Introduction: Cost and mass continue to be driving constraints in deep space instrument development. These constraints may result from programmatic considerations, as is typical on competed missions, or they may come from engineering factors, such as the small mass necessitated by high delta-V lander or probe missions. Either way, the science return from any such instrument is a strong function of its mass and cost efficiency.

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. However, science instruments for space missions are often “one-off” developments with little modularity and proprietary internal interfaces. Malin Space Science Systems, Inc. (MSSS) has an extensive heritage of science instruments with various types of modularity. The ECAM platform (Figure 1), originally conceived for engineering camera applications, is architected to further this modular off-the-shelf approach. 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. Science-grade cameras for the ECAM platform are currently in development at MSSS and will offer reduced cost and mass, shorter development times, and lower development risk for small science instrument applications.

Heritage of Modularity at MSSS: The technical underpinnings and architectural concepts of ECAM have evolved from MSSS heritage on numerous deep space science instruments and earth-bound engineering cameras, including (listed starting with the most recent delivery):

- Junocam on Juno (Jupiter orbiter)
- Mast Camera (Mastcam) on Mars Science Laboratory (MSL)
- Camera Monitoring Assembly (CMA) on a classified LEO mission
- Mars Hand Lens Imager (MAHLI) on Mars Science Laboratory (MSL)
- Mars Descent Imager (MARDI) on Mars Science Laboratory (MSL)
- Lunar Reconnaissance Orbiter Camera (LROC) on Lunar Reconnaissance Orbiter (LRO)
- Mars Descent Imager (MARDI) on Phoenix lander
- Context Camera (CTX) and Mars Color Imager (MARCI) on Mars Reconnaissance Orbiter (MRO)
- Thermal Emission Imaging System (THEMIS) Visible Camera on Mars Odyssey (MO)
- Mars Descent Imager (MARDI) on Mars Polar Lander (MPL)
- Mars Color Imager (MARCI) on Mars Climate Orbiter (MCO)

While each of these instruments had unique requirements, they also share common traits and leverage various modular strategies.

Partitioning of Sensor and Processing/Interface Design Elements. LROC, Mastcam, MARDI, MAHLI, and Junocam are all partitioned as shown in Figure 2, with one or more sensor heads with digital and power interfaces to a digital element that provides the spacecraft interface and some combination of preprocessing, compression, storage, post-processing, and readout/playback functions.
the crowded turret at the end of a robotic arm).  
• Maximize survivability in harsh thermal or ionizing radiation environments (e.g., the MSL camera heads are exposed to the extreme Martian climate and Junocam is fully exposed to the harsh Jovian radiation environment; partitioning allows much of the instrument to be located within the S/C bus enclosure, where the environments are more benign).  
• Support multiple sensors from one spacecraft interface (e.g., LROC includes two narrow-angle cameras and one wide-angle camera, but these were proposed as one instrument with one interface to the spacecraft).  
• Minimize mass and power by sharing processing and storage between multiple sensors (e.g., CMA used two sensors with two fields of view, but both sensors share the same pre-processing, compression, and storage functions).

Integral to this partitioning approach is this design strategy: make the sensor element as simple as possible, providing bare-bones functionality at the lowest possible level of abstraction. To minimize mass and volume, the sensor heads typically utilize a one-time programmable Field Programmable Gate Array (FPGA).

Conversely, the digital processing/interface element typically utilizes a Static Random Access Memory (SRAM) type FPGA, which is configured at power-on from external memory. The architecture may include various types of configuration memory that allow in-circuit re-programming by dedicated electrical interface prior to flight, and/or in-flight patching/reconfiguration of logic and/or software.

Experience has shown that the part of the system with interfaces to the spacecraft is most likely to require patching, and by putting as much of the system complexity in the parts of the system that can be reconfigured, we maintain maximal flexibility to address issues that may be discovered late in the integration and test flow.

Duplication of Design Elements. Some design challenges are best solved with more than one copy of the same sensor head. For LROC, two identical Narrow-Angle Cameras (NACs) placed side-by-side meet the resolution and field-of-view requirements. For CMA, two identical sensors with different optics provide the necessary views without need for more complex and expensive pan/tilt or zoom/focus mechanisms.

