Satellite Radar Altimetry for Monitoring Small River and Lakes in Indonesia

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Abstract

Remote sensing and satellite geodetic observations are capable for hydrologic monitoring of freshwater resources. For the case of satellite radar altimetry, limited temporal resolutions (i.e., satellite revisit period) hinder the use of this method for a short (<weekly) interval monitoring of water level or discharge. In terms of spatial resolution, current satellite radar altimeter footprints limit the water level measurement to large rivers (e.g. wider than 1 km). Some studies indeed reported successful retrieval of water level for small rivers as narrow as 40 m. However, the processing of current satellite altimetry signals for small water bodies to retrieve accurate water level remains challenging. Physically, the return radar signal returned by water bodies smaller than the satellite footprint most likely contaminated by non-water surface, which presumably degrading the quality of the measurement. To address this scientific challenge, we tried to carefully select the waveform shapes correspond to the range measurement resulted by standard retrackers for the European Space Agency's (ESA's) Envisat (Environmental Satellite) radar altimetry. We applied this approach to small (40–200 m width) and medium-sized (200–800 m width) rivers and small lakes (extent <1000km^2) in the humid tropics of Southeast Asia, specifically in Indonesia, where similar studies do not yet exist.

The major challenges in this study include the size of the water bodies that are much smaller than the nominal extent of the Envisat satellite footprint (e.g. ~250 m compare to ~1.7 km, respectively) and slightly smaller than the along track distance (i.e. ~370 m). We addressed this challenge by optimally using geospatial information and optical remote sensing data to define the water bodies accurately, thus minimizing the chance for the altimetry measurement from contamination due to non-water returns. Previous studies show that Ice-1 is the best waveform retracking procedure for inland water measurement relative to other retrackers. Considering that satellite altimetry processing may vary with different geographical regions, meteorological conditions, or hydrologic dynamic, we evaluated the performance of all four Envisat standard retracking procedures to test the hypotheses presented above.

As the result, we found that satellite altimetry provides a good alternative or the only means in some regions, to measure the water level of medium-sized river and small lake with good accuracy that represented by the root mean square error from 0.21 to 0.69 m and correlation coefficient from 0.94 to 0.97. In addition, we also found that Ice-1 is not necessarily the best retracker as reported by previous studies, among the four standard waveform retracking algorithms for Envisat radar altimetry observing inland water bodies. As a recommendation,

we propose to include the identification and selection of standard waveform shapes to complete the use of standard waveform retracking algorithms for Envisat radar altimetry data over small and medium-sized rivers and small lakes.

1 Introduction

A number of small to medium-sized rivers are poorly gauged (Alsdorf and Lettenmaier, 2003). Small rivers are defined as those with 40-200 m width and 10-100 m^3/s average discharge, while medium rivers with 200-800 m width and 100-1000 m^3/s average discharge (Meybeck et al. (1996)). The installation and operation of in situ measurement such as permanent gauging is costly and not a priority for developing countries such as in Indonesia. However, the interest for continuous satellite-based monitoring of hydrologic bodies, including narrow or small rivers, is increasing. Therefore, with the absence of continuously operating in-situ measurements, it is a scientific and social challenge to develop a complementary water resources monitoring system, with water level and discharge as the essential variables.

Space geodesy and satellite remote sensing are viable sources of observation to complement or replace in-situ measured data that is lacking or unavailable. Copious research has demonstrated that remote sensing is capable to measure hydrological variables (Tang et al., 2009). Initiatives to develop global river and lake water level database exist to date, but none of them account for small to medium-sized rivers and lakes in the humid tropics.

Satellite altimetry missions were initially supporting oceanographic studies (Brown and Cheney, 1983). However, scientists were able to retrieve water surface elevation of large rivers and lakes. These studies include those utilizing early satellite altimetry missions (Wingham and Rapley 1987, Koblinsky et.al., 1993, Morris and Gill, 1994), as well as the recent satellite altimetry missions (e.g. Birkett, 1998, Benveniste and Defrenne, 2003, Kouraev et.al, 2004, Calmant and Seyler, 2006, Frappart et.al, 2006, Cretaux et.al, 2011).

Application of satellite altimetry to monitor inland waters has several limitations. The long satellite repeat cycle makes the satellite potentially misses important hydrological events (e.g. flash flood) between the repeat. For instance, the repeat period of for TOPEX/Poseidon and Jason-1/2 is 10 days, 35 days for ERS-1/2, Envisat and SARAL/Altika and 91 days for ICESat. The low spatial resolution of radar altimeter that is represented by the radar altimeter footprint (about 1.7 to 3 km for calm waters) limits the measurement only to wide rivers, due to interference of returned radar signal by non-water features. Earlier studies shown that satellite radar altimetry was useful for large rivers (>1 km width) (Birkett, 1998, Birkett et al., 2002), but recent studies present successful retrieval of water level of small rivers (<100 m width) (Kuo and Kao, 2011, Michailovsky et al., 2012). Nonetheless, the processing of satellite altimetry measurement for small water bodies remains a challenge considering its spatial and temporal limitations.

Early studies of satellite altimetry to retrieve water level of a river used waveform shape to match the specular characteristics that exclusively belongs to the signals returned by the river (Koblinsky et al., 1993). Specular refers to a reflection characteristic where a signal reflects into one direction, thus match the reflection by a mirror (e.g. Torrance and Sparrow, 1967). In the context of radar signal processing, this happens when the radar signal hits calm or smooth water surface, which represented as a peak in a return signal power. Along with this principle, scientists developed non-ocean retrackers in the last decade. These include the offset center of gravity (OCOG) (Wingham et al, 1986), or Ice-1, volume scattering retracker (Davis, 1993), sea ice retracker (Laxon, 1994), NASA ß- retracker (Zwally, 1996), surface / threshold retracker (Davis, 1997) and Ice-2 (Legresy and Remy, 1997). The offset center of gravity (OCOG) or Ice-1 (Wingham et al., 1986) is a simple but robust retracker that only requires the statistics of the waveform samples and does not require any model (model-free retracker) (Bamber, 1994). The Ice-2 algorithm modifies Ocean retracker (Brown, 1977) by adding scattering distribution coefficient that describes the vertical profile of the reflecting surfaces. This coefficient accounts for the interference to the default scattering pattern as generated by snow, ice sheet, sand or vegetation (Legresy and Remy, 1997). Laxon (1994) introduced Sea Ice algorithm to specifically study sea ice elevation by (1) characterizing the power and shapes of the radar return, (2) classifying the sea ice and determine the waveform parameters, followed by (3) the correcting of the retracked range. Ice-1, Ice-2 and Sea Ice along with the Ocean retracker (that is exclusively developed for ocean studies) are the standard retrackers for European Space Agency (ESA)'s Envisat (Environmental Satellite) until the satellite decommissioned in June 2012. Recent developments of inland water retracking methods include the improvements of the threshold retracker (Davis, 1997) by Lee, (2008) and Bao et al. (2009), sub-waveform analysis (e.g. Hwang et al., 2006 and Fenoglio-Marc et al., 2009) and sub-waveform filtering and track offset correction (Tseng et al., 2012).

For inland water studies (e.g. river and lake), Frappart et al. (2006) found Ice-1 as the best retracker for large rivers (e.g. Amazon River) over the other standard retrackers for Envisat (e.g. Ocean, Ice-2 and Sea Ice). None of these retrackers are specifically developed for inland waters. Satellite altimetry processing also varies depending on geographical regions, meteorological conditions, and hydrological dynamics of the water bodies. Up to this point, no "one size fits all" method for satellite altimetry waveform retracking is readily available to measure water level of small (40–200 m width) and medium-sized (200–800 m width) rivers and lakes. Hence is the need of developing specific algorithm or additional procedure for satellite altimetry applications to study inland waters. Furthermore, there is also a need to evaluate the commonly used Ice-1-based retracker in different regions of interest

Since the size of the water bodies is smaller than the satellite footprint, the surrounding non-water surface often contaminates the satellite altimetry's returned radar signal. In this study, we solved this issue by integrating geospatial information and optical remote sensing with satellite altimetry measurement to monitor small water bodies. Our study indicates that careful demarcation of water bodies reduces the contamination of return radar signal caused by the presence of non-water surface, thus improving the quality of the measurement.

In this study, we processed the results of Envisat standard waveform retracking procedures (Ocean, Ice-1, Ice-2 and Sea Ice) to monitor water level of a small river, a medium river and two lakes in the tropics. In addition to the standard waveform retracking procedures, we performed careful spatial and waveform shape selection and outlier detection to screen out low quality data. We then evaluated the results against in-situ measured water level to assess their accuracy.

2 Study Area

This study was conducted in the following water bodies in Indonesia (Figures 1 and 2): Mahakam and Karangmumus Rivers in East Kalimantan Province (Borneo Island), Lakes Matano and Towuti in South Sulawesi Province (Sulawesi Island). Karangmumus River is a tributary downstream of Mahakam River, while Lakes Matano and Towuti are part of Malili Lakes Complex. These water bodies represent different geomorphology, climate and anthropogenic situations as described below.

2.1 Mahakam and Karangmumus Rivers

The Mahakam watershed is located at 113° 40' to 117° 30' E longitude and 1° 00' S to 1° 45' N latitude. Mahakam is the second largest river in the country, which stretches to ~920 km and drains an area of 77,095 km^2. The Mahakam River rises in the mountainous forest ranges with dramatic elevation drops in the first hundreds kilometres of the main stem, where the formation of rolling hills and steep slopes form the upstream part of this watershed. The Middle Mahakam Lake and Wetlands forms up starting from the fifth hundreds kilometres of the river length and transforms into the Mahakam Delta estuary in the last hundred kilometres (MacKinnon et al., 1996). The upstream part of Mahakam River presents narrow channel width of 40-100 m with depth varies from 5 to 10 m and slope greater than 2%, with forest and small patches of subsidence agricultural farms dominate the land use. The middle part presents channel width of 100-300 m, 10-24 m depth and 0.5-2% slope, with extensive lowland and agricultural areas spread about everywhere along with country-style residential areas, lakes and swampy shrubs. The lower part and the Mahakam Delta present wide channel of 500-850 m width, 10-24 m depth and 0-0.5% slope. The lower sub-watershed is typically a developed area with residential areas, scarce forest patches and heavily inhabited land (Estiaty et al., 2007).

Karangmumus River is a narrow channel (3 to 45 m width) that is an important waterway for the residents of Samarinda City in East Kalimantan Province. The Karangmumus sub-watershed often experiences gradual increases and steady high water level during simultaneous heavy rainfall and backwater intrusion from ocean tide through the Mahakam Delta.

2.2 Lake Matano and Lake Towuti

Lake Matano is located at 121° 12’ to 121° 29’ E longitude and 2° 23’ to 2° 34’ N latitude. This lake counts as the seventh deepest lake of the world (Herdendorf, 1982) despite its small extent (164 km^2). With the maximum depth of 595 m and mean water surface elevation measured at 392 m, Lake Matano represents a cryptodepression (i.e. the lake bed is below the mean sea level) (Hehanussa and Haryani, 1999). Originated by tectonic process since 2–3 million years ago, this lake is one of the oldest lakes of the world. The lake hosts endemic faunas that provide remarkable examples of ecological diversification and speciation (Cristescu et al., 2010). The basins in the surrounding of Lake Matano are formed by the hardness of the rocks and the softness of uplift tectonic fault that forms limited number of alluvial plains. Lake Matano also has two flat depressions separated by a saddle. It drains through the Petea River into Lake Mahalona that is located in the same Malili Lakes complex (Vaillant et al., 1997).

Lake Towuti is recognized as the largest tectonic lake in Indonesia (Russel and Bijaksana, 2012). Located at the downstream end of the Malili Lakes Complex, this lake covers an extent of 562 km^2 with 206 m depth. Similar to Lake Matano, Lake Towuti carries locally endemic fauna since this lake is also one of the ancient lakes.

