

Volume Changes in the Aral Lake from 1992-2015 from satellite

Bachelor's Thesis

Tanya Pheiffer Sunding
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Supervisors:
Ole Baltazar Andersen
Karina Nielsen

DTU Space
National Space Institute

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The Aral Sea was once the fourth largest lake in the World. Since the 1960's it has shrunk to a fraction of its original size, which has had disastrous consequences for the area. The purpose of this project is to calculate the volume change of the southern part of the lake in the period between 1992 and 2015, using satellite altimetry. For this, data from predominantly the CryoSat-2 satellite was used, but also from Jason-2, Envisat and GeoSat, through the PISTACH project and the Hydroweb database. The volume change, the Sea Surface Height and area shows the different developments of the lakes and gives an indication of their fates.

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1 Introduction

The Aral Sea once covered 67500km²(16), making it the fourth largest lake in the World. Situated in the middle of the Karakum and Kyzylkum deserts in the former Soviet Union and the modern Kazakhstan and Uzbekistan,(13) it was an important part of the lives of people of all of Central Asia. Many sustained themselves by fishing in the brackish lake, living in the surrounding coastal towns and ports and on the islands within it and its water was used in the surrounding industry. The two rivers that feeds the lake, Amu Darya and Sur Darya, that runs through the deserts from the Tian Shan and Pamir Mountains supports agriculture along them.

Under the Soviet Union, the goals of economic independence of the Union also included the cotton supply. Wanting to be selfsupplying with cotton, the Soviet government cleared vast areas of land and used large amounts of water to grow cotton.(13)

In the 1960's the Soviet government had the fields around the Amu Darya and Sur Darya included in the cotton industry and many irrigation channels were build from the rivers to supply the water demanding industry. This lessened the flow of water into the Aral Sea considerably and the water level has been dropping ever since. Former fishing towns were increasingly further from the coast and industries died down without the water nearby. The water became too salty to sustain wild life and between land and islands the lake began drying out and the largest island, Vozrozhdeniya, fused with the coast in 2001(13). The lake became several smaller lakes, the major of these, the northern, eastern and western lakes appears to have developed differently since. Attempts have been made to save the northern lake, while the eastern lake was reported to have dried out in 2014(12)(15) and the lake bed is becoming the new Aralkum desert.

The monitoring of the Aral Sea crisis has been varying. In situ data has become increasingly difficult to obtain due to the remote location of the lakes.(22) Satellite altimetry is then a good alternative to measure the development of the lake, finding the height of the water surface compared to a chosen geoid model. This is called the Sea Surface Height as altimetry is developed to measure over oceans and has later been used over ice and since inland lakes. It started with Skylab in 1973, but the difficulties of measuring close to coasts means that measurements over the Aral lake is not available as far back. The main satellites providing altimetry data over lakes are GeoSat, Envisat, the Jason satellites and the CryoSat 2 satellite.

This project will look at the volume change of the Aral Sea in the period 1992-2015 using CryoSat 2 products as the main sea surface height data source, processing the raw data from the satellite to gain the height of the lake surface. This process includes converting the travel time of a signal to a distance, choosing and adding correction connected to the conditions and converting waveforms into a retracking correction.

The satellite has only been producing data since July 2010, so the earlier lake surface heights is obtained from other databases that have data by the other satellites.

The changing areas of the lake is found by tracing over satellite images in a Geographic Information System software, which then calculate the areas.

The most drastic changing parts of the Aral Sea is the western and eastern lakes, these are the lakes that the project will focus on as the northern lake has stabilised since the efforts of saving it.

2 Theory

2.1 Satellite Altimetry

Satellite altimetry is the practice of measuring heights of surfaces using satellites. The satellite sends out a pulse of microwave signals which, on a plane and reflective surface, will be partly reflected back and picked up by the satellite. The travel time is then an expression of the distance between satellite and surface (range). This time can be expressed:

$$t = \frac{2 \cdot range}{c} \quad (1)$$

meaning that the range can be found:

$$range = \frac{t \cdot c}{2} \quad (2)$$

For the satellite measurements, the t is the window delay, corrected using the DORIS Ultra Stable Oscillator Drift(6). Large bodies of water, mostly oceans, are usually what is measured, as these are better reflectors and usually more plane than land surfaces.

The distance is only accurate to a certain degree, to ascertain a more precise measurement, the retracking correction must be found. To do this the waveform of the received signal is used. The waveforms are recorded as power over gate, which is the power of the returned signal at closely following times, making it possible to detect the distance very precisely. The range is the distance as measured by the reference gate, the retracking correction is the distance to the retracking gate. The waveforms must be processed as described in section 2.4

To find the height it is important to know the position of the satellite relative to a reference ellipsoid. The measured height over the ellipsoid is the height of the satellite over the ellipsoid subtracted the distance measured. From here the actual height is calculated by subtracting the height of the geoid (height of equal gravitational potential) from the measured height:

$$h = range - h_{geoid} + retracking\ correction \quad (3)$$

Still this height is inaccurate as the conditions also plays in to the travel time. The signal will be slowed through the atmosphere and other conditions related to the surface have an impact. These are accounted for in the corrections.

The Sea Surface Height (SSH) is found:

$$SSH = Height\ of\ orbit - (corrections + range - retracking\ correction) - geoid\ height \quad (4)$$

The height of the orbit is specified in section 3.1, corrections and geoid height in 2.2, retracking correction in 2.4.

2.2 Corrections

The corrections needed over inland waters are not the same as over open sea. At open sea the ocean tides play a role as these explains the rise and fall of the sea level at well-described patterns dependent on the Moon and Sun, but these do not apply to lakes. The Sea State bias accounts for the imprecision that occurs in the received signals caused by the small fluctuations in the sea surface: waves. The sea state bias depends on wave height, wind and wave types, but the sea state bias correction can be neglected over lakes as the waves will not build as high.

The corrections needed are:

Dry troposphere:

The dry tropospheric gases have the largest influence on the measurements and therefore gives the largest correction. The induced pole moment of the molecules gives the delay. The data is provided with values for this correction from the European Center for Medium-range Weather Forecasts (ECMWF) using the mean pressure.

Wet troposphere:

Water vapour is the other type of tropospheric gas which slows the radar signal. Here it is the dipole nature of the molecules. The values in the data also comes from the ECMWF and for both tropospheric corrections the values are found using Earth based measurements of the pressure and temperature.

Ionosphere:

The ionosphere is being ionized by the Sun's radiation and therefore consists of high concentrations of electrically charged particles such as free electrons. These electrons interferes with the pulse of the radar and slows it down. To account for this, the Global Ionospheric Map is used. In the data the ionospheric correction value is provided, which is derived from the map that shows the instantaneous distribution of the electron content in the ionosphere. Where this value can not be obtained, the correction provided is given by the Bent model using the solar radio flux.

Solid Earth tides:

As the ocean tides is the 'deformation' of the ocean by the gravity of the Sun and Moon, the solid Earth tides are the 'deformation' of the Earth beside the oceans.

Pole tides:

Is the flexing of the Earth's crust as the rotational axis of the Earth moves.

Geoid:

The geoid is the approximated "true" shape of the Earth. The shape the Earth would take if it was completely covered by oceans and there were no other forces than gravity and Earth's own centrifugal forces, meaning a model of Earth's geopotential. Cryosat makes use of the hybrid Mean Sea Surface model UCL04 over oceans, while the EGM96 geoid is used over land. These are provided in the Level 2 data set and the EGM96 is used to calculate the sea surface height in the project. Another geoid model is provided with the Pistach data set. This is the EGM2008 model.

2.3 Waveforms

The received waveforms will peak at the gate number where most cast back energy is received, as the surface will be the main reflector and therefor the height of the surface is represented by a gate close to the one with the highest amplitude.

The nature of the reflecting surface in the footprint of the satellite, can be detected in the shape of the waveform. The waveforms can then be divided into many different classes depending on the shapes. The number of classes can be many, but some of the classes are:

- Various Brown echos (Class 1 in figure in appendix L)
- Peaky echos (Class 2/5/6 in figure in appendix L)
- Brown + peak (Class 12/21/24 in figure in appendix L)

- Peak + noise (Class 23 in figure in appendix L)
- Noise (Class 3 in figure in appendix L)

The Brown echos, also called ocean waveforms, are seen over the ocean, at a distance from the coast (from figure in appendix M : these are predominant from around 3 km from the coast for the Jason-2 satellite). The highest amplitude of these are (mostly) found after a short climb of the leading edge, after this comes a slow fall of of the trailing edge. The rise time of the leading edge depends on the flatness of the surface: a faster climb means a 'neater' surface, i.e. smaller waves, whereas a surface with large waves produce a waveform with a slower rise time.

In coastal regions the presence of land within the footprint disturbs the waveform and can create peaks in the trailing edge of the waveform. The amount of disturbance in the waveform depend on the location of the land in the footprint and the reflectiveness and geometry of that land.

For very calm water, such as lakes, the reflectiveness is very high and the waveform will take the shape of a very narrow peak.

2.4 Retracking correction

The 1b level CryoSat data needs to be processed so the Sea Surface Height can be derived, for this the retracking correction is needed. A correction to the height can be derived from every waveform and is given by the gate number at which most reflection is detected. Firstly the threshold is needed. Here is used a simple threshold of 80% of the maximum amplitude.

$$Threshold\ level = 0.8 \cdot (maximum\ amplitude) \quad (5)$$

To make this more accurate, the first five bins are meaned, as they have a tendency of having outlying amplitudes, and this is taking as the starting value.

$$Starting\ value = \frac{1}{5} \sum_{n=1}^5 (amplitude\ of\ bin)_n \quad (6)$$

n is the bin number

$$Threshold\ level = (starting\ value) + 0.8 \cdot (maximum\ amplitude - starting\ value) \quad (7)$$

The location, in bin number, of this on the leading edge of the waveform is found:

$$n_{retrack} = (n_{first} - 1) + \frac{Threshold\ level - (amplitude\ of\ bin)_{n-1}}{(amplitude\ of\ bin)_n - (amplitude\ of\ bin)_{n-1}} \quad (8)$$

Where n_{first} is the first bin where

$$(amplitude\ of\ bin) > Threshold\ level \quad (9)$$

Then the retracking correction is:

$$retracking\ correction = -(n_{retrack} - n_{max}) \cdot conversion\ factor \quad (10)$$

The conversion factor is the conversion factor for the equipment from bin to meter and n_{max} is the total number of bins.(20) The data format (number of bins, size of records and so on) is specified in section 3.1.

2.5 Topography and snagging

Some waveforms can show a peak in the leading edge, causing a disturbance. This an error due to topography. The signal reflects off a tall topography in the fringes of the footprint. If the coast has high elevation and the satellite's signal reaches it before reaching the water surface, the land might reflect the signal before and the peak will show up in earlier bins than the actual measured surface.

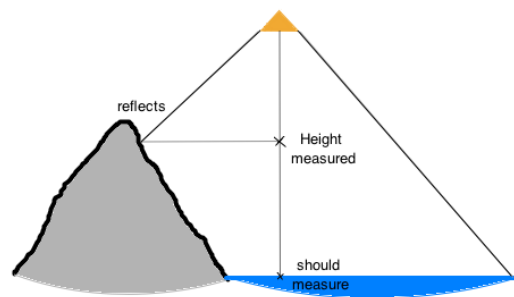


Figure 1: Error due to topography

When the peak is located in the trailing edge, this can be due to what is called snagging, also a common error in coastal areas or over lakes. This occurs if the satellite's footprint passes over shallow reflective water. While it should be measuring the the water surface just bellow the satellite only, it also picks up a second signal as the shallow water further away reflects it.

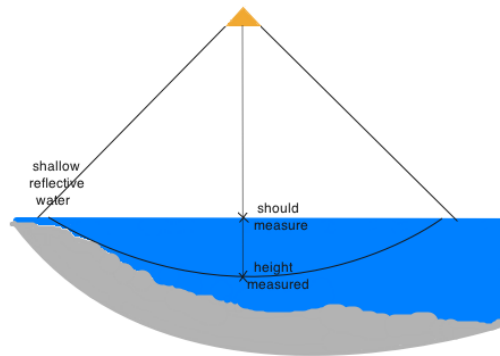


Figure 2: Error due to shallow water (snagging)

2.6 Aral Sea

The Aral Sea was an important source of food, transport and employment, situated in the desert between present day Uzbekistan and Kazakhstan. Its waters stems from the rivers of Amu Darya and Syr Darya that flows from the Tian Shan and Pamir mountains and into the Lake from the East and South. In the 1960's, under the Soviet Union, a large amount of irrigation channels were build from the rivers to provide water for the cotton fields in the surrounding desert. Since then the area of the lake has only been diminished, until it separated into several lakes, covering a small percent of the original extent of the lake. The consequences of this has been obvious: fishing communities, suddenly several kilometers from the coast, collapsing and the unavailability of water for other trades as well meaning the loss of livelihood to the locals. The exposed sea bed, now called the Aralkum Desert, has also been credited as the source of atmospheric aerosol pollution. Small particles are blown into the atmosphere where they contribute to climate change. Other studies show a deterioration of water quality of the drinking water in the area. The irrigation has led to that while the Aral Sea has shrunk, the groundwater level has risen, which means heightened risk of the agriculture polluting it. According to an article in Environmental Health Perspectives(14)

the groundwater in 1996 the content of total dissolved salts (TDS) in the ground water ranged from 0.5g/L to 6g/L compared to $\sim 0.3\text{g/L}$ in North America.

The Aral Sea is a saltwater endorheic basin, meaning that no river leads out of it, the water leaves solely by evaporation and seepage. As the water has evaporated and no new fresh water has been provided by the rivers, the salinity of the lake has risen until some of the separated lakes has become uninhabitable to fish.

The Aral Sea now consists of three major lakes: the northern lake, the western lake and the eastern lake. To the North is the Syr Darya river and to the South the Amu Darya.

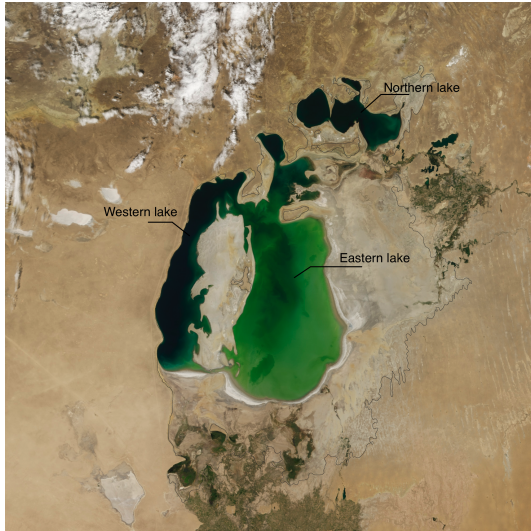


Figure 3: Aral lake in 2000 (17)



Figure 4: Aral lake in 2015 (17)

2.6.1 Rescue programs

A few attempts at rescuing what remains of the Aral Sea, has been made. Most notably the attempt at saving the North Aral Sea. Between 2005 and 2007 the government of Kazakhstan with help from the World bank build a damn, preventing the water from the northern lake to drain into the eastern, and made restoration work on the Syr Darya river, increasing the flow of water into the lake. This has worked to increase the surface area of the northern lake(10), but the cut off also means that less water now runs into the eastern lake.

2.6.2 Did the eastern lake disappear in 2014

In 2014, the news that the eastern lake had dried out completely in August of that year spread on sites such as the National Geographics (12) and the Guardian (15). This conclusion is based on this image by the spectraradiometer MODIS onboard the Terra satellite (figure 5).



Figure 5: East Aral apparingly dried out in August 2014(12)

2.7 CryoSat

To identify the satellite providing the best coverage of the Aral Sea, the AVISO pass locator(7) is used. The tracks can then be put into Google Earth. The images from this can be seen in appendices H and I. From these images it is easy to see that the passes of CryoSat lie much closer together and that it is the only satellite that can solely provide a good coverage for both lakes. This is due to CryoSat's long repeat-period orbit.

The CryoSat 2 (in this mostly referred to as just CryoSat) satellite was launched 8th of April 2010 with the main purpose of measuring land- and sea ice mass and thickness fluctuations. It can only provide data from mid-2010, so other data must be used before this time.

Using a mode mask map, the satellite switches between three modes of measurements according to which mode is advantageous over the local topography.

Onboard is SIRAL, DORIS and LRR instruments, the latter used for measuring the orbit.(2)

The orbit of CryoSat is such that it will not cover the same spot on the Earth before it has orbited 5344 times and the repeat cycle is 369 days. This provides more all-covering data for a small area, such as a lake, instead of just a single track across.

