

# Lake Level Variations Monitored With Satellite Altimetry Waveform Retracking

Jinyun Guo, Xiaotao Chang, Yonggang Gao, Jialong Sun, and Chainway Hwang

**Abstract**—Over lake shores, altimetric waveforms are generally contaminated by lands, rough lake surfaces, and lag effects of the altimeter's automatic gain control. To improve altimeter ranging accuracy and in turn to get better surface height measurement, contaminated waveforms should be retracked against geophysical corrections. In this paper, an improved threshold retracker (ITR) is developed to retrack waveforms over lakes. ITR considers not only the physical characteristics of the reflecting surface, but also the stochastic feature of waveform, and two new retrackers, the N-Beta function model, and the N-5-Beta function model, are also put forward to develop the waveform retracking program of this study. TOPEX/POSEIDON waveforms over Hulun Lake in the North China are retracked to monitor the temporal lake level variations. A comparison with the *in situ* hydrological data indicates ITR is very efficient to monitor the lake level variations with the retracked altimetric data. The result of our study shows accurate seasonal level variations and the descending trend of Hulun Lake.

**Index Terms**—Improved threshold retracker, lakes, lake level variations, level measurement, radar altimetry, satellite altimetry, waveform analysis, waveform retracking.

## I. INTRODUCTION

SATELLITE altimetry missions are mainly designed to measure sea surface heights. However, the satellite altimetric data have also been used to study inland lakes in the USA [1], Africa [2], and South America [3]. Because the radar satellite altimetric waveforms are always contaminated by terrains and physical environments over inland lakes, the satellite altimetric data quality should be improved with the waveform retracking technique for the monitoring of the lake level.

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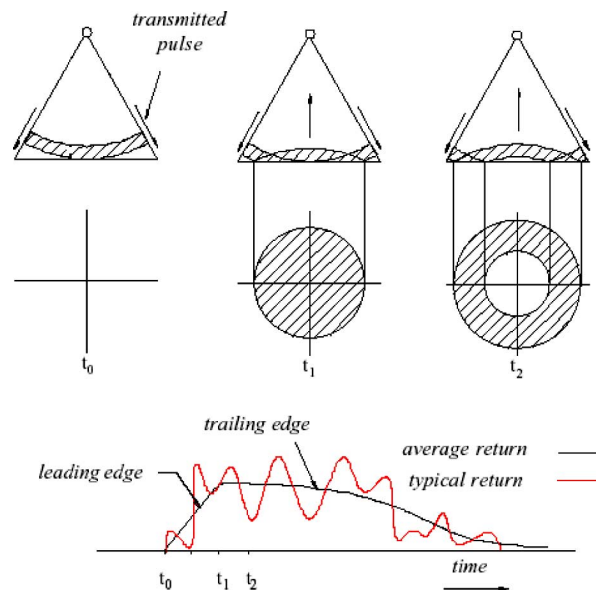


Fig. 1. Schematic geometrical description of a returned waveform over the duration of a pulse.

Satellite altimetry employs a nadir-pointing radar with high resolution to measure the range to the oceanic surface with precision up to centimeter level [4], [5]. The range to the at-nadir sea surface is measured by the altimeter directly through a measurement of the time interval between the transmission of a radar pulse and the reception of the echo. The returned radar altimeter waveforms are the basic measurement for observing geophysical parameters of the earth surface. Fig. 1 shows a schematic description of the interaction of a pulse-limited radar pulse with a diffuse, horizontal and planar sea surface. Initially ( $0 < t < t_0$ ), a pulse of electromagnetic energy is transmitted from a satellite-borne altimeter antenna, propagating in a spherical wavefront. When the wavefront encounters the nearest crests of ocean waves directly beneath the satellite at time  $t = t_0$ , it illuminates one point and a reflected signal begins to return to the altimeter. As the time and the pulse progress, the wavefront reaches the surface at points away from the nadir point. Once the rear of the pulse reaches the lowest trough at nadir, the region of interaction between the surface and the pulse forms an annular ring of increasing diameter, narrowing width, and the constant mean area. The backscattered energy reaches its maximum at the point of transition to an annular ring ( $t = t_1$ ). Thereafter ( $t > t_1$ ), the backscattered energy begins to decay owing to the finite antenna beam width and the fewer proper reflected facets available at larger off-nadir angles. The returned power is recorded within the duration of the pulse, building up a returned waveform with a rapidly rising leading edge and long decay of the trailing edge.

