Camera Response Simulation for Planetary Exploration

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Planetary Rover Testbeds are Oversubscribed

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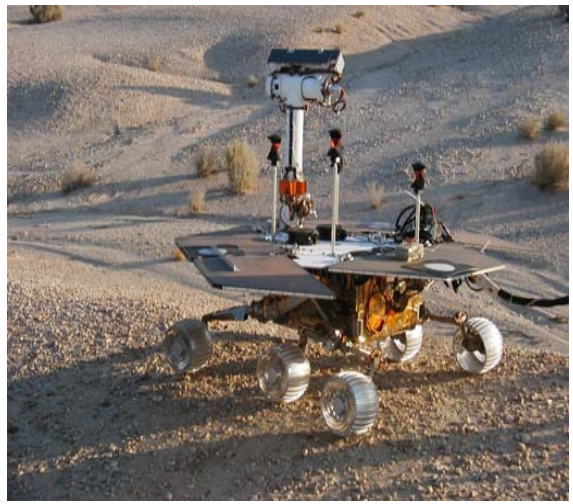

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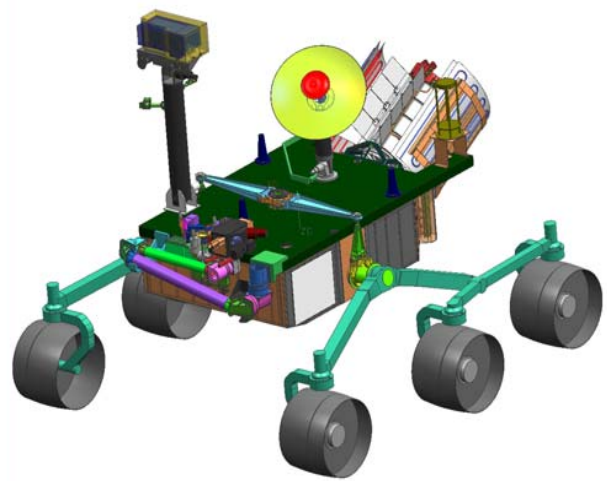


- Many developers, few rovers
- Use simulation instead of hardware testbed

Planetary Rover Testbeds are Limited

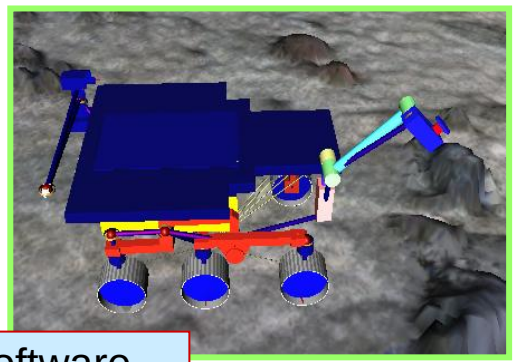
- Simulation can provided environments unavailable to hardware rovers (at reasonable expense)
  - Custom terrain
  - Arbitrarily large terrain
  - Custom lighting

