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HiPeG: A high performance balloon gondola for fine angular resolution X-ray telescopes

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Abstract

A platform for balloon-borne hard X-ray experiments capable of tens of arcsec pointing accuracy is a necessary condition for the new generation of high angular resolution X-ray telescopes. We have designed a new multi-mission platform in which the attitude determination system is based upon a high performance GPS and a star sensor equipped with a high-dynamic range CCD detector. The device is an autonomous and flexible system which, by means of efficient star identification and tracking algorithms, permits a fine dynamical pointing and reconstruction of the pointing trajectory down to the arcsec level. This paper presents specifications of the gondola and summarizes its characteristics which will be tested in a balloon flight scheduled in near future.

Keywords: Attitude control; Balloon-borne; Pointing precision; Star sensor; X-ray telescope

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1. Introduction

A wide range of techniques are being developed which enable efficient focusing of hard X-ray radiation. Large area, long focal-length X-ray optics have been developed based on grazing incidence reflection as well as Bragg and Laue diffraction: these techniques promise to extend the arcsec precision level obtained so far in the soft X-ray range to the 30–500 keV photon energy range. This is a major advance compared with previous telescopes working in this energy range, hardly capable of sub-deg resolution.

The concepts of the hard X-ray astronomy instruments approved for the satellite missions (see e.g. Fiore et al., in press) are usually tested and verified in balloon-borne experiments. Due to the severe requirements on pointing accuracy, new techniques are being developed to enhance the control and pointing performances of these platforms. In fact, the long focal length (a few to several meters) requires high aspect ratio telescope structures with consequent large changes of moment of inertia during zenith motion. Moreover, the high angular resolution ($\sim 20'' - 30''$) and the narrow field-of-view ($\sim 10' - 20'$) require high pointing accuracy and stability of the platform. Some of these new telescopes have already been flown with attitude control systems specifically fitted (see e.g. Harrison et al. (2000) for the HEFT telescope by the Caltech-Columbia University groups or Ramsey et al. (2000) for HERO telescope by NASA Marshall Space Flight Center). On the other hand, none of these devices was built to be autonomously tested as a standardized system to guide a range of different experiments. This condition, in particular, requires some features (complexity of the star

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identification software or accurate pointing error modelling) which are not completely discussed in the available literature since it is secondary to their main scientifical purposes like multi-layer mirror optimization or electronics and detector testing.

In Section 2 a general introduction of the HiPeG system is given, while Section 3 is dedicated to a detailed description of the star sensor hardware, modelling and laboratory tests.

2. The HiPeG concept

2.1. Requirements and specifications

We have developed a gondola concept (Silvestri et al., 2000) capable to achiving a pointing accuracy of $\pm 20''$ with a post-facto pointing knowledge of $\pm 10''$ or better.

The present high performance gondola (HiPeG) attitude control design contains a motorized pivot between the balloon cord and the gondola, which features an active decoupling from the platform. The reaction wheels, placed on the gondola plane, consist of two counter-rotating inertial wheels with a inertial momentum of 0.8 kg m^2 and a maximum angular velocity of 1000 rpm. Prototypes of the reaction wheels are already available and a number of tests have already been performed.

In the final configuration the telescope will be supported by an azimuth–zenith pointing mount. There will be an attitude control electronics, a transmit/receive radio system and the ballast for altitude stabilization of the balloon, for a total weight of approximately 3000 kg with a moment of inertia up to 5000 kg m^2 (variable during flight).

2.2. The attitude system

The HiPeG attitude control is based upon a differential GPS and a star sensor system. The GPS is equipped by four antennas placed at the ends of two 1 m long crossed arms. This configuration ensures a geometrical pointing accuracy of ~1 milliradian (~3.4′). This kind of devices has already been successfully employed in previous experiments and can be considered now a standard approach for high-accuracy attitude control systems (Gunderson et al., in press; Dietz et al., 2002). Nevertheless in the HiPeG system these devices need to be optimized to ensure reliability for different flight conditions (e.g. experiment location, flight duration, variable star density for different field-of-view), and therefore fully adaptive as multi-purpose facilities for high energy astronomy experiments.

The newly developed star sensor system, based upon a high dynamic range, cooled CCD detector, provides the information for the absolute attitude control down to the arcsec level, with a night pointing precision of $10''$ or better with a 1 s refresh. This information, fed into a digital signal processing (DSP), allows the motors for the azimuth–zenith axis to be controlled (see Fig. 1).