The averaged returned waveform is a time series of the mean returned powers recorded by the satellite altimeter, and is referred to as the convolution of three terms based on the specular reflection from the sea surface, which are the system's point target response, the impulse response of the smooth spherical scattering surface, and the ocean-surface height distribution [6]–[8]. As can be seen, the waveform mainly consists of three parts, i.e., the thermal noise, the leading edge, and the trailing edge. The thermal noise contains the thermal noise power generated by the altimeter prior to the first return of a signal from the scattering surfaces. Its effect is to add a constant power level to the returned waveform. The leading edge includes the returned power from the scattering surface within the pulse-limited footprint, which includes the information about the significant wave height (SWH), and the range between the satellite altimeter and the mean sea surface at the nadir. The trailing edge consists of the returned power from the scattering surface outside the pulse-limited footprint, which can be approximated by a straight line whose slope depends on the antenna pattern and the off-nadir angle. If the ocean waves on the sea surface are assumed to be linear, the corresponding statistics of surface elevation and slopes are Gaussian. Therefore, the altimeter waveform is an odd function relative to the midpoint on the leading edge of the waveform, and the range to the at-nadir sea surface corresponds to the midpoint of the leading edge.

Modern satellite radar altimeters can measure the instantaneous sea surface height (SSH) up to a precision of approximate 5 cm over open oceans [9]. However, over lakes, the waveform measurements are affected by the noisier radar returns from the rough surface states, and by less reliable geophysical conditions, wet delay, orbit and instrument corrections [9]–[11]. This prevents the altimeter data from providing valuable information on the geoid shape, the wind field, oceanic current characteristics, and the sea surface topography (SST) over coastal regions and lakes.

Fig. 2 shows some waveforms of TOPEX/Poseidon in pass 27 over Hulun Lake in the North China. In the middle of the lake, the waveforms follow the Brown model. But closer to the shoreline, the waveforms differ from the Brown model. For example, waveforms 6–10 are spikes, waveforms 11–14 have two ramps, and waveforms 18–19 are irregular shapes. The leading edges do not match the predefined tracking gate 32.5 for TOPEX (Ku) in most cases. Thus, waveforms over lakes should be retracked for the precise ranges to monitor the lake level variations.

## II. WAVEFORM RETRACKING METHODS

Over lakes, the waveform is contaminated by the shoreline topography, lag response of the Automatic Gain Control (AGC) and so on. Waveform retracking aims to determine the offset between the predefined tracking gate derived from the on-satellite software and a known, fixed, instrument-independent position on the leading edge of the waveform and to correct the satellite range measurement accordingly [5], [12]–[16]. The main target of waveform retracking is to decrease the short-wavelength

random noise, long-wavelength errors from SWH bias, range errors, instrumental errors, and errors from the non-Gaussian lake surface. Methods of waveform retracking may be classified into two categories as the functional fitting model and the statistical method.

### A. Beta-Parameter Function Model

For most cases, waveforms follow the Brown model. So, a 5-beta-parameter function is used to fit the single-ramp return waves, and a 9-beta-parameter function is used to fit the two-ramp return, with the least squares method or the maximum likelihood method. The general beta-parameter function is [5], [12], [17]

$$y(t) = \beta_1 + \sum_{i=1}^n \beta_{2i}(1 + \beta_{5i}Q_i)P\left(\frac{t - \beta_{3i}}{\beta_{4i}}\right) \quad (1)$$

where  $y(t)$  is the returned power

$$Q_i = \begin{cases} 0, & \text{for } t < \beta_{3i} + 0.5\beta_{4i} \\ t - \beta_{3i} - 0.5\beta_{4i}, & \text{for } t \geq \beta_{3i} + 0.5\beta_{4i} \end{cases}$$

$P(x) = \int_{-\infty}^{\pi} (1)/(\sqrt{2\pi}) \exp(-0.5q^2) dq$ ,  $n = 1, 2$  is the number of the ramp in the waveform range window which corresponds to single or double reflecting surfaces, respectively.  $\beta_1$  is the thermal noise level,  $\beta_{2i}$  is the return signal amplitude,  $\beta_{3i}$  is the mid-point on the leading edge,  $\beta_{4i}$  is the return waveform risetime, and  $\beta_{5i}$  is the slope of the trailing edge.

