Vision Systems for Planetary Exploration

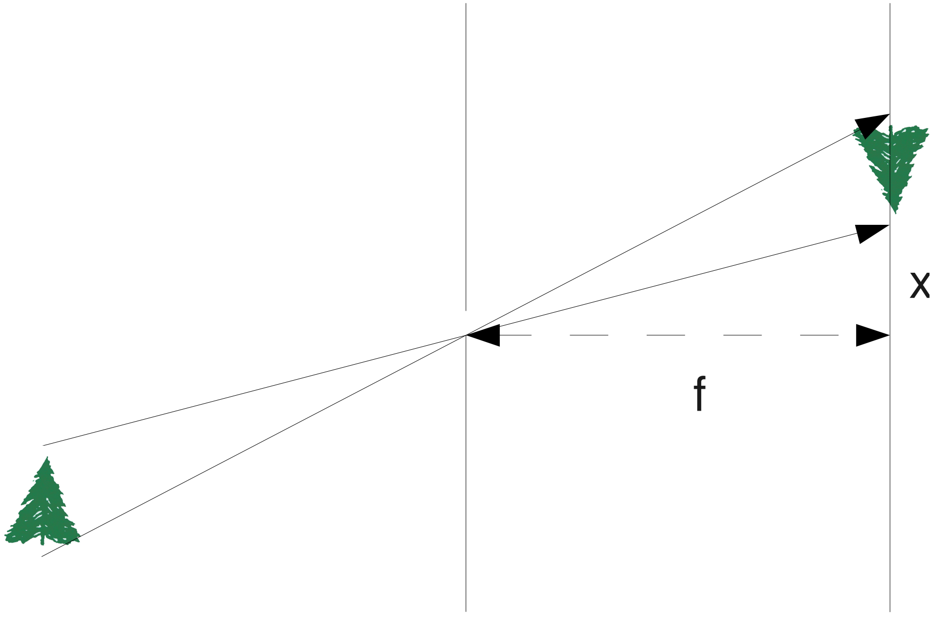
Arne Suppé
March 23, 2009

Introduction

- Camera calibration – Where something is.
- Imaging spectroscopy – What its made of.

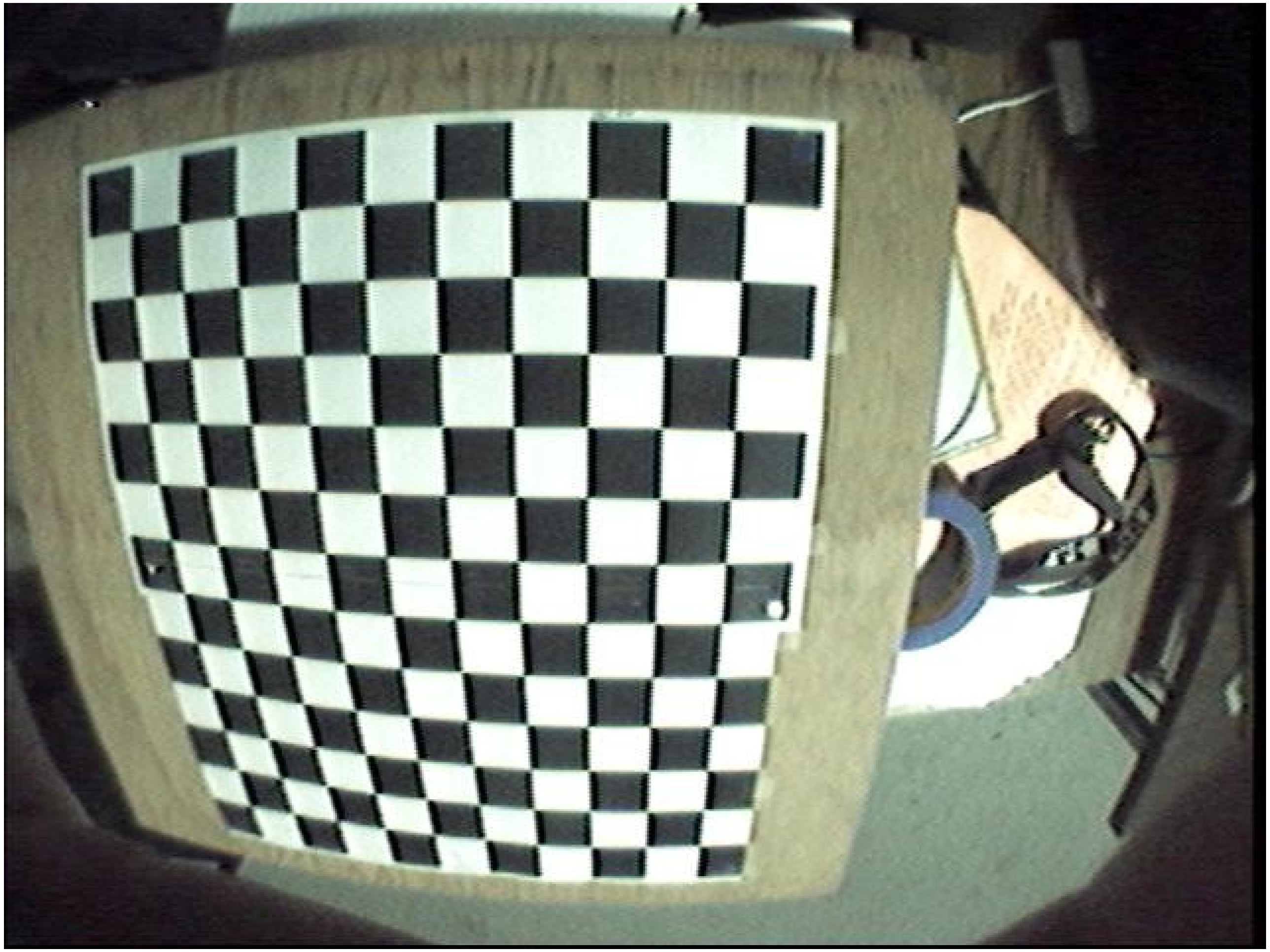
Camera/Lens Systems

- Pinhole camera model – *Camera Obscura*
- Possible to determine object location “to scale”



Pinhole

Lens Distortions



Camera Calibration

- Most camera systems we use are lens based
- Matlab Camera Calibration Toolbox, OpenCV
  - Focal length (fc) – the focal length of lens.
  - Principal point (cc) – location on image plane which meet the lens axis.
  - Lens Distortions (kc) – a nonlinear function that describes the radial and tangential distortion of the lens.

Camera Calibration

1. Convert real world coordinates to normalized projection

$$\mathrm{x}_n = \begin{bmatrix} X_c/Z_c \\ Y_c/Z_c \end{bmatrix} = \begin{bmatrix} x \\ y \end{bmatrix}$$

2. Apply lens distortion

$$\mathrm{x}_d = \begin{bmatrix} x_d(1) \\ x_d(2) \end{bmatrix} = \left(1 + kc(1)\, r^2 + kc(2)\, r^4 + kc(5)\, r^6\right) \mathrm{x}_n + dx$$

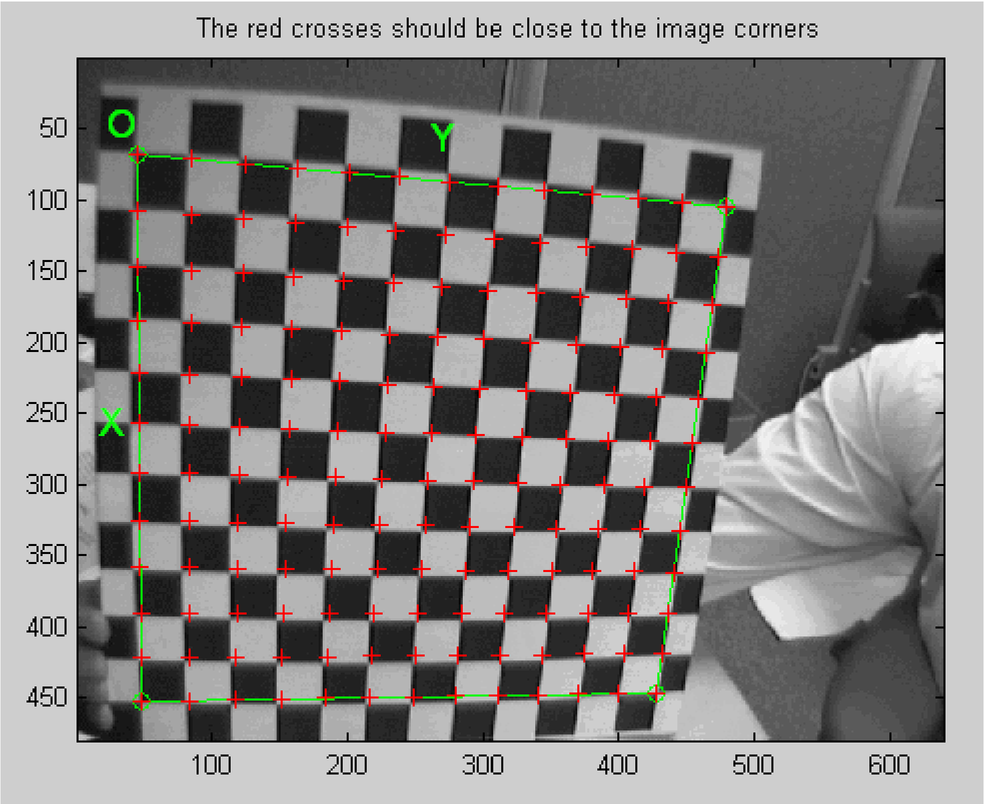
$$dx = \begin{bmatrix} 2\, kc(3)\, x\, y + kc(4)\left(r^2 + 2x^2\right) \\ kc(3)\left(r^2 + 2y^2\right) + 2\, kc(4)\, x\, y \end{bmatrix}$$

