Coastal sea level around Australia with S3A and other satellites

Introductory project - Earth and Space Physics and Engineering

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Contents

1 Introduction

Rising sea levels are becoming and increasing concern, especially in coastal areas. For example, almost 40% of the U.S. population lives in high density coastal areas [7], where a rise in sea level leads to an increase in flooding, shoreline erosion and hazards from storms. It is therefore becoming increasingly more important to measure the coastal sea level accurately, to estimate and reduce the potential negative effects. A tide gauge does the job perfectly, but they are highly localised. There are only 1420 tide gauges in the Permanent Service for Mean Sea Level (PSMSL) Revised Local Reference (RLR) database [6]. To achieve world wide coastal coverage with tide gauges, it would require enormous amounts of time, effort and resources. Other means of coastal surveillance must therefore be deployed to achieve coastal sea surface height monitoring on a global level.

Satellite-born radar altimeters have surveyed the global sea level for several decades, with a steady increase in altimeter accuracy. Coastal areas are still problematic though, as the coastline interferes with the measurements. To achieve greater accuracy in coastal areas, new measuring methods have been developed. Sentinel-3 is an observation satellite carrying an altimeter using different measuring methods. It is still a radar altimeter, but the antennas footprint is a thin rectangle instead of being circular. See figure 1. The rectangular footprint makes it possible to measure closer to the coastline without interference, hopefully improving the accuracy.

In this study we will try to determine whether Sentinel-3 has a greater accuracy than Jason-3 in coastal areas. We will examine coastal areas in three places: Thevenard and Port Lincoln in South Australia, and Darwin in Northern Australia. Each place has a tide gauge, which is used to cross correlate the altimetry data. For each location, we will compare large, medium and small areas, to see if we achieve greater accuracy when the altimeter measurements gets more and more localised to the tide gauge.

If it is possible to achieve accurate coastal measurements using Sentinel-3, it would provide far greater coastal sea level monitoring globally, even in remote areas.

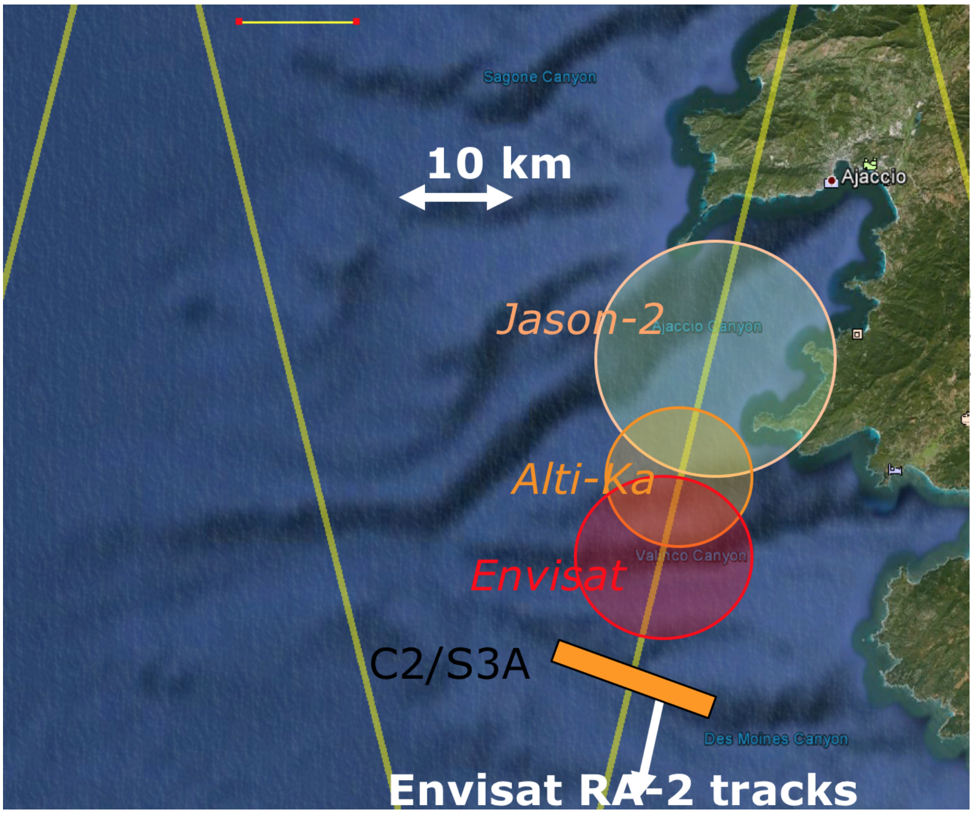


Figure 1: Comparison of antenna footprints for different satellite altimeters

2 Satellite altimetry

The radar altimeter is based on a satellite in orbit. Radar altimetry satellites determine the distance from the satellite to the Earth's surface, by measuring the time it takes a radar pulse to travel from the satellite to the surface and back. The energy of the pulse is known, and after it has interacted with the sea surface, it is send back to the satellite and its time and amplitude can be measured accurately. The satellites can determine the height of the surface with the earths geoid as its reference point (ellipsoid). The orbiting satellites can make very precise measurements of the ocean current, speed, topography and height. [8] (p.105)

The primary reason for satellite altimetry, is the study of dynamic sea surface height signals related to oceanographic processes. To get the desired information about the sea surface, you have to make multiple corrections to the signal. If there were no waves, and our atmosphere was a perfect vacuum, it would have been easy to determine the sea surface height. The distribution of waves and the wind condition will also affect the measurements. The wave troughs reflect more of the signal than the wave crests, and will cause the measurements of the sea surface height to be too low. This is called the sea state bias. The sea state bias attempts to account for the difference between the scattering of the sea surface, and the actual mean sea surface. The height of the surface is related to the accuracy of the orbit determination. The accuracy of the orbit has through the years improved from tens of metres down to centimetres. [8] (p.105)

The earths atmosphere can affect the travel time of the radar pulse. The different dry gasses, water vapour and free electrons can slow the signal, as the signal travel distance increases. Geophysical contributors like the earths geoid and tides also have to be removed.

The earths geoid has the largest impact on the measured sea surface height. The earths geoid is the shape the oceans would take, in absence of all forces other than gravity and centrifugal forces. It has little to no temporal variation, and therefore acts like a change in the reference system on observations and the sea surface heights are given relative to the geoid rather than the ellipsoid. One of the biggest contributors to the temporal sea surface height is the ocean tides. The tide signal can be modelled and described by the astronomical forces of the Sun and the Moon, and the hydrodynamic time-stepping-models. In coastal areas, the tides can vary a lot, and can be a bit more complicated to account for which can affect the results. The atmosphere exerts a downward force on the sea surface, changing its height. When the pressure is high it will lower the sea surface height, and when the pressure is low the sea surface height will be higher. The actual sea surface height is a superposition of all of the corrections. [8] (p.107)

3 Corrections in Coastal Regions

3.1 Sea Level Anomalies

By applying the corrections, and especially the geoid correction, the sea surface height h_D is reduced from ranging up to 100 metres, to a few metres. The sea dynamic surface height has both a permanent and a time variable component, and will therefore seldom have a zero temporal mean. The permanent component reflects the steric expansion of seawater, and the circulation of the ocean. The mean dynamic topography is the temporal average of the dynamic topography. When working with sea surface height variations, it is often more convenient to refer the sea surface height to the mean sea surface height, instead of referring it to the geoid. This is what creates the sea level anomalies. The sea surface anomaly is the difference between the total sea surface level and the mean sea surface level. [8] (p.109)

3.2 Dry Troposphere Correction

The dry troposphere can cause a delay of the signal. The permanent gasses in the atmosphere (nitrogen and oxygen) can slow the signal and cause an error in the altimetry. The correction for the refraction from the different dry gasses is the biggest adjustments applied to the range. Since it is not possible to obtain information about the sea level pressure from space, it is therefore necessary for the dry troposphere correction to be obtained from meteorological models. The dry troposphere varies a lot slower than the wet troposphere. This means the dry correction is not easily affected by the presence of land and expected to degrade significantly close to the coast. [8] (p.111)

3.3 Wet Troposphere Correction

The wet troposphere refraction is the refraction from the droplets and water vapour found in the troposphere. It is not one of the biggest contributors, but still have to be accounted for. The correction can vary depending on the climate. It can vary up to a few millimetres in a dry cold air, up to 30 cm in hot and wet air. The wet troposphere refraction has a higher temporal variation than the dry troposphere. With variations in time and space it needs careful attention in the coastal areas. [8] (p.114)

3.4 Tide Corrections

The biggest reduction to the temporal sea surface height variance comes from the ocean tide correction. An analysis of collinear differences of sea surface heights [8] (p.124) found, that in most regions, 80% of the total signal variance comes from ocean tides.

The tidal correction includes corrections from the ocean tide signal, but also several smaller tide signals: the loading tide, the solid earth tide and the pole tide. The sum of these corrections can be written as

$$\Delta h_{\text{tides}} = \Delta h_{\text{ocean tide}} + \Delta h_{\text{load tide}} + \Delta h_{\text{solid earth tide}} + \Delta h_{\text{pole tide}}$$

Only the ocean tide correction has been analysed in coastal regions. The solid earth and the pole tide corrections are independent of coastal regions, and are normally derived using mathematical formulas.

3.4.1 Ocean Tide

The altimeter senses both the ocean and the load tide. The sum of these is called the geocentric or elastic ocean tide, which can be written as

$$\Delta h_{\text{elastic ocean tide}} = \Delta h_{\text{ocean tide}} + \Delta h_{\text{load tide}}$$

In contrast, tide gauges mounted to the sea bottom measures only the ocean tide. The altimeter observes the sum of the ocean tide and small loading displacement of the seabed due to loading by the water column. The tide load has a magnitude of 4-6% of the ocean tide, and can be determined from models that calculates the upper lithospheric response to the ocean tide [8] (p.125).

3.5 Dynamic Atmosphere Correction

The ocean reacts greatly to atmospheric pressure, acting as a huge inverse barometer. When atmospheric pressure is high, the sea surface gets pushed down, and vice versa during low pressure. The sea surface height correction due to atmospheric pressure variations is divided into low-frequency contribution (periods longer than 20 days), and high-frequency contributions (periods shorter than 20 days).

The classical inverse barometer correction is used for the low-frequency contribution, to account for the *presumed* hydrostatic response of the sea surface changes [4] [8] (p.129). One hecto-Pascal increase in atmospheric pressure depresses the sea surface by about 1 cm. The instantaneous sea level correction can be calculated from the following formula

$$\Delta h_{\mathrm{ib}} \approx -0.99484\,(P_0 - P_{\mathrm{ref}}) \tag{3.1}$$

P_0 can be determined from the dry atmosphere correction. P_{ref} is the reference pressure, traditionally given as a constant global "mean" pressure of 1013.3 hPa. The mean global pressure and the mean oceanic pressure is not the same though, as the mean pressure over the ocean is closer to 1011 hPa. On top of that, the mean global pressure (and therefore the mean oceanic pressure also) is not constant, but fluctuates with an annual amplitude of around 0.6 hPa. Using a non-constant reference pressure when applying an inverse barometer correction, the standard deviation of the residual sea surface height signal is lower, than when using a constant reference pressure to calculate the effects of the inverse barometer correction. Using a non-constant, localised pressure reference yields a greater accuracy when correcting atmospheric pressure effects, and should be used when possible.

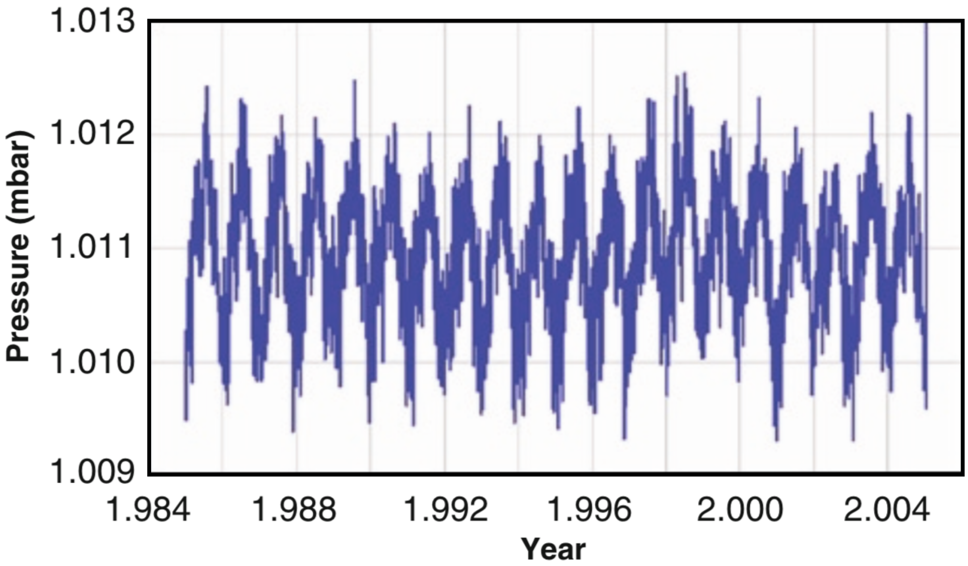


Figure 2: Global mean pressure integrated over the oceans from the ECMWF model for the period 1985-2005. The global mean pressure is around 1011 mbar (hPa) and it has a clear annual signal with amplitude of roughly 0.6 mbar [8] (p.129).

4 Methods

All of the data manipulation and plotting was done using MATLAB. In essence, four main scripts was used to achieve the resulting tables and figures: One script that doesn't apply any altimetry corrections, but applies an inverse barometer correction derived from the local barometric pressure. The second script does the same as the first script, but applies a MOG2D inverse barometer correction to the altimetry data. "MOG2D (2 Dimensions Gravity Waves model) is a barotropic, non linear and time stepping model, derived from Linch and Gray (1979, Greenberg and Lyard, personnal communication). The model governing equations are the classical shallow water continuity and momentum equation."[2]. The third script applies a local inverse barometer correction to the tide gauge data, and an inverse barometer correction derived from either the global or local mean pressure. The fourth script plots the satellite tracks on a Google Maps image.

36 scripts were used in total to achieve the data seen in this report, not including prototyping scripts. The 36 scripts are all variations of the 4 main scripts, with the only difference being the data files used (for the 3 different cities), and the desired coordinates to confine the data set. In theory, the number of scripts could could be reduced greatly if it was deemed unnecessary to have a separate script for each individual area (small, medium, large) for each city.

All of the altimetry data is supplied by RADS (Radar Altimeter Database System), and has the following corrections applied: ocean tide, load tide FES2014 and wet troposphere. These corrections are applied to all of the altimetry signals, no matter what kind of inverse barometer correction is used.

Below is a step by step explanation of the code and methods used. The code is from the script that both applies the local inverse barometer correction to the tide gauge, and either the global or local inverse barometer correction to the altimetry data, for the small area in Darwin. This script was used, as it is one of the more complex scripts, and everything explained here can be applied to the other script variations.

