ECAM, a Modular Spaceflight Imaging System—Case Studies.

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Introduction: Modular systems can enable cost reductions through economies of scale, by allowing duplication and re-use of design elements. Modularity can also enable mass reduction, by providing a larger base over which to amortize new, lower mass technology development. Over the last several years, Malin Space Science Systems, Inc. (MSSS) has used our extensive experience in science instruments to develop the modular, space qualified, ECAM imaging platform (Figure 1). An ECAM system can have one, four or eight camera heads, integrated with a digital electronics that provides gigabytes of buffer and a capable hardware and software processing system [1]. While ECAM was originally conceived for engineering camera applications, its flexibile architecture makes it useful for science applications as well. Over the last year, MSSS has been awarded contracts from three different customers for ECAM systems for different missions. This transition from an IRAD program to multiple customer-driven programs has provided real-world applications scenarios that highlight the flexibility of the patform while also providing valuable feedback regarding the process by which this off-the-shelf hardware is applied to each unique mission.

Figure 1. ECAM 4-port Digital Video Recorder and CMOS and thermal IR Cameras (IR camera, center; camera head, lower left; DVR4, right).

ECAM modular spaceflight imaging system platform: Each ECAM system consists of a DVR and one or more camera heads. Camera heads interface to the DVR through a standardized interface that provides power and data on a single cable, with pin counts minimized to reduce cable mass. Examples of the DVR4 and the visible and thermal IR camera heads are shown in Figure 1.

Digital Video Recorders (DVRs). There are three configurations of DVRs, supporting one, four, or eight sensor heads. DVRs include a 128MB volatile buffer and non-volatile buffers of 8, 16, or 32GB. The baseline system performs JPEG (lossy) and Huffman first-difference lossless compression. JPEG2000, LOCO-I, or H.264 compressors may also be implemented. The embedded processor runs the instrument flight software, which implements the higher-level layers of the camera and spacecraft interface protocols and orchestrates all functions performed by the logic peripherals.

A qualification version of the DVR4 board is shown in Figure 2.

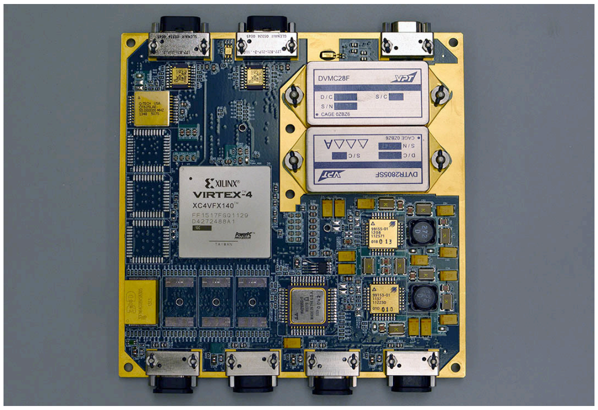

Figure 2. ECAM 4-port Digital Video Recorder PCB.

Visible Wavelength CMOS Camera. The ECAM-C50 acquires 2592 x 1944 format images with 2.2 µm pixel pitch; either Bayer pattern (color) or monochrome versions of this sensor are available. The C50 camera head weighs less than 250 g (without optics or mounting brackets).

Long-Wave Infrared Microbolometer Camera. The ECAM-IR3A uses an uncooled amorphous silicon microbolometer to acquire 640 x 480 format images with 17 µm pixels in the Long Wave Infrared band (8-13µm wavelength). It has a similar (though somewhat larger) mass and form-factor as the C50.

Optics. For the visible camera (C50), there are four standard lens options, ranging from ~90° to 15° fields of view. These optics are fixed focus, have no moving parts, are athermalized to provide stable performance over a wide temperature range. There are two standard LWIR lenses, with fields of view of ~20° and ~60°.

Interface. The DVR data interface to the spacecraft is comprised of eight LVDS differential pairs (RS-422 optional) in each direction, split across redundant connectors with independent drivers and receives. The interface is implemented in programmable logic, allowing substantial customization. The interface signals may be utilized in a redundant configuration to improve reliability, or may be used in parallel to improve transfer rates. Signaling protocols ranging from a simple (very slow) asynchronous interface, synchronous serial (moderate speed), or SpaceWire (high speed) may be implemented. Synchronous parallel interfaces are also possible, providing higher throughput at lower clock speeds and with less complexity than SpaceWire.

DVRs accept redundant +28V power, and include appropriate filtering to comply with typical MIL-STD-461 electromagnetic compliance requirements.

All ECAM system components are designed for a minimum 5 year life in a GEO radiation environment. The mechanical configuration accommodates additional radiation shielding for longer lifetime requirements.

Standard Flow. Based on prior experience from numerous NASA missions, MSSS has developed a standard assembly and screening program. Development begins by enumerating requirements, establishing an ICD, and developing an engineering model system for early verification.

Flight processing includes board-level burn-in and thermal-cycle acceptance, system-level vibration and thermal-vacuum testing, and EMC qualification of a non-flight assembly. This program is tailored to address mission-specific requirements and test levels.

TRL. The ECAM platform qualification has been proceeding in anticipation of deliveries of flight hardware in the second half of next year. As a result of those qualification efforts, the baseline ECAM system will be at TRL 8 by Q2 2015.

