HIGH-PERFORMANCE PUSHBROOM IMAGERS FOR PLANETARY MISSIONS.

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Introduction: Imaging systems for planetary missions are generally a compromise between the desired science (e.g., spatial and spectral coverage and resolution, SNR) and limited available resources (e.g., mass, power, and data rate). Fortunately, camera architectures have been developed that enable superior science imagery from very constrained systems. In particular, pushbroom imagers – those that take advantage of the spacecraft orbital motion build an image over long or multiple exposures – are highly beneficial in conditions with either limited ambient lighting, or scenes with high dynamic range. Planetary surfaces are often ideally suited to this application. This paper summarizes the features of multiple pushbroom imagers built by Ball, and describes several technical trends that are pushing the capabilities of this approach to new levels.

Planetary imager performance requirements are driven by multiple factors. A spatial resolution of well below 1m, for example, is set by the desire to resolve surface features of scientific interest, such as the recurring slope lineae (RSL) on the Martian surface that indicate an active hydrologic cycle, and by the need to resolve surface hazards such as rocks and slopes at appropriate scales for landing site selection and surface operations planning. Signal-to-noise requirements (SNR) of >50 are typically sufficient to reveal morphologic features such as scarps, lineaments, or strata that provide the visual evidence needed to make meaningful guesses about the geologic context in the image. If compositional information is desired from multiband color imaging, SNR values >100 are desired.

Instrument Heritage: Over the last ~15 years, Ball Aerospace has developed many high-performance space-based pushbroom imagers for both planetary and Earth-orbiting missions. The inclusion of example Earth-orbiting instruments illustrates the range of the design space; however the detailed implementation would be optimized for the resources available in a deep space mission. The HiRISE and Ralph instruments are good examples of what can be done to minimize the mass and power requirements. Table 1 shows a comparison of key instrument parameters for several of these imagers. More detailed descriptions of these imagers are given below.

HiRISE. The High Resolution Imaging Science Experiment (HiRISE) camera on MRO was launched in August 2005 and remains the largest imager in orbit around another planet. The HiRISE camera has proven to be a very successful high performance imager in a very mass-efficient implementation. During the MRO mission it has completed more than 26,000 observations containing ~ 60 Tbits of data.

HiRISE is the first orbital camera to resolve all boulders large enough to constitute a serious hazard for landing on Mars (Figure 1). By taking images on different orbits, HiRISE is able to collect stereo data that can be converted into 1 m/post digital terrain models (DTM; See Figure 2, for example). Both of these capabilities are the result of a combination of very small ground sampling distance and high SNR [1]. One of the more surprising results from HiRISE is the extent of seasonal variations observed, such as avalanches, vents & fans (Figure 3) and RSL.

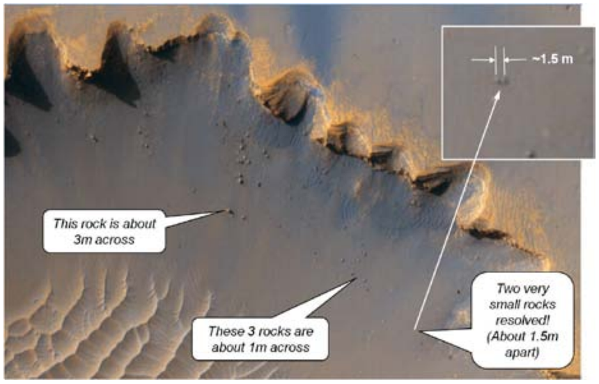

Figure 1 - Victoria Crater image demonstrates HiRISE ability to resolve 1-m hazards [2].