3 Materials and Methods

3.1 Envisat Radar Altimetry

In this study we used satellite radar altimeter measurements from The European Space Agency (ESA)’s Envisat Radar Altimeter (RA-2) during the period of July 2002 to October 2010, corresponding to cycle 6 to 93 (ESA, 2007). The RA-2 determines the two-way delay of radar echo from the Earth’s surface in a very high precision of less than a nanosecond. In addition, it measures the power and shape of the reflected radar pulses, which were represented by the waveforms. The RA-2 on-board signal processor averages about 100 measurements of individual echo burst at ~1800 Hz. These data, along with the waveforms, then averaged into the 18 measurements per second (18 Hz). The 18 Hz data correspond to an along-track sampling interval of ~350 m (ESA, 2011). The averaged 18 Hz waveforms are arranged into 128 gates with 3.125 nanosecond temporal resolution and presents the default tracking gate at #46 (ESA, 2007). We also utilized the Envisat RA-2/Microwave Radiometer (MWR) Sensor Geophysical Data Record (SGDR) (hereafter, RA-2/MWR SGDR) Level-2 product. The RA-2/MWR SGDR contains parameters for time tagging, geo-location, output from retrackers (i.e. range, wind speed, significant wave height) at 1 Hz, and other 18 Hz-parameters such as range and orbital altitude. The RA-2/MWR SGDR also contains the 18 Hz waveforms that we used in the waveform shape selection procedure. We used the 18 Hz re-tracked range to infer the water surface elevation. Before comparing the altimetry with in-situ measurements, we first corrected the instrumental (i.e. Doppler shift and oscillator drift), the geophysical (i.e. inverse barometer, polar and solid Earth tides) and the media (i.e. ionosphere and dry/wet troposphere) range in order to match the standard retrackers range (Ocean, Ice-1, Ice-2 and Sea Ice) produced from the Level-2 radar altimeter product.

Satellite radar altimetry measures water surface elevation with respect to the reference ellipsoid. Due to the uncertainty in the relationship between the elevations of the field gage benchmark relative to the local vertical datum, we used the water level anomaly in our analysis. The anomaly was calculated by subtracting the water level mean over the study period (July 2002 – October 2010) from the observed level. Hence, it represents the fluctuation of water level relative to its mean level. In order to test the current assumption of Ice-1 as the best retracking algorithm for inland waters (Frappart et al., 2006), we compared the water level anomaly obtained from water surface elevation measured by the Ocean, Ice-1, Ice-2 and Sea Ice retrackers with those obtained from the in-situ gage measurement.

3.2 Optical Remote Sensing and Geospatial Dataset

We applied standard optical remote sensing data processing techniques in order to obtain imageries with precise position and better contrast ratio between land and water. The processing included geometric correction, development and contrast adjustment of the pseudo-natural color composite imagery from red-green-blue combination (bands 5, 4 and 3 of Landsat 5 and Landsat 7; or bands 6, 5 and 4 for the recently launched Landsat 8). We then measured river and lake width through visual interpretation of remote sensing image (i.e. through dark-blue color reflected by the water bodies in the pseudo-natural color composite of Landsat imagery) and marked the boundaries. When the object was too small to detect using visual inspection of remote sensing images, we used medium-scale (1:50,000) topographic maps released by the Indonesian Geospatial Agency to identify and mark the boundary.

Previous study (Sarmiento and Khan, 2010) showed that satellite altimetry measurements were less accurate when the center of satellite altimetry footprint was closer to the lakeshore. In order to test this hypotheses, we created masks with varying distances to the lakeshore (i.e. 0-500 m, 500-1000 m and >1000 m). The footprint diameter of the Envisat RA-2 over a smooth surface is about 1.7 km (Rees 1990, ESA 2007). We assumed that the Envisat altimeter measurements within the last mask (i.e. > 1000 m from lakeshore) were not influenced by the surrounding non-water surface. We then analysed the performance of altimeter measurements based on these masks. As for the river, we created a mask with 5-meter buffer distance to the riverbank, in order to reduce the land surface-waveform contamination and to tolerate any geo-referencing and projection errors of the satellite imagery and topographic maps.

3.3 In-situ Water Level Data

Indonesia’s Ministry of Public Works provided the datasets used for validation of water level of Mahakam River at Melak site (2002-2004) and Karangmumus River (2008-2010), while PT Vale Indonesia provided validation data for Lake Matano and Lake Towuti (2002-2012). Similar to the satellite altimetry data, we transformed the water level time series into water level anomaly by removing the mean water surface elevation over the period of observation.

3.4 Waveform Shape Analysis

The presence of variable land cover (e.g. vegetation in the riverbank, lakeshore or coastline, as well as islands or sandbanks within the river or lake) affects the returned radar signal in altimetry measurement (e.g. Deng and Featherstone, 2006; Berry et al, 2005). Therefore, we analysed the waveform shapes considering that the radar pulse reflected by the small water bodies might be influenced by other surface within the projected radar footprint. For the lakes, 1-km distance to the lakeshore was sufficient since the radius of the Envisat footprint (half of its diameter) is about 850 m. However, this issue becomes more challenging for small and medium-sized rivers (40-800 m width), rendering the waveform produced by the processed radar pulse return unpredictable.

Due to the fact that inland water surface is smoother than the ocean (Birkett, 1998), we assumed that (quasi) specular shape is the standard waveform shapes for radar pulse returns reflected by inland water bodies, in contrast to the ocean-reflected diffuse shape (Koblinsky, 1993). Additional shapes of Envisat RA-2 returned radar pulse over inland water include (Berry et al., 2005): (i) quasi-Brown shape representing a transition from land to water; flat patch shape denoting intermediate surface; and complex shape indicating a mixture between water and vegetation (Dabo-Niang et al., 2007). In this study, we considered (quasi) specular, quasi-Brown and flat-patch shapes as qualified waveform to perform reliable range measurement. However, we disqualified complex and non-classified shapes, which were discarded from further process. We assumed that the mixture of water, vegetation and or shoreline provides less accurate elevation measurements as compared to the radar signal returned by water-dominated surface. Some examples of actual waveforms that classified into “Brown-like”, specular, flat-patch, as well as complex and non-classified shapes are presented in Figure 3. In practice, we displayed the standard waveform shapes (Brown-like, specular, flat-patch) with another window showing waveform shapes from each measurements along with their IDs. Then we noted down the IDs of measurements that matched waveform shapes for further processing.

3.5 Outlier Removal, Validation and Performance Evaluation

Although the altimetry measurements that carry non-qualified waveform shapes were excluded, some measurements remained far beyond the mean and median values. In order to obtain a dataset with minimum influences from outliers, we excluded mild outliers – defined as any values outside of the the 1.5 times of the inter-quartile-range (IQR) (Kenney and Keeping, 1947;

Panik, 2012). IQR is defined as the range between the 25% quartile value ($Q_{0.25}$) and 75% quartile value ($Q_{0.75}$). If we denoted WSE_{min} and WSE_{max} as the minimum and maximum water surface elevation from the Envisat radar altimetry, respectively, then:

$$\mathrm{IQR} = Q_{0.75} - Q_{0.25} \qquad \text{Therefore} \quad WSE_{min} = Q_{0.25} - 1.5 \times \mathrm{IQR} \tag{1}$$

$$WSE_{max} = Q_{0.75} + 1.5 \times \mathrm{IQR}$$

Consequently, we discarded any measurements below the WSE_{min} and above the WSE_{max} threshold in the further processing.

We used root-mean-square error (RMSE) and the coefficient of correlation (r) as measures of performance (or validation) between satellite altimetry water level measurements and the virtual stations where in-situ measurements were available. The RMSE is a measure of how close the estimated measures from the "truth" values. It is as (e.g. Nagler, 2004 and Li, 2010):

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(x_i - y_i)^2}{n}} \tag{2}$$

where:

x_i is the Envisat water level anomaly

y_i is the *in-situ* measured water level anomaly

The Pearson correlation coefficient is the standard measure of association for continuous type of data (deSa, 2007). Therefore, we used it to measure the association between satellite altimetry and in-situ water level measurements as described in the following equation.

$$\mathrm{r} = \frac{S_{xy}}{S_x S_y} \qquad \text{with} \qquad S_{xy} = \sum_{i=1}^{n} \frac{(x_i - \bar{x})(y_i - \bar{y})}{(n-1)} \tag{3}$$

With S_x and S_y are variances for each measurement and n is the number of observations. The correlation coefficient (r) value falls within the interval [-1, 1], where coefficient of 0 indicates no correlation between two measurements, +1 indicates total correlation in the same direction (proportional relationship) and -1 indicates total correlation in the opposite direction (inverse relationship).

In order to provide a comprehensive understanding on the data processing sequences in this study, Fig. 4 shows each data processing step and their relationship.

4 Results and Discussion

4.1 Mahakam and Karangmumus River

Table 1 shows that most of the radar pulse returns from both small-sized river (40-200 m width) and medium-sized river (200-800 m width) produced qualified waveforms to infer water level fluctuation. The percentage of qualified waveforms relative to all measurements within the water bodies are high (90-97%) even for a small river at virtual station UM03 (river width 54 m). It is also interesting to see more missing cycles (regular satellite repeat schedule without available measurements within the water bodies) in the smaller river. Although we observed a slightly opposite trend between Melak01 and Melak02 virtual stations (fewer missing cycles in a slightly narrower river), but we confirm that wider rivers have more chance to be observed by satellite altimetry mission in all its regular cycles.

For the water level measurements at Melak, we combined two virtual stations (i.e. Melak01 and Melak02) since they were just separated by 14–40 km distance and there was no drastic change in terrain and configuration of the channel (e.g. no reservoir or steep gradient) as we observed from topographic map and digital elevation model. Having two different satellite tracks nearby in fact increases the spatial and temporal sampling intensity for this location. Fig. 5 shows the location of the Ministry of Public Works' gage station, which is right in the between these two virtual stations. Fig. 5 also indicates dynamic channel morphology in this area. The channel is heavily meandering just before and along the virtual station Melak01, which then changes into 13 km straight channel along the heavily populated Melak Town before it is back into lightly meandering channel. Fig. 6 shows the combined water level anomaly from the two virtual stations, along with the water level anomaly observed by the gage station for the period of 2002-2004.

To facilitate visual investigation, we presented the correlation between the satellite altimetry observed and gage-measured in Fig. 7, which shows scatter plots between each retracking algorithm and the in-situ measured water level anomaly. Regarding the retracking algorithm inter-comparison, we found that Ice-1 is not necessarily the best retracking algorithm for inland water body elevation measurement, since Sea Ice retracking algorithm performs best compared to other standard retrackers (i.e. Ocean, Ice-1 and Ice-2), as shown in Table 2. With the coefficient of correlation up to 0.97, the satellite radar altimetry presents very convenient alternative for monitoring of the medium-sized river (200-800 m width), even for poorly-gauged basin such as the Mahakam Watershed. Referring to other studies, the magnitude of root-mean-square error (RMSE) reflected in this study, i.e. 0.69, is just about the average of RMSE obtained from other studies deal with medium sized rivers (200-800 m width), as summarized in Table 3.

It is important to note that we did not adjust the magnitude of the satellite altimetry range measurements in any way. Beside the spatial selection of the range measurements with the projected nadir footprint center within the water body and the removal of outliers, the only manipulation we did was the selection of the range measurements based on its waveform shape to strictly follow the standard waveform shape for inland water body as described in the previous studies (Koblinsky et al, 1993; Birkett, 1988; Berry et al, 2005; Dabo-Niang et al, 2007). Therefore, we see an ample room for improvement to increase the accuracy of the satellite altimetry measurement of river water level, especially for this study area. Among the improvements are using other altimetry missions (e.g. Jason-1, ICESat), detailed evaluation of retracked water elevation within a cycle and include the actual river slope into the processing.

In this study, we found that Envisat altimetry showed a potential to observe small-sized river. Satellite altimetry crossing at UM03 virtual station returned a high percentage of qualified measurement even with fewer measurements within the water body (i.e. 46 over 51) compared to the other virtual stations. Figure 8 indicates the water level fluctuation along with the estimated precipitation inferred from Tropical Rainfall Measuring Mission (TRMM). Figure 9 shows variable gaps that exist between the measurements, with average of 84 days and maximum gap lasts for 300 days (~10 months). This temporal gap is a serious problem for hydrological applications, especially those requiring the measurement of hydrological variables at short interval. Further, there was no in-situ gage station in the vicinity that provides validation data for this particular virtual station (UM03). Therefore, we could not validate these water level retrieval, thus rather conclude that small rivers (40-200 m width) are potentially observable by satellite altimetry.

