SOME DESIGN CONSIDERATIONS OF CCD IMAGING APPLIED TO HIGH ACCURACY SPACE BORNE STAR SENSORS

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ABSTRACT

Charge coupled imaging arrays are being considered for the detecting devices in strapdown off-axis star sensors required for high accuracy pointing of spacecraft. Tracking accuracies greater than the basic resolution of present or future arrays are required, and the most likely method of achieving such performance is described. Fundamental advantages of CCD are indicated, with particular reference to image dissector tubes. Some estimates of signal levels and random noise performance are given, and the implications for star sensor design of certain CCD characteristics are discussed.

INTRODUCTION

The European Space Agency (ESA) is presently engaged in projects requiring pointing or attitude reconstruction to arc second accuracy, such as Exosat (the European X-ray Observatory Satellite) and the Instrument Pointing System (IPS) for Spacelab. It is clear that future scientific space missions will continue to ask for pointing accuracies of the order of one arc second or even better. To achieve such pointing accuracy in an arbitrary inertial direction star sensors or trackers are and will be normally used for drift-free attitude determination and control system up-date.

The preferred type of star sensor for 3-axis stabilised satellites is now a strapdown sensor with off-axis tracking capability. The alternative, a high accuracy gimballed tracker, tends to be expensive and unreliable.

The most commonly used detector in present day star sensors/trackers of the former type is the image dissector tube. The main reasons for this choice are the high sensitivity and the inherent scan pattern flexibility. The image dissector has several serious disadvantages. Apart from the basic problems of size, high voltage requirement and fragility the tube also suffers from performance limiting factors, such as geometric distortion caused by the electron-optical imaging, dependence of the geometric properties on scan history, high stability requirements on supply units and sensitivity to variations of surrounding magnetic and electric fields. Non-uniformities in the sensitivity over the surface of the tube may furthermore result in positional errors. As a result such a star sensor will require accurate calibration before launch and frequent updating of its alignment while in orbit.

An R&D activity has been initiated by ESTEC in the field of star sensors with the aim of finding a different approach to their design. The goal is to conceive a sensor with an accuracy of the order of one arc second with maximum operational flexibility and simplicity. A study carried out at Sira Institute has shown that CCD imagers offer many

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advantages and some of the results of this investigation obtained so far will be discussed in this paper.

INSTRUMENT FIELD OF VIEW AND SENSITIVITY REQUIREMENTS

To achieve the intended degree of operational flexibility the instrument must have a field of view of at least $2^{\circ} \times 2^{\circ}$ and be able to find at least one suitable guide star for 95% of pointing directions. The sensor will therefore be required to locate and track stars down to 8th or 9th visual magnitude. Brighter stars would be available within a larger field but the required measurement tolerance would be a very small proportion of the total field angle. To operate with a smaller field would require the sensor to distinguish fainter target stars from a background of many similar stars and other celestial objects of comparable magnitude.

To begin with the sensor must search the field of view systematically to identify a suitable target star. 95% correct identification must be achieved within about 10 seconds of starting to search. This level of reliability must be achieved with signal levels of typically 1500 photoelectrons per second per cm^2 of telescope aperture, for a silicon detector.

Subsequently the star position must be continuously measured for as long as required to an accuracy of better than 1 part in 7000. The satellite attitude control system requires positional information at intervals no greater than 1 second, preferably less.

FUNDAMENTAL ADVANTAGES OF A CCD-BASED SENSOR

The major advantage of the CCD as a position measuring device is its stable geometry.

Ideally we should like to use a detector having sufficient elements to enable the required accuracy to be met directly, but this would require a 7200 x 7200 array, or an equivalent configuration of smaller devices and an extremely sophisticated optical system.

We must therefore attempt to achieve by interpolation an accuracy some 15-20 times better than the basic resolution of currently available devices. This requires comparison of the signals generated in adjacent elements of the device in order to locate the centroid of the energy distribution within the star image. Typically the image is spread over a 4-quadrant configuration of elements so that positional information referred to two orthogonal axes may be derived, as shown in figure 1. In practice the elements are not isolated perfect apertures. Non-ideal aperture response functions, cross-talk between adjacent elements and non-ideal image spread functions distort the transfer characteristic, causing "bias errors" in position measurement.

Rather than decode the position of the star directly from the error signal, we shall probably employ a null-seeking servo mechanism to deflect the star image to, and maintain it at, the centre of the nearest quadrant of elements. This "energy balance" technique reduces the dependence of the measurement on the shape of the transfer curve.