When the linear trailing edge is replaced by an exponential decay term [17], (1) is rewritten as

$$y(t) = \beta_1 + \sum_{i=1}^n \beta_{2i} \exp(-\beta_{5i}Q_i)P\left(\frac{t - \beta_{3i}}{\beta_{4i}}\right) \quad (2)$$

where

$$Q_i = \begin{cases} 0, & \text{for } t < \beta_{3i} - 2\beta_{4i} \\ t - \beta_{3i} + 2\beta_{4i}, & \text{for } t \geq \beta_{3i} - 2\beta_{4i} \end{cases}$$

### B. Off-Center of Gravity (OCOG) Retracking Algorithm

Based on the definition of a rectangle about the effective center of gravity of waveform, the amplitude and width, the OCOG retracking method [16] uses full waveform samples to locate the half-power point as

$$\text{LEG} = \frac{\sum_i i P_i^2}{\sum_i P_i^2} - \frac{1}{2} \frac{(\sum_i P_i^2)^2}{\sum_i P_i^4} \quad (3)$$

where  $P_i$  is the sampled power.

OCOG is simple to implement, though it is purely statistical and is not based on any physical model of the reflecting surfaces. It is sensitive to the waveform shape affected by surface undulations and off-nadir pointing, because it uses the full samples in waveform bins.

