

"Innovative Video Diagnostic Equipment for Material Science"

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Abstract

Materials science experiments under microgravity increasingly rely on advanced optical systems to determine the physical properties of the samples under investigation. This includes video systems with high spatial and temporal resolution. The acquisition, handling, storage and transmission to ground of the resulting video data are very challenging. Since the available downlink data rate is limited, the capability to compress the video data significantly without compromising the data quality is essential.

We report on the development of a Digital Video System (DVS) for EML (Electro Magnetic Levitator) which provides real-time video acquisition, high compression using advanced Wavelet algorithms, storage and transmission of a continuous flow of video with different characteristics in terms of image dimensions and frame rates. The DVS is able to operate with the latest generation of high-performance cameras acquiring high resolution video images up to 4Mpixels@60 fps or high frame rate video images up to about 1000 fps@512x512pixels.

Introduction

Microgravity provides a number of unique advantages for performing materials science investigations. For example, electromagnetic levitation experiments with undercooled melts can be performed under microgravity conditions with very weak levitation fields compared to experiments on ground leading to a situation where the disturbances induced in the samples by the levitation fields are very small and the temperature range accessible during the experiments can be extended to much lower values compared to ground-based experiments. This allows performing experiments that are targeted to measure a wide range of solidification phenomena and thermophysical properties, such as the direct observation of the solidification front upon recalescence, as well as the measurement of the heat capacity, surface tension, viscosity, and thermal expansion [1].

Due to the nature of the experiments and the measurement objectives, non-contact diagnostics systems are needed to perform such measurements. Among others very often high-resolution and high-frame rate video cameras are used producing a very high data amount. Therefore, advanced video compression and handling systems are essential for many diagnostic systems of materials science payloads. An example of such a video system and its application is presented in this paper.

Measurement Objectives and System Requirements

The main scientific data provided by electromagnetic levitation experiments are data on the size, shape, brightness distribution and temperature of the sample and their evolution over time. Physical data that can be extracted by analyzing the shape of the sample include surface tension and viscosity, which are derived from sample shape oscillations (see figure 2), and the thermal

expansion which is directly derived from the diameter of the sample. Other physical data such as the solidification speed is derived from direct observation of the solidification front (see figure 1). To perform these measurements with the required accuracy either a high spatial or a high temporal resolution is needed or intermediate settings of both, whereas these settings may need to be drastically changed within single measurements to cope with various scientific goals. Typically digital video cameras with advanced optics are used meeting these needs due to their high flexibility in spatial and temporal resolution [2].

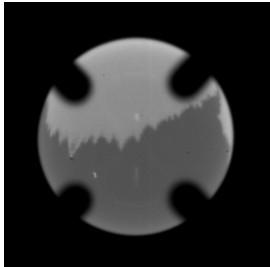


Figure 1 – Solidification (bright area) of undercooled sample

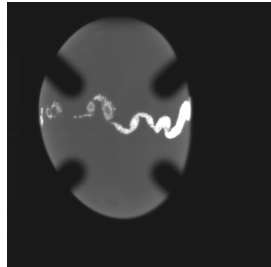
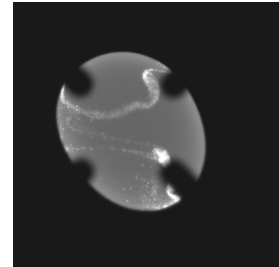
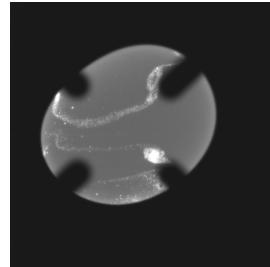


Figure 2 – Induced sample shape oscillations of a liquid sample, oxide particles are observed as bright white structures visualizing the fluid flow



The samples in both figures are levitated in an EML-like facility for parabolic flights; the 4 dark patterns in front are parts of the sample holder preventing the hot sample from leaving the confined area for levitation.