Systems using duplicate design elements also benefit from economies of scale. Dating back to MCO-MARCI, the Medium Angle (MA) and Wide Angle (WA) cameras used identical electronics with different optics and color filter arrays, to reduce cost and development time.

MSL realized substantial cost savings by using one electronics and logic design for all four camera head/processing element sets required for Mastcam, MAHLI, and MARDI.

Re-use of Design Elements. Substantial reductions in cost, schedule, and risk can be realized by re-using existing, proven, design elements. For LRO, the electronics of the NAC were derived with minimal hardware modification by speeding up the Context Camera (CTX) electronics from the MRO mission. The Wide Angle Camera (WAC) used the MCO-MARCI electronics design (build-to-print). In fact, the MCO-MARCI electronics were used, without modification, for MPL-MARDI, THEMIS-VIS, Phoenix-MARDI, and MRO-MARCI, as well.

For Junocam, the camera head used a build-to-print copy of the Mastcam/MAHLI/MARDI electronics with the FPGA logic revised to provide Time Delay and Integration (TDI) capability.

The primary objective of ECAM is to coalesce all of these modularity strategies into an off-the-shelf hardware platform that maximizes flexibility, minimizes cost and spacecraft overhead, and uses standardized, configurable, modules with standard interfaces.

Baseline ECAM Modular Off-The-Shelf Platform: The baseline ECAM platform is comprised of:

• Digital Video Recorders (DVRs)
• Compact cameras with standardized electrical and optics interfaces and configurable mounting options
• Standard lens options

Each ECAM system consists of a DVR and one or more cameras or sensors. DVRs are available in configurations supporting one, four, or eight sensors from a single spacecraft interface.

Sensors 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. The sensor data interface is SpaceWire [1], operating at up to 200 Mbit/s, and sensors are supplied +5V regulated power.

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.

CMOS Cameras. The ECAM-C30 acquires 2048x1536 format color images with 3.2µm pixel pitch. The ECAM-C50 acquires 2592x1944 format images with 2.2µm pixel pitch; either Bayer pattern (color) or monochrome versions of this sensor may be
The C30 and C50 camera heads share an identical form factor, measuring 65x65x49mm with a mass less than 250g (without optics or mounting brackets). One of the configurable mounting options is illustrated in Figure 3. In total, four different mounting orientations are possible using the standard mounting brackets.

Figure 3 - ECAM-C30/C50 in z-axis mounting configuration (U.S. quarter shown for scale)

Long-Wave Infrared Microbolometer Camera. The ECAM-IR1 uses an uncooled amorphous silicon microbolometer to acquire 384x288 format images with 25µm pixels in the Long Wave Infrared band (8-13µm wavelength).

Optics. A basic set of three standard lens options are offered for the ECAM-C30/C50, with specifications summarized in Table 1. These optics are fixed focus, have no moving parts, are athermalized to provide stable performance over a wide temperature range, and are built to withstand the hazards of launch and long-term operation in orbit.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NFOV</th>
<th>MFOV</th>
<th>WFOV</th>
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<tr>
<td>Mass (g)</td>
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<td>95</td>
<td>90</td>
</tr>
<tr>
<td>Dimensions (mm, Diameter x Height)</td>
<td>58x90</td>
<td>58x82</td>
<td>58x76</td>
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<td>Focal Ratio</td>
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<tr>
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<td>50</td>
<td>88</td>
</tr>
<tr>
<td>Vertical FOV (°, w/C30)</td>
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<td>38</td>
<td>63</td>
</tr>
<tr>
<td>Operating Temperature (°C)</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

The standard lenses are adapted from optics designs developed originally for the MSL cameras. Figure 3 shows the NFOV lens, which flew on CMA.

For missions with requirements that cannot be addressed by the standard lens options, MSSS develops custom optics with fields-of-view from 5° to 180° using standard refractive optics. Longer focal lengths are supported using catadioptric and reflective telescopic optics. Additional capabilities for custom optical systems include motorized focus adjustment and zoom lenses.

Digital Video Recorders (DVRs). There are three configurations of DVRs, supporting one, four, or eight sensor heads. The DVR4 is shown in Figure 4.