The axes to which these measurements are referred are defined during the construction of a CCD array. For an ID tube the elements of figure 1 represent sequential positions of a fixed aperture relative to a scanning electron image. The electron-optic imaging and deflection mechanisms are subject to a variety of interfering factors which affect the linearity, distortion and boresight alignment of the instrument during a mission. The resulting bias errors require complicated in-flight calibration procedures, whereas the geometric bias errors caused by CCD characteristics are not liable to vary in flight and may be determined before launch.

A further advantage of the CCD is its image integrating capability. This is particularly significant when the sensor is scanning the whole field of view whilst searching for a suitable guide star. Over the 10 second period allowed for a search operation a CCD element will accumulate over 300,000 photoelectrons from the faintest star to be detected. For comparison the ID tube will collect only 5 photoelectrons from the same star during the brief dwell time allowed at each point in its sequential raster. This difference in signal size offers a huge improvement in search mode random noise performance.

RANDOM NOISE AND SIGNAL LEVEL CALCULATIONS

For the purpose of estimating likely performance characteristics we have postulated a 200 x 400 element FT device, interlaced to 400 x 400 in search mode (see later). We have assumed an exposure rate in track mode of 1 Hz, and that the device will be cooled to $0^{\circ}C$ to reduce dark charge accumulation.

We calculate that, at null, the signal from the faintest guide star will be about 1½% of saturation charge in each of the four elements. (Saturation charge is assumed to be 10^6 electrons). The signal from background illumination (stellar background and stray light) may be around 3/4% of saturation, and the average level of dark charge will be of the order of 2%.

The random (shot) noise resulting from the generation of these charges, together with amplifier noise (assumed 100 electrons r.m.s.) and random variations in charge transfer loss, will contribute around 200 electrons r.m.s. noise to the signal. The corresponding noise equivalent angle (3σ) for a star diameter of two line widths (36 arc seconds) is about 1/3 arc second.

For search mode the lowest single element star signal occurs when the star is quartered by the search raster. In such a situation we could rely on a minimum star signal of around 12% of saturation after a 5 second integration time, against a background illumination signal of 4% and a dark charge accumulation of 10% of saturation. The range of measurable star brightness would be approximately 7 to 1. Subsequent frames using shorter integration times would be required to enable brighter stars, which would saturate in the first frame, to be measured.

The random noise in the search mode signal has been calculated at around 400 electrons r.m.s. The probability of statistical error in the detection procedure caused by the noise level is almost negligible. In fact star signals are much more likely to be confused with coherent noise in the frame, comprised of variations in the background light and uncalibrated fixed pattern noise in the array. This is discussed in more detail later, but the conclusion is that variations in responsivity and dark current across the array will be the limiting factors in search mode.

IMPLICATIONS OF DEVICE CHARACTERISTICS FOR SENSOR DESIGN

Organisation

Simple parallel-serial arrays cannot be used because image smearing during readout would be too serious for the integration times we shall require. In the absence of any line-addressed imaging arrays the choice lies between frame transfer and interline transfer. An array with separate photosites has several advantages, and the insensitive strips in the image plane of ILT arrays do not present insuperable problems for energy balance techniques. However, ILT arrays are unsuitable for back illumination, which is probably necessary as explained later. A frame transfer organisation is therefore preferred.

Fixed pattern noise

Fixed pattern noise in the array is caused by non-uniformity in both responsivity and dark current. These correspond in measurement terms to gain and offset respectively. These characteristics have not yet been accurately quantified by the industry, nor predicted in detail for devices under development.

It will not be practicable to include in the star sensor sufficient digital memory to calibrate FPN for each element of a high resolution device. The feasibility of incorporating an analogue CCD memory is being assessed. In track mode, in-flight calibration of only those four elements forming the tracking pattern is probably feasible following acquisition of the guide star. If in search mode the FPN remains uncalibrated, then its effect will be similar to random noise in obscuring small star signals.

In the calculations mentioned previously we have a star signal in search mode of 11.6% on a mean total background of 14.9%, a total signal of 26.5% of saturation. To achieve the required detection reliability against a uniform background, taking only the small amount of random noise into account, we could set the threshold at or below 26.2%. Setting the threshold at 20.5% would allow the background fixed pattern noise to rise to ± 5.6% before the statistical requirements would be no longer met. (Note that this reasoning treats fixed pattern noise simplistically as an offset, and so only properly applies to dark current and background light contributions, not to responsivity variations).

By some predictions of future device characteristics this "allowable margin" of FPN is low, but we do not have sufficient data on the behaviour of FPN with changing conditions, or on the distribution of variations across the array. It may well be feasible to calibrate out a few of the largest variations from the mean. If we find that the FPN is higher than we can accept then we must reduce the only one of the contributing factors which we can control, the dark current, by further cooling. This would have the added advantage of decreasing our total signal and therefore of increasing our measurable range of star brightness in one frame.