The satellite collects data above ice, some ocean basins and coastal zones as well as some lake areas. The data is collected with a 20Hz frequency and the range resolution, the distance between samples is 0.47m.

2.8 PISTACH and Hydroweb

PISTACH is a project that takes Jason-2 data and corrects so these are better suited for coastal regions. Obtained through the Aviso website(7)

Hydroweb is a database of water levels, merging data from several missions. For the Aral Sea, the satellites in Hydroweb are: Jason 2, Envisat and GeoSat.

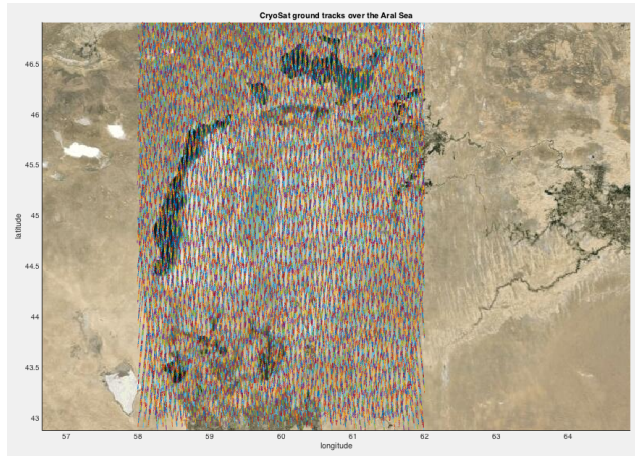


Figure 6: The track of the CryoSat data used, plotted over satellite image of the Aral Sea

2.9 Mode

(6) Over the area used Cryosat measured in SarIn mode continuously throughout the period. The Geographical Mode Mask is the model that decides which mode is used at which coordinates. The

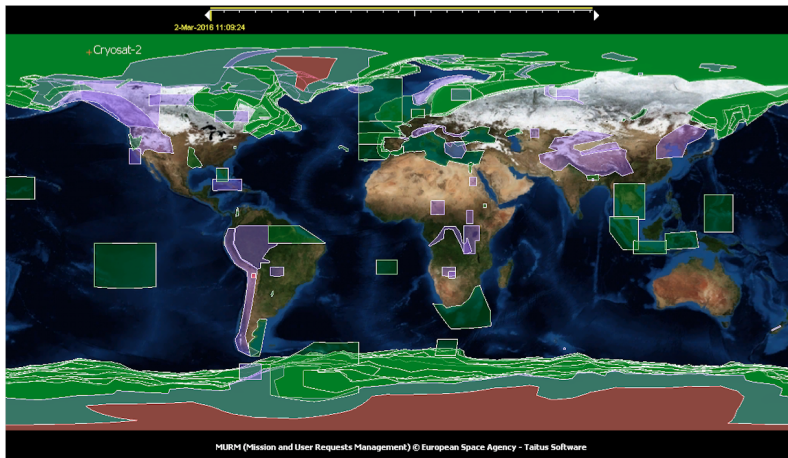


Figure 7: Geographical Mode Mask for CryoSat(5). Area where SAR mode is used is green, SARIn is purple and LRM are the rest (including the red)

three different modes used by Cryosat is LRM, Sar and SarIn. LRM, Low Resolution Mode, is used over oceans, continental ice sheets and some land. For LRM a radar pulse is emitted from the satellite with an interval of $500\mu\text{s}$ and the footprint it covers is circular. The number of samples in this mode is 128. In SAR mode, Synthetic Aperture Radar, the pulses are sent more frequently (interval of $50\mu\text{s}$) and taking into account the Doppler effect, which gives a slight frequency shift along the flight path, the footprint is divided into strips orthogonal to the flight path. The width of

these strips is 250m, overlapping strips are then superimposed. In SAR mode the sample number is 128. SarIn mode makes use of two, 1m apart, antennas. As the antennas receives the signal, it will only be exactly the same for the two antennas if the signal received is from directly below the satellite. 512 is the number of samples for this mode, because the range window is increased to 240m.

3 Processing data

To get digestible information out of the received data, it had to be transformed from Level 1 data to Level 2 data and from this the volume needed to be calculated. For this process scripts were created in Matlab.

3.1 Data structure

The CryoSat-2 data is found in the Radar Altimeter Database System (RADS)(9) by DEOS, using the data selection arguments:

- lat = 42.9, 46.9
- lon = 57.9, 62.0

This gives the data between latitude 42.9 and 46.9 and longitude 57.9 and 62.0 at all times, beginning in July 2010. The data used is a mixture of Level 1 and Level 2 data. The level 1b data is a product obtained from CryoSat. For the area, the SIRAL mode is in SarIn, which, consulting the CryoSat handbook means that the provided data has the record size is 88652 bytes and the structure includes:

- Time and orbit
- Measurements
- Corrections
- Averaged waveforms
- Waveforms

The time and orbit is recorded at 20Hz and informs about the time and the location, in latitude and longitude. The measurements includes the range at 20 Hz. The corrections provides the corrections as discussed in the "Corrections" sections 2.2 at only 1Hz. The averaged waveforms gives the averaged values at 1Hz of several measurements. The waveform of the signal is provided by the waveform section of the structure and is recorded at 20Hz.

The data consists of a number of records, containing a number of waveforms each. The waveforms are recorded by a set number of gates.

Specifications for the satellites can be seen in table 1:

Table 1: Specifications for relevant satellites (6)(4)(11)(3)

	CryoSat 2	Jason 2	GeoSat	Envisat
Launch	April 2010	June 2008	March 1985	March 202
Gates per waveform	128	104	60	128 (Ku-band) 64 (S-band)
Bin width	0.2342cm	3.125ns	3.125ns	3.125ns 6.25ns
Sample rate (Hz)	20	20	10	18
Repeat cycle (days)	369 (after 5344 orbits)	10	17 (near repeat)	35
Geoid model	EGM96 over land UCL04 over ocean	EGM96 PISTACH uses EGM2008	JGM-3 corrected in Hydroweb	EGM96 corrected in Hydroweb
Average orbit height (km)	730	1336	800	784
Reach (latitude) (deg)	88	66	72	81.5

3.2 scripts

3.2.1 script 1: CryoSat SSH

The function of this script, appendix N, is to read the Level 1 data and transform it into Level 2 data, giving a schematic of heights with latitude, longitude and time as a product. Using the 'dir' command a directory is created where data can be read from. The waveforms are saved and the time is converted into seconds and various other information is saved into matrices, like position on the ground and the needed corrections. Here the heights can be found as well, these are already converted from the travel time to measured height as described in section 2.1. After this every single waveform is treated as section 2.4 and the range correction is found. The corrections are subtracted from the measured heights and the corrected SSH is saved in a matrix with the according latitude, longitude and time. The product is a data file with this array.

3.2.2 script 2: Mean

Included in appendix O

This script allows one to take data of the type: height, latitude, longitude and time and remove extreme height outliers that is mainly caused by snagging. The data consist of many heights with the same time stamp: the heights measured across the lake. As each lake should only have one height, the mean of these are found at each time. These are plotted for each lake along with the standard deviation of the heights. The script produces a plot of the water level, represented as means and standard deviations, each year, for both lakes and two data files with the mean SSH, one for each lake. The plot is used to decide how the data can be divided to achieve accurate linear fit to the mean SSH development. See 3.3

3.2.3 script 3: Volume and area

The purpose of this script as seen in appendix P is to calculate the volume changes. Data files with the mean heights and year is imported as well as files with the areas of the lakes. The mean area from one year to the next is found and the heights fitted in best linear fits. See 3.3. The linear regressions are multiplied with the mean area change to get the change in volume. The output is a plot of volume change in km^3/y with a the a volume change for each year for both lakes. The uncertainties are found and plotted lastly.

3.2.4 script 4: PISTACH SSH plotter

As seen in appendix Q this script takes the PISTACH data and applies the provided corrections to the provided range, giving the SSH. The mean SSH at each time is found and plotted,

3.3 Linear fit

The mean SSH, found and plotted using 3.2.1, creates two non-linear graphs, but a linear regression can be approximated when dividing the graphs into three sections each. They will come to look like this when plotted:

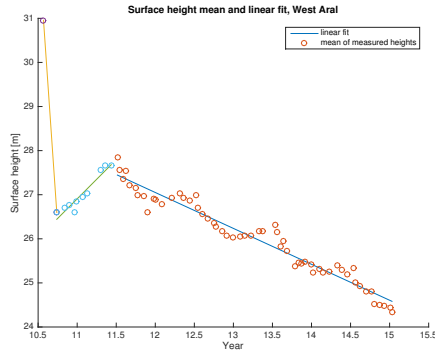


Figure 8: The linear regression (solid lines) of the mean (circles), for the western lake

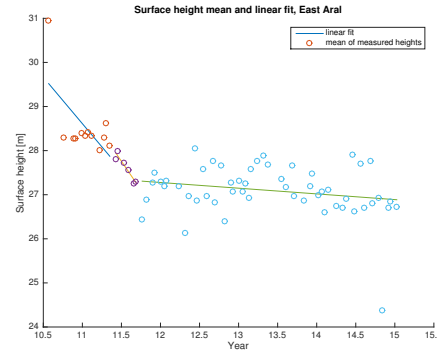


Figure 9: The linear regression (solid lines) of the mean (circles), for the eastern lake

3.4 Area measured in QGIS

To get a volume, the area of the lake is also needed. The program QGIS, an open source geographic information system application, is used. Landsat pictures from USGS Global Visual Viewer(8) are added to a raster layer, the WGS 84/UTM 40 is chosen, and on a new layer, polygons are drawn over the water of the lake. The area can be calculated with an in-built function in QGIS. Using this projections means that the area is given in m^2 . This method means that the area can be found for every time the Landsat has passed over the lake, but the precision of the measurement depends on how far you are willing to zoom. The quality and cloud cover makes for less precise measurements and at times, if the boundary is made of shallow water, the coast of the lake is unclear. Some images are obscured by a bright blue/turquoise colour along the coast, maybe from cloud cover or shallow water.

The area used is easily definable for the western lake as the lake for the period is well-defined with only its link to the eastern lake before 2007 to consider. The eastern lake on the other hand is more difficult to define as its borders with the smaller lakes between it and the northern lake is none existent before 2006. The easiest way to define the borders is to define them as where the eastern lake's coastline is after this and then project this as accurately as possible on the satellite photos before this. Figure 10, 11 and 12 shows how the areal was defined in the boarder between eastern and northern lake.

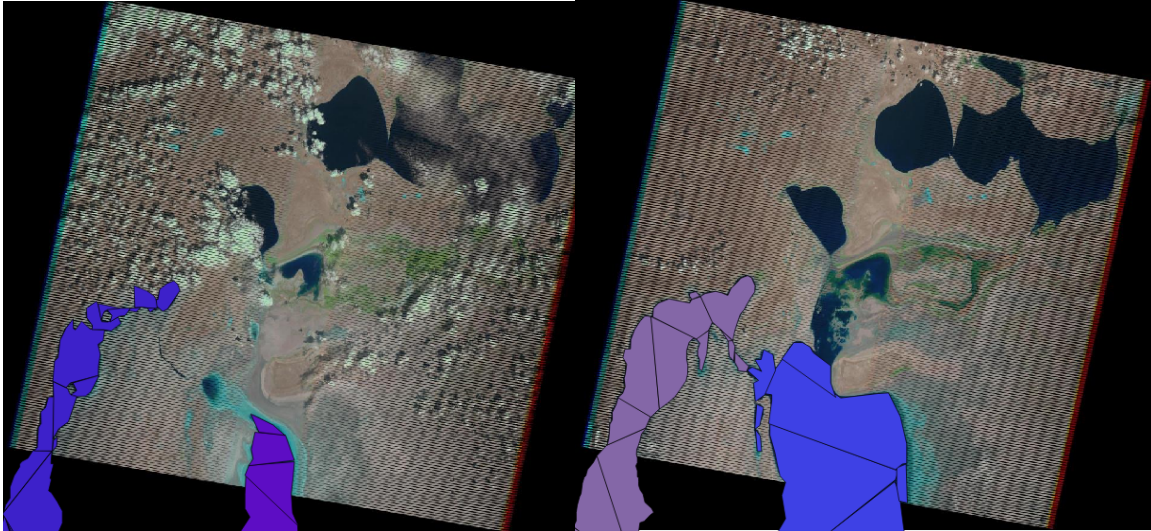


Figure 10: 2015: blue polygon over the western lake, purple over eastern

Figure 11: 2005: purple polygon over the western lake, blue over eastern

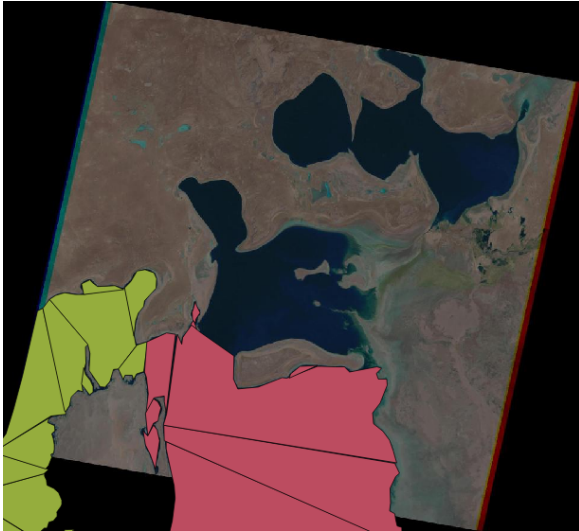


Figure 12: 1996: green polygon over the western lake, red over eastern

Polygons is also used to cut out the height data calculated in 3.2.1 according to the specific longitude and latitude encased in the polygons. In this case the polygons used describes an area of the lake that is within the lakes, a distance from the coast, at all times (2014 for the eastern lake is an exception). This decision is based on the need to reduce disturbance from the shallow water areas and coast at all times, to avoid snagging and topography disturbances.

3.5 Landsat

The satellite images used to calculate area are products of the Landsat missions. The images used for the area before 2000 is by the Thematic Mapper (TM) instrument. After this the images are by Enhanced Thematic Mapper Plus (ETM+) instrument. These both create images with a resolution of 30m per pixel (21).

