Improving our understanding of the Spitzer Space Telescope's pointing drifts

Carl J. Grillmair[a], Sean J. Carey[a], John R. Stauffer[a], James G. Ingalls[a]

[a]Spitzer Science Center, California Institute of Technology, Mail Stop 220-6, 1200 E. California Blvd., Pasadena, CA, USA 91125,

ABSTRACT

Spitzer observations of exoplanets routinely yield photometric accuracies of better than one part in 10,000. However, the attainable precision is limited in part by pointing drifts, which have the effect of moving the target to less stable or less-well characterized regions of Spitzer's IRAC detector arrays. Here we examine a large sample of observing sequences in an effort to identify the causes of these pointing drifts. We find that short term and higher order drifts are correlated on various time scales to the temperatures of components in and around the spacecraft bus, and are most likely due to very slight angular displacements of the star trackers. Despite the constraints imposed by a limited pool of targets, such pointing drifts are best mitigated by optimal scheduling, minimizing large and/or lengthy excursions in telescope pitch angle within 24 hours of a high-precision photometry sequence. Such an effort is currently being initiated by the Spitzer Science Center.

Keywords: Spitzer Space Telescope, Exoplanets

1. INTRODUCTION

Putting scientifically useful limits on the atmospheric characteristics of brown dwarfs and transiting exoplanets requires high precision photometry over extended periods of time, ranging from several hours to several days. The Spitzer Space Telescope has made enormous contributions in this area by virtue of its Earth-trailing orbit and exceptionally stable thermal environment. The spacecraft pointing system has greatly exceeded its design requirements, and Spitzer observations with the Infrared Array Camera (IRAC) typically reach to within < 50% of the photon-noise limit. Precisions of 100 ppm are routinely reached, and 30-60 ppm have recently been achieved[1,2]. Over 25% of the allocated observing time in recent observing cycles has been devoted to science requiring very high precision relative photometry (either exoplanet validation and characterization or investigations of cloud cover and weather for brown dwarfs).

Yet this very precision has revealed a number of small amplitude pointing wobbles, drifts, and jitter[3], some of which are illustrated in Figure 1. While it is both possible and effective to correct for these effects using a "pixel phase map"[4], which maps the response of the array near the "sweet spot" at very high, sub-pixel resolution, such a map is subject to unavoidable measurement errors. Moreover, observations of a variety of sources show that there are significant non-linearities at play: e.g., the relative sensitivities depend not only on the sub-pixel position of the source, but also on the number of photons collected. Linearity corrections are in development, but given the finite amount of calibration time available, they will necessarily also be subject to uncertainties. Achieving the best possible photometric precision would therefore nominally require that target images be placed accurately on the detector, and that subsequent movement of the image be minimized.

2. LONG TERM –Y-PIXEL DRIFT

The most obvious single effect in Figure 1 is a relatively large, nearly linear drift in the –y-pixel direction. This drift is believed to be due to a difference in the way that differential velocity aberration corrections are handled by the spacecraft's Command and Data Handling computer (C&DH) and by the star trackers. Velocity aberration causes targets to appear up to 20 arcsec away from their true positions on the sky, depending on the angle between the sight line to the star and Spitzer's
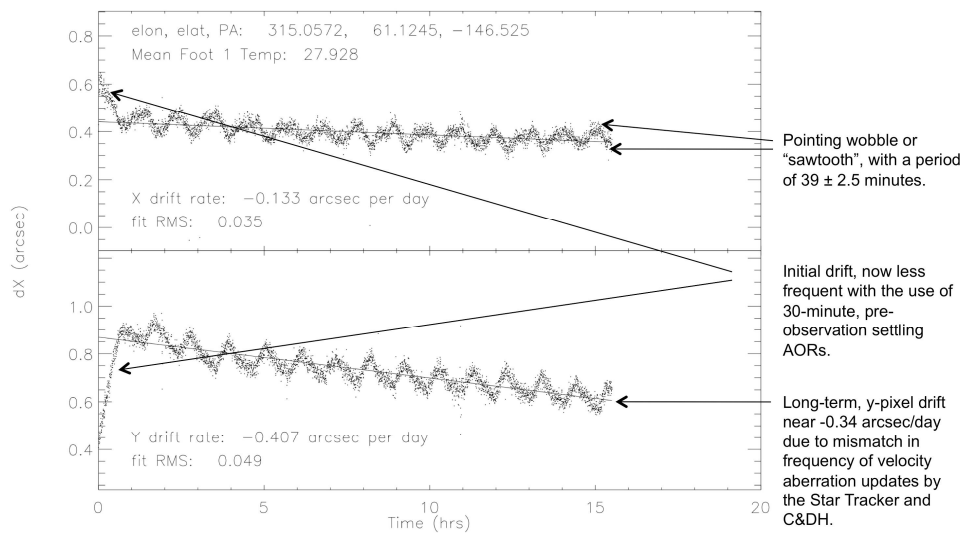
Figure 1. A typical high precision photometric sequence with IRAC, illustrating the consequences of a number of different semi- and aperiodic pointing drifts.