Moreover, monitoring of the levitation process needs a real-time downlink of the captured video, within the limitations of the currently available downlink capacity, for process control purposes and near real-time evaluation. The limited downlink capacity also motivates the need for storage of data on-board the spacecraft of the high amounts of captured video data. Data compression applied due to constraints on the on-board storage resources shall not impair the video images' quality because of the scientific need of image evaluation accuracy on pixel scale. Playback of these high quality video data stored on-board is needed for non real-time evaluation on ground allowing improving experiment settings for upcoming experiment runs.

Technological Challenges

The operation scenario demands from the video acquisition system not only a high data acquisition rate but also flexibility and fast reaction time on changed camera settings. Moreover the system has to duplicate the video into two streams, real-time and playback, which puts an even higher requirement on the data throughput of the system. Both streams have to be handled differently in terms of compression, frame rate adjustment and routing to meet the downlink requirements for the real-time video on one hand and the requirements for video storage on-board on the other hand. Further, the entire handling of the acquired video stream needs to be performed without delay since the camera does not provide for any video buffer and no image captured shall be lost. Provided this, the video system must fit within a small available volume and a tight mass and power budget.

Design Solution and Technology

TSD (Techno System Dev.) has been working since 1991 on the development of digital video systems for space applications, exploiting different hardware and software architectures. The DVS (Digital Video System), subject of the present paper, is based on a compact and very powerful platform, named H²VMU (High Resolution/High Frame Rate Video Management Unit), developed by TSD, and whose first generation implementation flew on board a Sounding Rocket on May 2005 [3]. The H²VMU has been designed for real-time video acquisition, lossy and/or loss-less compression and transmission/storage of a continuous video data flow. The

H²VMU platform is periodically enhanced and in the current third generation it is able to operate with very high performance cameras (both high resolution and high frame rate) with an input data throughput up to 240Mpixels/s. The H²VMU is based on a modular architecture comprising compact and low power modules implementing a wide set of functions:

- Camera interface & video acquisition
- Wavelet lossy and/or loss-less compression
- Custom image processing
- Volatile or no volatile video data storage on different technologies
- Command reception and decoding for unit configuration and control according to CCSDS (Consultative Committee for Space Data Systems) standard
- Video Data packetization and encoding according to CCSDS standard
- Low power management

The modules can be arranged in different configurations in order to fulfill different and specific user requirements. The modules are also available with different qualification levels, including radiation tolerant versions. Table 1 reports the maximum specifications that can be achieved. Since budgets strongly depend on the configuration, the values reported in the table 2 are provided for three typical configurations.

Table 1 - H²VMU maximum specifications

Video input data rate:	up to 240 [Mpixel/s] for each video input module
Image resolution	up to 4[Mpixel] @ 60[frame/s]
Frame rate	1000[fps] @ ≈512x512 [pixel] (higher frame rate at lower resolution available)
Pixel depth:	up to 12[bit]
Compression rate:	<ul style="list-style-type: none"> - up to 60[Mpixel/s] in loss-less mode for each compression module - up to 300[Mbyte/s] in lossy mode for each compression module
Storage rate and capacity:	<ul style="list-style-type: none"> - 60[Mbyte/s] and 64[Gbyte] for each custom high rel solid state storage module - 100[Mbyte/s] and 250[Gbyte] for each COTS (Commercial Off The Shelf) removable SATA hard disk

Table 2 - H²VMU Budgets

Configuration	60 [Mpixel/s] single Channel & 32 GB custom storage module	240 [Mpixel/s] four Channels & 148 GB custom storage module	60 [Mpixel/s] single Channel & Removable SATA disk (250 GB)	
			H ² VMU	HDD
Mass [kg]	2.7	4.7	5.8	2.2
Dimensions [mm]	150x140x150	149x252x140	186x114x254	58x140x220
Power@28V [W]	13.4	40	46 (including HDD)	

Internal Communication Architecture

The DVS is based on a novel approach for board interconnection and data communication. Depending on the unit configuration, an application-specific back-plane is designed based on:

- high-speed point-to-point SerDes (Serializer/Deserializer) links with multi-drop bus configuration for data transfer
- low-speed redundant CAN (Controlled Area Network) network for control and configuration

The SerDes links are based on the National ChannelLink technology that provides high speed data transfer (up to 1,785 Gbps) over a reduced size interconnection (a reduction up to 80% is possible with respect to the classic parallel bus approach), thus allowing the implementation, in a single back-plane PCB (printed circuit board) of a significant number of those links working at the same time. The physical level is LVDS (low voltage differential signaling) that provides differential signaling with small swing, low noise and good noise tolerance. The unit implements ChannelLink communication channels between modules with multi-drop configuration, thanks to a careful PCB design that requires to follow demanding guidelines to ensure signal integrity; these include, for instance, hand routing, impedance control, electrical length matching, proper track separation and loading balance.

The source module requiring transmitting data acts as driver of the communication channel while destination nodes are on the receiver side. As these modules support different input data rates (either as sustained or peak rate) a simple request/grant scheme is then implemented to manage the communication flow. The driver asserts the request line whenever it has valid data to transfer. A dedicated module generically acts as router (implemented as a stand-alone module or embedded in one of the already existing others) moving those requests to the destination nodes. The receivers, whose input request lines are set, acknowledge the request by asserting their relevant grant lines whenever they're available to accept the incoming data. They can release the grant line during the data transmission, as well, to add wait state to the communication. The router implements the logical and of the grant lines of the receivers that are involved in the communication and asserts thereafter the grant line towards the driver to start the data transmission. It can also implement the masking of the request and grant lines to/from one or more receivers. So, according to the chosen configuration, data can be moved to all the receivers physically connected to the multi-drop bus or only to a subset of them. All the same, faulty receivers that are no more capable of receiving data can be isolated to prevent any dead-lock in the communication.

Video Compression

Video data reduction techniques are of utmost importance in space applications, due to the often reduced on-board resources devoted to data storage and transmission to ground. The importance for data reduction is increasing over time as modern diagnostic instruments like high resolution digital cameras provide increasingly large amount of data.

The choice of compression factors to be applied to video data obviously depends on the use to be made of the images. As a rule of thumb one can say that for scientific images that have to be stored on-board a lossless or quasi-lossless compression is often required in order to guarantee the maximum scientific return. This imposes the use of compression factors in the range 2÷5. On the other hand, for images to be transmitted to ground in real-time to be used for control and monitoring purposes it is often possible to achieve much higher reduction levels. By applying different techniques like image lossy compression, image binning, frame rate reduction it is possible to have overall reduction factors in the range 100÷300.

Most of the image compression techniques use the signal expansion as major component. Generally this is achieved via digital filter banks. The reasons for expanding the video signals and process them in the transform domain are numerous. Usually the signal processing in the transform domain allows us to achieve a better data compression for a prefixed encoder complexity. The signal in the transform domain can be submitted to a more efficient quantization that takes into account also criteria about the human vision perception.

The most common transform is the DCT (Discrete Cosine Transform); it is still used for image compression standard like MPEG and JPEG. This type of compression technique exhibits several limitations from the implementation point of view. The algorithm needed to perform the DCT

requires a great amount of calculations to obtain the transformed image. This is due to the nature of the basis function used for signal expansion that has not a finite time extension (Cosine function is periodic). Therefore, in order to limit the amount of calculations to a reasonable level, the image is decomposed in 8x8 block of pixels. When high compression ratio is applied, this results in block artifacts that are typical of this compression technique.

In the recent years the image compression technique based on Wavelet transform has been considered an extremely interesting alternative due to the several advantages that it offers with respect to the DCT. This technique also uses signal expansion, but the basis function employed appears more appropriate in order to achieve the following goals:

- high quality image compression
- considerable reduction of transform computational complexity

As clearly visible in figure 3, the block artifacts are present, at high compression factors, only in the image compressed with JPEG; the same image compressed with the same factor using Wavelet, exhibits only a very small degradation.