We did another experiment of satellite altimetry measurement over the narrow Karangmumus River (width 8-45 m). The northeast-southwest orientation of this river makes it difficult to find the crossing with Envisat ground tracks. However, high resolution IKONOS image (1 m ground resolution) allows detailed selection of the altimeter ground tracks that fall within its narrow channel. Still, the ultra-narrow channel width seriously hampered successful satellite radar altimetry measurement of this study site. After careful spatial filtering and waveform shape selection procedure, we extracted only 11 water surface elevation from Karangmumus River. Figure 10 depicts the location of this experiment, while Table 4 summarizes the qualified measurements. Due to unknown relationship with the vertical datum, we present the water level anomaly.

Figure 11 shows the time series of the water level anomaly during 2004-2006, along with TRMM estimated precipitation for the area. From Figure 11, it is obvious that the number of retrieved water level anomaly was very limited. Visual inspection shows that the relationship between the estimated precipitation and the water level anomaly was not so clear. However, this result may serve as preliminary indication to the range of water level magnitude in this river. Further, the in-situ measurement record from the nearest available gage stations (i.e. Pampang, Muang, Gununglingai and the outlet of the Karangmumus River) were available only during year 2008–2010. Therefore, we could not evaluate the performance of satellite altimetry measurements over this very small river.

By the time of this write up, no other studies indicated successful exploitation of the river with 100 m width or less, except Michailovsky et al., (2012), who extracted 13 useful water level measurements from a river with 40 m width and Kuo and Kao (2011), who revealed the water level of Bajhang River in Taiwan with less than 100 m width with standard deviation of error of 0.31 m. We therefore urge for further exploration of satellite altimetry observation to monitor small rivers supported by complete validation data.

Previous studies showed that 1 km seems to be the ideal width to expect typical altimetry radar returns from the water surface (Birkett, 1998, Birkett et al., 2002). We demonstrated that medium size rivers as narrow as 240 m can still be monitored and validated, given the water surface boundary is identified accurately. We also emphasize that successful retrieval of qualified satellite radar altimetry measurement in this research was very much supported by detailed geographic masking, which carefully excludes all altimetry measurements with projected nadir position outside of the water bodies.

4.2 Lake Matano and Lake Towuti

Inland water has been known to produce different, sometimes irregular waveform shapes and pattern compared to the ocean with respect to their response to radar pulse signal transmitted by satellite based active sensor. Some examples of distinguished waveform shapes from Lake Matano and Lake Towuti at different buffer distances from the lakeshore are presented in Fig.

12. As the result of our visual inspection, it seems like the waveform shapes resulted from satellite altimetry measurement over the lakes are more variable compare to those over the small to medium-sized rivers. We suspect this is due to the fact that lakes possess larger extent of water surface and much more influenced by wind that may develop wave with some height. Fig. 12 shows the typical ocean-like, multi and low peaks, gradually rising and many other kinds of irregular patterns that were not present in the dataset from small and medium-sized rivers. Up to now, a systematic and verified classification of waveform shapes especially for inland waters does not exist, except the early development such as presented by Dabo-Niang et al. (2007). Hence, further study on this subject is warranted.

Table 5 summarizes the results of satellite altimetry waveform selection over Lake Matano and Lake Towuti. Similar to the result of satellite altimetry measurements to the small to medium-sized river in the previous section, most of the radar pulse returns produced qualified waveforms that were used to compute water level anomaly at these two lakes. We also found an interesting fact, that separation of distance to the lakeshore seems does not significantly affect the number of qualified waveforms. For instance, from Table 5 the percentage of qualified waveforms for the lake surface with distance more than 1 km in Lake Matano and Lake Towuti is lower than those closer to the lakeshore. This complex result calls for further investigation in the field of satellite altimetry application for small and medium lakes in the tropics, given the fact that the land cover does not always influence the shapes of the returned altimeter waveform.

Upon the completion of waveform sorting, we processed the range measurements performed by Ocean, Ice-1, Ice-2 and Sea Ice retrackers and evaluated against observed water level from in-situ gage station. Fig. 13 and 14 shows the satellite altimetry and in-situ measured water level anomaly at Lake Matano and Lake Towuti. These plots visually indicate that the satellite altimetry observed water level anomalies were matched closely with the in-situ gaged water level anomaly. From Figs. 13 and 14, we estimated that the water level anomaly at Lake Matano ranges in the magnitude of 1.2 m, while Lake Towuti only ranges in the magnitude of 1.4 m. Figs. 15 and 16 show the correlation between the Envisat radar altimeter measurements as processed by Ocean, Ice-1, Ice-2 and Sea Ice retrackers with the gage measured water level anomaly for Lake Matano and Lake Towuti, respectively.

In terms of performance, Envisat radar altimetry measurements over Lake Matano and Lake Towuti performed equally well, as reflected by the lowest RMS error obtained by the best retracker for each lakes (0.21, see Table 6). The result of performance evaluation presented in

Table 6 shows that the hypothesis about the lower accuracy of satellite altimetry measurement due to the shorter distance to the lakeshore cannot be verified. The satellite altimetry measurement of water level anomaly over Lake Matano indicates lower RMS error and higher correlation coefficient relative to the in-situ gaged water level anomaly with the increase of distance from the altimeter footprint to the lakeshore, while the satellite altimetry measurement over Lake Towuti shows the opposite (see Figs. 17 and 18). Table 6 presents all statistical measures from the performance evaluation over different distance to the lakeshore. Considering the inconclusive results from splitting the altimeter measurements by the distance from the lakeshore, we do not recommend such classification of samples based on the distance to the lakeshore.

Inter-comparison between the available retrackers (i.e. Ocean, Ice-1, Ice-2 and Sea Ice) also cannot suggest any single retracker to infer water level of the small lakes, since Ocean retracker surprisingly performed best for Lake Matano, while Ice-1 retracker performed best for Lake Towuti. An important conclusion that could be drawn from this part of research is that Ice-1 is not necessarily the best retracker to measure water level anomaly over small to medium lakes.

Compared to other studies, the best RMS error obtained from measurements of water level anomaly in this study (0.21 m at both Lake Matano and Lake Towuti) is quite close to the lowest one among the small lakes being studied throughout the world. Table 7 states that satellite altimetry measurements over the small lakes give the RMS error magnitude in the range of 30 to 50 cm, as compared to large lakes that produce RMS error as low as 3 cm. Lake Matano is in fact the smallest among all lakes listed in Table 7.

5 Conclusions

We have demonstrated that satellite altimetry was capable to monitor the water level of medium-sized (200–800 m width) rivers in the Southeast Asia’s humid tropics, as indicated by the correlation as high as 0.97 between the water level measured by satellite altimetry and the validation dataset measured on the ground. Even the results vary in terms of the performance; water level anomaly inferred by Envisat radar altimetry through standard waveform retracking method has been validated and therefore, capable to represent the fluctuations of water level of medium rivers. Aside from the medium-sized rivers, we also found that small rivers (40–200 m width) are *potentially* observable through satellite altimetry, as indicated by high percentage of qualified range measurements that we filtered based on the waveform shapes. It is important to note however, that this situation might be different from one region to another; therefore a specific approach should be developed for each region, as part of the development of permanent monitoring effort of those regions.

In contrast with the common assumption as summarized by Frappart et al. (2006), Ice-1 is not necessarily the best retracker for monitoring small water bodies, especially for the Southeast Asia humid tropics area. We also found that Ocean retracker surprisingly performed best for retracking small lake (i.e. Lake Matano), along with Sea Ice for Mahakam River and Ice-1 for Lake Towuti.

The RMS error of satellite altimetry measurement of Lake Matano and Lake Towuti, i.e. 0.21 m for both locations, is about the average of small lakes being studied throughout the world. It is worth noting that Lake Matano is the smallest water bodies among any other studies of satellite altimetry measurement of water level involving lakes and reservoirs.

Learning from obstacles and problems encountered during the experiment, we recommend the following: (1) in addition to the use of standard retrackers, we propose the selection of the range measurements based on its waveform shape to strictly follow the standard waveform shape for inland water body (Koblinsky 1993, Birkett 1998, Berry et al, 2005, Dabo-Niang et al, 2007) for future studies involving small (40-200 m width) to medium rivers (200-800 m width), as well as small lake (e.g. those with extent less than 1000 km^2), and (2) over lakes, we do not recommend to analyse the performance of the satellite altimetry retrackers based on the distance from the satellite altimetry measurements to the lakeshore.

Lastly, we found that geographic orientation of the river affects the application of satellite altimetry for monitoring small rivers. For instance, small (40-200 m width) and medium-sized (200-800 m width) river with north-south orientation suffers from the satellite altimetry orbit deviation, which ranges from ± 1 km relative to its theoretical orbit.

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Table 1 Number of qualified and non-qualified altimeter measurements and outliers for study sites at Mahakam River

Site Name	Cycles	# of Missing Cycles	Measurements in water body	Qualified Measurement		Non-qualified Measurement		# of Outlier	River width (m)
				(#)	(%)	(#)	(%)		
UM03	9 – 93	34	51	46	90.2	5	9.8	N/A	54 m
Melak01	7 – 93	8	225	220	97.8	5	2.2	8	247 m
Melak02	7 – 93	11	148	134	90.5	14	9.5	0	294 m

Table 2 Performance evaluation of Envisat RA-2 radar altimetry measurements over Melak virtual stations at Mahakam River (width 247 m)

Site Name	Cycles Covered	Validated Measurement	Number of Pass	Retracker	RMSE (m)	Correlation Coefficient
Melak	7 - 33	46	2	Ocean	0.885	0.955
				Ice-1	0.720	0.962
				Ice-2	0.724	0.966
				SeaIce	0.685	0.970

Table 3 Summary of studies on satellite radar altimetry for water level over river

Reference	Location	River Width	Satellite / Sensor	Reported Error (m)
Koblinsky et al (1993)	Amazon Basin	N/A	Geosat	STDE: 0.31-1.68 m
Birkett, et al (1998)	Amazon Basin	3-9 km	T/P	RMSE: 0.11-0.60 m
Birkett, et al (2002)	Amazon Basin	2-6 km	T/P	RMSE: 0.40-0.60 m
Kouraev et al (2004)	Ob' River	3 km	T/P	%: 8 % (Discharge)
Frappart et al (2006)	Mekong River	450 m	Envisat,	RMSE: 0.23 m
			T/P	RMSE: 0.15 m
Birkinshaw et al (2010)	Mekong River	400 m – 1.7 km	ERS-2, Envisat	RMSE: 0.44–1.24 m
Kuo and Kao (2011)	Bajhang River	100 m	Jason-2	STDE: 0.31 m
Michailovsky et al (2012)	Zambezi River	40-380 m	Envisat	RMSE: 0.27-1.07 m
This study (2013)	Mahakam River	240-279 m	Envisat	RMSE: 0.69 m

* STDE (Standard Deviation of Error), % (% difference), RMSE (Root Mean Square Error)

Table 4 Qualified Envisat RA-2 altimetry measurements for Karangmumus River

Cycle	Date	ID	Longitude	Latitude	Water Level Anomaly*	Remarks
8	07/23/2002	KM08	117.181540	-0.404124	-0.07 m	
9	08/27/2002	KM10	117.194581	-0.408362	-4.52 m	Benanga Reservoir
13	01/13/2003	KM11	117.195384	-0.407573	2.94 m	Benanga Reservoir
23	12/30/2003	KM01	117.157190	-0.507934	-1.92 m	
23	12/30/2003	KM02	117.157910	-0.504634	-2.32 m	
28	06/22/2004	KM09	117.188367	-0.405981	3.63 m	47 m to field gage
37	05/03/2005	KM06	117.169721	-0.448573	-0.11 m	
37	05/03/2005	KM07	117.170441	-0.445263	-0.12 m	
39	07/12/2005	KM03	117.158610	-0.503317	-2.28 m	
42	10/25/2005	KM05	117.171486	-0.452076	4.12 m	
49	06/27/2006	KM04	117.159139	-0.501533	-0.93 m	