Aperture response

It is clear from the brief description given earlier that, for a given star image, the shape of the error angle transfer characteristic is dependent upon the cross-sectional responsivity profile across each element. This we call the aperture response. Ideally it would be a smooth function, but in practice local responsivity variations are likely to cause non-ideal profiles. This causes bias errors due to shifts of nominal null, asymmetry of, and local perturbations in the transfer curves.

One probable disturbing influence is the overlapping polysilicon electrode structure now almost universally used in area imagers. This structure will almost certainly lead to a very complex aperture response across an element in the vertical direction, although this has not yet been verified experimentally. We must, therefore, probably use back illumination.

For imaging purposes frame transfer arrays are usually interlaced by collecting the generated carriers under different phase electrodes in alternate fields. The most favoured scheme is that in which photoelectrons are collected under ϕ_1 electrodes in one field and combined ϕ_2 and ϕ_3 electrodes in the next. This should theoretically yield aperture responses as shown in figure 2. Photoelectrons generated under the non-collecting electrodes are collected by either of the adjacent collection sites, so the MTF at the Nyquist limit is zero and the cross talk between adjacent lines is considerable.

Convolution of the star image spread function with the aperture responses shown in figure 2 yields transfer curves which are unsymmetrical, with the origins of adjacent curves being unevenly spaced. A large degree of overlap renders one set of alternate curves redundant, and it is better to disregard the interlacing and use only one field. Figure 3 shows the idealised transfer curves which result from using the $\phi_2 + \phi_3$ lines only, with a star diameter equal to approximately one element width. Both fields would still be used in the search mode to achieve the highest possible raster resolution.

Reducing the size of the star image increases the gradient of the transfer curve near null (see figure 4) and theoretically reduces the noise equivalent angle. However, a small star image causes more sensitivity to local non-uniformities in the aperture response, as well as requiring a more complex optical system.

REQUIREMENT FOR DEVICE DEVELOPMENT

The type of device we shall require is a 500 x 500, buried channel, frame transfer array, thinned for back illumination. We choose 500 lines, although we should ideally prefer higher resolution, because this is likely to be available shortly in view of the impetus given to development by the American TV format. The interline transfer and front illuminated frame transfer arrays now available may in the meantime be used for lower accuracy sensors.

It will have become clear by now that many of the design trade-offs cannot be finalised because various properties of CCD imagers have as yet been insufficiently characterised and quantified, particularly fixed pattern noise and sub-elemental aperture response. Several projects aimed at improving knowledge in these areas are now under way or in prospect.

ACKNOWLEDGEMENT

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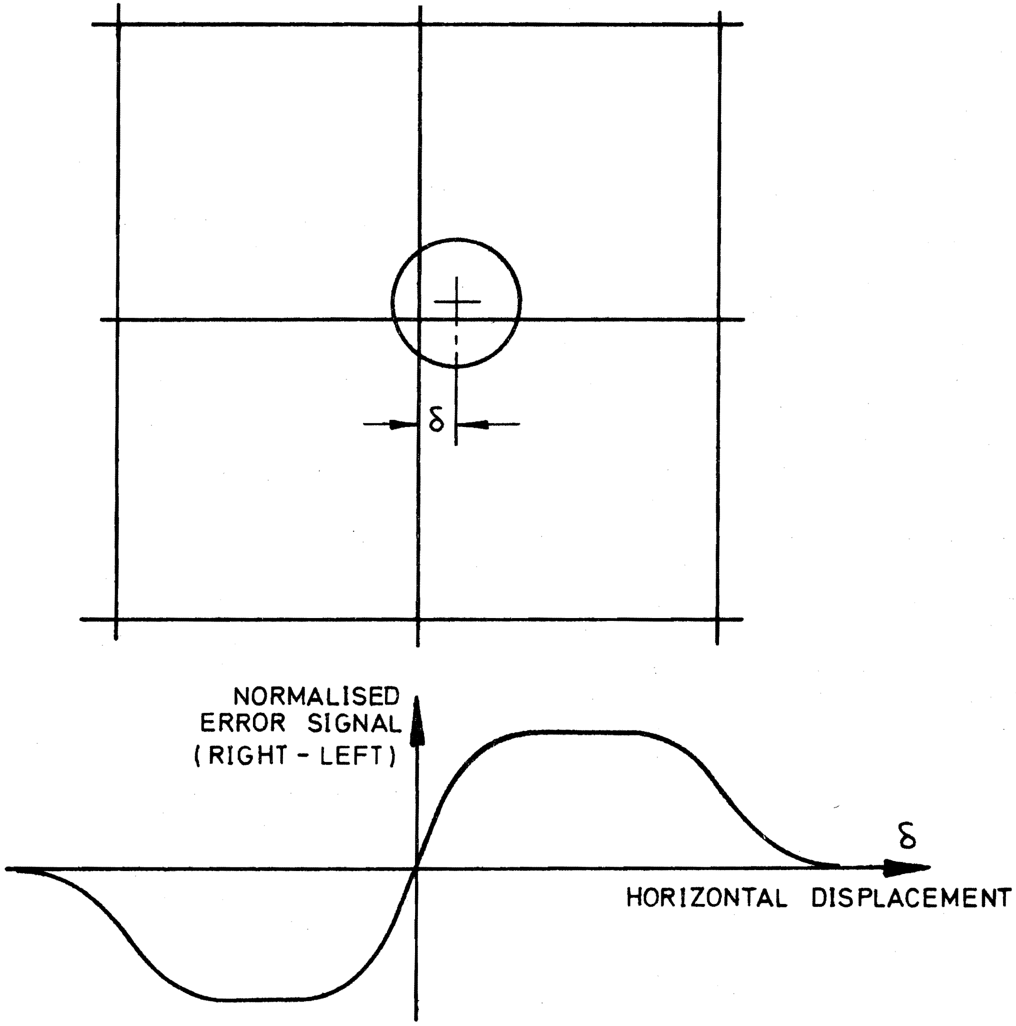

