

A Gigapixel commercially-manufactured cryogenic camera for the J-PAS 2.5m survey telescope

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ABSTRACT

The J-PAS (Javalambre Physics-of-the-Accelerating-Universe Astrophysical Survey) project will perform a five-year survey of the northern sky from a new 2.5m telescope in Teruel, Spain. We describe the design concept of a complete cryogenic camera with a mosaic focal plane and 1.2 gigapixel science array which is to be commercially supplied. The focal plane is contained within a novel liquid-nitrogen-cooled vacuum cryostat, with proximity drive electronics designed to achieve a 4 e- readout noise from the 224-channel CCD system.

Keywords: cryogenic camera, CCD, J-PAS, survey, low noise, gigapixel, mosaic, FPA.

1. INTRODUCTION

The J-PAS project uses a 2.5m telescope under construction in Teruel and requires a large focal plane mosaic camera as the primary instrument. The main purpose of this telescope is to perform a dark energy survey using a set of narrow band filters. The camera utilises fourteen 82 Megapixel science CCDs and must operate with high performance and minimum maintenance for at least ten years. We describe the concept design of the cryogenic camera which utilises several novel features, including- rotary cryogen couplings to feed the Cassegrain-mounted camera, correlated double sampling of differential signals in the digital domain for low and secure read-noise of the 224-channel mosaic, custom CCD packages for focal plane integration, multi-layer CCD coatings for high spectral response.

2. OUTLINE OF CAMERA

2.1 JPCAM requirements

The camera needs a 476 mm focal plane diameter to achieve a 3 degree field of view. This is achieved using a set of large-area science CCDs together with auxiliary CCDs for autoguiding and image quality control (wavefront sensing). A key requirement is low readout noise combined with a readout time no greater than 10 seconds.

The camera is mounted at the Cassegrain focus of the 2.5m telescope and must fit within an allocated volume and mass limit, which is shared with other “warm” components [filter unit and shutter unit]. Operational and environmental requirements must be met as well as appropriate connections to telescope service. Excess heat must be managed and removed. The camera should be designed for a minimum lifetime of ten years, require low maintenance, and defined servicing time.

The cryogenic focal plane must be flat to 40 μm peak-valley and have controlled separation and tilt relative to the entrance window. The science sensors need to be configured with defined separations to match the filter trays above the cryostat. The figure below illustrates components of the JPCam instrument, which is described also in an associated paper in this conference¹. Within this paper we describe the camera subsystem which is under construction at e2v².

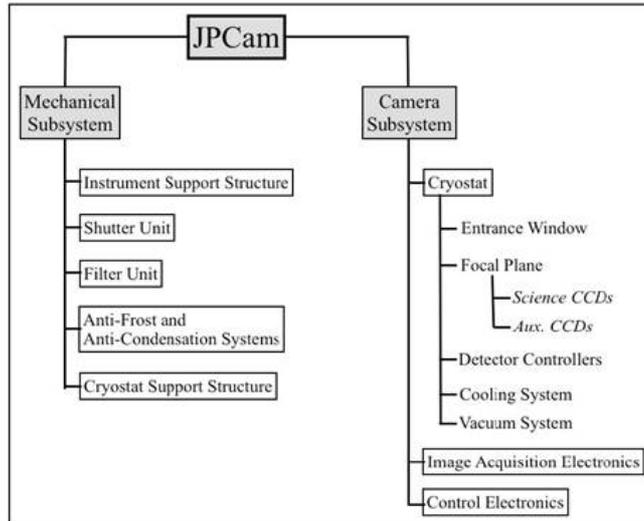


Figure 1. JPCam components.

2.2 Description of the e2v camera

The camera consists of the following main components- sets of three CCD types in custom packages, precision focal plane cold plate, cryogenic vacuum cryostat, precise mounting of cold plate and cooling via liquid nitrogen, external feed of cryogen via rotary couplings, vacuum pumps and system controller, local low-noise electronics designed for mosaic use, CCD interface electronics and data transfer, interfaces to mounting system and telescope. See diagram below and subsequent sections.