Combined Hardware & Software Simulation Rover Testbed

Darts Lab

Closed-Loop Interfaces

Hardware simulators



Software simulators

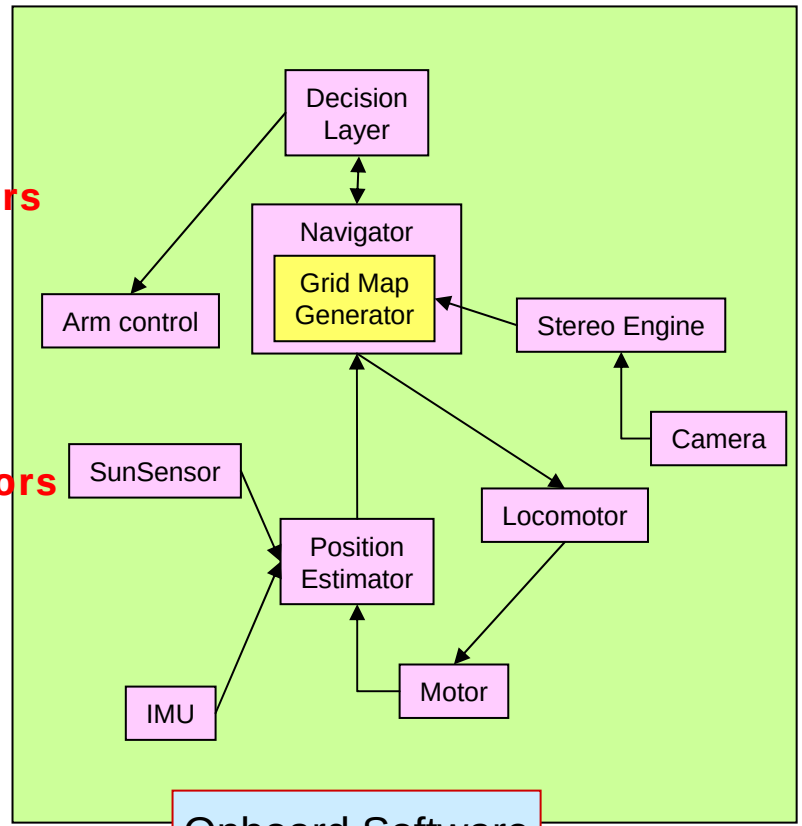
Vision Sensors

Navigation Sensors

Inertial Sensors

Locomotion Sensors

Motor Control



Onboard Software

Vehicle Sensors/Actuators Environment Interfaces

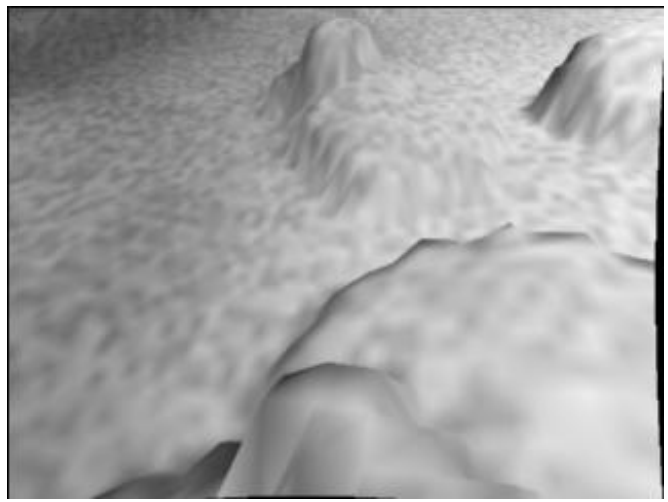
ROAMS Simulator

- Rover Analysis, Modeling, and Simulation
- Simulates rover subsystems and interaction with environment
- Close control loops in simulation

ROAMS Image Synthesis

- Many rover control algorithms input images
  - Visual odometry, path planning, instrument pointing, hazard avoidance, target tracking