velocity vector. As the telescope moves along its orbit, its velocity vector changes at a rate of roughly 1° per day. The use of a fixed velocity aberration correction per hours-long observation request by the C&DH and a frequently updated correction by the star trackers leads to a constant correction signal in the pointing control system. This correction signal generates a linear drift rate in the –y-pixel direction on the IRAC detectors that ranges from -0.31 arcsec/day near the outer limit of Spitzer's operational pointing zone (OPZ), to -0.36 arcsec/day near the inner, sunward limit of the OPZ.

Experiments have been carried with the goal of correcting this drift by commanding a tracking rate of equal magnitude but opposite sign. These efforts were defeated by relatively large and unavoidable drifts produced by the gyroscopic inertial reference units used during tracking maneuvers. Modifications to the flight software to remove the source of the drift signal have been considered but are largely ruled out at this stage of the Spitzer mission by cost and risk. Another work-around that essentially turns of velocity aberration updates during long, high precision photometric sequences is currently under study and may be implemented if the Spitzer mission is extended beyond the current cycle.

3. POINTING WOBBLE

The second largest effect in Figure 1 is a pronounced oscillation in the centroid position with an amplitude of <0.1 arcsec and a period of about 40 minutes. This "sawtooth" has long been recognized[5] and, by virtue of having a period similar to the transit durations of many exoplanets, has complicated both photometric and spectral observations of such systems. The source of this sawtooth has been traced to the periodic cycling of a survival heater for a battery within the spacecraft. The period and amplitude of the wobble were successfully reduced in 2012 by adjusting the heater dead band, but further mitigation does not appear to be possible owing to the limited resolution of the battery temperature sensors.

Two hypotheses have been put forward to explain the pointing wobble. The first stipulates that, as a result of increased current draw during battery heating, the temperature of the solar arrays is reduced. This reduction in temperature reduces

the emissivity of the arrays, altering the asymmetric momentum imparted to the telescope. The drawback of this hypothesis is that, in the absence of any other changes, this change in the pitching force on the telescope should be detected by the star tracker and corrected by the pointing system on time scales of a few seconds. Moreover, even if the pointing system did not correct for this changing pitching force, the wobble would be confined almost entirely to the IRAC x-pixel direction. In fact, the pointing wobble appears to manifest in both x-pixel and y-pixel directions, with amplitudes actually being ~20% higher in the y-pixel direction. We note that the x- and y-pixel drifts are always in anti-phase with one another. The shorter, steeper heating phase always produces drifts in the -x and +y pixel directions.

The second hypothesis is that changes in temperature cause expansion or contraction in the composite structures of the telescope bus to which the star trackers and/or the telescope are mounted. Movement of the star trackers relative to the telescope boresight would defeat the closed-loop pointing system to the extent that the star trackers would remain fixed on the sky while the telescope boresight would drift in accordance with the net angular offset of the mount points. The battery and heater are situated along the line of symmetry of the spacecraft bus, but on the side farthest from the solar panels. If the thermal paths to the left and right cryogenic telescope assembly (CTA) low conductivity, gamma alumina support trusses are similar, and if the wobble was due to differential expansion and contraction of the forward and rear telescope trusses, then we would again expect the primary component of the wobble to lie along the IRAC x-pixel direction, at odds with the observed behavior. Moreover, the eight attach points of the struts are connect by a heat pipe embedded in the upper deck of the spacecraft bus specifically to maintain equal temperatures.