The DVR data interface to the spacecraft is comprised of eight LVDS differential pairs (RS-422 optional) in each direction, split across independent connectors with independent drivers and receivers. 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 clocks 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.

The DVR architecture utilizes a resource-rich SRAM-based FPGA, on which an embedded controller with custom logic peripherals is configured. The logic peripherals implement the signaling protocols for the sensor head and spacecraft interfaces, memory controllers for the volatile and non-volatile buffers, and image processing and compression functions.

Logic peripherals are only utilized for processing functions that cannot be performed sufficiently quickly by the embedded processor.

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. Flight software may also perform software post-processing of data, i.e. the Z-stack processing in MAHLI [2].

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.
Depending on the particular requirements of the mission, several operations concepts are possible, such as:

- Sensor data is processed and compressed at acquisition-time and buffered in compressed form for later playback to the spacecraft; allows for storage of more data.
- Sensor data is buffered in raw form, and compressed at playback-time: allows for transmission of data at more than one compression ratio and ad-hoc reprocessing/retransmission of data subsets.
- Sensor data is streamed directly to the spacecraft (compressed/processed or raw).

Custom Peripherals. In addition to sensors, the DVR ports may also support custom peripheral devices such as light sources and mechanisms (i.e. small pan/tilt platforms, sample manipulators, etc.).

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.

Flight Heritage. The ECAM platform derives substantial heritage from the MSL instruments, with CMA representing the first flight of an ECAM prototype, bringing the ECAM system to TRL 7.

Science-Grade ECAM Cameras: MSSS is currently developing several science-grade cameras compatible with the ECAM platform. Below is a summary of these various cameras.

Scientific CMOS, Visible Bands. Rivaling the performance of CCD cameras, the ECAM-C55S scientific CMOS camera uses a high performance 2560x2160 format sensor with 6.5µm pixels. The sensor can operate in rolling shutter or global shutter modes and achieves less than 2 e− RMS noise at 30 fps in rolling shutter mode, with a dynamic range in excess of 15000:1. This camera will be available with monochrome and Bayer pattern color sensors.

Large-Format Long-Wave Infrared (LWIR) Microbolometer. Evolving the ECAM-IR1, the ECAM-IR8A acquires 1024x768 format LWIR images with a 17µm pitch amorphous silicon microbolometer array. While the IR1 uses integrated video amplifiers and A/D converters, the IR8A utilizes an external analog processing and conversion signal chain. For a 30 Hz frame rate, the 300 K average temporal pixel NEAT of the array is better than 60 mK.

Uncooled InGaAs Short Wave Infrared (SWIR). With its 1280x1024 format sensor with 15µm pitch, the ECAM-SW13 images in the 0.9-1.7µm band. The noise of this sensor is less than 95 e− RMS and the dynamic range is 1000:1 in high-gain mode. Two-point non-uniformity correction (offset and gain) will be performed within the DVR.

Back-Illuminated CMOS Ultraviolet (UV) and Near Infrared (NIR). Using a 1280x1024 format back-illuminated CMOS sensor with 10.8µm pitch, the ECAM-BI13 is optimized for sensitivity from 200nm to 900nm. With appropriate narrow-band filters, this camera supports applications in the UV and NIR bands. The read noise is 30 e− RMS with 40 Ke− full well capacity.

Example Application, Mars Weather Camera: To illustrate the application of the ECAM modular off-the-shelf architecture to a science instrument, we consider the case of a Mars weather camera. From 1999 to 2006, the wide angle system on the Mars Orbiter Camera (MOC) on Mars Global Survey provided daily global weather maps of Mars in two visible bands. These low resolution (3-7 km pixel) images, acquired at local 2 PM, provided the uniform spatial and temporal sampling and the duration of coverage (3 martian years) to reveal the details of the martian weather patterns over the year, and to begin to show how those patterns varied from year to year. In 2006, the Mars Color Imager (MARCI) on the Mars Reconnaissance Orbiter began acquiring the same type of coverage from a 3:30 PM orbit, but in five visible and two ultraviolet (UV) bands. The UV bands allow MARCI to track ozone, which is anticorrelated with water in the martian atmosphere. Between MOC and MARCI, we have a continual record of the global afternoon weather for over six martian years. While continuing this record forward past the operation of MRO and extending it to other times of day are high priorities in studying Mars’s weather, it would be at most a secondary goal of any future Mars orbiter. Being able to address this goal with a compact, low cost instrument will provide more options for it to fly as a subsidiary instrument, whatever the primary goals of the mission.