Table 5 The number of qualified and non-qualified altimeter measurements and outliers over Lake Matano and Lake Towuti

Location	Width	Cycle	Distance to Shore	Measurement Within water body	Qualified		Non-Qualified		No of Outlier
					#	%	#	%	
Lake Matano	8,159	8-79	< 500 m	453	416	91.8	37	8.2	42
			500 m – 1 km	253	215	85.0	38	15.0	26
			> 1 km	989	805	81.4	184	18.6	115

Lake Towuti	28,818	8-79	< 500 m	1314	786	59.8	528	40.2	79
			500 m – 1 km	1328	764	57.5	564	42.5	64
			> 1 km	2450	1353	54.3	1137	45.7	156

Table 6 Performance evaluation of Envisat RA-2 radar altimetry measurements over Lake Matano and Lake Towuti

Site	Lake width (m)	Cycles	Validated measure-ment	Re-tracker	Correlation coefficient	RMSE (m)	No / % of Outliers
Lake Matano	8,159	8 – 79					
0 – 500 m			75	Ocean	0.214	0.981	42/387
				Ice-1	0.242	0.835	10.85%
				Ice-2	0.290	0.819	
				SeaIce	0.358	0.743	
500 – 1000 m			71	Ocean	0.605	0.555	26/214
				Ice-1	0.538	0.624	12.15%
				Ice-2	0.723	0.458	
				SeaIce	0.745	0.417	
> 1000 m			73	Ocean	0.692	0.493	115/805
				Ice-1	0.647	0.535	14.29%
				Ice-2	0.667	0.518	
				SeaIce	0.666	0.518	
All			75	Ocean	0.948	0.209	183/1406
				Ice-1	0.881	0.311	13.02%
				Ice-2	0.837	0.364	
				SeaIce	0.839	0.359	
Lake Towuti	28,818	8 – 79					

Site	**Lake width (m)**	**Cycles**	**Validated measurement**	**Re-tracker**	**Correlation coefficient**	**RMSE (m)**	**No / % of Outliers**
0 – 500 m			77	Ocean	0.880	0.380	79/786
				Ice-1	0.917	0.296	10.05%
				Ice-2	0.898	0.321	
				SeaIce	0.911	0.291	
500 – 1000 m			79	Ocean	0.942	0.244	64/764
				Ice-1	0.903	0.312	8.38%
				Ice-2	0.890	0.339	
				SeaIce	0.887	0.341	
> 1000 m			79	Ocean	0.689	0.608	156/1353
				Ice-1	0.802	0.494	11.53%
				Ice-2	0.777	0.490	
				SeaIce	0.774	0.507	
All			80	Ocean	0.940	0.241	299/2903
				Ice-1	0.953	0.212	10.30%
				Ice-2	0.941	0.231	
				SeaIce	0.938	0.239	

1 **Table 7** Summary of studies on satellite radar altimetry for water level over lakes

Reference	Location	Lake Extent	Satellite / Sensor	Reported Error
Morris and Gill (1994a)	Superior, Ontario	Large	Geosat	RMSE: 0.09 m
	Michigan, Huron	Large	Geosat	RMSE: 0.11 m
	Erie		Geosat	RMSE: 0.13 m
	Lake St Clair		Geosat	RMSE: 0.17 m
Morris and Gill (1994b)	Great Lakes		Topex / Poseidon	RMSE: 0.03 m
Korotaev et al (2001)	Black Sea	436,402 km^2	T/P, ERS-1	RMSE: 0.03 m
Mercier et al (2002)	Victoria, Tanganyika Malawi and Turkana	131-390 x 10^3	TOPEX / Poseidon	RMSE: 0.10 m
	Rukwa and Kyoga	75-80 x 10^3	TOPEX / Poseidon	RMSE: 0.50 m
Coe and Birkett (2004)	Lake Chad	2.5 x 10^6 km^2	TOPEX / Poseidon	RMSE: 0.21 m
Zhang et al (2006)	Dongting Lake	2,623 km^2	TOPEX / Poseidon	RMSE: 0.08 m
Medina et al (2008)	Lake Izabal	717 km^2	Envisat	RMSE: 0.09 m
Munyaneza et al (2009)	Lake Kivu	2,400 km^2	Envisat	RMSE: 0.30 m
Cai and Ji (2009)	Poyang Lake	20,290 km^2	Envisat	Mean Error: 0.31 m
Guo et al (2009)	Hulun Lake	2,339 km^2	TOPEX / Poseidon	RMSE: 0.13 m

Reference	Location	Lake Extent	Satellite / Sensor	Reported Error
Troitskaya et al (2012)	Gorki Reservoir	1,358 km^2	T/P, Jason-1	RMSE: 0.15 m
Tseng et al (2013)	Qinghai Lake	4,186 km^2	Envisat	RMSE: 0.06 m
This study	Lake Matano	164 km^2	Envisat	RMSE: 0.32 m
	Lake Towuti	562 km^2	Envisat	RMSE: 0.29 m

* RMSE (Root Mean Square Error)

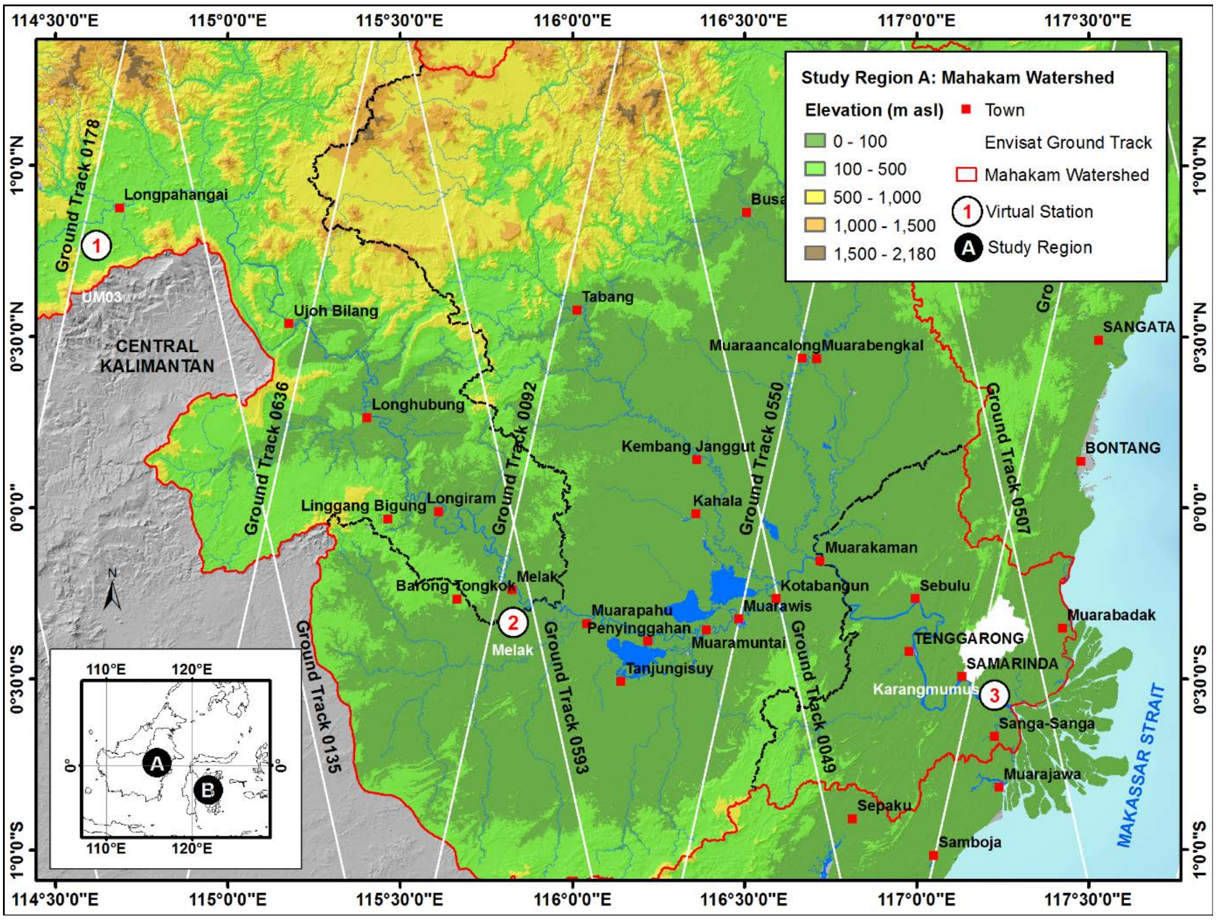


Figure 1 Study Sites at Mahakam Watershed, East Kalimantan, Indonesia

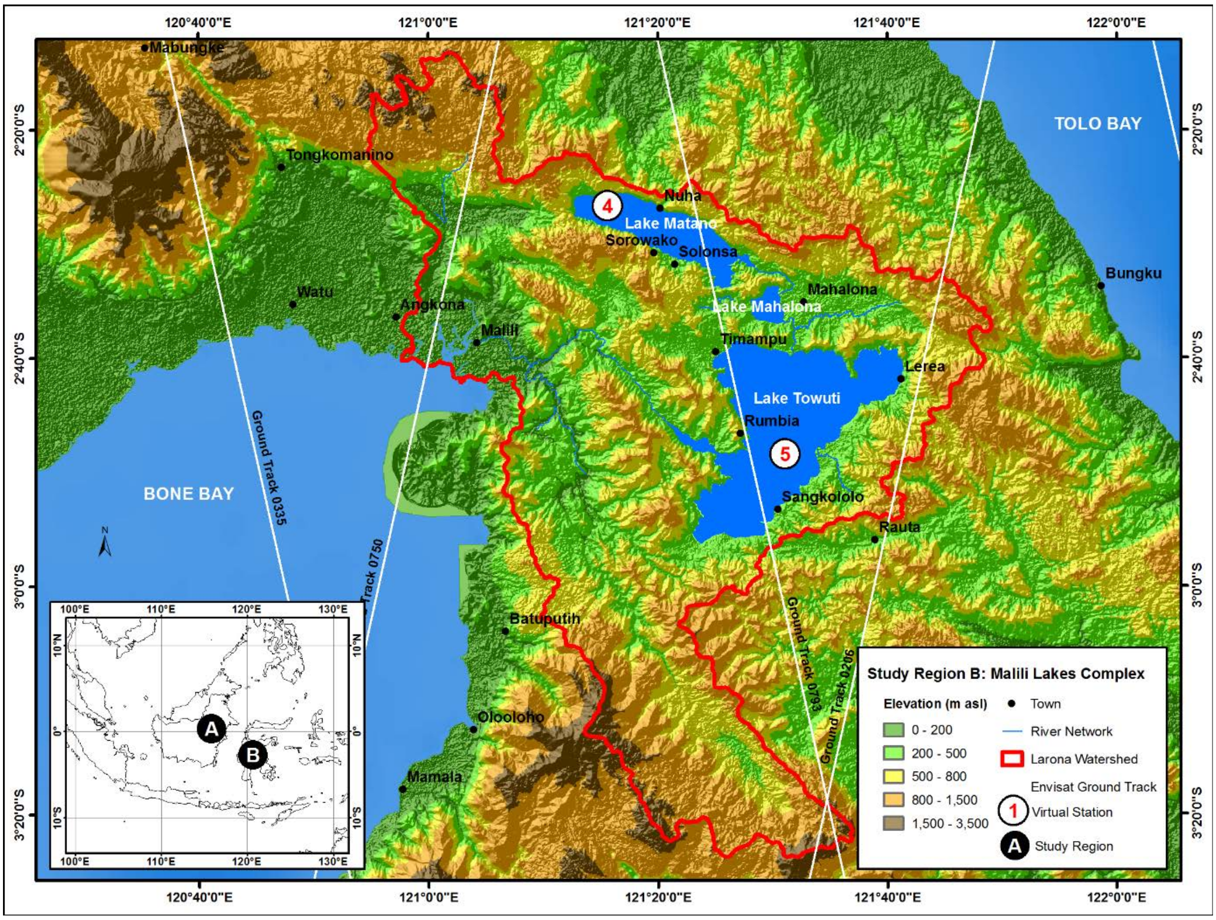
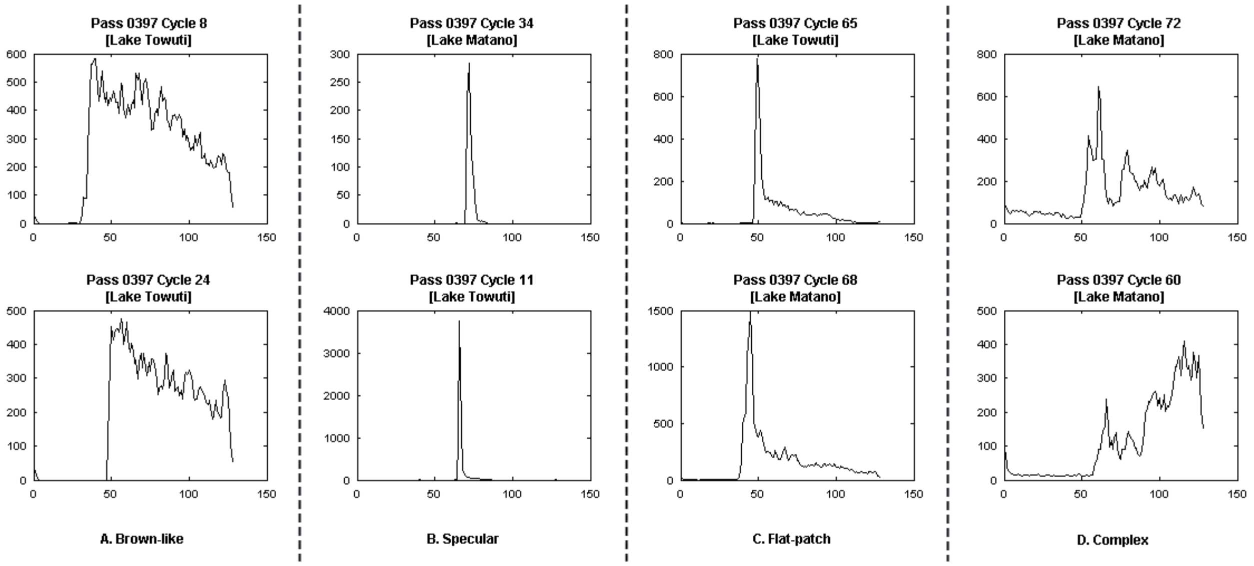


