DYNAMICAL BINNING FOR HIGH ANGULAR RATE STAR TRACKING

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ABSTRACT

Recent advances in CCD and Active Pixel Sensor (APS) technology and the development of efficient star pattern recognition algorithms hold the prospect of realising a star tracker system that can serve as the only on-board attitude sensor. One of the obstacles to be overcome to attain this objective is the loss of performance of star trackers in the presence of high angular rates. Typically, accuracy degradation sets in at rates of 0.1-0.2 deg/s and most sensors have lost track at 1-1.5 deg/s. This is a severe limitation since angular velocities of up to 1 deg/s or higher are not uncommon on spacecraft.

This paper describes a concept, called “dynamical binning”, for enhancing the robustness of star trackers to high angular rates. Under dynamical conditions, the star image appears to be moving on the pixel array. The photon flux from the star is spread over a large number of pixels thus resulting in a low SNR. The proposed concept aims to de-spread the star image by oversampling and combining the pixel read-outs from successive subsamples in a manner that compensates for the motion of the star image.

Dynamical binning is considered here in the context of APS-based star sensors. APSs are well-suited to this technique because they offer greater flexibility in the processing of pixel-level information and because the logic required for dynamical binning can be implemented directly on the same imager chip hosting the pixel array.

After describing the dynamical binning algorithm, the paper presents the results of simulations that confirm the gains in SNR afforded by this technique. Implementation aspects are also discussed. In particular it is argued that on-chip implementation of the algorithm is feasible with current technology. Finally, plans for a prototype imager with dynamical binning to be realised in ESTEC are discussed. A patent application for the dynamical binning concept has been filed by ESA.

I. INTRODUCTION

Conceptually, three subsystems can be identified in a star tracker: *optics*, *sensing device* and *microprocessor*. The optics subsystem consists of a system of lenses that focuses the light from a star or other object on a focal plane where the sensing device is located. The latter is normally based on an array of light-sensitive pixels that measure the intensity of the light they receive. The pixels are read out by a microprocessor that processes their outputs to estimate the position of the source of illumination within the star sensor's field of view.

The optics is designed to focus the light from a point-like source (such as a star) in a star image of circular shape and of a diameter equivalent to 2-3 times the side of a pixel. The pixels are usually integrating devices that, when reset at time t and read out at time $t+T_u$, should ideally return the number of photons deposited upon them by the light source over the interval $[t, t+T_u]$. In reality, their operation is affected by noise. A pixel's output contains both a *signal component* (proportional to the number of photons from the light source) and a *noise component*.

Conceptually, the processing of the pixel outputs done by the star sensor processor can be divided into two stages. There is first a *detection stage*. The processor must identify the pixels which have been illuminated by a star. Secondly, given a cluster of contiguous pixels that have been marked as "illuminated", the exact position of the source of the illumination must be estimated. This is done by assuming that contiguously illuminated pixels have been illuminated by a single star whose image on the pixel array is circular. The centre of the star image is then found by applying a *centroiding algorithm* which essentially takes a weighted average of the centres of the illuminated pixels where the weights are a function of the output of each illuminated pixel.

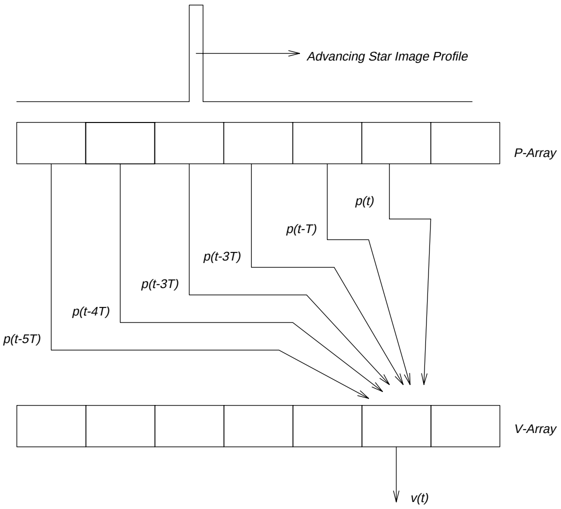
Both the detection and centroiding phases can only be reliably performed if the noise component in the pixel outputs is not large. A high noise level relative to the signal level makes detection difficult (because the illuminated pixels do not 'stand out') and degrades the accuracy of the centroiding algorithm.

Under static conditions (i.e. star positions constant in the sensor's field of view) good signal-to-noise properties in the pixel outputs can be ensured by increasing the exposure time thus increasing the number of photons deposited on each illuminated pixel. When the star moves in the sensor's field of view, its image on the pixel array is also moving. Under such conditions, the time it takes the star image to sweep over a pixel puts an upper bound on the number of photons that can be collected by that pixel. The robustness of a star sensor to angular rates is therefore intrinsically limited. This paper proposes a concept intended to partially overcome this limitation. This concept will be referred to as *dynamical binning* because of its analogy with conventional, static, binning as performed in some imaging systems.

II. CONCEPT DESCRIPTION

The principle behind the dynamical binning concept is to simulate the effect of physically moving the pixel array to follow the motion of the star image. If the pixel array were moved in the same direction and with the same velocity as the star image, then the star image, relative to the pixel array, would appear to be stationary and star position estimation could again be done under static conditions with all the advantages.

The practical implementation of this concept is best illustrated by means of a single-dimensional example. Consider a 'linear' star sensor consisting of a linear array of pixels on which a system of lenses projects a star image. Assume that the star image slides along the pixel array at a velocity v_{star} expressed in pixels/second. If one also assumes that the star image is very narrow relative to the pixel side (i.e. there is a very high degree of focusing), then the time the star image dwells over each pixel as it sweeps past it is simply $T_s=1/v_{star}$. Clearly, T_s is also the optimal sampling time for the pixels. This situation is depicted in the figure:



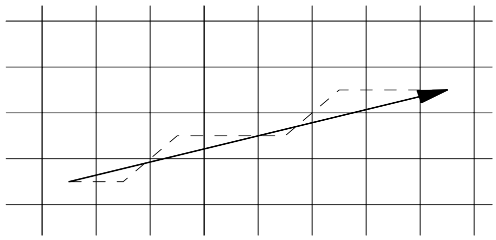
Normally, the output from the pixels is directly sent to the sensor's processor for star image detection and for application of the centroiding algorithm. Here, it is proposed to introduce an intermediate stage where pixel outputs are accumulated in a 'virtual' pixel array. The virtual array, or *V-array* for short, consists of a set of memory locations implementing the same configuration as the real pixel array (or *P-array* for short). The V-array will be sampled at an interval T_u which is a multiple of T_s, i.e. $T_u=mT_s$. T_u is the *user sampling time* representing the time interval at which users require star sensor data. The coefficient m will be called the *binning factor*. The outputs of the P-array will be shift-accumulated in the V-array in such a way that the output of the n-th V-pixel at time t will be given by:

$$v_n(t) = p_n(t) + p_{n-1}(t - T_s) + ... + p_{n-m}(t - mT_s)$$

It should now be clear that, from the point of view of the V-array, the star image is stationary. Hence, if the sensor processor is made to sample the V-array rather than the P-array, it will see an output that resembles that which is seen under stationary conditions and will therefore be able to apply the detection and centroiding algorithm with the same accuracy as would be done under static conditions.

