High-Performance Pushbroom Imagers for Planetary Missions

J. Bergstrom & R. Dissly
Ball Aerospace & Technologies Corp.

International Workshop on Instrumentation for Planetary Missions (2012)
October 10, 2012

Agility to Innovate, Strength to Deliver

Ball Aerospace
& Technologies Corp.

Imaging Systems for Planetary Missions

- Compromise between desired science and limited resource allocations

  Spatial/spectral coverage and resolution, SNR

  vs.

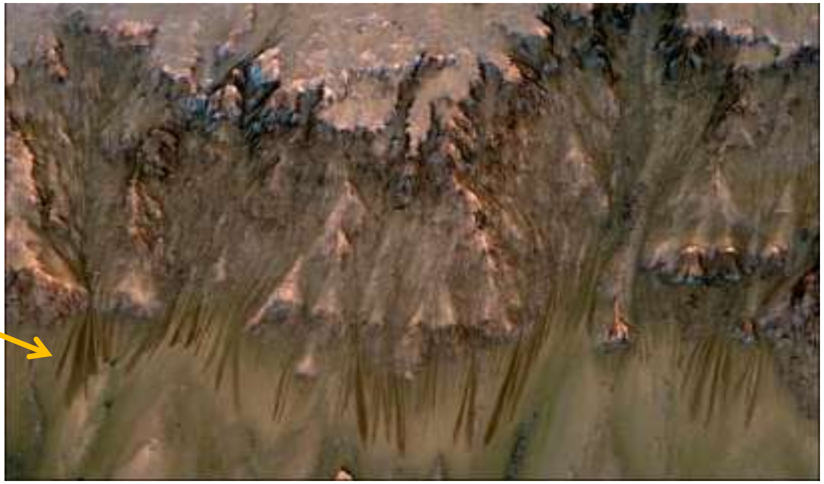
  Cost, mass, power, envelope and data rate
- Pushbroom imagers use spacecraft orbital motion to build up an image over long or multiple exposures
  - Detector arrays may use time delay integration (TDI) to achieve long effective integration times
  - Highly beneficial for limited ambient lighting or scenes with low contrast

- This paper summarizes features of various pushbroom imagers built by Ball Aerospace
- Includes technical trends that are pushing capabilities to new levels

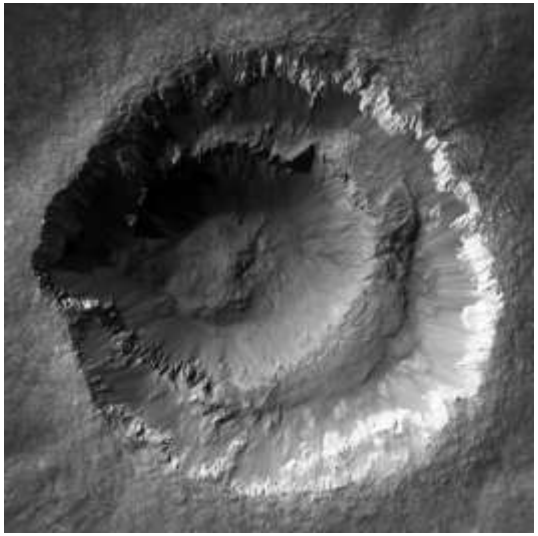
HiRISE image of MER rover Opportunity perched on rim of "Santa Maria" crater

Key Planetary Imager Performance Requirements

- Spatial resolution well below 1 meter
  - Resolve surface features of scientific interest
  - Observe key time variability on small spatial scales such as recurring slope lineae (RSL)
  - Recognize surface hazards such as rocks and slopes
    - Landing site selection and surface operations planning
- SNR > 50
  - Usually sufficient to reveal morphology such as scarps, lineaments or strata
- SNR > 100
  - Compositional information from multi-band color images
  - Scene content in shadows
  - Low contrast images, such as seen through Mars' dusty atmosphere



Oblique View of Warm Season Flows in Newton Crater



Space-Based Pushbroom Imagers Developed at Ball

- High-performance imagers for both planetary and Earth-orbiting missions
  - Illustrates the range of the design space
- High Resolution Imaging Science Experiment (HiRISE)
- High resolution Stereo Color Imager (HiSCI) – achieved PDR-level design only
- QuickBird(QB) & WorldView(WV)
- Ralph-Multispectral Visible Imaging Camera (MVIC)
- Operational Landsat Imager (OLI)

