Aquarius Pointing Analysis

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1. Introduction

Three months after launch, we saw the first indications of an error in the Aquarius pointing specification [*Aq t/c Nov 29, 2011*]. We examined Aquarius observations near land-ocean transitions along well-studied segments of the Somalia and Australia coastlines. These coastlines are smooth and do not have islands or inland waters. We calculated the average T_A as a function of distance from the coastline, and then calculated the T_A derivative with respect to distance. A land-ocean step-function should produce a Gaussian centered on zero if the pointing were correct. However, Aquarius showed very clear offsets on the order to 10 km (Figure 1). This behavior can also be seen with careful examination of T_A plotted footprint-by-footprint over land-ocean transitions [*Aq t/c Dec 13, 2011*]. The differences could be explained by a forward shift along the track, a shift to the right of the along-track direction, or some combination of both.

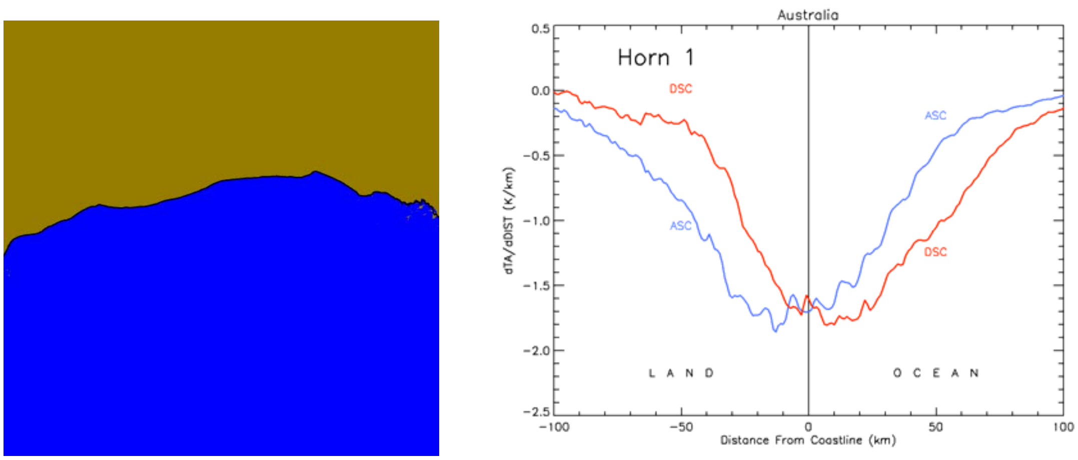

Figure 1. Initial geolocation results using The Great Australian Bight. The left panel shows the land-ocean mask and coastline. The right panel shows the derivative of antenna temperature with respect to distance from the coastline. If pointing were correct, both curves should have their minima at zero. The ascending curve (blue) is shifted onto the land, while the descending curve (red) is shifted out over water.

Our next step was to calculate Earth latitudes and longitudes for a set of perturbed pointing parameters, and determine what values were needed to minimize the observed ascending-descending T_A differences [*Aq t/c Jan 3, 2012*]. The team pointed out that even if ascending and descending observations have the same center locations, they do not see the exact the same scene because of the elliptical shape of the footprint. Thus, one must remove this expected ascending-descending T_A difference before finding a minimum [*Aq t/c Jan 10, 2012*]. Section 2 describes our methodology in detail.

At RSS, Kyle Hilburn performed one set of analysis, and at JPL, Alex Fore performed a similar but different set of analysis. Kyle found that after removing the expected T_A difference, the nadir angles for all three horns converged to the same value near 0.5°, and the azimuth angles were all small [*Aq t/c Jan 17, 2012 and Jan 24, 2012*]. Alex found similar results with two notable exceptions. Alex found a nadir angle for Horn 2 that was 0.25° smaller, and an azimuth angle for Horn 1 that was 0.50° larger. It should be noted, however, that both of these angular differences translate to only a 4 km error on the Earth – a small difference for 100 km size footprints.