III. ALGORITHM DEFINITION

This section defines the algorithm for the general case of a 2-dimensional array. Consider the figure:



The star image moves diagonally across pixels (solid arrow). The shift-accumulate operations on the other hand can only be done horizontally or vertically or across diagonally adjacent pixels. Hence a diagonal direction of motion must be approximated as a sequence of horizontal and vertical steps (dashed line). Note that the algorithm assumes knowledge of the velocity of motion of the star image. The next section considers how this information can be obtained in a practical operational context.

The dynamical binning algorithm must determine the output of a V-array pixel at a user sampling time as a function of m consecutive outputs of the P-array pixels. Since there are many ways in which a broken line can approximate a straight line, there are correspondingly many implementation of the dynamical binning algorithm. One possible such implementation is described below as pseudo-code. An orthogonal y-z reference frame is superimposed on the pixel array with axes parallel to the array sides. The algorithm is specified for the case of a star image velocity vector being closer to the y-axis than to the z-axis (i.e. $abs(v_y)>abs(v_z)$). If this were not the case, then the ‘y’ and ‘z’ indices should be exchanged.

m := round ($T_u v_y$)

T_p := T_u / m; t := 0; i := 0; j := 0

Δr := round ($T_u v_y$) - sign(v_y); Δp := round ($T_u v_z$)

FOR all pixels in the active window DO:

    $V_{r,p}$:= 0

ENDFOR

While t < T_u *DO*

    FOR all pixels in the active window DO:

    $V_{r,p}$:= $V_{r,p}$ + $P_{r-\Delta r+i,\, p-\Delta p+j}$

    ENDFOR

    t: = t + T_p ; i: = int(t v_y); j: = int(t v_z)

ENDWHILE

The variable t measures the time from the last user data acquisition. m is the binning factor. T_p is the sampling time for pixels in the P-array. v_y and v_z are the y and z components of v_{star}, the velocity of the star image expressed in pixel/second. $V_{i,j}$ is the output of the (i,j) pixel on the V-array. $P_{i,j}$ is the output of the (i,j) pixel on the P-array. The variables Δr and Δp give the distance, expressed in number of pixels along the horizontal and vertical direction, over which the star image moves over a user integration interval T_u. The variables i and j are incremented from 0 to Δr and Δp.

The algorithm mentions an 'active window'. This is the set of pixels where star tracking is performed which may be a sub-set of the pixel array. Note that because the field of view of the star sensor can be large, the velocity with which a star image moves on the pixel array may vary in different parts of the pixel array. Thus, if several windows are active at the same time, they may have to use different sampling times optimised for the local star velocity conditions.

Since it is proposed to implement the dynamical binning algorithm directly on the imager chip, it is necessary to keep the processing required to implement it as simple as possible. In the form in which it is given above, the algorithm appears to imply the need to carry out floating point multiplications and additions. In reality this is unnecessary because practical implementation of the algorithm reduces to a series of shift-accumulate operations which must be done across adjacent pixels. The processor controlling the imager computes the number and sequence of shift-accumulate steps as a function of the assumed star image velocity and passes this information to the imager chip which only has to perform data shifts across pixels and integer additions.

IV. ANGULAR RATE ESTIMATION

The dynamical binning algorithm requires as one of its inputs the direction and magnitude of the velocity with which the star image is moving across the pixel array. This must be derived from the angular velocity of the spacecraft. The simplest way to obtain this information is to attach a set of gyros to the star tracker. Low-quality gyros would be sufficient for this purpose. The quality of a gyro is essentially determined by its random drift but, in this context, high drift is acceptable because the angular rate estimate is only needed at initialisation. After the star tracker has achieved star lock, it can estimate the spacecraft angular velocity from its own data (either by differentiating successive attitude estimate or through a Kalman filter). While lock is maintained, it can also estimate the gyro drift and corrected gyro outputs can be used to aid its position/rate estimates. Note also that the simulation results presented in section VIII indicate that the dynamical binning algorithm is comparatively insensitive to misestimates in the spacecraft angular velocity of up to 10% in magnitude and 9 degrees in direction. Thus, low-accuracy solid-state gyros would be suitable for coupling to the star tracker resulting in a very compact, light-weight and low-cost, inertial navigation package capable of delivering both position and attitude information over a very wide range of operational conditions.

V. PIXEL READ-OUT MODEL

This section describes the pixel-read out model used for the analyses discussed in this paper (and presented in greater detail in ref. 1).

Pixels were modelled as devices that receive as their input a flow of photons over an integration interval [t, t+T_p] and which output a number of electrons at the time they are read out. The read-out electrons are then passed through an A/D converter where the pixel output is digitised. The raw (uncalibrated) number of electrons N_{pr} read out of the pixels will be expressed as a stochastic variable given by:

$$N_{pr} = k_f k_q N_{star} + N_{dc} + N_{ron}$$

Where:

- k_f is the fill ratio coefficient (the fraction of a pixel area which is covered by photosensitive material). It represents the fraction of photons impinging the pixel which are effectively absorbed.
- k_q is the quantum efficiency coefficient representing the efficiency with which photons are converted into electrons. This coefficient gives the number of electrons generated by a single absorbed photon.
- N_{star} represents the number of star photons received by a pixel. It is a stochastic variable with Poisson distribution with mean μ_{star}. Because photon numbers are large, this will be approximated by a stochastic variable with Gaussian distribution with mean μ_{star} and standard deviation sqrt(μ_{star}). μ_{star} can be expressed as:

$$\mu_{star} = F_0 \int_t^{t+T_P} e(t)dt$$

  where F_0 is the total photon flux from a star reaching the star tracker and e(t) is the *exposure coefficient* representing the fraction of the flux captured by the pixel at time t.
- N_{dc} represents the contribution to the pixel output due to the dark current noise. It is a stochastic variable with Poisson distribution with mean $\mu_{dc}T_P$ which will again be approximated by a stochastic variable with Gaussian distribution with mean $\mu_{dc}T_P$ and standard deviation sqrt($\mu_{dc}T_P$).
- N_{ron} represents the contribution to the pixel output due to the read-out noise. It is a stochastic variable

with Poisson distribution with mean μ_{ron} which will be approximated by a stochastic variable with Gaussian distribution with mean μ_{ron} and standard deviation sqrt(μ_{ron}).