4 Results

4.1 Area of Aral West and East from 1992 - 2015

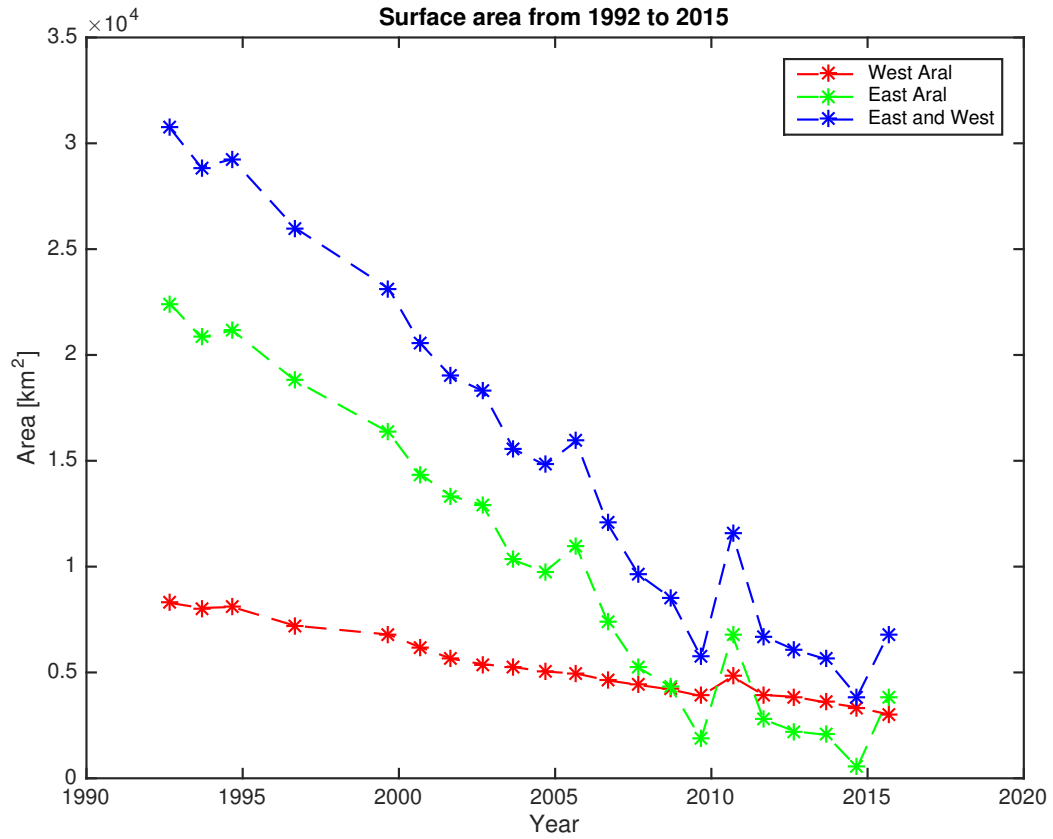


Figure 13: The Area of the lake as described in 3.4 with both lakes as one area and split up in two

4.2 SSH from 2010 - 2015

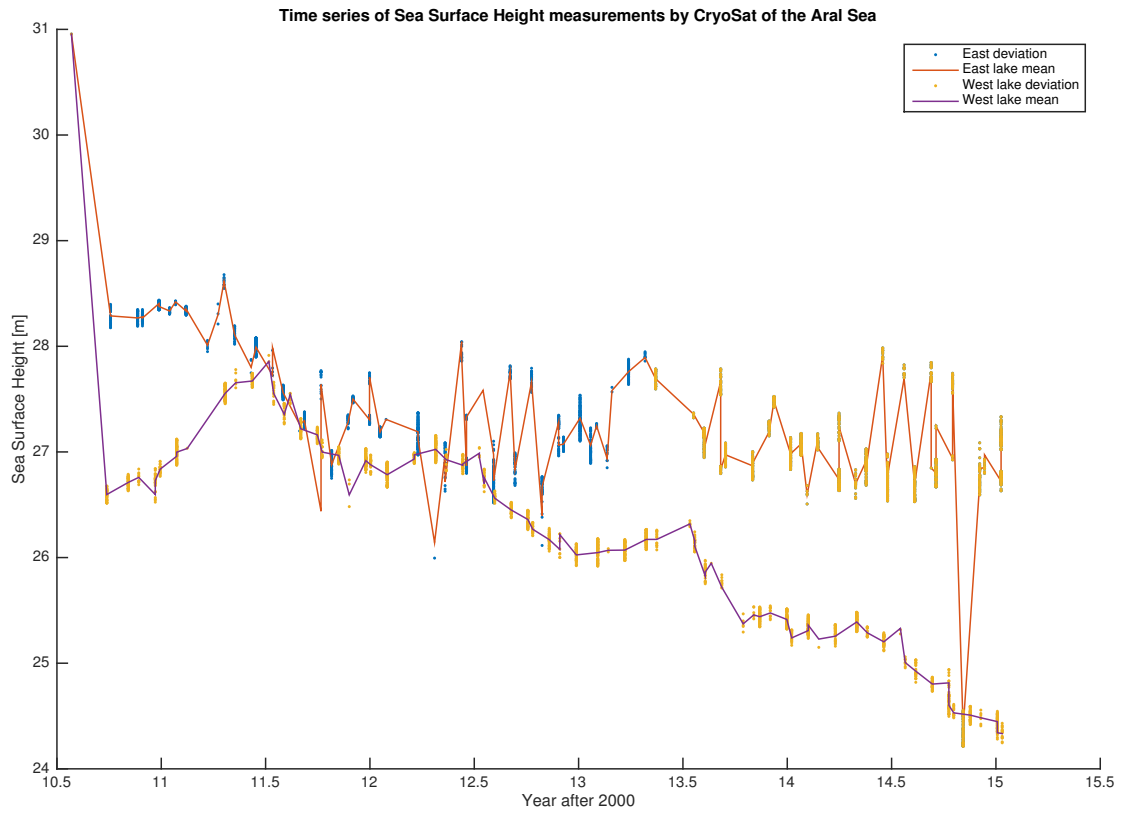


Figure 14: Sea Surface Height mean and standard deviation (both in meters) by CryoSat 2010-2015. Standard deviation is the vertical bars, plotted on top of the mean it belongs to, no matter the colour.

4.3 Volume change

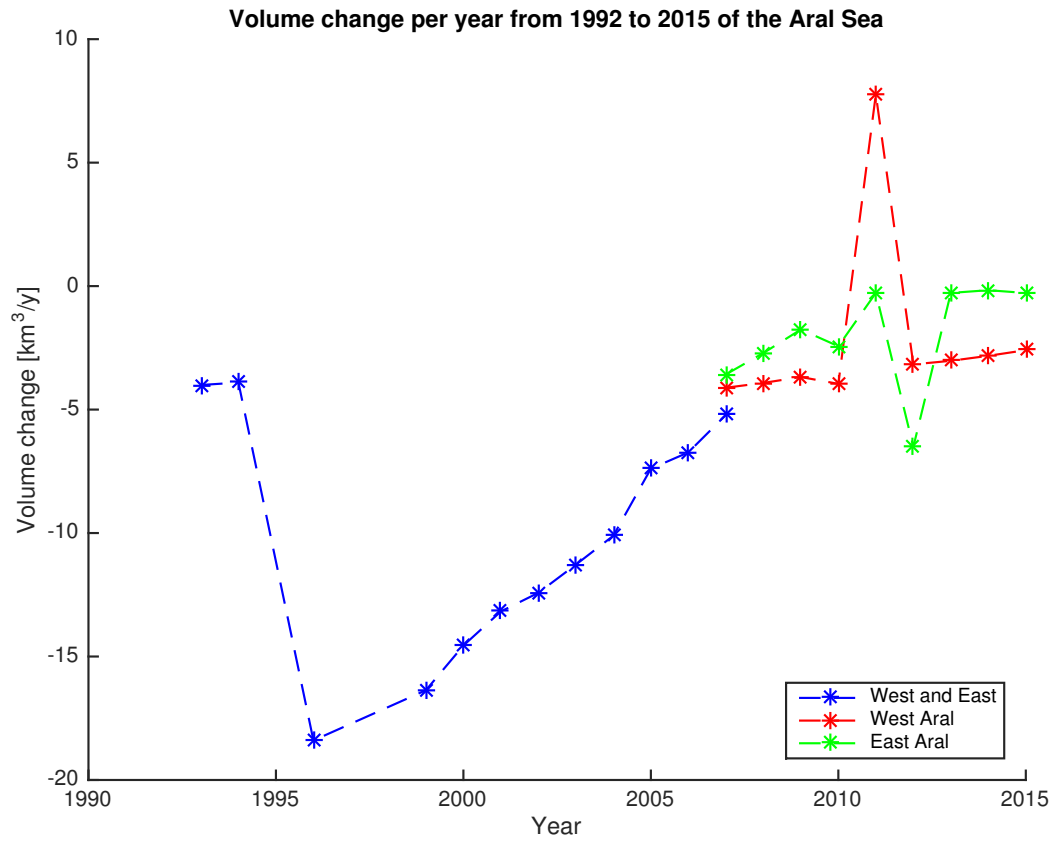


Figure 15: Volume change in km^3/year for the whole period, using both Cryosat and Hydroweb SSH and area from Landsat images

5 Discussion

The discussion will refer to the results in section 4 (the section of the volume change between 2007 and 2015 can be seen on its own in appendix C) . The compared plots is in the following referred to as the plots of PISTACH data in appendix B and Hydroweb data in appendix A.

5.1 CryoSat

The SSH plot, figure 14, shows an over all fall in surface height for both lakes, although more dramatic for the western lake of around 2m, while the drop is 1.5m for the eastern lake. The very first data point for both lakes is so far from the other points that it has been considered an outlier in the further use of the data and the linear fit that includes this point has not been used and a fit starting from the next data point has taken its place. The plot of volume change, figure 15, shows that the water is disappearing from the Aral Sea as expected. As the water gets sparser, the volume change slows, but throughout the period, the water of the Aral Sea is draining, with exception of the western Aral lake in 2011. This event will be discussed in the section 5.3 below.

The area of the western lake decreases at a much lower rate than the eastern lake, while after 2008, the sea surface height of the eastern lake is more stable than the western. This will also be discussed in the following.

5.2 Comparison

The PISTACH and the CryoSat SSH plots compare well, both having an almost unchanging level for the eastern lake and a peak between 2011 and 2012 and subsequent fall for the western lake. The two data sets are plotted together for better comparison (figure 16):

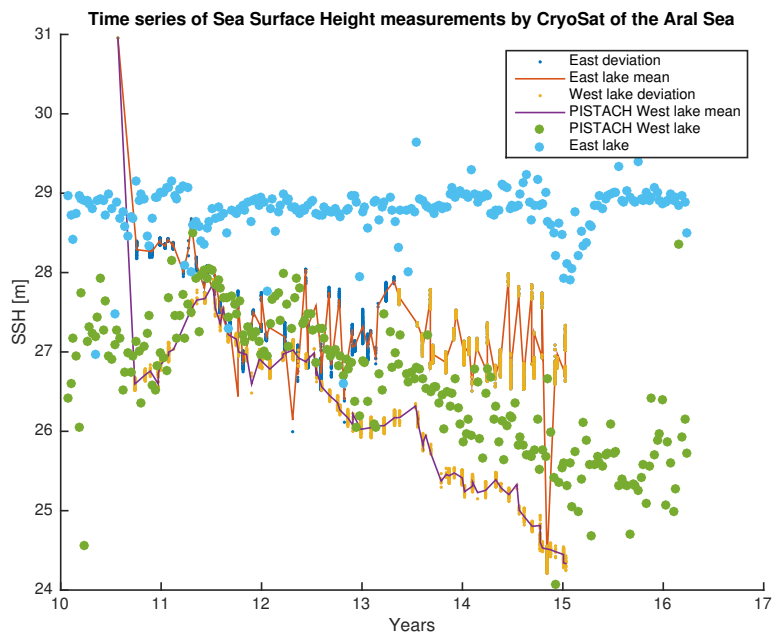


Figure 16: PISTACH and CryoSat data

The SSH values of the plots all have $\sim \frac{1}{2}$ m difference, but as mentioned in section 2.2, they are calculated using different reference geoids, the EGM2008 and EGM97 respectively. This does not make a difference for the volume change calculations as only the slope for the SSH is used.

Looking at the SSH plot from the Hydroweb data, it can be seen that this holds for the graph of the western lake as well. The eastern lake is more difficult as there is no more data for it after 2012, due to measuring difficulties as the lake becomes too small. The Jason satellites and the GeoSat satellite does not cover the lake as well as CryoSat (appendices H and I), simply because of the greater distance between their tracks. This might also be the reason for the discrepancy in the PISTACH eastern SSH until 2012. In the PISTACH data, the western lake is not constant, but rises almost 1m.

The previously mentioned first SSH data point does not appear to show up on either Hydroweb or PISTACH data.

5.3 Events

In the resulting plots in section 4 the graphs draw out some interesting events, that gives rise to speculations of the cause, the accuracy and the consequences here off. This sections will go through these events.

One of these events is the 2010-11 western lake rise in surface height on the CryoSat figure 14. It is supported by the PISTACH and Hydroweb data, that, although only the Hydroweb data goes further back than 2010, shows the same increase of ~ 1.5 m, in Cryosat data a rise from around 26.5m to around 28m, which is significantly more than the yearly oscillation as seen on the Hydroweb data. This can also be seen as a volume growth in the western lake on the volume change plot, as the only year with a positive volume change for any of the lakes. The area, figure 13, had a small growth from 2010-2011. What could cause this sudden growth in water content? Looking at the eastern lake, the area might have expanded by ~ 5000 km², but the subsequent decrease in area and the stability of the height at that time seen on the Cryosat data and the PISTACH data, gives a negative change in volume for 2011, if a smaller negative change than the previous year.

This could be due to a rainy year in the mountains that feed the Amu Darya, that branches out and supplies both lakes. The western lake, supplied with new water, has a smaller outflux of water than influx and the volume grows. Meanwhile the eastern lake is not as good at keeping its water and the outflux still surpass the influx. This could be due to a higher evaporation rate in the eastern lake.

As there is very little in-situ data available, the actual cause of this rise is difficult to know.

Another interesting observation is the stability of the eastern lake after 2013. The volume change is still negative but very close to 0, the area does change, but the height is either stable or slightly falling. The drastic fluctuations in area, but stable height indicates that the water throughout the lake is very shallow, meaning it dissipates and spreads quickly. In the section 2.6.2 is described how satellite images showed that the eastern lake had vanished entirely by August 2014, coinciding with this event. The areas used to calculate the volume change does not reflect that, because the data appears to have measured reflections of water over the area at that time, as shown in appendix ?? and it can therefor be argued that water, shallow, but deep enough to create these reflection are

present. This is the reason for considering the darker area on the Landsat image for August 2014 as water, as seen in appendix K, even for the difficulties discerning water from land.

Another interesting point that can be derived from this is that the stable sea surface height of around 27–28m to the geoid, which differs only slightly to the $\sim 29\text{m}$ of the PISTACH data, is for this very shallow basin of water, meaning that it is the height of the earth over the geoid at this point. Holding it up against the sea surface heights of the western lake, it is clear that the western lake lies much deeper. Its drainage seems to lie stable at $\sim -2.5\text{km}^3/\text{yr}$ and the area decreases at a much slower and steadier rate, meaning it is much deeper than the eastern lake, and that the sea bed has a steeper incline. This allows it to keep the evaporation at a lower rate than the shallow, quickly evaporation of the eastern lake, supporting the 2010-2011 volume growth theory mentioned above.

In early 2015, there is a visible downward spike of the sea surface height of the eastern lake, which can be seen in the PISTACH data, appendix B. This can be due to a cold winter, freezing over the shallow water of this lake.

The volume change is smaller in 1992-1993, which comes from the stable SSH here.

An important event when collecting and processing data is when the two lakes separated. This is important to know because it changes how data can be processed: the surface height of the lakes will be the same as long as the water flows freely between them, this is the nature of water, but when the two separate, suddenly they can have completely different levels and taking the mean of them both together would give a surface height between them. To see when the two lakes separate, their sea surface level can be found and plotted separately and the when they differ from each other is when they are not connected. The CryoSat and PISTACH data does not go far enough back for them to be connected, but from the Hydroweb sea surface height plot in appendix A it is seen to be around 2008. The data is plotted so that it is the graph for both lakes that is plotted until 2002, where they are separately plotted. This is because the data for the separate lakes are only available from that year.

5.4 Uncertainty

The uncertainties stem from the mean taken of the SSH, the error of the linear regression and the area measuring uncertainty.

Here the SSH uncertainties are taken from the uncertainty of the linear regression to the mean SSH. The linear regressions are made for the whole period in this project and the uncertainties can therefor be calculated for the whole period. The standard deviation for the linear regression of the SSH is plotted in appendix E. It can be cross referenced with the figures 8 and 9 to see that where the SSH points lie further away from the linear regression or are fewer, the uncertainty is bigger.

From the area measurements the uncertainty is difficult to gain, and can only be given by a rough estimate. If the conditions are good, the coast is easily outlined, and the images are fully zoomed in when drawing the areas, the minimum uncertainty is as small as the resolution of the pictures, which, for Landsat ETM+ and TM, is 30 meters per pixel. The real measurements were made as accurate as possible without zooming in to a pixel level, and at times the boarder between water and coast was very obscured by very shallow water. This obscuring was much more prominent in

the eastern lake, and the estimated uncertainty must reflect this. The standard deviation estimates are: 1% for the eastern lake and 0.5% for the western lake. For the whole area, the standard deviation is the 1% of the eastern lake and 0.5% of the western put together. This can be seen in appendix D

As the volume change is calculated by multiplication of the height change and area, the uncertainty is calculated:

$$2\sigma dV = |dV| \sqrt{\left(\frac{2\sigma A}{A}\right)^2 + \left(\frac{2\sigma dSSH}{dSSH}\right)^2} \quad (11)$$

This will give standard deviations that are plotted over time in figure 17:

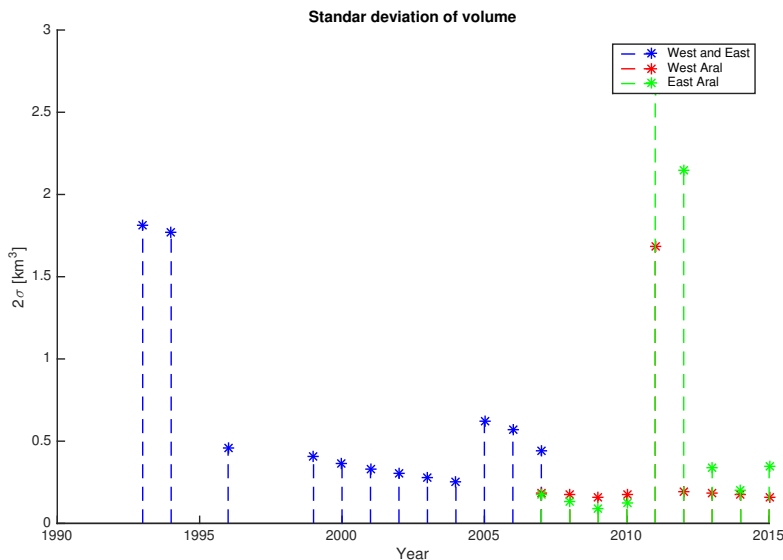


Figure 17: standard deviation of volume

As seen in the plot in appendix D, the deviation of the area before 2007 is very large, due to the large area, but at this point the edges of the lake was better defined visually and the high uncertainty seems too high, therefore the uncertainty for area and volume is plotted when uncertainty of area before 2007 is changed to only 0.2% in appendix F. It can be seen that while the area uncertainty change, the volume uncertainty appear unaffected. It can therefore be concluded that the uncertainty of the slope of the linear regression affect the volume uncertainty much more than the area uncertainty.

