Estimation of Satellite Attitude for SSM/I and SSMIS Geolocation

CSU Technical Report

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http://rain.atmos.colostate.edu/FCDR/

TABLE of CONTENTS

LIST of FIGURES

LIST of TABLES

ACRONYMS AND ABBREVIATIONS

Acronym or Abbreviation	**Meaning**
CATBD	Climate Algorithm Theoretical Basis Document
CDR	Climate Data Record
NCDC	National Climatic Data Center
NOAA	National Oceanic and Atmospheres Administration
TA	Antenna Temperature
TB	Brightness Temperature

1. Introduction

Estimates of satellite attitude are a key input for the geolocation code for the FCDR that are required to ensure that the boresight direction is correctly characterized. Satellite attitude is likely to have a relatively small effect on the pixel latitude/longitude; however, the implications for the Earth Incidence Angle (EIA) are far larger since small changes in EIA can lead to discontinuities in the calibration that could have an important impact in climate datasets. In particular, an accurate EIA is required for intercalibration as well as for use in retrievals of geophysical data.

Satellite attitude is usually split into three components: roll, pitch and yaw. The definitions of roll, pitch and yaw used here are taken from the geolocation ATBD. For convention, a positive pitch is in the “nose-up” direction, positive roll is in the “bank-left” direction and positive yaw is to the right, with the z-axis pointed towards the Earth as shown in Figure 1. Sensor alignment also controls the boresight direction and is usually characterized in three dimensions using the same conventions used for satellite attitude. Two other parameters can also affect the boresight direction: the elevation offset and the scan angle offset. The elevation offset is the mount angle error that is added to the nominal mount angle (45° for SSM/I and SSMIS), which was measured in the lab. The scan angle offset essentially measures the error in the alignment of each beam position and is not measured.

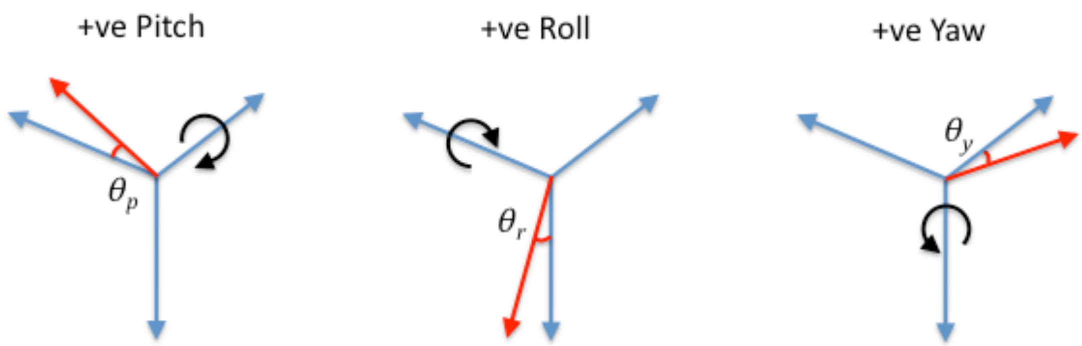

Figure 1. Directions of positive pitch, roll and yaw used in SSM/I and SSMIS FCDR geolocation code.

The geolocation code for the SSM/I and SSMIS FCDR requires values for satellite attitude, sensor alignment, elevation offset and scan angle offset. Elevation angle is known for all satellites and so the published values are used. No information is known about the scan angle offset and so this is simply set to zero. Sensor alignment cannot be disentangled from satellite attitude since they can cancel each other out. For SSM/I, the sensor alignment is set to zero and the satellite attitude is allowed to vary in order to correctly locate the boresight. SSMIS differs from SSM/I in that it uses six different feedhorns that should have a common satellite attitude but different sensor alignment offsets. Therefore, the sensor alignment is used for SSMIS to account for differences between the feedhorns.

This document describes the estimation technique used to derive satellite attitude and sensor alignment for SSM/I and SSMIS. The goal of the estimation procedure was to produce time varying estimates of attitude that can account for slowly-varying changes that should be represented in the EIA. The cause of such changes is not known or speculated upon due to insufficient information and we acknowledge that such changes could be due to factors other than genuine attitude changes. In fact, the SSM/I attitude was supposed to be controlled to within 0.1° (Hollinger et al., 1990), so changes greater than this magnitude should be scrutinized. It is expected that the error in SSM/I might exceed 0.1° as the end of life of the satellite approached and such changes need to be characterized. Another important source of errors for the estimate of attitude for SSM/I and SSMIS is timing errors. Errors in the time can affect the pitch and the yaw, but cannot affect the roll. Pitch errors due to timing are likely to be small because they are caused by along-track errors: it takes 1.899s for the SSM/I and SSMIS to cover ~15km of ground track, so a 1km error would require a ~.13s error in timing. Yaw is actually far more sensitive to timing errors, since very small errors can lead to large discrepancies in the reported and actual beam position: the time between pixels in a scan is 4.22 msecs. The technique described essentially compounds all of these effects into the satellite attitude, but it is expected that the roll estimate will be the most robust and the yaw estimate might be quite variable (due to timing changes). This would be consistent with the other studies of the geolocation errors for SSM/I (Colton and Poe, 1999) and SSMIS (Poe et al., 2008).

2. Estimation of Roll

One of the major issues for the estimation of satellite attitude is the high level of dependence between roll and yaw. For polar orbiting satellites aligned in a North-South direction, changes in roll and pitch both affect the geolocation by shifting the pixel geolocation in the East-West direction. A common technique used for the estimation of satellite attitude is to use the position of land masses to estimate offsets required to make the TBs line up with the land. In this methodology, a roll error can be offset by a yaw error and so simultaneous derivation of roll and yaw will be inaccurate. An independent technique was thus sought to estimate roll, since it is expected to vary the least. Once the roll is derived a second step is performed to estimate pitch and yaw using an analysis of the coastlines.

The roll was estimated from the shape of the across scan track mean TBs. This technique exploits the fact that pitch and roll each have a very distinct effect on the TBs: pitch causes curvature across the scan and roll causes a straight-line gradient across the scan. Yaw does not have an effect on the across scan TBs for conical scanners. The across scan mean TB was obtained by running the stewardship code on a basefile with only the TA to TB conversion, quality control and the SSMIS correction modules turned on. The modules for the scan non-uniformity correction, intercalibration and geolocation were all switched off. The scan non-uniformity correction was the most important module to switch off, since that would correct across the scan for the roll effect amongst other things.

The TBs were aggregated by scan position and channel for each month and stored along with the number of observations aggregated. 11 months of aggregated TBs were then further aggregated and used to calculate the mean 11-month TB as a function of scan position and channel for each satellite. 11-months was chosen to remove any potential effect of the annual cycle. Shorter-term variations are not expected to exist for SSMI or SSMIS. Simple linear regression of the mean across scan TB against scan position was applied to the middle 50% of pixels to obtain the slope of TBs as d(TB)/d(Beam Position).