An on-board computer is dedicated to the real-time calculations of the coordinates of the target object. Another computer is dedicated to the star sensor image processing to extract possible off-sets to be fed into the DSP in order to update the telescope pointing. This procedure will be repeated with a very high frequency (1 Hz) to ensure effective tracking of the source.

A specific software (Silvestri, 1994) has been developed which enables the user to send and receive control string, to acquire and display the status of all subsystems and to perform preliminary scientific data analysis.

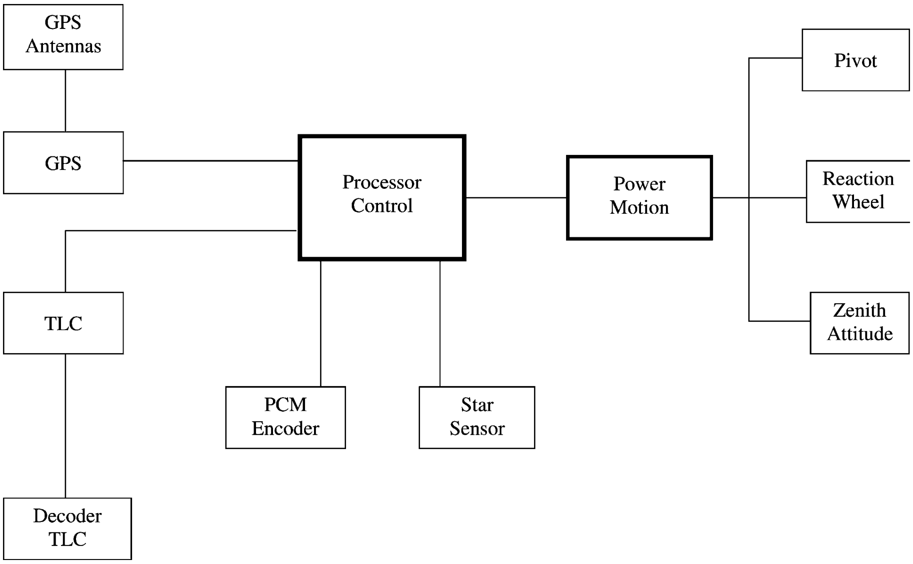

Fig. 1. A flow chart scheme of the HiPeG attitude system. The main components are described in the text.

3. The star sensor

3.1. The hardware

The HiPeG star sensor prototype uses a compact SenSys digital camera by Roper Scientific, equipped with a Kodak KAF 400 CCD chip. This CCD features a thermoelectrically (Peltier) cooled array of 768 × 512 squared pixels of 9 μm × 9 μm size. The pixel signal is read by a data digitizer in the camera head (12 bits ADC). The CCD readout speed of 1 MHz implies about 0.5 s for the full frame reading. This frame read out time leaves a maximum of 0.5 s for exposure and star identification with attitude determination, in order to achieve a 1 Hz refresh rate. The camera operates with high sensitivity in the 5000–9000 Å range to avoid the scattered-light background components of the atmosphere, which peaks at ∼4500 Å.

The CCD camera is equipped with an optics consisting of a nominal 100 mm photographic lens, that gives a field-of view of ∼4° × 3° with a diffraction-limited spot size (calculated at wavelength of 5650 Å) of ∼3.4 μm, which is smaller than the CCD pixel size. As tested during a night exposure of the camera at sea level, and considering sensitivity and optics transmittance, in experimental conditions this device will be able to acquire at least ∼20 star images down to magnitude 9 (Allen, 1973).

In the final configuration a zoom lens may be necessary to ensure the best matching between the required angular resolution and the pixel size. In the case of daylight operation, a blue rejecting filter will be studied and tested to cut the sunlight components (Rayleigh) scattered from the residual atmosphere of ∼4−5 g/cm^2.

3.2. The software: tests and simulations

The implementation of the star sensor prototype, including the software for star identification using a star catalogue (ESA's Hipparcos), also included the verification of an analytical model of the errors affecting the centroid determination and its propagation.

The physical quantities affecting the centroid determination are essentially the noise coming from each CCD pixel and the discretization caused by the pixel geometry. Considering the high dynamic range (12 bits) of the CCD, the signal output discretization effect is negligible.