The digitisation process (A/D conversion) was ignored. The raw (uncalibrated) pixel output was consequently represented as a Gaussian variable with mean μ_{pr} and standard deviation σ_{pr} given by:

$$\mu_{pr} = k_f k_q \mu_{star} + \mu_{dc} + \mu_{ron}$$
$$\sigma_{pr} = \sqrt{k_f k_q \mu_{star} + \mu_{dc} + \mu_{ron}}$$

The mean components of the dark current noise and of the random noise are normally compensated for. Two techniques are used for this purpose. With Correlated Double Sampling (CDS) the pixel is sampled at the beginning and at the end of the integration interval and the pixel output is the difference between these two measurements. This removes the mean component of the read-out noise. The mean component of the dark current noise can instead be eliminated by subtraction of a reference signal obtained during calibration when the sensor is exposed to the dark sky. Here it was assumed that these forms of calibration completely remove the mean components of the noise. Thus, the pixel output was modelled as a Gaussian variable with mean μ_p and standard deviation σ_p given by:

$$\mu_p = k_f k_q \mu_{star}$$
$$\sigma_p = \sqrt{k_f k_q \mu_{star} + \mu_{dc} + \mu_{ron}}$$

VI. TRACKING TECHNIQUES

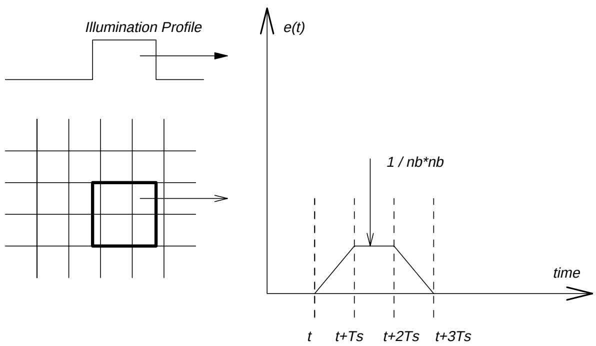
This section compares three tracking techniques in respect of their signal-to-noise ratio (SNR) properties. The three techniques are:

- *Conventional Tracking*: the pixel array is sampled at interval T_u and the pixel outputs are directly transferred to the microprocessor where the detection and centroiding algorithms are applied. The sampling time T_u is dictated by the frequency with which users (typically the attitude control system of the hosting satellite) requires updates of star position estimates. Common values of T_u lie between 0.2 to 0.5 seconds.
- *High Frequency Tracking*: this is similar to Conventional Tracking but the pixel array is sampled at a high frequency selected on the basis of the angular rate at which stars are moving in the sensor's field of view. Ideally, the pixel integration time should be only as long as the time it takes a star image to move over a pixel. In this way, illuminated pixels integrate only while they receive star light and their signal-to-noise ratio is maximised.
- *Dynamical Binning*: this resembles High Frequency Tracking in that the pixel sampling interval is matched to a star's pixel crossing time but it improves upon it by combining pixels' outputs to compensate for the motion of the star image on the pixel array thus achieving further gains in signal-to-noise ratio.

The signal-to-noise ratio is the crucial parameter in assessing the quality of a star tracking technique. It is defined for an individual pixel as:

$$SNR = \frac{mean\ value\ of\ a\ lit\ pixel\ output}{std\ dev\ of\ noise\ component\ of\ that\ pixel's\ output}$$

The SNR determines the accuracy with which centroiding can be carried and the reliability with which illuminated pixels can be distinguished from pixels whose output is pure noise. Expressions for the SNR were derived for the two extreme cases of slow-moving and fast-moving star image. In order to make analytical treatment possible, the following simplified scenario was assumed: the star image is perfectly square in shape; its sides are parallel to pixel rows and are equal in length to n_b pixel sides; its direction of motion is along a pixel row; its centre lies on the edge between two successive pixel rows. This scenario and a typical shape for the exposure coefficient e(t) are illustrated in the figure (for the case n_b=2).



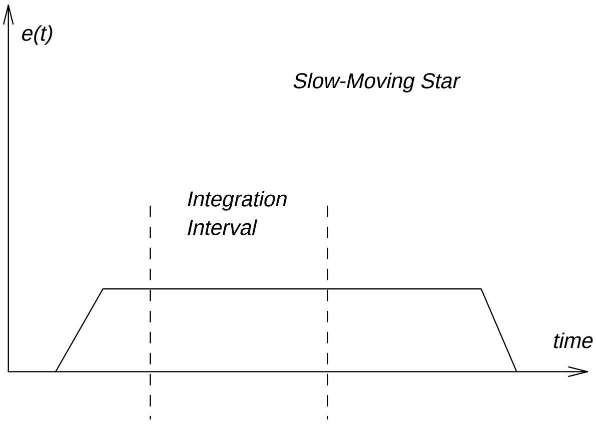
Note that the maximum value of e(t) is $1/(n_b*n_b)$. T_s in the figure is the 'dwell time' or the time it takes a star image to cross one pixel. It is equal to the inverse of the star image velocity (expressed in pixel/sec):

$$T_s = \frac{1}{v_{star}} = \frac{\phi}{\omega n_p}$$

Where ϕ is the star sensor's field of view, n_p is the length (in number of pixels) of the pixel array, and ω is the star's angular velocity.

The performance of a certain tracking techniques depends on the angular velocity of the star being tracked. Consider first the case of nearly-static or "slow-moving" stars.

A star can be considered to be slow moving when the dwell time T_s is much longer than the user sampling interval T_u:



Under nearly-static conditions, it can be assumed that there is always at least one pixel that is completely covered by the star image during the entire pixel integration interval. In this case one has:

$$\mu_{star} = F_0 \int_t^{t+T} e(t)dt = \frac{F_0 T}{n_b^2}$$

In the case of Conventional Tracking, the SNR can therefore be expressed as:

$$SNR = \frac{\frac{F_0 T_u}{n_b^2} k_f k_q}{\sqrt{\mu_{dc} T_u + \mu_{ron}}}$$

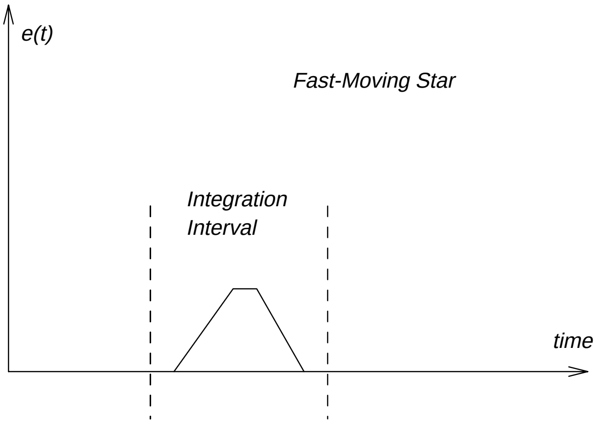
Because a pixel is continuously illuminated, there is nothing to be gained from switching to high frequency tracking. Consider for instance, halving the integration time. The useful signal, being proportional to integration time, would also be halved. The noise would decrease because its dark current component is also proportional to integration time but the read-out component would remain constant. The total decrease in the noise level would thus be less than the decrease in the signal level and hence the SNR would rise.

