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The Performance of Altimeter Waveform Retrackers at Lake Baikal

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ABSTRACT

At each of five fixed locations along the ground tracks of JASON-1 and ENVISAT, a repeat-track analysis of 1-Hz sea surface height (SSH) data has been conducted to assess the performance of waveform retrackers over Lake Baikal in Siberia, Russia. This simple analysis of time series at each point location is needed to minimize the effect of the range correction artifacts in current Geophysical Data Record (GDR) data products of radar altimeters in in-land areas. Using the retracked data available in the GDRs as the baseline, two retrackers are evaluated in terms of the number of valid data points produced and the degree of agreement with in-situ data of water level record. The threshold retrackers that are based on the amplitude of the robust OCOG algorithm (Offset Center of Gravity) are found to perform the best in Lake Baikal.

Key words: Lake Baikal, Satellite altimetry, Waveform retracking

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1. INTRODUCTION

Monitoring the relative lake level changes became possible on a global scale starting with the TOPEX/POSEIDON altimeter mission (Birkett 1995). This remote sensing technology is well validated; the altimeter-monitored data of lakes and reservoirs are available at several websites (Crétaux et al. 2011a, b). The accuracy of altimeter range data depends primarily on the method of waveform retracking as well as on the data quality of the precise orbit and geophysical range corrections. This study focuses on waveform retracking methods. The radar altimeter returns from the surface of inland bodies of water can be contaminated by coastal land surface, seasonal ice, snow, or vegetation. Also, because of calm waters of rivers and lakes, the waveforms often are specular echoes (Gommenginger et al. 2011) having a peak amplitude that is significantly increased rendering the retrackers unsuitable based on the Brown ocean model (Brown 1977). Strong peaky echoes are returned also from thin sea-ice (Peacock and Laxon 2004; Kouraev et al. 2008).

The geophysical range corrections available in the Geophysical Data Records (GDRs) of ENVISAT and JASON-1 have known problems over inland bodies of water. Crétaux et al. (2009), for example, reported a decimeter-level artifact of dry troposphere correction that is caused by atmospheric pressure interpolated at the altitude of the bottom floor instead of the surface, of Lake Issykkul. To minimize the effect of this GDR artifact, the time series data set of altimeter-derived water level at each fixed location was analyzed separately in this investigation. Lake Baikal, located in Siberia, Russia, the world's deepest (maximum depth > 1.6 km), oldest (older than 25 million years), and largest in terms of storage, is increasingly warming and

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undergoing other environmental changes over the last six decades (Hampton et al. 2008). Recent studies of Lake Baikal geophysical and climate change processes include the role of lake ice cover in climate and environmental change in Lake Baikal (Kouraev et al. 2007), Lake Baikal tide modeling and lake seiche using lake gauge data (Timofeev et al. 2009), and lake storage change observed from radar altimetry and space gravimetry (GRACE) (Hwang et al. 2011). Here we choose Lake Baikal, an environmentally diverse lake undergoing climate change, to assess the performance of various radar altimeter retrackers for two different radar altimetry systems, ENVISAT and JASON-1.

The test locations of altimeter data were selected near the center of the lake as much as possible to avoid the waveform data contaminated by radar echoes from land reflectors and the loss of lock of onboard trackers near the coasts. The ionospheric correction derived from a dual-frequency altimeter is not available at every inland data point thus, to retain more data points over the lake surface, the JPL Global Ionosphere Maps (GIM) data were used instead. Due to similar reasons in land areas, the model-based wet tropospheric correction was used instead of that of onboard radiometers. The repeating orbits of satellite altimeter missions are maintained within a cross-track band, usually 2 km wide. In addition, the GDR data are sampled at a regular time interval rather than at a fixed along-track distance. Thus, both the along- and cross-track distances from each ground-fixed location of the 1-Hz GDR data sample points vary from cycle to cycle. The correction for lake surface gradient coupled with this variation in horizontal position (Brenner et al. 1990) was made using the EGM 2008 geoid (a model product called the EGM 2008 for Oceanographic Applications). The JASON-1 Sensor GDR (SGDR) data product provided by the AVISO-CNES Data Center and the ENVISAT MWS (reprocessed V2.1 SGDR) data of the European Space Agency were used.