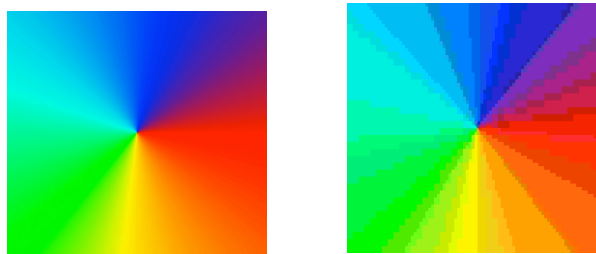


Figure 3 – Image compressed (170:1) by Wavelet (left) vs. JPEG (right)

The reduction of the amount of calculation to perform the image transformation is due essentially to an important property of the wavelet basis functions: their finite time extension.

A compression system based on the discrete transform consists mainly of 3 blocks:

- mapper
- quantizer
- entropy encoder

The mapper transforms the image from a space/time domain in a new domain where the redundant information between the pixels is reduced. In the case of a wavelet compressor, the mapper is represented by the discrete wavelet transform that transforms the image from a space/time domain in a time/frequency domain. The quantizer reduces the redundant psychological-visual information; the entropy encoder reduces the redundant numerical information. The solution that TSD has tuned over several years is a Wavelet compressor based on an EZW (embedded zerotree wavelet) encoder. The EZW is an algorithm for data compression derived from a scheme designed by J.M. Shapiro [4] especially to work with the discrete wavelet transform. The EZW coder is progressive in nature. This means that as more data is added to the compressed stream, the more detailed the reconstructed image will be. Progressive coding is also known as embedded coding - thus the E in EZW. EZW utilizes the observation that in natural images most of the energy (or information) is in the low frequency spectrum. After a wavelet transform has been calculated, the coefficients in the lower frequency subbands tend to be larger (in absolute value) than the coefficients in the higher frequency subbands. This allows for the creation of structures called zerotrees. Another observation used by EZW is that larger valued coefficients are more important than small value coefficients. Therefore EZW codes the larger coefficients first. The TSD solution offers significant higher quality especially at high compression factors than other Wavelet compressors, as visible in the example pictures of figure 4 using a factor of 160:1.



Original photo



TSD Wavelet



JPEG2000 Wavelet

Figure 4 – Comparison between TSD Wavelet and JPEG2000 Wavelet at extreme compression factor 160:1.

All the functional blocks needed to carry out the above described image compression algorithm, have been implemented, by TSD, in a hardware solution using high-density FPGAs, employed as complete System-On-Chip solutions. The newest implementation, running on Xilinx Virtex4 FPGA, is able to perform lossy compression at a rate of 300 Mbytes/s.

Video Storage

The video data storage functionality can be implemented with either custom solutions based on an array of flash memory devices or with commercial solutions like SATA disks. Custom arrays of flash devices are to be preferred in applications requiring high levels of reliability, while SATA mechanical disks offer higher storage density and better radiation tolerance.

TSD has developed products in both categories, reaching high levels of storage rates. For custom arrays of flash devices the latest implementation allows to store up to 240Mpixel/s, thanks to a proprietary pipelined architecture, with storage capacity up to 64GByte per module, while in the case of SATA disks it is possible to store more than 100MByte/s per disk with up to 4 disks running in parallel. The disk is used as a raw device, i.e. without a file system, so to maximize the performances.

Usability

One of the most appealing characteristics of the DVS for the end user is its high degree of flexibility. The on board software provides a rich set of commands and house keeping data that allows the facility controller to configure the DVS on-the-fly according to the user needs.

Among the various features, the most remarkable are:

- Possibility to modify various parameters while a video acquisition is running, like compression factors, binning, frame skipping, test patterns generation
- Possibility to route the different video streams (loss-less science video, lossy real-time video, etc.) to the on board storage devices and to the payload data transmitter in a number of different configurations
- Possibility to perform the software update during flight
- Possibility to interrogate any processing node (either main CPU or FPGAs) by means of low level CAN bus commands in case of troubleshooting
- Possibility to power off the video processing modules in case a low power mode is needed

Apart from its flexibility, the DVS is remarkable for the responsiveness: all the operations are executed in “real-time”; no latency is expected when a command is issued, regardless of the operations that are being performed in that moment. This is due to the hardware and software architecture of the DVS that features a powerful CPU, a highly deterministic real-time operating system, a number of highly specialized FPGAs and very fast internal communication links.