Figure 2 Study Sites at Malili Lakes Complex, South Sulawesi, Indonesia



Pass 0397 Cycle 8 [Lake Towuti]

Pass 0397 Cycle 34 [Lake Matano]

Pass 0397 Cycle 65 [Lake Towuti]

Pass 0397 Cycle 72 [Lake Matano]

Pass 0397 Cycle 24 [Lake Towuti]

Pass 0397 Cycle 11 [Lake Towuti]

Pass 0397 Cycle 68 [Lake Matano]

Pass 0397 Cycle 60 [Lake Matano]

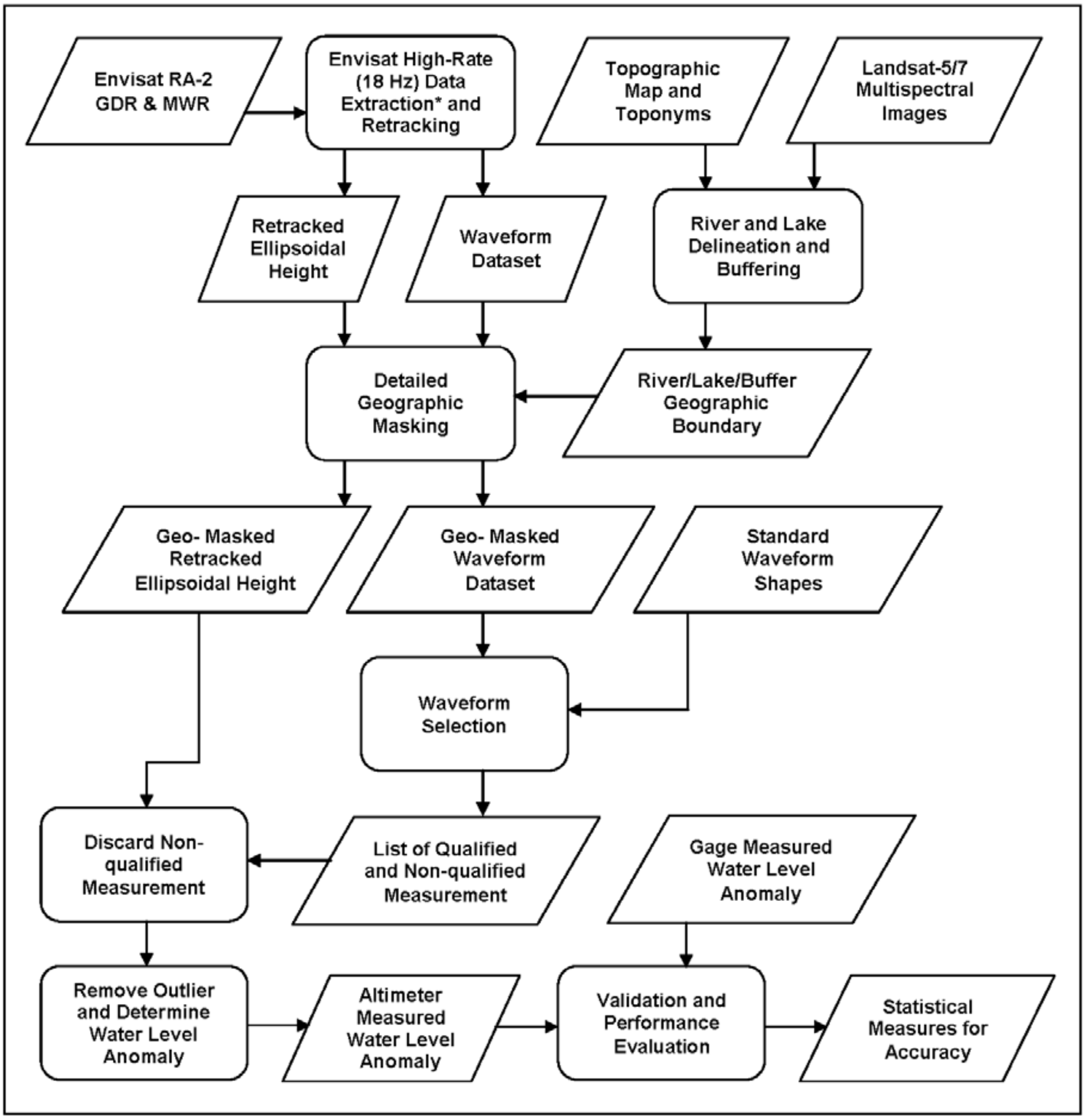
A. Brown-like

B. Specular

C. Flat-patch

D. Complex

Figure 3 General categories of waveform shapes



* The initial data extraction includes rough masking based on geographic boundary while ensuring all measurements are within the land

Figure 4 Data processing workflow

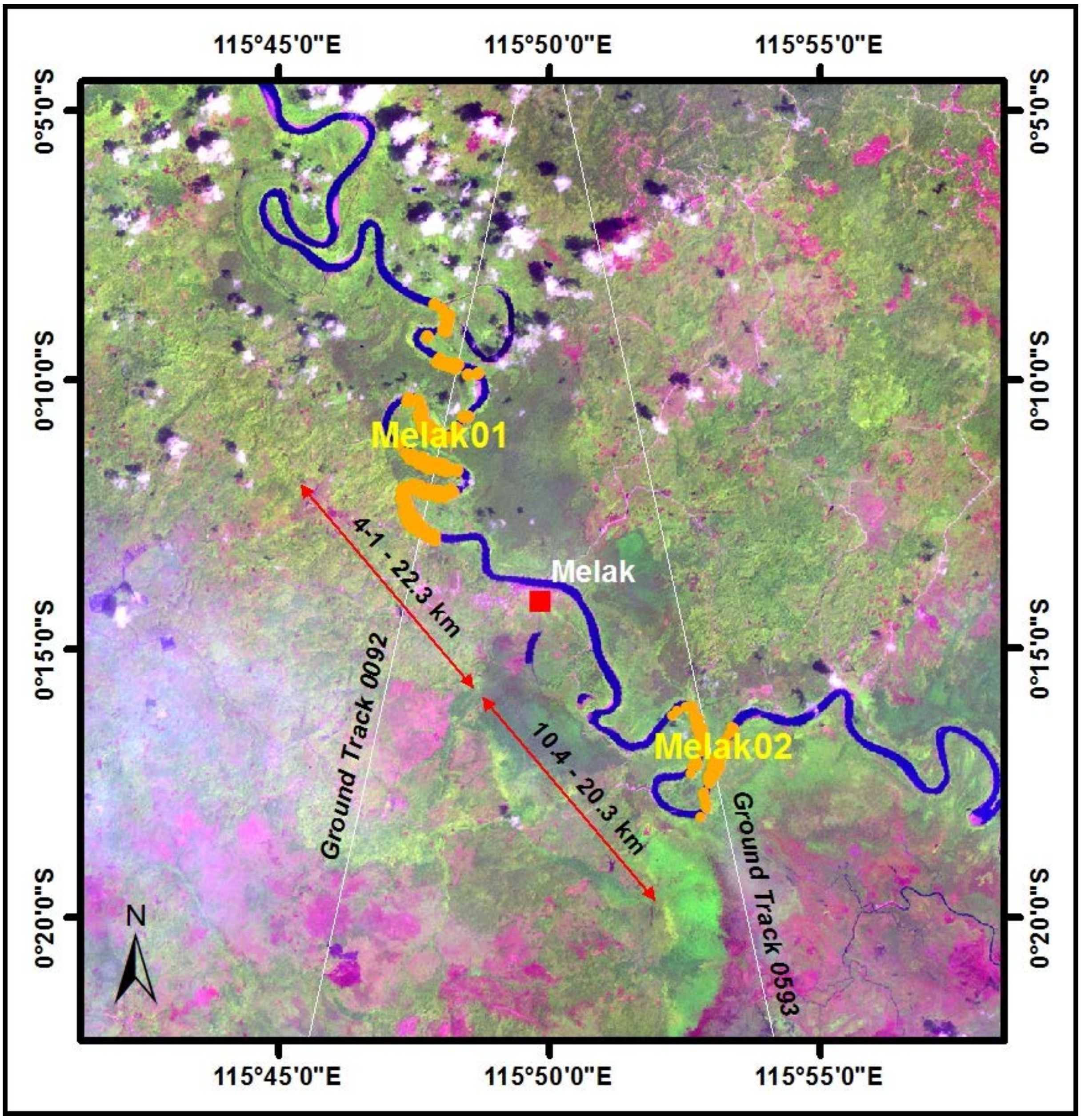


Figure 5 Location of Envisat virtual stations and in-situ water level gage stations at Melak Town