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	-

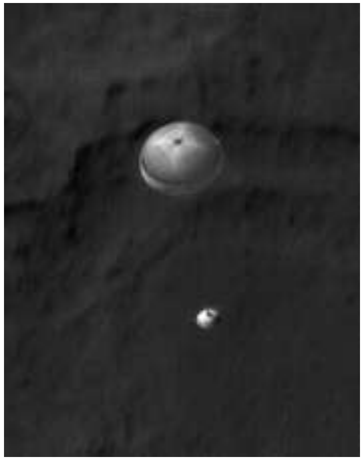
* Effective aperture – not circular

Instrument Heritage – HiRISE on Mars Reconnaissance Orbiter

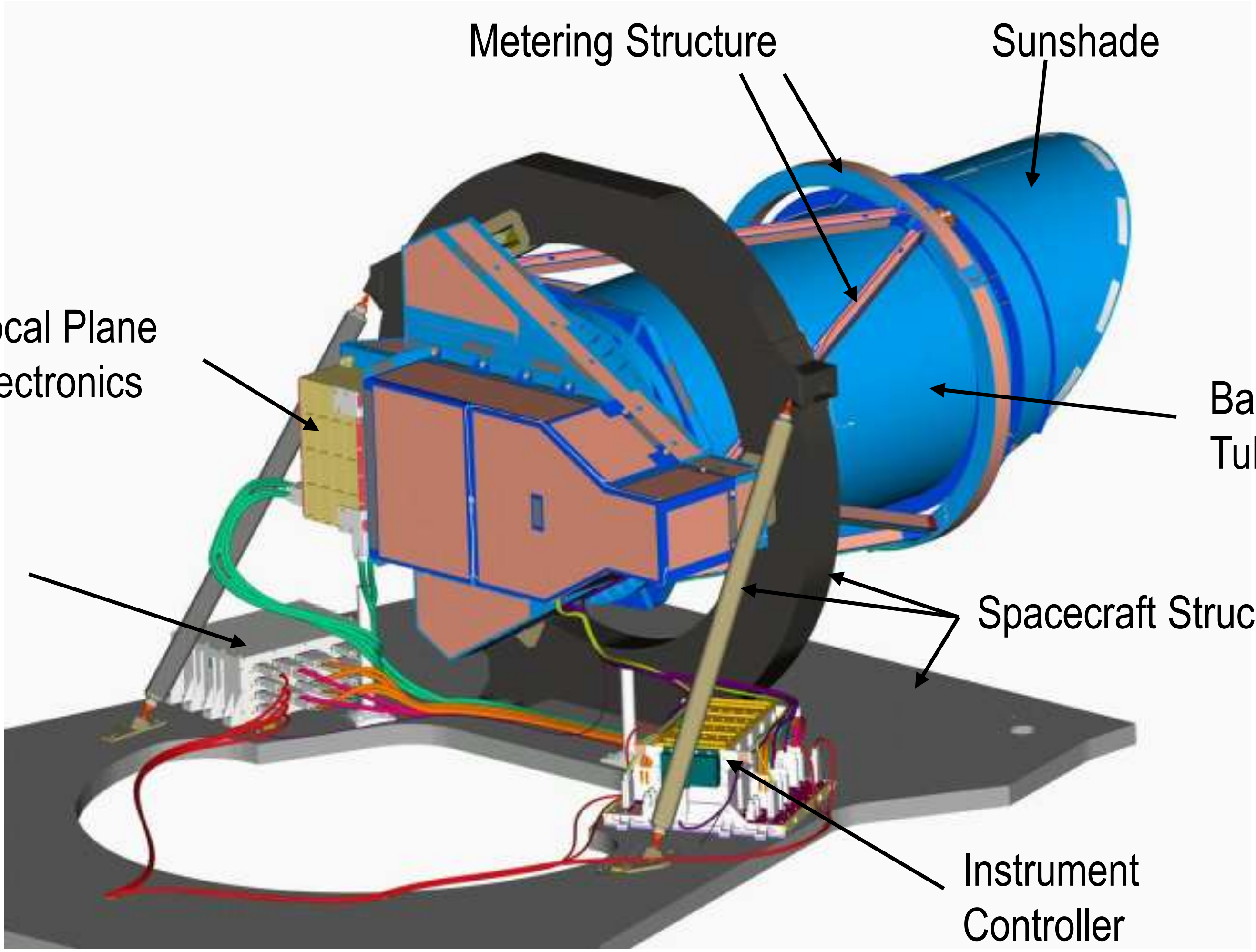
- Launched in August, 2005
  - In 2nd extended mission
- Largest imager orbiting another planet
- Completed more than 28,000 observations
- Returned >60 Tbits of data
- 25 cm ground sample distance (GSD) at lowest MRO altitude
- Up to 128 TDI stages
- By taking images on different orbits, HiRISE is able to collect stereo data that can be converted into 1 m/post digital terrain models
- Surprising result from HiRISE - extent of seasonal variations observed, such as avalanches, vents & fans and RSL
- Successfully imaged Phoenix and Curiosity during critical EDL sequences & on surface