Script

It's practical to create an variable for each of the .nc (NetCDF) files containing the altimetry and in situ data. This way one can quickly see the different variable names and sizes for each of the .nc files

```
% Creates overview of the Jason 3 and Sentinel 3 files
info_D=ncinfo('Darwin.nc');
info_S=ncinfo('Darwin_Sentinel3_2.nc');
info_J=ncinfo('Darwin_Jason3_2.nc');
```

Next the script reads all of the longitudinal and latitudinal info for each of the satellites

```
% Reads satellite coordiantes
latJ=ncread('Darwin_Jason3_2.nc','lat');
lonJ=ncread('Darwin_Jason3_2.nc','lon');
latS=ncread('Darwin_Sentinel3_2.nc','lat');
lonS=ncread('Darwin_Sentinel3_2.nc','lon');
```

If it is deemed necessary to confine the altimetry data to a set of sub coordinates, it can be specified here.

```
% Specifies minimum and maximum coordinate limits
latmin=-12.4;
latmax=-11.6;
lonmin=130.4;
lonmax=131.3;
```

An index is created from the specified coordinates, to easily retrieve the data correlating with the coordinates

```
% Creates index of the coordinate limits
giJ=(latJ>latmin & latJ<latmax & lonJ>lonmin & lonJ<lonmax);
giS=(latS>latmin & latS<latmax & lonS>lonmin & lonS<lonmax);
```

The main coordinates are trimmed to the desired coordinates

```
% Confines the coordinates to the specified limits
latJ2=latJ(giJ);
lonJ2=lonJ(giJ);
latS2=latS(giS);
lonS2=lonS(giS);
```

Here the time stamps from the satellites are read

```
% Data from the satellites
J3_time=ncread('Darwin_Jason3_2.nc','time'); % Time data from Jason 3
S3_time=ncread('Darwin_Sentinel3_2.nc','time'); % Time data Sentinel 3
```

The altimetry measured Sea Level Anomaly (SLA) with different corrections are saved as variables. Here with MOG2D applied. The SLA signal has all corrections applied. To remove certain corrections, the have to be added manually.

```
% MOG2D
slaJ=ncread('Darwin_Jason3_2.nc','sla')...
    +ncread('Darwin_Jason3_2.nc','tide_pole')...
    +ncread('Darwin_Jason3_2.nc','tide_equil')...
    +ncread('Darwin_Jason3_2.nc','tide_ocean_fes14');
slaS=ncread('Darwin_Sentinel3_2.nc','sla')...
    +ncread('Darwin_Sentinel3_2.nc','tide_pole')...
    +ncread('Darwin_Sentinel3_2.nc','tide_equil')...
    +ncread('Darwin_Sentinel3_2.nc','tide_ocean_fes14');
```

To evaluate only the data relevant to the chosen area, the data is confined to the specified coordinates.

```
% MOG2D Confined coordinates
slaJ1=slaJ(giJ);
slaS1=slaS(giS);
```

Later it is necessary to have SLA data without an inverse barometer correction applied. When applying our own inverse barometer correction based on the global/local mean pressure, the correction must be applied to the data set without MOG2D corrections.

```
% Sea Level Anomaly without inverse barometer correction
slaJ2=ncread('Darwin_Jason3_2.nc','sla')...
    +ncread('Darwin_Jason3_2.nc','tide_pole')...
    +ncread('Darwin_Jason3_2.nc','tide_equil')...
    +ncread('Darwin_Jason3_2.nc','tide_ocean_fes14')...
    +ncread('Darwin_Jason3_2.nc','inv_bar_mog2d');
slaS2=ncread('Darwin_Sentinel3_2.nc','sla')...
    +ncread('Darwin_Sentinel3_2.nc','tide_pole')...
    +ncread('Darwin_Sentinel3_2.nc','tide_equil')...
    +ncread('Darwin_Sentinel3_2.nc','tide_ocean_fes14')...
    +ncread('Darwin_Sentinel3_2.nc','inv_bar_mog2d');
```

Again it is necessary to confine the data to the specified coordinates

```
% Confines the data to the specified coordinates
slaJ3=slaJ2(giJ);
slaS3=slaS2(giS);
```

As the altimetry data is time stamped in the format 1985-01-01 00:00:00, it is necessary to convert this to a more usable format. First it gets converted to matlab time, and then the funtion 'decyear' is used to convert it to decimal years

```
% Converts from seconds to decimal years
time_reference = datenum('1985', 'yyyy'); % The .nc files time format is...
%seconds after 1985-01-01 00:00:00
time_matlab_J = time_reference + J3_time/86400; % 86400=seconds per day
time_matlab_S = time_reference + S3_time/86400; % 86400=seconds per day

tid_J2=decyear(time_matlab_J); % Converts to decimal years
tid_S2=decyear(time_matlab_S); % Converts to decimal years
```

Some days contain more than one data point. To avoid "walls" when plotting the data, only one data point per given time is desired

```
% Finds number of unique days
% Converts Jason 3 time to a yyymmdd string
time_matlab_string_J = datestr(time_matlab_J, 'yyyymmdd');
% Converts Sentinel 3 time to a yyymmdd string
time_matlab_string_S = datestr(time_matlab_S, 'yyyymmdd');
daydate_J=str2num(time_matlab_string_J);
daydate_S=str2num(time_matlab_string_S);
unique_days_J=unique(daydate_J); % Finds no. of unique days
unique_days_S=unique(daydate_S); % Finds no. of unique days

daydate_J3=daydate_J(giJ); % Confines to the specified coordinates
daydate_S3=daydate_S(giS); % Confines to the specified coordinates

unique_days_J3=unique(daydate_J3); % Saves days as a variable
unique_days_S3=unique(daydate_S3); % Saves days as a variable
time_matlab_J3=time_matlab_J(giJ); % Saves time as a variable
time_matlab_S3=time_matlab_S(giS); % Saves time as a variable
```

On days with more than one data point, the script finds the mean value of the data using two small for loops

```
% Finds mean value of days with more than one data point (Jason 3)
for i=1:length(unique_days_J3)
   sla_J_mean(i)=nanmean(slaJ3(daydate_J3==unique_days_J3(i)));
   time_J_mean(i)=nanmean(time_matlab_J3(daydate_J3==unique_days_J3(i)));
end

% Finds mean value of days with more than one data point (Sentinel 3)
for i=1:length(unique_days_S3)
   sla_S_mean(i)=nanmean(slaS3(daydate_S3==unique_days_S3(i)));
   time_S_mean(i)=nanmean(time_matlab_S3(daydate_S3==unique_days_S3(i)));
end
```

To make proper plots, the time is converted to decimal years

```
tid_J=decyear(time_J_mean'); % Converts to decimal year
tid_S=decyear(time_S_mean'); % Converts to decimal year
```

To apply the global or local inverse barometer correction, the BP (Barometric Pressure) data must first be read. The BP data is saved, with the 9999.9 values converted to NaN

```
% Reads BP Data (Barometric Pressure)
BPdata=readtable('dnBP.csv','Format','%{dd/MM/yyyy HH:mm:ss}D %f');
BPtid=BPdata{:,1};
plBP=BPdata{:,2};
plBP(plBP == 9999.9) = NaN;
```

To fill in the NaN values, the function BPinpaint.m is used.

```
% BP interpol
BPinpaint=inpaint_nans(plBP);
```

The time stamps is read and converted to decimal years, so the time format matches the other time formats

```
% BP time
BPdata2=readtable('dnBP.csv');
BPtid2=BPdata2{:,1};
BPdecyear=decyear(BPtid2);
```

The BP data that corresponds with the altimetry data is found

```
Jason_BP = interp1q(BPdecyear,BPinpaint,tid_J2);
Sentinel_BP = interp1q(BPdecyear,BPinpaint,tid_S2);
```

To calculate the change in the sea surface height, equation 3.1 is used. To find the local mean pressure, the mean of the barometric pressure is calculated using the nanmean function. To switch between global and local mean pressure, simply comment out the irrelevant correction

```
% Global mean pressure
% BPheightJ=-0.99484*(Jason_BP-1013.3)/100;
% BPheightS=-0.99484*(Sentinel_BP-1013.3)/100;

% Local mean pressure
BPheightJ=-0.99484*(Jason_BP-nanmean(plBP))/100;
BPheightS=-0.99484*(Sentinel_BP-nanmean(plBP))/100;
```

First the inverse barometer correction is applied to all of the altimetry data, and then it gets trimmed to the desired coordinates

```
slaJ4=slaJ2-BPheightJ; % Applies inverse barometer correction to SLA (J3)
slaJ5=slaJ4(giJ); % Confines to specified coordinates
slaS4=slaS2-BPheightS; % Applies inverse barometer correction to SLA (S3)
slaS5=slaS4(giS); % Confines to specified coordinates
```

The data from the tide gauge is read, and measurements from before the earliest altimetry measurement is trimmed away. There is no need to plot many years of tide gauge data, if there isn't any altimetry data to compare it to

```
% Data from Darwin tide gauge
Dtime=ncread('Darwin.nc','time'); % Time vector
% Days from January 1st 1700 to January 1st 2016. Requires Financial Toolbox
Days=daysact('1-jan-1700', '1-jan-2016');
A=Dtime>=Days; % Creates a vector showing where time is greater than 'Days'
start_time=length(A)-sum(A); % Calculates no. of days to be removed
Time=Dtime(start_time+1:end); % Removes all days from before the wanted date
```

The Sea Surface Height (SSH) is read, trimmed, and the units adjusted to metres (it's given in millimetres)

```
% Sea Surface Height
ssh=ncread('Darwin.nc','sea_surface_height_above_reference_level'); % Reads SSH
ssh2=squeeze(ssh); % Converts to vector form
ssh3=(ssh2-nanmean(ssh2))/1000; % Adjust the sea level unit to metres
ssh4=ssh3(start_time+1:end); % Removes data from before the wanted date
PLSLA=ssh4;
```

The time format gets converted to decimal years so all time formats are the same

```
% Converts from seconds to decimal years
time_reference = datenum('1700', 'yyyy'); % Starting from year 1700
time_matlab_D = time_reference + Time; % Counts forward to year 1700
tid_D=decyear(time_matlab_D); % Converts to decimal year
```

As seen earlier, days with multiple data points gets identified and a mean value is found. This time with inverse barometer corrected data

```
% Finds mean value of days with more than one data point (Jason 3)
for i=1:length(unique_days_J3)
   sla_J_mean(i)=nanmean(slaJ5(daydate_J3==unique_days_J3(i)));
   time_J_mean(i)=nanmean(time_matlab_J3(daydate_J3==unique_days_J3(i)));
end

% Finds mean value of days with more than one data point (Sentinel 3)
for i=1:length(unique_days_S3)
   sla_S_mean(i)=nanmean(slaS5(daydate_S3==unique_days_S3(i)));
   time_S_mean(i)=nanmean(time_matlab_S3(daydate_S3==unique_days_S3(i)));
end
```

The local inverse barometer correction needs to be applied to the tide gauge data also. To do this, the change in SSH is again found from equation 3.1. The correct data point are found, and the correction gets applied to the tide gauge signal

```
%% Inverse barometer correction
% Calculates the height of the inverse barometer correction

% Global mean pressure
%BPheight=-0.99484*(BPinpaint-1013.3)/100;

% Local mean pressure
BPheight=-0.99484*(BPinpaint-nanmean(plBP))/100;

% Finds the appropiate correction data for the tide gauge
BPheight_D=interp1(BPdecyear,BPheight,tid_D);

% Applies the correction to the tide gauge data
PLSLA2=PLSLA-BPheight_D;
```

To make proper comparisons, the tide gauge data must be interpolated with the altimetry data. This is done with and without an inverse barometer correction for the tide gauge

```
%% Reference
% Interpolates the tide gauge data to the altimetry times

% Tide gauge data without inv bar correction
```

```
interpol_2_S3=interp1(tid_D,PLSLA,tid_S'); % Sentinel 3
interpol_2_J3=interp1(tid_D,PLSLA,tid_J'); % Jason 3

% Tide gauge data with inv bar correction
interpol_3_S3=interp1(tid_D,PLSLA2,tid_S');
interpol_3_J3=interp1(tid_D,PLSLA2,tid_J');
```

The mean and STD of the interpolated data can be found

```
% Calculates mean and STD of interpolated tide gauge data
mean_Sentinel3_large=nanmean(interpol_3_S3); % Mean S3
std_Sentinel3_large=nanstd(interpol_3_S3); % STD S3

mean_Jason3_large=nanmean(interpol_3_J3); % Mean J3
std_Jason3_large=nanstd(interpol_3_J3); % STD J3
```

The difference between the altimetry data and tide gauge data is found, with the corresponding STD and mean deviations

```
% Finds difference between Jason 3 and tide gauge data
diff_J=(sla_J_mean)-(interpol_3_J3);
std_diff_J=nanstd(diff_J) % STD of difference
mean_diff_J=nanmean(diff_J) % Mean of difference

% Finds difference between Sentinel 3 and tide gauge data
diff_S=(sla_S_mean)-(interpol_3_S3);
std_diff_S=nanstd(diff_S) % STD of difference
mean_diff_S=nanmean(diff_S) % Mean of difference
```

The correlation between the altimetry signals and the tide gauge signal (with and without inverse barometer correction) gets calculated

```
%% Correlation
% Correlates the interpolated tide gauge data (not corrected)
% with the altimetry data
corr_J=corrcoef(interpol_2_J3,sla_J_mean','rows','complete'); % J3
corr_S=corrcoef(interpol_2_S3,sla_S_mean','rows','complete'); % S3

% Correlates the interpolated tide gauge data (local pressure corrected)
% with the altimetry data
corr_J_BP=corrcoef(interpol_3_J3,sla_J_mean','rows','complete'); % J3
corr_S_BP=corrcoef(interpol_3_S3,sla_S_mean','rows','complete'); % S3
```

The figures can then be plotted

```
%% Plots
% Comparison between tide gauge and altimetry
figure('Name','Comparison') % Navn på figur
hold on
plot(tid_D,PLSLA2,'linewidth',1); % Tide gauge data
scatter(tid_J,sla_J_mean,'filled'); % Jason 3
scatter(tid_S,sla_S_mean,'filled'); % Sentinel 3
title('Tide Gauge and Altimetry - Both Local Mean Pressure Corrected','fontsize',18)
xlabel('Year','fontsize',18) % x-axis label
ylabel('meter','fontsize',18) % y-axis label
lgd=legend('Port Lincoln Tide Gauge','Jason 3','Sentinel 3');
lgd.FontSize = 18; % Legend font size
```

```
set(gcf, 'Position', [0, 0, 2000, 700]) % Figure size
set(gca,'fontsize',20) % Axis font size

% Difference between S3 and J3 vs altimetry
figure;
plot(diff_S)
hold on
plot(diff_J)
legend('Sentinel 3 difference vs tide gauge',...
    'Jason 3 difference vs tide gauge')
xlabel('Measurement no.') % x-axis label
ylabel('meter') % y-axis label
```

5 Darwin

Darwin is the capital city of the Northern Territory of Australia, with its coast facing north towards the Timor Sea. Like the rest of the Top End, Darwin has a tropical climate, with a wet and dry season. Darwin experiences heavy monsoonal downpour, high lightning and cyclone activity during the wet season. Milder weather with clear skies and light sea breezes comes with the dry season.

Darwin was the first area of interest. Data retrieved from different area sizes, large, medium and small, are going to be compared to see what effect is has on the in situ vs altimetry correlation and deviation. A larger sample area might contain more viable and undisturbed altimetry data, reducing the noise level, but it also contains more data away from the tide gauge. Too small of an area gives localised data only, but the altimetry measurements might get interfered by the coastal topography and thus only bad data could be available.

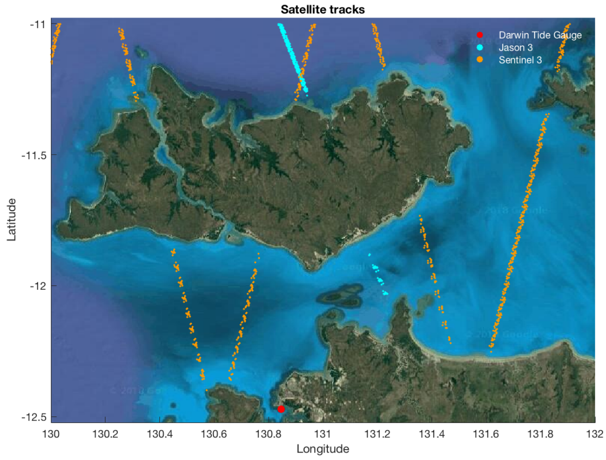


Figure 3: Location of in situ and altimetry data for large area

5.1 Large area

The large area contains altimetry data from both the northern and southern sides of the Tiwi islands. It is theorised, that as the tide comes, the narrow strait between the islands and mainland Australia inhibits tide flow, delaying it as it has to travel all around the Tiwi Islands instead of passing through the strait. As such, big tidal variations are expected when comparing each side. Looking at table 1, it is clear that the data from Sentinel-3 is better than the data from Jason-3 (although the correlation is worse). The standard for Sentinel-3 deviation is nearly 30 cm more than Sentinel-3, which could be explained by the isolated satellite tracks. There aren't any great data point for Jason-3, and the standard deviation reflects that.

The correlation for both altimeters are not great, but this is to be expected given the location of the measurements. The standard deviation is pretty poor for both though, with Jason-3's measurements deviating with almost an entire meter! Sentinel-3's measurements have a much better deviation, while still being suboptimal. Surprisingly, it doesn't seem to matter much which inverse barometer correction is used. Neither MOG2D nor an inverse barometer correction derived from both global and local mean pressures improved the standard deviation of the altimetry signals compared to the in situ signal. The mean deviation improved when using both MOG2D, global mean pressure and local mean pressure corrections, but this doesn't say much about the overall quality of the altimeter measurements.

Correlation tide gauge (local DAC corrected) vs altimetry	Jason-3	Sentinel-3
No DAC	0.7587	0.6915
MOG2D	0.7633	0.6905
DAC (GMP)	0.7566	0.6931
DAC (GMP)	0.7566	0.6931
STD of Differences tide gauge (local DAC corrected) vs altimetry	**Jason-3**	**Sentinel-3**
No DAC	1.3327	1.0796
MOG2D	1.3271	1.0808
DAC (GMP)	1.3338	1.0781
DAC (LMP)	1.3338	1.0781
Mean of Differences tide gauge (local DAC corrected) vs altimetry	**Jason-3**	**Sentinel-3**
No DAC	-0.0394	0.0604
MOG2D	-0.0456	0.0538
DAC (GMP)	-0.0777	0.0333
DAC (LMP)	-0.0351	0.0759

Table 1: Comparisons between altimetry and in situ data for the large area. Dynamic Atmosphere Correction (DAC), Global Mean Pressure (GMP), Local Mean Pressure (LMP). STD and mean deviation in metres

In table 2 we find the STD and mean deviation of each individual signal, with different inverse barometer corrections applied. It wasn't possible to apply the MOG2D correction to the tide gauge data, as the correction is contained in the altimetry data.