2. TEST LOCATIONS AT LAKE BAIKAL

The location of a single ground truth gauge site, Port Baikal, is marked by a cyan circle in Fig. 1. The ground tracks of ENVISAT 1-Hz data points are denoted by empty diamonds whereas those of the original JASON-1 orbit (until cycle 259 before the orbit change) are shown by black dots. Three locations (blue diamonds), A (pass 879), B (pass 94), and C (pass 335), were selected on three ENVISAT tracks passing through the southwestern Lake Baikal near the ground truth. Pass 62 of JASON-1 crosses the Lake Baikal nearby the ground truth location to the east and pass 79 to the west around the western-most tip of the lake. To avoid the land contamination, points D and E (two red dots in Fig. 1) on pass 62 of JASON-1 away from the coast were selected for this study. The short segment of pass 79 was not used because of the inevitable closeness of few JASON-1 data points to the coast.

3. ENVISAT DATA ANALYSIS

Frappart et al. (2006) found that the ice1 retracker's SSH data in the GDR agreed best with the in situ gauge data of inland water level in their study of ENVISAT validation over the Amazon Basin. They found also the ice1 retracker

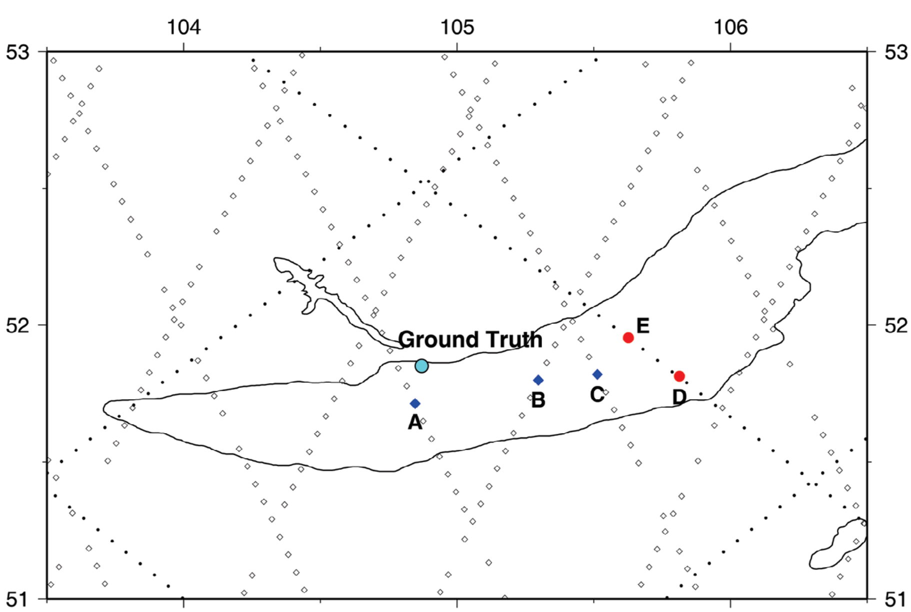

Fig. 1. Location of the Ground Truth gauge station and five test locations selected for the ENVISAT and JASON-1 ground tracks in the southwestern area of Lake Baikal.

yielded a larger number of valid SSH data points. Thus, in this study as the baseline, we included the ENVISAT GDR data of the ice1 retracker and the ocean retracker as well which is preferred for ocean applications.

Frappart et al. (2006) also pointed out that none of the four retracking algorithms (ocean, ice1, ice2, and sea ice) used for production of the ENVISAT GDR were developed for inland water applications. Thus, in an effort to include more SSH data points than the GDR, we retracked the ENVISAT waveforms using two additional retrackers: a 50% threshold retracker and an MLE3-type (3-parameter Maximum Likelihood Estimation) retracker (Zanifé et al. 2003) which corresponds to the GDR ocean retracker. The MLE3-type retracker is based on the Brown ocean model (Brown 1977) and corresponds to the MLE4 (4-parameter Maximum Likelihood Estimation) retracker (Amarouche et al. 2004) with the parameter of the off-nadir angle held fixed. The Gaussian distribution of the linear ocean wave field is assumed which happens to be true also for the implementation of the GDR ocean retracker (Gómez-Enri et al. 2006).

The 50% threshold retracker (50% TR/OCOG) included in this study corresponds to the ice1 retracker of the GDR. There are subtle differences in the detailed processing of threshold retrackers. The ice1 retracker determines the range to surface by finding the sample location in a waveform at which the amplitude is 25% of the OCOG amplitude (Frappart et al. 2006), whereas the 50% TR/OCOG retracker locates the range corresponding to one half of the OCOG-estimated amplitude. The sea ice retracker in the ENVISAT GDR, on the other hand, is a 50% threshold retracker that uses as the reference amplitude for the threshold detection the maximum amplitude of waveform (Frappart et al. 2006; Laxon 1994). Compared with the maximum amplitude based on a single sample in a waveform, the OCOG amplitude based on an average of multiple samples is less sensitive to speckle noise. To suppress the contribution of low amplitude samples, a squared waveform amplitude is used in the OCOG method (Bamber 1994) which is an update of the original algorithm designed for an onboard tracker (Wingham et al. 1986).