The mean areas between each year were used in the volumes and the uncertainties are applied to these, but it is then assumed that the area develops linearly. An more frequent area measurement or knowing the topography of the cross section of the lakes could give the exact development of the area. Where the lake bed is steep, the area develops slower than where the slope has a lesser

incline. The lake bed might in have varying inclines which will give a different volume than a linear incline.

6 Conclusion

To obtain values for the changing volume in the Aral Sea, parts of the Aral Sea was chosen as the points of focus. Here the South Aral lake was chose, looking at the eastern and western part as individual lakes. To observe these the satellite that best covers the lakes was found. This turned out to be CryoSat, which has a much longer repeat cycle and passes over the lake in a much tighter grid. But CryoSat data only date backs to mid-2010, meaning that data from other satellites, Jason-2, Envisat, GeoSat, combined by Hydroweb, supply heights for the time before. As these is more difficult to compare to CryoSat data, PISTACH data from Jason-2 was used to compare with. The CryoSat data is processed from level 1 data to the Sea Surface Heights using a MatLab script. The mean for each lake at each pass is plotted to find the periods where the development could be fitted linearly. It's the linear regressions of the heights that is used.

The area needed is taken for August (September when not available) each year, using Landsat images to draw after. The volume is calculated by multiplying the change in height per year with the mean area between each year.

The volume change plot shows how the volume has been almost continuously dropping for the eastern and western lake through out the period of 1992 to 2015. The only rise in volume happened in western Aral in 2011, a result of a rise in area and surface height. The same slight rise in the change of volume in the eastern lake could indicate that water was released into the lakes, but that the shallow waters of the eastern lake evaporated at a much quicker rate.

In the beginning of the period, the still connected lakes lost water volume at a faster rate, except for in the first two years where a steady SSH made for a slower volume change. As the lake lost water, the water disappeared slower.

In 2007 the change of the lakes were almost the same, but after this point they develop differently. After the separation, the eastern Aral has evened out to a non-growth rate (taking the uncertainties into account), which comes from the evening out of the surface height, as the area still fluctuates. The reason for this is that the water level in the eastern lake is so low that it can barely be seen on satellite images and the SSH found here is the height of the sea bed. The shallow water spreads quickly when added to the lake and that gives the fluctuation of the area.

Meanwhile, the SSH of the western lake is lower than the eastern lake, but is still falling. This means that the sea bed of the western lake is much lower and the lake is deeper. It can also be seen from the slow area change that the western lake bed is much steeper.

Looking at the volume change, Sea Surface Height and area, the characteristics of the lake can be seen, for the Aral Sea, the western and eastern lake easily discernible in the results, where one is shallow and the other deep. This gives a volume change leveling to a close to zero change and a slowly decreasing volume change, respectively, although both has a negative volume change. The volume change is very sensible to the change in SSH.

The volume change can also give an indication of the circumstances at that time. A particularly dry or wet year would show up in the volume change as well as any successful preservation efforts. For the southern Aral, the interference with its water sources is clear. 50 years after the lake is just a small part of what it used to, the lake shrinking at 4km^3 a year!

7 Further studies

What could be interesting for further study would be to see the future development of the lake. To see if the lake will continue to shrink and it would be especially interesting to follow the rescue programs that is already being implemented and the ones that might be undertaken in the future. Here the eastern Aral lake would probably be the least likely candidate as it is already almost dry, although the oscillation in its area, if looking at several satellite images over a year, implies that water is still being supplied by the rivers, if very little. The western lake is deep enough that it seems to change much slower and this could mean that it would be fit for rescuing projects.

The Northern lake, on the other hand has been under process of preservation since 2006, section 2.6.1, and just from satellite images, it appears to have grown in area. Here it would be very interesting to use altimetry to determine the SSH both from the years before 2006 and after. Using this to determine the change in volume, if it changes from negative to positive and when this change happened. This could indicate how long it took from implementation to effect and if the method used to save it is efficient.

Getting a more detailed area progress would also benefit future studies.

8 User manual

Here the scripts created to process the data.

8.1 script 1: SSH

The input of the script is two lists of files or two folders; the first containing level 1 altimetry data and the second, level 2 data. The last input is a list of the file names, alternating between the level 1 file name and the accompanying level 2 file name. This will be reshaped into a matrix with level 1 file names in the first column and level 2 file names in the second. This is to be used when calling the two functions. `Cryo_L2_read` and `Cryo_L1b_read`. Each gives two 1x1 structs: the header and the data. The fields of these structs are described in are described in the CryoSat handbook(6). After extracting the waveforms, it is checked that the file contain 9 or more waveforms as anything less is not usable. The rest of the needed information is extracted from the level 1 data. The corrections are put into matrix and the unneeded corrections is removed. The range correction is found and the measured height is subtracted all corrections to give the SSH. To avoid confusion later, all zero values in latitude and longitude and the latitude and longitude that is not within the boundaries specified when requesting the data is prescribed a NaN value, meaning that they will not be plotted.

Lastly, the output of the script is a data file named `Heights.dat` that contains latitude, longitude, time and SSH of all the files.

See code in appendix N

8.2 script 2: Mean

This script is designed to handle the western and eastern lake separately and the data has therefore been pre-cut to fit these two locations. The input is files with SSH and to run for two locations, the variables of the file names is required. The data from the file currently being processed is assigned a matrix `M`, and it is checked if the dimensions of the matrix is good. The software used to cut, `QGIS`, will give either a matrix of 4 or one of more, depending on the method. One can contain both location, while the other contains only one. The one containing both locations will need its two first columns deleted as all the data lies in the last 5 and the rest of the script assumes a matrix of 4 columns or 5 columns where one describes the location. The mean of the SSH for each time is to be found and to get the most reasonable value, 'extreme' outliers are reassigned as a NaN value. These values can be adjust according to what is deemed appropriate, but here is used the limits: over 50m and below 20m is removed. Next the rows with the same time is found and for each time, the mean and standard deviation is calculated using build-in functions. The output is a SSH in meters over Year in years after 2000 plot containing the means and standard deviations of both locations and a file where the mean and time to each mean is saved. The file is called 'mean' followed by the location variable.

See code in appendix O

8.3 script 3: Volume and area

This script is a merge of two separate scripts, why the structure seems a bit odd. The first part handles the data from 1992-2010. The first input is the import of the SSH files with the CSV format: year,SSH, saved in separate arrays. Second input is the area data, each file an area for one

of the lakes for a single year. The years are defined beforehand. As the areas are given as the areas of several polygons, the area is summed for each year for each lake. For the SSH data, the linear regression with standard deviation is calculated for each array.

The third input is the SSH data for the period 2011-2015, one file for each lake, same format as the previous SSH file. The area for this period is also imported and summed here and the area for the full period is plotted as km^2 . The SSH values for the later period is split and fitted linearly, standard deviation also calculated. The linear fits are plotted over the SSH values for comparison. To find the volume changes, the slopes of the linear regressions (remembering to change from meter to kilometers) are multiplied with the mean between each subsequent areas. This is plotted in the resulting output: a plot with volume change over year for eastern Aral, western Aral and the collected lake before 2008. the units are km^3/year .

In the last part the uncertainties are plotted: firstly the already found slope deviations, the the area uncertainties as 0.5% and 1% of the full area for the western and eastern lake. Lastly the volume uncertainties are calculated and plotted. The three last plots are 2σ over year.

See code in appendix P

8.4 script 4: PISTACH SSH plotter

This is the script that takes a provided directory of files in the format provided by Aviso and PISTACH. The data is already level 2 data, and only needs to be corrected with the provided corrections. These corrections are the same as described for CryoSat in section 2.2. The latitude, longitude, time and SSH are then put into an array and the user can choose to save it in a file.

Hereafter the 'extreme' outliers are removed like in script 2. The mean is then taken for each year and plotted in a scatter plot.

See code in appendix Q

References

- [1] *Aviso Pass Locator*, <http://www.aviso.altimetry.fr/en/data/tools/pass-locator.html>, By CNES, Accessed: 4-2-2016.
- [2] *CryoSat info page*, http://www.esa.int/Our_Activities/Observing_the_Earth/CryoSat, By European Space Agency, Accessed: 9-6-2016.
- [3] *ENVISAT RA2/MWR Product Handbook*, https://earth.esa.int/documents/10174/1912962/ra2-mwr.ProductHandbook.2_2.pdf, 2007.
- [4] *OSTM/Jason-2 Products Handbook*, http://www.aviso.altimetry.fr/fileadmin/documents/data/tools/hdbk_j2.pdf, 2015.
- [5] European Space Agency, *CryoSat Geographical Mode Mask*, <https://earth.esa.int/web/guest/-/geographical-mode-mask-7107>, Accessed: 7-6-2016.
- [6] Catherine Bouzinac, *CryoSat Product Handbook*, Accessed: 8-6-2016.
- [7] CNES, *Aviso*, <http://www.aviso.altimetry.fr/en/home.html>, Accessed: 7-2-2016.
- [8] USGS GloVis Database.
- [9] DEOS, *Radar Altimeter Database System*, <http://rads.tudelft.nl/rads/rads.shtml>, Accessed: 7-2-2016.
- [10] Rick Docksai, *Reviving the Aral Sea*, *Futurist* **44** (2010).
- [11] eo Portal, *GEOSAT (Geodetic/Geophysical Satellite)*, <https://directory.eoportal.org/web/eoportal/satellite-missions/g/geosat>.
- [12] Brian Clark Howard, *Satellite images show Aral Sea basin 'completely dried'*, the Guardian (2014), <http://news.nationalgeographic.com/news/2014/10/141001-aral-sea-shrinking-drought-water-environment/>.
- [13] A. Kostianoy A. Kosarev I. Zonn, M. Glantz, *The Aral Sea Encyclopedia*, Springer, 2009.
- [14] J. van der Meer Ian Small and R.E.G. Upshur, *Acting on an Environmental Health Disaster: The Case of the Aral Sea*, *Environmental Health Perspectives* **109** (2010).
- [15] Enjoli Liston, *Aral Sea's Eastern Basin Is Dry for First Time in 600 Years*, National Geographic (2014), <https://www.theguardian.com/world/2014/oct/01/satellite-images-show-aral-sea-basin-completely-dried>.
- [16] Philip Micklin, *The future Aral Sea: hope and despair*, *Environmental Earth Sciences* **75** (2016).
- [17] NASA, *NASA satellite images of Aral*, http://earthobservatory.nasa.gov/Features/WorldOfChange/aral_sea.php, Accessed: 8-6-2016.
- [18] Andrey G. Kostianoy Stefano Vignudelli, Paolo Cipollini and Jerome Benveniste, *Coastal altimetry*, Springer, 2011.

- [19] CNES Theia, Legos, *Hydroweb Database*, <http://hydroweb.theia-land.fr/>, Accessed: 7-2-2016.
- [20] Treshold, *Treshold Retracker Documentation*, http://icesat4.gsfc.nasa.gov/radar_data/data_processing/threshold.php, Accessed: 4-5-2016.
- [21] USGS, *Frequently asked questions about the landsat missions*, http://landsat.usgs.gov/band_designations_landsat_satellites.php, Accessed: 8-6-2016.
- [22] Peter O. Zavialov, *Physical Oceanography of the Dying Aral Sea*, Springer, 2007.