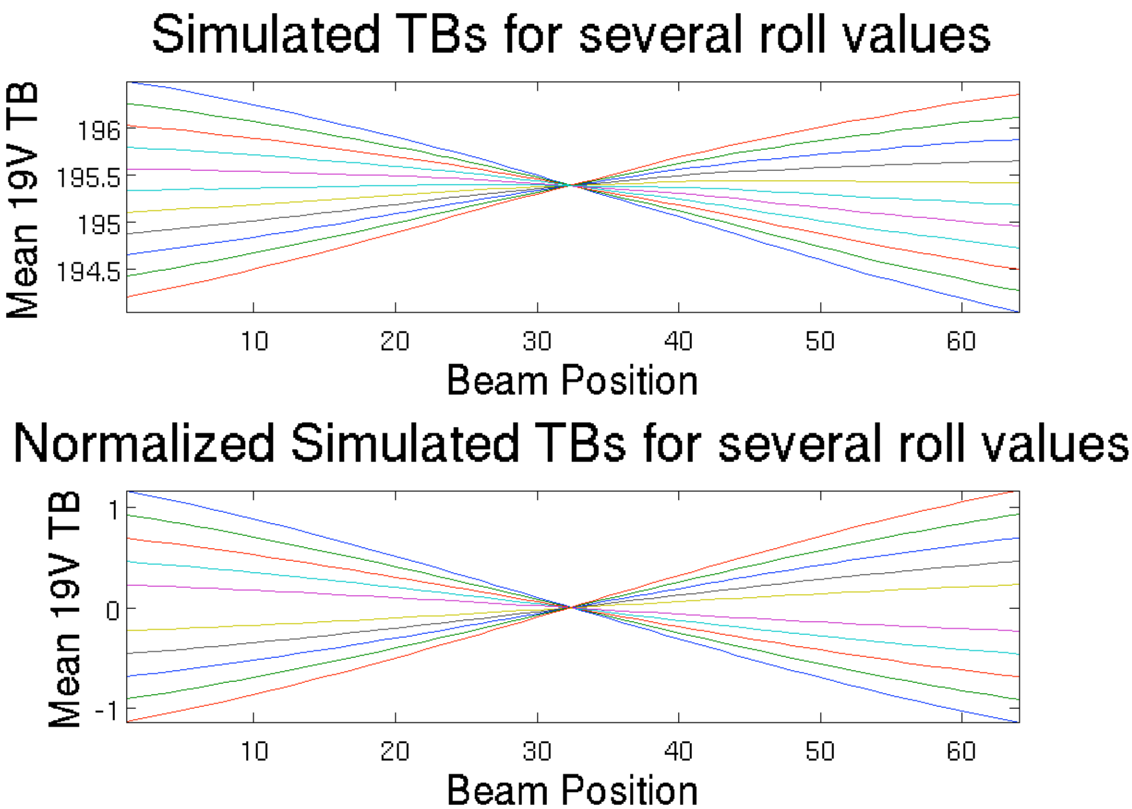

Figure 2. (a) Mean across scan TB patterns for several values of roll and (b) mean TBs for non-zero roll values normalized by mean TBs for the zero roll values. Elevation offset, pitch and yaw were set to zero.

Simulations were used to estimate the relationship between TB and beam position: d(TB)/d(Beam Position). In order to ensure realistic sampling qualities, TBs were simulated for 12 months of SSM/I data from F13 (2004). Unsurprisingly, it was found that a single month was sufficient to obtain stable estimates, but 12 months were still used for the final version. Profile data from six-hourly, 1° (29 vertical levels) resolution ECMWF ERA-Interim were used as input to a radiative transfer model (Elsaesser and Kummerow, **????**) and TBs were simulated for values of roll ranging from -0.5° to 0.5° in 0.1° increments with elevation offset, pitch and yaw set to zero. Figure 2a shows the pattern for each value of roll across the scan for the 12-month averaging period. The simulated mean TBs for zero roll were subtracted from the non-zero roll simulations in order to further reduce the effect of sampling. Figure 2b shows the normalized values, which are extremely close to straight lines

As with the actual TB data, linear regression was used to calculate d(TB)/d(Beam Position) for the 10 normalized non-zero values of roll for each channel and satellite. The slope for each of these values was found to be nearly identical, indicating that this is indeed a robust estimation method. Linear regression was again used to calculate the effect of a unit change in roll on d(TB)/d(Beam Position) which is d(Roll)/[d(TB)/d(Beam Position)]. Table 1 shows the slope for each channel for SSM/I and SSMIS that was used to estimate the roll given an estimate of d(TB)/d(Beam Position). The effect of a roll on the horizontal polarizations is generally very small and this is reflected in the large values in Table 1 for those channels. In contrast, the effect of a unit change in roll on the 19V and 37V channels is ~13-14° per d(TB)/d(Beam Position). That value is double for the 85V channel since there are twice as many beam positions for that channel (hence it is very similar to the 19v for SSM/I). The value for the 22V (water vapor) channel is a little larger, which probably reflects errors in the profile data related to the characterization of water vapor that have a larger effect on the 22V channel. The SSMIS values are consistent with those from SSM/I, but with opposite sign since SSMIS scans in the opposite direction to SSM/I. [the SSM/I mounted on F08 was mounted in the opposite direction, so this should change the effect on roll (pitch and yaw are properly accounted for in the geolocation code)]

Channel	**19V**	**19H**	**22V**	**37V**	**37H**	**85V/91V**	**85H/91H**
SSM/I	12.96	-97.89	15.72	14.23	-174.78	26.16	92.25
SSMIS	-14.06	108.66	-17.12	-15.49	198.66	-31.07	-123.83

Table 1. Effect of a unit change in roll on d(TB)/d(Beam Position) by channel for SSM/I and SSMIS. These values were derived from simulated data matched o the F13 2004 sampling.

The roll estimates were made by simply multiplying the estimated d(TB)/d(Beam Position) for each 11-month period by the unit change of a roll. Figure 3 shows the time series of each of these roll estimates for each satellite separately for the 19V, 22V, 37V and 85V channels for the SSM/I. In general, variations are very small with each satellite showing variations below the expected 0.1° level of accuracy, although several satellites have roll values slightly high than 0.1°. As expected, the 22V channel shows slightly higher sensitivity than the other channels. Additionally, the estimate for F15 sharply decreases in the 22V estimate due to the effects of the RADCAL beacon interference known to affect this channel. The 85V channel has some problems for the estimation of the F08 satellite after mid-1989 due to the failure of this channel. Since the 85V and 22V cannot provide complete coverage in time and because of the issues with the sensitivity of the 22V estimate, it was decided to exclude these channels for the analysis in order to ensure consistency amongst satellites. The estimates of roll from the 19V and 37V channels were therefore averaged together and smoothed using a smoothing spline.