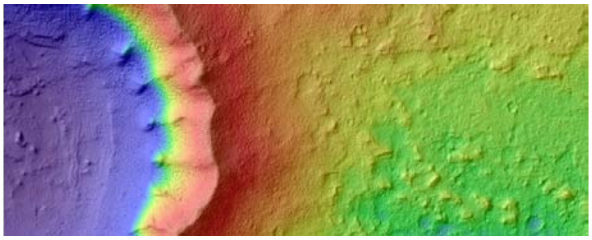

Figure 2 - DTM of the MSL Rover Landing Site in Gale Crater [3] Credit: NASA/JPL/University of Arizona/USGS

HiSCI. The High resolution Stereo Color Imager (HiSCI) is currently being designed for the ExoMars Trace Gas Orbiter (TGO) mission to provide 2 m/pixel images in four colors with a full swath width of 8.5 km [4]. HiSCI is designed to acquire the best-ever color and stereo images over significant areas of Mars. HiSCI will exceed by >20x the color and stereo coverage of Mars per year by HiRISE on MRO, and will

Figure 3 - Polygons on Defrosting Dunes, an example of Mars seasonable variability observed by HiRISE. Image: NASA/JPL/University of Arizona

image at significantly better resolution and SNR than previous or current imagers – excluding HiRISE.

A key feature of HiSCI is its ability to align the TDI array from an arbitrary yaw orientation (Figure 4) and collect stereo image pairs within an orbital pass using a single instrument mechanism along with bi-directional TDI capability (Figure 5).

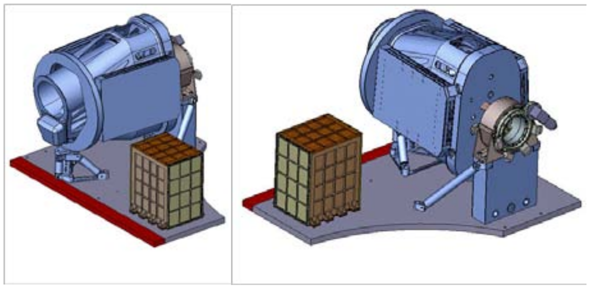

Figure 4 – The yaw rotation mechanism can be seen attached to the mount of the right-side image. The HiSCI instrument design is a joint effort between Univ. of Arizona, Ball Aerospace and Univ. of Bern (Switzerland).

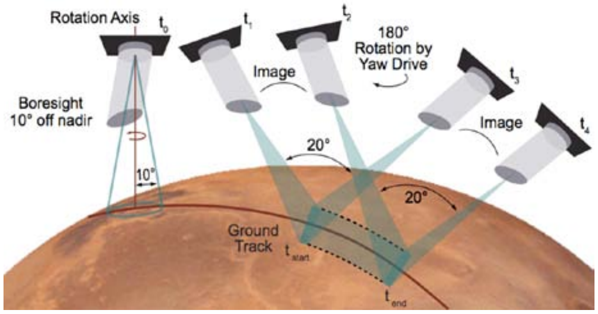

Figure 5 - Concept of operations for collection of a stereo image pair in a single orbital pass, used by the HiSCI instrument.

HiSCI implements the CCSDS (Consultive Committee for Space Data Systems) wavelet compression standard, which is incorporated in the focal plane electronics. It also needs less than half the resources (mass & power) required for HiRISE.

Ralph. The Ralph instrument (Figure 6) on the New Horizons spacecraft provides two imagers sharing the same aperture by virtue of a dichroic beamsplitter: the Multispectral Visible Imaging Camera (MVIC) and the Linear Etalon Imaging Spectral Array (LEISA). The LEISA focal plane and associated electronics were provided by Goddard Space Flight Center. The cryo-radiator and thermal control system were developed by Ball [5].

The telescope uses an un-obscured, off-axis, three-mirror anastigmat design. The entire telescope assembly, including the three diamond turned mirrors, is constructed from aluminum. The combination of an all-aluminum structure and optics produces a lightweight, athermal and thermally conductive assembly. It ensures that the optical performance of the system is much less sensitive to temperature and that thermal gradients are minimized. The 75 mm aperture VIS/IR telescope provides ample sensitivity at Pluto/Charon, while minimizing size and mass. The f/8.7 telescope offers a good compromise between radiometric throughput and alignment stability. The beamsplitter transmits IR wavelengths longer than 1.1 µm to LEISA and reflects shorter wavelengths to MVIC [5].