On the other hand, the star trackers are situated well off the spacecraft centerline (Figure 2), at one corner of the spacecraft bus in the telescope +Y direction. Depending on the details of the thermal expansion/contraction and warping of the upper deck of the spacecraft bus at the star tracker mount points, it is plausible that any movement at these mount points could naturally give rise to comparable x- and y-pixel drifts. Moreover, the direction of the warping (see below) would be consistent with the expected thermal gradient in the structures (e.g. warmer on the inside of the spacecraft bus, cooler on the outside surface of the upper deck and spacecraft shield). Firmer conclusions would require thermal detailed modeling, but based on the available evidence, we consider small angular displacements of the star trackers in response to thermal cycling to be the most likely cause of the observed pointing wobble.
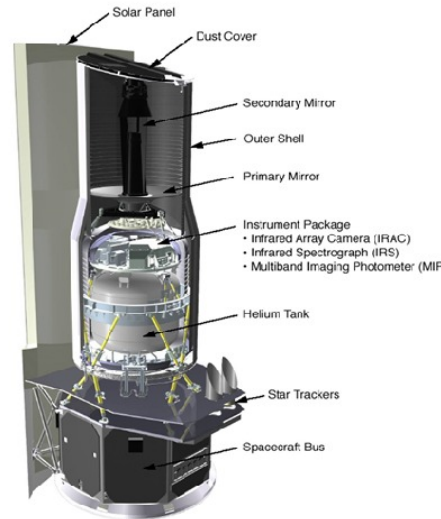

Figure 2. The Spitzer Space Telescope, showing various components discussed in the text.

4. OTHER THERMAL VARIATIONS

Another source of heat in the spacecraft bus is insolation into the high gain antenna enclosure, mounted to the bottom of the spacecraft bus. At pitch angles $\theta < 0°$ (when the telescope boresight is $90°$ or less to the Spitzer-Sun radial), this enclosure is entirely in the shadow of the solar arrays. However, for $0 < \theta < +40°$ the enclosure becomes increasingly illuminated by the Sun (Figure 3). Owing to the conical shape of the enclosure, this insolation goes roughly as θ^2 for $\theta > 0°$. At $\theta < 0°$, the enclosure must radiate at a rate proportional to T^4. This sort of behavior can be seen in Figure 4, where we plot the run of pitch angle and temperatures of the reaction wheel assemblies (RWAs) over a two-day period. The RWAs are situated roughly at the four corners of the spacecraft bus. Temperatures are seen to rise quickly at high pitch angles, and decrease for $\theta < 0°$. Moreover, temperatures on the sunward side of the spacecraft bus (RWA1 and RWA2) are seen to rise and fall more quickly than those on the anti-sun side (RWA3 and RWA4). Pitch angle and solar insolation evidently have a direct bearing on temperature inside the spacecraft bus, though this heat is not uniformly distributed.
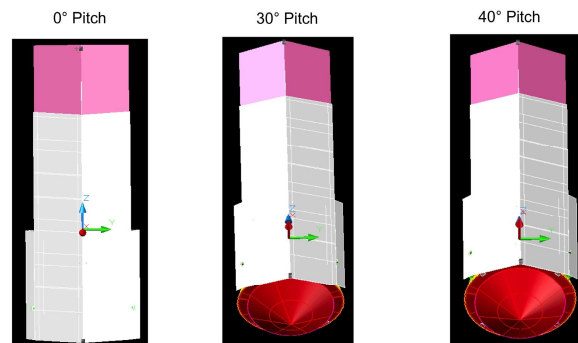