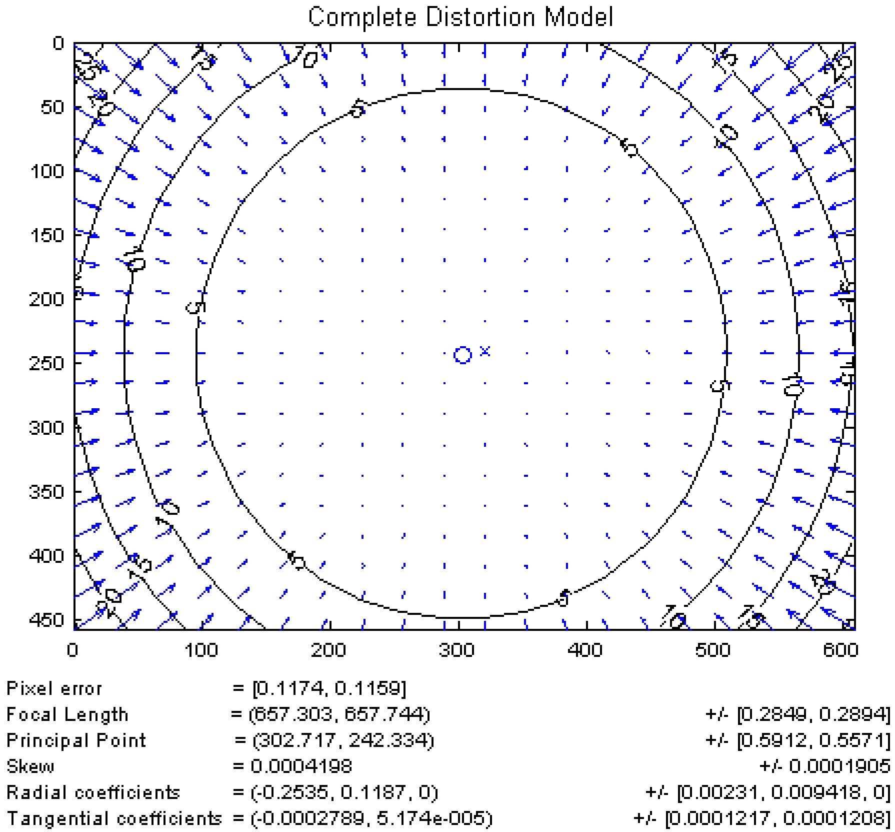
3. Apply camera matrix

$$\begin{bmatrix} x_p \\ y_p \\ 1 \end{bmatrix} = KK \begin{bmatrix} x_d(1) \\ x_d(2) \\ 1 \end{bmatrix} \qquad KK = \begin{bmatrix} fc(1) & alpha\_c * fc(1) & cc(1) \\ 0 & fc(2) & cc(2) \\ 0 & 0 & 1 \end{bmatrix}$$

Parameter Estimation

- Recursive nonlinear optimization on labeled dataset.


The red crosses should be close to the image corners


Complete Distortion Model

```
Pixel error            = [0.1174, 0.1159]
Focal Length           = (657.303, 657.744)          +/- [0.2849, 0.2894]
Principal Point        = (302.717, 242.334)          +/- [0.5912, 0.5571]
Skew                   = 0.0004198                   +/- 0.0001905
Radial coefficients    = (-0.2535, 0.1187, 0)        +/- [0.00231, 0.009418, 0]
Tangential coefficients = (-0.0002789, 5.174e-005)   +/- [0.0001217, 0.0001208]
```

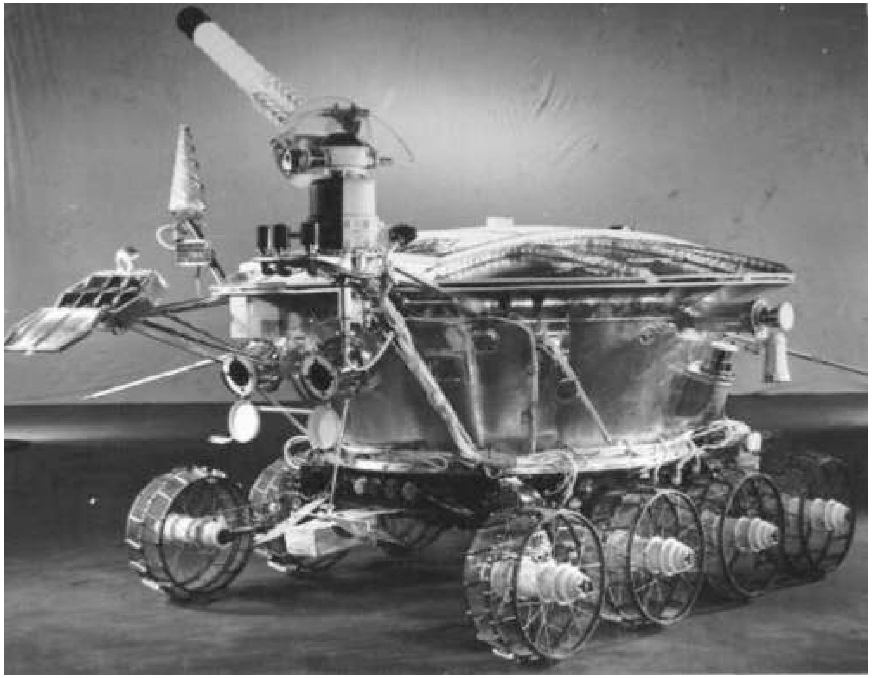
http://www.vision.caltech.edu/bouguetj/calib_doc/htmls/example.html

Problem

- Suppose I have pixels in image coordinates and I want to find the corresponding rays in world coordinates. This is called image rectification. For example, I want to use the rays that intersect the same object from two different perspective so I can triangulate the distance to that point. How can I reverse this camera model? Is this a trivial problem? Can you suggest a crude algorithm that approximates the solution? (Hint: work backwards) Are there better ways?

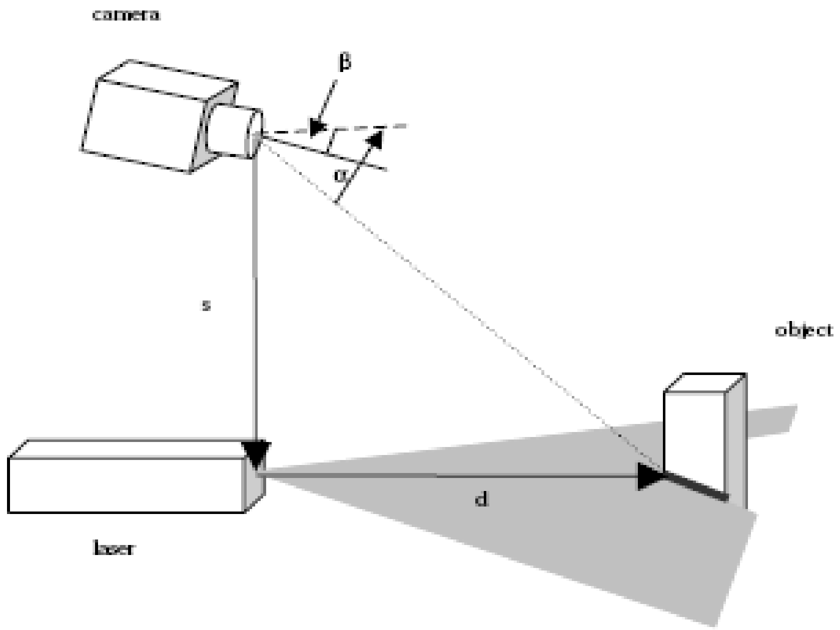
Stereo Vision on the Moon

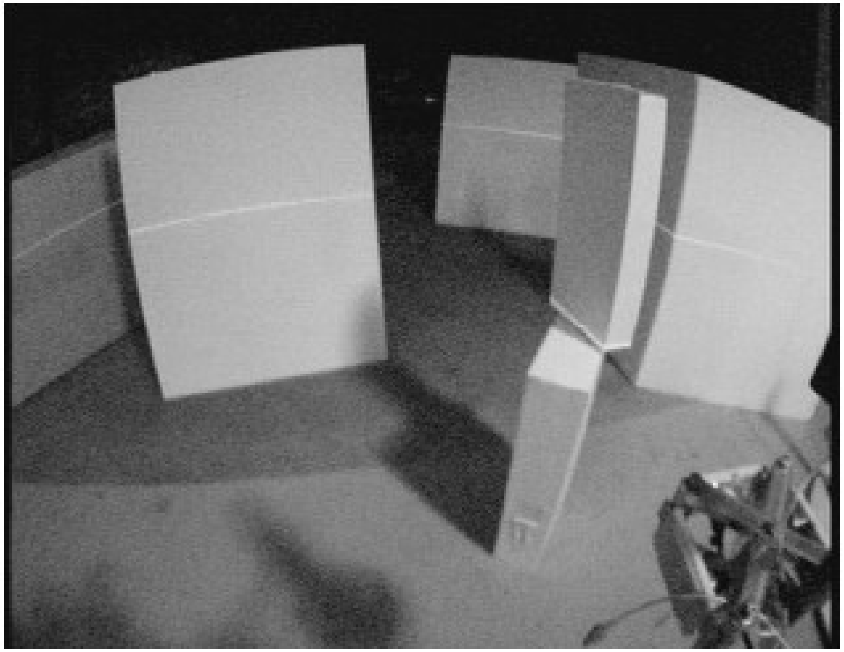
- Lunakhod – USSR 1970, 1973
- Human guided by 5 person team
- Remote control – small time of flight lag