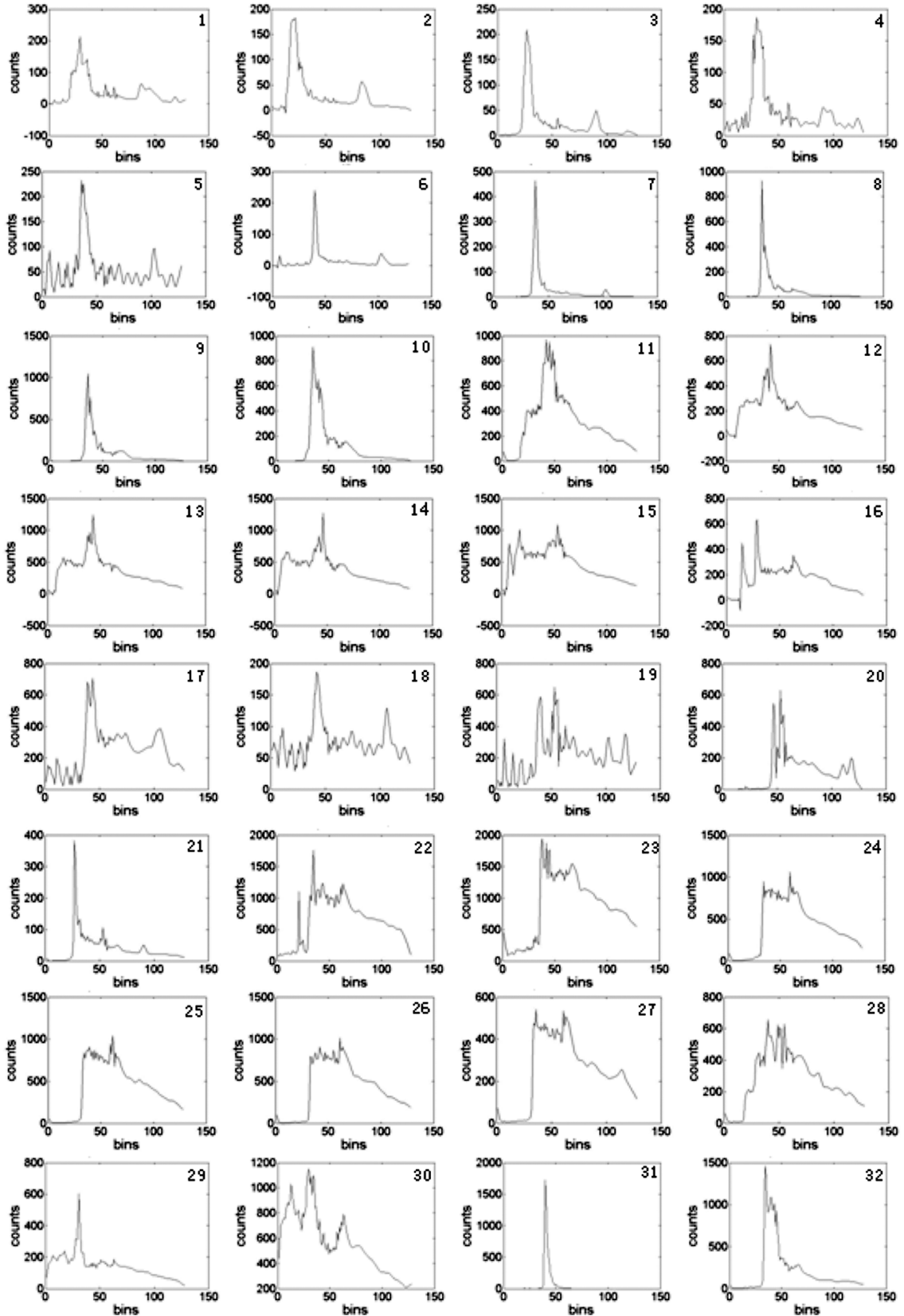


Fig. 2. Waveforms of TOPEX/Poseidon over Hulun Lake.

### C. Threshold Retracking Algorithm

The threshold retracking technique is used to retrack the waveforms over coastal seas and lakes as it takes advantages

of sensitivity to the surface topography and is simple to implement. Furthermore, if given an appropriate threshold level, it can retrack the waveforms to obtain the robust range corrections [18], [19]. The thermal noise  $P_N$  is determined by calculating

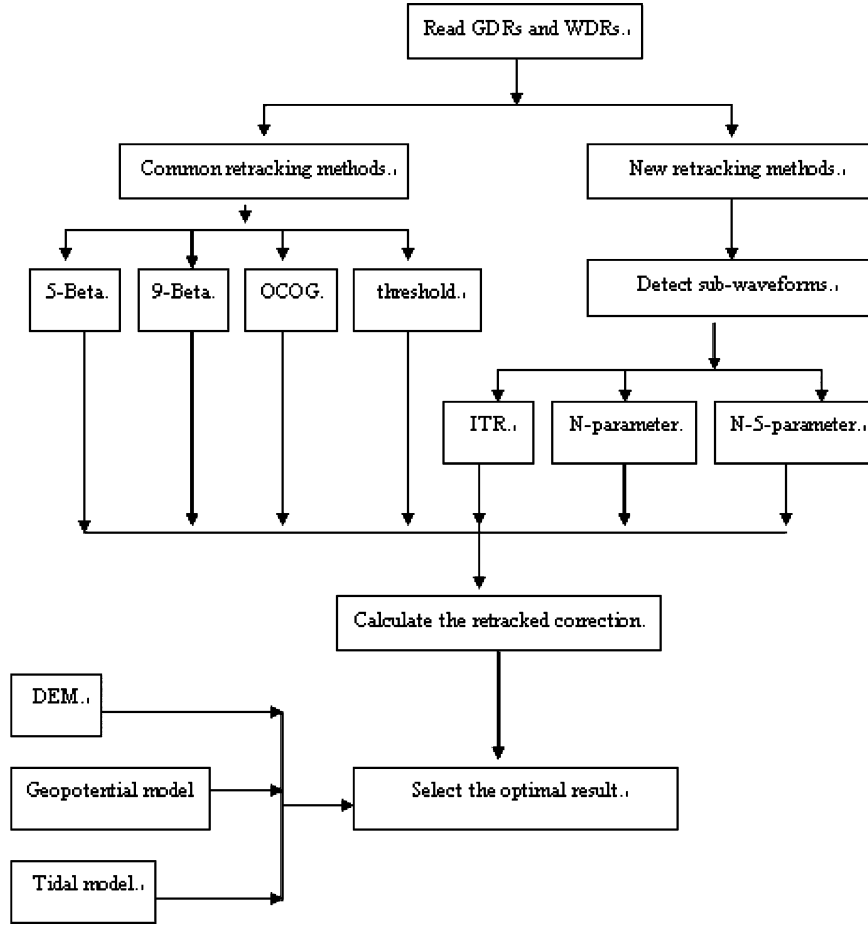


Fig. 3. Flow of the waveform retracking system.

the average amplitude of the waveform samples over 5–10 of earlier gates. Then the threshold level is

$$T_l = P_N + p(A - P_N) \quad (4)$$

where  $A$  is the amplitude of the waveform, and  $A = \sqrt{\sum_{i=\text{num}1}^{\text{num}2} W_i^4 / \sum_{i=\text{num}1}^{\text{num}2} W_i^2}$ .  $p$  is a percentage,  $0 < p < 1$ . It is very difficult to choose the optimal  $p$ , in general,  $p = 20\%, 30\%, 50\%$ , or  $70\%$  [5].