Applications

Main task of the H²VMU is to compress huge amounts of acquired data in real-time to make them accessible to users whenever the data transmission rate between facility and control station is limited. This feature is often employed to scientific systems using video diagnostics but also for data of X-ray detectors. The H²VMU has been successfully employed on-board several MASER Sounding Rockets [3], [5] and Foton Russian capsule [6], providing video diagnostic capabilities to different microgravity experiments. Figure 5 refers to the CDIC-2 experiment (Chemically Driven Interfacial Convection) while figure 6 refers to the SOURCE experiment (SOUnding Rocket Compare Experiment) which studies heat and mass transfer in a heated tank with a liquid pressurized by non-condensable gas. Both performed on board MASER 11.

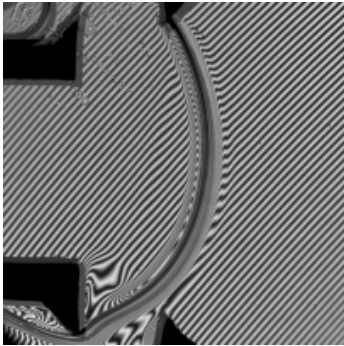


Figure 5 – Interferometric image of fluid interface, Compression factor 48:1

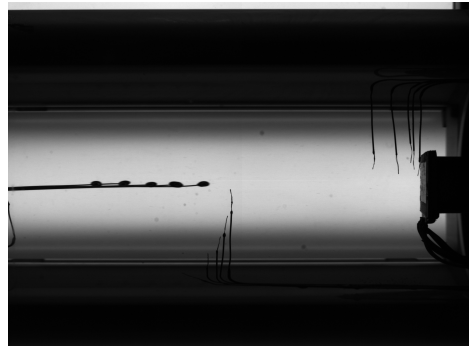


Figure 6 – Shadowgraph image of fluid science experiment cell, Compression factor 68:1

Other H²VMU based specific configurations are currently flown on board the ISS and on the main spacecraft of the PRISMA formation flying mission [7]. Next applications are foreseen for Maser 12 and for the ISS, supporting the EML Material Science Experiment [2].

Electro Magnetic Levitator (EML) on the International Space Station (ISS)

For EML the DVS plays a central role in the chain of optical diagnostics acquiring the digital video stream of a highly flexible camera wrt spatial and temporal resolution [2]. Since the acquired video stream is used twofold, for scientific and for process control purposes, the H²VMU (see figures 7 and 8) has to duplicate the video stream and have the capability to treat both streams (scientific & process control) in different ways wrt compression, pixel reduction and frame rate reduction. All the above actions have to be performed in real-time, storing the scientific data on the DVS owned hard drive and provide the process control video at the video interface for downlink to ground control. Moreover, playback of the scientific data from HDD via the downlink interface is possible offline, i.e. between two experiment runs, and the DVS configuration can be quickly changed to match the current scientific needs and camera settings.

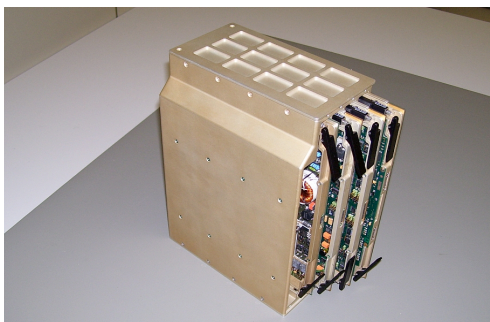


Figure 7 – The engineering model of the H²VMU for EML (internal view of the boards)