Structured Light

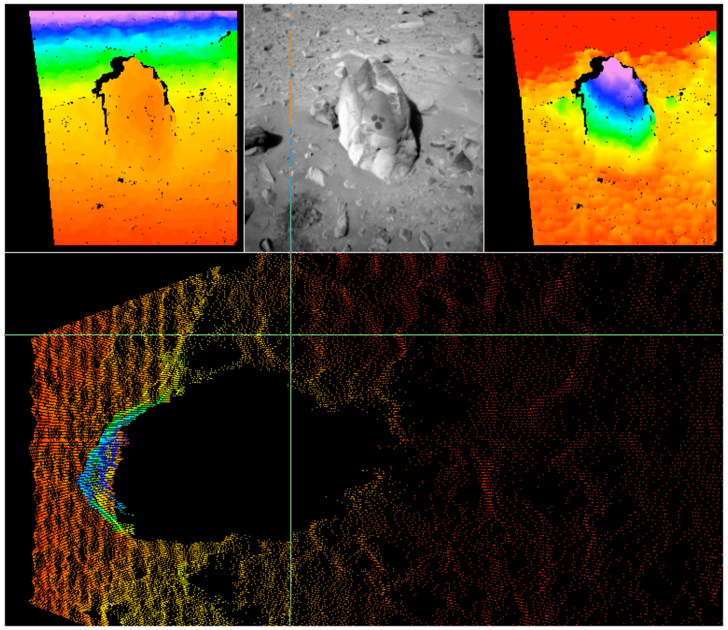
- Instead of a camera, one sensor is a light source with known geometry.
  - Simple, cheap, high resolution, low CPU usage
  - Sojourner, 1997 – 2MHz CPU, obstacle avoidance

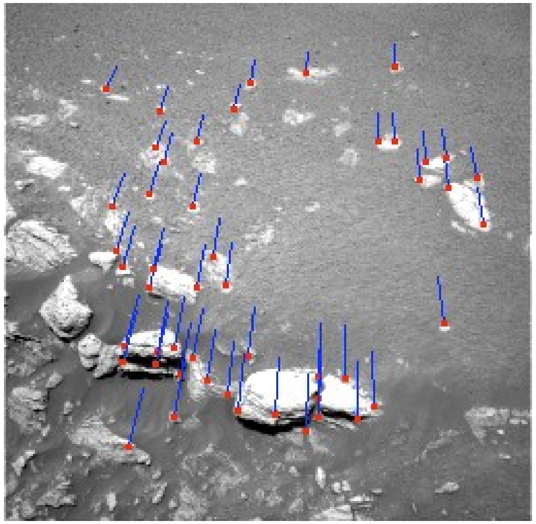




Stereo on Mars

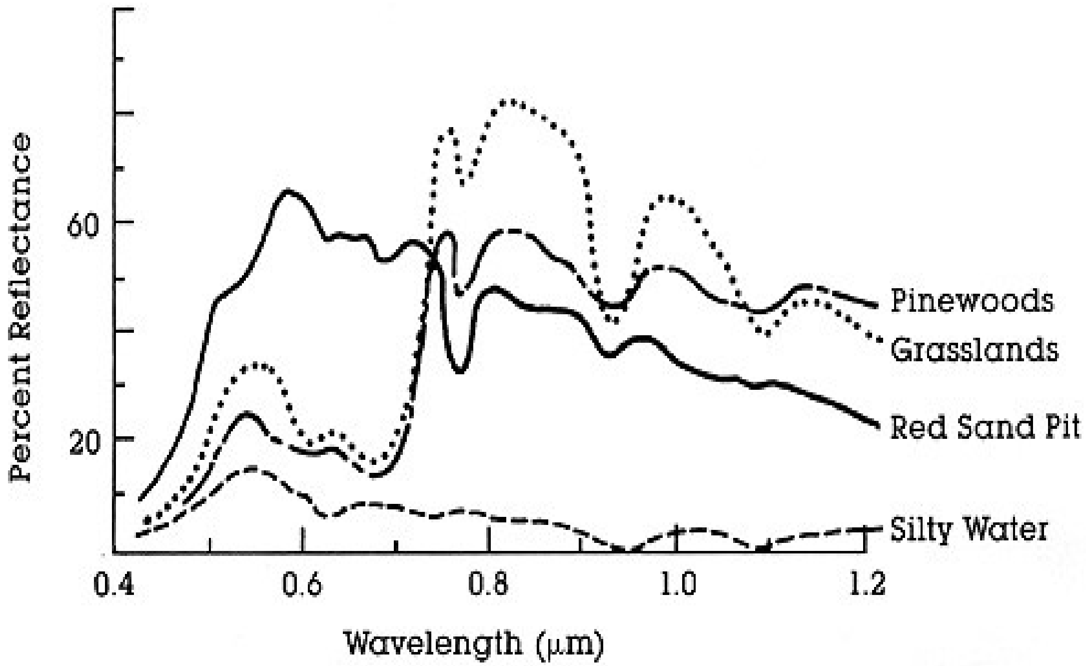
- Not until MER (2004), has stereo been used to control an autonomous rover
- 256x256 resolution takes 30 seconds per frame
- Also used for visual odometry.
  - See [11] for a CMU PhD thesis on this principle, implemented on Hyperios/Zoe

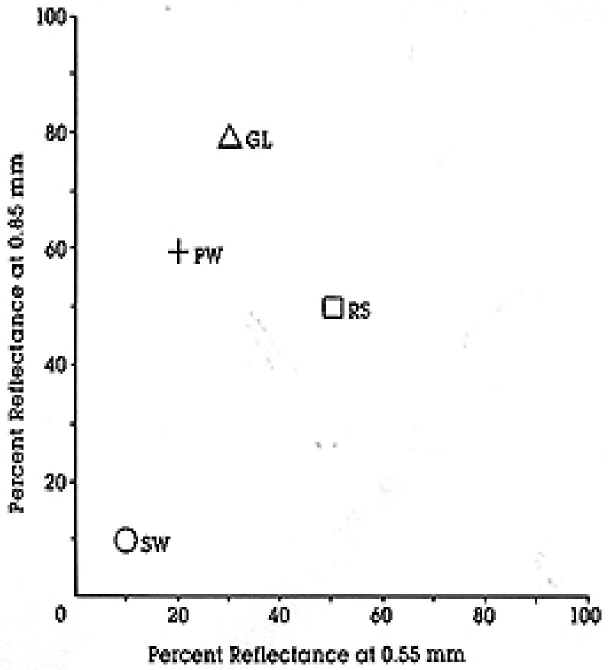




Multi-Spectral Imaging

- Spectral signature is a non-unique descriptor
  - Light source is usually natural (the Sun)
  - http://rst.gsfc.nasa.gov





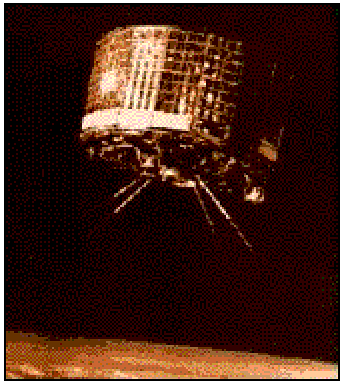
False Color Imagery

- B&W Film based method using optical filters
  - Earliest use of multispectral imaging
  - Healthy plants viewed under .7-1.1 um reflect strongly
  - Military reconnaissance – camouflaged structures will not have the same signature
  - National Geographic research as early as 1930

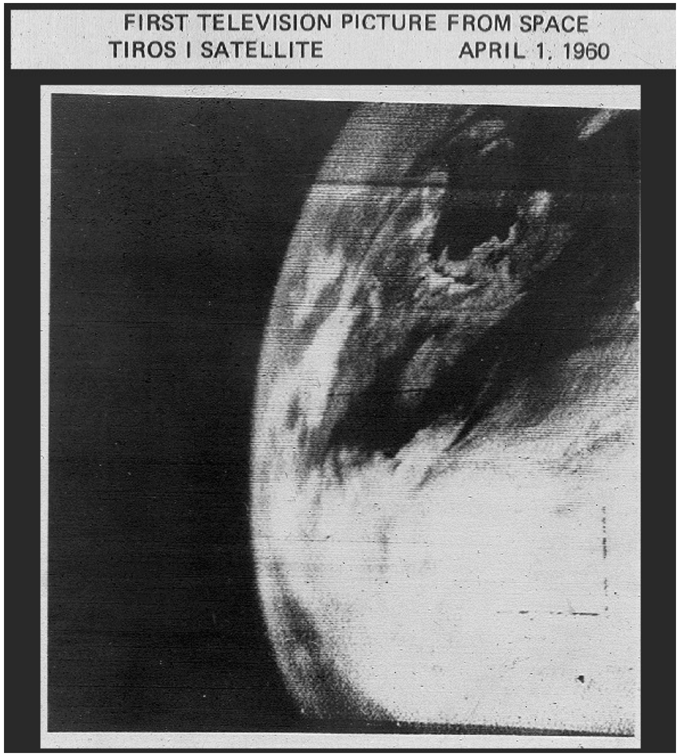
Apollo 9 (1968), Skylab (1973)

- Apollo, 4 camera array mounted in window – RGB,IR
- Skylab, 6 camera array, 163 km^2
- Film cameras were still the best way to get high resolution imagery

TIROS (1960)