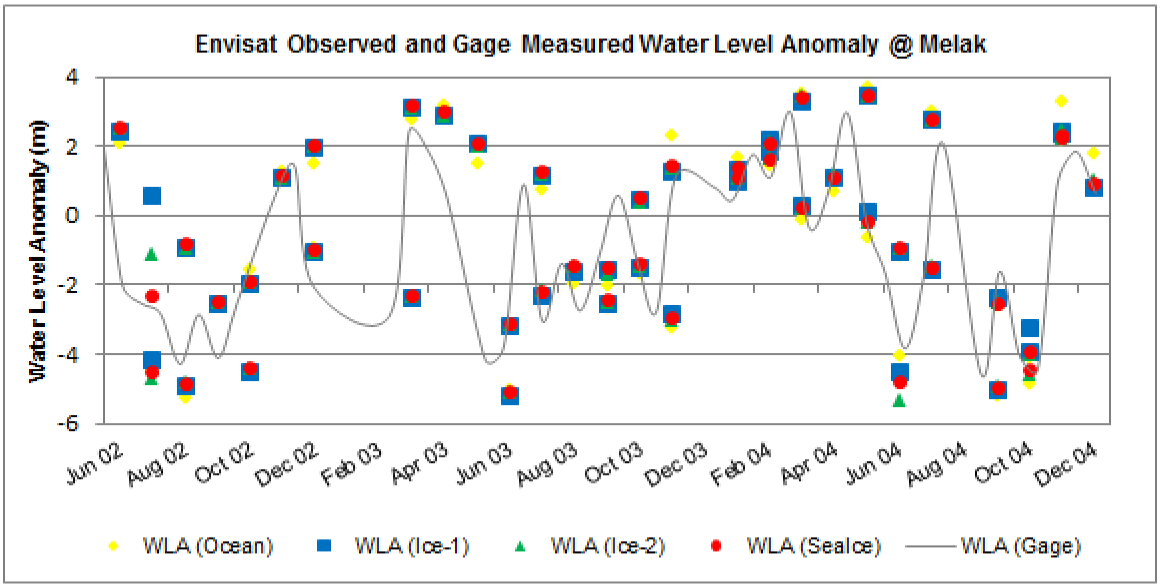


Figure 6 Water level anomaly at Melak as observed by two Envisat passes and retracked by four retrackers; compared with in-situ water level anomaly

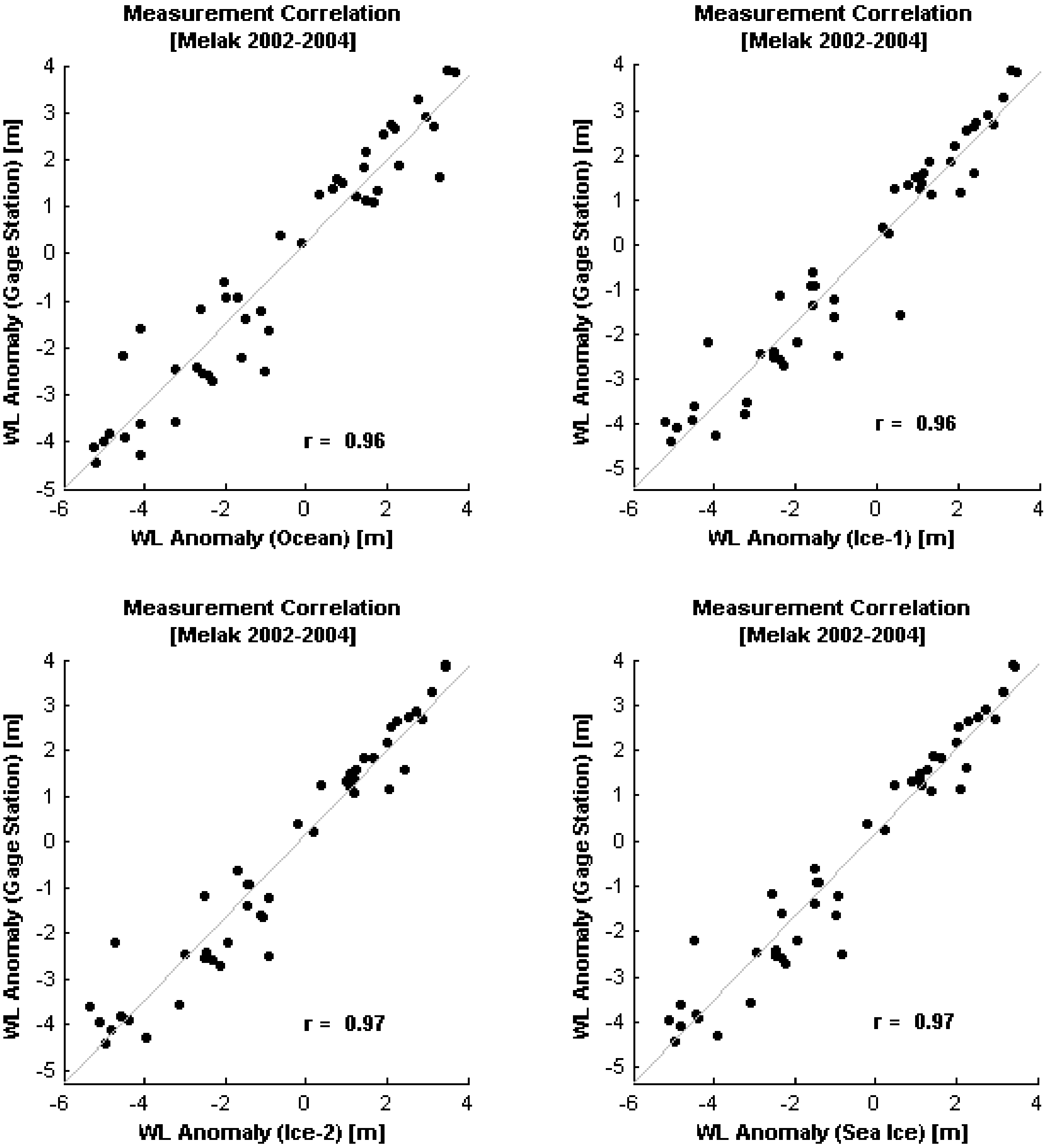


Figure 7 Correlation between water level anomaly measured by Envisat altimeter and processed with Ocean (top left), Ice-1 (top right), Ice-2 (bottom left) and Sea Ice (bottom right) retrackers and in-situ water level measurement over Melak

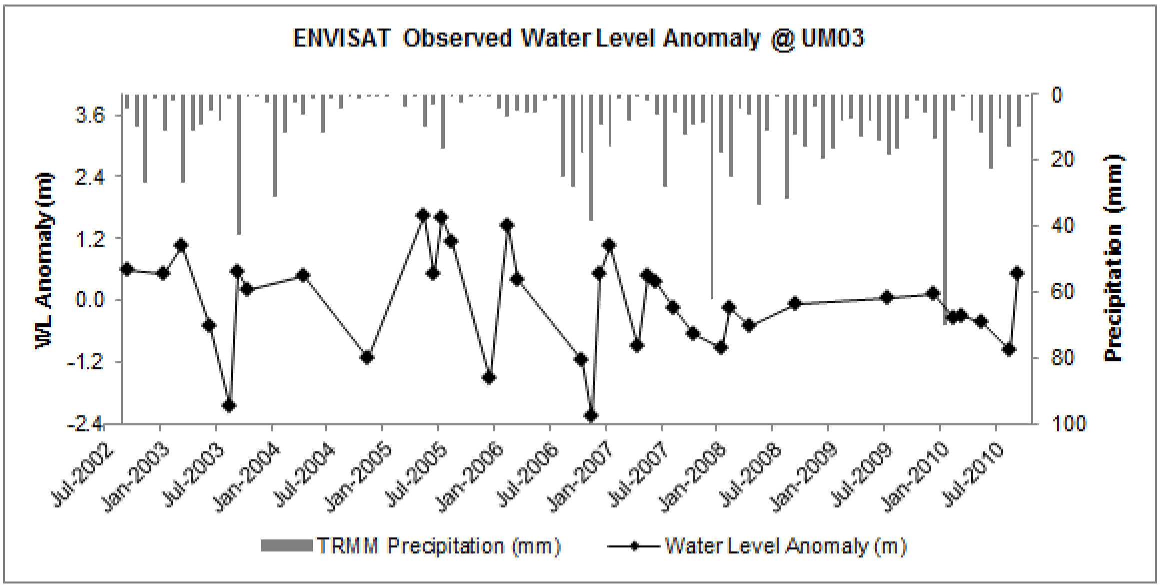


Figure 8 ENVISAT observed water level anomaly at site UM03 (river width 54 m) as measured by Envisat RA-2 and processed by Ice-1 retracker. Also shown is the TRMM estimated precipitation for the area

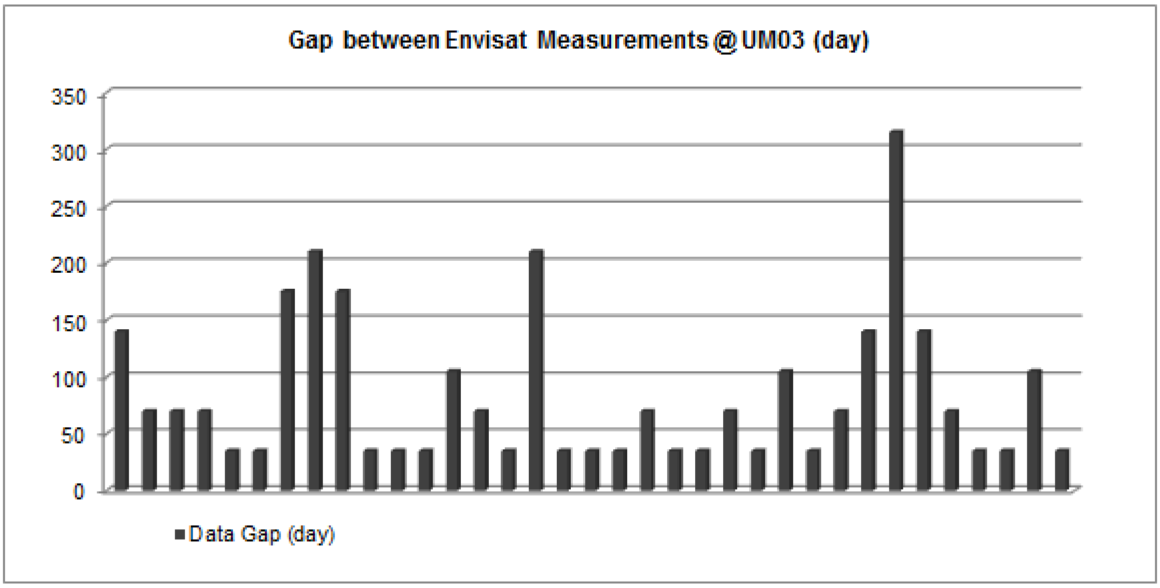


Figure 9 Gap between Envisat observation of water level at over site UM03

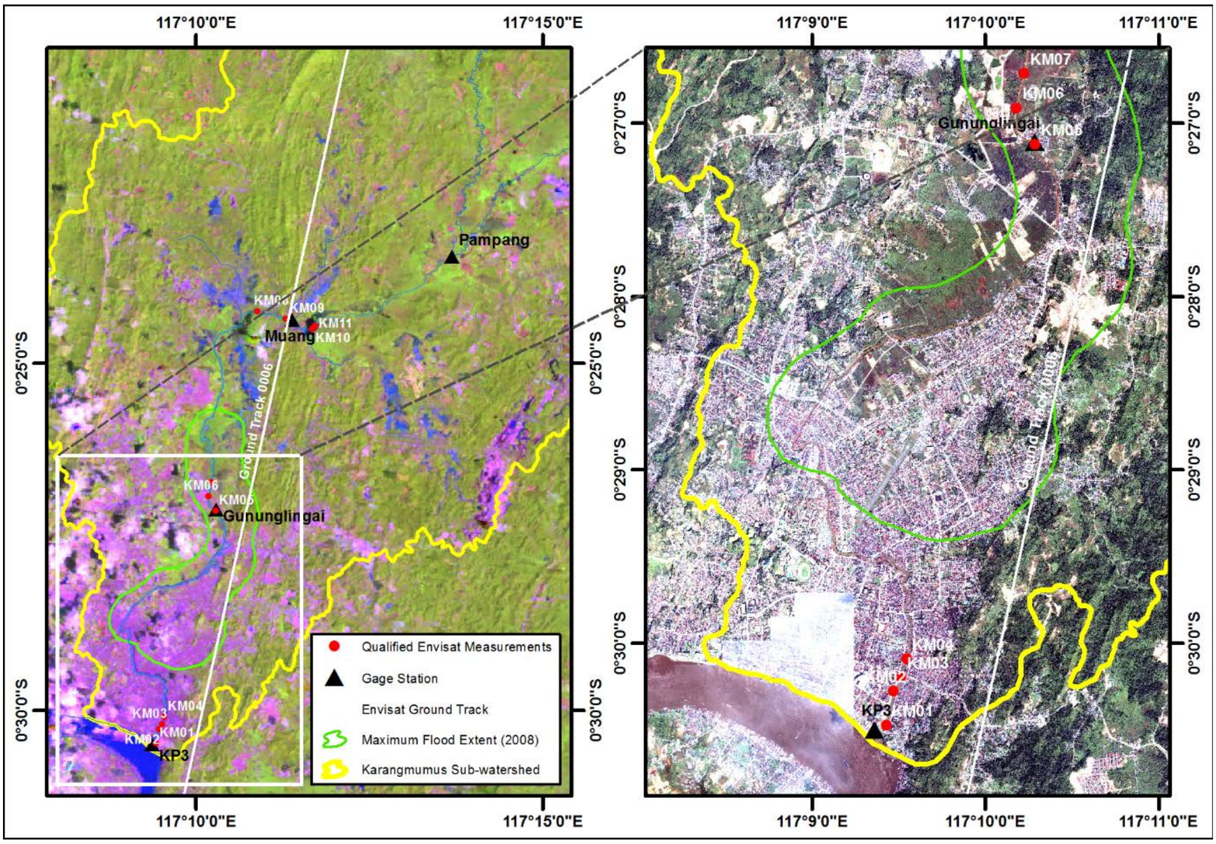


Figure 10 Overview of Karangmumus Sub-watershed and Envisat ground track with background of Landsat-7 image of January 2007 (left) and IKONOS of February 2002 (right, in the extent of white box of the left image)