Standard deviation of signals	Jason-3	Sentinel-3	Tide Gauge
No DAC	0.7194	0.9454	1.6209
MOG2D	0.7208	0.9517	NA
DAC (GMP)	0.7177	0.9456	1.6203
DAC (LMP)	0.7177	0.9456	1.6203
Mean deviation of signals	**Jason-3**	**Sentinel-3**	**Tide Gauge**
No DAC	0.0212	0.2089	0.0730
MOG2D	0.0152	0.2031	NA
DAC (GMP)	-0.0191	0.1830	0.0309
DAC (LMP)	0.0235	0.2255	0.0735

Table 2: Standard and mean deviation of altimetry and in situ signals for the large area. All deviations in metres

Figure 4 shows a comparison between the tide gauge signal and the altimetry signals. It is clear, that the amplitude of the altimetry signals isn't nearly as great as the tide gauge signal. The tide gauge signal varies by nearly ± 4 metres, while the altimetry signal only varies by ± 2 metres at most. This discrepancy could be explained by the low mesh resolution of the FES2014 (Finite Element Solution 2014) tide model. See section about tide comparisons for further elaboration.

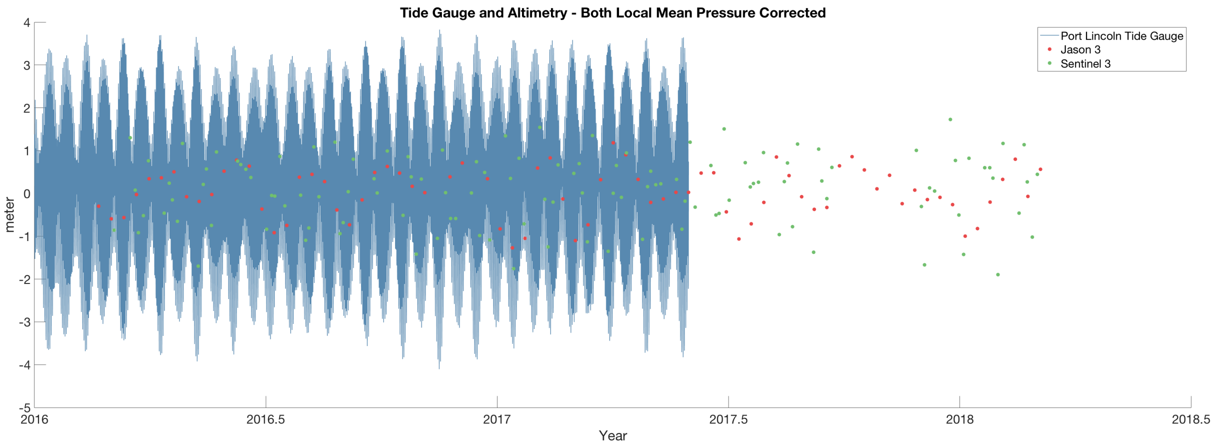
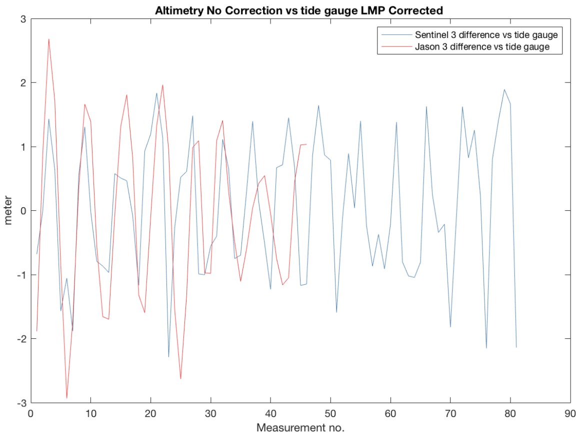
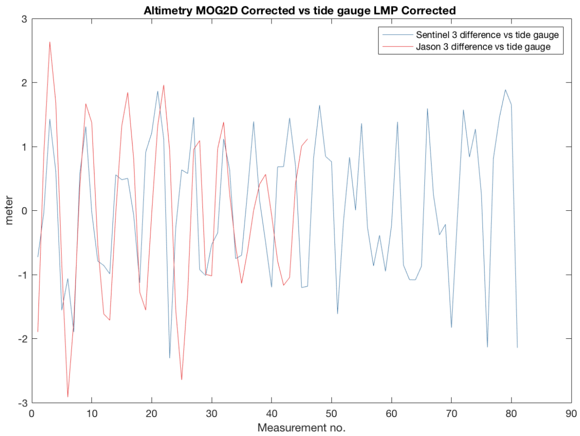


Figure 4: Altimetry Local Mean Pressure Corrected vs Tide Gauge Local Mean Pressure Corrected

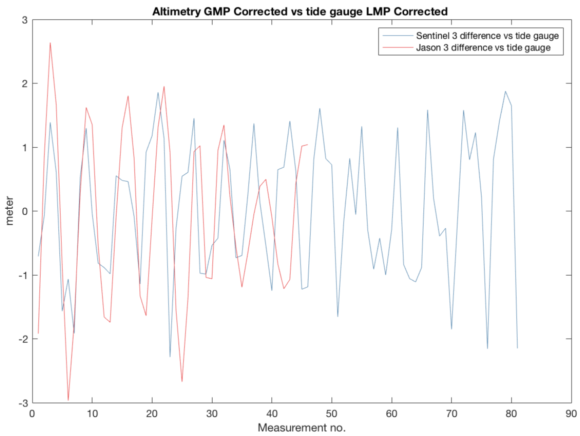
Figure 5 shows how the altimetry signal varies compared to the tide gauge signal. The variation in the plots are almost negligible, as both MOG2D and the global/local mean pressure corrections only contribute with a sea surface height change of 3-4 cm. The small corrections drowns in the overall signal, as the amplitude of these is in the order of several metres. Even though the differences are difficult to visualise, they do have an impact when calculating the standard and mean deviations, and the tables reflects that.



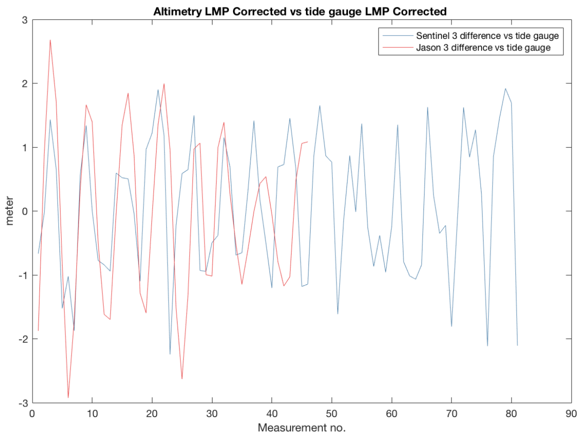
(a) No correction



(b) MOG2D



(c) Global Mean Pressure



(d) Local Mean Pressure

Figure 5: Altimetry vs tide gauge difference

5.2 Medium area

Looking at the medium area, every data point north of the Tiwi Islands has been removed. As we theorise the northern and southern altimetry data to be tidally isolated from each other (or rather tidally delayed), we have tried to see what happens if we remove the northern data, as it is considered bad in this case. Jason-3's single satellite track is very short, and is located on the eastern side of the problematic strait. As such, it is expected that Jason-3's measurements are worse than Sentinel-3's in this area, as there aren't any great data point available.

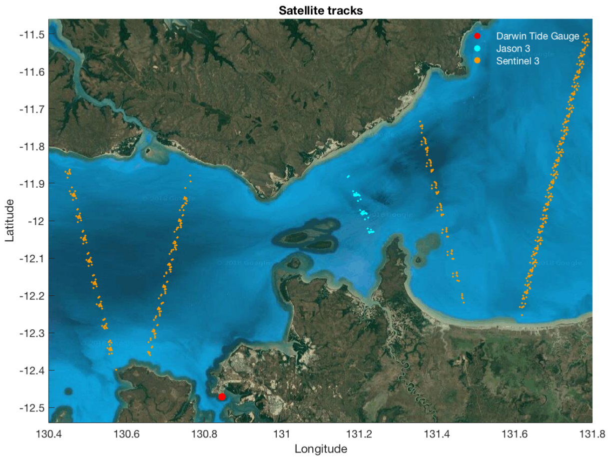


Figure 6: Location of in situ and altimetry data for the size medium area

In table 3, as with the large area, it is seen that Jason-3 has a better correlation with the tide gauge signal, but Sentinel-3's measurements has a lower STD of approximately 17 cm. Both altimeters still deviate a lot more than desired, at around 94 cm and 77 cm for Jason-3 and Sentinel-3. There isn't much help to get from the inverse barometer corrections. MOG2D doesn't even improve the STD by a centimetre for Jason-3, and even makes it worse for Sentinel-3. For the global/local mean pressure correction the change is on the scale of millimetres, and can thus be considered negligible.

Correlation tide gauge (Local DAC corrected vs altimetry	Jason-3	Sentinel-3
No DAC	0.9015	0.8616
MOG2D	0.9062	0.8587
DAC (GMP)	0.9039	0.8598
DAC (LMP)	0.9039	0.8598
STD of Differences tide gauge (Local DAC corrected) vs altimetry	Jason-3	Sentinel-3
No DAC	0.9386	0.7655
MOG2D	0.9298	0.7720
DAC (GMP)	0.9380	0.7701
DAC (LMP)	0.9380	0.7701
Mean of Differences tide gauge (Local DAC corrected) vs altimetry	Jason-3	Sentinel-3
No DAC	0.3074	0.1714
MOG2D	0.3010	0.1645
DAC (GMP)	0.2673	0.1433
DAC (LMP)	0.3099	0.1859

Table 3: Comparisons between altimetry and in situ data for the medium area. Dynamic Atmosphere Correction (DAC), Global Mean Pressure (GMP), Local Mean Pressure (LMP). STD and mean deviation in metres

Standard deviation of signals	Jason-3	Sentinel-3	Tide Gauge
No DAC	0.9965	1.0677	1.6209
MOG2D	1.0035	1.0766	NA
DAC (GMP)	1.0039	1.0676	1.6203
DAC (LMP)	1.0039	1.0676	1.6203
Mean deviation of signals	Jason-3	Sentinel-3	Tide Gauge
No DAC	-0.0769	0.4002	0.0730
MOG2D	-0.0757	0.3965	NA
DAC (GMP)	-0.1201	0.3746	0.0309
DAC (LMP)	-0.0776	0.4172	0.0735

Table 4: Standard and mean deviation of altimetry and in situ signals for the medium area. All deviations in metres

Figure 7 shows a comparison between the tide gauge and altimetry signals. Again, the amplitude of the altimetry signal is much smaller that the tide gauge signal. The amplitude of the tide gauge signal is

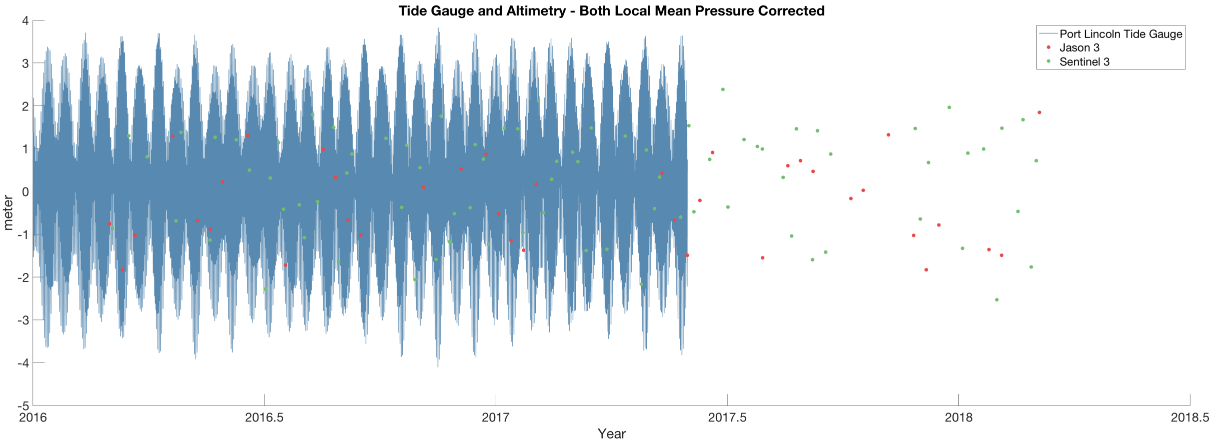
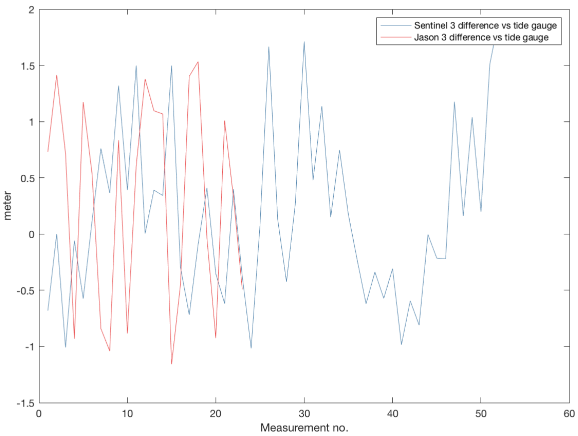
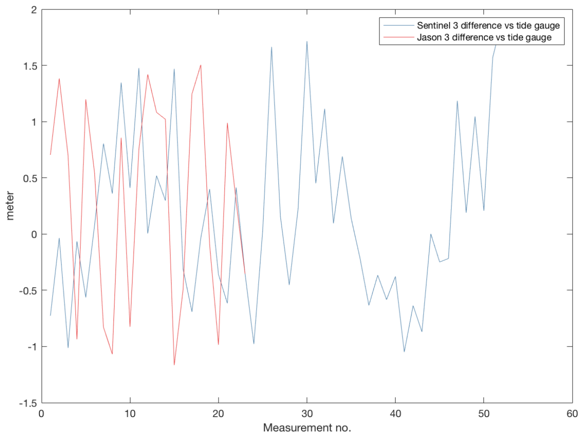


Figure 7: Altimetry Local Mean Pressure Corrected vs Tide Gauge Local Mean Pressure Corrected

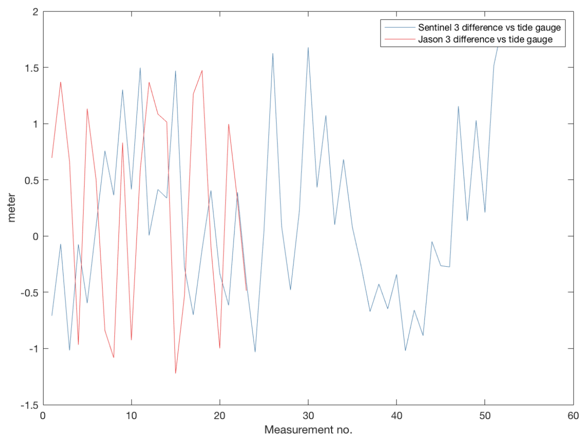
Figure 8 shows how the altimetry data differs from the tide gauge data. The the change in sea surface height from the different correction are on the centimetre scale, and is therefore hard to distinguish one plot from another. A change of only a few centimetres, is nothing compared to the overall signal amplitude of several metres. The difference is there though, and as seen earlier, the different corrections have an impact on the correlation and deviation of the signals.



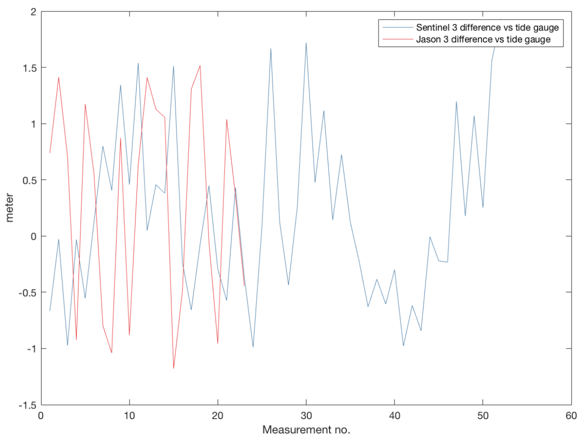
(a) No correction



(b) MOG2D



(c) Global Mean Pressure



(d) Local Mean Pressure

Figure 8: Altimetry vs tide gauge difference

5.3 Small area

By looking at the small area, it is sought to achieve greater accuracy by removing even more of the bad data. As theorised before, there seems to be little tidal correlation between the west and east side of the strait. To further improve the deviation and correlation, all data points east of the strait is removed from the Sentinel-3 files. This way, only good data point should be present, with good tidal correlation between the tide gauge and the Sentinel-3 altimeter. It isn't possible to further confine the data for Jason-3, simply because no better data is available. Thus it is the same data as the medium area, and is only present to make a comparison possible.