The retracking location on the leading edge of the waveform is linearly interpolated between the bins adjacent to  $T_l$  using

$$g_r = g_w - 1 + \frac{T_l - W_{k-1}}{W_k - W_{k-1}} \quad (5)$$

where  $g_w$  is the location of the first gate exceeding  $T_l$ . If  $W_k = W_{k-1}$ ,  $g_r = g_k - 1$ .

#### D. Improved Threshold Retracker

Based on the altimetry principle, the middle point of leading edge, which is the criterion for ranging timer, is corresponding to the half power of returned pulse. Sub-waveforms are first formed based on leading edges detected in a waveform with the improved threshold retracker (ITR). Then the middle point of each leading edge is estimated to compute the retracking range

correction. Finally, the referenced water surface height is calculated according to the geoid undulation from a local geopotential model, SST and tide heights from an ocean tide model, and compared with all retracking ranges to determine the best one.

Suppose that  $P_i$  is the returned power for the  $i$ th gate. The mean difference between returned powers of spacing one is defined as

$$d_2^i = \frac{1}{2}(P_{i+2} - P_i). \quad (6)$$

The standard deviation for all differences of waveform powers of spacing one is

$$S = \sqrt{\frac{(N-2) \sum_{i=1}^{N-2} (d_2^i)^2 - \left( \sum_{i=1}^{N-2} d_2^i \right)^2}{(N-2)(N-3)}} \quad (7)$$

where  $N$  is the maximum gate in the waveform.

If  $d_2^i > 0.1S$ , go on to resolve  $d_2^{i+1}$ . If  $d_2^{i+1} > 0.1S$ , continue to calculate  $d_2^{i+2}$ . When  $d_2^{i+j-2} > 0.1S$ ,  $d_2^{i+j-1} \leq 0.1S$  and  $j \geq 3$ , a leading edge is found with a doubt. Then the power difference between neighboring gates is defined as

$$d_1^k = P_{k+1} - P_k (k = i, i+1, \dots, i+j-1). \quad (8)$$

The standard deviation of all single power difference for the waveform is

$$S_1 = \sqrt{\frac{(N-1) \sum_{i=1}^{N-1} (d_1^i)^2 - \left(\sum_{i=1}^{N-1} d_1^i\right)^2}{(N-1)(N-2)}}. \quad (9)$$

If  $d_1^k > 0.1S_1$  for  $k = i, i+1, i+j-1$ , we think a real leading edge is found. If only one  $d_1^k \leq 0.1S_1$  appears, we also think it a leading edge. Let  $\tilde{P}_{k+1} = (1)/(2)(P_{k+2} - P_k)$  take the place of original  $P_{k+1}$ . If there are two single-differences dissatisfying the above condition, that is,  $d_1^k \leq 0.1S_1$  and  $d_1^{k+1} \leq 0.1S_1$ , we think no leading edge is found.

Based on the above procedure, the whole waveform should be searched for all leading edges. For each leading edge, for example,  $P_k(k = i, \dots, i+j-1)$ , select  $n$  samples forward and backward from the  $i$ th gate and  $i+j-1$ th gate, respectively, to form a new sub-waveform  $P_k(k = i-n, i-n+1, \dots, i-1, i, \dots, i+j-1, i+j, \dots, i+j-1+n)$ . In general,  $n \leq 5$ . For each sub-waveform, the retracked range correction can be calculated with the following equations as:

$$A = \sqrt{\frac{\sum_i P_i^4}{\sum_i P_i^2}} \quad (10)$$

$$P_N = \frac{1}{5} \sum_{i=1}^5 P_i \quad (11)$$

$$T_L = \frac{1}{2}(A + P_N) \quad (12)$$

$$G_R = G_k - 1 + \frac{T_L - P_{k-1}}{P_k - P_{k-1}} \quad (13)$$

$$\Delta R = R_0(G_0 - G_R) \quad (14)$$

where  $A$  is the power amplitude of sub-waveform,  $P_N$  is the thermal noise,  $T_L$  is called as the threshold level,  $G_k$  is the gate whose power is first to be greater than  $T_L$  for sub-waveform,  $G_R$  is the middle point of leading edge for sub-waveform,  $G_0$  is the tracking gate,  $R_0$  is the one-way range corresponding to the sampling interval, and  $\Delta R$  is the retracked range correction.