The question then becomes, given the two independent estimates, how do we objectively combine these to produce a best estimate? Kyle's results suggested the pointing mis-specification could be a simple roll offset [*Aq t/c Jan 31, 2012*]. So, in order to combine their results, Kyle proposed the physical constraint that the yaw error should be as close to zero as possible, and the pitch error should be the smallest value possible [*Aq t/c Feb 10, 2012*]. These constraints produce a best estimate of **Roll = -0.51°, Pitch = 0.16°, and Yaw = 0.00°**. These are the final values that were used to correct the Aquarius pointing. Section 3 describes our constrained estimation in detail.

After the pointing was changed, we evaluated the new data and confirmed that it was implemented correctly: the total displacement between the old and new pointing is about 8 km. The effect of the new pointing is primarily to shift locations to the right relative to the along-track direction, and secondarily there is also a small displacement forward.

2. Methodology and Results

The satellite coordinate system is defined as: the x-axis points in the direction the satellite is moving, the y-axis points to the right of the x-axis, and the z-axis points down towards the Earth. The azimuth angle increases counter-clockwise from the y-axis. Pointing perturbations are relative to the pre-launch pointing values given in Table 1.

Table 1. Pre-launch boresight nadir and azimuth angles (degrees) for Aquarius.

Horn	Boresight Nadir	Boresight Azimuth
1	25.828	9.848
2	33.818	-15.291
3	40.367	6.547

To derive the new pointing values, we ran the Level 2 geolocation processing repeatedly for a set of perturbed values of boresight nadir and azimuth angle. Our final results were based on a minimization over a total of 9 x 9 = 81 perturbed values using 3 months of Aquarius data (Sep-Nov 2011). The nadir angle was varied by 0.05° over the range 0.25° to 0.65°. The azimuth angle was varied by 0.1° over the range -0.1° to 0.7°. Since a change in nadir (azimuth) angle corresponds to a change of 19 (8) km/degree, these bins correspond to a precision of 1 km on the Earth.

Then for each perturbation and each horn, we compute the T_A difference (h-pol) between ascending and descending swaths after RFI filtering. The difference is binned as a two-dimensional function of the land fraction and the angle towards land. Land fractions less than 10% or greater than 85% were excluded to avoid small islands and small inland water bodies. We used the 1/128th degree (about 1 km) Ocean Discipline Processing System (ODPS) land mask. This mask was originally based on the World Vector Shoreline, but was later updated to include inland waters based on the World Data Bank. The mask gives the land-water determination based on the location of the grid point center.

We also calculate the expected T_A difference and bin it as a function of land fraction and angle towards land. The expected T_A difference is given by:

$$T_{A,exp} = (1-L)T_{A,ocean} + LT_{A,land} \quad (1)$$

where L is the land fraction, $T_{A,ocean}$ is the average antenna temperature of the ocean (88.5 K, 82.9 K, 77.1 K) and $T_{A,land}$ is the average antenna temperature of the land (251.9 K, 248.6 K, 242.8 K) for each horn (1, 2, 3).

Next we calculate a score metric s for each perturbation and horn. The score metric is defined as the RMS difference between the observed and the expected ascending minus descending T_A difference, summing over all land fraction L and land angle ω bins:

$$s = \sqrt{\frac{1}{N}\sum_{L,\omega}\left(\left(T_{A,obs} - T_{D,obs}\right) - \left(T_{A,exp} - T_{D,exp}\right)\right)^2} \quad (2)$$

The minimum score metric gives the optimal values of nadir and azimuth angle perturbations shown in Table 2, and Figure 2 shows the score metric in two-dimensional nadir-azimuth space.