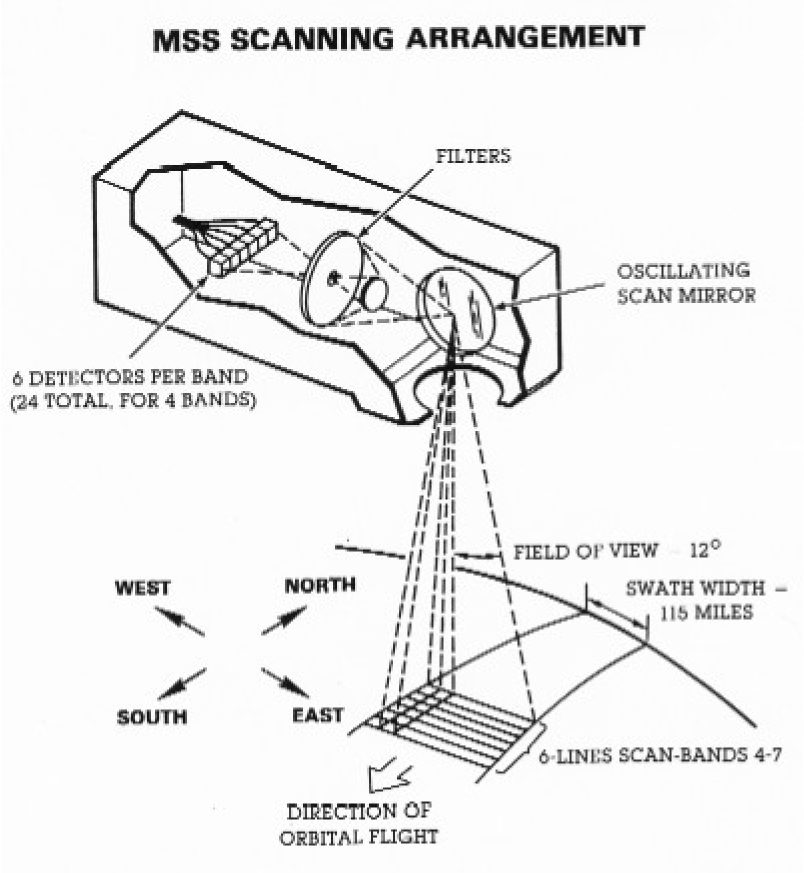


- Television Infrared Orbiting Satellite
  - Water vapor imaging
  - Vidicon image broadcast to ground where it was photographed (!)
  - 500x500 line camera, 8 bit B/W – near IR (hard to find specs)
  - Follow on satellites were longer wave IR, 6-7 um where water reflects best, and thermal IR to measure temperature of sea surface and clouds



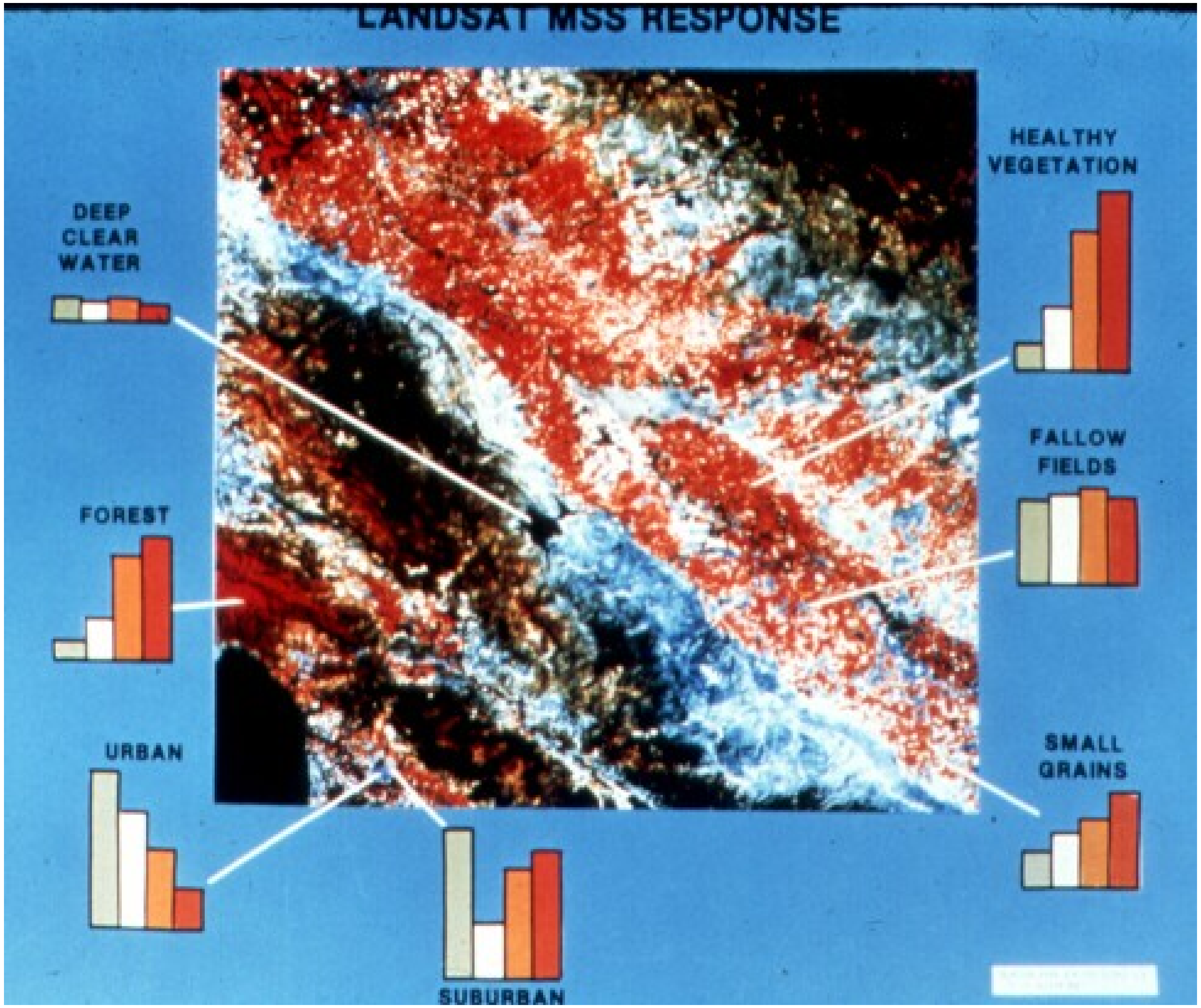
LandSat (1972)

- Vidicon with filter in BG, YR, R-IR.
- MultiSpectral Scanner
  - Uses orbital motion to create image
  - Photodetectors are specifically for the band they are in – 6 bands with 4 detectors each.
  - Resolution is limited by the scanning of the mirror and orbital motion



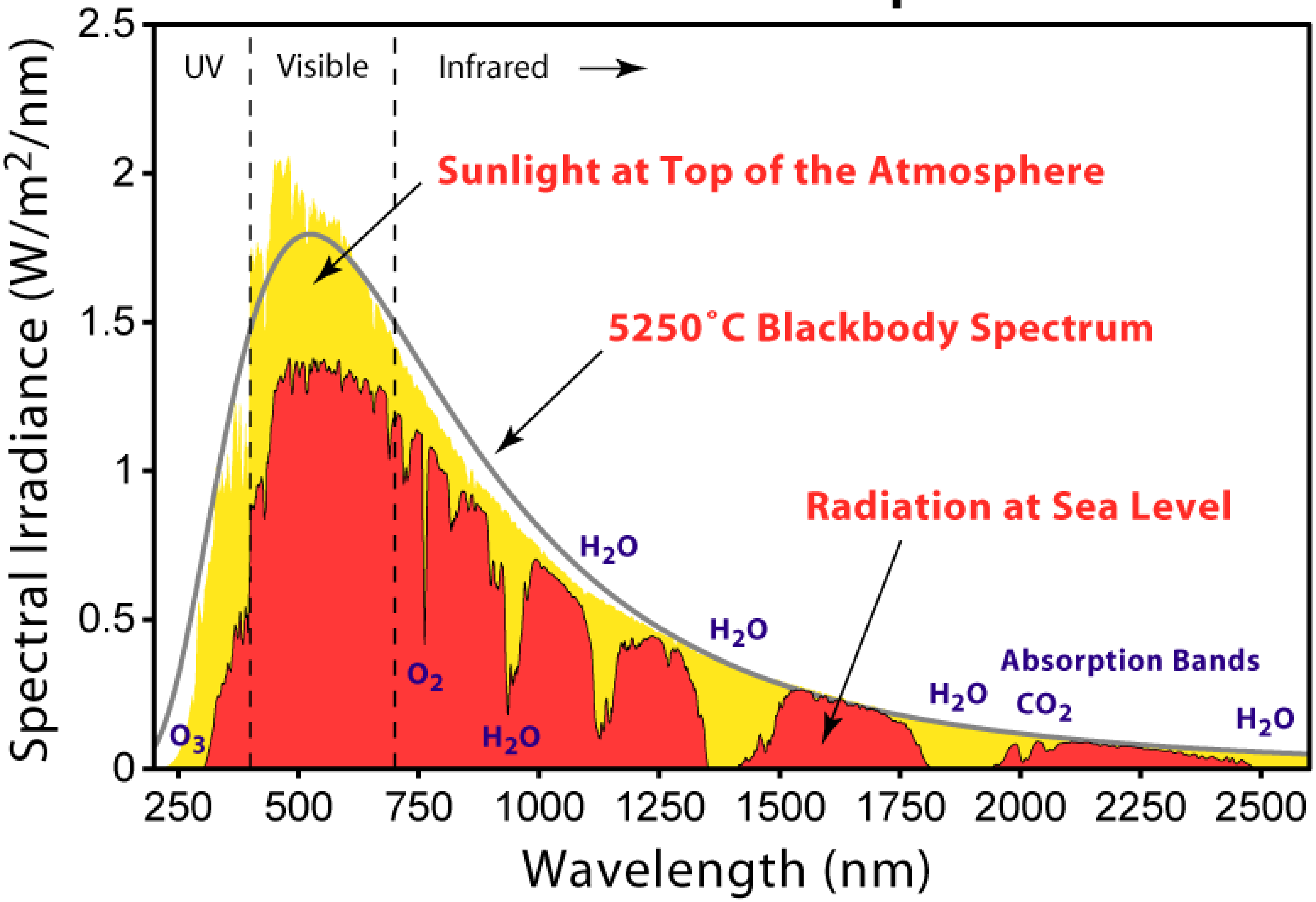
Identifying Land Usage

- Band 4: 0.50–0.60 um
- Band 5: 0.60–0.70 um
- Band 6: 0.70–0.80 um
- Band 7 0.80–1.10 um
- Landsats 4-7 extend to mid IR, 1.5 um–1.75 um and thermal IR, 10-12 um
- Easy to see how machine learning is applicable...