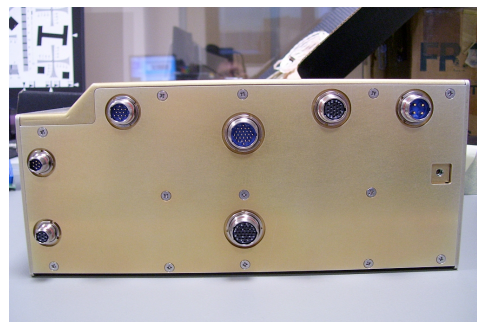
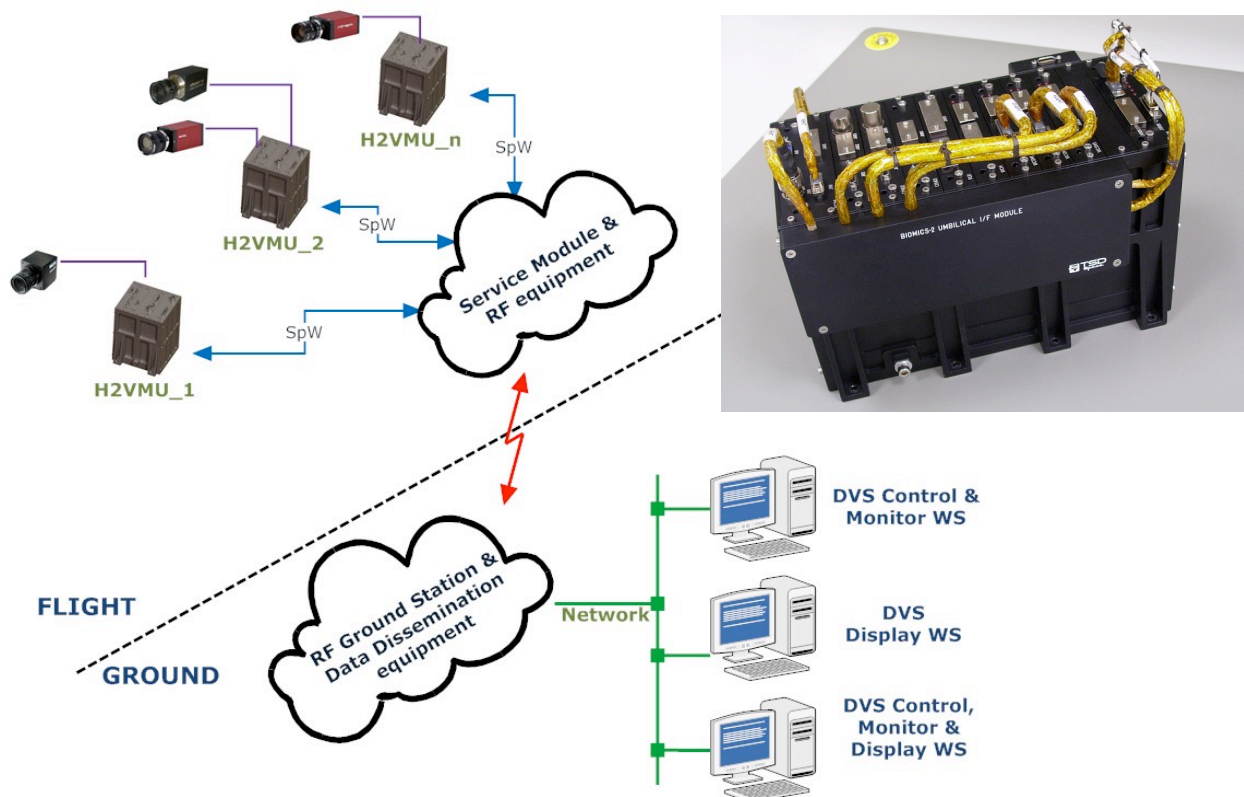


Figure 8 – The engineering model of the H²VMU for EML (rear view showing the connectors)