An ECAM-based Mars weather camera would consist of a DVR4 unit and four camera heads. Each of the camera heads would cover a different wavelength band:

Visible. Visible imaging is performed using the ECAM-C55S scientific CMOS camera. A 140° field of view lens gives this camera a limb-to-limb swath. The visible camera images in two bands: 400-450 nm and 575-625 nm. These “blue” and “red” bands are the same as those used on MGS MOC and MRO MARCI to discriminate between water-ice clouds and dust clouds. The colors are provided by two fixed-
mounted strip filters which cover the width of the detector in the cross-track direction and use the spacecraft motion to scan the image. This is the same “pushframe” imaging approach used on MARCI, and it provides the color capability for low mass and without moving parts. In addition to providing the low resolution swaths for the daily global maps (generated by summing within the DVR), the visible camera also provide images at resolution of ~300 m per pixel from a 300 km orbital altitude.

**Ultraviolet.** The back-illuminated CMOS ECAM-BI13 is fitted with a wide field lens and strip filter array of similar configuration to the visible camera. The filter array has bands between 240-290 nm and 305-330 nm. These two bands allow the characterization of the Hartley ozone absorption band. The short band directly samples the absorption, while the longer band, which is insensitive to ozone, provides constraints on the atmospheric state. Because ozone varies inversely with atmospheric water, this camera constrains the spatial and seasonal distribution of Mars atmospheric water. To achieve appropriate signal-to-noise ratio, 8 x 8 pixel summing is required, yielding a nadir resolution of ~5 km per pixel.

**Thermal IR.** Thermal IR (LWIR) imaging is performed by the ECAM-IR8A. As with the UV and visible cameras, the thermal IR has a wide field lens and a two-band strip filter for pushframe imaging. One of the bands is at 9.4 µm (±0.6 µm), centered on the IR dust absorption band, the other images at 7 µm to capture the continuum adjacent to the dust absorption [3]. From these two bands together, daily global dust opacity is derived. As with the UV, summing is necessary to get the desired signal-to-noise, so the resolution of global IR dataset will also be ~5 km per pixel.

**Education and Public Outreach (EPO) camera.** With the above three cameras, the DVR4 has an unused camera port. For minimal mass and cost, an ECAM-C50 color camera head could be added to the instrument. The C50 can take 5 megapixel still frame images and HD format video. While not directly addressing any scientific questions, this camera could provide images to support the mission EPO efforts. In addition, if positioned to provide the proper field of view, this camera also provides useful (as well as publicly engaging) HD video of spacecraft deployments and maneuvers.

**DVR4.** The DVR4 would have 32 Gbytes of non-volatile memory and lossless and lossy compressors implemented in hardware. All science data would be acquired raw, at the maximum usable resolution. With the large buffer, it is possible to buffer multiple weeks of full resolution data. For nominal operations, the reduced resolution global map products would be generated and downlinked on a daily basis, without deleting the original, full resolution data. After ground analysis of the downlinked global map products, the option would be available to downlink selected areas of it at full resolution. This capability would, for instance, allow the instrument to capture the development of a dust storm at full resolution, by being able to “go back in time” in the DVR4’s buffer a week or more to when the storm started.

The DVR4 weighs less than 1.2 kg and each camera head, about 0.4 kg, for a total mass of ~2.8 kg. Figure 10 illustrates the capability of this Mars weather camera, with analogous images from previous flight instruments.

![Figure 5 – Flight images illustrating ECAM based Mars weather camera products: UV (upper left, from MRO MARCI), visible (upper right, from MRO MARCI), thermal IR (lower left from Mars Odyssey THEMIS) and color EPO (lower right, from Rosetta CIWA).](1130.pdf)

**Conclusion:** The ECAM platform, through its modular off-the-shelf approach, provides substantial science capability for modest mass and cost and within a faster, lower-risk, development cycle.