The retracked 18-Hz SSH data were compressed to 1-Hz using a robust line fit. This along-track data compression reduces the noise level of 18-Hz range data which is about 8.5 cm RMS. This noise level estimate of the 18-Hz range is based on the robust line fit of the GDR ocean retracker data in the Pacific bounded by 20°S - 0°/260°E - 280°E. Figure 2 shows the 1-Hz SSH data of four retrackers around point B on pass 94 with the in-situ data of water level (on the first day of each month, blue curve) in the background. An arbitrary shift of the in-situ water level data by 40.3 m was needed for a better visual comparison. This relative bias between two height data sets should include the geoid gradient effect and difference in vertical datum. The absolute height calibration of radar altimeters is not intended in this study. Thus to assess a retracker's agreement to the ground truth data of lake level, the RMS difference about the mean was used instead of that about zero. Only the ENVISAT cycles 33 through 75 were included corresponding to a 4-year period of 2005 - 2008. Based on a visual inspection and thus rather arbitrarily, it was decided to exclude few seemingly wild data points that fall outside the band between height levels 414.4 and 416 m from further data analysis.

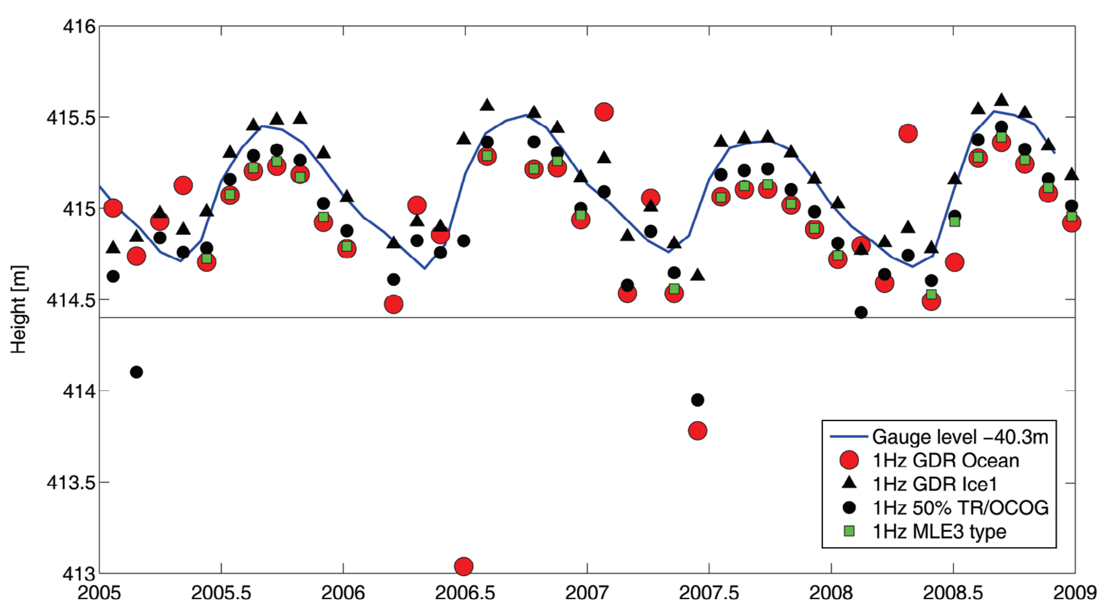

Fig. 2. The ENVISAT SSH data (1 Hz) of multiple retrackers at point B on pass 94 compared with the in situ data of monthly water level (blue curve).

The lake surface is frozen from January - May (Timofeev et al. 2009). In Fig. 2, it is clearly visible that the agreement of all retrackers' data becomes worse with the in situ data curve during the local winter. Over the lake surface presumably covered by ice, it is seen in Fig. 2 that ocean retrackers perform the worst and even most of the MLE3-type retracker data points are missing. No attempts were made to isolate or distinguish data points over the lake surface covered by ice or snow from those over water surface in this analysis. However, it should be noted that Kouraev et al. (2008) reported a reliable method of ice discrimination in Lake Baikal based on a joint classification of altimeter backscatter coefficient and a radiometer parameter.

