 0.010 47, 0.005 66 | 0.010 76, 0.005 88 |
| 7             | 0.011 28, 0.006 35              | 0.012 10, 0.006 99 | 0.012 50, 0.007 32 | 0.012 75, 0.007 52 |
| 9             | 0.013 06, 0.007 75              | 0.013 85, 0.008 40 | 0.014 24, 0.008 72 | 0.014 49, 0.008 92 |
| 11            | 0.014 31, 0.008 77              | 0.015 07, 0.009 40 | 0.015 48, 0.009 73 | 0.015 74, 0.009 94 |
| 13            | 0.015 23, 0.009 53              | 0.015 99, 0.010 15 | 0.016 37, 0.010 48 | 0.016 60, 0.010 69 |
| 15            | 0.015 94, 0.010 12              | 0.016 64, 0.010 73 | 0.017 02, 0.011 06 | 0.017 32, 0.011 30 |
| 17            | 0.016 47, 0.010 57              | 0.017 17, 0.011 19 | 0.017 66, 0.011 57 | 0.018 04, 0.011 85 |
| 19            | 0.016 87, 0.010 94              | 0.017 71, 0.011 62 | 0.018 28, 0.012 04 | 0.018 67, 0.012 33 |
| 21            | 0.017 25, 0.011 27              | 0.018 23, 0.012 01 | 0.018 80, 0.012 44 | 0.019 15, 0.012 73 |
| 23            | 0.017 65, 0.011 57              | 0.018 67, 0.012 35 | 0.019 18, 0.012 77 | 0.019 44, 0.013 03 |

Fig. 3 Illustration of scattering geometry

Fig. 4 Reflected power waveform wrt time delay
From Eq. (2), neglecting the effect of the Doppler shift and normalized by the direct signal $<|Y(\tau, f_0)|^2>_R/T_0$, we can obtain the modeled waveforms with respect to different receiver height, GPS satellite elevation, sea surface wind speed and direction as shown in Fig. 5-Fig. 8. These figures show that larger wind speed means lower peak and flatter trailing edge of the waveform; the effect of the wind direction on the waveform is mainly on the trailing edge; lower GPS satellite elevation means flatter trailing edge of the waveform; higher receiver height means lower peak and flatter trailing edge of the waveform. Therefore, given the satellite elevation and receiver height, it is possible to retrieve the wind speed and direction in theory by use of the reflected waveforms.

![Fig. 5 Reflected waveforms wrt different wind speed](image1)

![Fig. 6 Reflected waveforms wrt different wind direction](image2)

![Fig. 7 Reflected waveforms wrt different GPS elevation](image3)

![Fig. 8 Reflected waveforms wrt different receiver height](image4)

### 5 Retrieval result

The aircraft of the NASA and the University of Colorado equipped with GPS reflection receiver flew into the Hurricane Michael off the South Carolina coast on October 18, 2000, as shown in Fig. 9[2]. In order to test the feasibility of the retrieval method, we processed the experiment data and the datasets at 15:35 were chosen to analyze the problem, when the receiver height is about 4.5 km, the specular points and the elevations of the GPS satellite PRN5, PRN15, PRN21, PRN23, PRN29, PRN30, whose reflected signal has been received, are shown in Table 2 respectively. Before retrieving the wind, the datasets must be preprocessed. Firstly, the noise floor is computed for each dataset and subtracted from it. Secondly, the datasets are normalized by the total reflected power. Neglecting the effect of the Doppler shift and averaging the 60 datasets at 15:35 (the receiver’s data sample rate is 1 Hz, so there are 60 datasets per one second), then we can obtain the experimental waveforms and the corresponding modeled waveforms of the GPS satellite PRN5, PRN15,
PRN21, PRN23, PRN29, PRN30, as shown in Fig. 10-Fig. 12. The retrieved results and errors with respect to Topex solutions are shown in Table 2. The disagreement of the results among the GPS satellites is mainly due to the random noise of the receiver, the coarse step (1 m/s) of the modeled waveforms and the error of estimating the delay of the specular point and so on. In order to obtain a more accurate result, the average of the six satellites’ results is chosen.

| Index | GPS satellite | GPS satellite elevation | Specular point | Retrieve result from GPS reflection/m·s⁻¹ | Topex solution/m·s⁻¹ | Error/m·s⁻¹ |
|-------|---------------|------------------------|----------------|-------------------------------------------|---------------------|------------|
| 1     | PRN05         | 30.8°                  | 30.144°N 75.953°W | 7.0                      | 8.2                 | 1.2        |
| 2     | PRN15         | 52.6°                  | 30.137°N 76.137°W | 6.2                      | 8.2                 | 2.2        |
| 3     | PRN21         | 61.1°                  | 30.170°N 76.049°W | 9.8                      | 8.2                 | 0.8        |
| 4     | PRN23         | 58.6°                  | 30.142°N 76.008°W | 7.2                      | 8.2                 | 1.2        |
| 5     | PRN29         | 50.0°                  | 30.172°N 76.070°W | 7.2                      | 8.2                 | 1.2        |
| 6     | PRN30         | 28.8°                  | 30.092°N 75.972°W | 6.2                      | 8.2                 | 2.2        |
| Average |               |                        | 30.1°N 76.0°W     | 7.2                      | 8.2                 | 1.2        |

6 Conclusions

According to the discussion in this paper, we can draw the conclusions as follows.

1) It is feasible to retrieve the sea surface wind from the GPS reflected signals both in theory and in practice.

2) It is necessary to develop a receiver with high antenna gain and high receiver gain because the GPS reflected signal power is very low.

3) The current ocean elevation spectrums are mainly valid for wind speed from 3 to 24 m/s, so