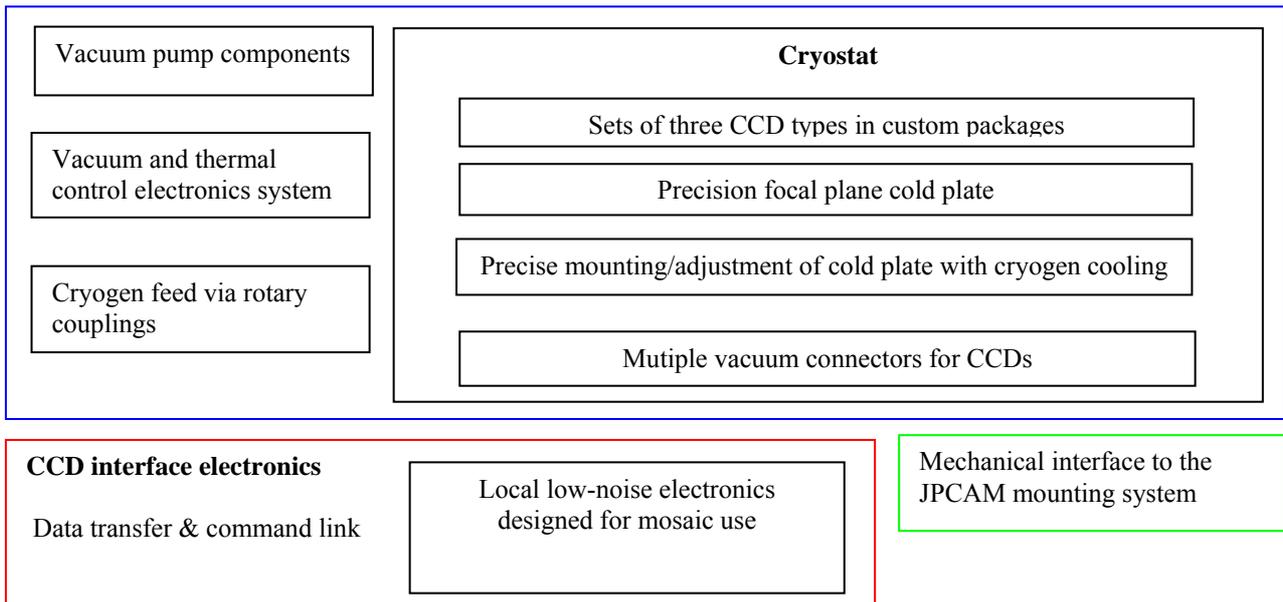


Figure 2. Main items of e2v camera

3. THE CCDS

3.1 Science CCD290-99

The science sensors have 9216 X 9216 pixels of 10 μm size. These devices have a 92 X 92 mm format which fills the six-inch silicon wafer. A precision silicon carbide package with 140 mm flex-cable connectors is used. They use sixteen outputs in order to achieve a nominal 10 second read-time at 500 kHz pixel rate. The sensor is the same size as the e2v CCD231-C6 sensor although this latter device has four outputs with 15 μm pixels. The readout amplifiers are the same as the CCD231 devices, with well-established 2 e- read-noise floor. The devices also have a real and dummy output for differential use (see later) and a two-stage output for low impedance and good drive capability to local electronics. The figures below illustrate the sensor and the readout noise.



Figure 3. CCD290-99 package model.

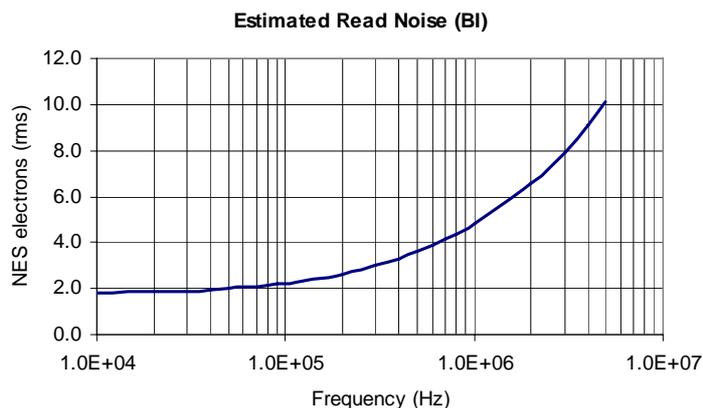


Figure 4. Read-noise

The sensors use deep depletion silicon, backthinned with a multilayer AR coating for maximum sensitivity. The wavelength range is 330 to 1000 nm, with optimised use desired over the 360 to 885 nm range. High response is achieved for much of this range, as shown below.

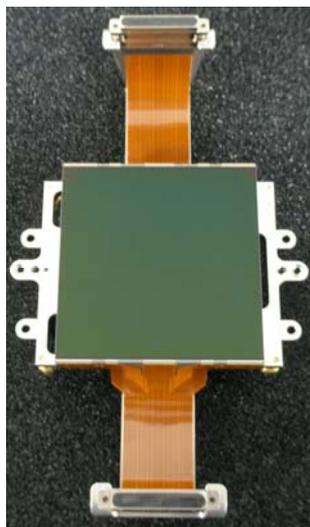


Figure 5. CCD290-99 in shipping frame

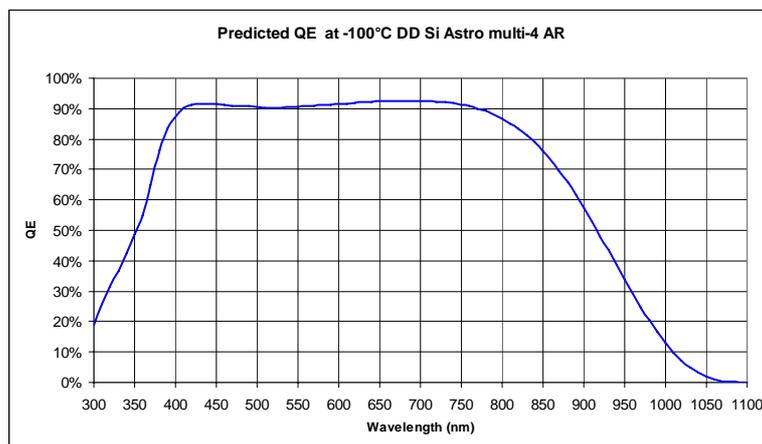


Figure 6. Spectral response

3.2 Auxiliary CCDs

Existing standard devices are used, except that custom packages have been designed for the mosaic application, to match the layout constraints within the field of view. These sensors are illustrated below.