H²VMUs on board Sounding Rockets

The H²VMU represents the core of the DVS employed in all the MASER Sounding Rocket Program since 2005. A number of H²VMUs are used on board the MASER supporting all the Experiment Modules requiring video functionalities such as real-time image processing, on board storage, compression and downlink. Figure 9 below shows typical concept of DVS as applied to the MASER missions. The performance requirements of the experiments are more and more increasing and currently culminating to 313Mpixel/s (pixel depth up to 12 bit) on MASER12. The DVS architecture is decentralized and each Experiment Module is provided with a local H²VMU with multichannel capability in accordance with the requirement of the specific video diagnostic systems; a three channel H²VMU used on board MASER 12 is hereinafter shown in the insert of figure 9.



**Figure 9 – DVS architecture for Sounding Rocket missions as e.g. MASER
Insert: 3 channel H²VMU for BIOMICS-2 experiment on MASER 12**

ERB-2 Stereoscopic Camera

The Erasmus Recording Binocular 2 (ERB-2) is a digital stereoscopic camera, based on the H²VMU platform, allowing the simulation of human binocular vision. The ERB-2 has been proposed by ESA-ESTEC as a technology experiment to be flown on board the ISS able to capture and send to ground 3D films and related audio of the scenes filmed by the camera (see figure 10).

The ERB-2 is presently on-board the ISS. The first tests were successfully performed in July and August 2010. During March 2011 the Astronaut Paolo Nespoli conducted a fly-through filming program, starting in Kibo JPM (JEM Pressurized Module) and proceeding through Node-2, US Lab, and Node-3 with Cupola to COLUMBUS Laboratory (see figure 11). ERB-2 is also provided with two motorized objectives, driven by the H²VMU electronics, providing auto-iris and auto-focus functionalities.



Figure 10 – The flight model of ERB-2 at TSD premises



Figure 11 – Astronaut P. Nespoli with ERB-2 on board the ISS

Conclusions

Data compression has become a key technology for applications which produce high amounts of data and also suffer from a low data transmission rate. The technique introduced in this paper using EZW Wavelet compression is capable of maintaining the original data information by applying medium compression factors and achieves an unparalleled image quality for high compression factors compared to other Wavelet techniques.

The compression algorithm, as well as other customized features, is embodied in a hardware solution, called H²VMU, using state of the art and radiation hardened components. This modular and very flexible platform allows for real-time video acquisition, customized processing, lossy and/or loss-less compression and transmission/storage of a continuous video data flow.

The successful application of the H²VMU on board different space platforms (Sounding Rockets, Capsule, ISS, and Satellites) has demonstrated firstly its maturity to be now widely employed on board of various space platforms and secondly that it is best suited for material science facilities utilizing demanding image diagnostics.

References

1. “Materials Science Investigations using Electromagnetic Levitation”, A. Seidel, W. Soellner and C. Stenzel, Proceedings to 4th ISPS conference – Bonn, July 2011
2. “EML - Containerless Processing Facility for Material Science Research onboard The ISS”, W. Soellner, A. Seidel, C. Stenzel, W. Dreier and B. Glaubitz, J. Jpn. Soc. Microgravity Appl. 27 No. 4 183, 2010
3. “Digital Video System on-board Maser10”, G. Capuano et. al., 17th ESA Symposium on European Rockets and Balloon related research – Sandefjord, Norway 30 May – 2 June 2005
4. “Embedded Image Coding Using Zerotrees of Wavelet Coefficients”, Jerome M. Shapiro, IEEE Transactions on Signal Processing, December 1993
5. “Digital Video System on-board Maser11”, G. Capuano et. al., 18th ESA Symposium on European Rockets and Balloon related research – Visby, Sweden 3 - 7 June 2007
6. “Data Handling Unit for Foton-M3 Mission”, D. Titomanlio et. al., DASIA 2007, June 2007, Naples (Italy).
7. “Video System for PRISMA Formation Flying Mission”, G. Capuano, M. Severi, F. Cacace, et. al., 4th Symposium on Small Satellite, Systems and Services – Rhodes (Greece), May 2008