Figure 3. The effect of telescope pitch angle on solar illumination of the high gain antenna enclosure.
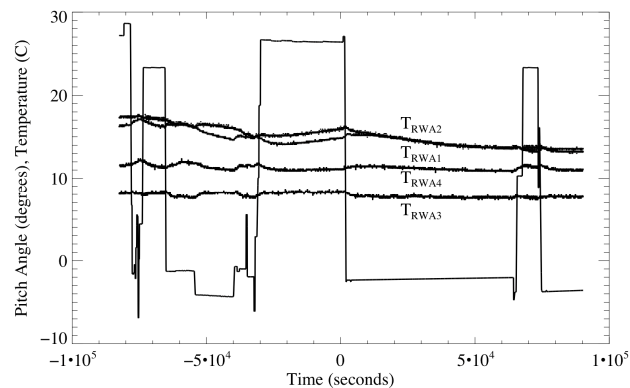

Figure 4. Temperatures measured at the Reaction Wheel Assemblies compared with pitch angle, as a function of time. RWA1 and RWA2 are on the sunward side of the spacecraft, and their temperatures appear to react quickly to changes in telescope pitch, warming at high pitch angles where the Spitzer high gain antenna enclosure is exposed to sunlight, and cooling as T^4 at pitch angles < 0, where the antenna enclosure is in the shadow of the solar arrays. RWA3 and RWA4 are on the anti-sunward side of the spacecraft bus and show far smaller variations.

While Figure 4 shows that the RWA temperatures respond very quickly to changes in pitch angle, Figure 5 shows that there are longer time scales at work as well. We find a correlation between RWA temperatures and average recent pitch angles that is strongest for a look-back time of 24 hours or longer. The correlation essentially disappears for look-back times of less than three hours, and tails off only slowly for look-back times of 36 and 48 hours. This suggests that, whereas the RWAs and surrounding areas can warm or cool quite quickly, other spacecraft components have much longer thermal time scales.
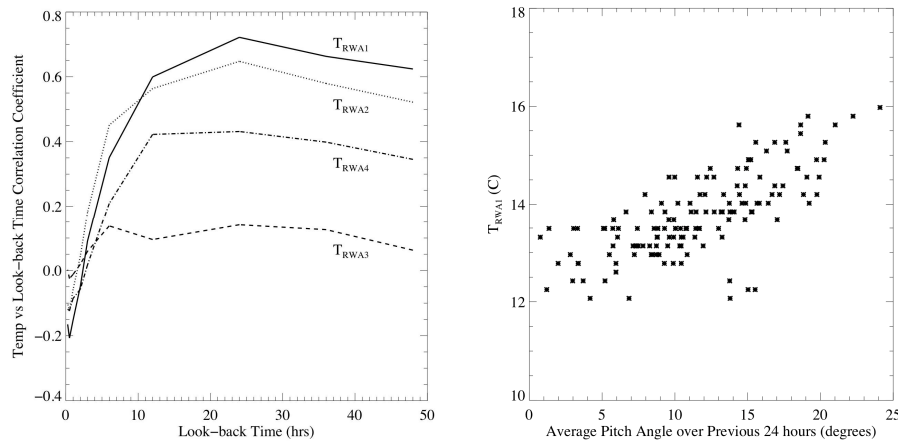

Figure 5. Correlations between instantaneous temperature and average pitch angles. The left panel shows Pearson's correlation coefficient for the temperatures measured at each of the four Reaction Wheel Assemblies (RWAs) and the average telescope pitch angle over various look-back times. The strongest correlation is seen between T_{RWA1} and the average pitch angle during the previous 24 hours. The right-hand panel shows the values of T_{RWA1} at the beginning of each of 143 time series AORs plotted against average pitch angle over the previous 24 hours.