Current ECAM customers: MSSS has three ECAM systems in development for delivery in CY 2015. They are as follows:

OSIRIS-REx TAGCAMS (Lockheed Martin). The Touch-and-Go Camera System (TAGCAMS) is a multi-purpose imaging system that will fly on the OSIRIS-REx asteroid sample return mission [2]. TAGCAMS consists of a DVR8 and three C50 camera heads each with ECAM medium field of view (MFOV) lenses. One camera will monitor the delivery of the sample from the asteroid Benuu to the Earth sample return capsule (StowCam); the other two cameras will image the asteroid and background star field to support optical navigation when the spacecraft is the vicinity of the asteroid (NavCam). Each NavCam is operated from a different DVR board, providing end-to-end redundancy. The layout of the TAGCAMS camera heads on the OSIRIS-REx nadir deck is shown in Figure 3.

The key challenge in adapting the baseline ECAM design for TAGCAMS was in meeting the requirement to be able to image 4th magnitude stars with Benuu covering a significant fraction of the field of view (25-50%). To determine the feasibility of meeting this requirement and to develop a strategy for doing so, we used a combination of test and analysis:

<u>Test</u>: we used an ECAM engineering model unit to image 4th magnitude stars with an equivalent radiance to Benuu in the field of view (simulated with a light box), demonstrating that it was, in fact, feasible.

<u>Analysis</u>: working with the Breault Research Organization (BRO), we developed models of the scattered light for the various cases of interest (with different positions of the asteroid in the field of view). Like the testing, the analysis indicated the feasibility of meeting the requirement, while also providing the piece-part requirements necessary to meet the overall stray light performances: the lens elements are being fabricated with a surface roughness of less than 10 Angstroms RMS, and the broadband anti-reflection coatings on the lenses are designed to have a visible bnadpass reflectance of less than 0.35%. In addition, a larger baffle (relative to the baseline ECAM configuration) was included in the BRO analysis and incorporated into the TAGCAMS design.

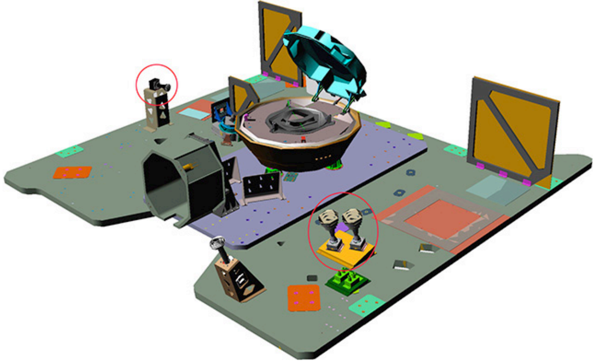

Figure 3. The StowCam (left red circle) and the two NavCams (right red circle) of TAGCAMS, shown in their mounting locations on the nadir deck of the OSIRIS-REx spacecraft. The DVR8 is mounted inside the spacecraft bus.

Another modification from the ECAM baseline required for OSIRIS-REx was implementing redundant, Junocam heritage, asynchronous (command and housekeeping) and synchronous serial telemetry interfaces using RS-422 at the electrical level.

Undisclosed customer #1. The second ECAM system currently in development is for a customer that prefers not to be identified at this time. The system in question is a DVR4 system with four camera heads: one C50 color visible camera, and three IR3A thermal infrared cameras. The visible camera has a narrow field lens; the IR cameras have a combination of wide- and narrow-field lenses.

There were several challenges in adapting ECAM for this application. First, there were specific dynamic range and NEDT requirements on the infrared cameras that, taken together, exceeded the baseline configuration. This is being worked with a combination of test and analysis to guide the tradeoff between detector operating parameters and optical design to provide the necessary overall performance. A lesser challenge was the need for multiple, high-speed interfaces to output data from the DVR to the spacecraft. This is being implemented as four (non-redundant) SpaceWire channels. While this differs substantially from the baseline of a single (redundant) SpaceWire data interface, the DVR design has enough flexibility to accommodate this without hardware modification.

Undisclosed customer #2. The third ECAM system currently in development is for a customer that also prefers not to be identified at this time. The system in question is a DVR4 system with a single camera head: a C50 color visible camera. This visible camera has a narrow field lens.

The key challenge with this system is meeting some very tight customer timing requirements. This included having after-the-fact knowledge of when an individual exposure started to within 1 ms. While the ECAM architecture was not envisioned to accommodate timing control at that level, analysis indicates that it will be possible to characterize the latencies in the system to a resolution that will support the required after-the-fact knowledge of the exact time each image was acquired.

Finally, this customer required replacing the baseline SpaceWire data interface with a simple synchronous serial interface using LVDS at the electrical level.

Lessons learned: While each of these three ECAM programs is unique, in considering them all together, patterns emerge:

- Each customer requested a different data interface with the spacecraft. While each of those was within the flexibility the ECAM architecture was designed to provide, in retrospect, each took more time and effort to negotiate than we had initially assumed.

- Each customer also had their own unique requirements for data handling, modes and rates. As with the interfaces, none of these tested the limits of ECAM's substantial flexibility, but defining them at the required level of specificity was more effort than expected.

- Many interface concerns were resolved not with custom hardware development, but by specific camera characterizations to inform the detailed system-level design.

The recurring theme here is the need to allocate somewhat more attention to interface and requirements definition early in the program. As expected, each customer had unique interface requirements; Despite this, all could be accommodated with customized FPGA logic, using the single, flexible, data interfaces of the DVR (the only unique hardware configuration being the selection of LVDS or RS-422 drivers and receivers).

References: [1] Schaffner, J. A., M. A. Ravine and M. A. Caplinger (2012), Int'l Workshop on Instrumentation for Planetary Missions, Abstract #1130. [2] Drake, M. J et al., American Geophysical Union, Fall Meeting 2011, abstract #P42A-03.