Appendices

A SSH 1992 to 2015 by Hydroweb

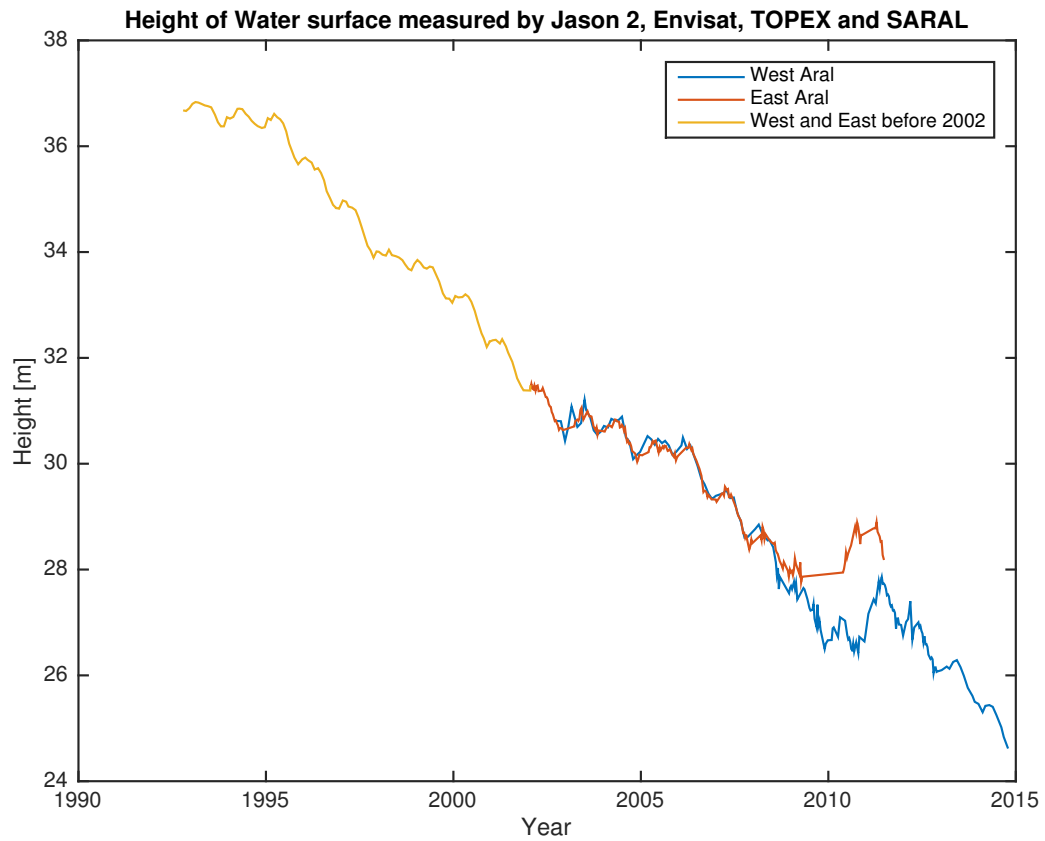


Figure 18: SSH for the period 1992-2015 by Jason 2, TOPEX, Envisat and SARAL

B SSH 2010 to 2016 by PISTACH

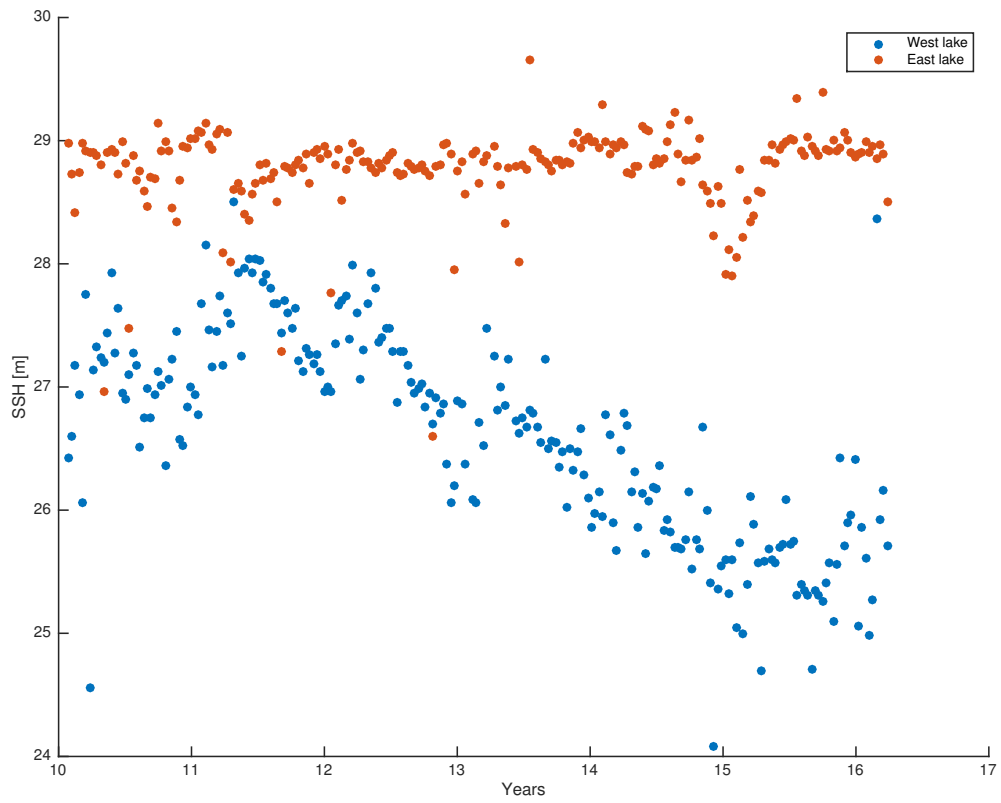


Figure 19: SSH for the period 2010-2016 by Jason 2 improved by PISTACH

C Volume change 2007-2015

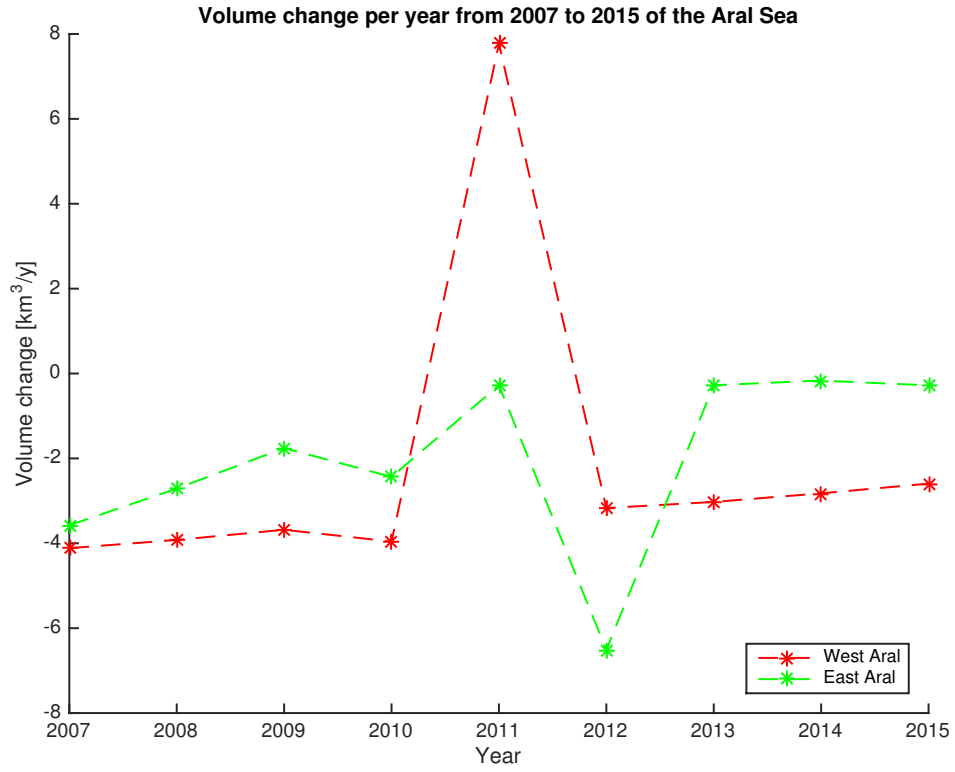


Figure 20: Change of volume in eastern and western Aral from 2007 to 2015

D Standard deviation of Area

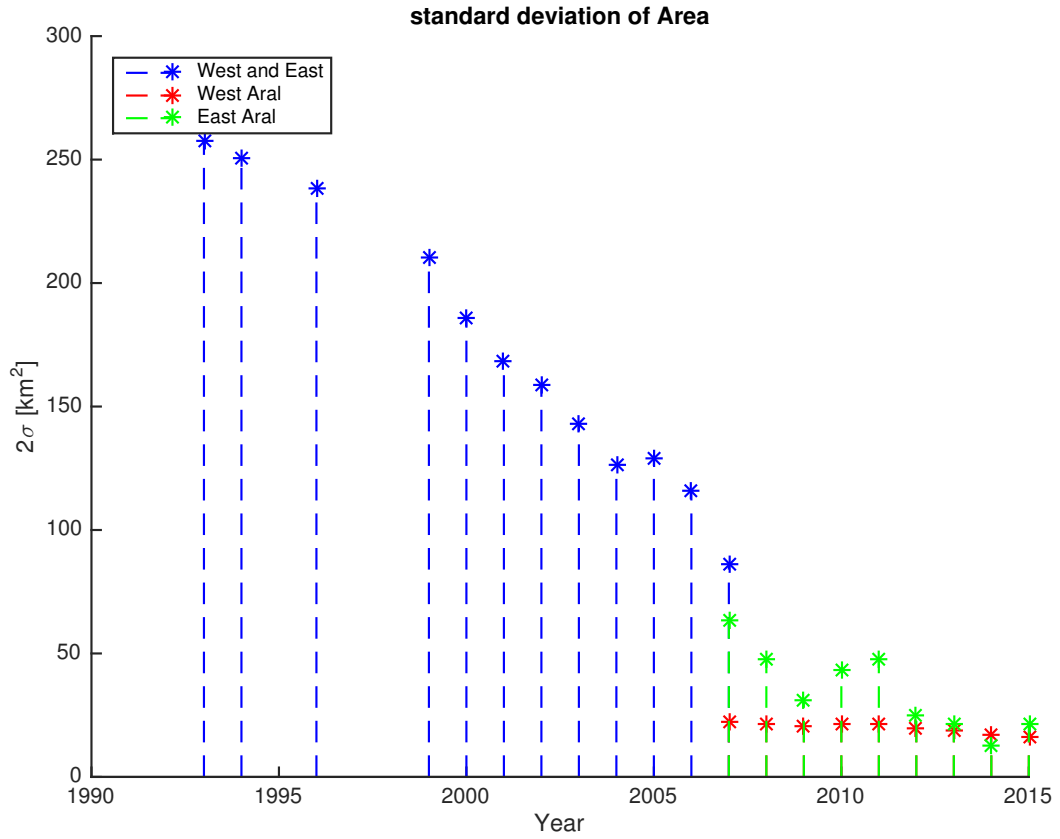


Figure 21: 2 times Standard deviation of the area

E Standard deviation of linear regression

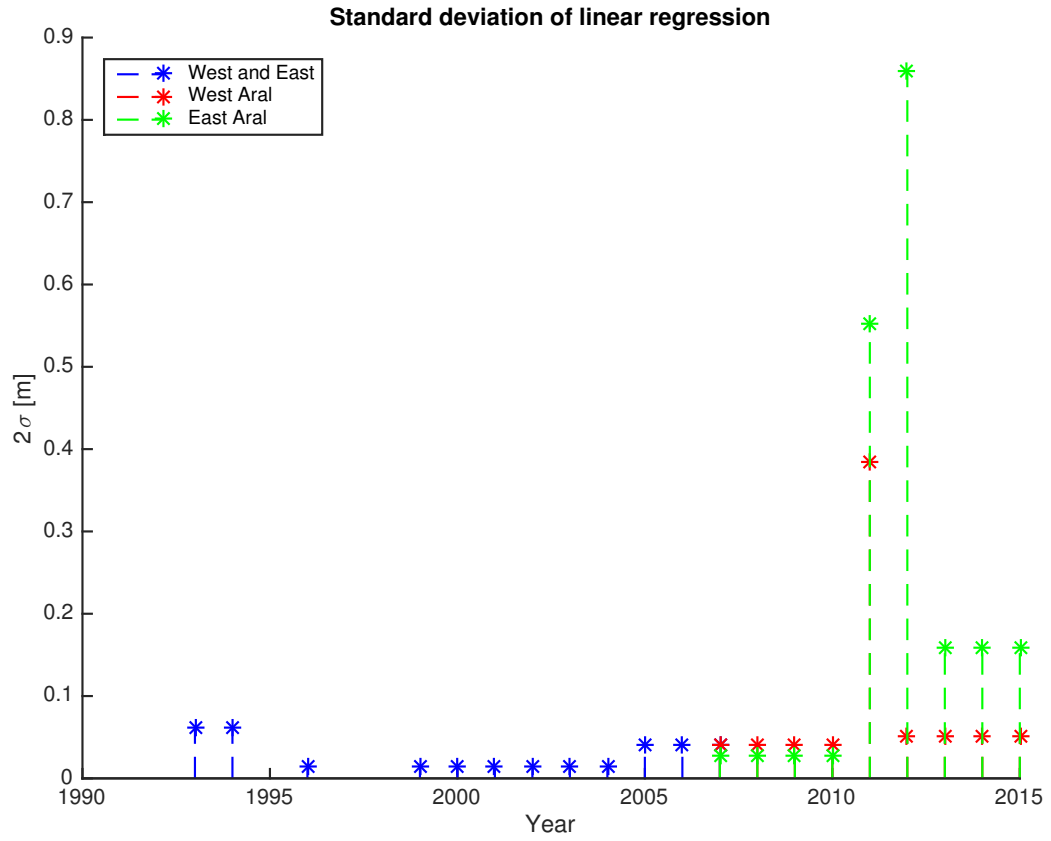


Figure 22: 2 times Standard deviation of the slope of the linear regression

F Changed standard deviation of area and volume

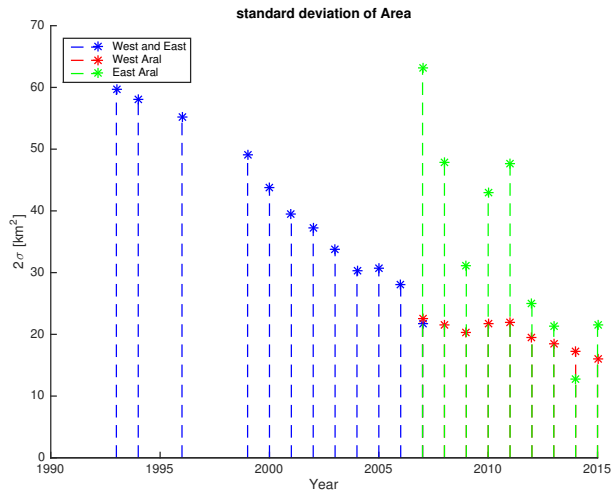


Figure 23: 2 times Standard deviation of the area when uncertainty of area is only 0.2% before 2007

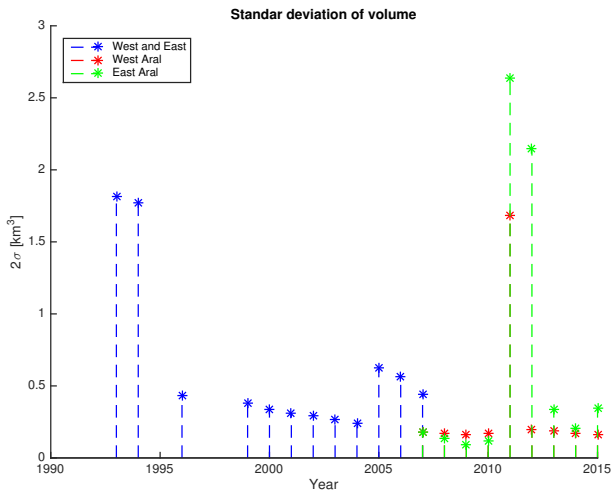


Figure 24: 2 times Standard deviation of the volume when uncertainty of area is only 0.2% before 2007

G Volume change values as a table

Table 2: Volume change results

Year	Volume change both [km ³ /year]	Volume change West [km ³ /year]	Volume change East [km ³ /year]
1993	-4.0 ± 1.8	-	-
1994	-3.9 ± 1.8	-	-
1996	-18.4 ± 0.4	-	-
1999	-16.4 ± 0.4	-	-
2000	-14.6 ± 0.3	-	-
2001	-13.2 ± 0.3	-	-
2002	-12.4 ± 0.3	-	-
2003	-11.3 ± 0.3	-	-
2004	-10.1 ± 0.2	-	-
2005	-7.4 ± 0.6	-	-
2006	-6.7 ± 0.6	-	-
2007	-5.2 ± 0.4	-4.12 ± 0.18	-3.58 ± 0.18
2008	-	-3.92 ± 0.17	-2.71 ± 0.13
2009	-	-3.68 ± 0.16	-1.76 ± 0.09
2010	-	-3.96 ± 0.17	-2.43 ± 0.12
2011	-	7.8 ± 1.7	- (error too large)
2012	-	-3.17 ± 0.19	-7 ± 2
2013	-	-3.03 ± 0.19	-0.3 ± 0.3
2014	-	-2.82 ± 0.17	-0.2 ± 0.2
2015	-	-2.59 ± 0.16	-0.3 ± 0.3

H Satellite coverage 1

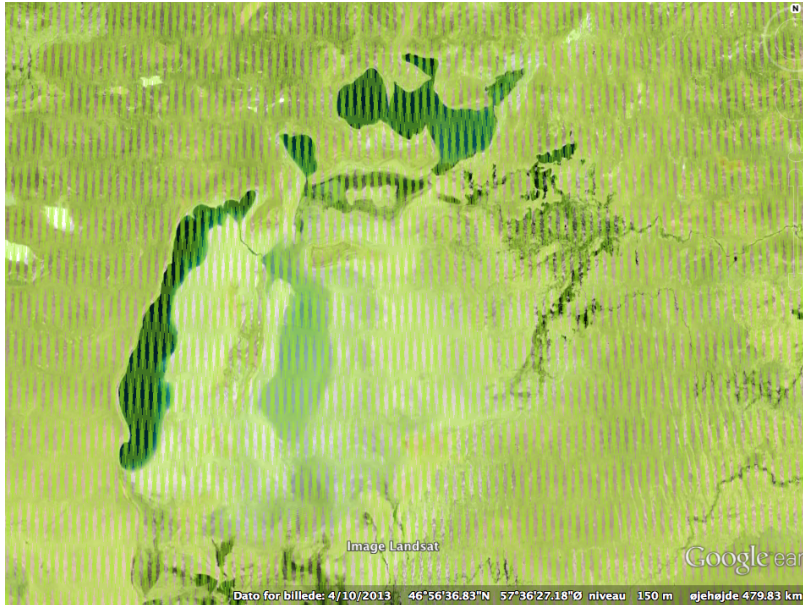


Figure 25: CryoSat coverage of the Aral Sea area by Aviso Pass Locator(1) and Google Earth

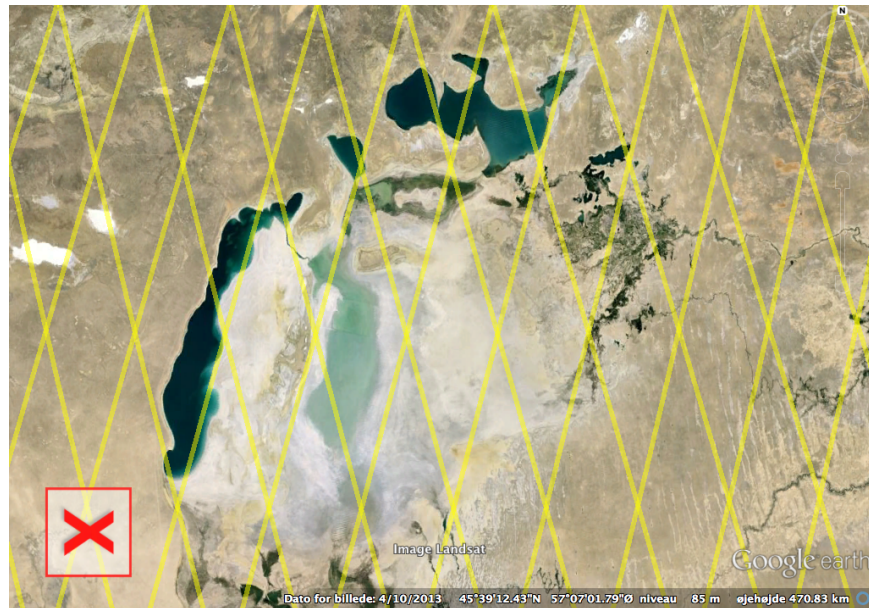


Figure 26: Envisat coverage of the Aral Sea area by Aviso Pass Locator(1) and Google Earth