To verify the centroid precision model, a Monte Carlo test has been performed on the star localization algorithm. Every star has been simulated with a bidimensional Gaussian with the centroid randomly placed on the CCD surface to test different effects of pixel discretization. Fixing at 5 ADC levels the presence of noise fluctuation for every pixel, the simulation tested 1000 stars with intensity ranging between 50 and 5×10^5 ADC levels and diameters (the σ of distribution) ranging between 0.2 and 20 pixels. According to real star images taken at the ground level, the values of noise, intensity and diameters are expected to fall within the above ranges during in-flight operations.

Fig. 2 shows the dependence of the centroid positioning error as a function of the star diameter σ as obtained from the simulation. According to the same plot, a σ value exists that minimizes the error centroid; below this value the effect of the pixel discretization dominates while for greater σ values the centroid error is caused by noise fluctuations. The effect visible at higher intensity (10^4 and 10^5 SNR values) for little values of σ are due to pixel saturation.

The influence of pointing precision caused by centroid error propagation has been evaluated with a Monte Carlo test on the attitude calculation only. The simulation consisted on a varying centroid number (from the minimum of 3 to 100) with known coordinated but de-localized in an arbitrary direction for a quantity equivalent to the pixel size. Due to linearity of the calculations involved in the attitude determination, this choice permits to obtain error values as a reference: the behaviour of the attitude precision can be therefore obtained by simply multiplying these data for the appropriate factor of de-localization.

Fig. 3 shows the pointing precision expressed as the variance of the vectorial differences between the calculated pointing direction and the nominal pointing (i.e. not affected by the introduced centroid error). The components of the differences are along the CCD x (long) side and y (short) side. For every number of centroids the simulation has a statistics of 10^5 events. The slightly different precision levels along x and y axes can be attributed to the CCD rectangular shape.

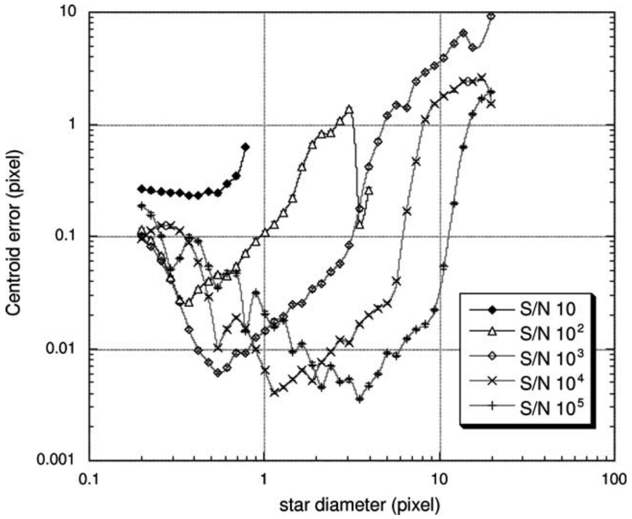

Fig. 2. Monte Carlo result of the total error affecting the centroid localization as a function of acquired star diameters for different SNR values. Errors are given in units of number of CCD pixels.

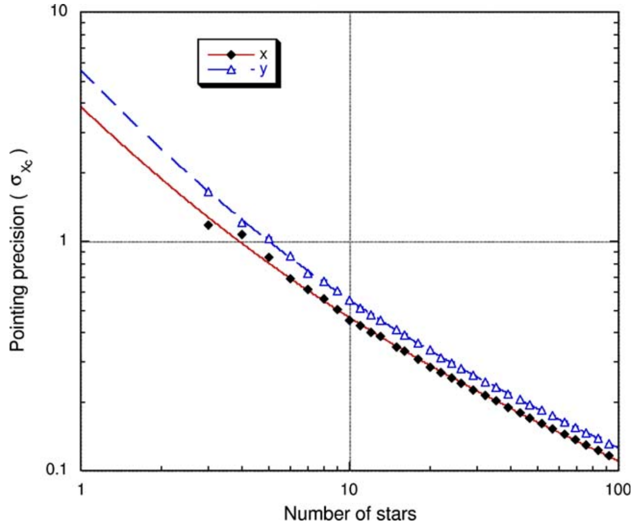

Fig. 3. Monte Carlo result of the pointing precision obtained as a function of the number of identified stars. Errors on centroid localization precision are expressed in units of number of CCD pixels.

A more detailed description of the star sensor software and its specifications is in preparation and will be the object of a future work.