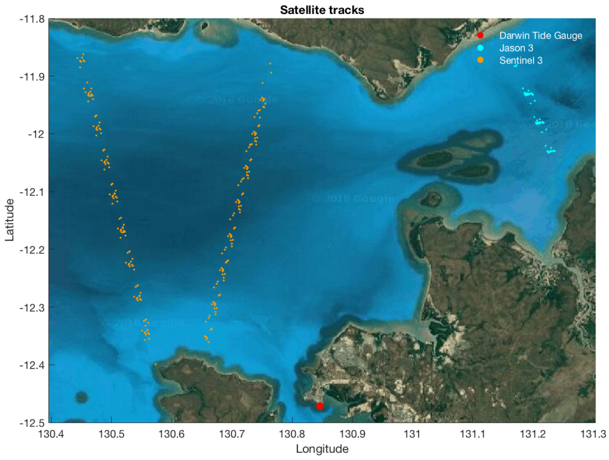


Figure 9: Location of in situ and altimetry data for the small area

Table 5 shows, that the accuracy of the measurements for Sentinel-3 has improved by a lot. The STD has fallen to circa 28 cm, which is nearly half a metre better than the STD for the medium area, and nearly 70 cm better than the large area. This is a huge improvement, which shows that there are huge tidal variations and delays in the area. The correlation for all altimetry signals with inverse barometer corrections are above 0.98, which is a great result. The mean deviation for all Sentinel-3 signals are really low, with a maximum mean of -0.0481.

The correlation, STD and mean deviation hasn't changed for Jason-3. This makes sense, as we haven't further manipulated the signal since the medium area. The data is still plagued by the isolated/delayed tide, and therefore only produces mediocre results.

Correlation tide gauge (Local DAC corrected) vs altimetry	Jason-3	Sentinel-3
No DAC	0.9015	0.9872
MOG2D	0.9062	0.9874
DAC (GMP)	0.9039	0.9870
DAC (LMP)	0.9039	0.9870
STD of Differences tide gauge (Local DAC corrected) vs altimetry	Jason-3	Sentinel-3
No DAC	0.9386	0.2761
MOG2D	0.9298	0.2771
DAC (GMP)	0.9380	0.2816
DAC (LMP)	0.9380	0.2816
Mean of Differences tide gauge (Local DAC corrected) vs altimetry	Jason-3	Sentinel-3
No DAC	0.3074	-0.0157
MOG2D	0.3010	-0.0282
DAC (GMP)	0.2673	-0.0481
DAC (LMP)	0.3099	-0.0055

Table 5: Comparisons between altimetry and in situ data for the small area. Dynamic Atmosphere Correction (DAC), Global Mean Pressure (GMP), Local Mean Pressure (LMP). STD and mean deviation in metres

Table 6 shows the STD and mean deviation for the signals, with different inverse barometer corrections applied. Notice how the STD for all Sentinel-3 signals are bigger than when comparing with the STD in the large and medium area. At first glance this seems to be a bad thing, but the STD of the tide gauge signals has a STD of 1.6 metres. The STD of the Sentinel-3 and tide gauge signal becoming so similar might contribute to the excellent signal correlation coefficient of 98.7

Standard deviation of signals	Jason-3	Sentinel-3	Tide Gauge
No DAC	0.9965	1.3237	1.6209
MOG2D	1.0035	1.3355	NA
DAC (GMP)	1.0039	1.3235	1.6203
DAC (LMP)	1.0039	1.3235	1.6203
Mean deviation	Jason-3	Sentinel-3	Tide Gauge
No DAC	-0.0769	0.2779	0.0730
MOG2D	-0.0757	0.2599	NA
DAC (GMP)	-0.1201	0.2460	0.0735
DAC (LMP)	-0.0776	0.2886	0.0735

Table 6: Standard and mean deviation of altimetry and in situ signals for the small area. All deviations in metres

Figure 10 shows a comparison between the altimetry and tide gauge data. The altimetry data set is heavily trimmed for the small area, which explains the low number of data points. There are a few outliers in the altimetry data, with amplitudes closer to the tide gauge amplitude. This is a small improvement, but ideally most of the altimetry data should have a much bigger amplitude, matching the tide gauge.

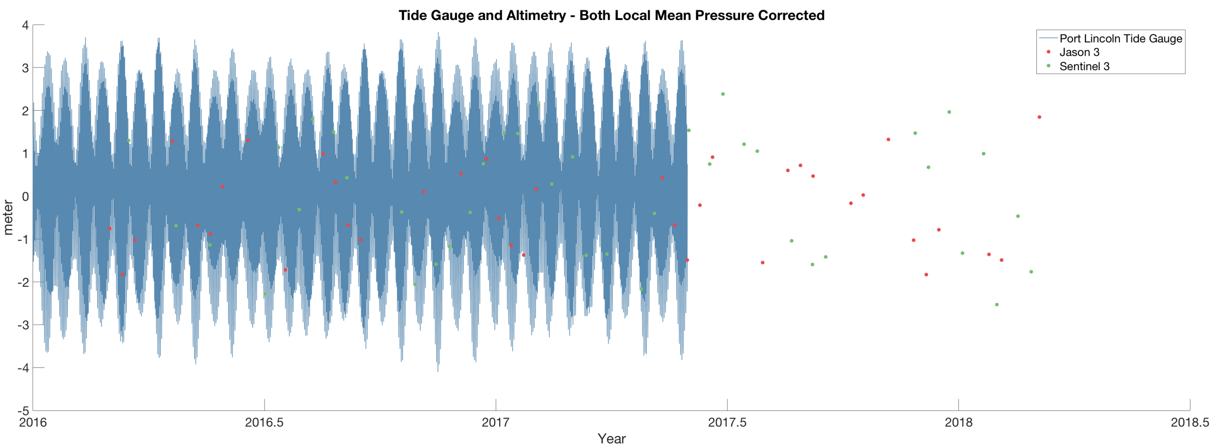
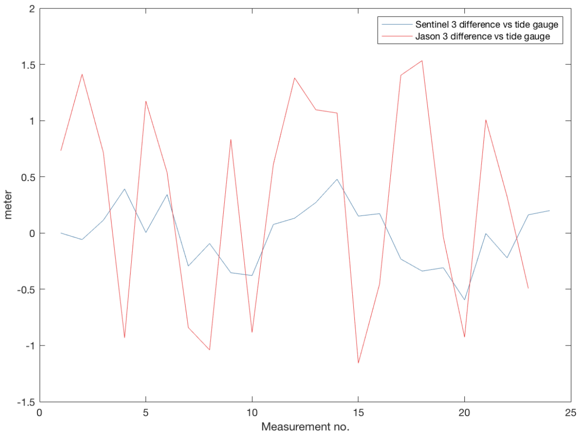
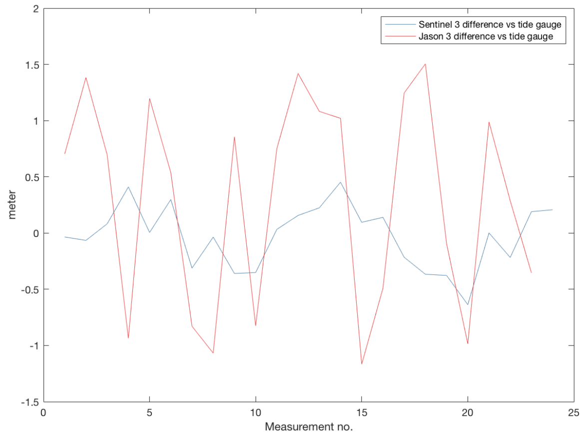


Figure 10: Altimetry Local Mean Pressure Corrected vs Tide Gauge Local Mean Pressure Corrected

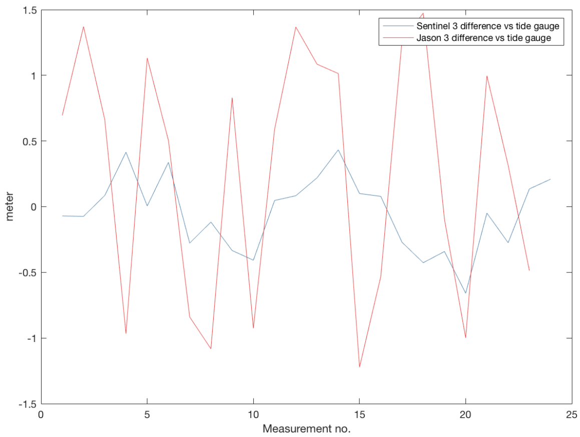
Figure 11 shows how much each of the altimetry signals differ from the tide gauge signal. Here it is clear, that the Sentinel-3 signal differs a lot less than the Jason-3 signal. Sentinel-3 has a maximum difference of around ± 0.5 metres, while Jason-3 is closer to +1.5 metres to -1 metre. The signal difference between different inverse barometer corrections is almost to small to be noticeable in the plot, but they make a difference in the statistics.



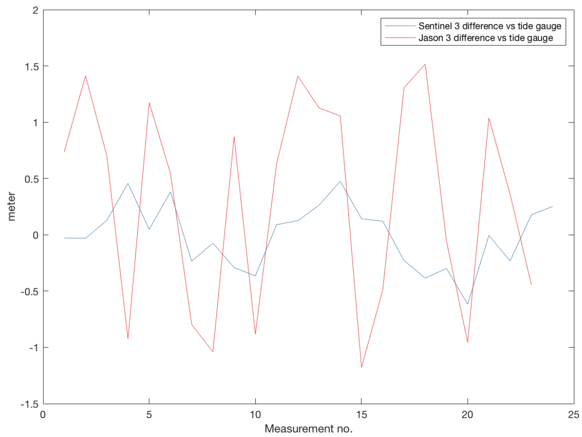
(a) No correction



(b) MOG2D



(c) Global Mean Pressure



(d) Local Mean Pressure

Figure 11: Altimetry vs tide gauge difference

6 Port Lincoln

Concluding that Darwin didn't produce the most desirable results, it was determined that it was necessary to look at other locations for tide gauge referencing. Port Lincoln was one of such locations, as it was possible to acquire the desired in situ data used.

Port Lincoln is a city on the Lower Eyre Peninsula, in the Australian state of South Australia. It is situated on the shore of Boston Bay, which opens eastward into Spencer Gulf.

The tide gauge in Port Lincoln is relatively close to Jason-3's satellite tracks, while Sentinel-3's tracks are a bit further out. The Sentinel-3 satellite has greater coverage of the area though, as it has a lower orbital period time, and thus a slightly "tighter" track coverage. While the tide gauge is in near proximity of the satellite tracks, it is located in a bay area which can disturb the water flow. Water flowing in and out of the bay has to diverge around Boston Island, which can lead to interference and delay in comparison to the open water tide.

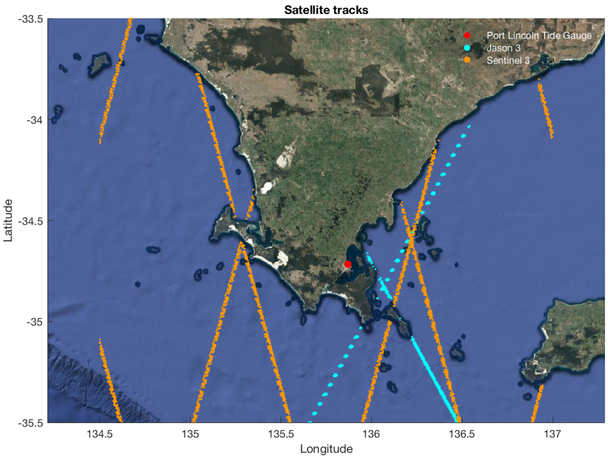


Figure 12: Location of in situ and altimetry data for large area

6.1 Large area

The Large area contains altimetry data from both sides of the Eyre Peninsula. With nearly 300 km between northwesternmost data point and the southeasternmost data point, some tidal delay is expected in the area. As the tide gauge is located on the eastern coast of the peninsula, tidal discrepancy is also expected when comparing altimetry data west of the peninsula.

Table 7 shows the correlation between the tide gauge and altimetry signals, and the STD/mean deviation of the difference between tide gauge and altimetry signals.

The correlation coefficients are acceptable for both altimeters, considering the size of the area. The best correlation for Jason-3 is 0.9496, which is really good. The measurements are located closer to the tide gauge though, so Jason-3 was expected to perform better in this regard. The best correlation for Sentinel-3 is 0.8605, which is a good start. The STD for Jason-3 is also surprisingly good, at 14.29 cm at best. One of the satellite tracks for Jason-3 is situated really close to the tide gauge, which should help with the accuracy. It's no surprise that the STD for Sentinel-3 is worse than Jason-3, as it covers a much larger area, with a higher number of distant measurements. The STD is not awful though, with a deviation of 16.11 cm at best. The global/local inverse barometer correction is the best for both altimeters, improving the STD of about a centimetre or so, compared to the (inverse barometer) uncorrected signal.

Correlation tide gauge (Local DAC corrected) vs altimetry	Jason-3	Sentinel-3
No DAC	0.9266	0.8273
MOG2D	0.9359	0.8281
DAC (GMP)	0.9496	0.8605
DAC (LMP)	0.9496	0.8605
STD of Differences tide gauge (Local DAC corrected) vs altimetry	**Jason-3**	**Sentinel-3**
No DAC	0.1548	0.1785
MOG2D	0.1591	0.1775
DAC (GMP)	0.1429	0.1611
DAC (LMP)	0.1429	0.1611
Mean of Difference tide gauge (Local DAC corrected) vs altimetry	**Jason-3**	**Sentinel-3**
No DAC	0.0759	0.1860
MOG2D	0.1367	0.2530
DAC (GMP)	0.1177	0.2355
DAC (LMP)	0.0780	0.1957

Table 7: Comparisons between altimetry and in situ data for the large area. Dynamic Atmosphere Correction (DAC), Global Mean Pressure (GMP), Local Mean Pressure (LMP). STD and mean deviation in metres

Table 8 shows the standard and mean deviations of the individual signals. Notice how the amplitudes for all of the signals are much lower than the Darwin signals. This is probably due to the lower tide variation in Port Lincoln, compared to Darwin.

Standard deviation	Jason-3	Sentinel-3	Tide Gauge
No DAC	0.3197	0.2861	0.3621
MOG2D	0.2911	0.2608	NA
DAC (GMP)	0.3071	0.2741	0.3513
DAC (LMP)	0.3071	0.2741	0.3513
Mean deviation	Jason-3	Sentinel-3	Tide Gauge
No DAC	-0.0244	-0.0422	-0.0879
MOG2D	0.0405	0.0297	NA
DAC (GMP)	0.0215	0.0138	-0.0882
DAC (LMP)	-0.0183	-0.0260	-0.0882

Table 8: Standard and mean deviation of altimetry and in situ signals for the large area. All deviations in metres

Figure 13 shows how the altimetry data compared to the in situ data. Notice how there seems to be an annual tide signal, on top of the daily tide signal. The tide looks to have a higher amplitude in the summer, with two clear peaks at 2016.5 and 2017.5. There are several outliers for the in situ data. If this is erroneous measurements or freak weather is unknown.

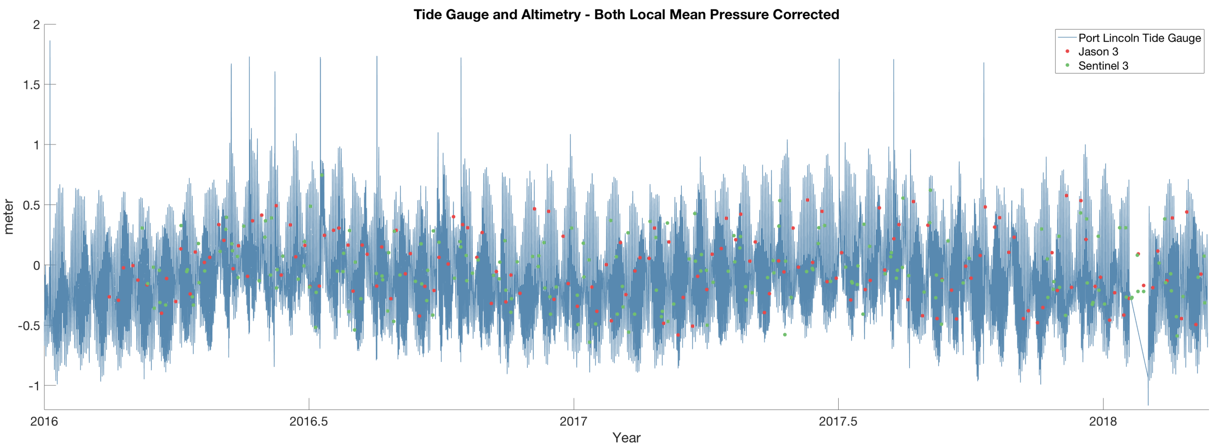
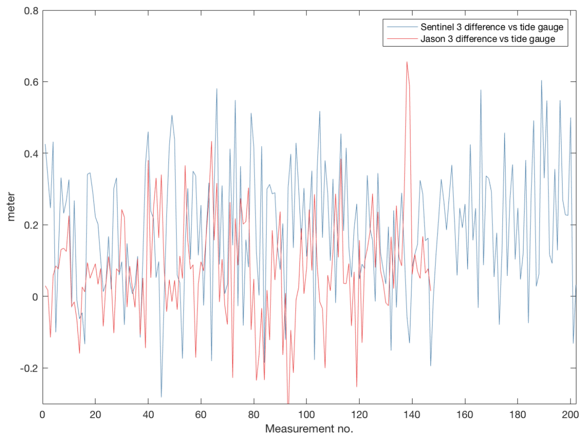
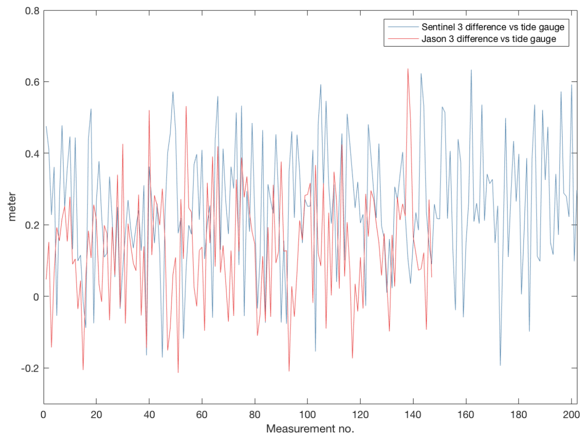


Figure 13: Altimetry Local Mean Pressure Corrected vs Tide Gauge Local Mean Pressure Corrected

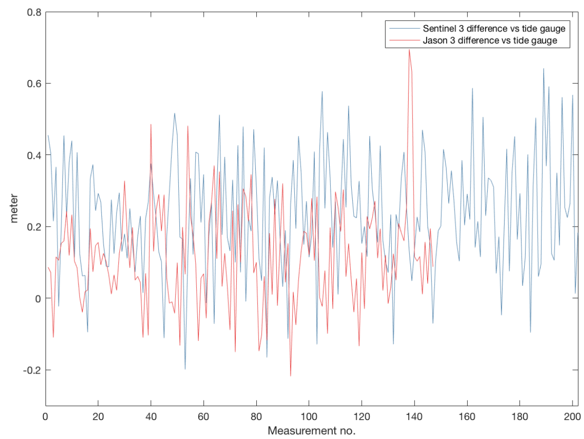
Figure 14 shows how Sentinel-3 has a consistently larger deviation to the tide gauge signal than Jason-3. Sentinel-3's deviation seem to increase as the time goes on, as the peaks are bigger for the later measurements, compared to the early ones.