Why Skip Bands

Solar Radiation Spectrum



http://en.wikipedia.org/wiki/File:Solar_Spectrum.png

Why Include Bands

- **Band 1:** 0.45 - 0.52 m (Blue). Band 1 is useful for mapping water near coasts, differentiating between soil and plants, and identifying manmade objects such as roads and buildings.
- **Band 2:** 0.52 - 0.60 m (Green). Spanning the region between the blue and red chlorophyll absorption bands, this band shows the green reflectance of healthy vegetation. It is useful for differentiating between types of plants, determining the health of plants, and identifying manmade objects.
- **Band 3:** 0.63 - 0.69 m (Red). The visible red band is one of the most important bands for discriminating among different kinds of vegetation. It is also useful for mapping soil type boundaries and geological formation boundaries.
- **Band 4:** 0.76 - 0.90 m (Near infrared). This band is especially responsive to the amount of vegetation biomass present in a scene. It is useful for crop identification, for distinguishing between crops and soil, and for seeing the boundaries of bodies of water.
- **Band 5:** 1.55 - 1.75 m (Mid-Infrared). This reflective-IR band is sensitive to turgidity -- the amount of water in plants. Turgidity is useful in drought studies and plant vigor studies. In addition, this band can be used to discriminate between clouds, snow, and ice.
- **Band 6:** 10.4 - 12.5 m (Thermal infrared). This band measures the amount of infrared radiant flux (heat) emitted from surfaces, and helps us to locate geothermal activity, classify vegetation, analyze vegetation stress, and measure soil moisture.
- **Band 7:** 2.08 - 2.35 m (Mid-infrared). This band is particularly helpful for discriminating among types of rock formations.

Technology

- Bolometer – measurement of a body's temperature rise when exposed to radiation.
- Solid State Photodiode – Silicon 190-1100 nm, Germanium 400-1700 nm, Indium gallium arsenide 800-2600 nm, Lead Sulfide 1000-3500 nm

How This Relates to Exploration Robotics

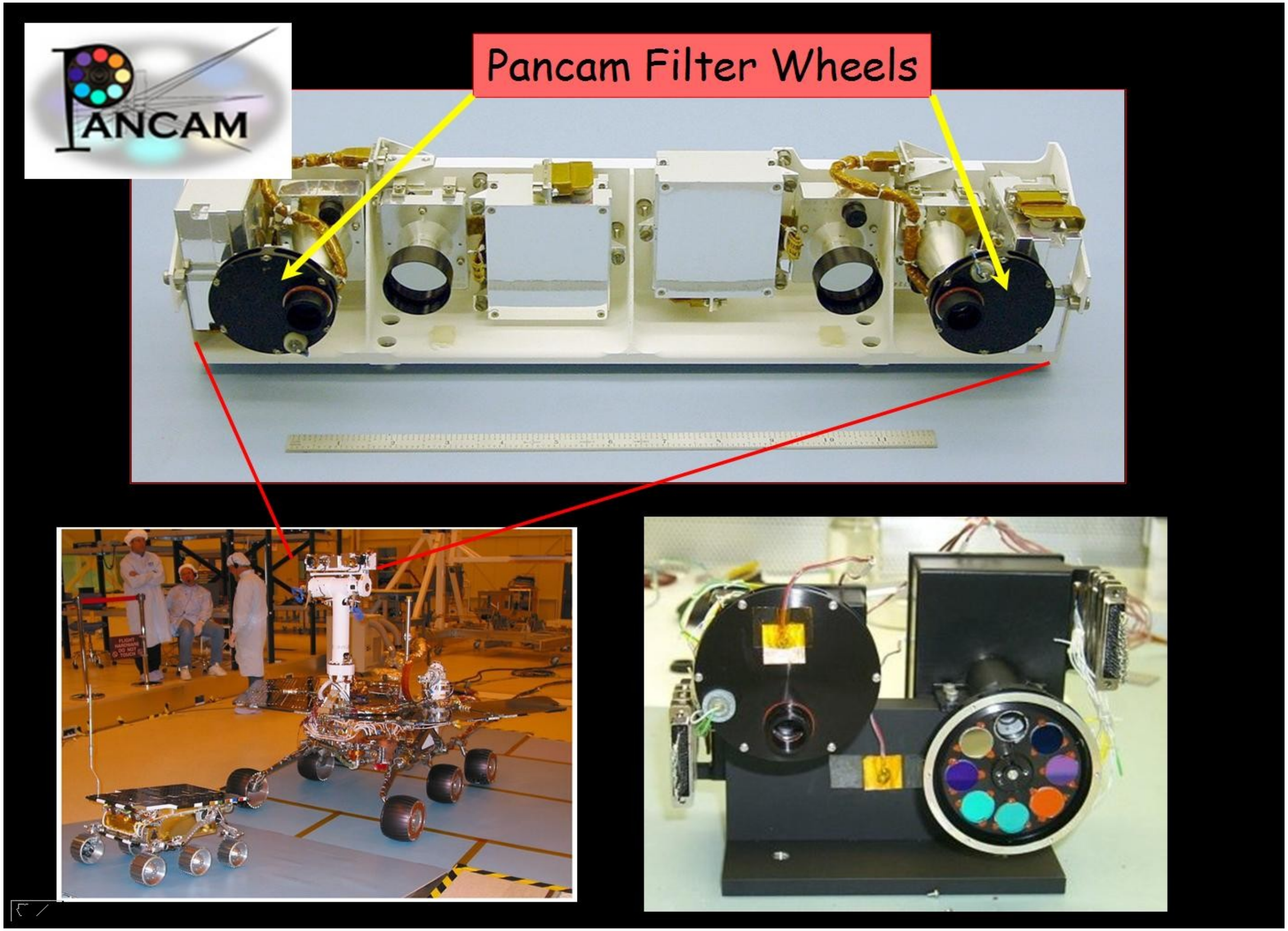
- Classify traversable areas – rock, vegetation, water, etc.

http://www-robotics.jpl.nasa.gov/applications/applicationArea.cfm?App=12

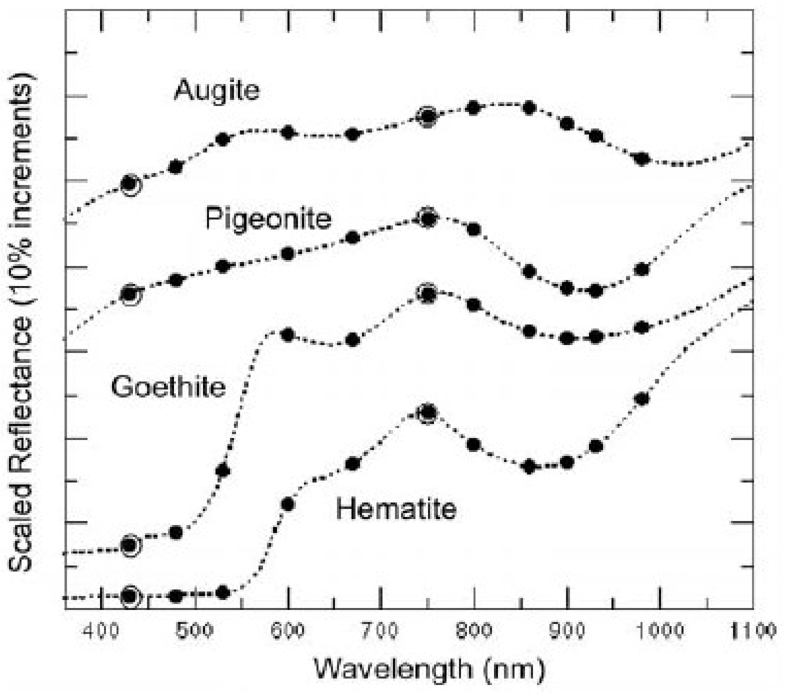
Multi-CCD Cameras

- Best suited for real time vision
- Half silvered mirror directs incoming light to multiple detectors, each with their own bandpass filter
- Equinox Sensors, Flux Data , Geospatial Systems, etc.
- Customizable by changing filters – Edmund Scientific, Omega Optical, etc.
- Filter wheels for less than real time imaging

PanCam (Opportunity, Spirit, 2004)