Dynamical binning, too, would not bring any benefits. The total signal accumulated in the V-pixel would still be the same as in the conventional tracking case. The share of the total noise due to dark current would also be the same but the read-out noise would have increased thus lowering the overall SNR. The full expression for the SNR for a binning factor of m is:

$$SNR = \frac{\frac{F_0 T_u}{n_b^2} k_f k_q}{\sqrt{\mu_{dc} T_u + m\mu_{ron}}}$$

Note that for devices where the dark current noise prevails over the read-out noise, the deterioration in SNR is minimal and dynamical binning is nearly equivalent to conventional tracking. In all other cases, dynamical binning, like high frequency tracking, reduces the SNR when applied in static or nearly-static conditions.

Next consider the case of a "fast-moving" star. A fast moving star implies a dwell time T_s which is very short relative to the pixel integration interval T_u:



In this case, one can assume that the non-zero part of the exposure coefficient lies entirely within an integration interval and hence:

$$\mu_{star} = F_0 \int_t^{t+T_U} e(t)dt = \frac{F_0 T_s}{n_b}$$

The SNR under conventional tracking is:

$$SNR = \frac{\frac{F_0 T_s}{n_b} k_f k_q}{\sqrt{\mu_{dc} T_u + \mu_{ron}}}$$

This form of tracking is not optimal because the pixel performs integration even when there is no useful signal (it is not illuminated by star light). High frequency tracking remedies this by shortening the integration time so that illuminated pixels again operate under optimal conditions by integrating only for as long as the star image dwells upon them.

If the high frequency pixel integration time is $T_p=T_u/m$, then, assuming that T_p is still much longer than T_s, the SNR becomes:

$$SNR = \frac{\frac{F_0 T_s}{n_b} k_f k_q}{\sqrt{\mu_{dc} T_p + \mu_{ron}}} = \frac{\frac{F_0 T_s}{n_b} k_f k_q}{\sqrt{\frac{\mu_{dc} T_u}{m} + \mu_{ron}}}$$

The gain in switching from conventional to high frequency tracking is all the greater if the dark current noise if much larger than the read-out noise. When the read-out noise prevails, there is not much to be gained from increasing the pixel sampling rate.

Dynamical binning affords a more decisive gain in SNR because it allows to increase the signal level by accumulating successive read-outs from illuminated P-pixels in the same V-pixel. Obviously, the noise level also grows but it grows more slowly. The overall effect is the same as when one averages a noisy signal: the noise level decreases with the square of the number of noisy samples that are added together. If m is the binning factor, the SNR under dynamical binning is:

$$SNR = \frac{m\frac{F_0 T_s}{n_b} k_f k_q}{\sqrt{m\mu_{dc} T_p + m\mu_{ron}}} = \frac{m\frac{F_0 T_s}{n_b} k_f k_q}{\sqrt{\mu_{dc} T_u + m\mu_{ron}}}$$

Depending on the relative weight of dark current and read-out noise, the increase in SNR with respect to the conventional tracking case can go from sqrt(m) (read-out noise prevails over dark current noise) to m (dark current noise prevails over read-out noise).

Note that since the dwell time T_s is inversely proportional to the star's angular rate, switching from conventional tracking to dynamical binning should increase robustness to star angular rates by a factor of between m and sqrt(m). For a typical value of m of between 5 and 10, this implies that the maximum angular rate at which stars can be tracked is approximately tripled.

The above analyses indicate that when stars are nearly-static, SNR is maximised by conventional tracking whereas when stars are moving very fast, SNR is maximised by dynamical binning. High frequency tracking by contrast is always dominated by one of the other two techniques. What then is the borderline star angular velocity at which conventional tracking is no longer optimal and dynamical binning becomes beneficial?

Since the star's angular velocity is uniquely determined by the star image dwell time T_s, another way of looking at this question is to ask what is the optimal (SNR-maximising) pixel integration time T_p given a certain dwell time T_s. Once the optimal T_p has been determined, one can compare it with the interval T_u at which users need star data. If the optimal T_p is close to T_u, then conventional tracking is the best strategy. If instead the optimal T_p is significantly lower than T_u, then dynamical binning is advantageous and the optimal binning factor is $m=T_u/T_p$.

VII. SIMULATION SCENARIO

A simulation campaign (described in detail in ref. 3) was conducted to assess the benefits of dynamical binning. The simulator (described in detail in ref. 2) modelled the star tracker at pixel level. Although it suffered from some limitations it remained adequate to establish the *relative* gains in SNR accruing from a switch from conventional to dynamical binning. Its results should be interpreted in this light, and not as indications of *absolute* SNR levels.

All simulations assumed a camera with effective optical aperture of 7.7 cm^2 and square field of view of 20 deg of side. A pixel array of 512x512 pixels of 20 μm of side was considered. Two sets of values for the pixel model parameters were used. Both refer to APSs. The first set roughly reflects the state of current APS technology while the second one is intended to reflect the properties of the next generation of APS systems as they will become available in 3-5 years. The assumed values for the model parameters are summarised in the table below. These values are affected by uncertainty. They were derived by collating public domain information (from ref. 4 to 8) which was often incomplete or ambiguous.

Parameter	Current	Advanced
Fill Ratio	0.7	0.95
Quantum Eff.	0.3 e/photon	0.5 e/photon
Dark Current	40000 e/sec	20000 e/sec
Readout Noise	200 e	25 e
Readout Freq.	3 MHz	5 MHz

All simulation results refer to the SNR computed for the brightest pixel for a single star of magnitude 4. A user sampling time T_u of 200 ms corresponding to a typical AOCS frequency of 5 Hz was adopted.

VIII. SIMULATION RESULTS - 1

Application of the dynamical binning algorithm requires an estimate of the velocity of the star image. In this first series of simulations, it was assumed that the star image velocity was known without errors.

The first set of simulations considered the choice of the pixel integration time T_p. The simulations confirmed the intuitive expectations that the optimal (SNR-maximising) T_p is equal to the dwell time T_s. Typical results from are shown in the table. They refer to a star moving across the diagonal of the field of view with an angular velocity of 1.5 deg. Advanced technology pixels are assumed:

Binning Fact. m	T_p (ms)	SNR
5	40.0	22.4
6	33.3	26.6
7	28.0	31.1
8	25.0	38.5
10	20.0	46.3
11	18.1	43.2
12	16.7	38.3
15	13.3	19.0
20	10.0	9.6

The SNR is maximised for m=10 corresponding to a T_p of 20 ms, very close to the dwell time of 19 ms. Note that if conventional tracking were used, the SNR would be only 14. The improvement due to the introduction of dynamical binning is therefore more than threefold.