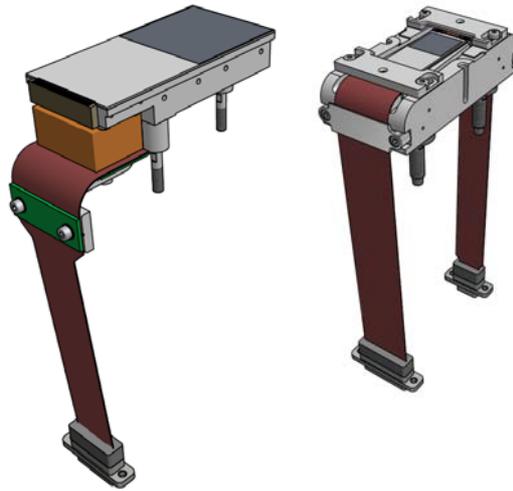


Figure 7. (a) WFS, (b) Guider

The CCD44-82 sensor is used in a frame-transfer format to deliver a 2048 X 2048 15 μm pixel format. These are used as wavefront sensors with a 500 X 500 pixel window and a 4 second read-time. They are mounted in pairs- each 1 mm above or below focus to provide wavefront information.

The CCD47-20 sensor provides a 1024 X 1024 pixel format for autoguiding. In this case a 50 X 50 pixel window can be read at 5 frames per second. These devices are co-planar with the science sensors.

Both devices have low read noise and are built with a deep depletion multi-layer coating to match the science device spectral response. They have precision invar packages for height control and flex cables for mosaic integration. They have two outputs, which are normally used for split readouts. However, in this application we use one (left) output for the image data and take the second (right) output to provide a no-signal differential output. See electronics section later.

4. FOCAL PLANE ASSEMBLY

The complete focal plane utilises an aluminium cold plate of approximately 500 mm diameter. Fourteen science CCDs, eight wavefront sensor CCDs, and four guide CCDs are co-mounted to achieve 40 μm total peak-valley flatness across the focal plane. The plate is designed for precision mounting in the cryostat via three radial adjustable fixtures to set its height and tilt relative to the cryostat window. It will operate at 173K and has cooling attachments on the underside.

The achievement of a larger and precisely flat focal plane is a non-trivial task, as discussed by others before^{3, 4, 5}. Extensive finite element modelling has been performed to ensure that the performance can be achieved. The aluminium plate is chosen for economy, easy of manufacture, and ease of procurement. However it has a considerable expansion mismatch to the silicon carbide and invar packages of the CCDs, and this is accommodated by a controlled torque on the fixing points per device that allow some compliance. The modelling emphasises that the flatness can only be achieved by allowing for expansion mismatch and also controlling the thermal distribution across the plate.

A project of this kind goes through the usual stages of concept design, modelling, detailed design and manufacture. This J-PAS project also involves considerable discussions with other parties involved, since the CCD layout must match the filter tray layout. In some cases, items such as this are being defined as the concept design is progressed.

The figures below show the cold plate layout and an example of temperature distribution from the FEA modelling.

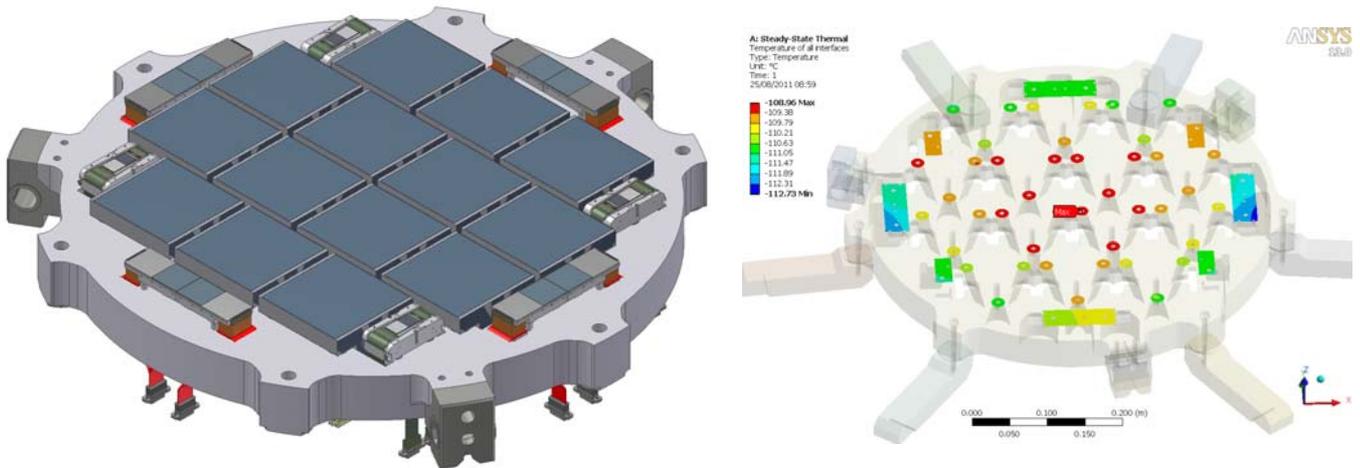


Figure 8. (a) Focal plane layout, (b) thermal modelling

5. CCD ELECTRONICS

5.1 Electronics overview

Amongst the multiple challenges of designing and supplying this large mosaic camera the electronics performance is recognised as a key element in achieving the scientific goals of the instrument; low readout noise is essential, together with reliable and flexible performance of the large set of three CCD types. Several organisations^{6, 7, 8} (academic and commercial) have made high-performance cameras and electronics but none offer commercial supply of a camera system optimised for this size of mosaic. Here we describe our solution to this requirement with a customised system that is nevertheless supplied under commercial contract with specified performance levels (and delivery schedule).