FIGURE 1. POSITION SENSITIVE QUADRANT PRINCIPLE AND RESULTING ERROR ANGLE TRANSFER CHARACTERISTIC

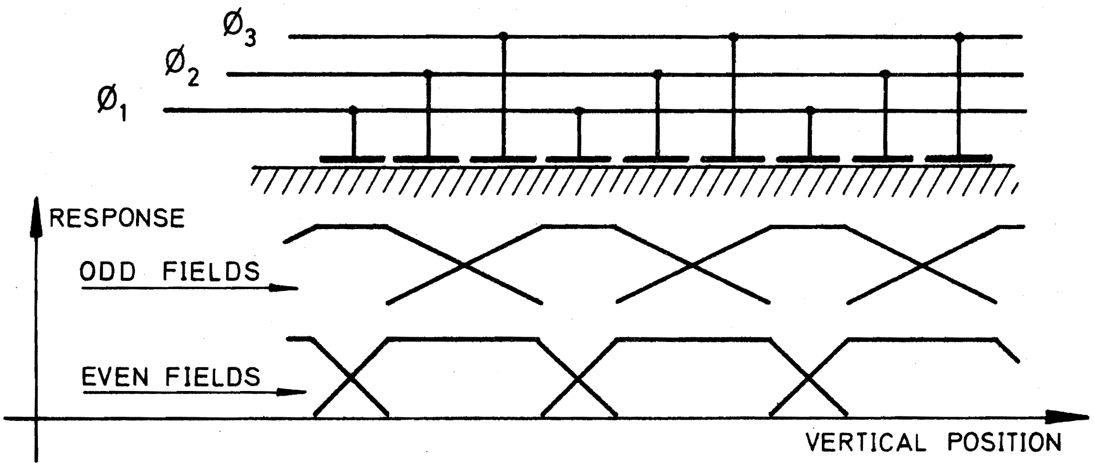

FIGURE 2. THEORETICAL APERTURE RESPONSES FOR $\varnothing_1/\varnothing_2+\varnothing_3$ INTERLACING