PanCam Filters



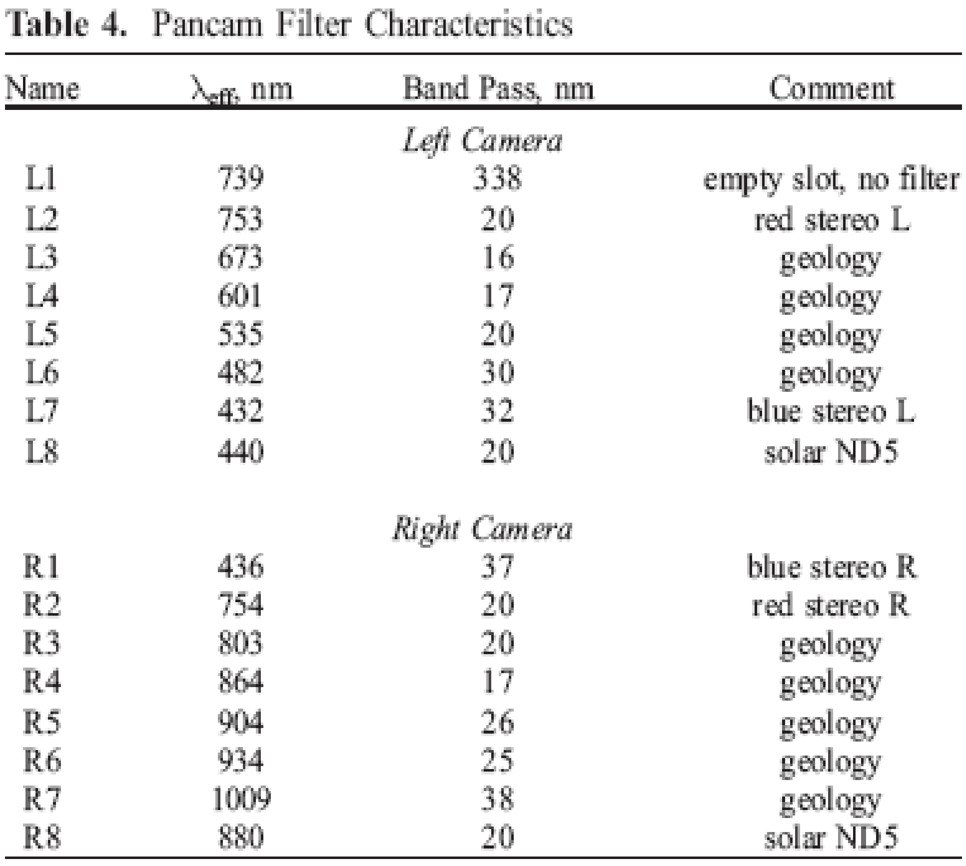
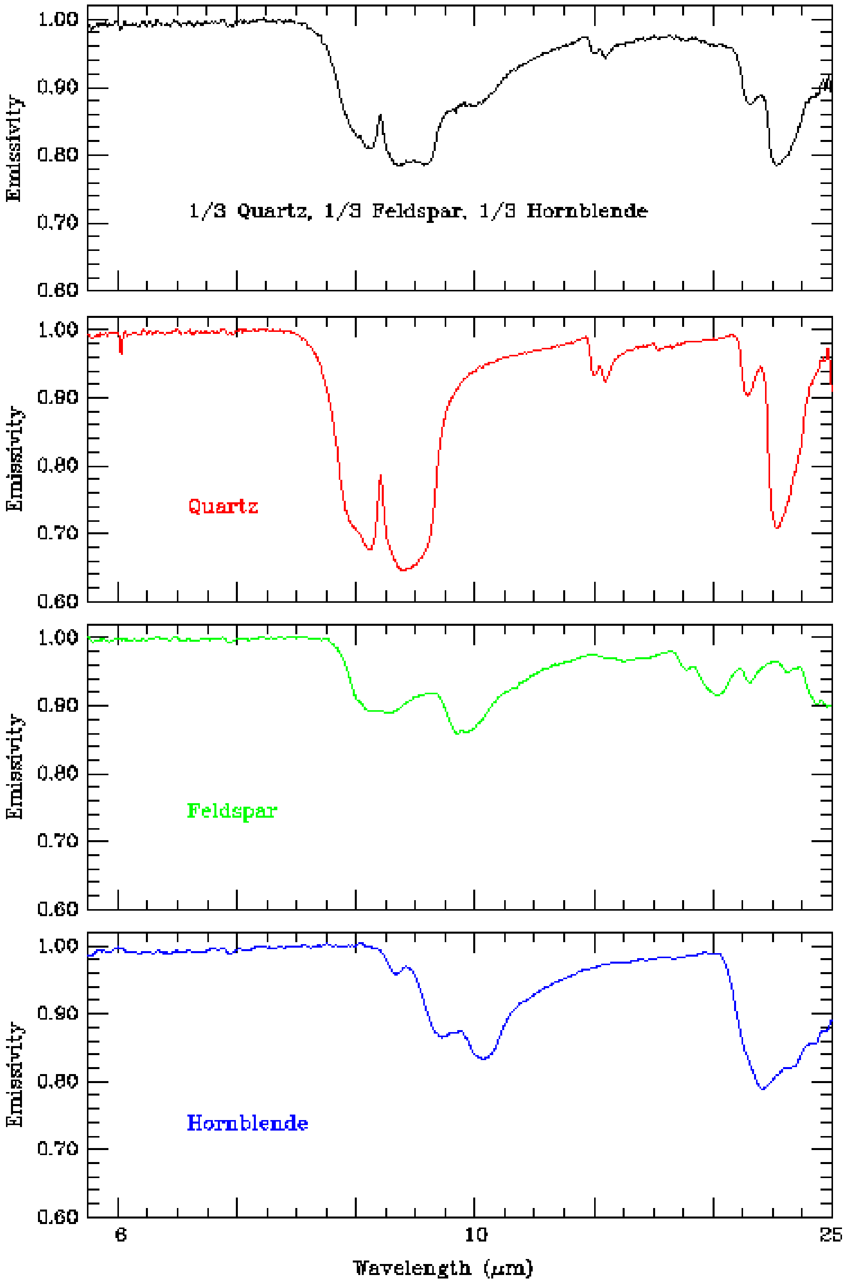


Table 4. Pancam Filter Characteristics

Name	λ_{eff}, nm	Band Pass, nm	Comment
		Left Camera	
L1	739	338	empty slot, no filter
L2	753	20	red stereo L
L3	673	16	geology
L4	601	17	geology
L5	535	20	geology
L6	482	30	geology
L7	432	32	blue stereo L
L8	440	20	solar ND5
		Right Camera	
R1	436	37	blue stereo R
R2	754	20	red stereo R
R3	803	20	geology
R4	864	17	geology
R5	904	26	geology
R6	934	25	geology
R7	1009	38	geology
R8	880	20	solar ND5

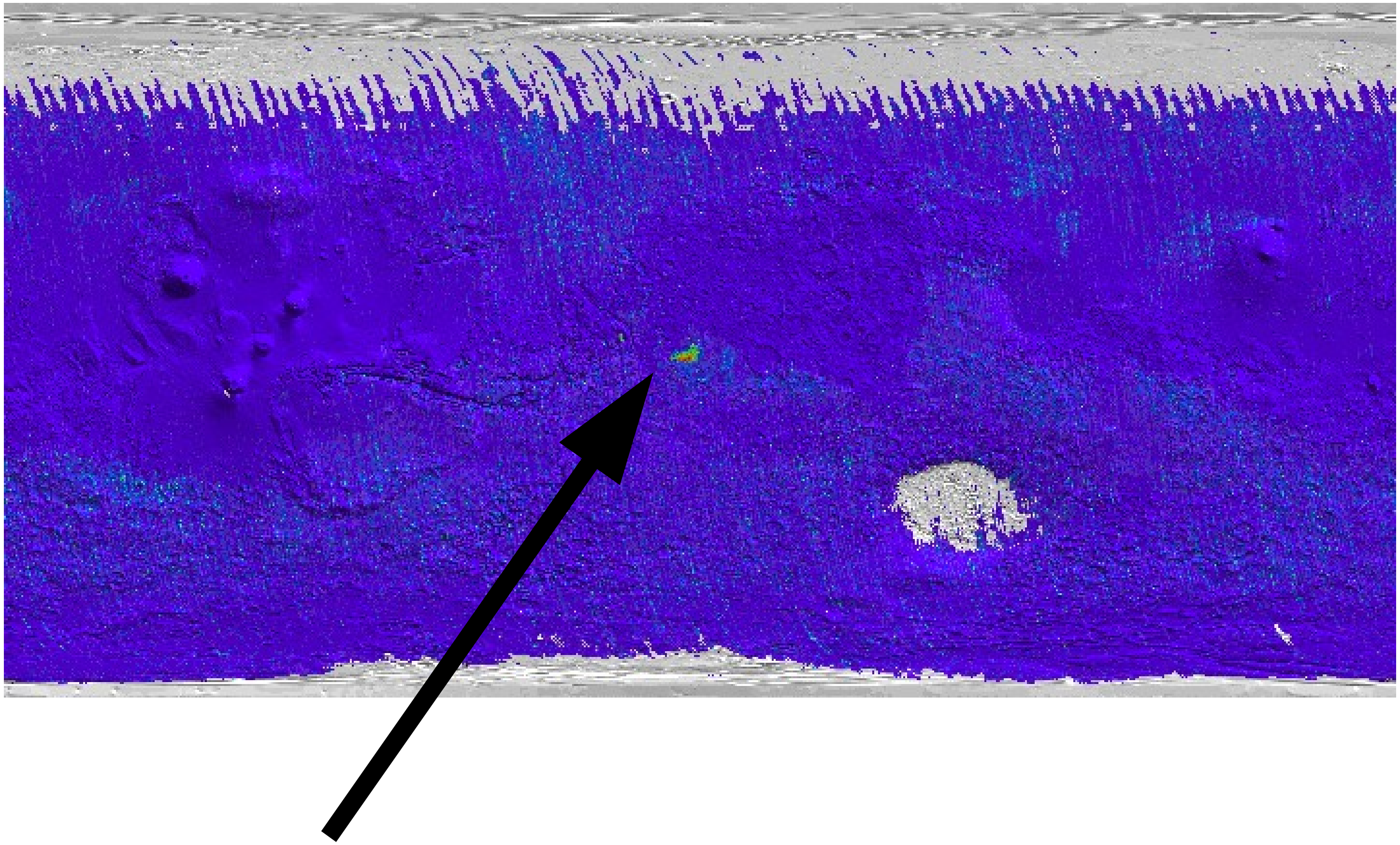
Finding Interesting Rocks

- TES (Thermal Infrared Spectrometry)
  - Arizona State University / Raytheon Santa Barbara Remote Sensing
  - Mars Global Surveyor (1996)
  - Spectra are additive