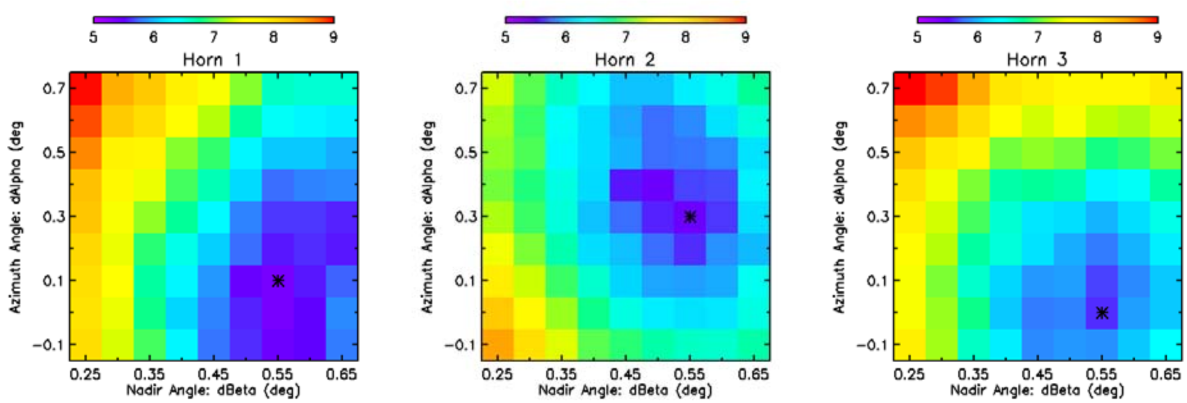

Figure 2. The score metric (units: K) plotted versus azimuth angle and nadir angle perturbations. The minimum is indicated by an asterisk (*).

Table 2. Perturbations to pre-launch nadir and azimuth angles that minimize the score metric.

Horn	Boresight Nadir	Boresight Azimuth
1	0.55	0.10
2	0.55	0.30
3	0.55	0.00

3. Constrained Estimation

The perturbations in Table 2 suggest that a simple roll offset could explain the pointing error. Figure 3A shows that a roll of -0.55° can reproduce the same Earth locations as using Kyle's nadir and azimuth perturbations. The squares in Fig. 3B show Alex's pointing results. For Horns 1 and 2, Alex finds a smaller shift to the right than Kyle. For Horns 1 and 3, Alex finds a larger shift forward than Kyle.

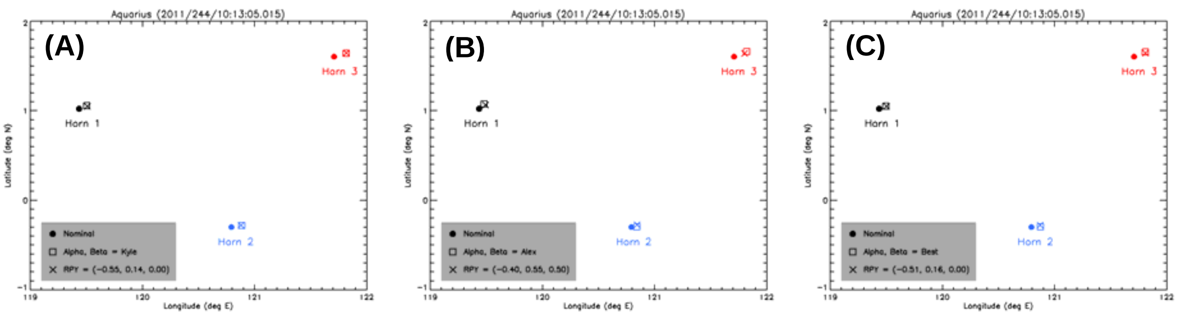

Figure 3. Examples comparing the nominal pointing (filled circles) and perturbed pointing for nadir and azimuth (open squares) and for roll, pitch, and yaw (Xs). The panels show: **(A)** Kyle's results, **(B)** Alex's results, **(C)** the combined best estimate. The colors (black, blue, red) indicate horn (1, 2, 3). This example is from the ascending segment of the orbit.