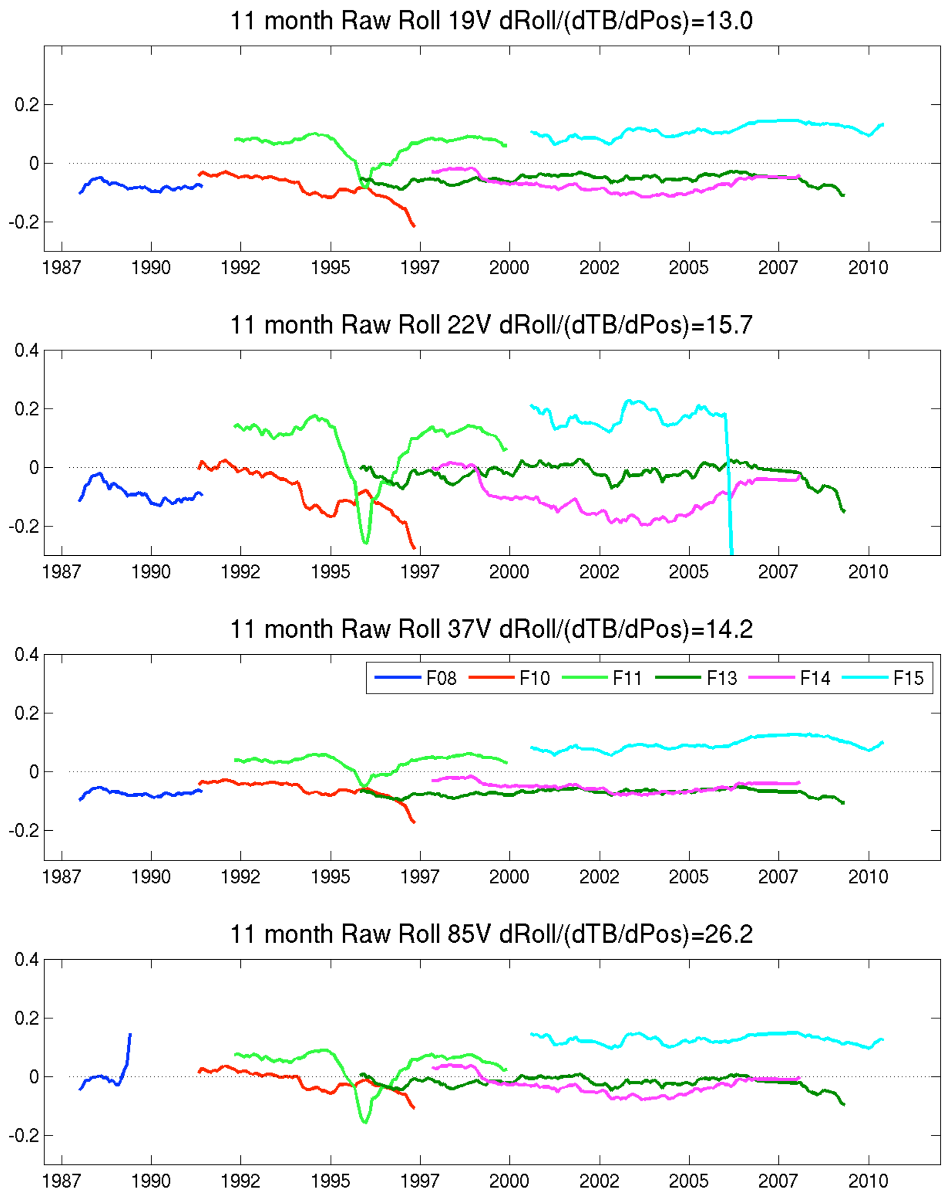

Figure 3. Unsmoothed estimates of 11-month roll for the 19V, 22V, 37V and 85V channels for all SSM/I satellites.

One potential anomaly in the estimates of roll is in the estimates F11 around 1996. There is a small dip in the estimate of roll in all channels that is surprising given the control specifications of the SSM/I. Figure 4 shows time series of the monthly mean TBs by scan position for all channels of F11. The anomaly in 1996 is clearly visible at time position 40 and is present in all channels, including the horizontally polarized channels. If this anomaly was caused by a spacecraft roll it would have to be far larger in the vertically polarized channels than in the horizontally polarized channels. Therefore, it is highly unlikely that the cause of this anomaly is spacecraft roll and so the roll during this period is not trustworthy. The values for this period were removed for the analysis and filled by a smoothing spline based on the rest of the data.

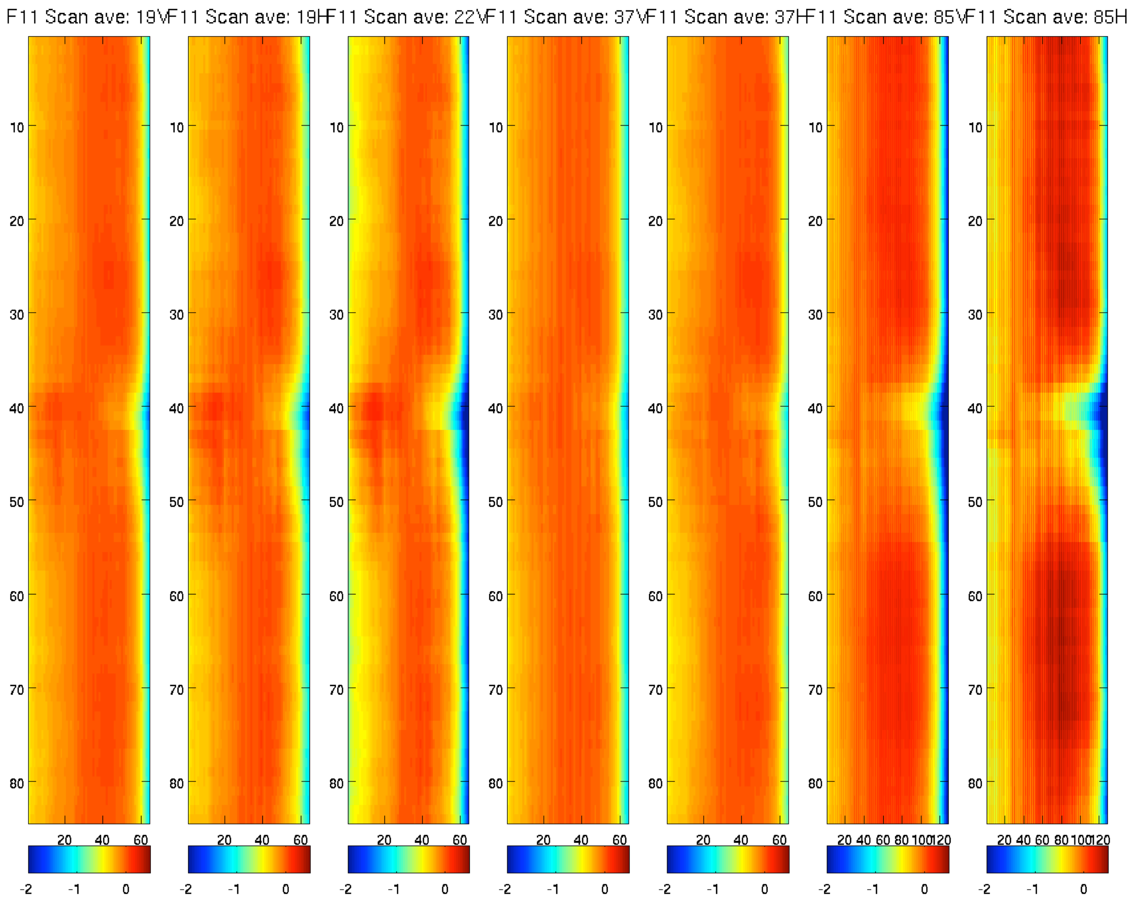

Figure 4. Plots of mean TB for each channel of F11 by scan position (x-axis) and time (y-axis). The colorbar represents the monthly mean TB value.