I Satellite coverage 2

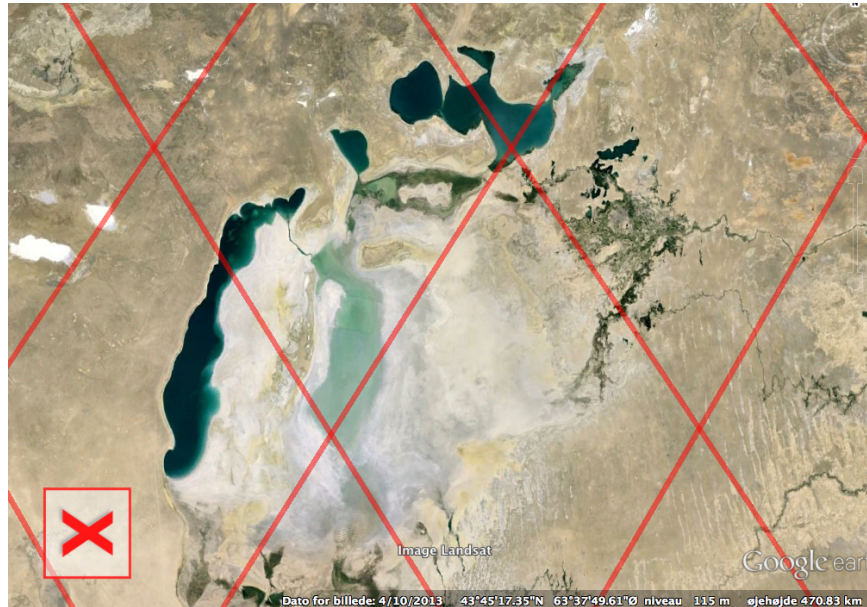


Figure 27: Jason 1 and Jason 2 coverage of the Aral Sea area by Aviso Pass Locator(1) and Google Earth

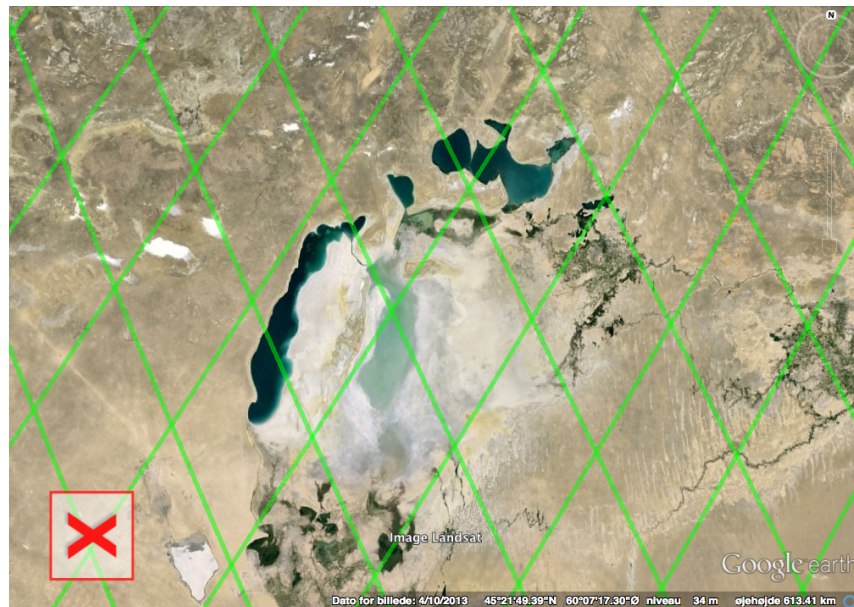


Figure 28: GeoSat coverage of the Aral Sea area by Aviso Pass Locator(1) and Google Earth

J SSH measured on a single track in August 2014 over the eastern Aral

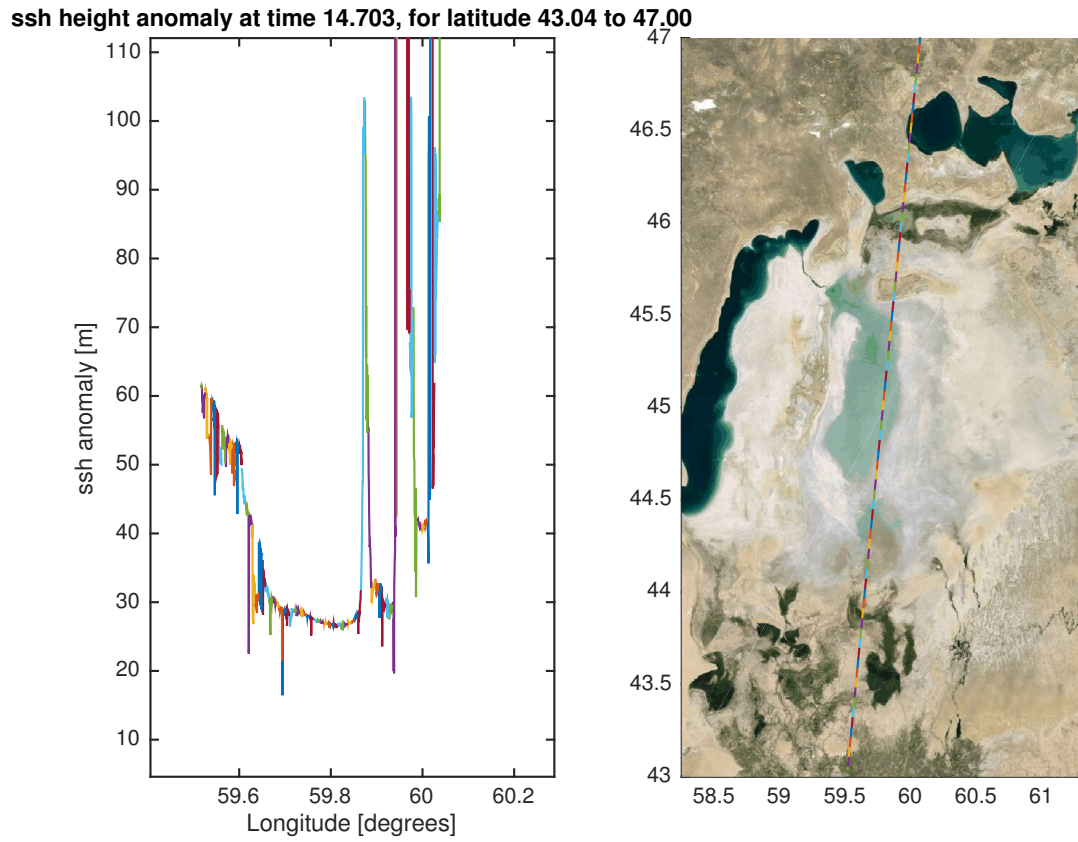


Figure 29: SSH measured on a single track in August 2014 over the eastern Aral showing reflection of water

K Area used for August 2014 over the eastern Aral

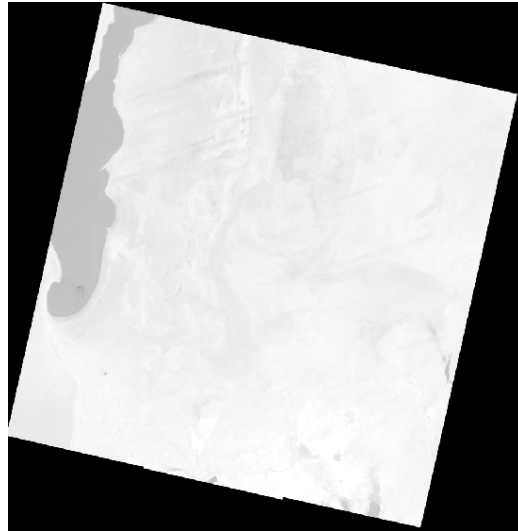


Figure 30: Landsat image August 2014: part of the western lake is seen in the left side of image, light shadow can be seen of the eastern lake

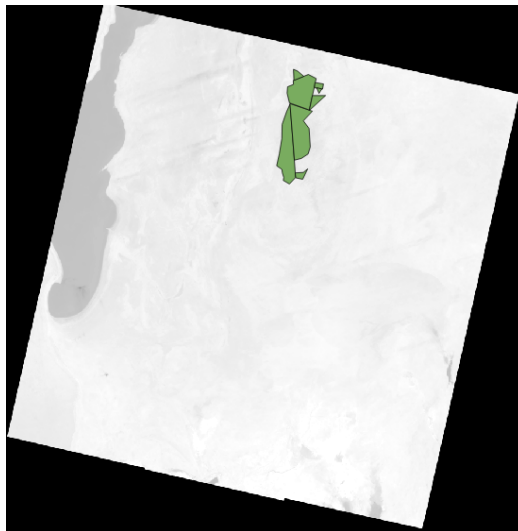


Figure 31: Landsat image August 2014: the area used for 2014

L Waveform types

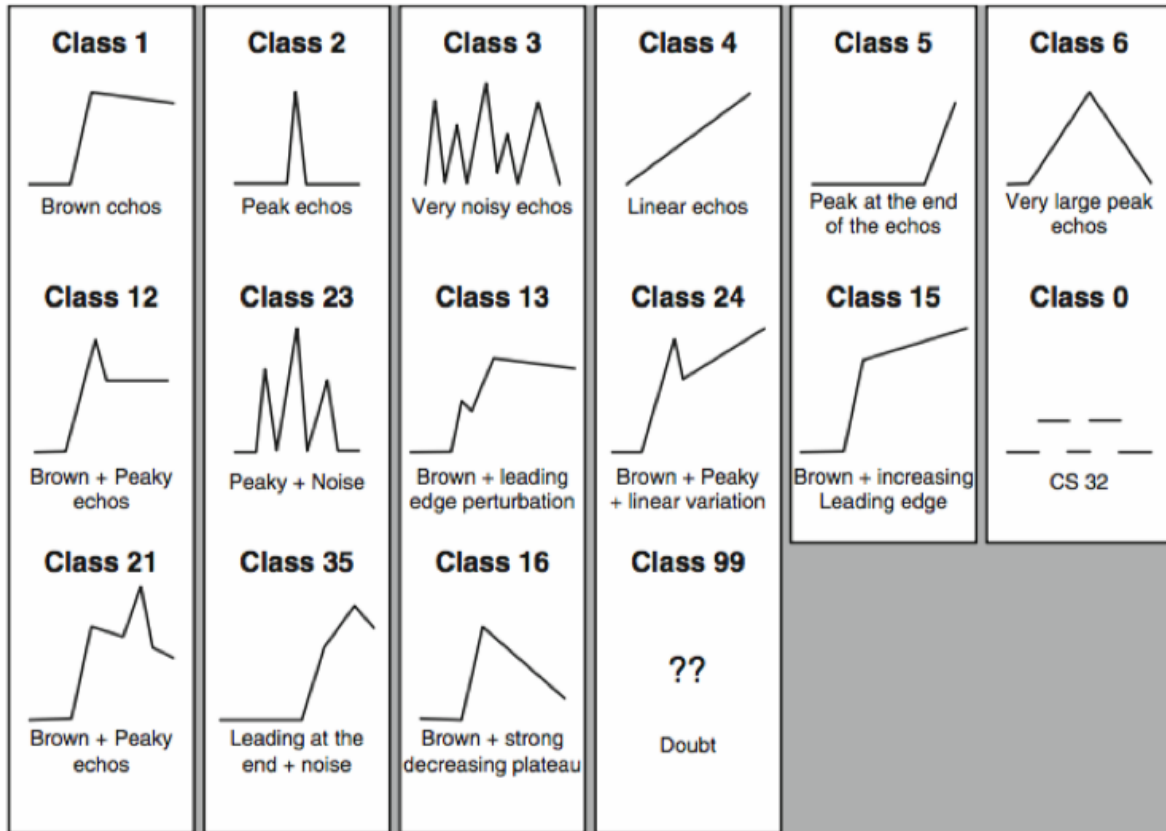


Figure 32: Types of waveforms, figure from page. 74, Coastal altimetry(18)

M Waveform types at distance from coast Jason-2

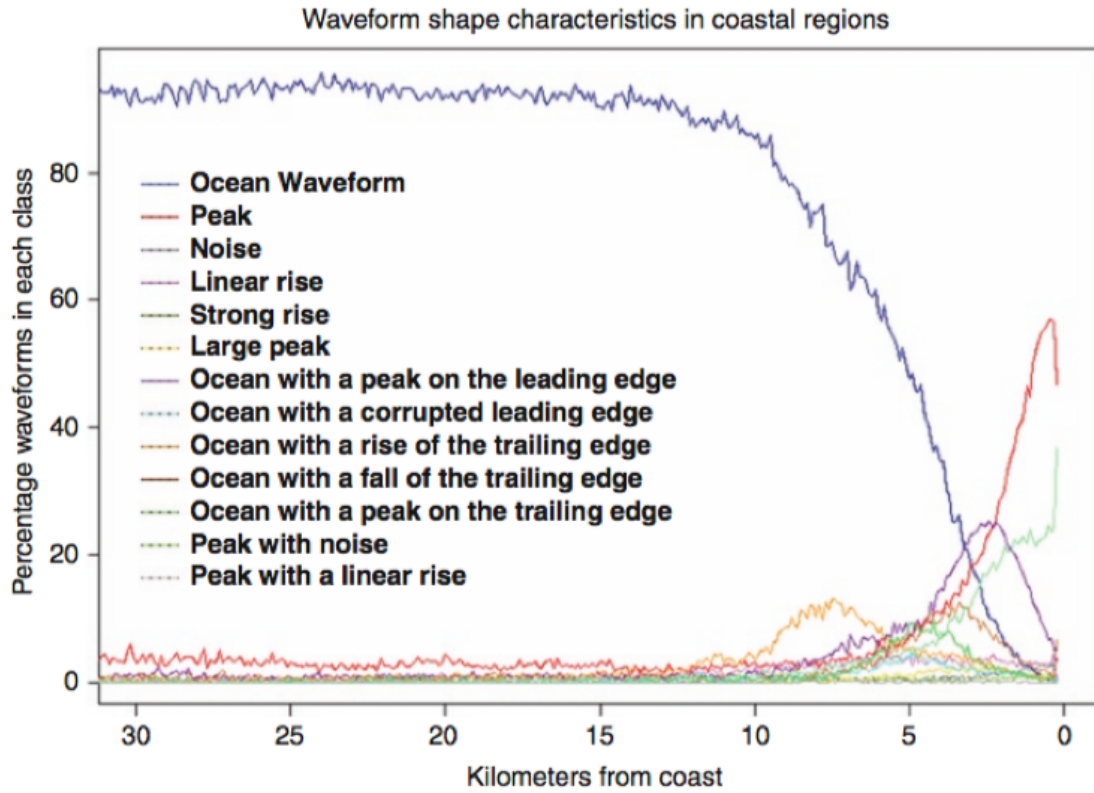


Figure 33: Prevalence of waveforms types at distance from coast from Jason-2 , figure from page. 74, Coastal altimetry(18)