DTM of the MSL Rover Landing Site in Gale Crater

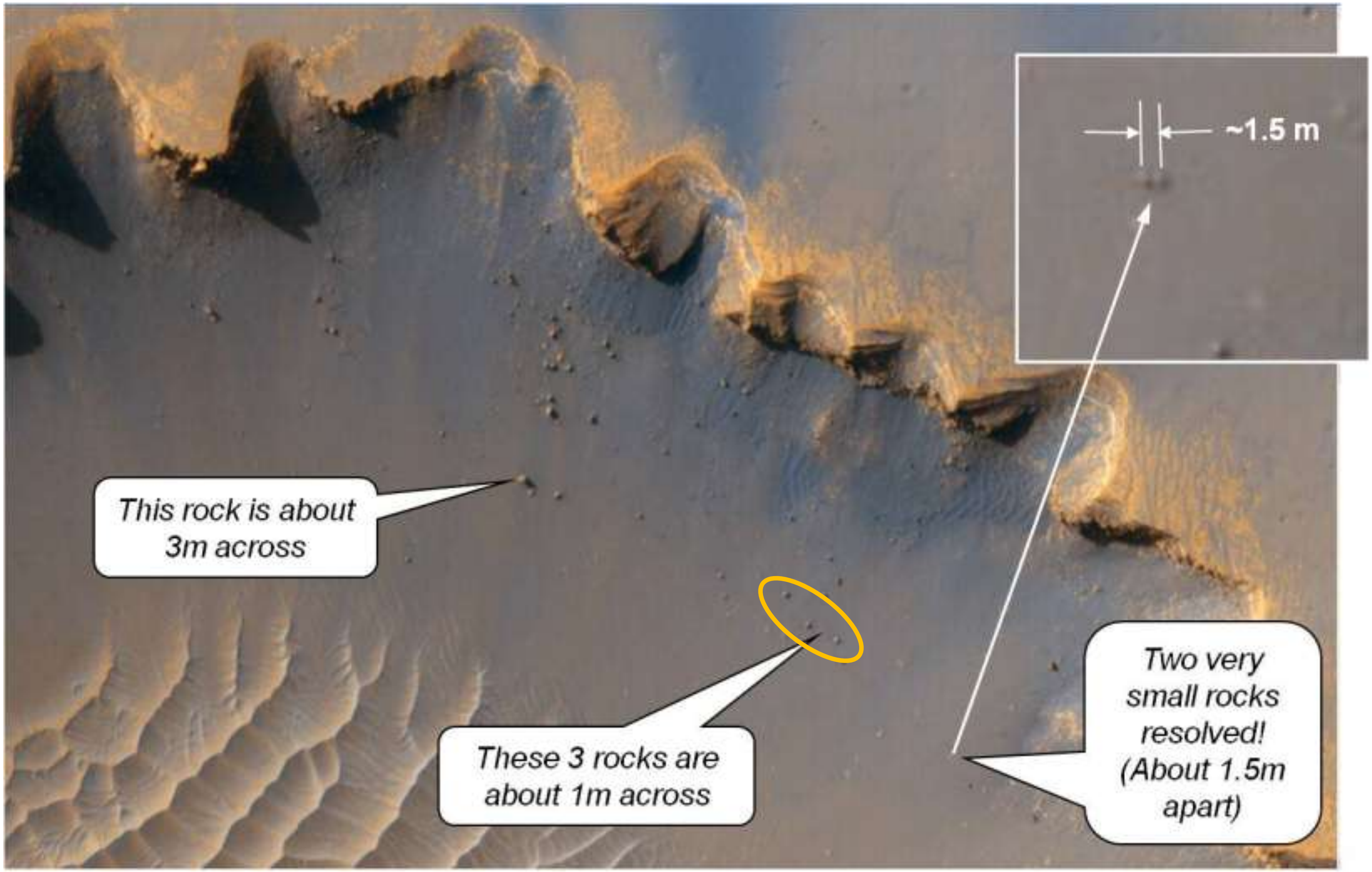
Polygons on Defrosting Dunes, example of Mars seasonal variability observed by HiRISE