Over 2005 - 2008, the GDR ice1 retracker produced more valid data points (40 black triangles in Fig. 2) of 1-Hz SSH at location B than both the GDR ocean retracker (38 red circles) and the 50% TR/OCOG retracker (38 black dots) do. On the other hand, the MLE3-type retracker (25 green squares) failed to produce more data points than the GDR ocean retracker (38 red circles). The RMS (about mean) difference of 1-Hz ENVISAT SSH data from the in situ monthly water level computed for each retracker is 25.6 cm for the GDR ocean, 9.5 cm for the GDR ice1, and 12.1 cm for the 50% TR/OCOG for 36 data points at which all three retrackers produce valid heights, excluding the MLE3-type. Thus, the SSH data of both the GDR ice1 retracker and the 50% TR/OCOG retracker agree with the in situ data regarding monthly water level better than the GDR ocean retracker concurring with the findings of Frappart et al. (2006). In addition, the GDR ice1 retracker produces a slightly more number of valid data points than the GDR ocean retracker does. The sea state bias correction in the GDR was applied. Table 1 comparing performance of retrackers for the 36 data points shows that the sea state bias correction improves the SSH data of retrackers rather insignificantly. Similar results were obtained at other along-track locations. For example, the RMS difference of the ice1 SSH data from the in situ water level is, with the GDR sea state bias correction applied, 10.5 cm at location A (15 km from GT, the ground truth site) and 13.8 cm at point C (44 km from GT) similar to 9.5 cm at point B (30 km). Frappart et al. (2006) noted that the ENVISAT RA-2 altimeter monitors most of water stages they included in their Amazon Basin study as accurately as 15 cm close to these statistics. It needs to be pointed out, however, that the ENVISAT data points over frozen lake surface (from January - May) are included in the RMS differences of this study and Fig. 2 reveals noisier retracked data over ice covered surface than those over water lake surface.

The study of Kouraev et al. (2009) on four retrackers' data in the ENVISAT GDR reports on the ice1 SSH data that are consistently higher (+25 ± 4 cm) than those of the GDR ocean retracker for the case of water surface in Aral Sea agreeing with the comparison of the GDR ocean retracker data (red circles) and the GDR ice1 retracker data (black triangles) in Fig. 2. Kouraev et al. (2009) reported a negative (opposite sign) relative bias with a large variance (-25 ± 16 cm) over the ice covered surface which too can be seen in Fig. 2 as discussed earlier.

4. JASON-1 DATA ANALYSIS

The only retracked range available in the JASON-1 GDR is produced by the MLE4 retracker to account for the off-nadir angle of the altimeter that can become as high as 0.8 degrees (Amarouche et al. 2004). In addition, the degree of series expansion for the modified Bessel function included in the flat surface impulse response function was increased to obtain the approximate analytic form of the Brown ocean scattering model that is appropriate for such large angles of pointing error. To compare the performance of different retrackers as we did for the case of the ENVISAT SSH data, we added retracked JASON-1 data of the 50% TR/OCOG retracker (ice1 type) and an ocean retracker (MLE4 type). There is little difference between the MLE4 retracker of JASON-1 GDR and the MLE4 type retracker as far as the theoretical model of microwave scattering with ocean surface is concerned. The latter retracker was tested in this study to see if a different software implementation can make a difference in producing more 1-Hz data points that are valid.

Figure 3 shows the SSH data of three retrackers (compressed to 1 Hz) at point E on pass 62 of JASON-1, about 53 km off the ground truth. The in situ data of monthly water level is included (blue curve, shifted down by 40 m) in the figure for comparison. In this study, cycles 110 - 257 were included to get the JASON-1 SSH time series of 2005 - 2008. Only those SSH data points that fall within a height range 414 - 417 m were used as valid for further analysis.

Here again, no attempts were made to distinguish data points over the lake surface covered by ice or snow on ice. In Fig. 3, slightly noisier data points of the 50% TR/OCOG (black triangles) and MLE4-type retracker (green squares) are visible during the local winter (January - May) whereas no GDR SSH data (red dots) are found over the lake surface presumably frozen. Including these additional points in winter, the 50% TR/OCOG produces more data points

Table 1. RMS differences of the ENVISAT SSH at location B on pass 94 from in situ monthly water level data with/without the GDR sea state bias (SSB) correction.