Could this variable heat flux be responsible for non-periodic pointing drifts, in a manner consistent with our model for pointing wobble? Figure 6 shows initial drifts in the x- and y-pixel directions as a function of change from the mean pitch angle during the previous 30 minutes for 143 staring AORs with total durations of more than 8 hours. Initial drift is here taken to be the observed drift during the first 30 minutes of each AOR. There are clear correlations in both the x- and y-pixel directions. Moreover, a cooling spacecraft (negative changes in pitch angle) produces –y and +x-pixel drifts, while a warming spacecraft (positive changes in pitch angle) produces –x and +y-pixel drifts. The directionality is entirely consistent with the results for pointing wobble. An even stronger correlation is seen when comparing the initial drifts with one another (Figure 4). The initial drifts describe a narrow, almost 1-dimensional path across the detector arrays, with a y-pixel drift that is 2.1 ± 0.1 times greater than the x-pixel drift. The difference in relative amplitudes of x and y-pixel drifts from those seen in pointing wobble may be a consequence of the different thermal paths to the upper deck and star trackers from the antenna enclosure and the battery heater, respectively. On the other hand, we cannot rule out a strong left-right asymmetry in thermal constants that might differentially offset the CTA truss mount points. As discussed previously, any fore-aft (sunward-antisunward) differential heating of the CTA support trusses by solar insolation of the antenna enclosure should cause a drift primarily in the IRAC x-pixel direction.
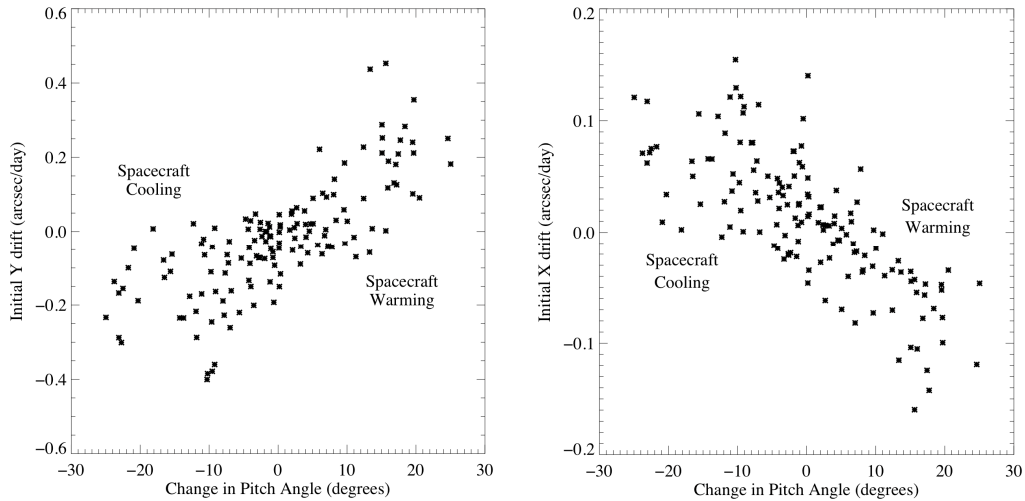
Figure 6. Initial drifts of x- and y-centroids in 143 exoplanet observing sequences versus the change from the average pitch angle during the preceding half hour. There are clear correlations in both axes, with the effect being stronger and of opposite sign in the y-axis.

In the case of pointing wobble, the relative x and y-pixel drift amplitudes indicate that flexure due to heating is driving the star tracker aim points roughly towards the center of the telescope when the battery heater is on. On the other hand, the initial drift vector in Figure 7 indicates that the star trackers are flexing toward a point considerably further along the telescope –Y axis when the spacecraft is warming, and away from the telescope along the same radial when the spacecraft is cooling.
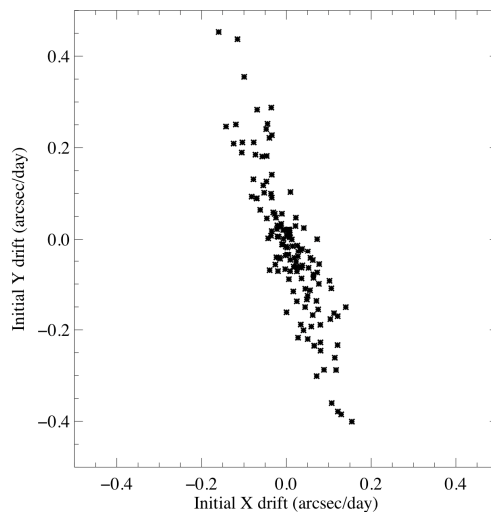

Figure 7. Initial drifts in the x- and y-pixel directions compared. Initial drift describes a well-defined vector on both arrays, with initial drift in the y-pixel direction being 2.2 ± 0.2 times larger than the initial drift in the x-pixel direction.