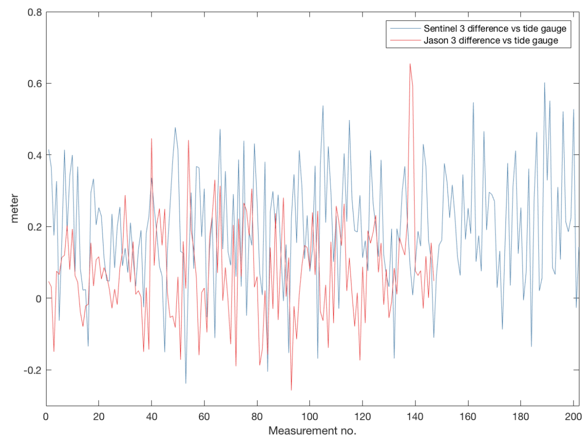
(a) No correction



(b) MOG2D



(c) Global Mean Pressure



(d) Local Mean Pressure

Figure 14: Altimetry vs tide gauge difference

6.2 Medium area

To further improve the correlation and deviation, the data points far away from the tide gauge were trimmed away. Sentinel-3 still has measurements west of the Eyre Peninsula, but they are all near the coast. The measurements far away from the tide gauge are expected to worsen the overall result, so removing them should only improve the correlation and deviation between the altimetry and tide gauge signals.

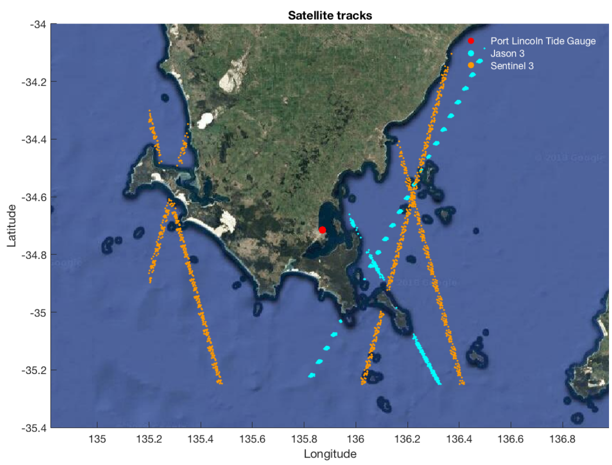


Figure 15: Location of in situ and altimetry data for medium area

Table 9 shows the correlation, standard deviation and mean deviation of the difference between the altimetry and in situ signals.

The correlation for both signals are better than when comparing to the large area. This comes as no surprise, as we removed some of the less compatible measurements this time. Highest correlation coefficients of 0.9593 and 0.8901 for Jason-3 and Sentinel-3 respectively are good, but leaves room for improvement. The best correction for both altimeters is the global/local mean inverse barometer correction, with MOG2D being second best.

The STD has fallen to just 12.03 cm and 13.98 cm at best, for Jason-3 and Sentinel-3 respectively. The deviations are below our target STD of 15 cm, which is great. The global/local mean inverse pressure correction is the best correction again, which isn't surprising.

Correlation tide gauge (Local DAC corrected) vs altimetry	Jason-3	Sentinel-3
No DAC	0.9384	0.8761
MOG2D	0.9451	0.8418
DAC (GMP)	0.9593	0.8901
DAC (LMP)	0.9593	0.8901
STD of Differences tide gauge (Local DAC corrected) vs altimetry	Jason-3	Sentinel-3
No DAC	0.1357	0.1493
MOG2D	0.1386	0.1652
DAC (GMP)	0.1203	0.1398
DAC (LMP)	0.1203	0.1398
Mean of Differences tide gauge (Local DAC corrected) vs altimetry	Jason-3	Sentinel-3
No DAC	0.0781	0.1931
MOG2D	0.1416	0.2660
DAC (GMP)	0.1208	0.2470
DAC (LMP)	0.0810	0.2072

Table 9: Comparisons between altimetry and insitu data for the medium area. Dynamic Atmosphere Correction (DAC), Global Mean Pressure(GMP), Local Mean Pressure (LMP). STD and mean deviation in metres

Standard deviation	Jason-3	Sentinel-3	Tide Gauge
No DAC	0.3469	0.3048	0.3621
MOG2D	0.3135	0.2765	NA
DAC (GMP)	0.3326	0.2943	0.3513
DAC (LMP)	0.3326	0.2943	0.3513
Mean Deviation	Jason-3	Sentinel-3	Tide Gauge
No DAC	-0.0250	-0.0701	-0.0879
MOG2D	0.0448	0.0047	NA
DAC (GMP)	0.0206	-0.0110	-0.0485
DAC (LMP)	-0.0192	-0.0507	-0.0882

Table 10: Standard and mean deviation of altimetry and in situ signals for the small area. All deviations in metres

Figure 16 shows a comparison between the in situ measurements and the altimetry measurements. The altimetry measurements match the in situ amplitude well, with good overall correlation.

Figure 17 shows, that the difference between the in situ measurements and the Sentinel-3 measurements are consistently bigger than the difference between the in situ measurements and the Jason-3 measurements.

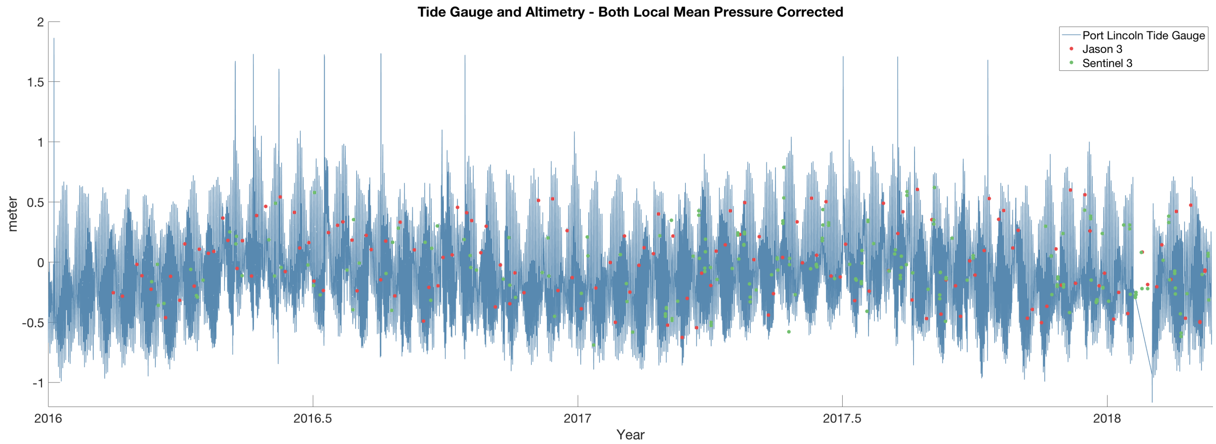
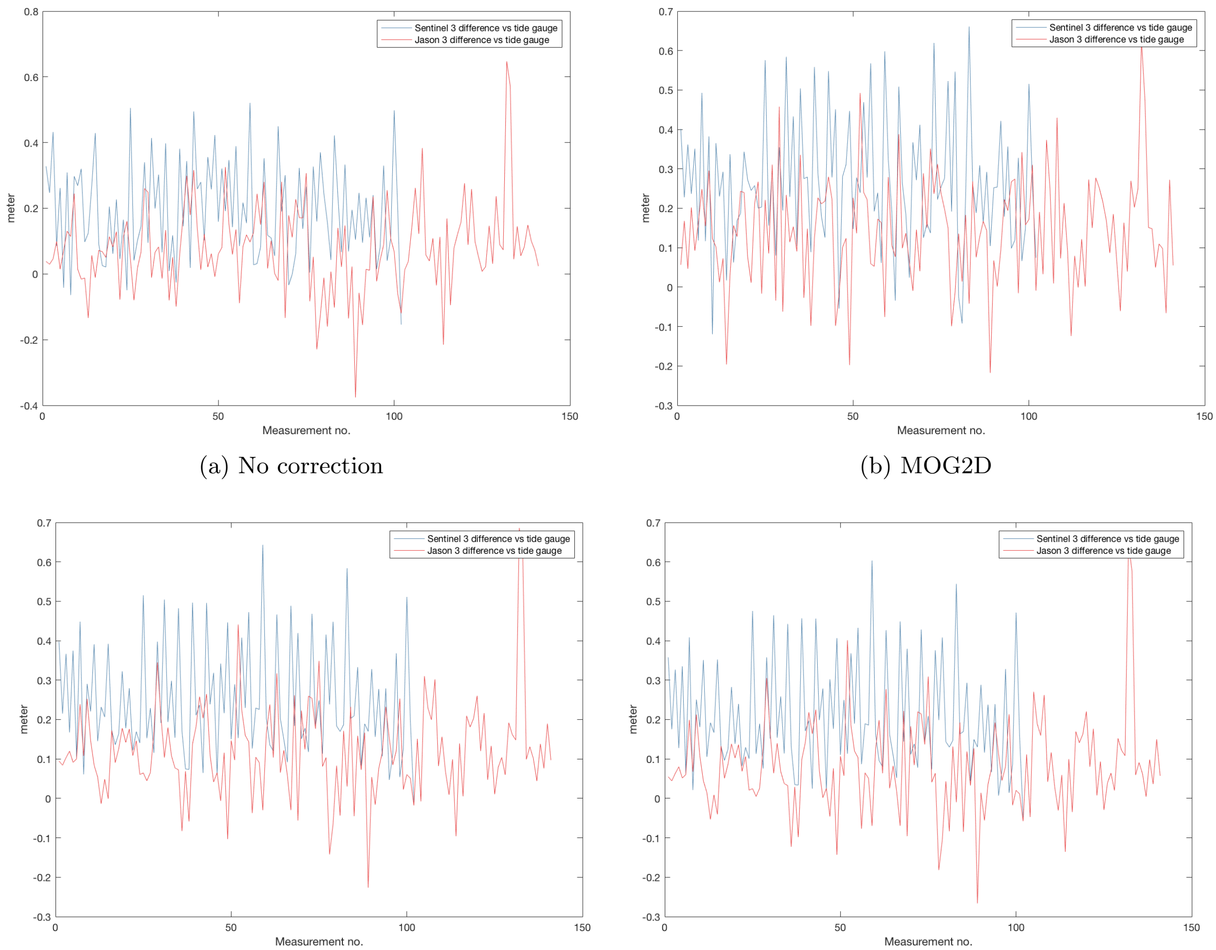


Figure 16: Altimetry Local Mean Pressure Corrected vs Tide Gauge Local Mean Pressure Corrected



(a) No correction

(b) MOG2D

(c) Global Mean Pressure

(d) Local Mean Pressure

Figure 17: Altimetry vs tide gauge difference

6.3 Small area

To achieve the best possible results, the data points got trimmed even further. Now only the absolute closest measurements are considered in the comparison, to hopefully achieve the best results. To make the measuring area even smaller than this would make no sense, as there wouldn't be enough data points to properly calculate the correlation and deviation.

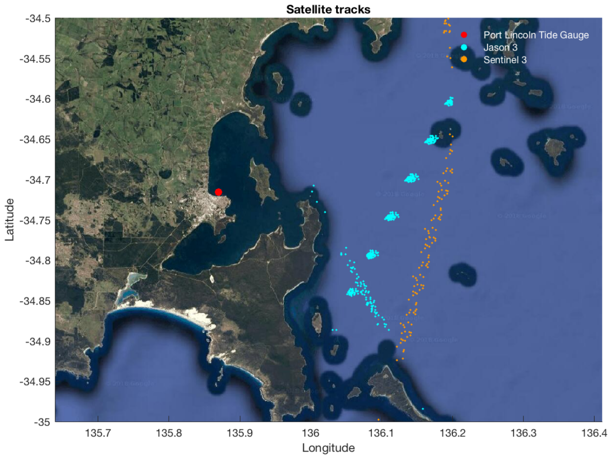


Figure 18: Location of in situ and altimetry data for small area

In table 11, we see that the correlation coefficient has improved for both altimetry signals. Jason-3's coefficient has improved by about 0.015 to .02 for all corrections. This is a fair improvement, that definitely is satisfactory. Sentinel-3's correlation coefficient has improved by around 0.07-0.08, which is a huge improvement. The correlation coefficients are now at best 0.9741 and 0.9652 for Jason-3 and Sentinel-3 respectively. The global/local mean inverse pressure correction gives the biggest improvement to the uncorrected signal, as we have seen before in the medium and large area.

The STD has also seen an improvement by further trimming and localising the altimetry measurements. Standard deviations are now only 9.13 cm and 8.26 cm at best for Jason-3 and Sentinel-3 respectively. This is well below the target deviation of 15 cm, and is a fantastic result. This shows us, combined with the improved correlation, that the tide on the western side of the Eyre Peninsula doesn't correlate with the tide on the eastern side in Port Lincoln. For the first time, Sentinel-3 has the lowest STD of the two altimeters, despite the correlation being slightly less than Jason-3. Normally Jason-3 has had the best STD, probably due to the more localised satellite tracks. Making measurements closer to the tide gauge definitely is an advantage when striving for the lowest possible STD.

Correlation tide gauge (Local DAC corrected) vs altimetry	Jason-3	Sentinel-3
No DAC	0.9594	0.9543
MOG2D	0.9592	0.9426
DAC (GMP)	0.9741	0.9652
DAC (LMP)	0.9741	0.9652
STD of Differences tide gauge (Local DAC corrected) vs altimetry	**Jason-3**	**Sentinel-3**
No DAC	0.1079	0.0926
MOG2D	0.1138	0.1043
DAC (GMP)	0.0913	0.0826
DAC (LMP)	0.0913	0.0826
Mean of Differences tide gauge (Local DAC corrected) vs altimetry	**Jason-3**	**Sentinel-3**
No DAC	0.1043	0.0820
MOG2D	0.1657	0.1410
DAC (GMP)	0.1447	0.1151
DAC (LMP)	0.1050	0.0753

Table 11: Comparisons between altimetry and insitu data for the medium area. Dynamic AtmosphereCorrection (DAC), Global Mean Pressure(GMP), Local Mean Pressure (LMP). STD and mean deviationin metres

Standard deviation	Jason-3	Sentinel-3	Tide Gauge
No DAC	0.3497	0.3297	0.3621
MOG2D	0.3182	0.2952	NA
DAC (GMP)	0.3344	0.3185	0.3513
DAC (LMP)	0.3344	0.3185	0.3513
Mean deviation	**Jason-3**	**Sentinel-3**	**Tide Gauge**
No DAC	-0.0188	-0.1964	-0.0879
MOG2D	0.0536	-0.1209	NA
DAC (GMP)	0.0289	-0.1358	-0.0485
DAC (LMP)	-0.0108	-0.1756	-0.0882

Table 12: Standard and mean deviation of altimetry and in situ signals for the small area. All deviations in metres

In figure 19, it is evident how few altimetry measurements there are, especially for Sentinel-3. They have good correlation with the tide gauge signal though, and there are still enough altimetry data to make a proper comparison. The amplitude of the tide gauge signal varies from -1 metre to +2 metres, although most of the measurements above 1 metre are probably erroneous. They are irregular, and has almost double the amplitude compared to the rest of the signal.