All CCDs are manufactured with flex-cables that terminate in micro-D connectors (as shown in section-3 above). These sensors are installed in the cold plate through which the flex-cables pass and the connectors then mate to corresponding ones in a custom vacuum plate which forms the lower disc of the vacuum cryostat. Underneath the cryostat, at ambient pressure, multiple drive board modules mate with the vacuum connectors- these provide all analogue signals in and out of each CCD and are physically located close to the sensors (with a flex cable length of order 150 mm). The drive modules digitise the CCD signals and each one is coupled to an interface module.

Early in the planning it was decided that in order to achieve high performance a digital correlated double sampling system would be adopted. This is more flexible than traditional analogue CDS designs and has been shown to achieve lower noise⁹. Furthermore, because this large mosaic has 224 channels of science data to digitise in close proximity to the auxiliary sensors, a differential CCD output is used. This has the strong advantage of being more immune to common mode signals- which can often plague large complex systems of this nature that operate in a noisy telescope environment.

Figure-9 illustrates the core components of the CCD electronics system: One drive module is used for each of the fourteen science CCDs, one drive module is used for each pair of WFS sensors, and one drive module is used for each guide sensor. An interface module acts a control and communications hub. Four fibre-optic cables link the CCD electronics to the host computers and utilise the Camera Link interface. Figure-10 shows the mechanical layout of these components and further details are provided in following sub-sections.