HiRISE Camera Installed on MRO



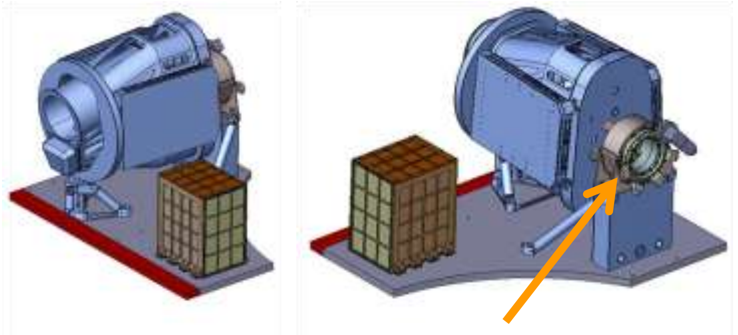
Instrument Heritage – HiRISE Meets Critical Resolution Requirement



Victoria Crater image demonstrates HiRISE ability to resolve 1-m hazards

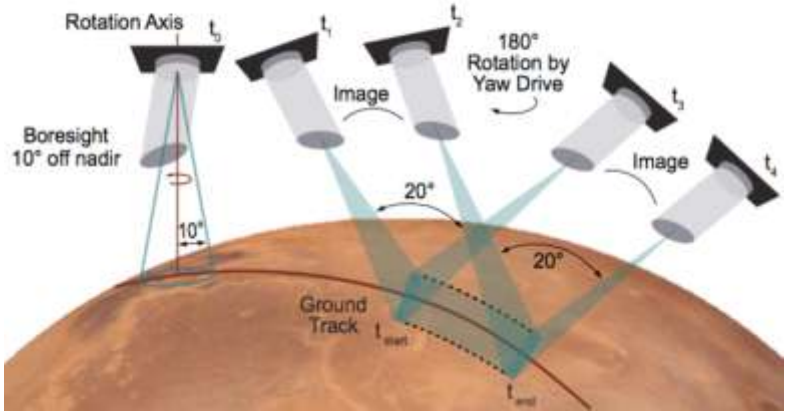
Instrument Heritage – HiSCI Design for Trace Gas Orbiter (TGO)

- Completed instrument PDR
  - Extended effort allowed post-PDR design of servo & controller board and focal plane electronics (FPE)
  - Wavelet compression standard implemented in FPE
- Designed to acquire the best-ever color and stereo images over significant areas of Mars
  - HiSCI would exceed by >20x the color and stereo coverage of Mars per year by HiRISE
- Key design features:
  - Four colors across entire swath width
  - Bi-directional TDI capability – up to 64 stages
  - Yaw rotation drive with boresight offset
- Benefits:
  - Ability to align the TDI array from an arbitrary yaw orientation
  - Collect stereo image pairs within an orbital pass using a single instrument mechanism



Yaw rotation mechanism

The HiSCI instrument design was a joint effort between Univ. of Arizona, Ball Aerospace and Univ. of Bern (Switzerland).



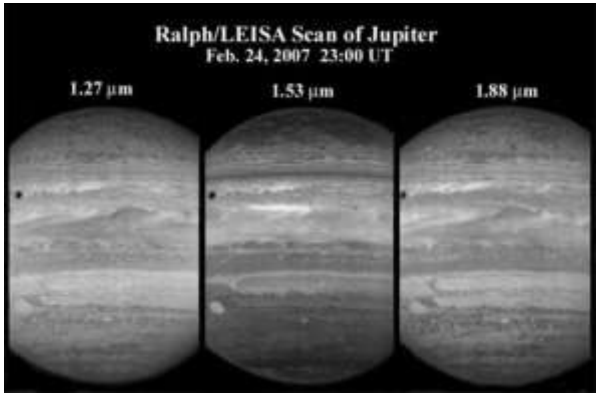
Concept of operations for stereo image pair collection in a single orbital pass

Instrument Heritage – Ralph on New Horizons Spacecraft

- Launched in January 2006; arrives Pluto in 2015
- All-aluminum off-axis telescope construction
- Dichroic beamsplitter separates Vis-NIR from SWIR wavelengths for two focal planes:
  - Multispectral Visible Imaging Camera (MVIC)
    - 6 CCD arrays with 32 TDI stages
    - Also includes a frame transfer CCD
  - Linear Etalon Imaging Spectral Array (LEISA)
    - Focal plane (<130 K) and electronics from GSFC
- Instrument support electronics provided by SwRI