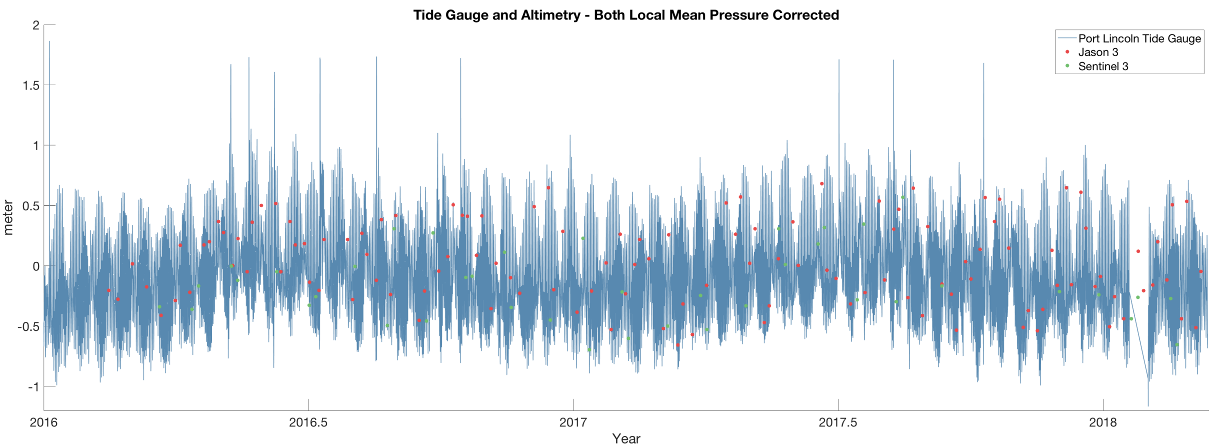
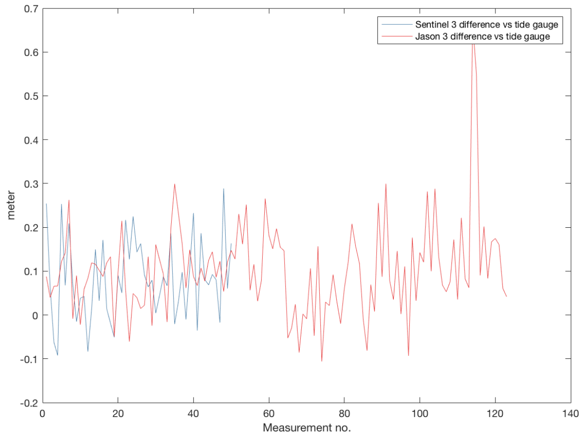
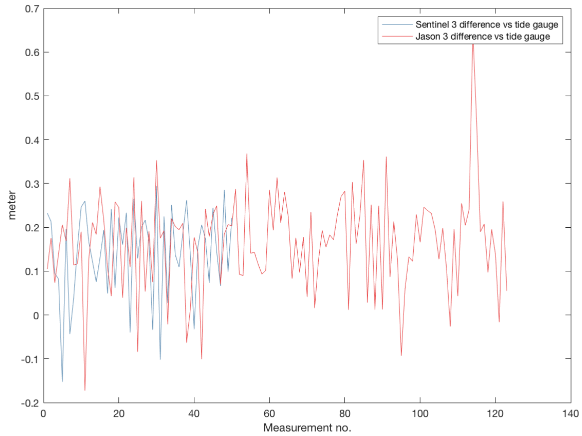


Figure 19: Altimetry Local Mean Pressure Corrected vs Tide Gauge Local Mean Pressure Corrected

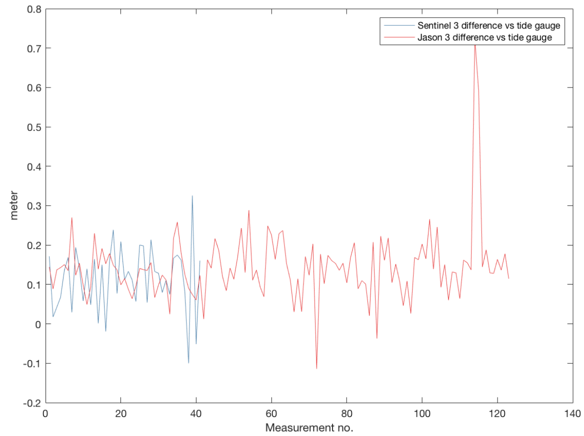
Figure 20 also shows how there are a lot more Jason-3 measurements than Sentinel-3 measurements. The origin of the big spike is unaccounted for, but it is probably due to a couple of bad measurements. Still, it is great that the biggest measuring difference is less than 80 cm, and even greater that most are below 30 cm for both altimeters.



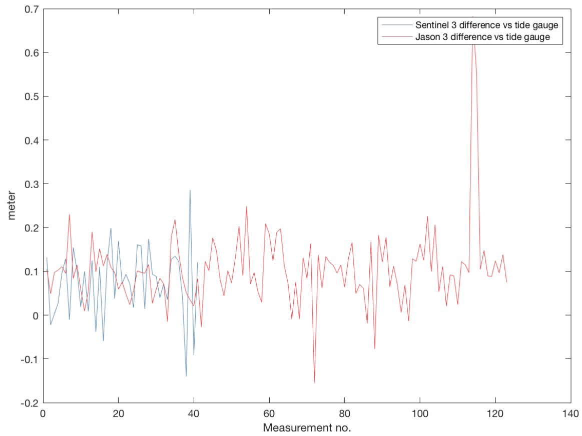
(a) No correction



(b) MOG2D



(c) Global Mean Pressure



(d) Local Mean Pressure

Figure 20: Altimetry vs tide gauge difference

7 Thevenard

Thevenard is a port town located in the south west of south Australia. Thevenard also has a climate with hot dry summers and cool slightly wetter winters.

After we started looking at our first area of interest, Darwin and did not get the results we wanted we decided to go further down south and found a new area to investigate. We were given data from to different stations one in Thevenard and one in port Lincoln.
As we did in Darwin we are going to look at a large area, a middle sized area and a small area. In Thevenard it was not possible to get satellite data from Jason-3 when looking at small area. This makes it hard to compare the two of them but by comparing the other areas you cans still get an idea of which satellite gives the best data.

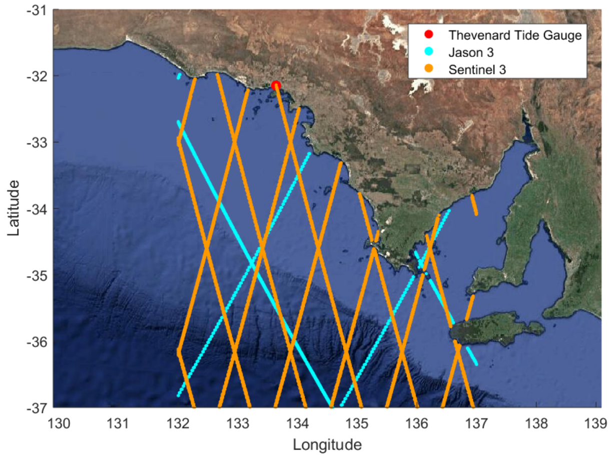


Figure 21: Location of in situ and altimetry data for large area

7.1 Large area

When looking at the large area it is easy too see that there is a lot of altimetry data covering the area, especially from sentinel-3. Sentinel-3 has a greater coverage and the tracks from sentinel-3 is almost directly on the tide gauge in Thevenard. There is a few islands around Thevenard which can affect the water flow from the tide but it is unknown how big of an influence it has on the data since Thevenard still faces open water.

Looking at the data table we can see that the difference between sentinel-3 and Jason-3 is not that big but Sentinel-3 is still a tad better when looking at the standard deviation and that is the important one. Sentinel-3 is down to about 22 cm where Jason-3 is roughly 26 cm. The standard deviation did not change much when applying the neither of the inverse barometer correction. The mean deviation did not improve at all applying any of the corrections.

In table 14 we found the standard deviation and mean for the signal with different inverse barometer corrections.

Correlation tide gauge (Local DAC corrected) vs altimetry	Jason-3	Sentinel-3
No DAC	0.7967	0.7894
MOG2D	0.7666	0.7343
DAC (GMP)	0.8113	0.8032
DAC (LMP)	0.8113	0.7721
STD of Differences tide gauge (Local DAC corrected) vs altimetry	**Jason-3**	**Sentinel-3**
No DAC	0.2627	0.2184
MOG2D	0.2627	0.2184
DAC (GMP)	0.2571	0.2143
DAC (LMP)	0.2571	0.2143
Mean of Differences tide gauge (Local DAC corrected) vs altimetry	**Jason-3**	**Sentinel-3**
No DAC	-0.1160	0.1071
MOG2D	-0.1160	-0.1071
DAC (GMP)	-0.0836	0.0683
DAC (LMP)	-0.1130	-0.0977

Table 13: Comparisons between altimetry and in situ data for the large area. Dynamic Atmosphere Correction (DAC), Global Mean Pressure (GMP), Local Mean Pressure (LMP). STD and mean deviation in metres

Standard deviation of signals	Jason-3	Sentinel-3	Tide Gauge
No DAC	0.2522	0.2473	0.4424
MOG2D	0.2403	0.2237	NA
DAC (GMP)	0.2508	0.2391	0.4375
DAC (LMP)	0.2508	0.2391	0.4375
Mean deviation	**Jason-3**	**Sentinel-3**	**Tide Gauge**
No DAC	-0.0424	0.0109	0.0785
MOG2D	0.0230	0.0676	NA
DAC (GMP)	-0.0071	0.0461	0.1078
DAC (LMP)	-0.0364	0.0168	0.0785

Table 14: Standard and mean deviation of altimetry and in situ signals for the large area. All deviations in metres

Figure 22 shows the comparison between the tide gauge in thevenard and the altimetry measurements. Jason-3 has a few data point which matches the in situ data a little bit better than Sentinel-3 and looking at the correlation it is a little bit better for Jason-3 but we still get a better standard deviation for sentinel-3. If one was to start counting all the data points one would notice an overflow of Sentinel-3 points.

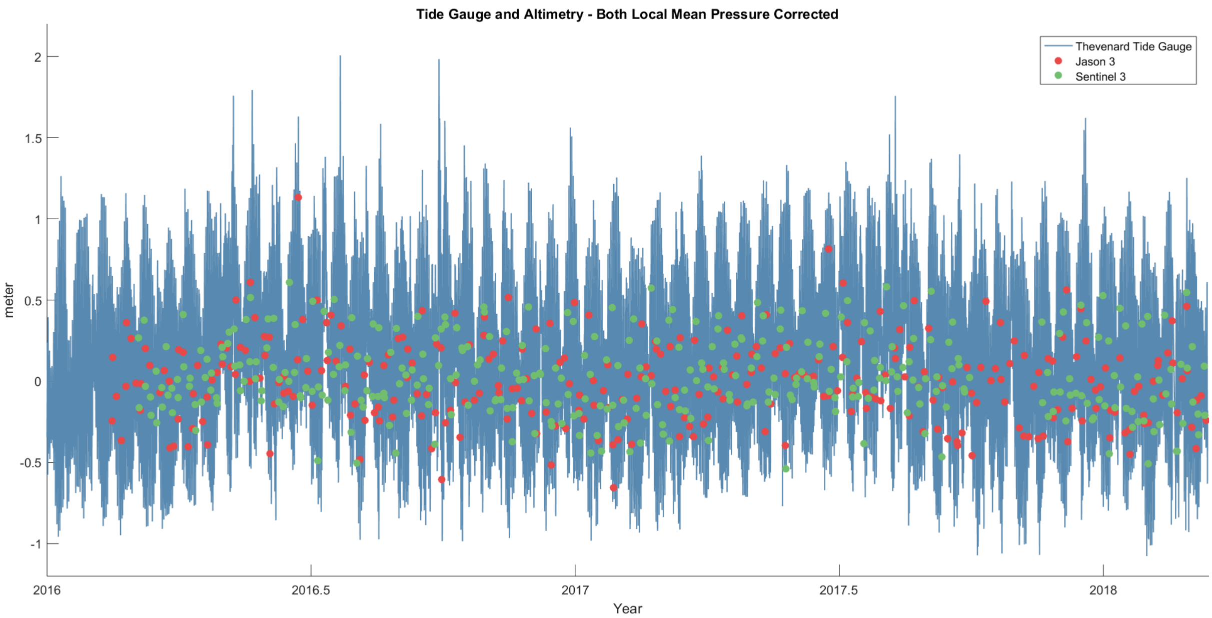
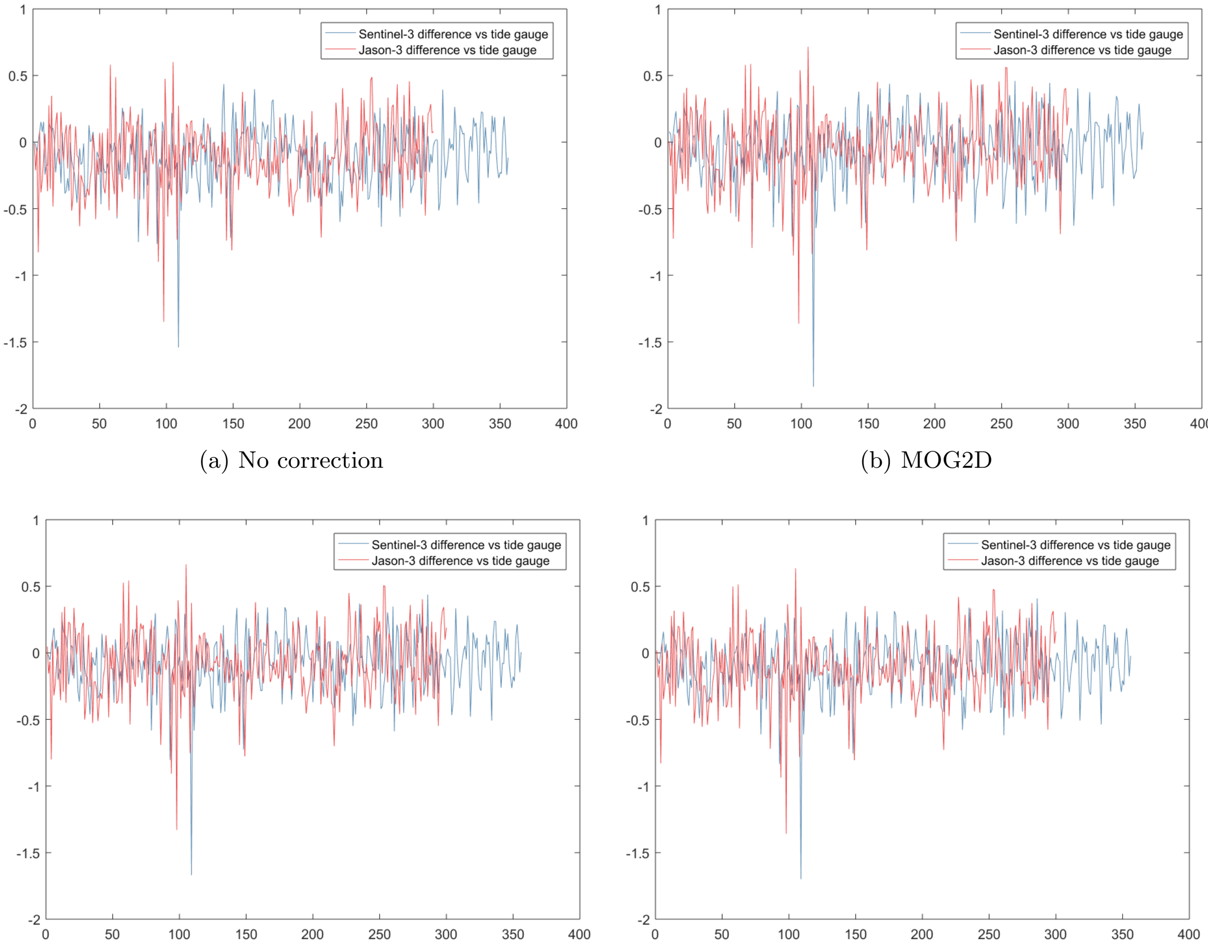


Figure 22: Altimetry Local Mean Pressure Corrected vs Tide Gauge Local Mean Pressure Corrected

In figure 23 it is easily seen that we have more measurements from Sentinel-3 it is a bit more visible here than on figure 22. The goal is to get as close to zero as possible. If the graph differs from zero by 1, it means that the satellite has measured one meter incorrectly from the tide gauge. Like for Port Lincoln you can see a few big spikes which can not really be explained. it could be bad weather or simply just bad measurements. The measurements are okay and lies within 50 cm (except for the spikes) but we would like for them to improve.



(a) No correction

(b) MOG2D

(c) Global Mean Pressure

(d) Local Mean Pressure

Figure 23: Altimetry vs tide gauge difference

7.2 Medium area

By narrowing the area down and thus eliminating bad data points should result in some better results. As for the larger area Sentinel-3 has a better coverage.

Looking at table ?? one can see that the results has improved from the larger area. The correlation has also improved by quite a bit and even though the correlation is better for Jason-3, Sentinel-3 still has a better STD which is down to 19.7 cm where Jason-3 is a bit higher about 21 cm. our target is to get below 15 cm When applying MOG2D it gets a bit worse which can be explained by the chosen model.