3. Estimation of Pitch and Yaw

As already mentioned, coastline analysis is a commonly used approach for estimating satellite attitude. Our approach relies on the minimization of the root mean square difference (RMSD) of the ascending and descending passes of the satellite around the coasts. The technique can be applied to the TBs for any channel, although the greatest accuracy for SSM/I is found when applied to the 85H channel since the 85GHz channels have twice the resolution of the other frequencies and the horizontal polarizations have better land-ocean contrast (i.e. larger dynamic range). For SSMIS, the procedure is applied to each of the horizontally polarized channels since they have different feedhorns that require different estimates of sensor alignment. The ascending and descending TBs are separately gridded to a 1/20th degree grid based on the location of the center of the gridboxes as calculated from the geolocation code. The difference of the ascending and descending grids is then calculated for the 2° zone surrounding the coastline of a chosen land mass and the RMSD of the ascending and descending grids is calculated. The land mass used must be sufficiently large to ensure that grossly wrong attitude estimates still give overlapping land in the ascending and descending passes, but small enough to avoid the need for large amounts of data. This discounts small islands and large continents. In addition to the size requirement, it is preferable to have a land-mass with relatively straight sides that are oriented with lines of latitude and longitude. For these reasons the analysis has been conducted for Japan and Spain, although Australia is the preferred target.

The process described gives a mechanism for the calculation of the relative error of geolocation associated with a given roll, pitch and yaw combination. This technique can then be used to estimate the optimal roll, pitch, yaw combination that minimizes the RMSD. This optimization uses a special implementation of the geolocation code that runs as compiled C code in Matlab. The optimization routine requires initial value estimates of the pitch and yaw that were obtained through an initial run of the ascending minus descending code over three months of files to obtain a coarse resolution estimate of the RMSD for roll, pitch combinations between -1° and 1° in 0.2° increments. This was then smoothed using a two-dimensional smoother and the minimum was visually read from a plot of the smoothed data. The pitch and yaw associated with the minimum RMSD were then used as initial values. Monthly estimates of pitch and yaw were obtained by using a similar technique, but with the ascending minus descending grids based on a running 11-month sample of files centered on the current month. 11-months was used to eliminate almost all of the annual cycle in weather that can produce a small variation (~.02°) in pitch and yaw estimates. Ascending minus descending grids for 11-months of data were constructed based on the geolocation calculated from a five-by-five grid of pitch and yaw combinations centered on the initial value. For each 11-month average, this gave a five-by-five grid of RMSD that should be approximately centered on the minimum RMSD. Multiple linear regression was used to estimate the parameters based on the equation

$$\mathrm{RMSD} = \beta_0 + \beta_1 p + \beta_2 y + \beta_3 p \times y + \beta_4 p^2 + \beta_5 y^2 \tag{1}$$

where *p* is pitch and *y* is yaw. The parameters of (1) are then used to estimate the roll and yaw at the minimum using

$$\begin{aligned} \hat{p} &= \frac{-2\beta_2\beta_4 + \beta_1\beta_3}{4\beta_4\beta_5 - \beta_3^2} \\ \hat{y} &= \frac{-2\beta_1\beta_5 + \beta_2\beta_3}{4\beta_4\beta_5 - \beta_3^2} \end{aligned} \tag{2}$$

It was found that the RMSD as a function of pitch and yaw was symmetric and so a simple two-dimensional parabola provided an adequate fit and was able to give an accurate estimate of the minimum RMSD.

Once the 11-month estimates of pitch and yaw have been obtained for each moth, smoothing was applied to remove any additional variability. A smoothing spline was used to smooth roll, pitch and yaw for use in the FCDR code. Finally, the estimates were simply duplicated forward or back in time to fill any gaps or to extend to the beginning or end of the satellite records. This copying assumes that the most recent value is the most accurate. Extrapolation of the smoothing spline was an alternative to simply copying the nearest value, but it was found that this lead to erroneous values.

4. Final estimates of Satellite attitude for SSM/I

The coastline analysis was applied to SSM/I as described above using the 85H channel where available. The 85H was not available for F08 after 1990, so the 37H channel was used instead. In this case, a bias correction was applied to pitch and yaw estimates derived from the 37H based on overlap with the 85H to ensure consistency with the rest of the record. The pitch and yaw for F08 derived from 85H and 37H are shown in Figure 5. The offsets added to the 37H pitch and yaw estimates were 0.067 and -0.036 respectively.

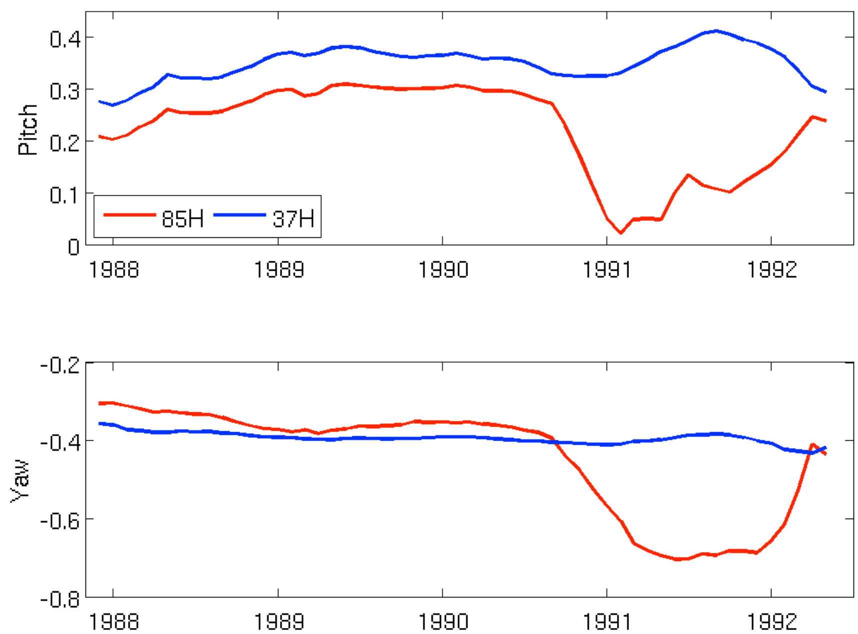

Figure 5. Comparison of pitch and yaw for F08 derived from 85H and 37H channels.

Figure 6 shows the final estimates of roll pitch and yaw for SSM/I F08 to F15 after smoothing, with the 37H estimates used for F08 after August 1990. Values of roll are generally within 0.1° apart from F10 and F15 towards the end of their lives, where values are slightly higher than 0.1°. Pitch variations are within the range of -0.1° and 0.5°, whilst yaw values can be relatively large with a range of -0.7° and 0.4°.