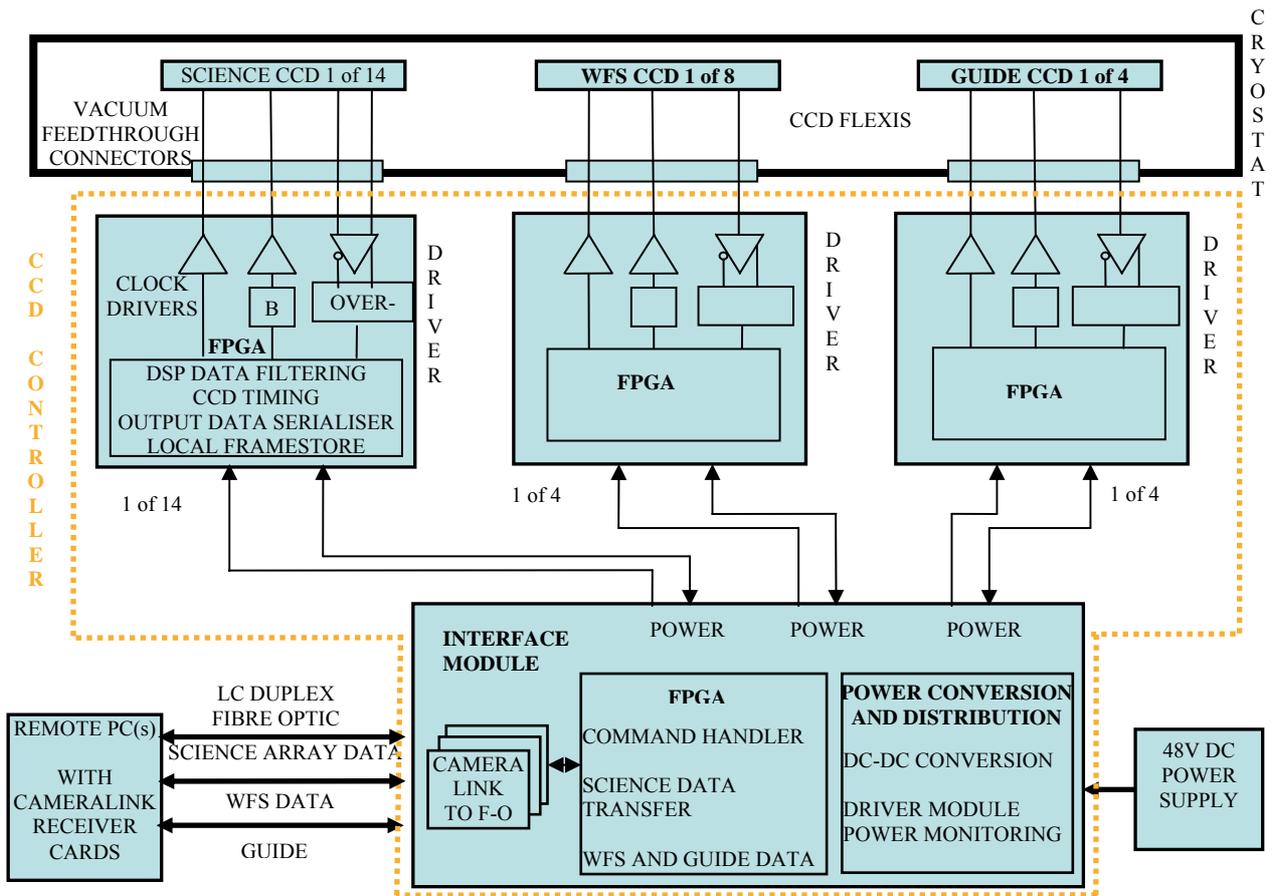


Figure 9. CCD electronics controller architecture

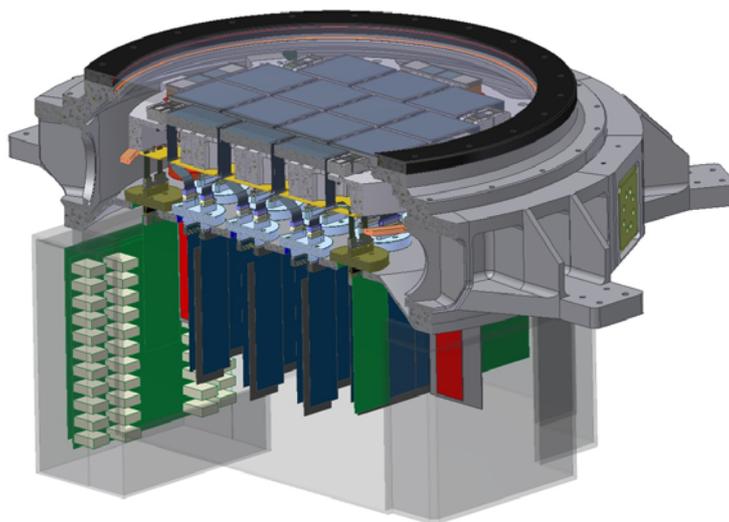


Figure 10. CCD electronics mechanical layout

5.2 Electronics driver modules

Each CCD is directly coupled to a drive module; this consists of three boards- two “digitiser” boards and one “bridge board”. These provide clock and bias signals to the CCD and process the analogue outputs. All readout patterns are locally generated, digital correlated double sampling [DCDS] is performed, a local frame store receives the image data, and digital communication is made to the interface module. FPGA’s perform most of the digital functionality.

A key element is the 8-channel digitiser using DCDS, as described more fully in the paper by Clapp⁹. This is designed to operate at 500 kHz- to provide the required readout time of less than 10 seconds. At this pixel rate the predicted readout noise is 4 e- rms. The CCD290 devices have true “real” and “dummy” outputs which feed into the differential input of the analogue signal chain. The Auxiliary CCDs do not have real/dummy pairs but do have two outputs per device; in this application we only use one output for reading out image data and use the second one as a differential reference output. Although the differential signals impose a $\sqrt{2}$ increase in read-noise the DCDS broadly compensates for this because of its improved performance compared to analogue-CDS.

The figure below illustrates this module and the CCD290 real & dummy outputs.

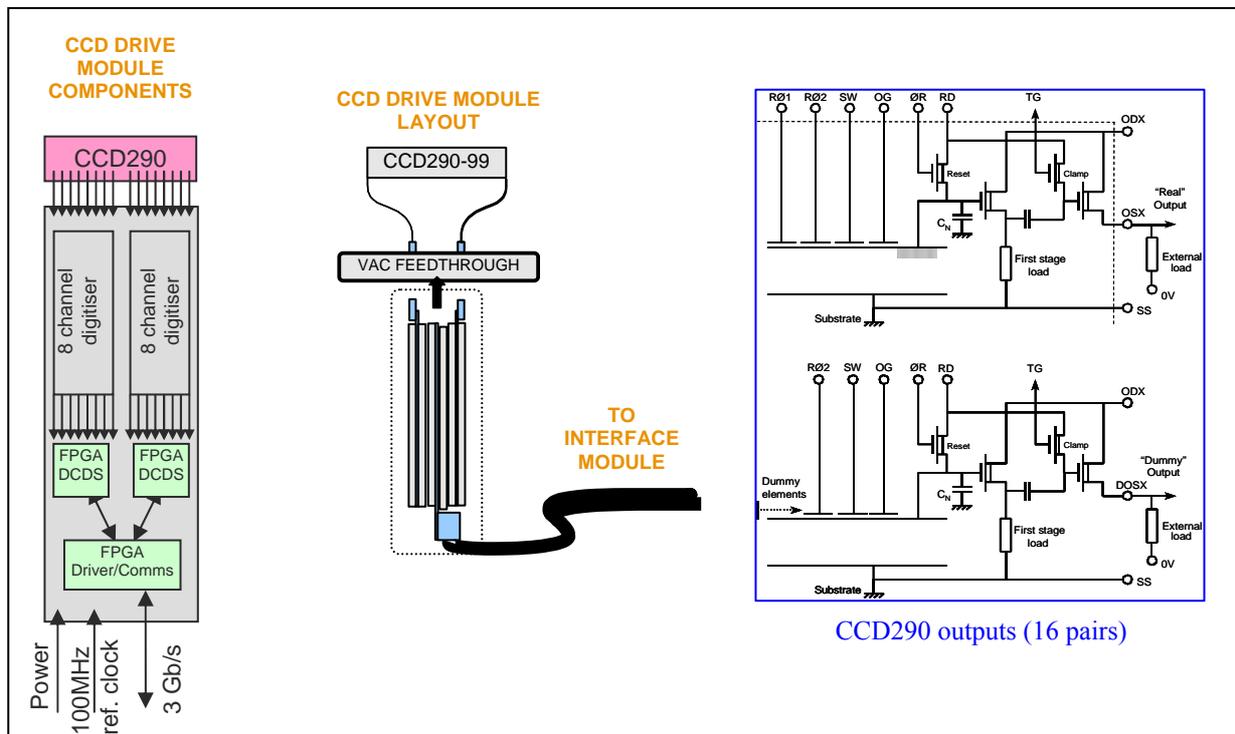


Figure 11. CCD drive modules, and CCD290 outputs

5.3 Electronics interface module

The second component of the CCD electronics system is the interface module. This receives 48V input power and performs appropriate conditioning to generate multiple lower voltage supplies. It has power and digital connections to the drive modules and is a central hub for communicating with these. It performs system monitoring, communicates with the observatory control computers and transmits image data to them- over four fibre-optic cables. See figure 12 below.

All drive modules and the interface module are housed in an enclosure under the cryostat which includes water cooling to control heat generation in the telescope environment. The 48V power supply is located close to the camera and supplies all power used by the CCD electronics; this is similarly cooled by telescope-supplied water.