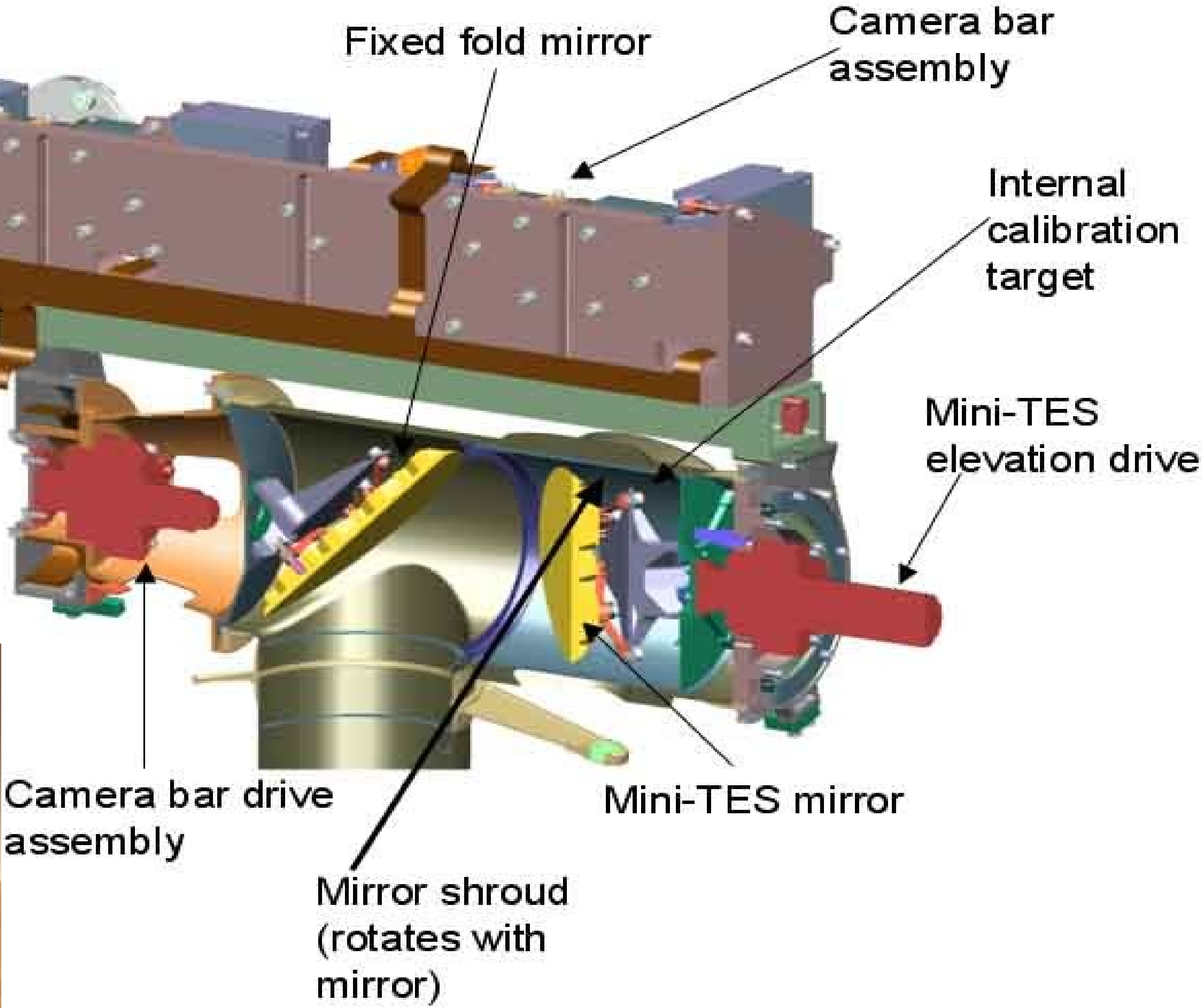


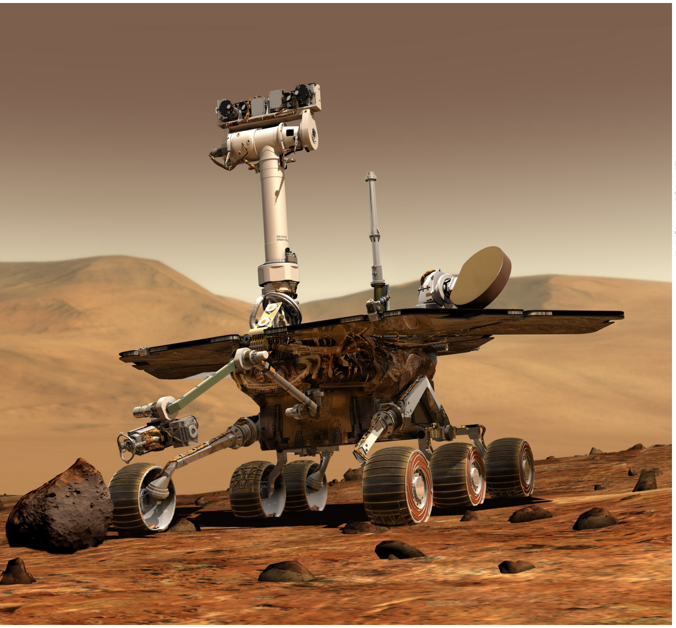
http://tes.asu.edu/about/technique/what2/index.html