The model used is not precise enough on this scale and it is difficult to account for. But in general the data from sentinel-3 is better than Jason-3.

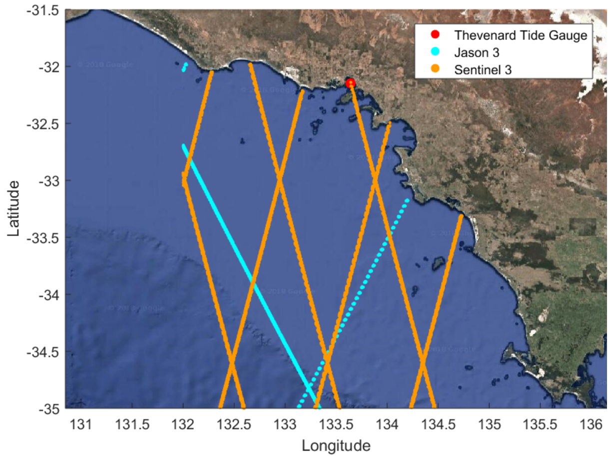


Figure 24: Location of in situ and altimetry data for medium area

Correlation tide gauge (Local DAC corrected) vs altimetry	Jason-3	Sentinel-3
No DAC	0.8870	0.8401
MOG2D DAC	0.8781	0.8208
BP DAC (Global Mean Pressure)	0.8984	0.8537
BP DAC (Local Mean Pressure)	0.8927	0.8504
STD of Differences tide gauge (Local DAC corrected) vs altimetry	Jason-3	Sentinel-3
No DAC	0.2129	0.1979
MOG2D DAC	0.2227	0.2092
BP DAC (Global Mean Pressure)	0.2064	0.1928
STD BP DAC (Local Mean Pressure)	0.2099	0.1942
Mean of Difference tide gauge (Local DAC corrected) vs altimetry	Jason-3	Sentinel-3
No DAC	-0.0921	-0.0584
MOG2D DAC	-0.0478	0.2092
BP DAC (Global Mean Pressure)	-0.1189	-0.696
BP DAC (Local Mean Pressure)	0.0269	-0.0847

Table 15: Comparisons between altimetry and in situ data for the large area. Dynamic Atmosphere Correction (DAC), Global Mean Pressure (GMP), Local Mean Pressure (LMP). STD and mean deviation in metres

Table 16 consists of the standard deviation and mean deviation for the signals with the different inverse barometer corrections. When comparing the STD for sentinel-3 it is a little bit bigger for the medium area than for the larger area.

Standard deviation of signals	Jason-3	Sentinel-3	Tide Gauge
No DAC	0.2663	0.2642	0.4424
MOG2D	0.2570	0.2390	NA
DAC (GMP)	0.2681	0.2579	0.4375
DAC (LMP)	0.2681	0.2579	0.4375
Mean deviation	Jason-3	Sentinel-3	Tide Gauge
No DAC	-0.0399	0.0336	0.0785
MOG2D	0.0269	0.0888	NA
DAC (GMP)	0.0058	0.0621	0.1078
DAC (LMP)	-0.0058	0.0621	0.1078

Table 16: Standard and mean deviation of altimetry and in situ signals for the Medium area. All deviations in metres

We still have a few more data points from Sentinel-3 as you can see on figure 25 The measurements from the tide gauge in Thevenard lies between -1 metre to 2 metres. By comparing to the large area you can see that it has improved. All the data points follow the tide gauge quite alright.

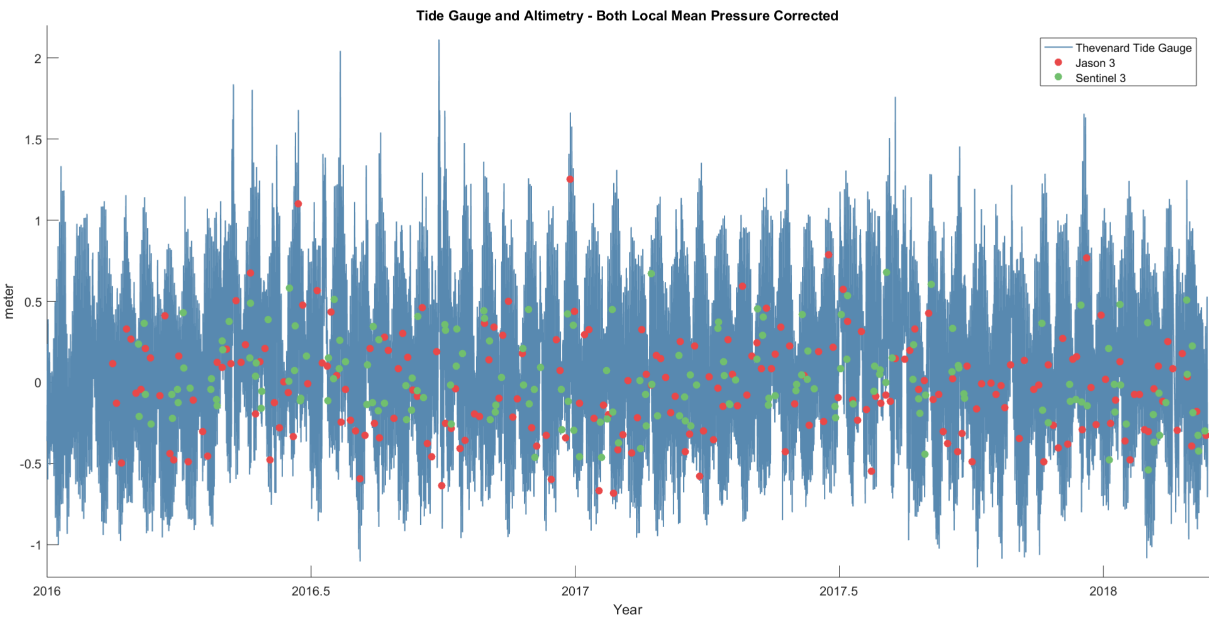
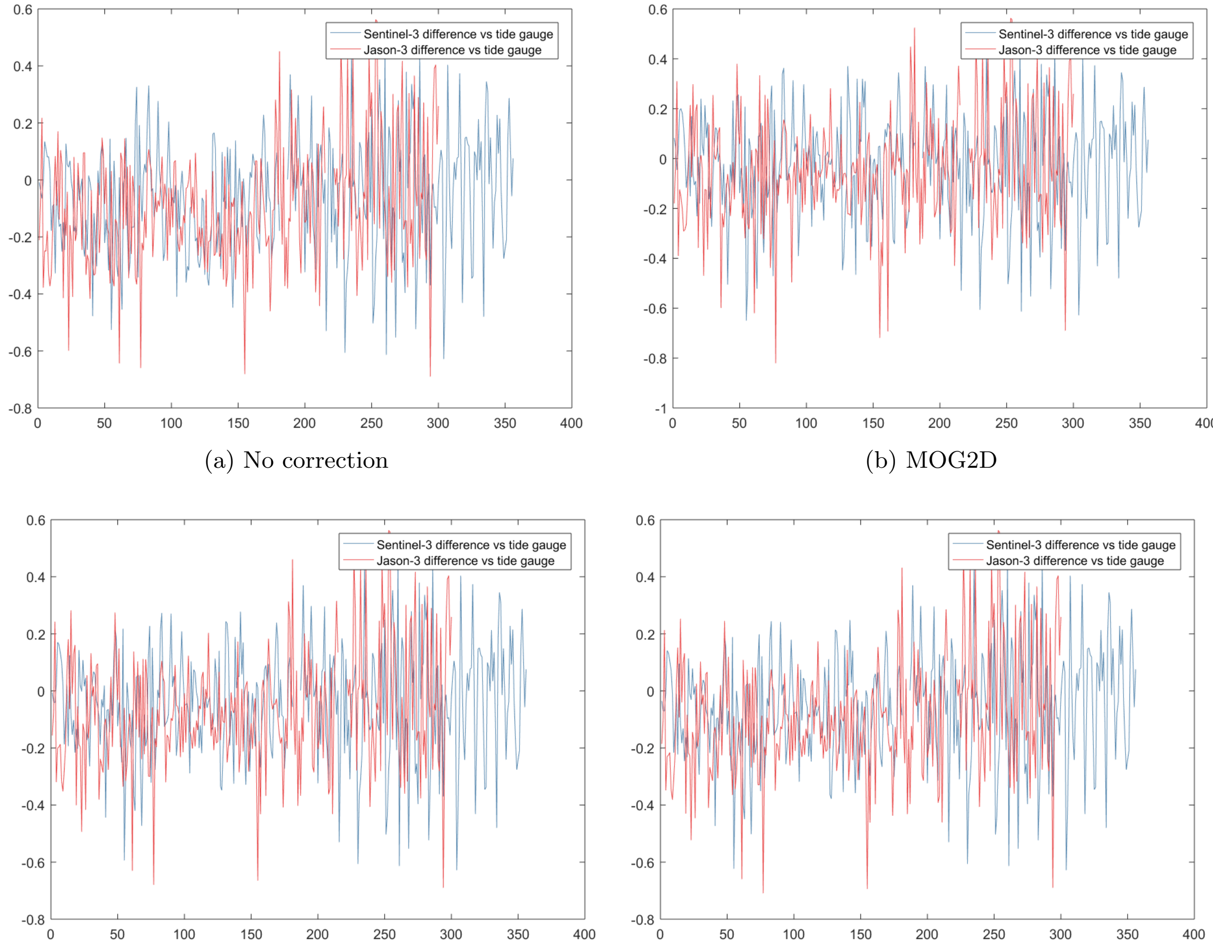


Figure 25: Altimetry Local Mean Pressure Corrected vs Tide Gauge Local Mean Pressure Corrected

Now looking at Figure 26 we can see that the signal from both Sentinel-3 and Jason-3 has improved a lot! Even though we still have spikes exceeding 50 cm the majority of the data stays within -40 cm to roughly 30 cm but we also see a big part of the data not exceeding 20 cm.



(a) No correction

(b) MOG2D

(c) Global Mean Pressure

(d) Local Mean Pressure

Figure 26: Altimetry vs tide gauge difference

7.3 Small area

Our goal is to get a standard deviation below 15 cm and by localising the area we are looking at we hope to achieve our goal. By going further in, in Thevenard the only altimetry available data are the ones from Sentinel-3. This of course makes it difficult to compare the two different satellite data, but it is still interesting to see if we can get a standard deviation under 15 cm.

As you can see on figure 27 the satellite track from Sentinel-3 is almost on top of the tide gauge and hopefully this will show on our results.

Since it was not possible to get data from Jason-3 it will show on the tables as Na (not available).

In table 18 we can see that the correlations has gone up quite a bit to 0.93 which is satisfactory.

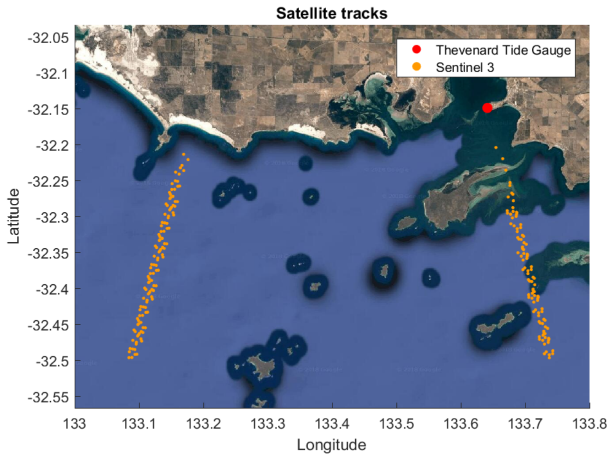


Figure 27: Location of in situ and altimetry data for small area

The standard deviation has improved a lot it has gone down approximately 7.5 cm. The standard deviation is down to 12 cm and is now below 15 cm which is what we wanted! By going further in you will only worsen the results since you remove to many of the measurements from Sentinel-3 so as of right now this is the best we can do.

Correlation tide gauge (Local DAC corrected) vs altimetry	Jason-3	Sentinel-3
No DAC	Na	0.9379
MOG2D DAC	Na	0.7175
BP DAC (Global Mean Pressure)	Na	0.9614
BP DAC (Local Mean Pressure)	Na	0.9614
STD of Differences tide gauge (Local DAC corrected) vs altimetry	Jason-3	Sentinel-3
No DAC	Na	0.1220
MOG2D DAC	Na	0.2373
BP DAC (Global Mean Pressure)	Na	0.0952
STD BP DAC (Local Mean Pressure)	Na	0.0952
Mean of Difference tide gauge (Local DAC corrected) vs altimetry	Jason-3	Sentinel-3
No DAC	Na	-0.0305
MOG2D DAC	Na	-0.1780
BP DAC (Global Mean Pressure)	Na	-0.0072
BP DAC (Local Mean Pressure)	Na	-0.0366

Table 17: Comparisons between altimetry and in situ data for the large area. Dynamic Atmosphere Correction (DAC), Global Mean Pressure (GMP), Local Mean Pressure (LMP). STD and mean deviation in metres

Standard deviation of signals	Jason-3	Sentinel-3	Tide Gauge
No DAC	Na	0.3409	0.4424
MOG2D	Na	0.3064	NA
DAC (GMP)	Na	0.3414	0.4375
DAC (LMP)	Na	0.3414	0.4375
Mean deviation	Jason-3	Sentinel-3	Tide Gauge
No DAC	Na	0.910	0.0785
MOG2D	Na	0.1511	NA
DAC (GMP)	Na	0.1156	0.0785
DAC (LMP)	Na	0.0863	0.0785

Table 18: Standard and mean deviation of altimetry and in situ signals for the small area. All deviations in metres

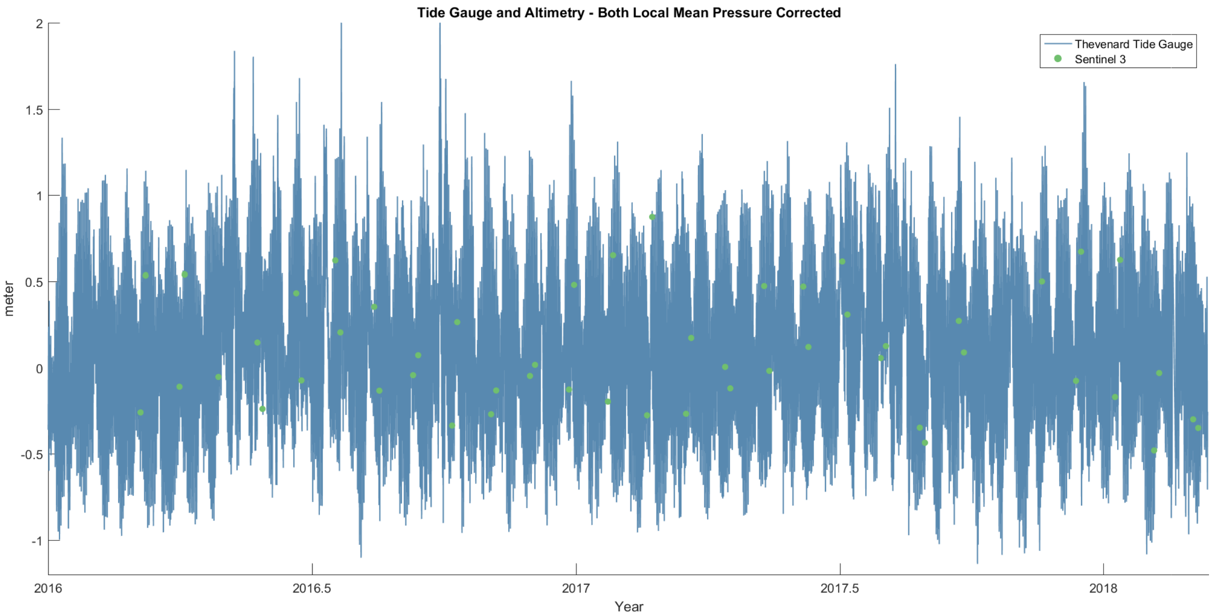
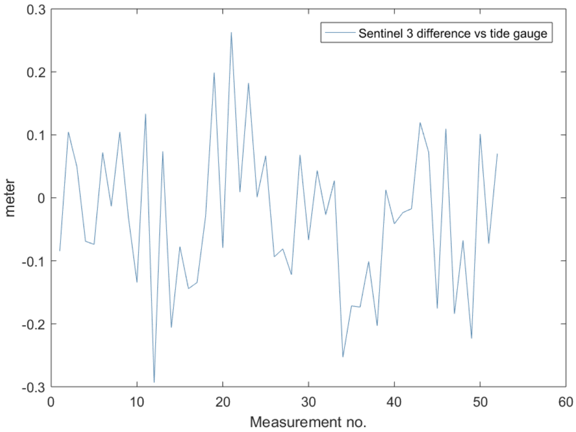


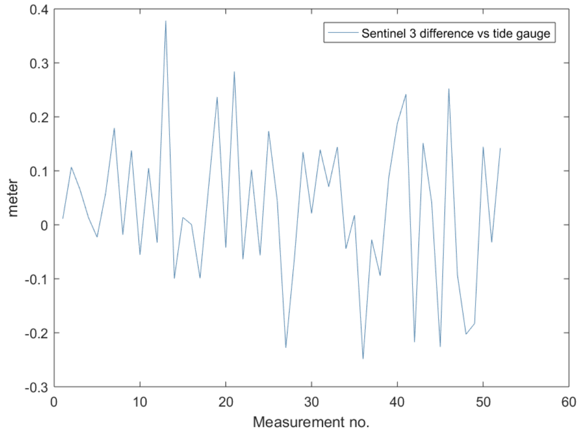
Figure 28: Altimetry Local Mean Pressure Corrected vs Tide Gauge Local Mean Pressure Corrected

As you can see on figure 28 we have removed a lot of the data points. The data points actually follow the tide gauge quite well which is reflected in the correlation. Even though we have removed a lot of the data points we still have enough to continue our work.