The next set of simulations compared "current technology" with "advanced technology" pixels. The table below gives the SNR before and after application of dynamical binning for both the current and advanced technology cases:

ω (deg/s)	m	SNR (u,-b)	SNR (u,+b)	SNR (d,-b)	SNR (d,+b)
0.5	3	6.1	6.1	39.0	58.0
1.0	7	4.3	4.4	20.5	50.3
1.5	10	2.4	4.0	13.6	46.3
2.0	13	1.7	4.1	10.5	42.0
3.0	20	3.0	4.3	7.7	38.3

'u'=current, 'd'=advanced, '+/-b'=no/with binning

It is clear that decisive benefits from dynamical binning are only present with "advanced technology" pixels. In the "current technology" case, gains in SNR are more modest (though not negligible at high angular rates) and are probably not sufficient to overcome the effects of high angular rates. The poor performance in the current technology case is due to the comparatively high value of read-out noise that penalises the frequent read-out operations required by dynamical binning. All further simulations reported in this paper refer to the "advanced technology" case.

The previous table also suggests that the limit angular rate at which it begins to make sense to apply dynamical binning under ideal conditions (i.e. no uncertainty on angular rate knowledge) is below 0.5 deg/s. Note also that dynamical binning is intended to compensate for the motion of the star and should ideally make the SNR independent of the star angular velocity. In reality, as can be seen from the table, there is a residual dependency due to the presence of a non-zero read-out noise.

IX. SIMULATION RESULTS – 2

The parameters for the dynamical binning algorithm are a function of the star image velocity. The simulations discussed in the previous section were made under the assumption of a perfect knowledge of the star image velocity. This is obviously unrealistic since, in practice, the star image velocity must be estimated from the angular velocity of the spacecraft, itself only poorly known. Hence, in practice, the dynamical binning parameters would be chosen in a sub-optimal way. In this section the loss in SNR that is introduced by an imperfect knowledge of the star image velocity is studied.

The next table presents the simulation results in the case of an imperfect knowledge of the *magnitude* of the star image velocity. Two levels of uncertainty, +10% and +20%, are considered for various star angular velocities. The angular velocities were chosen so as to make ($T_u v_y$) an integer. This is important because the binning factor is computed as the integer part of this product (see section III). The optimal SNR is that which is achieved for the case of no error on the star image velocity knowledge. Both the absolute SNR and the percentage degradation with respect to the optimal SNR are given.

ω deg/s	SNR (Opt)	SNR (+10%)	SNR (+20%)	m
0.4	60	58 / 2.3%	57 / 5.0%	3
1.0	51	49 / 3.3%	45 / 10%	7
1.5	47	42 / 9.2%	40 / 15%	10
1.9	42	38 / 9.3%	32 / 25%	13
2.9	39	33 / 16%	21 / 45%	20

The table results were computed with a star image moving along a pixel row. When the direction of motion is diagonal, results change but slightly.

The robustness to misestimates of the magnitude of the star velocity decreases as the angular rate increases ranging from 2-3% (at 0.5 deg/s) up to 45% (at 3 deg/s). Since the binning factor must be an integer, the application of the binning algorithm is subject to a sort of quantisation error of fixed size. At low angular rates, a 10% or even a 20% misestimate of the velocity may lie within the quantisation threshold and may therefore have a limited impact on the algorithm performance. At high rates, the quantisation threshold is proportionally smaller and a misestimate of 10 or 20% has a correspondingly higher impact on the SNR.

The next table illustrates the loss in SNR that accompanies an incorrect estimate of the star image velocity *direction*. The parameters for the binning algorithm were computed assuming a direction of motion parallel to a pixel row while in fact the actual direction of motion was slanted by 5, 7 and 9 deg. Once again both the absolute value of the SNR and percentage degradation with respect to the optimal case (no error in velocity direction estimate) are presented.

ω deg/s	SNR (Opt)	SNR (5 deg)	SNR (7 deg)	SNR (9 deg)	m
0.4	60	58/3.3%	57/4.3%	58/3.5%	3
1.0	51	48/4.3%	48/5.5%	47/6.0%	7
1.5	47	45/3.2%	42/9.6%	40/13%	10
1.9	42	39/7.6%	37/11%	36/13%	13
2.9	39	32/18%	29/19%	23/40%	20

It should be noted that an error in the direction of motion of the star image is intrinsic to the binning algorithm. When the direction of motion of the star image is not along a horizontal or vertical, the binning algorithm tracks it by means of a broken line that is meant to approximate the real (diagonal) direction of motion. To each broken line there corresponds one set of binning parameters. Since many different directions of motion can be mapped to the same set of binning parameters, dynamical binning introduces a quantisation error in the star image direction. As in the case of errors on the velocity magnitude, its presence explains the trends shown in the table. The impact of a given level of uncertainty in the star image velocity direction is small at low angular velocities (where it is drowned by the quantisation error) and is larger at higher angular velocities (where the quantisation threshold is low).

The last table of this section combines the effects of errors in the estimate of both the direction and magnitude of the star image velocity. A fixed 10% error in velocity magnitude is assumed.

ω deg/s	SNR (Opt)	SNR (5 deg)	SNR (7 deg)	SNR (9 deg)	m
0.4	60	59/2.3%	58/2.7%	58/2.8%	3
1.0	51	49/3.6%	48/5.3%	47/8.0%	7
1.5	47	43/7.0%	40/13%	39/16%	10
1.9	42	35/16%	34/18%	32/23%	13
2.9	39	27/30%	24/38%	21/45%	20

The general trend is the same as observed in the previous tables: the finer grain of the binning algorithm at high angular rates allows to track the star image with greater accuracy, but also exacts a greater penalty for mismodellings of the star image velocity.

In summary, the dynamical binning algorithm appears to be rather robust to errors in the estimate of the star image velocity. Even comparatively large errors of 10% in the magnitude and 9 deg in the direction result in SNR of less than 50%. Note that this loss should be set against expected gains from the application of dynamical binning of up to 3-400%.

X. VELOCITY NON-UNIFORMITY

The star image velocity is one of the inputs to the dynamical binning algorithm. In an operational setting, it must be derived from the angular velocity of the spacecraft hosting the star camera. This section shows how this derivation can be done and it examines the problems that arise from the non-uniformity of the star image velocity field on the pixel matrix.

The derivation will be done in an orthogonal reference frame defined as follows: origin in the geometrical centre of the pixel array; x-axis perpendicular to the plane of the pixel array and pointing towards the star camera optics; y-axis parallel to one of the sides of the pixel array (assumed rectangular in shape); z-axis completing the orthonormal frame.