We note that insolation of the antenna enclosure and warming of the spacecraft bus has at least one other unfortunate consequence. As the spacecraft bus warms or cools, the battery temperature sensor responds accordingly, lengthening or shortening the interval between heater cycles. This in turn alters the period of the pointing wobble by as much as 40% in sequences as short as 8 hours. Since the spacecraft is almost always warming or cooling (e.g. Figures 4 and 5), it is probably never safe to assume a purely periodic wobble. Given the relatively large amplitude of the pointing wobble, any such assumption has the potential for introducing serious systematics into the photometry.

5. LONG TERM DRIFTS

Are long-term drifts also related to pitch angle, and therefore temperature? Figure 1 shows that, aside from the predominant -0.34 arcsec/day drift due to inconsistent velocity aberration corrections, there are non-zero drifts and possibly higher order undulations in the x-pixel direction. Y-pixel drift rates also show a large dispersion, and higher-order variations in a significant fraction of sequences. Interestingly, long-term x-pixel drift appears most strongly correlated with current telescope pitch angle, as shown in Figure 8. On the other hand, the long-term y-pixel drift shows no such correlation. The next strongest correlations ($r \sim 0.5$), shown in Figure 9, are between current pitch angle and the average pitch angle during the previous 12 (y) or 48 hours (x). While the scatter is quite large, there do appear to be large zones of avoidance. While the evidence is not compelling at this stage, it suggests that long-term drifts are caused by the cooling or warming of spacecraft components that have relatively long thermal time scales. It also suggests that the x- and –y-drifts may respectively be motivated to some extent by different spacecraft elements.
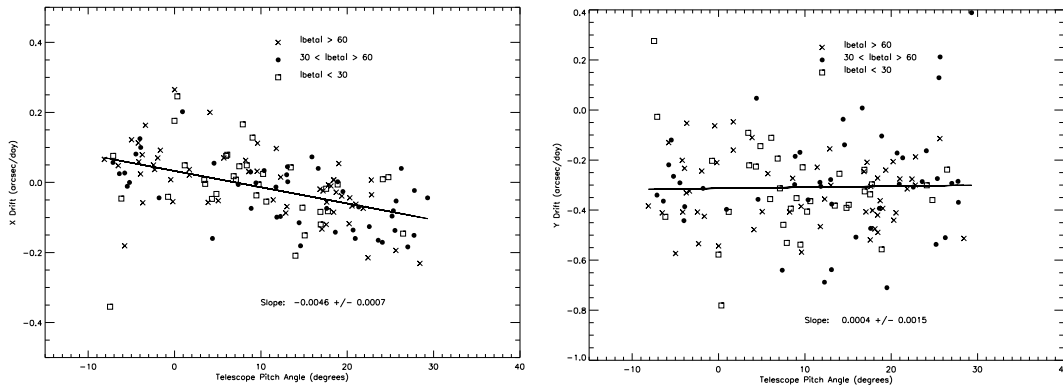