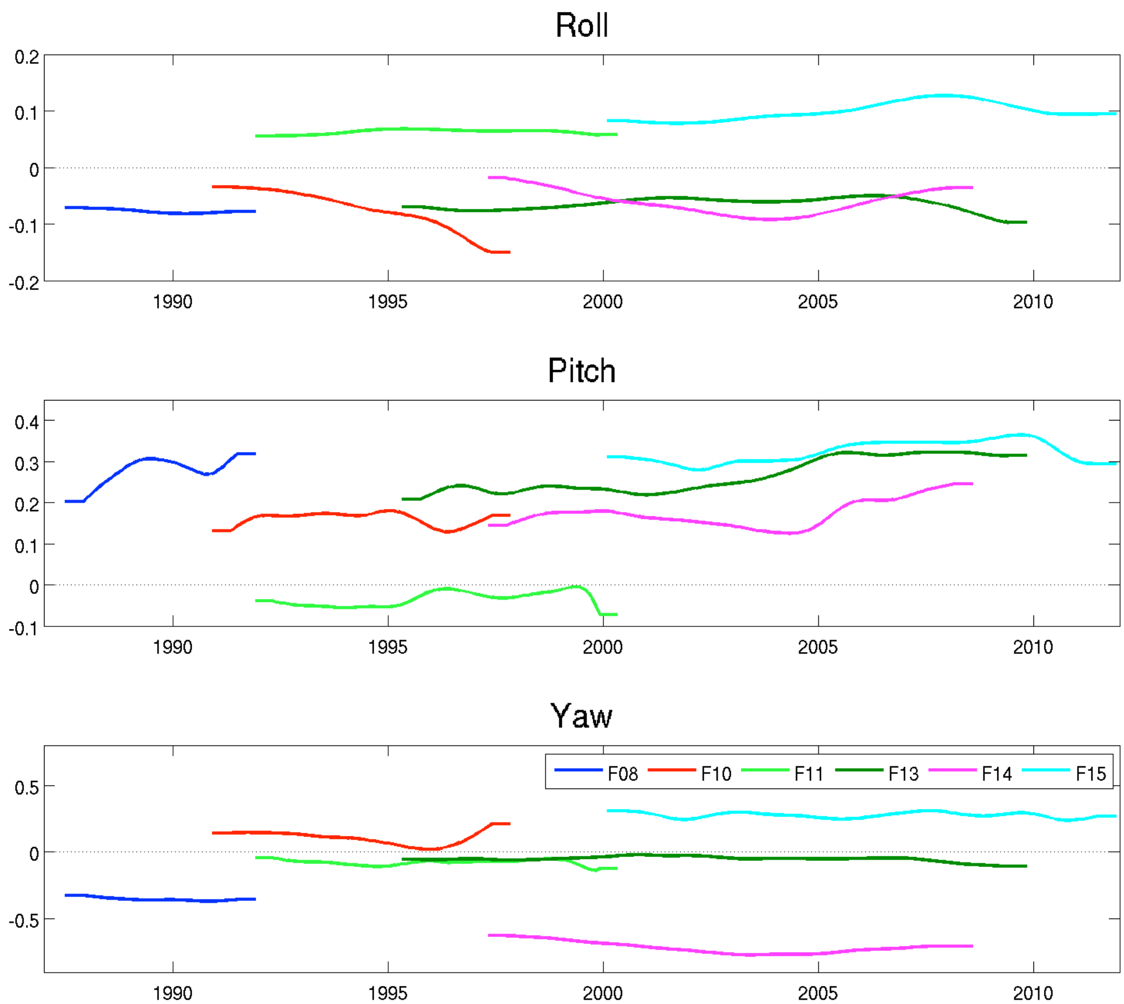

Figure 6. Satellite attitude estimates for SSM/I.

Figure 7 shows the raw roll as well as the raw pitch and yaw for five different running mean periods. The pitch and yaw were calculated using the 11-month running mean of roll so as to not alias errors in the roll with those of the yaw, since these are independent techniques. There is an annual cycle effect in both the roll and the pitch and yaw, although they are not in phase. The annual cycle in the roll must reflect slight variations across the scan that change the gradient of the mean across the scan. The annual cycle in pitch and yaw is more likely due to the effects of weather on sampling around the coastline of Australia. The magnitude of the annual cycle in the roll is larger than in the pitch and yaw with values of ~0.1° and ~0.05° respectively. In each case, the longer averaging period removes the annual cycle effect, which is presumed to be an artifact of the technique (ie: sampling issues) rather than a real signal.

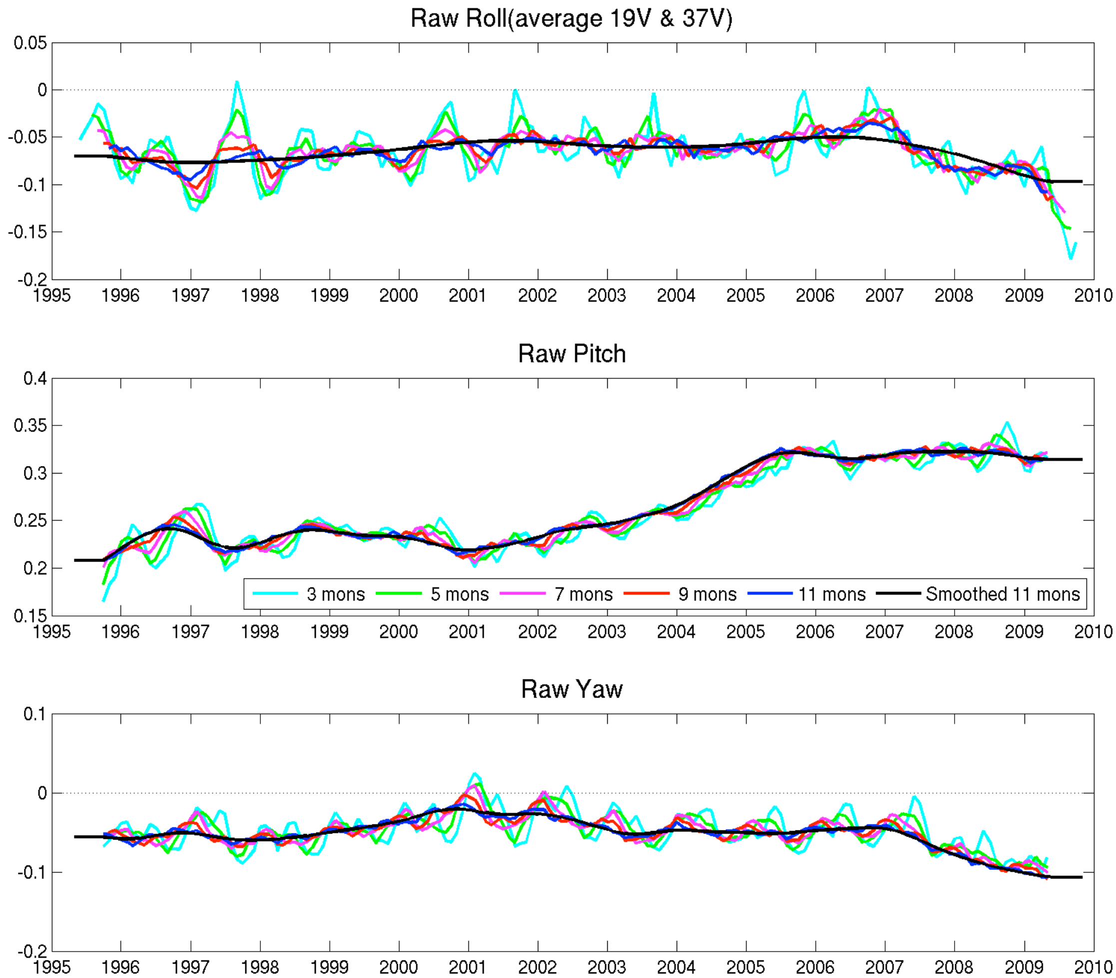

Figure 7. Attitude estimates for F13 derived from the 85H channel at 1/20° resolution for different averaging periods. The pitch and yaw estimates were derived using the standard 11-month smoothed estimate of the roll. The black lines represents the final smoothed values of roll, pitch and yaw.