Retracker	Corrected for SSB (in cm)	No SSB (in cm)
GDR ocean	25.6	26.1
Ice1	9.5	9.8
50% TR/OCOG	12.1	12.8

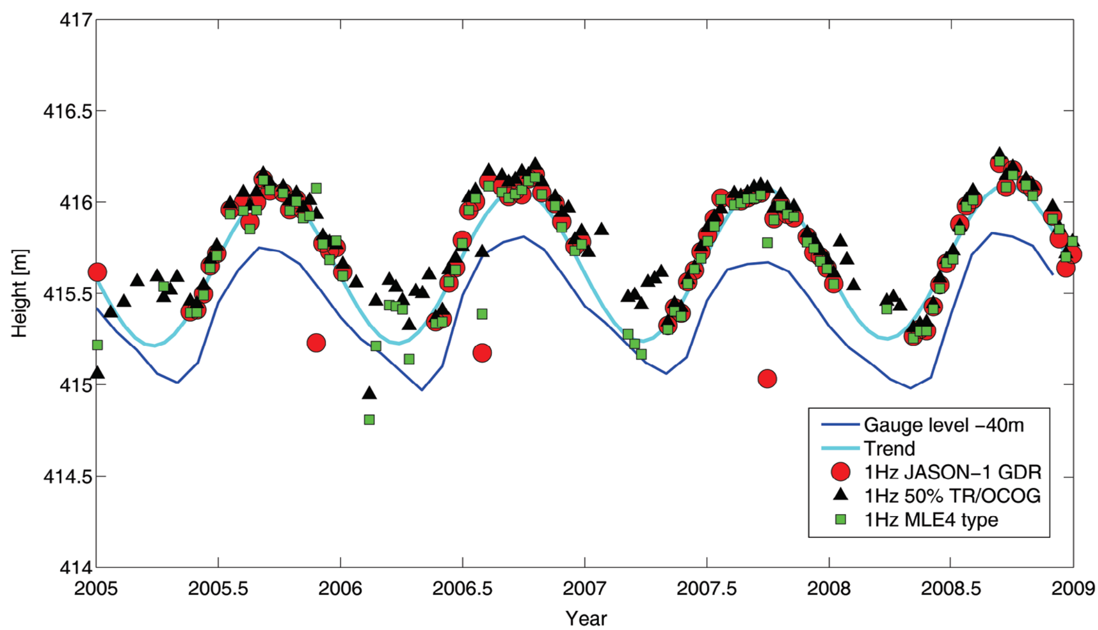

Fig. 3. The JASON-1 SSH data (1 Hz) of three retrackers at point E on pass 62. The trend curve (cyan) was estimated from the MLE4-type ocean retracker data (94 green squares).

of valid 1-Hz SSH (115 black triangles) than the GDR ocean retracker (81 red dots) within this 4-year time span. The MLE4-type retracker yields 94 valid data points (green squares), which are also more than those of the GDR retracker. The RMS difference of retracked 1-Hz SSH data from the monthly water level computed for each retracker is 16.4 cm for the GDR ocean, 10.7 cm for the MLE4-type, and 9.7 cm for the 50% TR/OCOG at 81 common data points mostly over water surface because there are apparent data gaps of the GDR retracked data during winter in Fig. 3 as noted earlier. Therefore, the 50% TR/OCOG retracker outperforms the ocean retrackers for the JASON-1, exactly like what we found for the case of the ENVISAT SSH data. The RMS differences from the in situ data increase by 1 - 3 cm when the sea state bias correction in the GDR is not applied (Table 2). Similar results were obtained at another point D on pass 62 (65 km from the GT). For example, the RMS difference of retracked 1-Hz SSH data with respect to the monthly water level is, with the GDR sea state bias correction applied, 14.8 cm for the GDR ocean, 15.6 cm for the MLE4-type, and 8.4 cm for the 50% TR/OCOG for 82 data points where all three retrackers produce valid SSH data.