Hematite Distribution on Mars

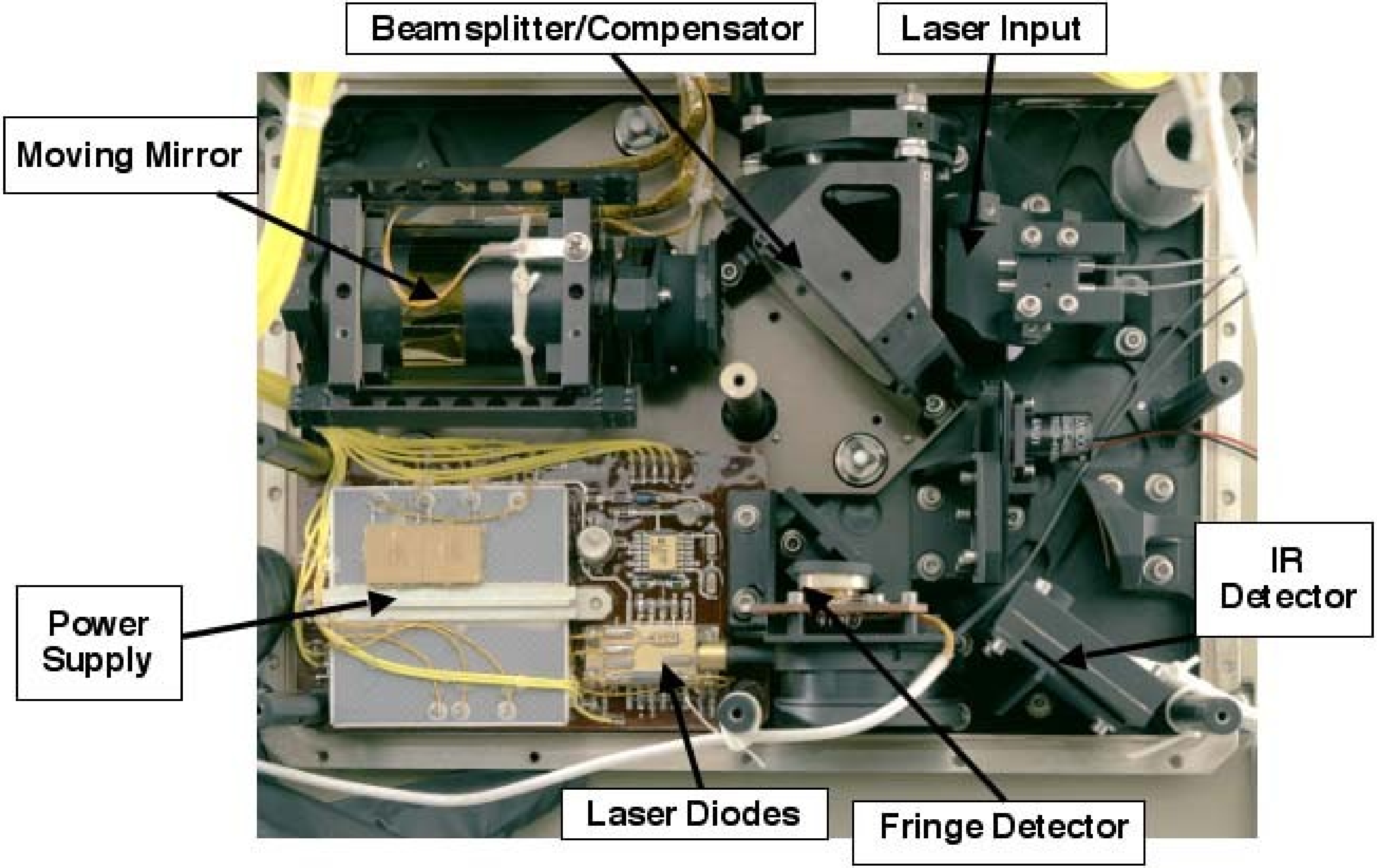


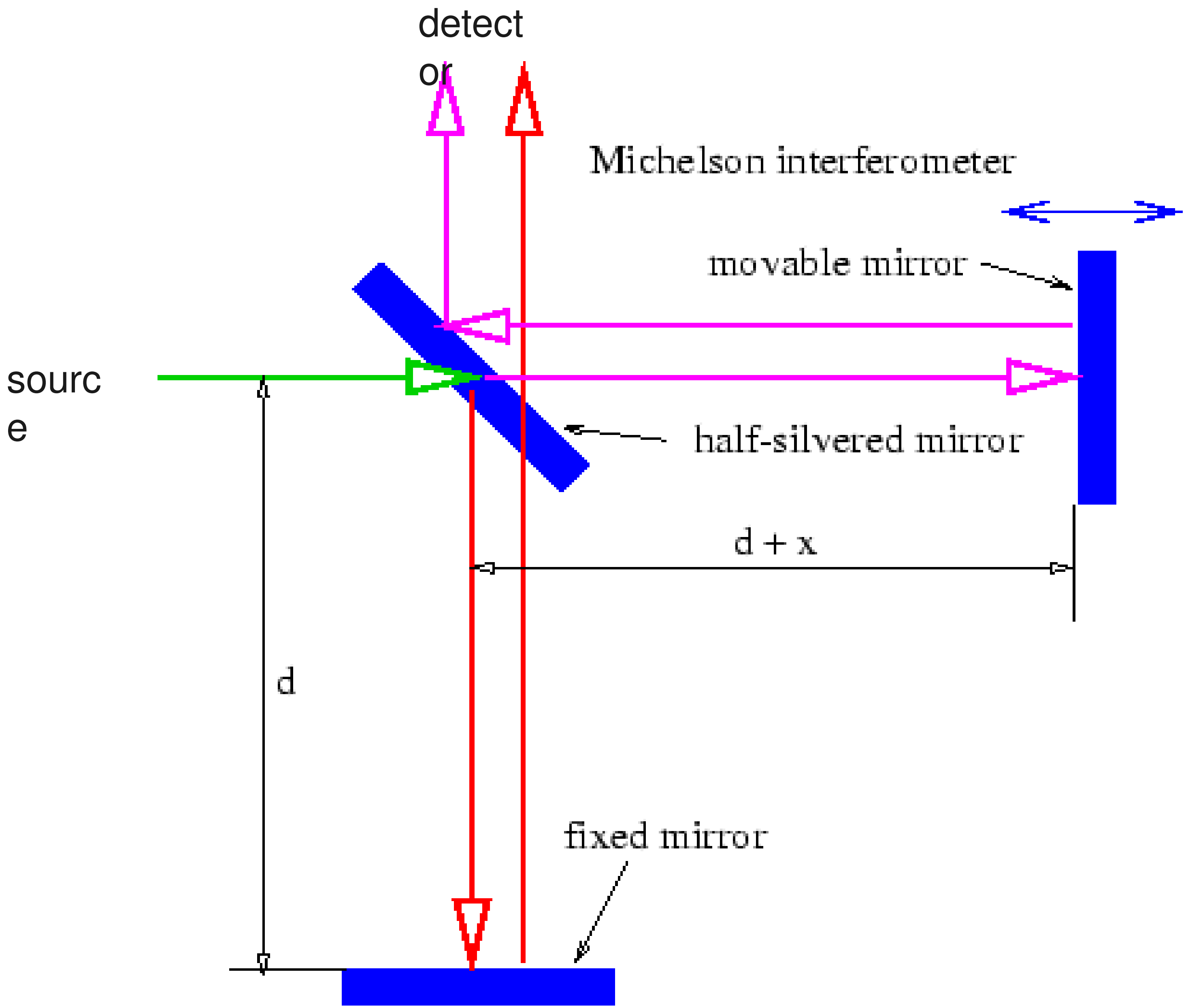
Meridiani Planum


Fixed fold mirror
Camera bar assembly
Internal calibration target
Mini-TES elevation drive
Camera bar drive assembly
Mini-TES mirror
Mirror shroud (rotates with mirror)



Mini-TES Optical Bench





detect
or

Michelson interferometer

movable mirror

source

half-silvered mirror

d + x

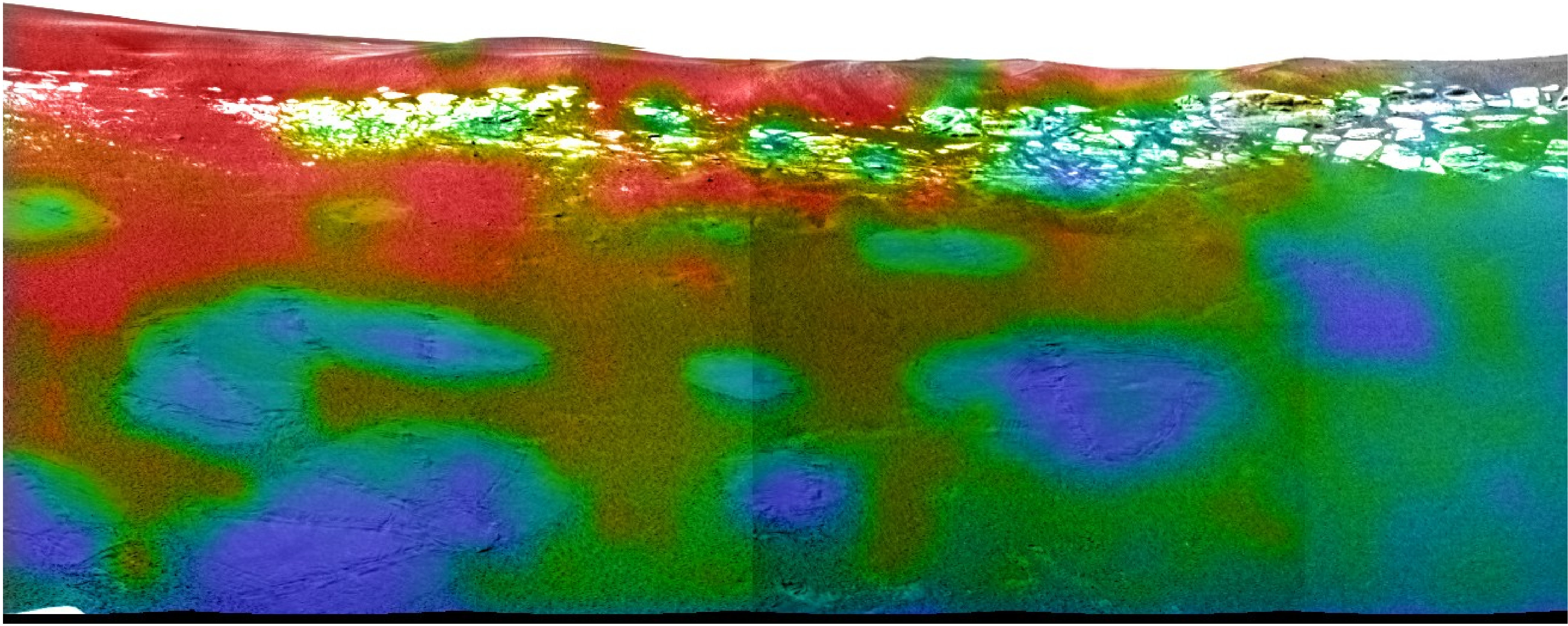
d

fixed mirror

Fourier Transform Spectrograph

- As mirror is scanned, intensity pattern is registered by IR element in this case
- Fringe detector detects the intensity patterns of the reference laser, used to calibrate motion of mirror
- Intensity pattern at IR sensor is the Fourier transform of the spectrum
- IR Detector is pyroelectric, which means it generates a temporary voltage when heated

Hematite Concentration



Improvements

- High dynamic range cameras
- Wider sensor bandwidth/greater sensitivity in a single single solid state device.
- On chip processing arrays to perform operations in situ – only possible with CMOS!
- Tunable filters – hyperspectral imaging

References

[1] Computer Vision: A Modern Approach, Forsyth, D. and Ponce, J. 2003, Prentice Hall.

[2] Matlab Camera Calibration Toolbox http://www.vision.caltech.edu/bouguetj/calib_doc/

[3] Multiple View Geometry in Computer Vision, Hartley, R., Zisserman, A., 2006 Cambridge University Press

[4] Remote Sensing Tutorial http://rst.gsfc.nasa.gov/Front/tofc.html

[5] A Basic Introduction to Water Vapor Imagery http://cimss.ssec.wisc.edu/goes/misc/wv/wv_intro.html

[6] Schueler, C.F.; Silverman, S.H.; Greenfield, M.I.; Christensen, P.R.; Aerospace Conference, 1997. Proceedings., IEEE

References

[7] Bell III, J.F., J.R. Joseph, J. Sohl-Dickstein, H. Arneson, M. Johnson, M. Lemmon, and D. Savransky. 2006. In-Flight Calibration of the Mars Exploration Rover Panoramic Camera Instrument. J. Geophys. Res. 111

[8] http://pancam.astro.cornell.edu/pancam_instrument/index.html

[9] Tanks on the Moon, http://www.youtube.com/watch?v=9K0_p2R13_8

[10] Autonomous Navigation Results from Mars Exploration Rover (MER) Mission, Mark Maimone, Andrew Johnson, Yang Cheng, Reg Willson, and Larry Matthies, Jet Propulsion Laboratory, California Institute of Technology

References

[11] Motion estimation from image and inertial measurements, Dennis Strelow doctoral dissertation, tech. report CMU-CS-04-178, Robotics Institute, Carnegie Mellon University, November, 2004

[12] http://minites.asu.edu/latest.html