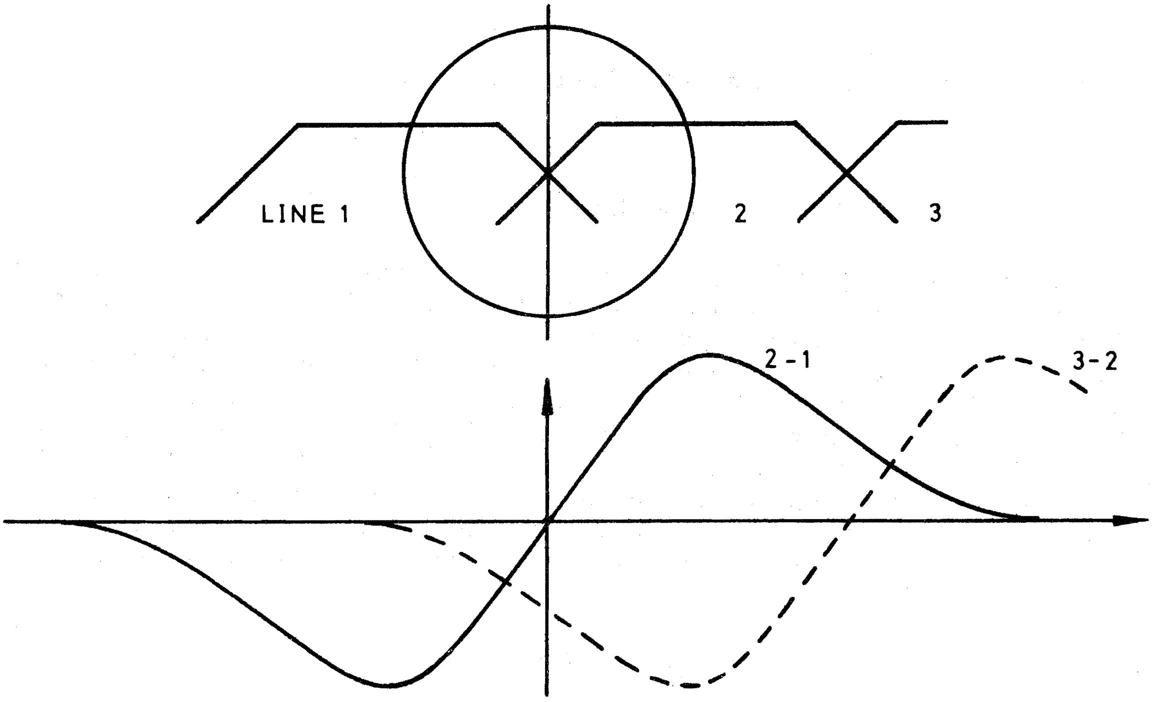

FIGURE 3. TRANSFER CHARACTERISTICS FOR A ONE-ELEMENT STAR DIAMETER WITH EVEN FIELD LINES ONLY

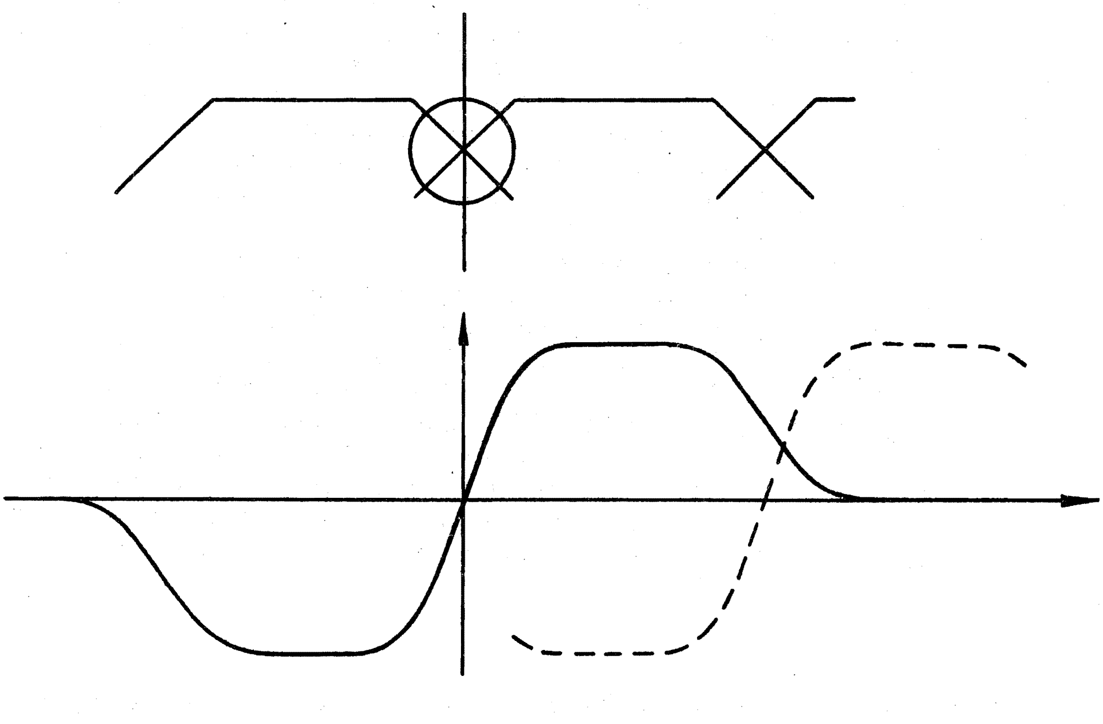

FIGURE 4. THE EFFECT OF A SMALLER STAR IMAGE