Several leading edges may be found in one waveform and the corresponding retracked range corrections can be calculated through the above procedures. Because the unknown range corresponds to a waveform with a fixed value, only one right retracked range correction exists in the waveform. Compared with a reference height, we can determine the best retracked range correction. The referenced heights are geoid anomaly, SST and tidal height.

#### E. N-Parameter Retracker

There are only one or two ramps in the waveform for the Beta-parameter function model, called as 5-beta retracking algorithm and 9-beta retracking algorithm, respectively. From ITR, the number of ramp in a waveform may be more. If a waveform contains  $n$  sub-waveforms, the waveform may be fitted by

$$y(t) = \beta_1 + \sum_{i=1}^n \beta_{2i} F(\beta_{3i}, \beta_{4i}, \beta_{5i}) P\left(\frac{t - \beta_{3i}}{\beta_{4i}}\right) \quad (15)$$

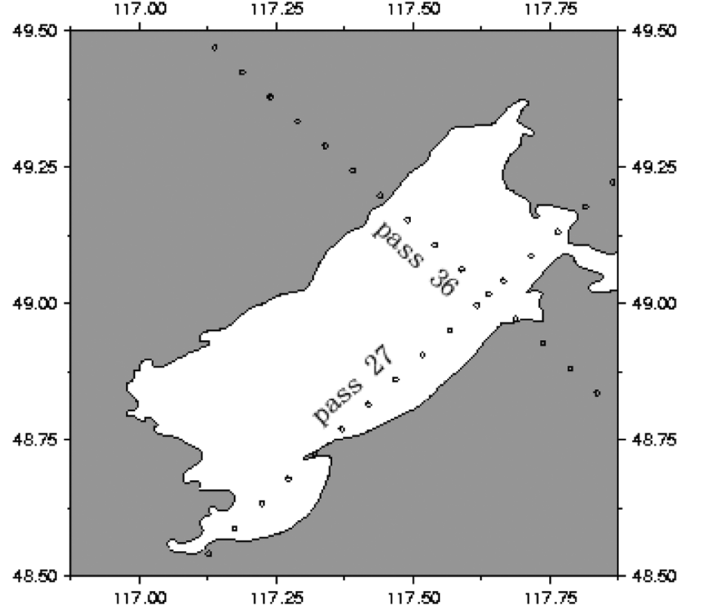


Fig. 4. Ground tracks of TOPEX/Poseidon over Hulun Lake (unit in degree for longitude and latitude).

where  $F(\beta_{3i}, \beta_{4i}, \beta_{5i})$  may be a linear or exponential function. If  $n = 1, 2$ , N-parameter retracker is reduced to be the 5-beta or 9-beta function.

#### F. N-5-Parameter Retracker

First, a waveform should be detected to find all sub-waveforms. Suppose there are  $n$  sub-waveforms. Then the 5-beta retracking algorithm is used to retracket every sub-waveform. Finally, the given referenced height compares with each retracked result to determine the best one.

Based on the above retracking algorithms, we design a waveform-retracking software to retracket altimeter waveform over lakes. The flow of the software is shown in Fig. 3.

### III. MONITORING WATER LEVEL VARIATIONS OF HULUN LAKE USING TOPEX/POSEIDON DATA

As shown in Fig. 4, Hulun Lake is located in the North China within  $116^\circ 58' - 117^\circ 48' E$  and  $48^\circ 31' - 49^\circ 20' N$ , covering an area of about  $2339 \text{ km}^2$ . The average depth is 5.92 m with a maximum depth of 8.0 m. Hulun Lake is an open lake: precipitation from 80 more rivers supplies its major water sources, and there is one river through which the lake water flows out. As shown in Fig. 4, there are two TOPEX/Poseidon passes across the lake, pass 36 and 27. Several points of pass 36 are located in the middle of the lake. As the waveforms in the middle of the lake follow the Brown model without the effect of land topography, the middle points of pass 36 located in the middle of the lake can give a better surface height. Pass 27 is may be contaminated by the land topography and the AGC response because it's close to the shoreline. So pass 27 of TOPEX/Poseidon over Hulun Lake is retracked to test the efficiency of the new retrackers in the paper for the monitoring of the lake water level variations.