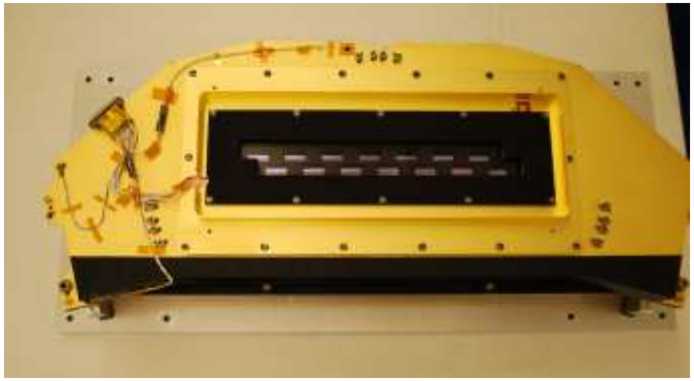
Ralph/MVIC composite image of Jupiter

Ralph/MVIC Images of Io



Landsat Data Continuity Mission – Operational Landsat Imager (OLI)

- Planned launch in early 2013
- Earth orbiting imaging radiometer with a four-mirror unobscured telescope
- Cooled focal plane includes hybrid SiPIN and HgCdTe detectors mounted on a single CMOS ROIC
- 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
- Includes a calibration system incorporating built-in lamps, shutter and solar diffuser.

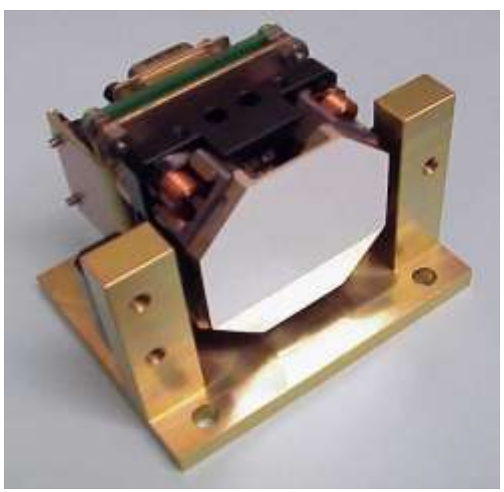


Key or Enabling Technologies

- Detectors
  - — Most heritage visible–NIR imagers have used CCD detectors
  - — CMOS (Complementary Metal-Oxide Semiconductor) arrays have now achieved performance approaching that of CCDs in some applications
    - — Greater radiation tolerance
    - — Simpler integration of the detector with supporting electronics
    - — CMOS sensor-on-a-chip (SOC) includes built-in drive, readout and processing electronics
    - — Focal plane power supply is greatly simplified
      - — Very low power dissipation and fewer power supply voltages
  - — Hybrid arrays allow optimization of the detector QE
  - — Signal integration through on-chip or off-chip time delay integration (TDI)
- Telescope Design
  - — Optimize the over-sampling ratio or 'Q': $Q = \lambda$ FN/pixel pitch
  - — $Q<0.8$ for radiometers and $Q>0.8$ for imagers
- Light-weighting the instrument
  - — Advances in primary mirror construction and silicon carbide telescope structures
  - — Greater use of low power, more capable field-programmable gate arrays, analog-to-digital converters and CMOS image sensors

Image Motion Compensation & Stabilization

- Very high resolution imagers (< 1 μrad/pixel) require quiet spacecraft
- May be achieved through passive or active vibration isolation
- Post-processing of images using attitude time sequences and overlapping pixels from the staggered detector arrays
- Image Stabilization May Be Required to Achieve Resolution Significantly Better than HiRISE
- Ball Fast Steering Mirror (FSM) located at fold mirror position can provide stabilization
  - Requirements
    - Size ~ 75 mm x 30 mm
    - Very small range of travel ~ 10 μradians
    - ~ 1000 Hz bandwidth
    - ~ 0.1 μradian repeatability & jitter