These results can be combined to produce a best estimate. We use the values found by Kyle and Alex to put bounds on the range of candidate (nadir, azimuth) pairs (Table 3). Using the same 1 km quantization for nadir and azimuth defined in Section 2, this produces a total of 1944 candidate best estimates with nadir and azimuth angles falling in the range between (or equal to) Alex's and Kyle's results. Then we calculate the (Roll, Pitch, Yaw) for each (nadir, azimuth) candidate.

Assuming that the pointing mis-specification is primarily due to a roll offset, we subset the candidates choosing those for which Abs(Pitch) < 0.20° and Abs(Yaw) < 0.05°. There are 149 candidates matching those criteria, shown by the red dots in Figure 4. Finally, we simply average the roll, pitch, and yaw over those candidates – weighing each candidate equally. This gives our best estimate of **Roll = -0.51°, Pitch = 0.16°, and Yaw = 0.00°**. Figure 3C shows Earth locations of the best estimate relative to the pre-launch pointing. For Horns 1 and 2, this splits the difference between the rightward shifts of Kyle and Alex. For Horns 1 and 3, this splits the difference between the forward shifts of Kyle and Alex.

Table 3. Range of nadir and azimuth candidates bounded by estimates from Kyle and Alex.

Horn	Boresight Nadir	Boresight Azimuth
1	0.45 - 0.55	0.10 - 0.60
2	0.30 - 0.55	0.10 - 0.30
3	0.55 - 0.60	0.00 - 0.20

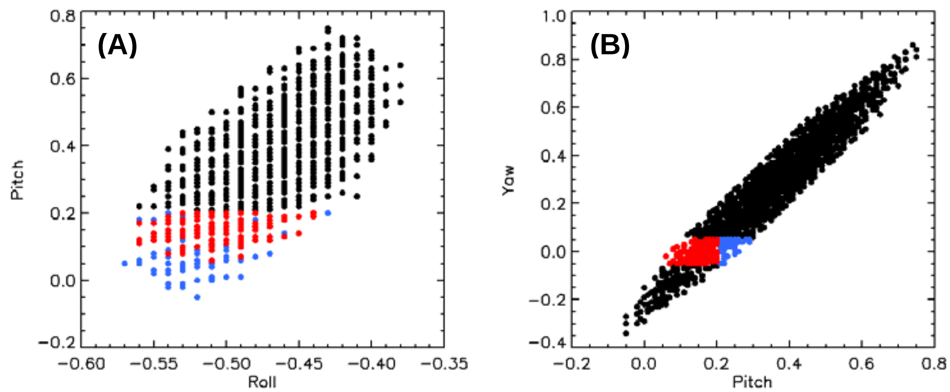

Figure 4. The scatterplots show the range of candidates from Table 3. The panels show the candidates in: **(A)** roll-pitch space and **(B)** pitch-yaw space. Candidates having Abs(Pitch) < 0.20° are shown in blue in panel (A) and candidates having Abs(Yaw) < 0.05° are shown in blue in panel (B). In both panels, the red points are those candidates satisfying both conditions.

4. Conclusions

Adam Freedman estimates the worse-case pointing error is expected to be less than 0.2° [*Summary of Aquarius Instrument Pointing Discussion, Feb 1, 2012*]. If the instrument unit is mis-pointed, then all beams will be mis-pointed equally. If the reflector is misaligned relative to the feeds, there will be small differences in pointing between the beams. The boom deployed reflector position could not be precisely measured.

The pointing error estimates described in this report were made by minimizing ascending minus descending T_A differences near land-ocean transitions. Kyle and Alex obtained values agreeing within 4 km for the worst case agreement. Kyle found an average boresight nadir offset of 0.55°, and Alex found an average nadir offset of 0.45°. Both estimates are double the expected worst-case pointing error. Additional research would be needed to understand why these estimates exceed the expected error.