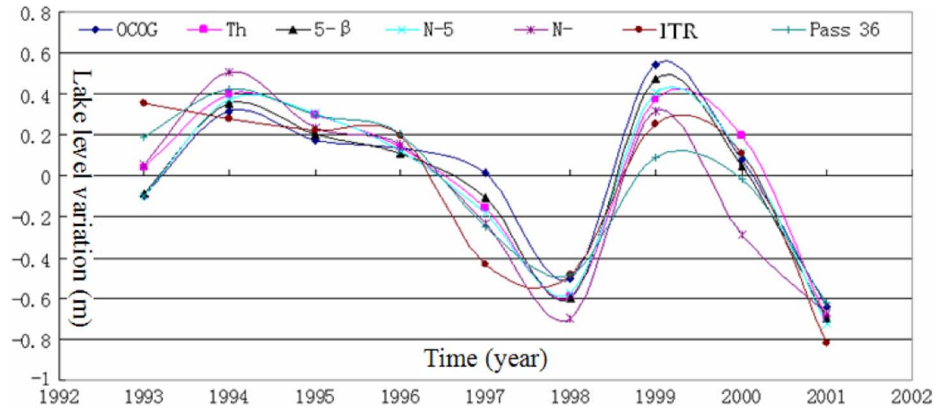


Fig. 5. Comparison of Hulun Lake level variations.

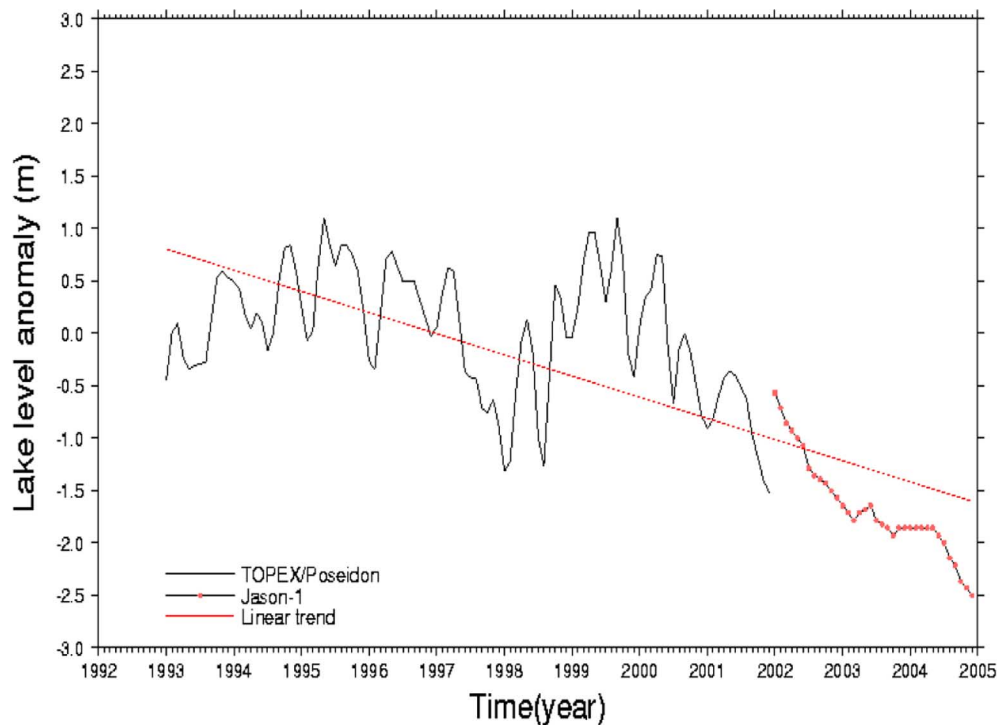


Fig. 6. Monthly lake level anomaly of Hulun Lake.