The MVIC focal plane uses a frame transfer CCD along with six TDI CCDs (four color & 2 redundant panchromatic). For 1.1-2.5 µm wavelengths, the LEISA focal plane has a HgCdTe array cooled to <130 K along with a linear variable wedge filter. This filter has a higher resolution segment designed to detect the solid nitrogen transition feature at ~2.15-µm.

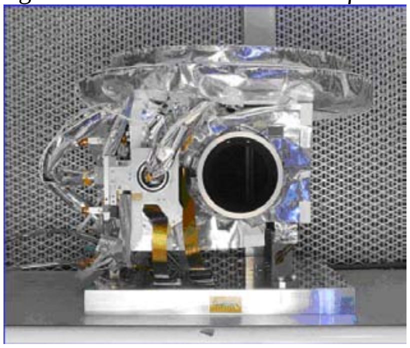

Figure 6 – The New Horizons Ralph telescope and detector assembly.

Ralph/New Horizons was launched on January 19, 2006 and is currently in hibernation en route to an encounter with Pluto in 2015. Instrument performance has been proven during a flyby of the Jovian system in 2007 (Figures 7, 8 & 9).

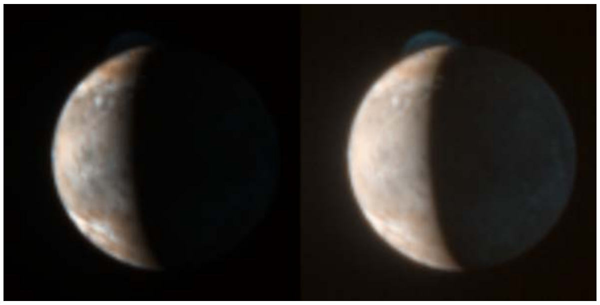

Figure 7 – Two versions of an MVIC image of Io taken from 2.4 million kilometers. Credit: NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute

Figure 8 – MVIC composite image of Jupiter released 9 October, 2007. Credit: NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute

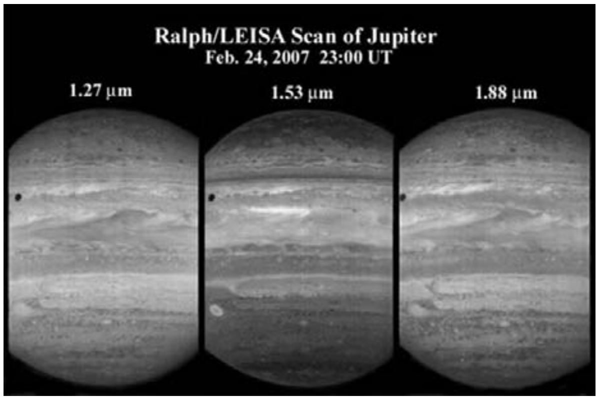

Figure 9 – LEISA images of Jupiter collected at three wavelengths. Credit: NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute

Operational Landsat Imager (OLI). The OLI instrument, with a planned launch in early 2013, is an Earth orbiting imaging radiometer with a four-mirror unobscured telescope. The cooled focal plane includes SiPIN and HgCdTe detectors with nine filters covering the visible to SWIR spectral bands. From an altitude of 705 km, the GSD is 15 m for the panchromatic band and 30 m for the other bands. The instrument includes a calibration system incorporating built-in lamps, shutter and solar diffuser.

***QuickBird(QB) & WorldView(WV)*:** Both of these Earth imaging spacecraft use the standard Ball High Resolution Camera (BHRC 60), which operates in the visible and near infrared bands [6]. A ground sample distance of approximately 0.5 meters panchromatic and 2.5 meters multispectral can be achieved. The push-broom instrument, pointed and oriented by the spacecraft bus, is capable of imaging a strip of the Earth's surface between 15 and 34 km wide depending on orbital altitude. The multispectral bands mimic the first four bands of the Landsat system. The instrument, shown below in Figure 10, was designed for a 5-year mission lifetime. The QB spacecraft & camera are in their 11th year of normal operations and recently achieved over 60,000 revolutions (orbits) since launch.