N Script 1: CryoSat SSH

```
1 %This script takes satellite level 1 and 2 data and convert into SSH values
2 %input: files with level 1 data, files with level 2 data, list of file
3 %names
4 %output: file containing latitude , longitude , time and SSH
5 close all
6 clear all
7
8 %open directory
9 fn1 = dir('/Volumes/HD-PCU2/Tanya/Aral/SIR_SIN_L1/*.DBL');
10 fn2 = dir('/Volumes/HD-PCU2/Tanya/Aral/SIR_SIN_L2/*.DBL');
11 %list of file names
12 names = textread('/Volumes/HD-PCU2/Tanya/Aral/cryosat_filenames.txt', '%s', '
    delimiter', ' ');
13 lnames = length(names);
14 names = reshape(names,2,lnames/2)';
15 lfn1 = length(fn1);
16
17 for kounter = 1:lfn1
18
19 kounter;
20 clear rangec
21
22 name2 = (strcat('/Volumes/HD-PCU2/Tanya/Aral/SIR_SIN_L2/',names(kounter,2)));
23 name1 = (strcat('/Volumes/HD-PCU2/Tanya/Aral/SIR_SIN_L1/',names(kounter,1)));
24
25 if exist(char(name1)) > 0 && exist(char(name2)) > 0
26     d = dir(char(name1));
27     if d.bytes > 0
28
29 [HDR1, CS1]=Cryo_L2_read(char(name2));
30 [HDR, CS] =Cryo_L1b_read(char(name1));
31
32 wf = (CS.AVG.data')/256;
33 wwf = (CS.SIN.data)/256;
34 wwf = permute(wwf, [3,2,1]);
35
36 n = size(wf,1);
37 m = 512;
38
39 %make sure there's enough data in the waveform
40 if n >=9
41
42
43
44 day = CS.GEO.TAI.days(:,:);
45 sec = CS.GEO.TAI.secs(:,:);
46 msec = CS.GEO.TAI.microsecs(:,:);
47 time = day*86400+sec+msec/1000000;
48 c = 2.99792458*1e8;
49
50 %latitude , longitude
51 lat = CS.GEO.LAT(:,:);
52 lon = CS.GEO.LON(:,:);
53 %min and max latitude and longitude
54 latmin = 44.5;
55 latmax = 47;
```

```

56 lonmin = 57.5;
57 lonmax = 62;
58
59 %%
60 %corrections
61 corr = zeros(n,1);
62 CS.COR.corr_status.dry_trop = CS.COR.corr_status.dry_trop';
63 CS.COR.corr_status.wet_trop = CS.COR.corr_status.wet_trop';
64 CS.COR.corr_status.gim_iono = CS.COR.corr_status.gim_iono';
65 CS.COR.corr_status.solidearth_tide = CS.COR.corr_status.solidearth_tide';
66 CS.COR.corr_status.geocentric_polar_tide = CS.COR.corr_status.geocentric_polar_tide
    ';
67
68
69 corr((CS.COR.corr_status.dry_trop>0),1) = CS1.COR.dry_tropo;
70 corr((CS.COR.corr_status.wet_trop>0),1) = corr+CS1.COR.wet_tropo;
71 corr((CS.COR.corr_status.gim_iono>0),1) = corr+CS1.COR.iono;
72 corr((CS.COR.corr_status.solidearth_tide>0),1) = corr+CS1.COR.solid_earth;
73 corr((CS.COR.corr_status.geocentric_polar_tide>0),1) = corr+CS1.COR.geoc_polar;
74 corr20 = interp(corr,20);
75 corr20 = reshape(corr20,20,n);
76 j=1;
77 k=1;
78 %%
79 %Treshold retracker
80 for j = 1:n
81     for k = 1:20
82         Singlewf = squeeze(wwf(j,k,:));
83         A = max(Singlewf);
84         P = 1/5*sum(Singlewf([1:5]));
85         TL = P+0.8*(A-P);
86         ns = find(Singlewf > TL);
87
88
89         if sum(Singlewf) == 0 || ns(1) == 1
90
91             rangec(k,j) = NaN;
92         else
93
94             nnew = ns(1);
95             %retracking bin number
96             nret = nnew-1+(TL-Singlewf(nnew-1))/(Singlewf(nnew)-Singlewf(nnew-1));
97             %retracking correction
98             rangec(k,j) = -(nret-256)*0.2342;
99
100
101             k = k+1;
102
103         end
104
105     end
106
107     j = j+1;
108 end
109
110 %%
111 %finding window delay
112 window_delay = CS.MEA.win_delay;

```

```

113 USO_drift = CS.GEO.USO;
114 window_delay_corrected = window_delay.*(USO_drift+1);
115 %finding the range
116 range = window_delay_corrected./2.*c;
117 %%
118 %ssh
119
120 H = CS.GEO.H; %height of orbit
121 mss = interp(CS1.COR.mss_geoid,20); %geoid
122 mss = reshape(mss,20,n);
123 ssh = H-(range+corr20-rangepc)-mss;
124
125 lat(lat==0 & lat<latmin)=NaN;
126 lon(lon==0 & lon<lonmin)=NaN;
127 lat(lat>latmax)=NaN;
128 lon(lon>lonmax)=NaN;
129 %%
130 %to plot a single track
131 %if kounter == 479 || kounter == 480 || kounter == 481 || kounter == 482 || kounter
    == 483 || kounter == 475 || kounter == 400 || kounter == 499
132
133 %   figure
134 %   subplot(1,2,1)
135 %   plot(lon,ssh);
136 %   str=sprintf('ssh height anomaly at time %0.3f, for latitude %0.2f to %0.2f',
    max(max(time))*(3.16887646*10^(-8)), min(min(lat)), max(max(lat)));
137 %   title(str);
138 %   xlabel('Longitude [degrees]');
139 %   ylabel('ssh anomaly [m]');
140 %   subplot(1,2,2)
141 %   hold on
142 %   plot(lon(:,i),lat(:,i));
143 %   plot_google_map('maptypes','satellite')
144 %   hold off
145 %
146 %else
147 %end
148
149
150 %%
151 %to save
152 for i=1:n
153     M = [ lat(:,i) lon(:,i) time(:,i) ssh(:,i) ];
154     dlmwrite('/Volumes/HD-PCU2/Tanya/Aral/Heights.dat',M,'-append','delimiter','\t','
    precision',11);
155     end
156 else
157     end
158 else
159
160 end
161
162 end
163 end

```

O Script 2: Mean

```
1 %This script takes SSH values for the same time and takes the mean of them
2 %with standard deviation. These are plotted and the mean SSH are saved in a
3 %file
4 %input: files with latitude, longitude, time and SSH values, precut within
5 %latitude and longitude limits
6 %output: plot of the mean SSH with their standard deviations and a file
7 %containing time and the mean SSH for that time
8 clear all
9 close all
10 local = ['East'; 'West'];
11
12 for i = 1:2
13 R = importdata(strcat('/Volumes/VERBATIM/Aral/min_', local(i,:), '.csv'));
14 M = R.data;
15 [Mr Mc] = size(M);
16 if Mc > 4
17 %using 'skring' gives two extra columns in the beginning, remove these
18 M(:,1) = [];
19 M(:,1) = [];
20
21 this = 1;
22 else
23     this = 0;
24 end
25 %finding and removing extreme outliers
26 outlx = find(M(:,4) < 22 | M(:,4) > 50);
27 M(outlx,:) = NaN;
28 M = M(~isnan(M(:,4)),:);
29 tid = M(:,3)/(86400*365);
30 format short
31 tid = round(tid, 4+2);
32 M(:,3) = tid;
33 %if need to find for specific period (remember to change M's to Q's)
34 %test = find(tid > 14.65 & tid < 15);
35 %Q = M(test,:);
36 %tid = Q(:,3);
37 if this == 1
38     cond1 = M(:,5) == 1;
39     cond2 = M(:,5) == 2;
40     ens1 = unique(tid(cond1));
41     ens2 = unique(tid(cond2));
42 else
43 [ens, iW, iens] = unique(tid);
44 l = length(ens);
45 meanh = zeros(1,l);
46 end
47
48 re = 1;
49
50 if this == 1
51     l1 = length(ens1);
52     l2 = length(ens2);
53     for n = 1:l1
54         B1 = tid == ens1(n);
55         meanh1(n) = mean(M(B1,4), 'omitnan');
56         stdh = mad(M(B1,4), 'omitnan');
```

```

57     outl = find(M(:,4) < meanh1(n)-stdh | M(:,4) > meanh1(n)+stdh);
58     F(B1,:) = M(B1,:);
59     F(outl,:) = NaN;
60     T(B1,:) = F(B1,:);
61     end
62     for s = 1:l2
63         B2 = tid == ens2(s);
64         meanh2(s) = mean(M(B2,4), 'omitnan');
65         stdh = mad(M(B2,4), 'omitnan');
66         outl = find(M(:,4) < meanh2(s)-stdh | M(:,4) > meanh2(s)+stdh);
67         F(B2,:) = M(B2,:);
68         F(outl,:) = NaN;
69         T(B2,:) = F(B2,:);
70     end
71 else
72
73 for n = 1:l
74     n;
75
76
77     B = tid == ens(n);
78     meanh(n) = mean(M(B,4), 'omitnan');
79     modeh(n) = mode(M(B,4));
80     if modeh(n) < 23
81         modeh(n) = NaN;
82     else
83     end
84
85     stdh(n) = mad(M(B,4), 'omitnan');
86     outl = find(M(:,4) < meanh(n)-stdh(n) | M(:,4) > meanh(n)+stdh(n));
87     F(B,:) = M(B,:);
88     F(outl,:) = NaN;
89
90
91
92     T(B,:) = F(B,:);
93
94
95
96 end
97     end
98 z = F(:,4) == 0;
99 F(z,4) = NaN;
100
101 if this == 1
102
103     ens1 = unique(T(:,3));
104     ens1 = ens1(~isnan(ens1));
105     ens1 = ens1(~isnan(meanh1));
106     ens2 = ens2(~isnan(meanh2));
107     meanh2 = meanh2(~isnan(meanh2));
108     cond1 = T(:,5) == 1;
109
110     figure(n+1)
111     hold on
112     plot(T(cond1,3),T(cond1,4), 'r.')
113     plot(ens1, meanh1(:), 'b-')
114     hold off

```

```

115
116     cond2 = T(:,5) == 2;
117     figure(n+2)
118     hold on
119     plot(T(cond2,3),T(cond2,4), 'r.')
120     plot(ens2, meanh2(:), 'b-')
121 else
122
123     hold on
124     plot(T(:,3),T(:,4), 'r.')
125     plot(ens, meanh(:), 'b-')
126     ylabel('Sea Surface Height [m]')
127     xlabel('Year after 2000')
128     title(strcat('Time series of Sea Surface Height measurements by CryoSat of the
129     Aral Sea'))
130
131     hold off
132
133 Sav = [ens, meanh(:)];
134 dlmwrite(strcat('/Volumes/VERBATIM/Aral/mean',local(i,:), '.dat'),Sav);
135
136
137
138
139 end
140 end
141 legend('East deviation','East lake mean','West lake deviation', 'West lake mean')

```

P Script 3: Volume and area

```
1 clear all
2 close all
3 clc
4
5 M1 = importdata('/Volumes/HD-PCU2/Tanya/Aral/SSH1.dat');
6 M2 = importdata('/Volumes/HD-PCU2/Tanya/Aral/SSH2.dat');
7 M3 = importdata('/Volumes/HD-PCU2/Tanya/Aral/SSH3.dat');
8 ME = importdata('/Volumes/HD-PCU2/Tanya/Aral/SSHE1.dat');
9 ME2 = importdata('/Volumes/HD-PCU2/Tanya/Aral/SSHE2.dat');
10 MW = importdata('/Volumes/HD-PCU2/Tanya/Aral/SSHW.dat');
11
12 %%
13 %Area
14 Names = ['1992'; '1993'; '1994'; '1996'; '1999'; '2000'; '2001'; '2002'; '2003'; '2004'; '2005';
15          '2006'; '2007'; '2008'; '2009'; '2010'];
16 WArea = 1;
17 EArea = 1;
18
19 for i = 1:length(Names)
20 W = importdata(strcat('/Volumes/HD-PCU2/Tanya/Aral/Area/', Names(i,:), '_West_Area.csv'));
21 E = importdata(strcat('/Volumes/HD-PCU2/Tanya/Aral/Area/', Names(i,:), '_East_Area.csv'));
22
23 WArea = sum(W.data(:,2))/1000^2;
24 EArea = sum(E.data(:,2))/1000^2;
25
26 WArea = [WArea; WArea];
27 EArea = [EArea; EArea];
28 end
29
30
31
32 %%
33 %linear regression of heights
34 X1 = [ones(length(M1(:,1)),1) M1(:,1)];
35 a1 = inv(transpose(X1)*X1)*transpose(X1)*M1(:,2);
36 err1 = transpose(M1(:,2)-X1*a1)*(M1(:,2)-X1*a1)/(length(M1(:,1))-2);
37 ss1 = err1*inv(transpose(X1)*X1);
38 sd1 = sqrt(ss1(2,2))*2;
39
40
41 X2 = [ones(length(M2(:,1)),1) M2(:,1)];
42 a2 = inv(transpose(X2)*X2)*transpose(X2)*M2(:,2);
43 err2 = transpose(M2(:,2)-X2*a2)*(M2(:,2)-X2*a2)/(length(M2(:,1))-2);
44 ss2 = err2*inv(transpose(X2)*X2);
45 sd2 = sqrt(ss2(2,2))*2;
46
47
48
49 X3 = [ones(length(M3(:,1)),1) M3(:,1)];
50 a3 = inv(transpose(X3)*X3)*transpose(X3)*M3(:,2);
51 err3 = transpose(M3(:,2)-X3*a3)*(M3(:,2)-X3*a3)/(length(M3(:,1))-2);
52 ss3 = err3*inv(transpose(X3)*X3);
53 sd3 = sqrt(ss3(2,2))*2;
```

```

54
55
56 XW = [ones(length(MW(:,1)),1) MW(:,1)];
57 aW = inv(transpose(XW)*XW)*transpose(XW)*MW(:,2);
58 errW = transpose(MW(:,2)-XW*aW)*(MW(:,2)-XW*aW)/(length(MW(:,1))-2);
59 ssW = errW*inv(transpose(XW)*XW);
60 sdW = sqrt(ssW(2,2))*2;
61
62
63 XE = [ones(length(ME(:,1)),1) ME(:,1)];
64 aE = inv(transpose(XE)*XE)*transpose(XE)*ME(:,2);
65 errE = transpose(ME(:,2)-XE*aE)*(ME(:,2)-XE*aE)/(length(ME(:,1))-2);
66 ssE = errE*inv(transpose(XE)*XE);
67 sdE = sqrt(ssE(2,2))*2;
68
69
70 X2E = [ones(length(ME2(:,1)),1) ME2(:,1)];
71 a2E = inv(transpose(X2E)*X2E)*transpose(X2E)*ME2(:,2);
72 err2E = transpose(ME2(:,2)-X2E*a2E)*(ME2(:,2)-X2E*a2E)/(length(ME2(:,1))-2);
73
74
75
76 %%
77 % begin 2nd script
78 %import the mean values of heights
79 East = importdata(strcat('/Volumes/HD-PCU2/Tanya/Aral/meanEast.dat'));
80 West = importdata(strcat('/Volumes/HD-PCU2/Tanya/Aral/meanWest.dat'));
81
82 %Area
83 Names = ['2011'; '2012'; '2013'; '2014'; '2015'];
84
85
86 for i = 1:length(Names)
87 W = importdata(strcat('/Volumes/HD-PCU2/Tanya/Aral/Area/', Names(i,:), '_West_Area.
      csv'));
88 E = importdata(strcat('/Volumes/HD-PCU2/Tanya/Aral/Area/', Names(i,:), '_East_Area.
      csv'));
89
90 WAreat = sum(W.data(:,2))/1000^2;
91 EAreat = sum(E.data(:,2))/1000^2;
92
93 WArea = [WArea;WAreat];
94 EArea = [EArea;EAreat];
95 end
96
97 WArea(1) = [];
98 EArea(1) = [];
99 figure(1)
100 plot([1992.67:1994.67,1996.67,1999.67:2015.67],WArea, 'r *--');
101 hold on
102 plot([1992.67:1994.67,1996.67,1999.67:2015.67],EArea, 'g *--');
103 plot([1992.67:1994.67,1996.67,1999.67:2015.67],EArea+WArea, 'b *--');
104 title('Surface area from 1992 to 2015')
105 xlabel('Year');
106 ylabel('Area [km^2]');
107 legend('West Aral', 'East Aral', 'East and West')
108 hold off
109