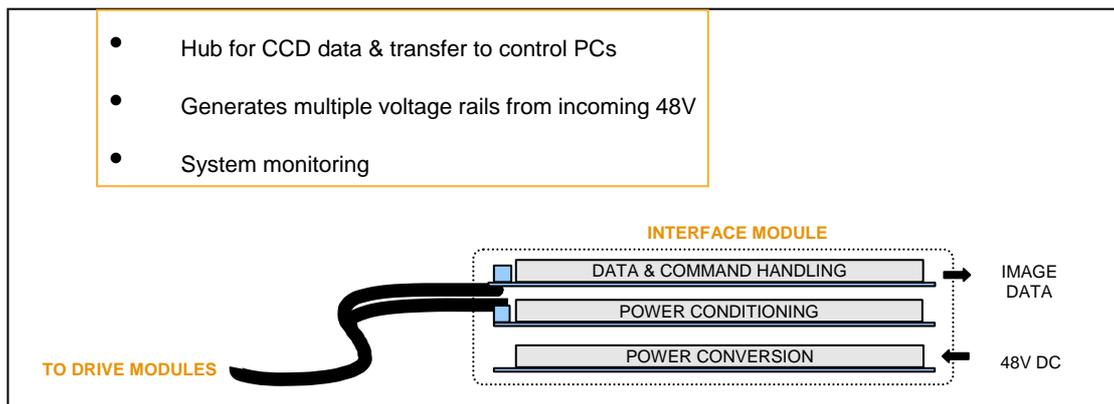


Figure 12. CCD electronics interface module.

6. THE CRYOSTAT AND COOLING

The cold plate (as in section 4) is housed within a cylindrical custom vacuum cryostat. Figure 13 below illustrates the primary chamber and shows a copper ring which is cooled via cryogen-fed pipes. The cold plate and upper vacuum-sealed window are not shown. Similarly the lower vacuum-sealed plate with multiple CCD connectors is not shown. The chamber is evacuated by a local turbo pump which has a removable backing pump; the initial evacuation is performed prior to use and then these items are not active during telescope operation. A sorption-pump chamber is also fitted and acts as a maintenance pump during normal use. Incoming cryogen cools the sorb to operating temperature and then passes to the copper ring in order to cool the focal plane cold plate. Two gate valves are used to isolate the turbo or sorb as required during pumping or sorb re-generation (a maintenance function). A short evacuation time and low-maintenance operation are important elements of the design.

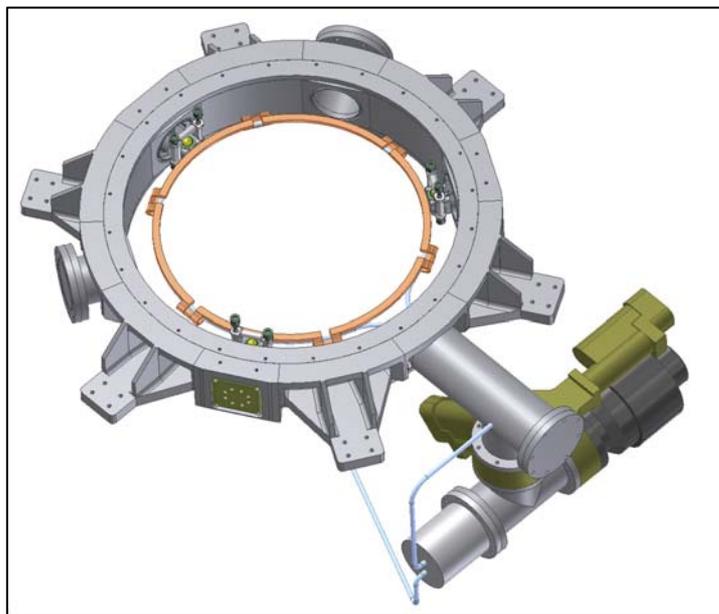


Figure 13. Cryo chamber showing vacuum & cooling detail

Liquid nitrogen cryogen is fed from a large Dewar mounted on the telescope fork (see later); a key element is the use of two cryogenic rotary couplings that are derivative from ideas of Lizon (ESO) and included in a paper by Vitali et al¹⁰. The rotary couplings and associated vacuum-insulated rigid pipework are provided by e2v after liaison with AMOS to establish the mechanical layout constraints at the telescope. The following section describes the overall system including vacuum and thermal control items.

7. THE CAMERA SYSTEM

The individual components have been discussed above and figure 14 illustrates the complete system; hashed lines illustrate the breaks in connections for components that are mounted away from the Cassegrain focus. The liquid nitrogen Dewar, with associated flow control components, is mounted on the telescope fork. A Programmable-Logic-Controller system (Beckhoff) is to be used for vacuum and thermal control, including appropriate safety interlocks and monitoring. Cold plate temperature will be established through a combination of LN2 flow control and traditionally controlled heater components on the plate.