The BHRC 60 instrument consists of an unobscured three-mirror anastigmatic telescope and a focal plane array with support electronics, which includes data compression. A one-time deployable aperture cover protects the instrument during launch and early mission operations, and a calibration lamp provides on-orbit performance tracking capability of the focal plane array.

Because these instruments were designed for earth orbit, minimal effort was placed on weight reduction. The mass value in Table 1 is a rough estimate of a light-weighted version of the camera.

Figure 10 – BHRC 60 instrument for QuickBird spacecraft.

Table 1 - Comparison of Instrument Parameters

Parameter\Instrument	HiRISE	HiSCI	QB/WV	Ralph-MVIC	OLI
Aperture (cm)	50	14	60/60	7.5	13.5*
FN	24	46	14.6	8.7	-
Nominal GSD (m)	0.3	2.0	0.6/0.5	200	15/30
$Q = \lambda FN/p$	1.40	1.01	0.82	0.45	-
FOV (deg)	1.15x0.2	1.2x0.2	2.1	5.7x0.85	~1.5x15
AIFOV (μradian)	1.0	5.0	1.37	20	21 pan
Nominal Wavelength (nm)	700	700	675	680	590 pan
Mass (kg)	64.2	25 est.	132 est.	10.5	-

* Effective aperture – not circular

Key or Enabling Technologies: The following paragraphs describe technologies incorporated into these imagers that either provide a required feature or greatly improve the performance or operability:

Detectors. The choice of a focal plane array (FPA) typically drives the design and performance of these imagers. In the past, most visible–NIR imagers have used CCD detectors with frame transfer or pushbroom configuration.

CMOS. Complementary Metal-Oxide Semiconductor detector arrays have now achieved performance approaching that of CCDs. Two significant advantages of CMOS imagers are much greater radiation tolerance and simpler integration of the detector with supporting electronics. A CMOS sensor-on-a-chip (SOC) includes built-in drive, readout and processing electronics. The focal plane power supply is greatly simplified since CMOS image sensors require very low power and typically a single power supply voltage.

Hybrid. To improve the performance of a monolithic CMOS imaging sensor, a separate optimized detector array can be bump-mounted to a silicon CMOS readout integrated circuit (ROIC). In particular, this must be done for infrared detector arrays, which are based on materials such as HgCdTe.

Signal integration. To achieve the SNR required for imaging at large distances from the sun various forms of signal integration are typically required. Time delay integration (TDI) is implemented in CCD arrays to increase the effective integration time for a linear array of detectors as they are swept across the scene. Photocharge from an individual image pixel is clocked down a column of detectors at the same rate as the scene motion. The signal to noise ratio can be increased by large factors if the instrument pointing can be maintained. Bi-directional TDI facilitates stereo image collection within a single orbit. Other forms of integration, such as pixel binning or aggregation can be performed on-or off-chip.

Telescope Design. It is well-known that the telescope aperture diameter (D) provides a limiting factor in the spatial resolution and light-gathering capabilities of the instrument. The familiar equation for the angular size of the diffraction-limited point spread function is $\theta = 2.44 \lambda/D$. However, the over-sampling ratio or ‘Q’ is a newer metric for comparing remote sensing systems, which has been in use for some time [7,8]. Table 1 lists the $Q = \lambda FN/p$ for several Ball Aerospace heritage instruments, where FN is the focal ratio or f-number and p is the detector sampling pitch. Traditionally, radiometers tend to have $Q<0.8$ and imagers have $Q>0.8$ [7].

Image Quality Optimization. For optimal design, extensive modeling of the end-to-end system is required. Ball Aerospace has developed a System Performance Model (SPM) using MATLAB that is tailored to the individual instrument concept. SPM provides both radiometric and spatial performance predictions [7].