Consider a star lying in direction **s**(t) and let P be the point on the pixel matrix array in which the centre of the star image due to **s**(t) lies. Let (y,z) be the co-ordinates on the array plane of point P at time t . Let **ω** be the angular velocity with which the spacecraft is rotating. The problem is to find the velocity v_{star} with which point P is moving on the pixel array as a consequence of the rotation of the spacecraft.

The star direction **s** can be expressed as a function of the co-ordinates of point P and of the focal length:

$$\underline{s} = [f \quad -y \quad -z]^T$$

Since the reference frame is attached to the star camera, it is simpler to imagine that the spacecraft (and hence the star camera) are fixed and that the star vector is rotating with angular velocity -**ω**. With this convention, the star vector at time (t+Δt) is:

$$\underline{s}(t+\Delta t) = \underline{s}(t) - \underline{\omega} \wedge \underline{s}(t)\Delta t = \begin{bmatrix} f + z\omega_y \Delta t - y\omega_z \Delta t \\ -y - f\omega_z \Delta t - z\omega_x \Delta t \\ -z + y\omega_x \Delta t + f\omega_y \Delta t \end{bmatrix}$$

From the star direction **s**(t+Δt), it is possible to derive the co-ordinates, in the pixel array plane, of the point P at time (t+Δt):

$$P(t+\Delta t) = \begin{bmatrix} -f \dfrac{s_y}{s_x} \\ -f \dfrac{s_z}{s_x} \end{bmatrix} = \begin{bmatrix} \dfrac{fy + f^2\omega_z \Delta t + fz\omega_x \Delta t}{f + z\omega_y \Delta t - y\omega_z \Delta t} \\ \dfrac{fz - yf\omega_x \Delta t - f^2 \omega_y \Delta t}{f + z\omega_y \Delta t - y\omega_z \Delta t} \end{bmatrix}$$

The star velocity can then be found as follows:

$$\underline{v}_{star} = \lim_{t\to\infty} \frac{P(t+\Delta t) - P(t)}{\Delta t}$$

Evaluating this limit gives:

$$\underline{v}_{star} = \begin{bmatrix} v_y \\ v_z \end{bmatrix} = \begin{bmatrix} f\omega_z + z\omega_x - zy\dfrac{\omega_y}{f} + y^2 \dfrac{\omega_z}{f} \\ -y\omega_x - f\omega_y - z^2 \dfrac{\omega_y}{f} + zy\dfrac{\omega_z}{f} \end{bmatrix}$$

This expression shows that, for a given spacecraft angular velocity **ω**, the star image velocity varies across the pixel array. There is therefore a non-uniform field of star image velocity vectors.

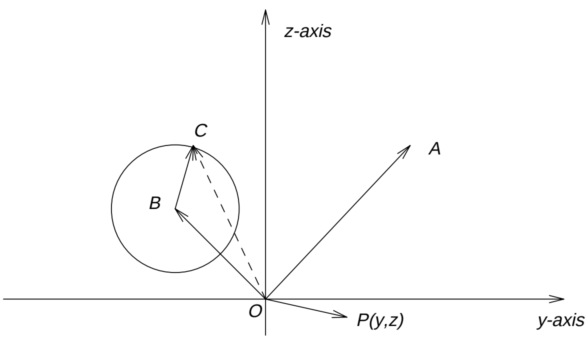
Since the dynamical binning parameters are a function of the star image velocity, it follows that, in order to correctly track star images in different points of the pixel array, the dynamical binning algorithm must be applied with different parameters at different points of the pixel array. This may be difficult to achieve in practice if it is desired to implement the dynamical binning algorithm in hardware directly on the star camera chip. The feasibility of doing this is discussed in section XII. For the time being, a simpler arrangement, more compatible with hardware implementation constraints, will be considered that consists in computing the dynamical binning parameters with reference to the mean value of the star image velocity over the pixel array. Obviously, this introduces an error but, if the variation of the star image velocity is not too large, the error can be contained within acceptable limits. In order to assess this error, it is necessary to assess the degree of non-uniformity of the star image velocity vector field.

The last expression shows that the star image velocity depends linearly on the components of the spacecraft angular velocity and quadratically on the pixel array co-ordinates of the star image. Because of its non-linearity, this expression is too difficult to study. A suitable simplification can be done by observing that, very often, the focal length is significantly larger than the maximum value of the y and z co-ordinates (which are equal to the size of the pixel matrix). This makes it legitimate to consider the ratios y/f and z/f as "small" and to neglect terms that contain them. This leads to the following approximate expression for the star image velocity:

$$\underline{v}_{star} = \begin{bmatrix} v_y \\ v_z \end{bmatrix} = \begin{bmatrix} f\omega_z + z\omega_x \\ -y\omega_x - f\omega_y \end{bmatrix} = f\,\underline{\omega}^p_{yz} + \omega_x \underline{r}^p$$

where $\underline{\boldsymbol{\omega}}_{yz}$ is the projection on the yz plane of the spacecraft angular velocity vector $\underline{\boldsymbol{\omega}}$, and $\underline{\mathbf{r}}$ is the vector joining the origin of the reference frame (i.e. the centre of the pixel array) to the star image P(y,z) and the superscript 'p' denotes the perpendicular to a vector in the pixel array plane (i.e. $\underline{\mathbf{x}}^p$ is the vector perpendicular to vector $\underline{\mathbf{x}}$).

Suppose now that the spacecraft angular rate $\underline{\boldsymbol{\omega}}$ is given. This fixes $\underline{\boldsymbol{\omega}}_{yz}$ and its perpendicular. What is the maximum degree of variation in the modulus and direction of $\underline{\mathbf{v}}_{star}$ for this given value of spacecraft angular rate $\underline{\boldsymbol{\omega}}$? A geometric interpretation of the expression of $\underline{\mathbf{v}}_{star}$ is the simplest way to answer this question.



Vector OA represents vector $\underline{\boldsymbol{\omega}}_{yz}$. Vector OB represents vector $(f{*}\underline{\boldsymbol{\omega}}^p_{yz})$. Vector BC represents vector $\omega_x \underline{\mathbf{r}}^p$. Vector OC then represents the star image velocity when the star image is located in P(y,z). As the star image moves on a circle centred on the origin of the reference frame, the star image velocity moves on the circle in the figure. The maximum relative variation in the star image velocity magnitude and angle can then be simply expressed as:

$$\delta v_{magnitude} = \frac{|BC|}{|OB|} = \frac{\omega_x r}{f\omega_{yz}}$$

$$\delta v_{angle} = angle\langle OC, OB\rangle = arcsin\left(\frac{\omega_x r}{f\omega_{yz}}\right)$$

As intuition would suggest, one can see that the variation of the star image velocity is greatest at the edges of the pixel array (it grows with r) and that it increases as the spacecraft angular velocity vector approaches the normal to the pixel array (i.e. as $\underline{\boldsymbol{\omega}}_{yz}$ gets smaller).