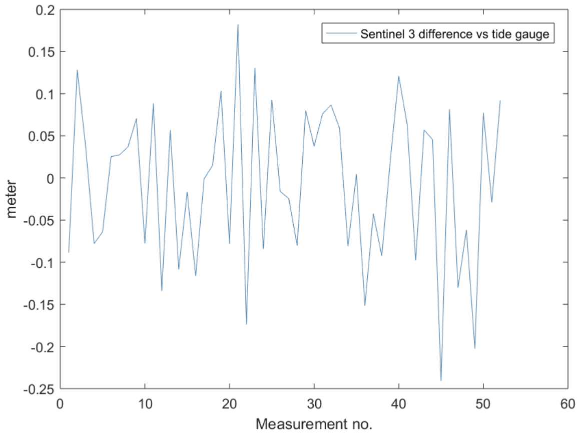
We can no longer compare the data from the satellites but looking at Figure 29 we can see a clear improvement of Sentinel-3. The highest peak has gone from 50 cm to 30 cm. In general the data is pretty good. You might notice that figure (b) has not improved much but the MOG2D data has not really done anything to improve the data so it is no surprise that the it is a little bit worse than the others. The biggest improvement is to be found in figure (c) and (d) it now stays within -25 cm to 20 cm which is quite good.



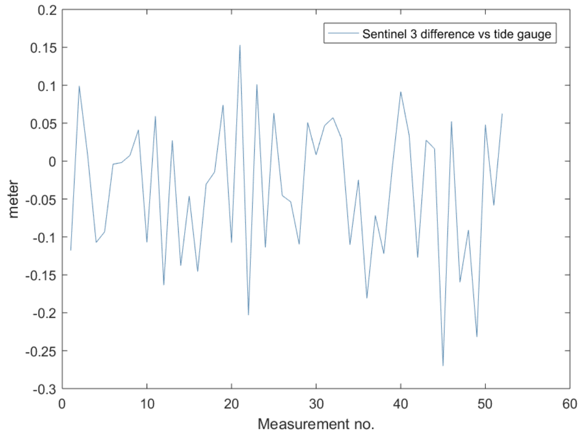
(a) No correction



(b) MOG2D



(c) Global Mean Pressure



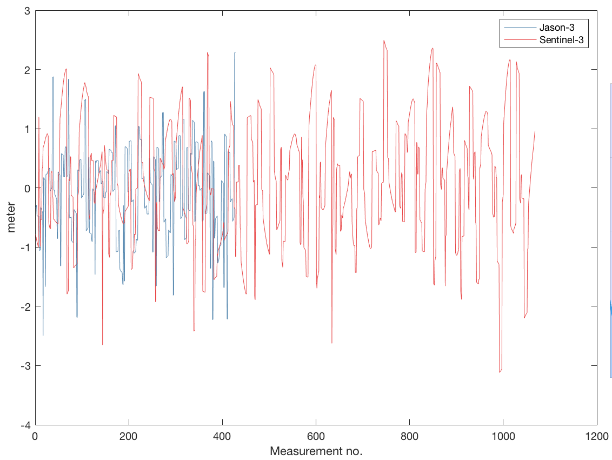
(d) Local Mean Pressure

Figure 29: Altimetry vs tide gauge difference

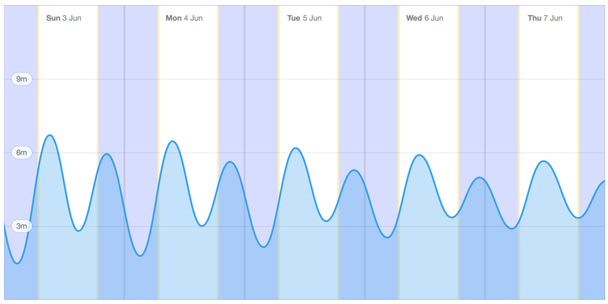
8 Tide comparison

Looking at comparison plots like 4, 7 and 10, it is clear that the amplitude of the altimetry signal is not nearly as big as the amplitude of the in situ signal. Darwin suffers the most in this regard, which might be why the STD is bigger than for the other locations. It is theorised, that the cause of this is due to the altimetry tide signal having a lower amplitude than the real tide signal. The tide signal is a big part of the whole signal, so if the tide signal is damped, so is the combined signal.

As seen in figure 30, it is clear that the Darwin tides are much higher than what is measured by the altimeters. The altimeters measures the tide to vary between -3.1 metres to +2.5 metres, with a maximum peak to peak amplitude of 5.1 metres. The actual tides reach amplitudes of more than 6 metres regularly. Notice the different reference points, as the altimeter tide can be negative values, while the actual tide measurements can't go below 0 metres.



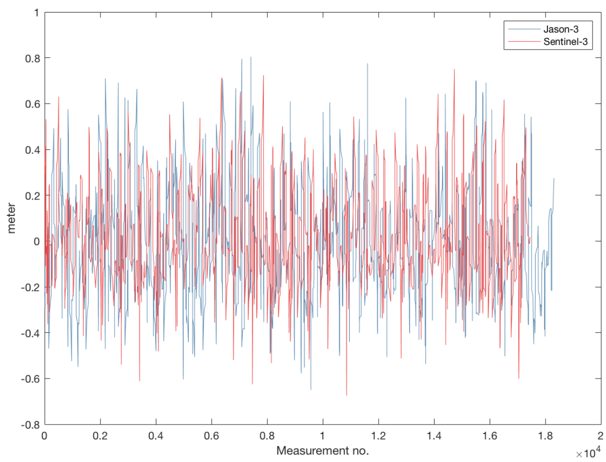
(a) Altimetry tide signal (tide_ocean_fes14)



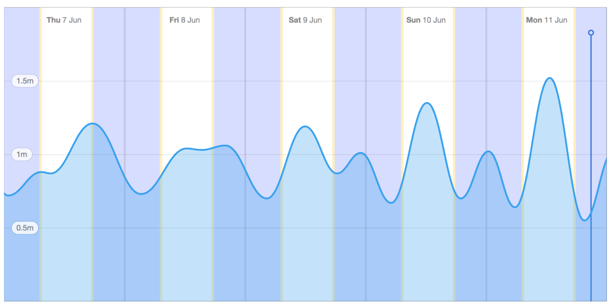
(b) Actual tide signal [1]

Figure 30: Comparison between altimetry tide and actual tide for Darwin

While not as drastic as Darwin, Port Lincoln also differs in the altimetry tide signal versus the real tide signal. The maximum amplitude of the altimetry tide signal is 1.4 metres (for the large area), as seen in figure 31, even though the actual tide reaches an amplitude of more than 1.5 metres.



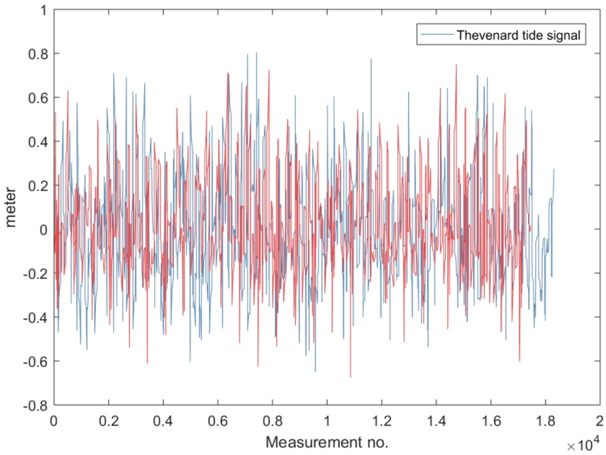
(a) Altimetry tide signal (tide_ocean_fes14)



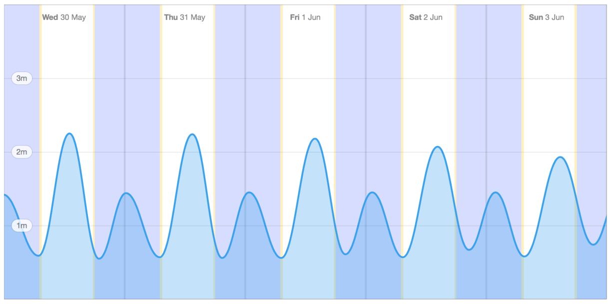
(b) Actual tide signal [3]

Figure 31: Comparison between altimetry tide and actual tide for Port Lincoln

The maximum peak to peak amplitude of the altimetry tide signal is 1.45 metres for the large area in Thevenard. The actual tide regularly exceeds 2 metres, as seen in figure 32.



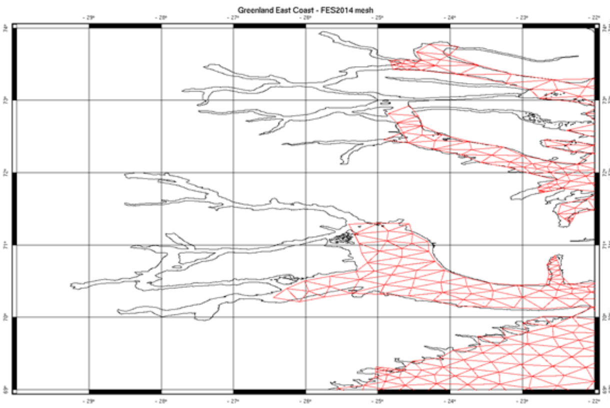
(a) Altimetry tide signal (tide_ocean_fes14)



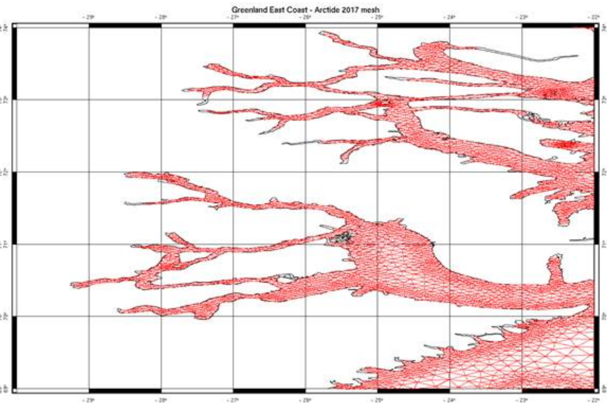
(b) Actual tide signal [5]

Figure 32: Comparison between altimetry tide and actual tide for Thevenard

Both altimeters use the FES2014 tide model for the tide corrections. The model has a low mesh resolution, which greatly impact its accuracy in coastal areas. Comparing to the Arctide 2017 mesh model in figure 33, we see how lacking the resolution of the FES2014 model is. It is speculated, that due to the low mesh resolution, a lot of the tide signal in especially Darwin isn't measured. Improving the mesh model to use a greater resolution, should result in much greater accuracy in the measurement of the tide signal. With proper tide corrections to the altimetry data, the overall accuracy and deviation should improve in areas with complex coastal geometry like Darwin. See figure 34



(a) FES2014



(b) Arctide 2017

Figure 33: Comparison between mesh models of the Greenland East Coast

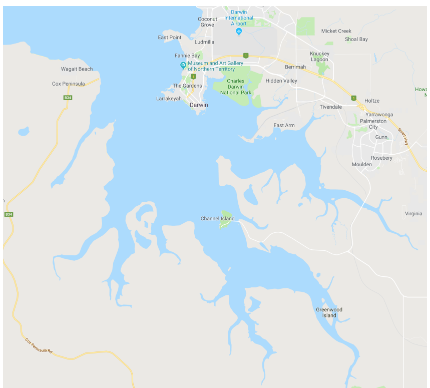


Figure 34: Coastal geometry of the Darwin Port area

9 Conclusions

In this study, we have compared altimetry data from two different altimeters, Jason-3 and Sentinel-3 at three different locations: Darwin, Port Lincoln and Thevenard. The altimetry measurements got compared with the cities local tide gauges, to see which altimeter is best at making measurements in coastal areas. Four types of altimetry signals got compared: One without any inverse barometer correction, one with an inverse barometer correction derived from the MOG2D gravity waves model, and two inverse barometer corrections using either global or local mean pressure to calculate the inverse barometer correction. The altimetry signals got compared to the tide gauge signal, which for all comparisons have been corrected with a local mean pressure inverse barometer correction. The correlation of the altimetry and tide gauge signals was found, and standard/mean deviations found of the difference between them.

The results varies for each area. Darwin had the worst overall deviation, with the best STD being 28.16 cm for Sentinel-3 at the small area. The minimum STD achieved by Jason-3 is 93.8 cm, also for the small area. It was concluded that the reason for the high Jason-3 deviation is the bad location of its measurements.

Port Lincoln saw considerable improvements compared to Darwin, and also got the greatest results overall, achieving a minimum STD of 9.13 cm for Jason-3, and 8.26 cm for Sentinel-3. It was the smallest area again that yielded the best results.

Thevenard also had better results than Darwin, with a minimum STD of 9.52 cm by Sentinel-3. As the trend goes, this measurement is achieved using the local mean pressure to calculate the inverse barometer correction for the small area. The best STD achieved by Jason-3 is 20.99 cm, with the same corrections applied as Sentinel-3. It was achieved using the medium area though, as there aren't any Jason-3 measurements available for the small area. Jason-3 has poor coverage in the area around Thevenard, with no data available in near proximity of the tide gauge.

For all areas, the best measurements were the ones with the inverse barometer correction found using the local mean pressure. The global and local mean pressure corrected measurements yielded the same STD, but the correction found from the local mean pressure always resulted in a better mean deviation, compared to the correction found using the global mean pressure. MOG2D made very inconsistent corrections, sometimes even worsening the result compared to the uncorrected altimetry signals. When MOG2D did improve the signal, it wasn't by nearly as much as the other two inverse barometer corrections.

Similarly, the best results were achieved when evaluating the small area. This doesn't come as a surprise, as localised altimetry measurements should correlate better with the tide gauge, than measurements far away from each other.

Sentinel-3 always produced results with the lowest standard deviation, at least when looking at the small area. Jason-3 produced better results for Port Lincolns medium and large area, so Sentinel-3 isn't always unambiguously the best altimeter in coastal regions. The reason for this is unknown, but by having the best measurements in 7 out of 9 cases, we can conclude that Sentinel-3 is promising as a coastal sea level altimeter. The sample size in this study is small at only 9 different areas compared, but there is reason to believe that the success rate of Sentinel-3 remains high as the sample size increases.

With more time and resources, it would be interesting to find areas where both altimeters have measurements equally close to the tide gauge. Distance has a big impact on the accuracy of the altimeter measurements, so equalising the comparison distance ensures that no altimeter gets an unfair advantage. It would be even better to find a coastal location, where the two satellite tracks cross each other. Placing a tide gauge directly on the intersecting point would be very interesting, as both altimeters would have an effective distance of 0 metres to the tide gauge, thus giving opportunity to achieve the best possible comparison.

By updating the mesh resolution of the tide model, greater accuracy could be achieved in areas with intricate coastlines like Darwin.

References

[1] *Darwin Tide*. WillyWeather. URL: https://tides.willyweather.com.au/nt/darwin/darwin.html (visited on 06/08/2018).

[2] *Dynamic ocean response to atmospheric wind and pressure forcing - Mog2D*. AVISO+. URL: https://www.aviso.altimetry.fr/en/data/products/auxiliary-products/atmospheric-corrections/description-atmospheric-corrections.html.

[3] *Port Lincoln Tide*. WillyWeather. URL: https://tides.willyweather.com.au/sa/eyre-peninsula/port-lincoln.html (visited on 06/08/2018).

[4] D Stammer and C Wunsch. *Atmospheric loading and the oceanic "inverted barometer" effect.* 1997.

[5] *Thevenard Tide*. WillyWeather. URL: https://tides.willyweather.com.au/sa/eyre-peninsula/thevenard.html (visited on 06/08/2018).

[6] *Tide gauge sea level data — NCAR - Climate Data Guide*. URL: https://climatedataguide.ucar.edu/climate-data/tide-gauge-sea-level-data (visited on 06/14/2018).

[7] National Oceanic {and} Atmospheric Administration US Department of Commerce. *Is sea level rising?* URL: https://oceanservice.noaa.gov/facts/sealevel.html (visited on 06/14/2018).

[8] S Vignudelli et al. *Coastal Altimetry*. Ed. by Stefano Vignudelli. Springer-Verlag Berlin and Heidelberg GmbH Co. K. 566 pp. ISBN: 978-3-642-12795-3.