Figure 8 shows the pitch and yaw estimates derived from the coastline analysis applied to each of the channels at 1/20° resolution as well as at 1/10° resolution for the 85H channel for F13. There is very good agreement between each of the channels with a spread of around 0.03°. The anticipated accuracy of the technique was 0.05°, so this is within the expected error. Fig. 8 gives confidence that the results from the different channels are indeed consistent. The 85H is still preferred for the analysis since the 85GHz channels have higher sampling and the land-ocean contrast in TBs is larger in the horizontal polarization. We therefore expect that the accuracy of the technique would be maximized by using 85H.

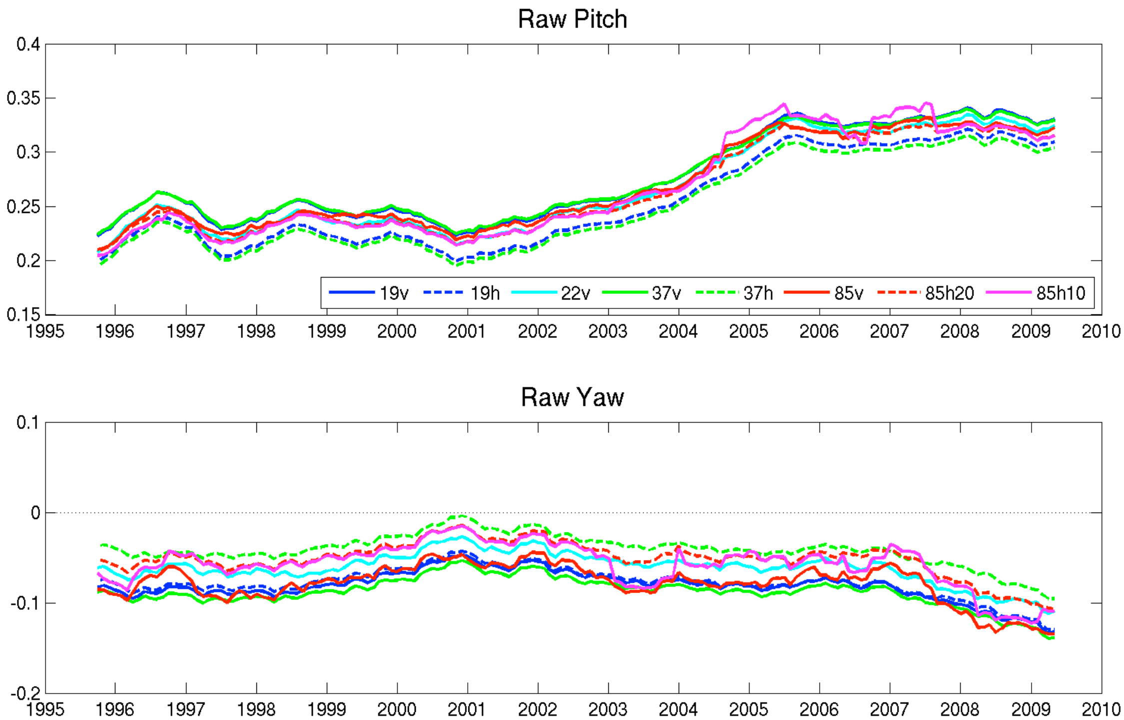

Figure 8. Pitch and yaw estimates for F13 derived from each of the seven channels at 1/20° resolution as well as from the 85h at 1/10° resolution. The estimates were derived using the standard 11-month smoothed estimate of the roll.

Figure 9 shows the pitch and yaw derived from the coastline analysis technique applied over Australia, Japan and Spain. Australia has been used for the main analysis since the Australian coasts are relatively straight and have good north-south, east-west orientation. In addition, Australia is a large land mass so that problems with completely misaligned land masses do not occur. Two other targets that were considered for this analysis were Japan and Spain, both of which have similar properties to Australia but in geographically diverse places: both are in the northern hemisphere, one is around the same longitude as Australia, the other is roughly on the other side of the world. The coastline analysis was run using these two targets to estimate the effect of the coastline on the results but using the same roll estimate base on the analysis over Australia. Differences between the pitch and yaw based on these three regions are around the 0.05° accuracy that was expected. The analysis made use of a 1/20° resolution grid which was arbitrarily placed over the coastline. Since the actual coastlines match up slightly differently with the grid, spatial sampling errors approaching the size of the grid are expected (this was actually the rationale for projecting an accuracy of 0.05°, ie.. 1/20°).

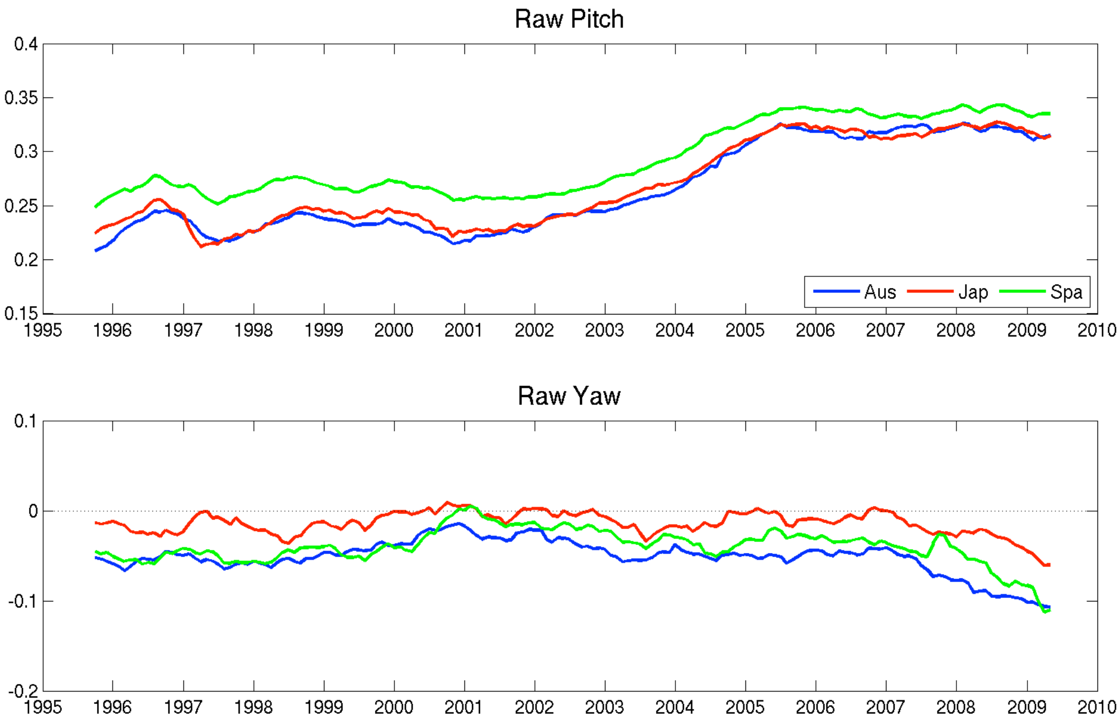

Figure 9. Pitch and yaw estimates for F13 derived from the 85H channel based on the coastlines around Australia, Spain and Japan at 1/20° resolution. The estimates were derived using the standard 11-month smoothed estimate of the roll.