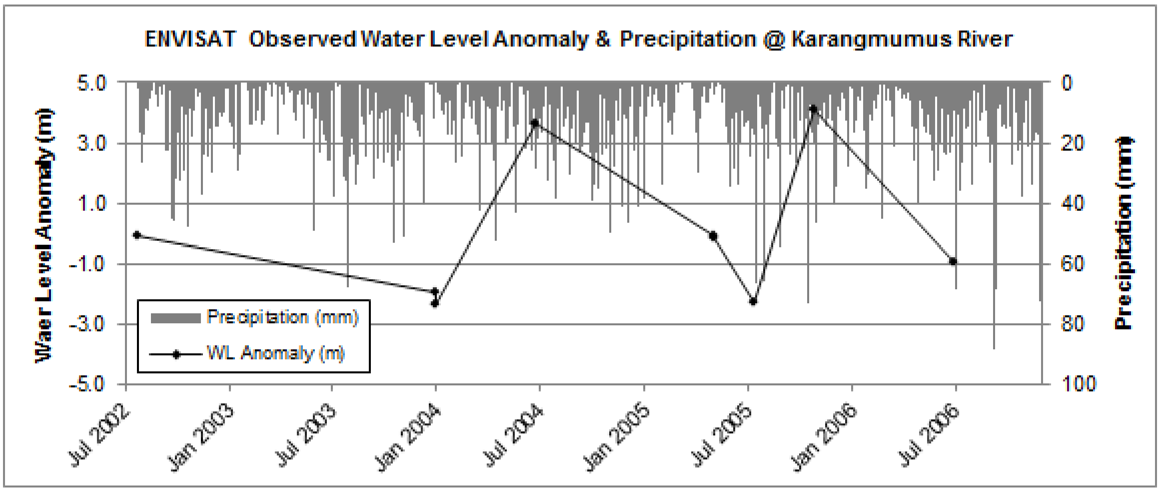


Figure 11 Water level anomaly of Karangmumus River from Envisat RA-2

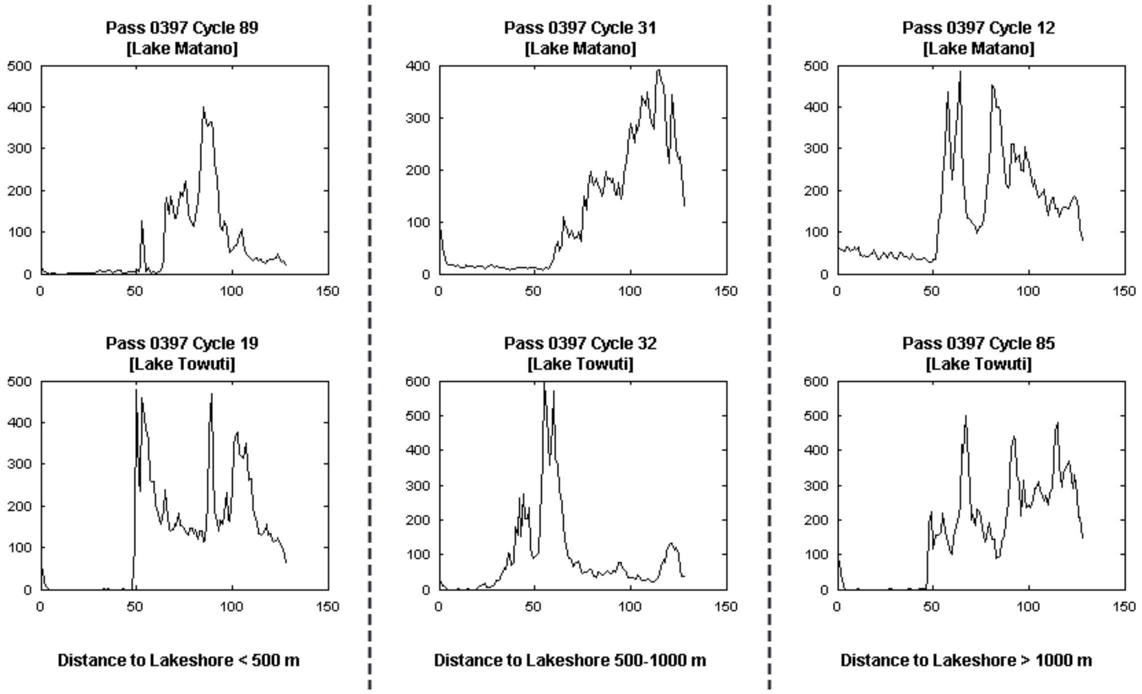


Figure 12 Distinguished waveform shapes as reflected by Lake Matano and Lake Towuti at different buffer distances to the lakeshore

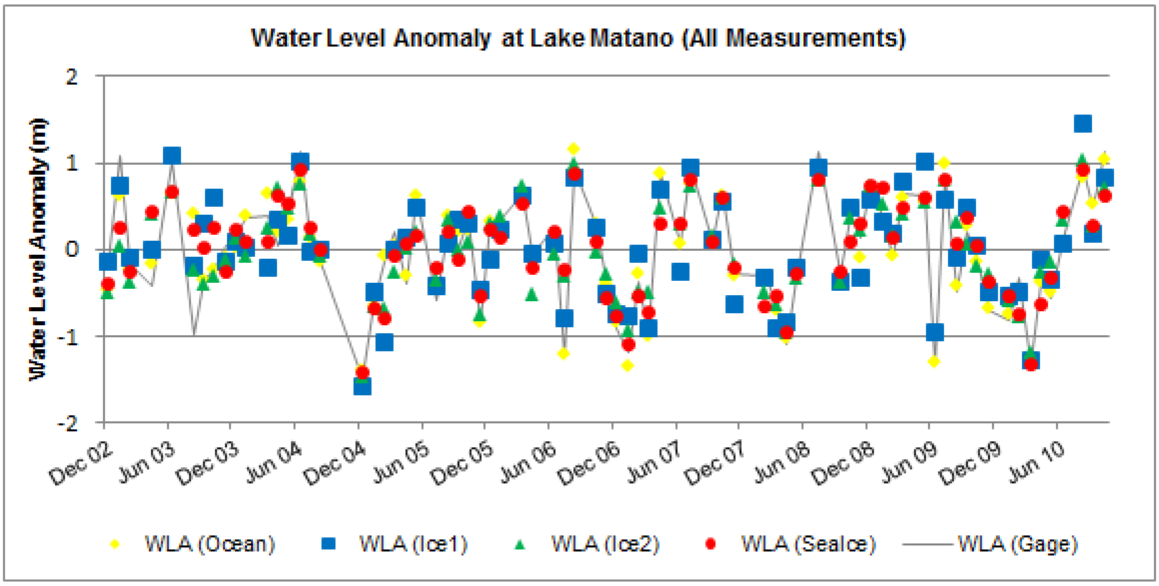


Figure 13 Water level anomaly at Lake Matano as measured by Envisat RA-2 and processed by all retrackers, compared with in-situ measurement

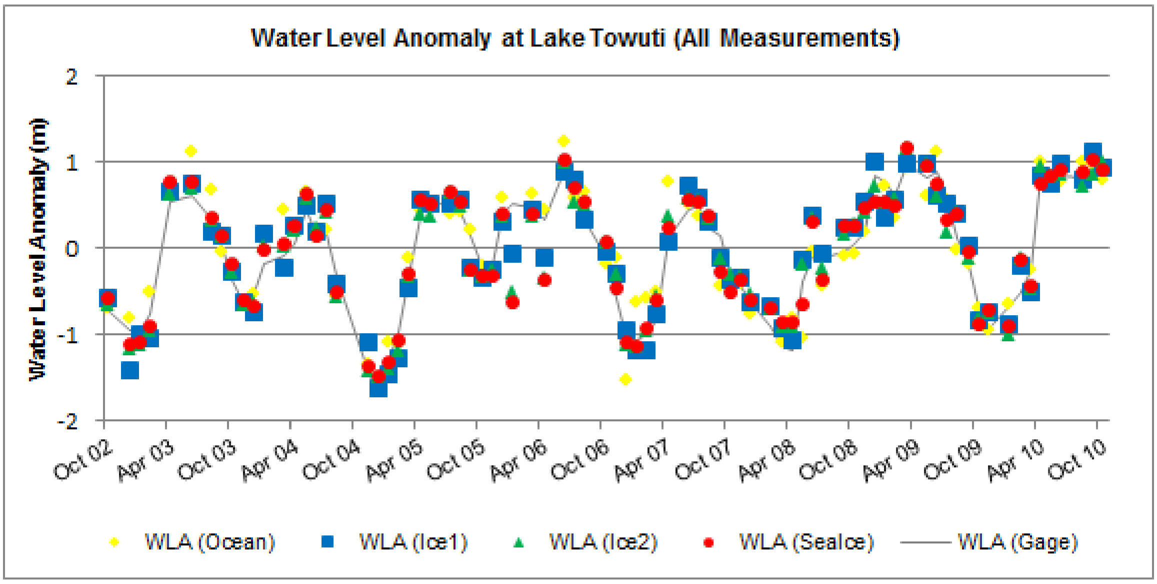


Figure 14 Water level anomaly at Lake Towuti as measured by Envisat RA-2 and processed by all retrackers, compared with in-situ measurement