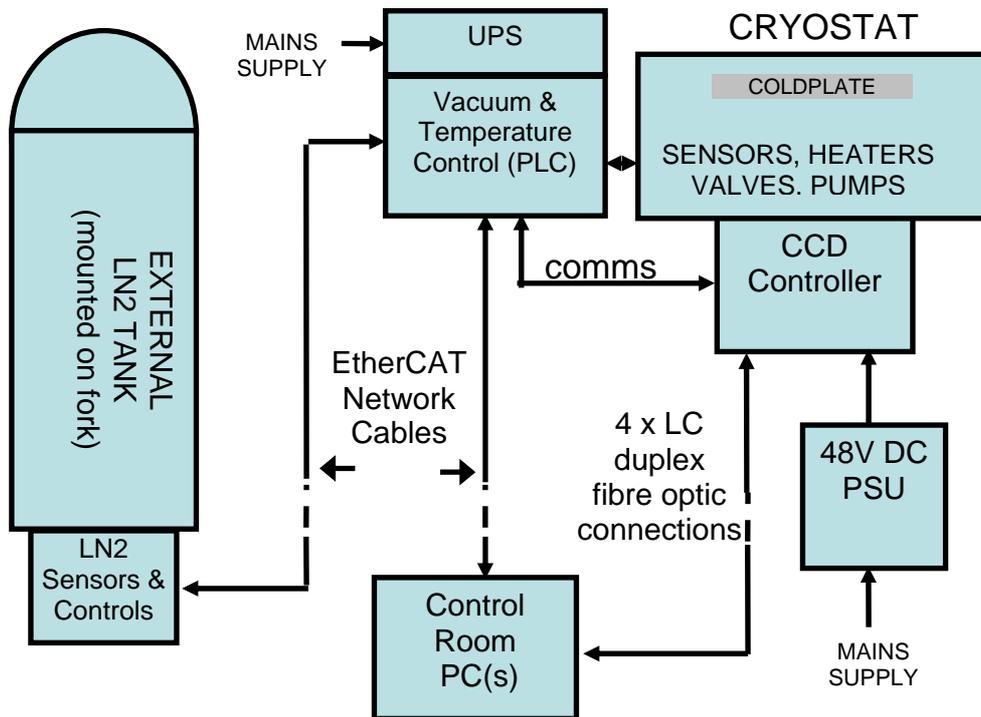


Figure 14. Camera system components

The complete camera is mounted at the Cassegrain focus via a set of adjustable arms (provided by NT Sener); this interface is important for stability and has been the subject of considerable interface discussion between e2v and the J-PAS team. The upper boundary of our camera is set by the optical window which is just below the shutter/filter unit- which is a J-PAS separately-procured item.

Figure 15 illustrates the camera mounted below the telescope mirror, with other non-e2v items also shown. The total weight (of e2v items) is estimated as 600 kg. Considerable FEA analysis is being performed to ensure adequate stability of the camera in association with the mounting components.

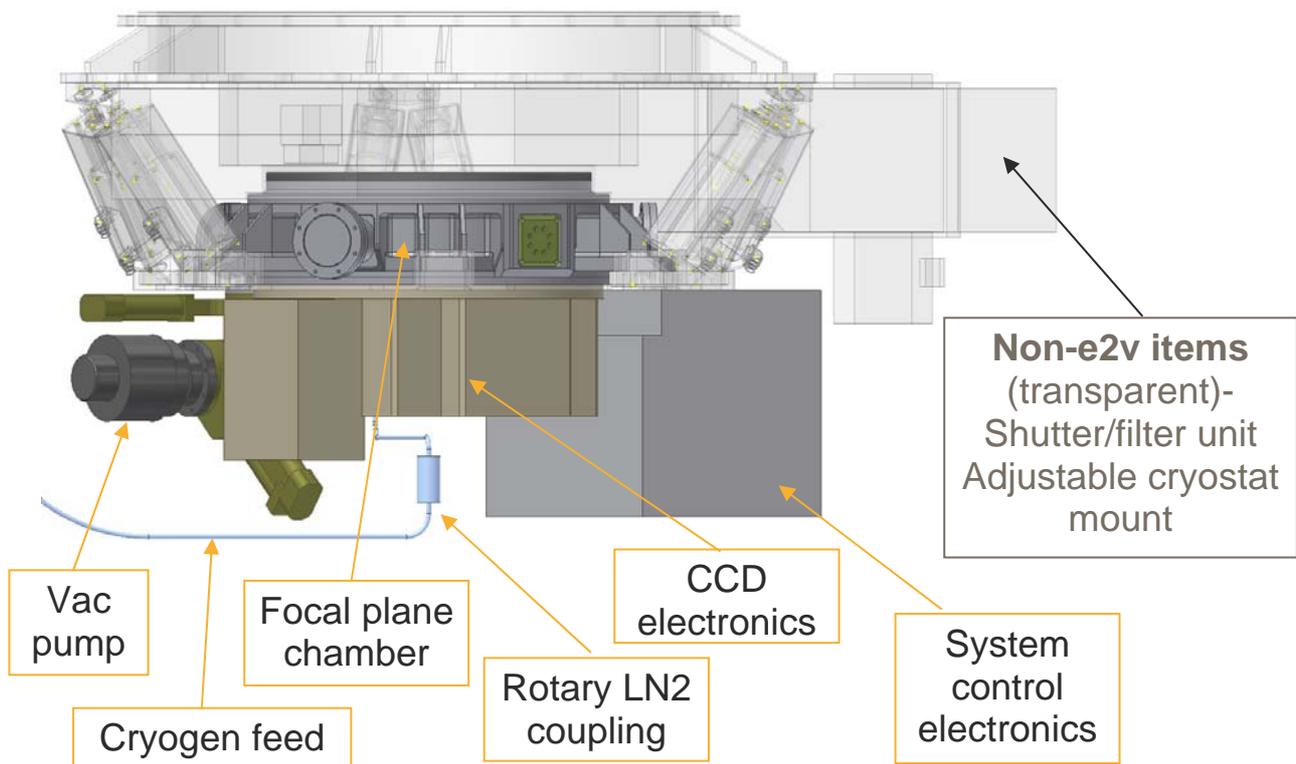


Figure 15. Mechanical layout of camera

8. CHALLENGES

This design and construction of such a complex system pose many challenges and a few of them are presented below.