5. Final estimates of Satellite attitude for SSMIS

The same technique was applied to SSMIS in order to determine the roll, pitch and yaw for F16, F17 and F18. SSMIS differs from SSM/I in that it has six feedhorns that can each have distinct alignment errors. There are separate feedhorns for the 19/22GHz, 37GHz, 91GHz, 150/183GHz, upper air and lower air sounding channels. The FCDR focused on the 19, 22, 37 and 91 GHz channels and so estimating the attitude associated with these channels was a priority. Additionally, the coastline technique was designed to work for these SSM/I like channels and it remain untested as to whether the technique works for sounder channels that see less of the surface. Tests showed that the technique converged reasonably well for all channels except the upper air channels that never see the surface, and so results were calculated for all but the upper air channels. A single channel (preferably a horizontally polarized channel) was used for each feedhorn: 19H, 37H 91H, 150±1.25 and 50.3H.

The geolocation code for SSMIS requires time varying satellite roll, pitch and yaw estimates and then static sensor alignment offsets for each feedhorn. This design assumes that the alignment of the feedhorns does not change so that any changes in time between the estimates for each feedhorn should match. Since the focus was on the SSM/I channels, the time varying roll/pitch and yaw estimates from the three feedhorns that serve those frequencies were used to estimate the satellite attitude. A simple offset was then calculated for all feedhorns (aside from the upper air sounding channels feedhorn) as the difference between the time mean of the satellite attitude and the time mean of the estimate for each feedhorn. Results for F16, F17 and F18 are shown in figures 10, 11 and 12 respectively. The black line represents the satellite attitude estimate used by the FCDR code, while the other three lines show the estimates from the 19H, 37H and 91H channels that were averaged to obtain the black line. The legend contains the static alignment offsets for each of the five fitted feedhorns.

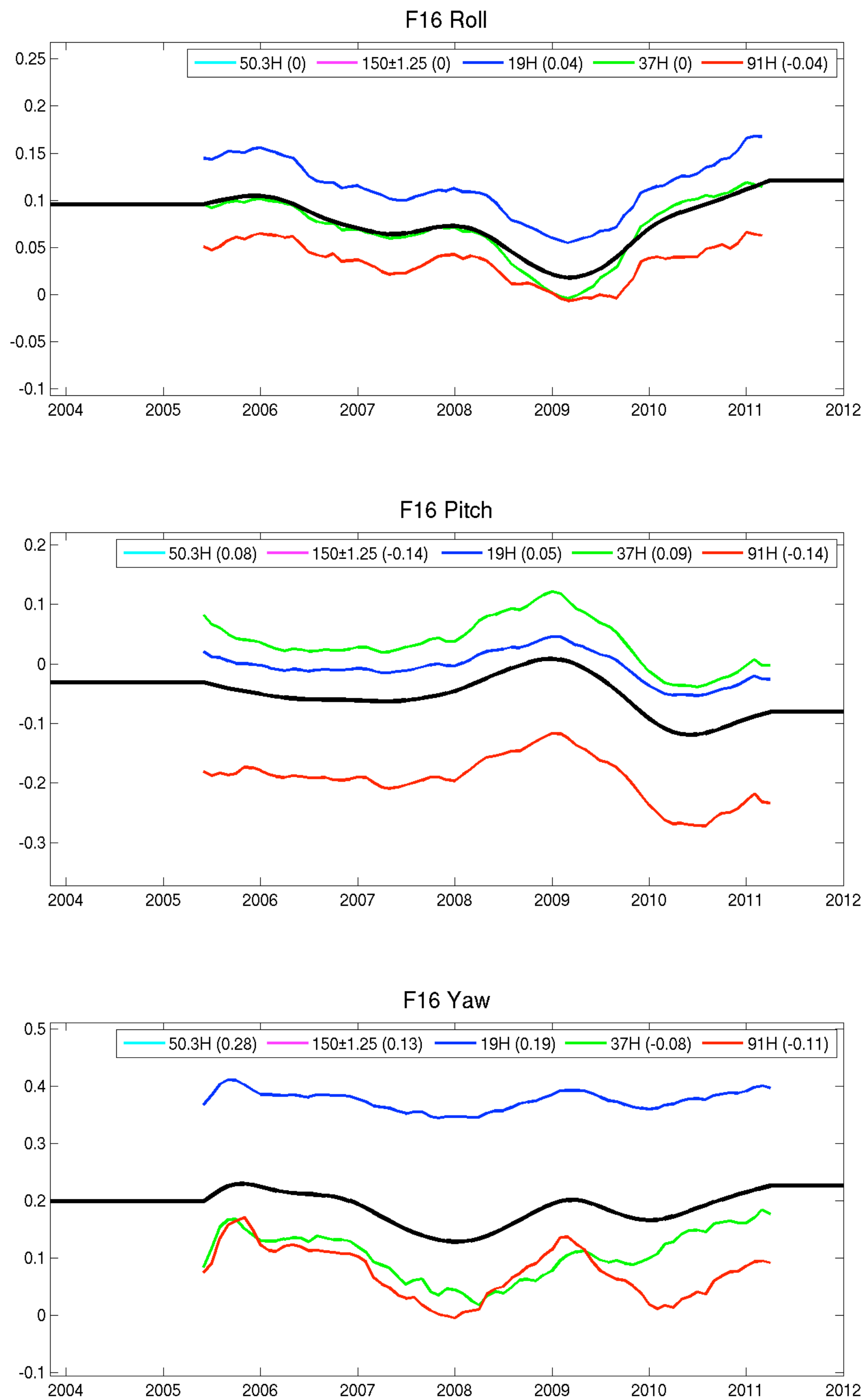

Figure 10. Roll, pitch and yaw for F16. Satellite attitude values (black line) are estimated as the average from the values for 19H, 37H and 91H. The legend gives sensor alignment offsets for all five feedhorns estimated using this technique. No estimate was made for the upper air sounding feedhorn.