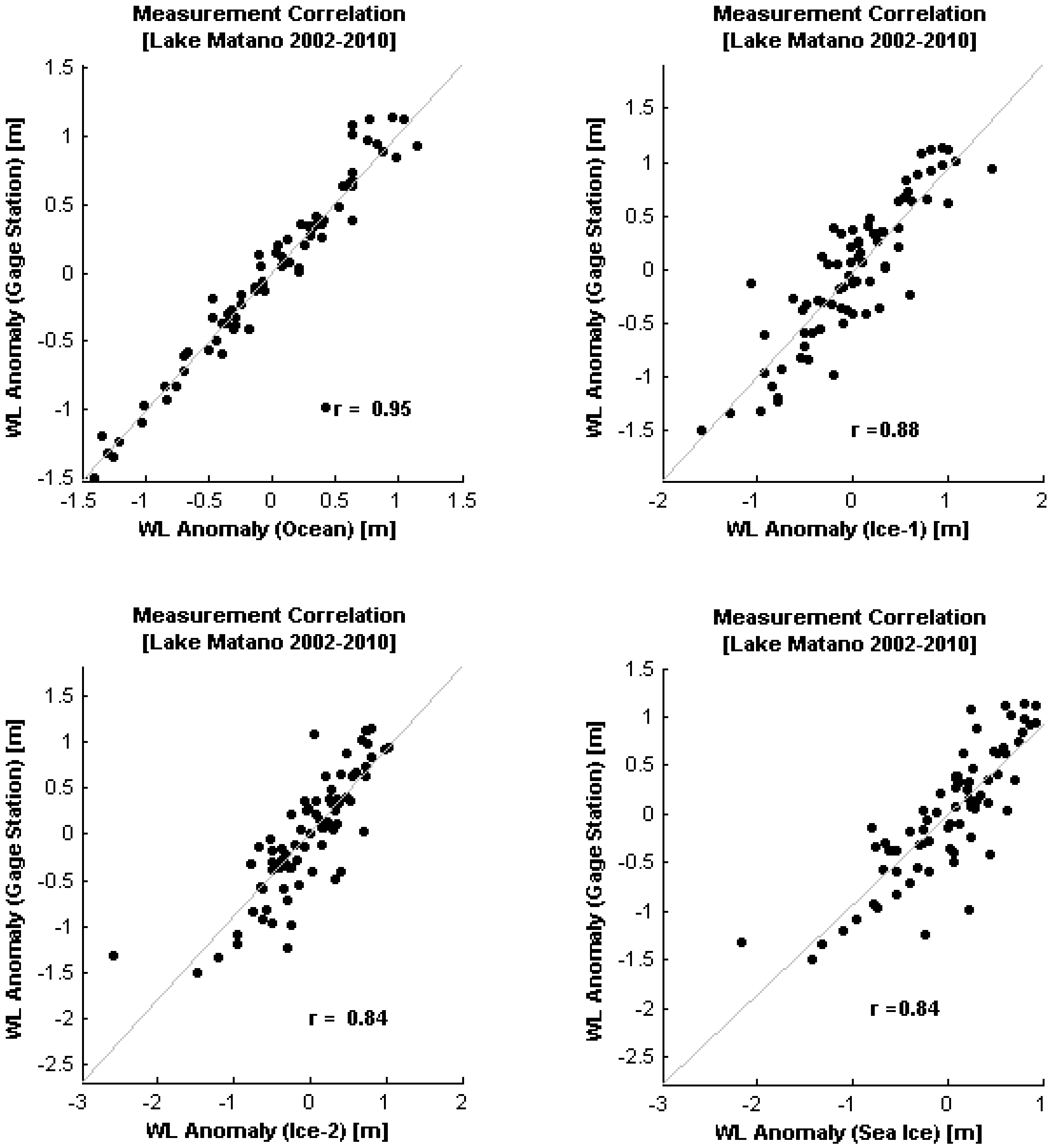


Figure 15 Correlation between water level anomaly at Lake Matano as measured by Envisat RA-2 altimeter and processed with Ocean (top left), Ice-1 (top right), Ice-2 (bottom left) and Sea Ice (bottom right) retrackers

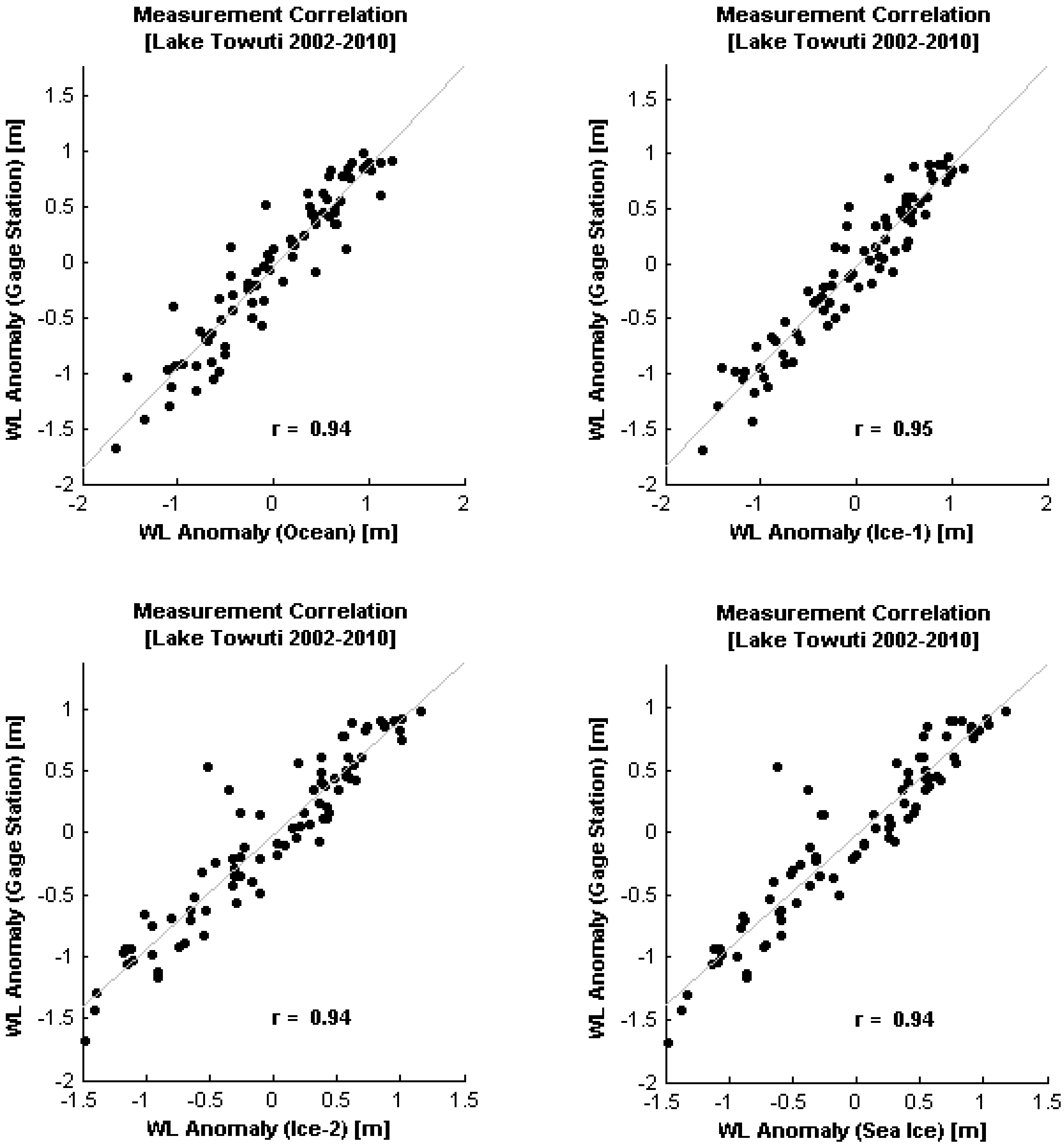


Figure 16 Correlation between water level anomaly at Lake Towuti as measured by Envisat RA-2 altimeter and processed with Ocean (top left), Ice-1 (top right), Ice-2 (bottom left) and Sea Ice (bottom right) retrackers

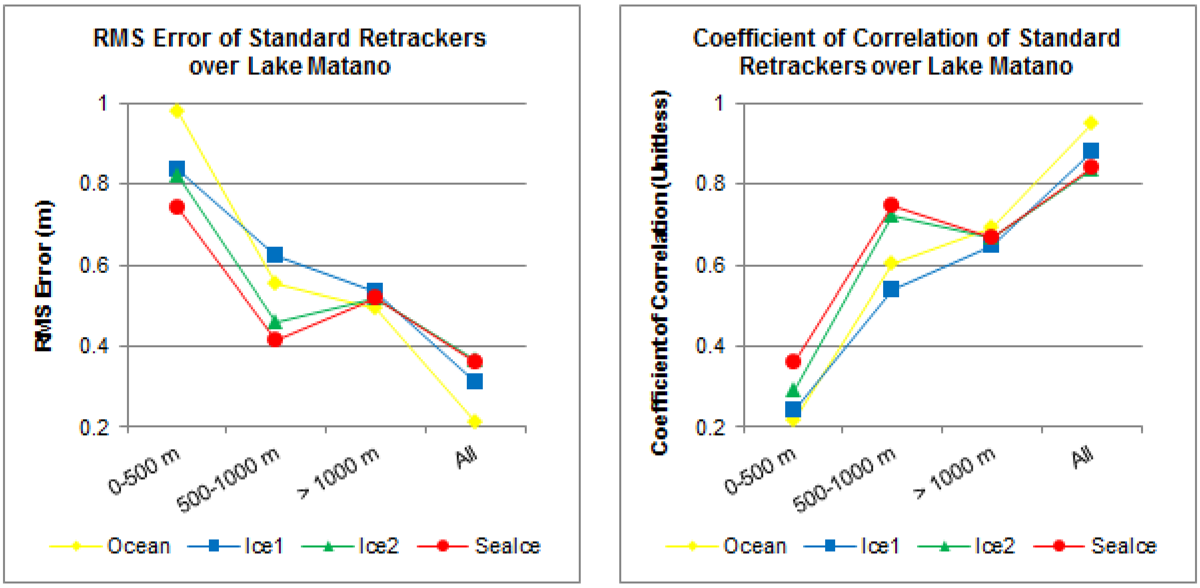


Figure 17 The performance of Envisat RA-2 radar altimetry measurements over Lake Matano, classified by the distance to the lakeshore

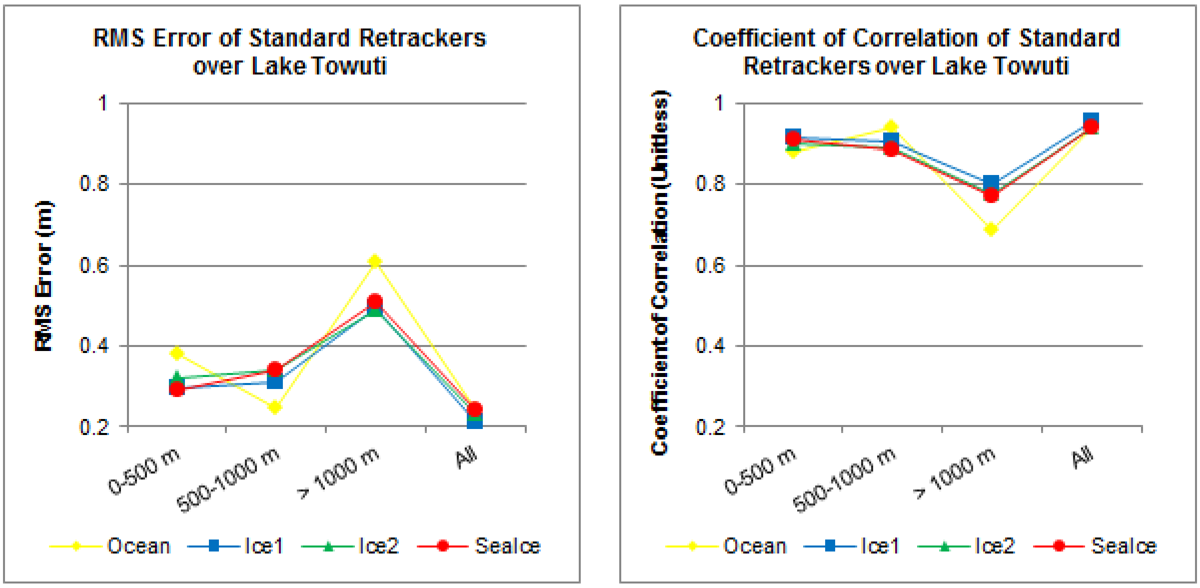


Figure 18 The performance of Envisat RA-2 radar altimetry measurements over Lake Towuti, classified by the distance to the lakeshore

6 Supplementary Materials

Table 8 Envisat RA-2 pass, cycles and observation period for each study sites

Site #	Site Name	Longitude	Latitude	Pass	River/Lake Width	In-Situ Data	Cycle	Period
	Mahakam Watershed							
1	UM03	114°35’10” E	0°50’02” N	89	54 m	No	6-93	2002-2010
2a	Melak01	115°53’20” E	0°17’08” S	46	247 m	Yes	6-93	2002-2010
2b	Melak02	115°47’58” E	0°11’03” S	297	294 m	Yes	6-93	2002-2010
3	Karangmumus	117°11’20” E	0°24’21” S	3	8-45 m	Yes	6-93	2002-2010
	Malili Lakes Complex							
4	Matano	121°24’6” E	2°28’59” S	397	8,159 m	Yes	6-93	2002-2010
5	Towuti	121°23’57” E	2°30’10” S	397	28,818 m	Yes	6-93	2002-2010