Using 94 data points (green squares) produced by the MLE4-type ocean retracker, the trend of water level change for 2005 - 2008 (cyan curve in Fig. 3) was estimated. A curve modeled by annual and semiannual fluctuations and a linear change was fitted to the 1-Hz data points. The amplitude of the annual cycle is 42 cm with a phase angle of 263° at the maxima corresponding to late September. Although it is devoid of detailed year-to-year changes except a linear slope of 13 mm yr^{-1}, the trend curve (cyan) appears to have a resemblance with the monthly water level curve (blue) exhibited in Fig. 3. It is observable in the figure that the winter data points of the 50% TR/OCOG retracker tend to lie well above the cyan trend curve, suggesting that radar echoes from the lake surface covered by ice and/or snow contain the freeboard height of a decimeter level. To get a closer look at this tendency, the height differences from the in situ water level data are shown in Fig. 4 for two retrackers, the 50% TR/OCOG and the MLE4-type. During local winter (yellow intervals) when the lake surface is frozen, the residual curve of the 50% TR/OCOG retracker (red dots) indeed goes well above 10 cm, the level of agreement with in situ data, although both retrackers' data look noisier than elsewhere.

Timofeev et al. (2009) reported sub-centimeter tides along with seiche signals that can be as big as 6 cm in Lake Baikal based on pressure sensor data at Listvyanka site.

Table 2. RMS differences of the JASON-1 SSH at location E from in situ monthly water level data with/without the GDR sea state bias (SSB) correction.

Retracker	Corrected for SSB (in cm)	No SSB (in cm)
GDR ocean	16.4	19.4
MLE4-type	10.7	12.3
50% TR/OCOG	9.7	11.0

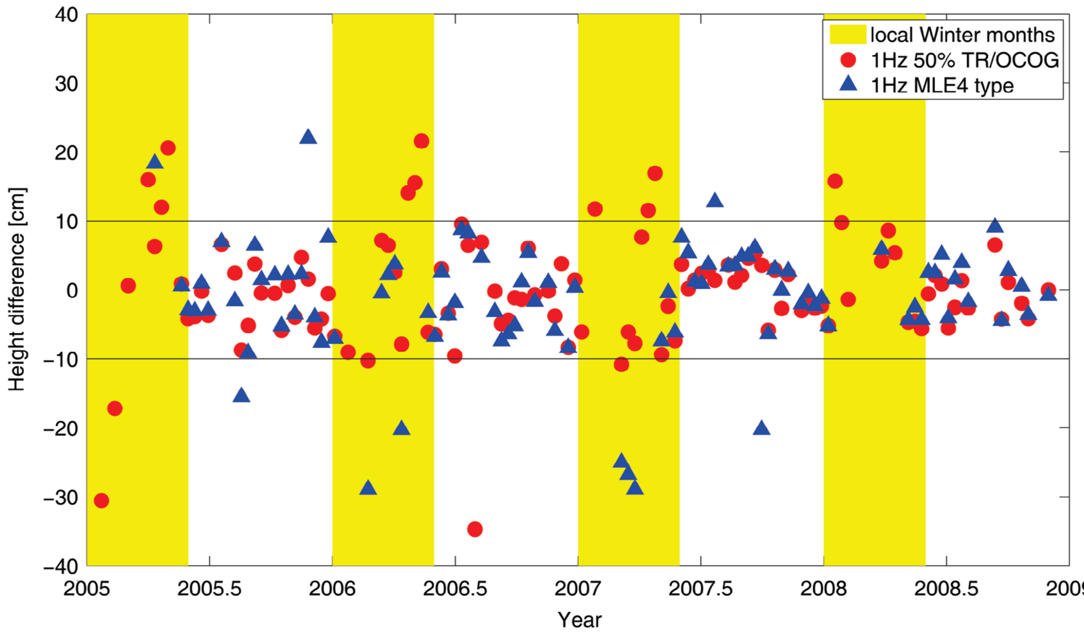

Fig. 4. Residual SSH with respect to the in situ lake level of the 50% TR/OCOG (red dots) and the MLE4-type (blue triangles) retrackers applied to the JASON-1 waveform data.

However, it is not deemed plausible to detect such small tidal signals from satellite altimetry alone, which agree with monthly in situ data by about 10 centimeters in Lake Baikal.

5. CONCLUSIONS

The threshold retrackers based on the OCOG amplitude perform better than the ocean-model retrackers in Lake Baikal for the altimeter data of both JASON-1 (50% TR/OCOG) and ENVISAT (ice1 retracker). The performance criteria hinge upon the abundance of valid data points that can be produced and the agreement with the in situ lake level data. The JASON-1 SSH data of 50% TR/OCOG retracker have a RMS difference of 8 - 10 cm from the in situ data and the ENVISAT ice1 retracker has a RMS agreement of 10 - 14 cm. When the lake surface is frozen, the freeboard height is evident up to a few tens of centimeters in the JASON-1 SSH data of 50% TR/OCOG retracker although the retracked data look noisier.

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