Light-weighting. Planetary science missions are inherently mass-constrained. A key aspect of the design is to minimize the mass while meeting performance and environmental requirements. Once an instrument concept is defined, the telescope construction and electronics design trades can have a great impact on final instrument mass. The use of silicon carbide (SiC) optics and structures shows great promise for reducing telescope mass. Electronics mass and electrical power savings can be realized by greater use of low power, more capable field-programmable gate arrays, analog-to-digital converters and CMOS image sensors. Of course these items must meet the radiation environment requirements.

Image motion compensation & stabilization.

Spacecraft accommodations. The actual resolution achieve in flight may be limited by the pointing accuracy and stability of the spacecraft imaging platform. Disturbances from reaction wheels, inertial reference systems, scanning instruments along with solar array and antenna tracking may be transmitted and even amplified to the instrument line-of-sight (LOS). For example, to achieve the highest resolution images from HiRISE, the MRO spacecraft must enter high-stability mode, where certain actuators are disabled during an imaging sequence. Post-processing of images using attitude time sequences and overlapping pixels from the staggered detector arrays can also be used to correct for image motion at certain vibration frequencies.

Vibration isolation. Some disturbances cannot be eliminated from the spacecraft structure or removed by post-processing. In those cases the instrument may require passive isolation from the spacecraft. Careful design and coordination with the spacecraft structural engineers is required to maximize isolation while maintaining adequate stiffness for launch loads.

Active stabilization. When passive isolation and post processing of data are inadequate to achieve the required image quality, an active stabilization system can be implemented. Such systems have been incorporated in Ball spacecraft and instrument mount designs for the most demanding applications.

Data Compression. Perhaps the most limiting constraint on high-resolution imaging of planetary surfaces is the reduced downlink bandwidth for science data as the range from Earth increases. The volume of image data produced can be staggering. For example, a single maximum-size image data set from HiRISE is 28 Gbits and requires 2.6 hours to transmit to Earth assuming a nominal 3 Mbits/sec rate from Mars. Consequently, virtually all HiRISE images are compressed, first by a look-up-table and then by the Fast and Efficient Lossless Image Compression System (FELICS) developed by JPL and incorporated into the MRO solid state recorder by SEAKR. Pixel binning is also used by HiRISE to increase SNR and reduce the number of pixels contained in many images.

Future missions will undoubtedly tend to produce higher data volumes and of course the data rate to objects more distant than Mars is even more severely limited. Ball has developed an implementation of the CCSDS compression standard that can be incorporated into the focal plane electronics or instrument control electronics.

Radiation tolerance. A driving constraint of certain candidate deep-space missions is the extreme ionizing radiation environment imposed upon the optics, electronics and focal planes. Radiation modeling and shielding analysis capabilities are key to finding the shielding design with the lowest possible mass and selecting appropriate components for the flight hardware.

Ball has developed modeling tools and design capabilities as demonstrated on various programs including HiRISE, OLI, MVIC, Kepler and Deep Impact. In addition, Ball personnel operate a radiation test facility, the InfraRed Radiation Effects Laboratory (IRREL) at the Air Force Research Laboratory (AFRL). They are particularly experienced in designing focal plane test equipment and understanding the results of such tests [9].

Future Imagers: Future planetary science missions will require imagers with improved spatial resolution, sensitivity and coverage using limited spacecraft resources and designed for challenging environments. Desirable features of such instruments include:

1. Full color coverage over the entire image area
2. Bi-directional TDI (or equivalent) to facilitate, stereo coverage and ease operational requirements
3. On-board lossy and lossless compression
4. Higher resolution or “hyper-resolution”. Resolutions higher than the nominal detector pitch, sometimes called hyper-resolution or sub-pixel sampling, can be achieved by capturing images that are shifted a fraction of the pixel pitch.

In order to provide such features in a resource-limited environment, the instrument provider must use the latest cost-effective techniques for development of such features.

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