Figure 8. Long term drift in the x and y centroids for 137 staring observations vs. telescope pitch angle. Different symbols indicate targets having different ranges of ecliptic latitude.
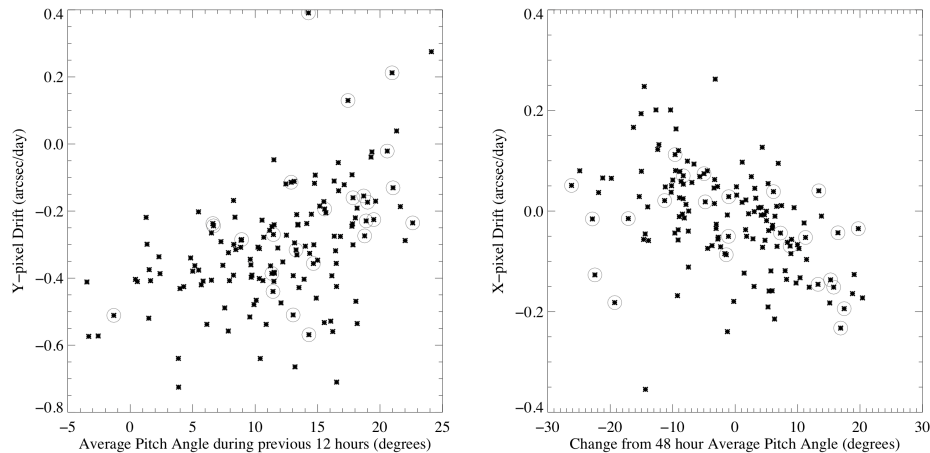
Figure 9. Long term, linear drifts in the x and y centroids versus average previous pitch angles. These particular comparisons yield the highest correlation coefficients (r ~ 0.5) for x- and y-pixel drift. Circled points are those with strong non-linear drift components. There are clear trends in each case, though the scatter is large. Note that for the y-pixel drift, the strongest correlation occurs when comparing to the average pitch angle during the prior 12 hours, and *not* to the difference between the current pitch angle and the previous average. This reinforces the notion that different thermal time scales are at work, that there is no attainable "equilibrium temperature" at every pitch angle, and that warming or cooling of some spacecraft components will cause long-term pointing drifts regardless of any efforts to control pre-observation pitch angles.

6. DRIFT VARIATIONS

Some time series observations are affected by variations in the drift rates on time scales of several hours. These non-linear drift components are generally small compared to the dominant –y-pixel drift, but can occasionally be quite significant. Efforts to prevent or mitigate this behavior would require some understanding of what is causing it. With this in mind, we have compared the observed centroid drift behavior with instantaneous or integrated measurements of various spacecraft parameters at the time of the observation. Instantaneous quantities include the RWA1-RWA4 temperature measurements and pitch angles at the beginning or end of each observing sequence. Integrated quantities include average temperatures and pitch angles over the course of each sequence, as well as average pre-observation pitch angles and temperatures over some "look-back" time that ranges in a roughly geometric sequence from 15 minutes to 48 hours.

Examining the departures of centroid movements from purely linear drifts, we have classified sequences on a scale of 0 to 3, where 0 indicates no sign of non-linear behavior and 3 corresponds to the most violent departures from a purely linear drift. Examples are shown in Figure 10. Of a sample of 139 well-populated observing sequences, 29 show no trace of higher order drifts (class 0), 45 have very small departures from linearity (class 1), 40 show more obvious undulations (class 2), and 25 show significant 2nd order and higher variations (class 3). We then look for correlations between our classifications and the average observing parameters in each class. The strongest correlations (**r** = 0.97 - 0.998) are found to occur when comparing with change from the average pitch angle over the previous 6 and 12 hours, respectively. The behavior for the 12 hour case is shown in Figure 11. This suggests that, like long-term linear drifts, non-linear drifts are a consequence of spacecraft components warming or cooling on time scales of several hours.
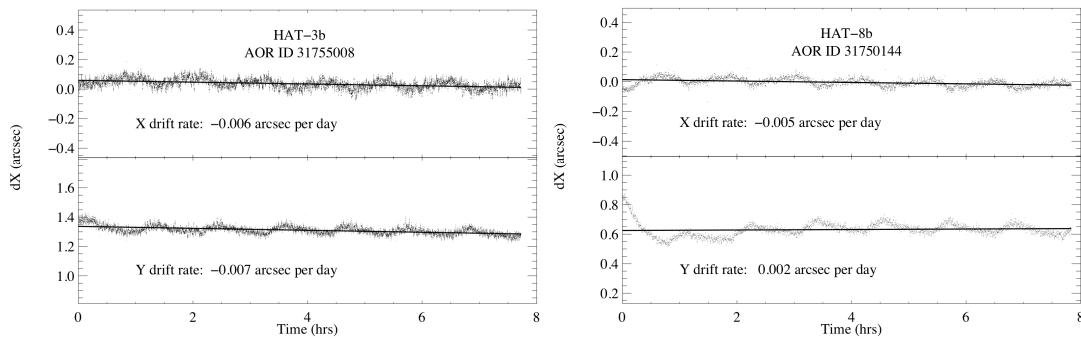
Figure 10. The left hand panel shows and example of purely linear drift (class 0) while the right-hand panel shows an example of pronounced non-linear drift with $d^2y/dt^2 < 0$ (class 3).
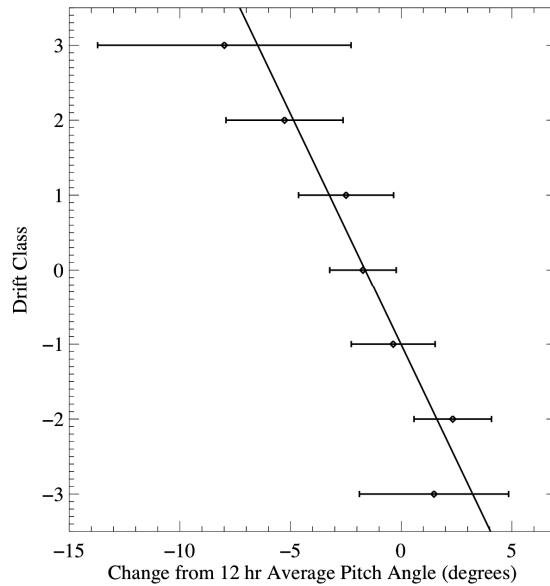