The geometric construction in the figure above also immediately gives the mean value of the star image velocity as:

$$\underline{v}_{star} = f\,\underline{\omega}^p_{yz} = \begin{bmatrix} v_y \\ v_z \end{bmatrix} = \begin{bmatrix} f\omega_z \\ -f\omega_y \end{bmatrix}$$

If it is desired to use the same set of binning parameters over the whole pixel matrix, the optimal way to derive them is to take the above as the expression of the star image velocity.

Suppose now that it is desired to keep the variation on the magnitude non-uniformity below 10% and the variation on the direction of motion below 7 deg. These are reasonable limits since, as shown in section VIII, they would ensure that maximum degradation in SNR would be below 40%. Assuming: f=0.04m and r=0.005m, the following constraints would ensue:

$$\delta v_{magnitude} < 0.1 \rightarrow \frac{\omega_x}{\omega_{yz}} < 0.76$$

$$\delta v_{angle} < \sin(7) = 0.12 \rightarrow \frac{\omega_x}{\omega_{yz}} < 0.91$$

In this case, the constraint on the velocity magnitude dominates and implies that the angular velocity vector must not be closer than arctg(0.76)=37 degrees to the normal to the pixel array.

XI. SNR BUDGET

The analyses done so far, have established that dynamical binning can have substantial benefits on the SNR at high angular rates but they have also identified the following sources of SNR losses:

- *Magnitude Rounding Losses* due to the choice of the binning factor as nearest integer to $(T_u v_y)$. When this product is not an integer, an error is introduced that is equivalent to an error in the estimate of the star image velocity.

- *Direction Rounding Losses* due to the approximation of the direction of motion of the star image with a broken line .
- *Velocity Uncertainty Losses* due to the poor knowledge of the star image velocity.
- *Velocity Non-Uniformity Losses* due to the fact that, in general, the field of star image velocities on the pixel matrix is non-uniform and therefore the binning parameters are selected on the basis of a mean value of star image velocity which differs from the actual star image velocity at a particular point on the pixel matrix.

Although the SNR degradation due to each error source taken in isolation has been estimated, a complete SNR budget cannot yet be drawn up because of the presence of sharp non-linearities. Consider for instance the combination of the velocity uncertainty and velocity non-uniformity. Both result in a mismatch between the actual star image velocity and the star image velocity that is assumed by the binning algorithm. However, the total loss in SNR due to both effects is *greater* than the sum of the losses due to each effect taken separately. The interaction between the rounding losses and the velocity uncertainty/non-uniformity may instead be more benign. If the velocity uncertainty/non-uniformity falls within the quantisation steps, then it has no effect at all. To complicate matters still further, the effect of velocity non-uniformity depends on the position of the star image within the pixel array: it is largest at the edges but goes to zero at the centre of the array.

Probably the only way to quantify the interaction and weight of the various error sources to generate a complete SNR budget would be to carry out a campaign of Monte Carlo simulations but this has not yet been done.

XII. STAR POSITION ESTIMATION

The analyses done to date have concentrated on the problem of star detection – ensuring that the SNR is sufficiently high to permit detection of the star amid random noise. Star detection must be followed by the measurement of the star position. Consider a simplified situation in which the star image is point-like and moves with the following velocity:

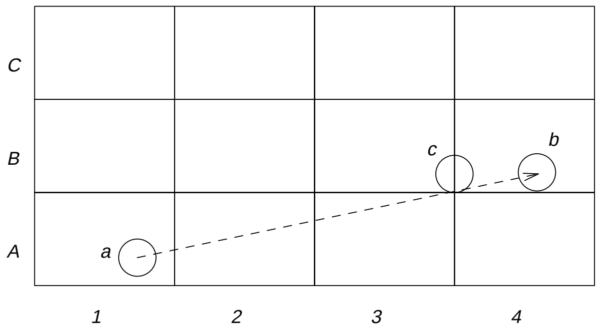
$v_y = 3.0$ *pixel/sec*

$v_z = 0.6$ *pixel/sec*

Let the user sampling time be T_u=1 sec. Suppose that at time t=0, the star image is at the centre of pixel A1 in the figure below (point 'a'). At the end of the a user sampling time, t=T_u, the star image will have moved along the dashed line to the centre of pixel B4 (point 'b'). If the photon flux from the star is 100 photons/sec, then at the end of the user sampling time, application of the dynamical binning algorithm given in section 1 would result in the following charges in the V-pixels:

B3 = 150 B4 = 100 C4 = 50

All other V-pixels would be empty. Application of a centroiding algorithm that finds the weighted average of the charge, would then estimate the star position at point 'c' different from the actual star position at t=T_u (point 'b').



The error in star position estimate can be seen as a form of local bias but in reality this is a phenomenon that can also be observed in conventional star trackers when they operate under conditions of non-zero angular rate. Star trackers are integrating devices. Hence, their attitude estimate refers to an instant in time within the integration window. In the case of a conventional star tracker, this bias can be seen as arising from a fixed delay in the output of the star tracker. When dynamical binning is applied, this representation is not necessarily adequate because the estimated star position 'c' does not lie on the path followed by the star image (the line joining 'a' to 'b'). Moreover, the extent of the bias depends on the velocity of motion of the star image. Finally, since in general the velocity of the star image on the pixel array varies from point to point on the pixel array, the position estimation bias too varies over the pixel array. It can therefore be conceptualised as a local, angular velocity-dependent bias. If the angular velocity of the star tracker were known, it could of course be fully compensated for. The form of this bias, its impact on the star pattern recognition algorithm, and ways to compensate it, still remain to be studied.

XIII. IMPLEMENTATION ASPECTS

The implementation of a sensing device with dynamic binning can be made in several ways of which one possible approach is discussed hereafter. As a starting point, it is assumed that the sensing device is implemented as a CMOS APS. For space applications, the benefits of an APS over a CCD are several, e.g. higher radiation tolerance, although only two features are essential in the context of dynamic binning: the high frame readout rate and the possibility for co-integration of sensor and processing logic. The latter point will be exploited throughout the discussion, aiming at reducing the complexity of the star tracker electronics. The discussion will concentrate on the implementation of dynamic binning without addressing opto-electrical requirements which were discussed above. The basic dynamic binning algorithm previously presented will serve as the basis for the following discussion, covering requirements on the pixel array size, pixel value digitisation, pixel storage, pixel array addressing and processing.