```



```

110 %heights
111 [ensW, iW, iensW] = unique(West(:,1));
112 West = West(iW,:);
113 IW = length(West(:,1));
114 [ensE, iE, iensE] = unique(East(:,1));
115 East = East(iE,:);
116 IE = length(East(:,1));
117
118
119 %fitting linearly to East
120 %first = before 11.5, second= after 11.5
121 firstE = find(East(:,1) < 11.4);
122 firstE(1) = [];
123
124 XE1 = [ones(length(East(firstE,1)),1) East(firstE,1)];
125 aE1 = inv(transpose(XE1)*XE1)*transpose(XE1)*East(firstE,2);
126 yfitfE = aE1(2)*East(firstE,1)+aE1(1);
127 errE1 = transpose(East(firstE,2)-XE1*aE1)*(East(firstE,2)-XE1*aE1)/(length(East(
    firstE,1))-2);
128 ssE1 = errE1*inv(transpose(XE1)*XE1);
129 sdE1 = sqrt(ssE1(2,2))*2;
130
131 secondE = find(East(:,1) > 11.4 & East(:,1) < 11.7);
132
133 XE2 = [ones(length(East(secondE,1)),1) East(secondE,1)];
134 aE2 = inv(transpose(XE2)*XE2)*transpose(XE2)*East(secondE,2);
135 yfitsE = aE2(2)*East(secondE,1)+aE2(1);
136 errE2 = transpose(East(secondE,2)-XE2*aE2)*(East(secondE,2)-XE2*aE2)/(length(East(
    secondE,1))-2);
137 ssE2 = errE2*inv(transpose(XE2)*XE2);
138 sdE2 = sqrt(ssE2(2,2))*2;
139
140 thirdE = find(East(:,1) > 11.7);
141
142 XE3 = [ones(length(East(thirdE,1)),1) East(thirdE,1)];
143 aE3 = inv(transpose(XE3)*XE3)*transpose(XE3)*East(thirdE,2);
144 yfittE = aE3(2)*East(thirdE,1)+aE3(1);
145 errE3 = transpose(East(thirdE,2)-XE3*aE3)*(East(thirdE,2)-XE3*aE3)/(length(East(
    thirdE,1))-2);
146 ssE3 = errE3*inv(transpose(XE3)*XE3);
147 sdE3 = sqrt(ssE3(2,2))*2;
148
149 figure(2)
150 hold on
151 plot(East(firstE,1),yfitfE)
152 scatter(East(firstE,1),East(firstE,2))
153
154 plot(East(secondE,1),yfitsE)
155 scatter(East(secondE,1),East(secondE,2))
156 plot(East(thirdE,1),yfittE)
157 scatter(East(thirdE,1),East(thirdE,2))
158 title('Surface height mean and linear fit , East Aral')
159 xlabel('Year');
160 ylabel('Surface height [m]');
161 legend('linear fit', 'mean of measured heights')
162 hold off
163
164 %fitting linearly to West

```

```

165 %first = after 11.5, second = before 11.5
166 first = find(West(:,1) > 11.5);
167
168 XW1 = [ones(length(West(first,1)),1) West(first,1)];
169 aW1 = inv(transpose(XW1)*XW1)*transpose(XW1)*West(first,2);
170 yfitf = aW1(2)*West(first,1)+aW1(1);
171 errW1 = transpose(West(first,2)-XW1*aW1)*(West(first,2)-XW1*aW1)/(length(West(first
,1))-2);
172 ssW1 = errW1*inv(transpose(XW1)*XW1);
173 sdW1 = sqrt(ssW1(2,2))*2;
174
175 second = find(West(:,1) < 11.5 & West(:,1) > 10.59);
176
177 XW2 = [ones(length(West(second,1)),1) West(second,1)];
178 aW2 = inv(transpose(XW2)*XW2)*transpose(XW2)*West(second,2);
179 yfits = aW2(2)*West(second,1)+aW2(1);
180 errW2 = transpose(West(second,2)-XW2*aW2)*(West(second,2)-XW2*aW2)/(length(West(
second,1))-2);
181 ssW2 = errW2*inv(transpose(XW2)*XW2);
182 sdW2 = sqrt(ssW2(2,2))*2;
183
184 third = find(West(:,1) < 10.9);
185
186 XW3 = [ones(length(West(third,1)),1) West(third,1)];
187 aW3 = inv(transpose(XW3)*XW3)*transpose(XW3)*West(third,2);
188 yfitt = aW3(2)*West(third,1)+aW3(1);
189 errW3 = transpose(West(third,2)-XW3*aW3)*(West(third,2)-XW3*aW3)/(length(West(third
,1))-2);
190 ssW3 = errW3*inv(transpose(XW3)*XW3);
191 sdW3 = sqrt(ssW3(2,2))*2;
192
193 figure(3)
194 hold on
195 plot(West(first,1),yfitf)
196 scatter(West(first,1),West(first,2))
197 plot(West(third,1),yfitt)
198 scatter(West(third,1),West(third,2))
199
200 plot(West(second,1),yfits)
201 scatter(West(second,1),West(second,2))
202 title('Surface height mean and linear fit, West Aral')
203 xlabel('Year');
204 ylabel('Surface height [m]');
205 legend('linear fit', 'mean of measured heights')
206 hold off
207
208 %%
209 %%median of Area * slope of linear regressions
210
211 DV = [a1(2)/1000*mean(WArea(1:2)+EArea(1:2)) a1(2)/1000*mean(WArea(2:3)+EArea(2:3))
a2(2)/1000*mean(WArea(3:4)+EArea(3:4)) a2(2)/1000*mean(WArea(4:5)+EArea(4:5)) a2
(2)/1000*mean(WArea(5:6)+EArea(5:6)) a2(2)/1000*mean(WArea(6:7)+EArea(6:7)) a2
(2)/1000*mean(WArea(7:8)+EArea(7:8)) a2(2)/1000*mean(WArea(8:9)+EArea(8:9)) a2
(2)/1000*mean(WArea(9:10)+EArea(9:10)) a3(2)/1000*mean(WArea(10:11)+EArea(10:11)
) a3(2)/1000*mean(WArea(11:12)+EArea(11:12)) a3(2)/1000*mean(WArea(12:13)+EArea
(12:13))];
212 DV.W = [aW(2)./1000*mean(WArea(12:13)) aW(2)./1000*mean(WArea(13:14)) aW(2)./1000*
mean(WArea(14:15)) aW(2)./1000*mean(WArea(15:16)) aW2(2)./1000*mean(WArea(16:17))

```

```

    ) aW1(2) ./1000.*mean(WArea(17:18)) aW1(2) ./1000.*mean(WArea(18:19)) aW1(2)
    ./1000.*mean(WArea(19:20)) aW1(2) ./1000.*mean(WArea(20:21))];
213 DV_E = [aE(2) ./1000.*mean(EArea(12:13)) aE(2) ./1000.*mean(EArea(13:14)) aE(2) ./1000.*
    mean(EArea(14:15)) aE(2) ./1000.*mean(EArea(15:16)) aE1(2) ./1000.*mean(EArea(16:17)
    ) aE2(2) ./1000.*mean(EArea(17:18)) aE3(2) ./1000.*mean(EArea(18:19)) aE3(2) ./1000.*
    mean(EArea(19:20)) aE3(2) ./1000.*mean(EArea(20:21))];
214
215 figure(4)
216 hold on
217 plot([1993:1994,1996,1999:2007],DV, 'b *--')
218 plot([2007:2015],DV_W, 'r *--')
219 plot([2007:2015],DV_E, 'g *--')
220 title('Volume change per year from 1992 to 2015 of the Aral Sea')
221 xlabel('Year');
222 ylabel('Volume change [km^3/y]');
223 legend('West and East', 'West Aral', 'East Aral', 'Location', 'southeast')
224 hold off
225
226 %%
227 %uncertainties
228 sd = [sd1 sd1 ones(1,7)*sd2 ones(1,3)*sd3];
229 sdWt = [ones(1,4)*sdW sdW2 ones(1,4)*sdW1];
230 sdEt = [ones(1,4)*sdE sdE1 sdE2 ones(1,3)*sdE3];
231 figure(5)
232 hold on
233 stem([1993:1994,1996,1999:2007],sd, 'b *--')
234 stem([2007:2015],sdWt, 'r *--')
235 stem([2007:2015],sdEt, 'g *--')
236 title('Standard deviation of linear regression')
237 xlabel('Year');
238 ylabel('2\sigma [m]');
239 legend('West and East', 'West Aral', 'East Aral', 'Location', 'northwest')
240 hold off
241
242 %Area uncertainties
243 stdmA = [mean(WArea(1:2)/100*0.5+EArea(1:2)/100) mean(WArea(2:3)/100*0.5+EArea(2:3)
    /100) mean(WArea(3:4)/100*0.5+EArea(3:4)/100) mean(WArea(4:5)/100*0.5+EArea(4:5)
    /100) mean(WArea(5:6)/100*0.5+EArea(5:6)/100) mean(WArea(6:7)/100*0.5+EArea(6:7)
    /100) mean(WArea(7:8)/100*0.5+EArea(7:8)/100) mean(WArea(8:9)/100*0.5+EArea(8:9)
    /100) mean(WArea(9:10)/100*0.5+EArea(9:10)/100) mean(WArea(10:11)/100*0.5+EArea
    (10:11)/100) mean(WArea(11:12)/100*0.5+EArea(11:12)/100) mean(WArea(12:13)
    /100*0.5+EArea(12:13)/100)];
244 %stdmA = [mean(WArea(1:2)+EArea(1:2)) mean(WArea(2:3)+EArea(2:3)) mean(WArea(3:4)+
    EArea(3:4)) mean(WArea(4:5)+EArea(4:5)) mean(WArea(5:6)+EArea(5:6)) mean(WArea
    (6:7)+EArea(6:7)) mean(WArea(7:8)+EArea(7:8)) mean(WArea(8:9)+EArea(8:9)) mean(
    WArea(9:10)+EArea(9:10)) mean(WArea(10:11)+EArea(10:11)) mean(WArea(11:12)+EArea
    (11:12)) mean(WArea(12:13)+EArea(12:13))] *0.2/100;
245 stdmAW = [mean(WArea(12:13)) mean(WArea(13:14)) mean(WArea(14:15)) mean(WArea(15:16)
    ) mean(WArea(16:17)) mean(WArea(17:18)) mean(WArea(18:19)) mean(WArea(19:20))
    mean(WArea(20:21))] *0.5/100;
246 stdmAE = [mean(EArea(12:13)) mean(EArea(13:14)) mean(EArea(14:15)) mean(EArea(15:16)
    ) mean(EArea(16:17)) mean(EArea(17:18)) mean(EArea(18:19)) mean(EArea(19:20))
    mean(EArea(20:21))] *1/100;
247 figure(6)
248 hold on
249 stem([1993:1994,1996,1999:2007],stdmA, 'b *--')
250 stem([2007:2015],stdmAW, 'r *--')
251 stem([2007:2015],stdmAE, 'g *--')

```

```

252 title('standard deviation of Area')
253 xlabel('Year');
254 ylabel('2\sigma [km^2]');
255 legend('West and East', 'West Aral', 'East Aral', 'Location', 'northwest')
256 hold off
257
258
259 %%
260 %volume uncertainties
261
262 %then volume
263 Amean = [mean(WArea(1:2)+EArea(1:2)) mean(WArea(2:3)+EArea(2:3)) mean(WArea(3:4)+
    EArea(3:4)) mean(WArea(4:5)+EArea(4:5)) mean(WArea(5:6)+EArea(5:6)) mean(WArea
    (6:7)+EArea(6:7)) mean(WArea(7:8)+EArea(7:8)) mean(WArea(8:9)+EArea(8:9)) mean(
    WArea(9:10)+EArea(9:10)) mean(WArea(10:11)+EArea(10:11)) mean(WArea(11:12)+EArea
    (11:12)) mean(WArea(12:13)+EArea(12:13))];
264 Ameanp = stdmA./Amean*100;
265
266
267 Volunc = abs(DV).*sqrt((sd./[a1(2) a1(2) a2(2) a2(2) a2(2) a2(2) a2(2) a2(2) a2(2)
    a3(2) a3(2) a3(2)]).^2 + (stdmA./Amean).^2);
268 VoluncW = abs(DV.W).*sqrt((sdWt./[aW(2) aW(2) aW(2) aW(2) aW2(2) aW1(2) aW1(2) aW1
    (2) aW1(2)]).^2 + (stdmAW./[mean(WArea(12:13)) mean(WArea(13:14)) mean(WArea
    (14:15)) mean(WArea(15:16)) mean(WArea(16:17)) mean(WArea(17:18)) mean(WArea
    (18:19)) mean(WArea(19:20)) mean(WArea(20:21))]).^2);
269 VoluncE = abs(DV.E).*sqrt((sdEt./[aE(2) aE(2) aE(2) aE(2) aE1(2) aE2(2) aE3(2) aE3
    (2) aE3(2)]).^2 + (stdmAE./[mean(EArea(12:13)) mean(EArea(13:14)) mean(EArea
    (14:15)) mean(EArea(15:16)) mean(EArea(16:17)) mean(EArea(17:18)) mean(EArea
    (18:19)) mean(EArea(19:20)) mean(EArea(20:21))]).^2);
270
271 figure(7)
272
273 hold on
274 stem([1993:1994,1996,1999:2007],Volunc, 'b *--')
275 stem([2007:2015],VoluncW, 'r *--')
276 stem([2007:2015],VoluncE, 'g *--')
277 title('Standar deviation of volume')
278 xlabel('Year');
279 ylabel('2\sigma [km^3]');
280 legend('West and East', 'West Aral', 'East Aral', 'Location', 'northwest');
281 hold off

```

Q Script 4: PISTACH SSH plotter

```

1 %This script takes the PISTACH data provided by Aviso and corrects them, plotting
  the SSH
2 %input: Aviso PISTACH data
3 %output: file of SSH data (latitude, longitude, time, SSH) and plot of SSH
4 %over time
5 close all
6 clear all
7 ll=0;
8
9     fn1 = dir(strcat('/Volumes/HD-PCU2/Tanya/Aral/data/*.nc'));
10     lfn1 = length(fn1);
11
12     k = 1;

```

```

13
14     for kounter = 1:lfnl
15         kounter
16         if isempty(strfind(fn1(kounter).name, '_142_')) == 0;
17
18             filename(k,:) = fn1(kounter).name;
19             k = k+1;
20
21         else
22         end
23
24     end
25 [lfil ign] = size(filename);
26 for kounter1 = 1:lfil
27     kounter1
28     [RES,genAtt] = nc_reader(strcat('/Volumes/HD-PCU2/Tanya/Aral/aviso/',filename(
29     kounter1,:)));
30     lat = RES.lat;
31
32     lon = RES.lon;
33     time = RES.time;
34     drycor = RES.model_dry_tropo_corr;
35     %drycor(isnan(drycor))=0;
36     wetcor = RES.rad_wet_tropo_corr;
37     %wetcor(isnan(wetcor))=0;
38     ionocor = RES.iono_corr_alt_ku;
39     ionocor(isnan(ionocor))=0;
40     solidcor = RES.solid_earth_tide;
41     range = RES.range_ice3_ku; %net_instr_corr_range_ku;
42     H = RES.alt;
43     mss = RES.geoid_EGM2008;
44     ssh = H - mss - (range + drycor + wetcor + ionocor + solidcor);
45
46     for i=1:lfil
47         data = [ lat(:) lon(:) time(:) ssh(:) ];
48         %to save
49         %dlmwrite('/Volumes/VERBATIM/Aral/tester1.dat',data,'-append','delimiter','\t','
50         precision',11);
51     end
52 end
53 %finding and removing extreme outliers
54 outlx = find(data(:,4) < 23.5 | data(:,4) > 30);
55 data(outlx,:) = NaN;
56 data = data(~isnan(data(:,4)),:);
57 tid = data(:,3)/(86400*365);
58 format short
59 tid = round(tid, 4+2);
60 data(:,3) = tid;
61
62
63 %Eastern lake
64 outlE = find(data(:,2) < 59.1 | data(:,2) > 60);
65 dataE = data;
66 dataE(outlE,:) = NaN;
67 dataE = dataE(~isnan(dataE(:,4)),:);
68 ensE = uniquetol(dataE(:,3),1e-3);

```

```

69 IE = length(ensE);
70
71 %Western lake
72 outIW = find(data(:,2) < 58.62 | data(:,2) > 59.1);
73 dataW = data;
74 dataW(outIW,:) = NaN;
75 dataW = dataW(~isnan(dataW(:,4)),:);
76 ensW = uniquetol(dataW(:,3),1e-3);
77 IW = length(ensW);
78
79
80 for n = 1:IE
81
82
83 BE = dataE(:,3) == ensE(n);
84
85 meanhE(n) = mean(dataE(BE,4), 'omitnan');
86
87 end
88 for m = 1:IW
89     BW = dataW(:,3) == ensW(m);
90     meanhW(m) = mean(dataW(BW,4), 'omitnan');
91 end
92
93
94 %figure(1)
95 hold on
96 scatter(ensW, meanhW(:), 'fill','b')
97 xlabel('Years');
98 ylabel('SSH [m]');
99 scatter(ensE, meanhE(:), 'fill','r')
100 legend('West lake','East lake')
101 hold off

```

DTU Space
National Space Institute
Technical University of Denmark

Elektrovej, building 327
DK - 2800 Kgs. Lyngby
Tel (+45) 4525 9500
Fax (+45) 4525 9575

www.space.dtu.dk