3.3. Laboratory test

To verify experimentally the pointing precision before a more accurate in-flight evaluation, a simple laboratory test was carried out. A simulated star field was obtained generating point-like light sources using 12 LED diodes fitted on a screen. The screen was placed in the field-of-view of the star sensor at a distance such that the width of the LED point spread functions fits within the pixel dimension. The LED wavelengths cover a wide range of values (from blue to infrared) to test the influence of chromatic aberration of the optics. In order to test the star identification algorithm, the LED position on the screen was used to generate a "LED catalogue" analogous to Hipparcos. The pointing precision was calculated on a series of more than 80 images taken with an exposure time adequate to avoid pixel saturation. Furthermore, during different image aquisitions the diodes was slightly translated by a known quantity (μm resolution) to simulate dynamical pointing conditions and to avoid systematical errors due to the lighting of the same CCD portion.

Figs. 4(a) and (b) show, respectively, the dispersion of the measured pointing direction and their radial distribution best fit. The value of the measured pointing precision of $0.86 \pm 0.05''$ is in good agreement with the one expected from the analytical model ($\sim 1''$).

4. Conclusions

At present the new HiPeG gondola system is in assembling state at the IASF facility in Bologna. Tests are in progress on every component of the system to ensure the attitude performances.

Laboratory test and numerical simulations confirm that the new developed star sensor system performs according to the design specifications which give a pointing knowledge of at least 10″ level.

A first balloon flight to test the whole HiPeG attitude control system is foreseen in 2005 from the Sicily launch base of Trapani – Milo of the Italian Space Agency (ASI).

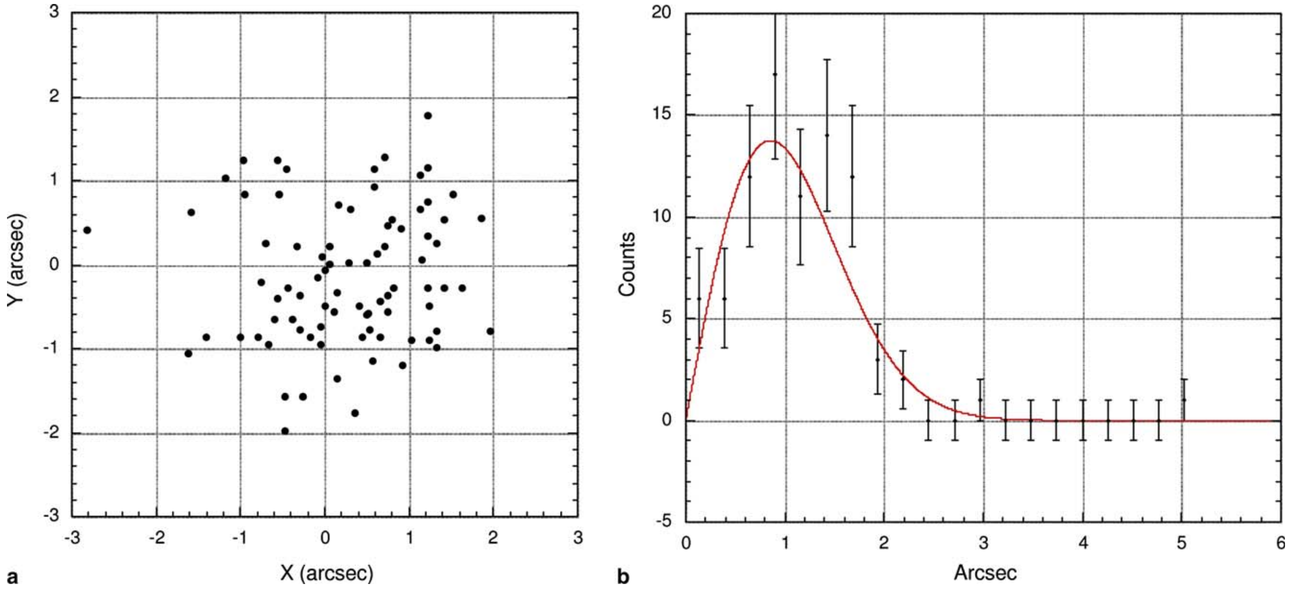

Fig. 4. Results of a laboratory test on pointing precision. (a) Spatial distribution of measured dispersion from the actual pointing direction. (b) Best fit on the radial distribution of the data dispersion shown in (a).

Acknowledgement

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