Dynamic binning requires high image frame readout rates on the level of the sensor to allow high binning factors. The binning factor is related to the presumed star image velocity rather than to the user sampling time. Normally, the star tracker sensor size is in the range of 512 by 512 pixels, although larger arrays are also being used. The discussion will be limited to the aforementioned size since the performance and requirements for larger arrays can be easily derived.

With the combined product of foreseen user sampling times and binning factors, the current upper bound for the image frame readout rate can be assumed to be at 128 Hz. Applying this to the array size results in pixel rates of 34 million pixels per second (MPPS). Pixel rates of about 15 MPPS have been reported for Analogue to Digital Converters (ADC) when integrated on an APS device. One way to overcome this limitation is to use multiple ADCs, each working on its own fraction of the pixel array. Devices currently exist capable of sustaining 40 MPPS using this approach by providing multiple data outputs. For dynamic binning, the outputs from the on-chip ADCs will be directly used by the binning algorithm. As a consequence, a future sensing device would integrate two to four ADCs to allow for the required image frame rates. The level of quantisation still needs to be analysed but will probably be somewhere between eight and twelve bits. The ADCs could also be placed off-chip to increase their performance but this would increase the system complexity, necessitating a future trade-off. If higher frame rates are required, one possibility would be to use subwindows of the physical image array. Since it would result in less pixels being read out per image, the performance of the ADC would not need to be increased. The drawback is of course the decreased field of view.

As mentioned, the additional image frames, or real pixel arrays, read out as a consequence of the binning factor are never presented to the user. At the end of a user sampling time the user will be presented with one image frame, or virtual pixel array. During the dynamic binning process, the virtual array needs to be stored and its contents are gradually refined according to the dynamic binning algorithm. The storage capacity required for a 512 by 512 pixel array will be in the range of 2 to 3 Mbits, depending on the number of bits required per pixel. This amount of memory is not readily integrated on the sensing device and will for now be assumed to be located in a separate memory device. Since the algorithm requires that each pixel value in the virtual array, being stored in the memory, is updated once each time a real pixel array is read out, the requirement on the memory performance is high. For the above example, the pixel in the memory needs to be read, modified and written back within 30 ns. This is achievable with commercial memories today but could be a problem with space grade parts, which could require the use of multiple devices, each associated with one of the on-chip ADCs.

The processing required to implement the baseline binning algorithm can be split in two parts: addressing of the virtual and real pixel arrays, and the pixel value accumulation. Assuming that the real pixel array is read out sequentially, each real pixel needs to be associated with a pixel in the virtual array. This addressing process is rather straightforward, only requiring a fixed point increment of the address pointer with a value being constant during the user sampling time. At the highest readout rate, the available time for each addition is in the range of 30 ns if pipelining is used. The constant is calculated once per user sampling period, requiring one integer division. The required performance is easily achieved with current submicron processes. The pixel value accumulation in the virtual array requires a simple integer addition. Since none of the above operations is performance critical, one could imaging that there is room for more complex algorithms. This could be approximation of non-linear pixel trajectories or varying trajectories in different parts of the pixel array.

When integrating on-chip processing for the dynamic binning, the natural step would be to include more of the star tracking functions currently implemented in software. The first function to include would probably be the identification and sorting of the brightest stars, something that could be part of the actual dynamic binning algorithm. To further reduce the size and complexity of the star tracker, one can imagine the integration of the off-chip memory which would require that dynamic binning is combined with simultaneous data decimation to reduce the required storage size.

To conclude the implementation aspects, there is little that indicates any unsolvable problems for implementing dynamic binning. The baseline chosen using CMOS APS seems to offer solutions to all demanding problems.

XIV. PROTOTYPE DEMONSTRATION

A prototype development is being planned for demonstrating the feasibility of dynamic binning, as well as showing that the star tracker front-end can be made using few electrical components. The objective is to show that a fast moving star pattern can be captured with sufficient accuracy using foreseen algorithms. The baseline architecture of the prototype will be presented hereafter. The following three functions/electrical components are foreseen: a CMOS APS device, a pixel array memory, and a Field Programmable Gate Array (FPGA) for control and processing. In addition to this, line drivers, voltage regulators and optics are required but not discussed any further.

The APS foreseen is the device developed within the Attitude Sensor Concepts for Small Satellites (ASCoSS) ESA activity. The device comprises a 512 by 512 pixel array with an on-chip 8 bit ADC. The pixel pitch is 25 micrometers and the pixel has been designed for high light sensitivity. The drawbacks are that the pixel output rate is limited to 2.88 MPPS and that the sensor is line-integrating resulting in long stare times. The architecture is however well known and the external timing control function is already developed. Also, it has been demonstrated that subwindows can be read out at rates as high as 1000 Hz. For the external pixel array memory a commercial 4 Mbit SRAM will be used.

All timing and control functions, dynamic binning and communication protocols will be implemented in the FPGA. It is foreseen to use a re-programmable device, supporting in-situ programming. This will allow modifications of the algorithm as the development and the evaluation progress. With devices offering more than 200 kgates and operating speeds well above 100 MHz, no direct limitations are currently foreseen. The FPGA will also implement a Universal Serial Bus (USB) interface through which the demonstrator will communicate with a personal computer.

Due to the limited performance of the on-chip ADC in the sensing device, the overall performance of the system will not be able to sustain an image frame rate of 128 Hz for the full pixel array. The solution will be to use subwindowing which will facilitate an operating range from 128 by 128 pixels at 128 Hz, to 512 by 512 at 10 Hz. The approach is in line with expected usage scenarios where a larger array at low readout rate is used when the spacecraft is stable, and a smaller array at a high readout rate is used when the spacecraft is rotating at high angular rates. The outlined demonstrator will be a first step towards the realisation of a single chip dynamic binning sensor.

XV. CONCLUSIONS

This paper has presented a method for enhancing the robustness of star trackers to high angular rates. The method is intended for APS-based devices and its full benefits will require APSs with advanced performance, in particular with a lower read-out noise than available at present.

The proposed method requires a good estimate of the velocity of the star image on the pixel array. In practice, this will entail combining the star tracker with a set of low accuracy, low cost, solid-state gyros.

Simulations indicate that theoretical gains in SNR of the order of 3-400% can be expected at angular rates of 1-2 deg/s. Several error sources have been identified with potential degradation of SNR of up to 40% but their combined effect is still unclear due to the presence of non-linearities.

Application of dynamical binning will introduce a bias in the estimate of star positions. The extent of the bias may be complex to compute but is deterministic and can in principle be compensated for.

Implementation of the dynamical binning algorithm on the imager chip hosting the pixel array is possible with current ASIC technology. This will result in a very compact system that hides the complexity of dynamical binning from users while giving them superior performance at high angular rates.

The architecture of an imager chip implementing dynamical binning as well as the architecture of a prototype currently being designed in ESTEC-TOS/ES have been presented. The prototype will demonstrate the practical feasibility of realising a star imager based on dynamical binning.

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