Ball Model BSM 45 Developed for German Space Agency Laser Communication

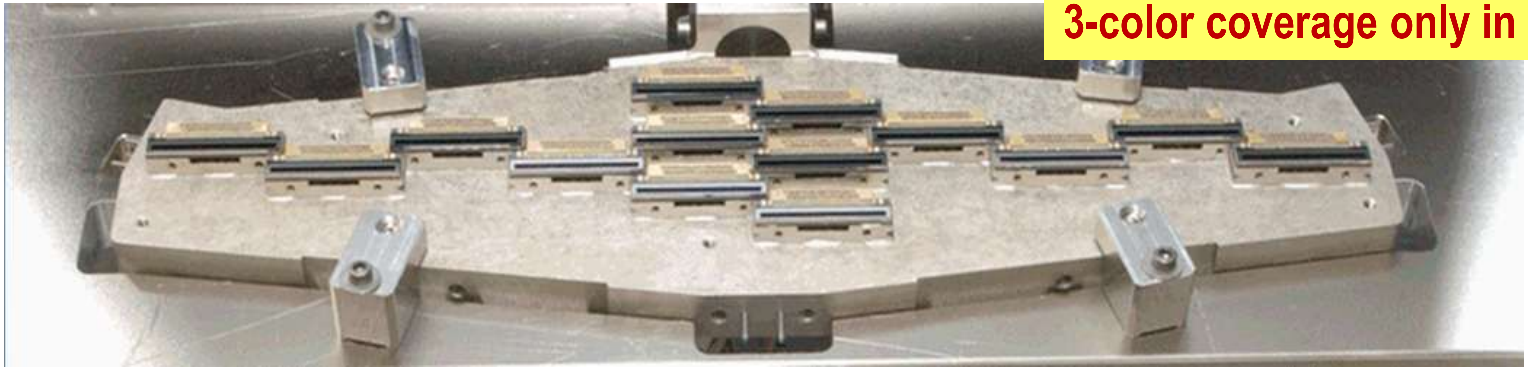
- Clear aperture: 45 mm diameter
- Closed loop bandwidth: up to 2,800 Hz
- Optical travel: up to ± 2.2 deg in two axes
- Resolution: 0.2 to 10 μrad depending on travel
- Acceleration: >5,000 rad/sec^2
- Size < 51 x 61 x 36 mm
- Weight < 0.25 kg

Data Compression

- Most limiting constraint on high-resolution imaging of planetary surfaces is reduced downlink bandwidth for science data
  - Dependant on range to Earth
- Volume of image data produced can be staggering.
  - Single maximum-size HiRISE image is 28 Gbits and requires 2.6 hours to transmit to Earth at nominal 3 Mbits/sec rate
- Pixel binning used by HiRISE to increase SNR and reduce number of pixels contained in images
- Ball developed an implementation of the CCSDS compression standard using wavelets
  - Can be incorporated into focal plane electronics or instrument control electronics
- Compression demonstrated in laboratory with focal plane subsystem development unit

Future Imagers

- Future planetary science missions will require imagers with improved spatial resolution, sensitivity and coverage
- 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"



HiRISE FPA
3-color coverage only in center

Sub-meter resolution from orbit is readily achievable. HiRISE has set the standard and raised expectations for future narrow angle planetary imagers.

Backup Slides

BHRC 60 Camera on QuickBird (QB) & WorldView (WV)

- Both Earth imaging spacecraft use standard Ball High Resolution Camera (BHRC 60)
- Pushbroom instrument is capable of imaging a strip of the Earth's surface between 15 and 34 km wide depending on orbital altitude.
- Includes un-obscured three-mirror anastigmatic telescope and a focal plane array with support electronics
  - Including data compression
- One-time deployable aperture cover protects the instrument during launch and early mission operations
- 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.
- Operates in the visible and NIR bands
- GSD ~ 0.5 meters panchromatic and 2.5 meters multispectral
- The instrument was designed for a 5-year mission lifetime.
  - QB spacecraft & camera are in their 11th year of normal operations

BHRC 60 instrument for QuickBird spacecraft.

Raw Image Captured in Lab with FPS EDU

Source photograph was attached to a Ball-developed belt scanner

Radiation Tolerance

- Driving constraint of certain candidate deep-space missions is the extreme ionizing radiation environment
- Radiation affects optics, electronics and focal planes
  - Thermal control surfaces
- Radiation modeling and shielding analysis capabilities are key to finding the shielding design with the lowest possible mass and selecting appropriate components
- Radiation modeling and shielding analysis capabilities are key to finding the shielding design with the lowest possible mass and selecting appropriate components
- Ball has developed modeling tools and design capabilities as demonstrated on various programs including HiRISE, OLI, MVIC, Kepler and Deep Impact
- Ball personnel operate a radiation test facility, the InfraRed Radiation Effects Laboratory (IRREL) at the Air Force Research Laboratory (AFRL).
  - Experienced in designing focal plane test equipment and understanding the results of such tests