The waveform retracking methods we used in the waveform retracking of pass 27 over Hulun Lake are OCOG, threshold method (Th),  $5\text{-}\beta$ -parameter function ( $5\text{-}\beta$ ),  $N\text{-}\beta$  retracker ( $N\text{-}$ ),  $N\text{-}5$ -parameter retracker ( $N\text{-}5$ , and improve threshold retracker (ITR). Comparisons of the retracked results with the *in situ* observation of Hulun Lake through 1993 to 2001 are made, shown in Fig. 5. The *in situ* observation is from the Hulun Lake hydrological observing station. The middle points of pass 36 are far away from the bank, so the root mean square (RMS) is only 11.3 cm. The maximum difference between the GDR of pass 27 and the observed data is 73 cm in 1997, the minimum difference is  $-0.7$  cm in 1999, and RMS is only 33.3 cm. Among all retracking results, ITR is the best, the maximum difference is 24.7 cm in 2000, and the minimum is  $-9.2$  cm. The RMS is only 13.4 cm, which is close to that of pass 36. The second is  $N$ -parameter retracker, whose RMS is 17.6 cm.

Fig. 6 shows the trend of monthly water level anomaly of Hulun Lake monitored with TOPEX/Poseidon and Jason-1. The trend is  $-0.09$  m/a in the least squares sense. The water level is descending which may be due to the reduction of precipitation and the increase of industrial and agricultural waters. The seasonal variations are also found in the time series with the radar altimetric technique in the least squares sense. The seasonal variation is the main part of Hulun Lake level fluctuation, and the amplitudes of annual and semiannual variations are 0.19 and 0.14 m, respectively.

In addition, we use the wavelet transformation to analyze the Hulun Lake level changes with the base wavelet of Morlet. The result is shown in Fig. 7. The periods detected by the wavelet technique are 1490-, 730-, 364-, and 180-days. Meantime, these periods are temporally changing.

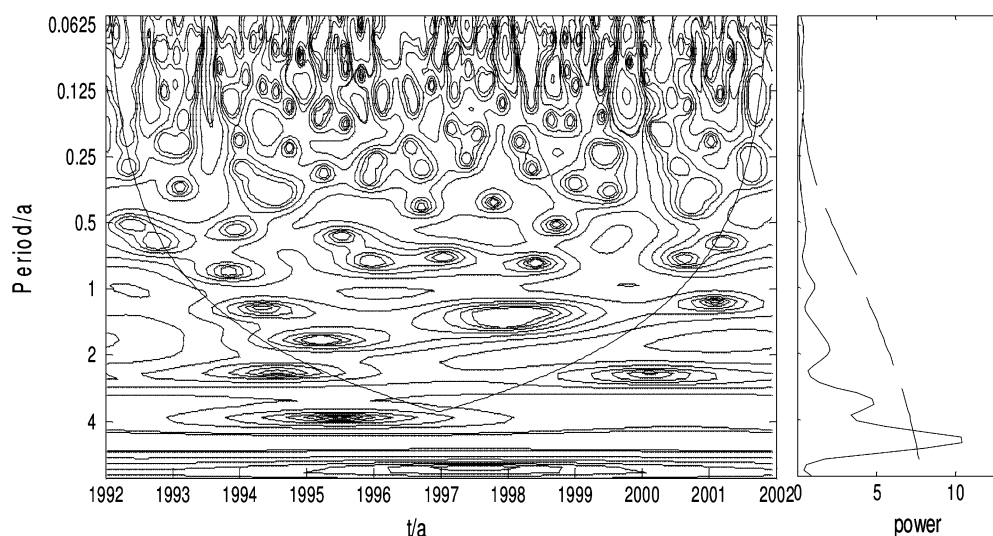


Fig. 7. Wavelet analysis on water level variation of Hulun Lake.

#### IV. CONCLUSION

Waveform retracking algorithms with three new retracers are proposed in this paper to improve the altimetric observation for the temporal change monitoring on the lake level. The case study of Hulun Lake indicates that the retracking technique perform quite well in the monitoring of the lake level variations. According to the study, the level of Hulun Lake is descending over the past several years, which corresponds exactly to the *in situ* hydrological observation. The analysis on the Hulun Lake level variations with the wavelet transformation gives several periods, that is, 1490-, 730-, 364-, and 180-days, and these periods are temporally changing.

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