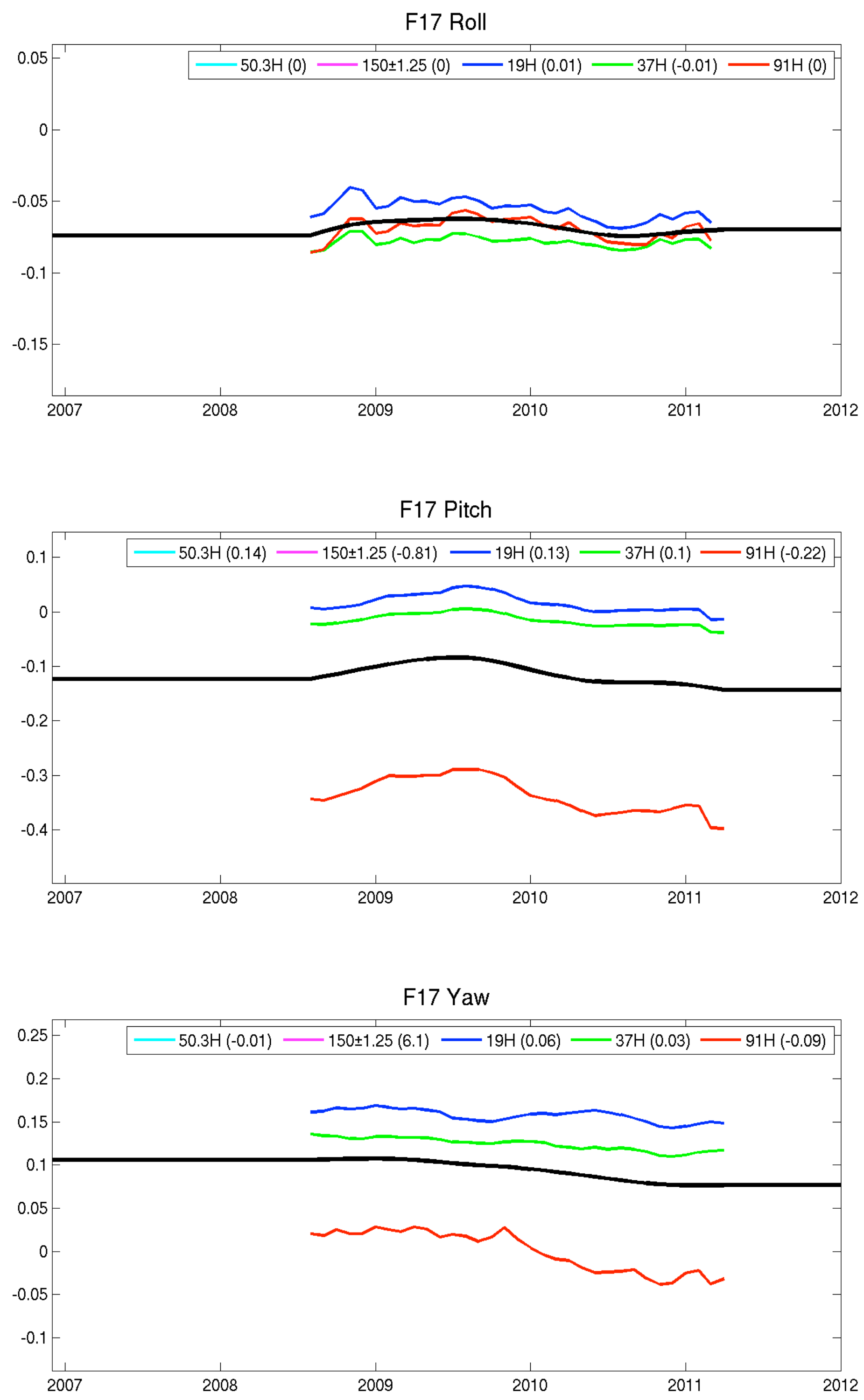

Figure 11. Roll, pitch and yaw for F17. Satellite attitude values (black line) are estimated as the average from the values for 19H, 37H and 91H. The legend gives sensor alignment offsets for all five feedhorns estimated using this technique. No estimate was made for the upper air sounding feedhorn.

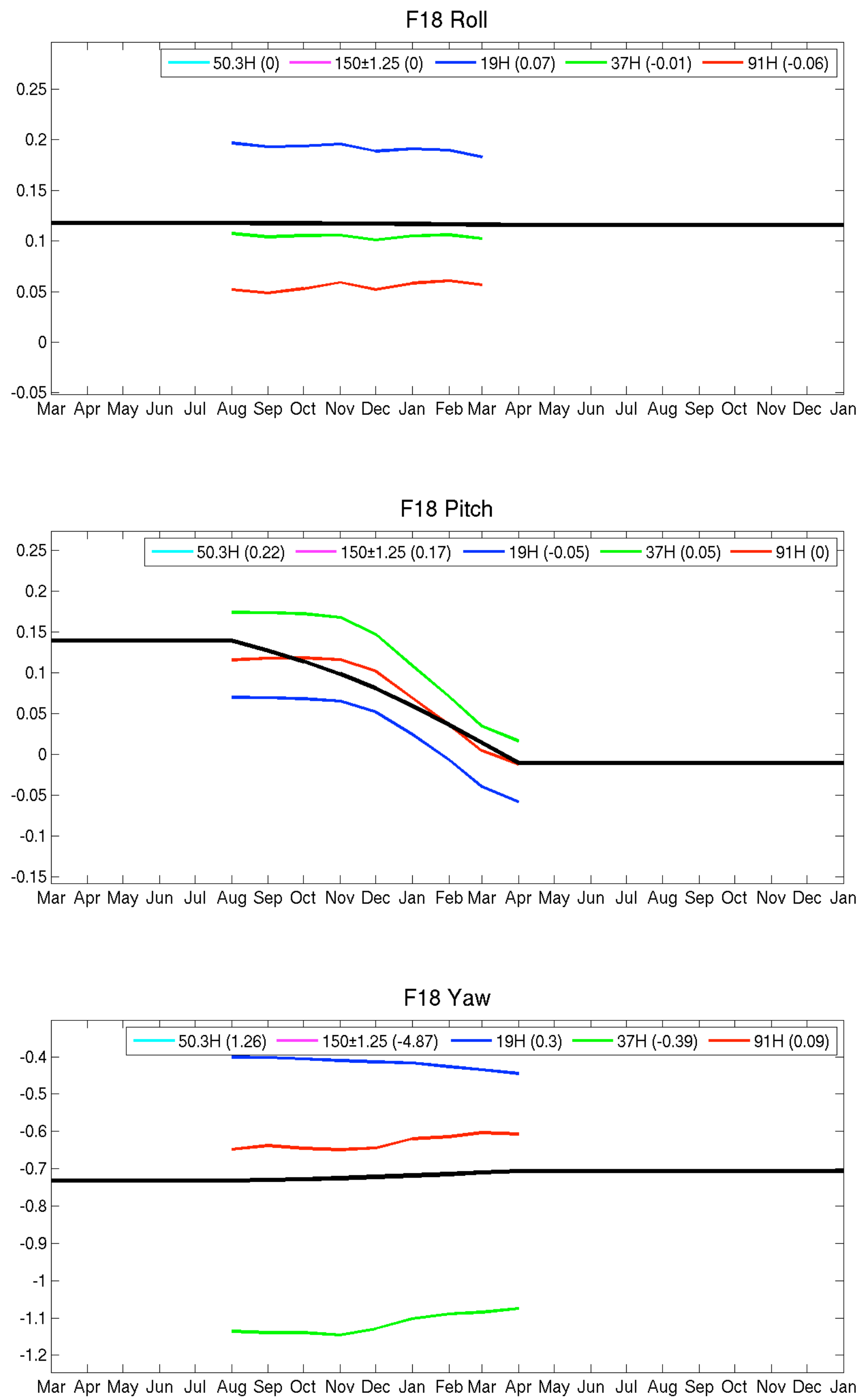

Figure 12. Roll, pitch and yaw for F18. Satellite attitude values (black line) are estimated as the average from the values for 19H, 37H and 91H. The legend gives sensor alignment offsets for all five feedhorns estimated using this technique. No estimate was made for the upper air sounding feedhorn.

6. References

Colton, M. C. and Poe, G. A. (1999), Intersensor calibration of DMSP SSM/I's: F-8 to F-14, 1987-1997, IEEE Transactions on Geoscience and Remote Sensing 37(1), 418–439.

Hollinger, J. P., Peirce, J. L. and Poe, G. A. (1990), SSM/I Instrument Evaluation, IEEE Transactions on Geoscience and Remote Sensing 28(5), 781–790.

Poe, G. A., Uliana, E. A., Gardiner, B. A., vonRentzell, T. E. and Kunkee, D. B. (2008), Geolocation Error Analysis of the Special Sensor Microwave Imager/Sounder, IEEE Transactions on Geoscience and Remote Sensing 46(4), 913-922.