Figure 11. Comparison of the drift class with the change in pitch angle from that measured during the previous 12 hours. Drift classes are defined so that purely linear drifts have class = 0, while drift rates that change with time are assigned progressively larger classes. The signs are such that drift rates having $d^2y/dt^2 < 0$ have drift class < 0. The fit shown has D.C. = (-0.62 ± 0.21) (Δθ) + 1.

7. CONCLUSIONS

The short and long-term pointing drifts of the Spitzer Space Telescope appear to be primarily a consequence of varying thermal loads on the spacecraft. These thermal variations can be attributed to both onboard systems and to changing solar insolation as the telescope is maneuvered. Thanks to careful design and the very stable thermal environment of Spitzer's orbit, these pointing drifts are relatively small, and well within the design requirements of the mission. Yet, from the standpoint of maximizing photometric stability, it would clearly be desirable to reduce these pointing drifts as much as possible.

The largest source of drift remains the inconsistency between the manner in which the star tracker and the spacecraft computer update velocity aberration corrections. Due to reduced funding and relatively high risk, it is unlikely that this problem will be corrected through flight software changes. Other options, such as temporarily preventing velocity aberration updates, also entail some risk and would require considerable testing and continuing, careful oversight to implement. In the general case, this long-term drift will move a target out of the detector array sweet spots on time scales of less than 24 hours. For the highest possible photometric precision, we therefore continue to recommend breaking long observing requests into sequences of no longer than 12 hours, and using PCRS peak-ups to return as nearly as possible to the preferred pixel location. This procedure necessarily creates discontinuities in orbit spanning phase curve sequences, but keeps the target always within the well-characterized and most uniform portion of the pixel phase map. P-map corrections can then be used to bring successive sequences back to a common system[6].

Pointing wobble is also unlikely to be further mitigated. Reducing the battery heater dead band in 2012 significantly reduced the period and amplitude of the wobble, but further reductions are not possible due to the limited resolution of the temperature sensors. Indeed, variations in the period and amplitude of the wobble may well become larger as both increased battery usage and higher pitch angles are needed during the remainder of Spitzer's extended mission.

Initial drifts have been largely mitigated through the use of settling AORs and PCRS peakups. By allowing the temperature to stabilize for 30 minutes prior to an observation, the initial drift is generally eliminated in subsequent observing sequences.

Other long term and non-linear drifts remain a relatively minor issue. Nonetheless, efforts are underway to keep track of pitch angles in the scheduling process, and to keep large pitch angle changes to a minimum during the 24-48 hour period leading up to a high-precision photometric sequence. Given the relatively small number of targets visible by Spitzer at any given time, this will not always be possible.

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