The focal plane array (FPA) requires a set of wafer-size CCDs; high performance and guaranteed specifications.

The precision FPA requires significant design, modelling and assembly care in order to achieve the specified performance.

The 224-channel science mosaic requires a novel and high performance electronics system with secure performance.

The 1.2 GPix mosaic generates a large data set requiring adequate system design.

A novel large cryogenic camera is required with high stability on the telescope. The handling of this heavy structure needs organisation in clean room conditions (at e2v) and for transport and mounting at the telescope.

There are many customer interfaces to manage- AMOS for telescope mounting, cabling, services, access; CEFCO for observatory coordination & telescope specifications; other J-PAS members or sub-contractors (design & manufacture), Shutter & Filter unit, Cryostat support unit, etc

9. SUMMARY

The camera is currently under design with delivery due in 24 months. It incorporates a mosaic focal plane array of 1.2 Gigapixels to be used for the J-PAS 2.5 survey telescope. The science array uses very large format CCDs with optimised performance for this astronomical application. The cryogenically cooled cold plate is designed to deliver an excellent flatness across a 500 mm diameter incorporating three CCD types. A novel electronics design offers to deliver state-of-the-art performance over a period of extended operation. The system is designed for flexible operation with minimum maintenance and incorporates full system control features for telescope operation. The figure below shows a view of the camera system mounted on the telescope.

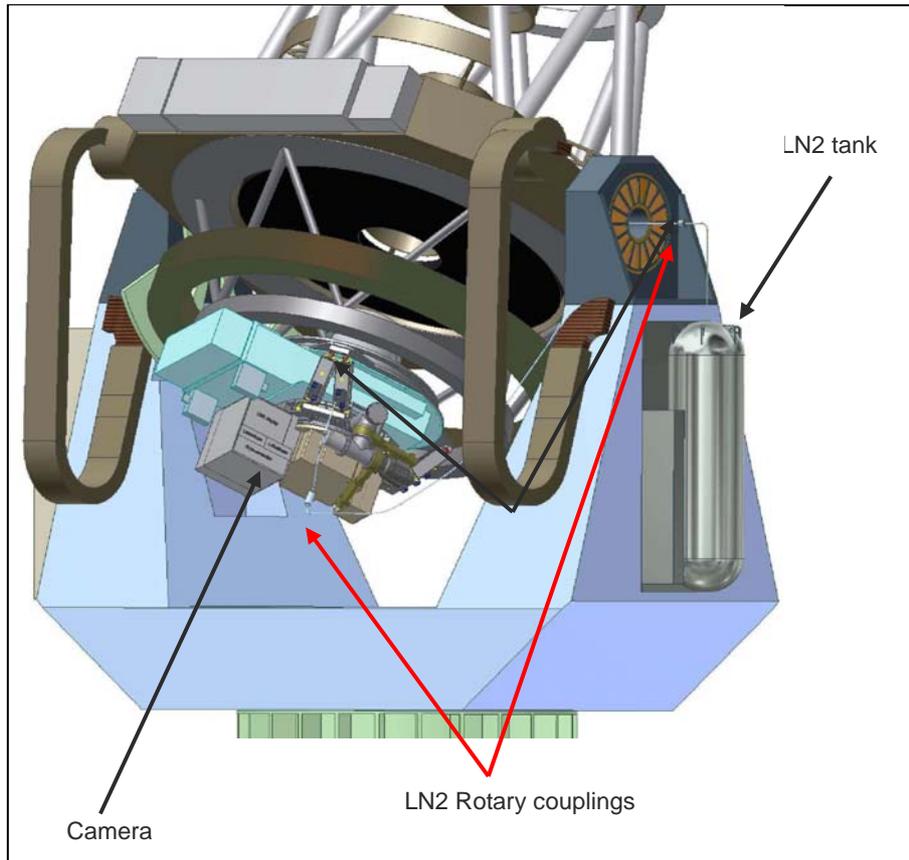


Figure 16. JPCAM on 2.5m telescope

10. ACKNOWLEDGEMENTS

Many e2v colleagues have contributed material and expertise to this work. The J-PAS collaboration is extensive and thanks go to all who have continued valuable discussions as this project progresses. CEFCA plays an important role as host of the telescope and AMOS¹¹ is manufacturing the telescope and providing valuable interface co-ordination. J P Lizon and O Iwert (ESO) are acknowledged for valuable cryogenic discussions.

REFERENCES

- [1] Taylor K, et al, "JPCam: a 1.2Gpixel camera for the J-PAS survey", Proc SPIE **8446**-36, 2012.
- [2] www.e2v.com
- [3] Aune s, et al, "The CFHT Megacam.." Proc SPIE **4841**, 513, 2002
- [4] McLeod B, et al, "Megacam.. for the MMT", Proc SPIE **3355**, 477, 1998
- [5] Iwert O, et al, "The Omegacam for the VLT", Proc SPIE **6276**-0A, 2006
- [6] <http://www.astro-cam.com/>
- [7] <http://www.specinst.com/>
- [8] <http://pan-starrs.ifa.hawaii.edu/>
- [9] Clapp M, "Development of DCDS readout system..", Proc SPIE **8453**-49, 2012
- [10] Vitali F, et al, "The REMIR Cryogenics Restyling", Proc SPIE **6269**-188, 2006.
- [11] www.amos.be