- ROAMS synthesizes images to allow closing these control loops



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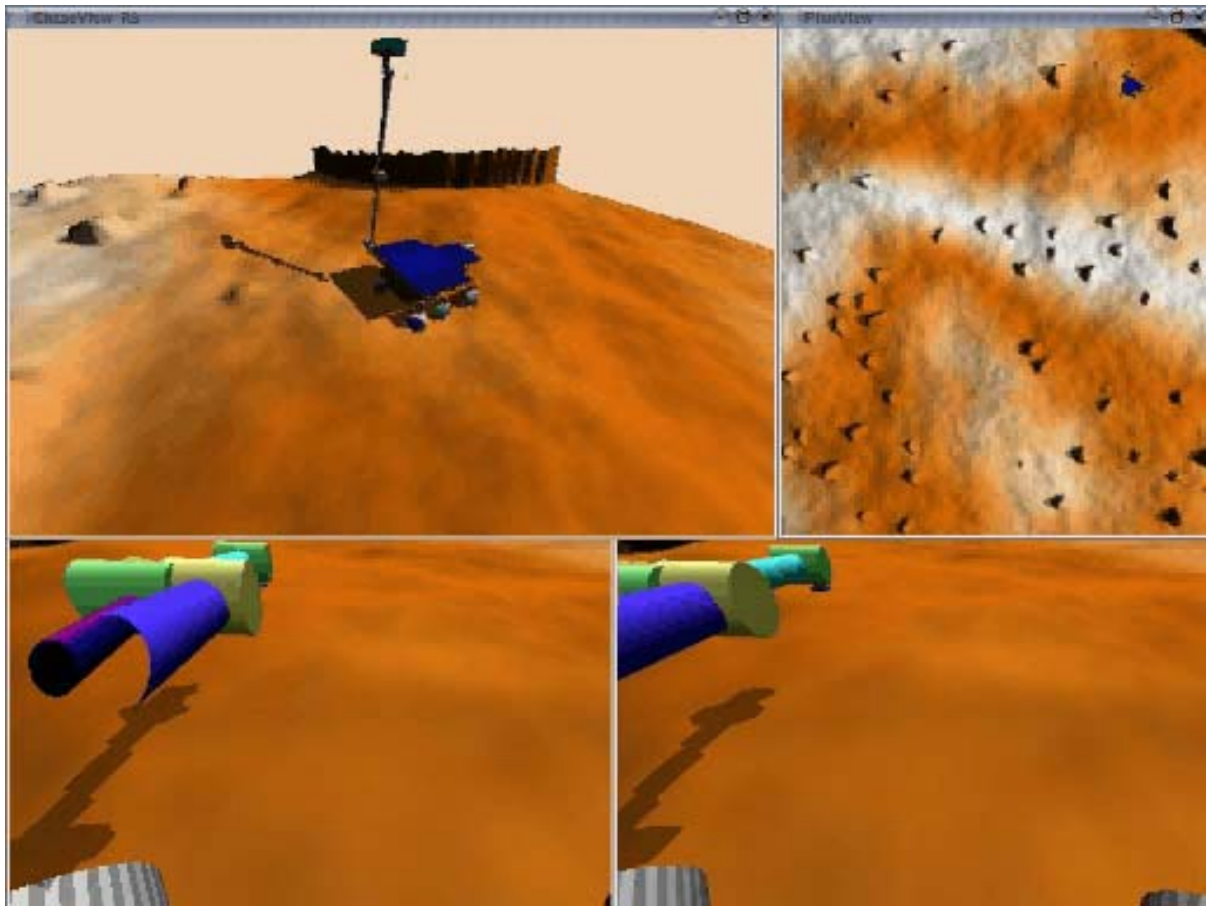
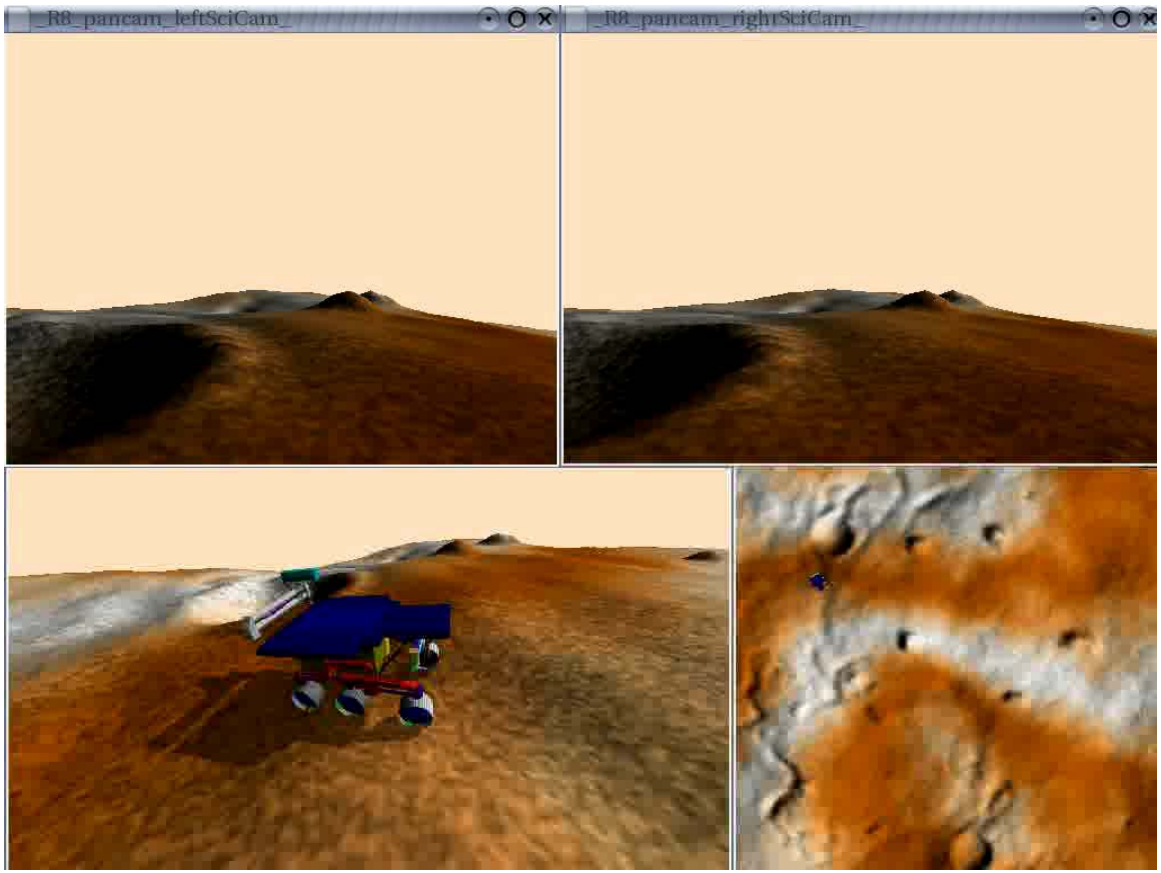
Movie of ROAMS



Another Movie



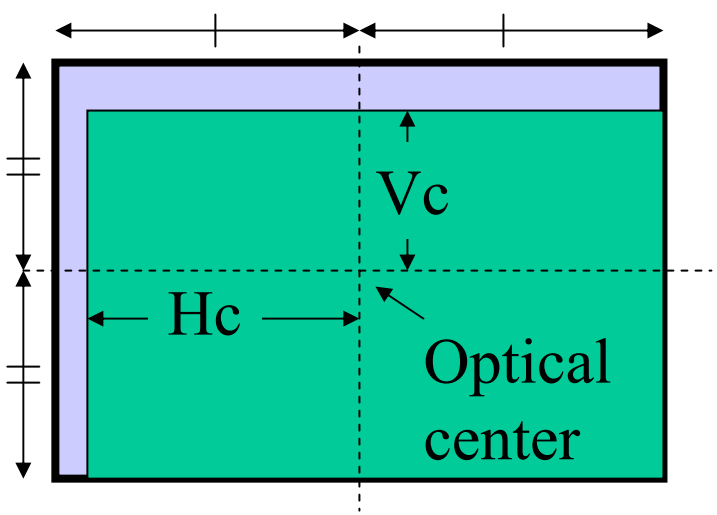
Imaging Features

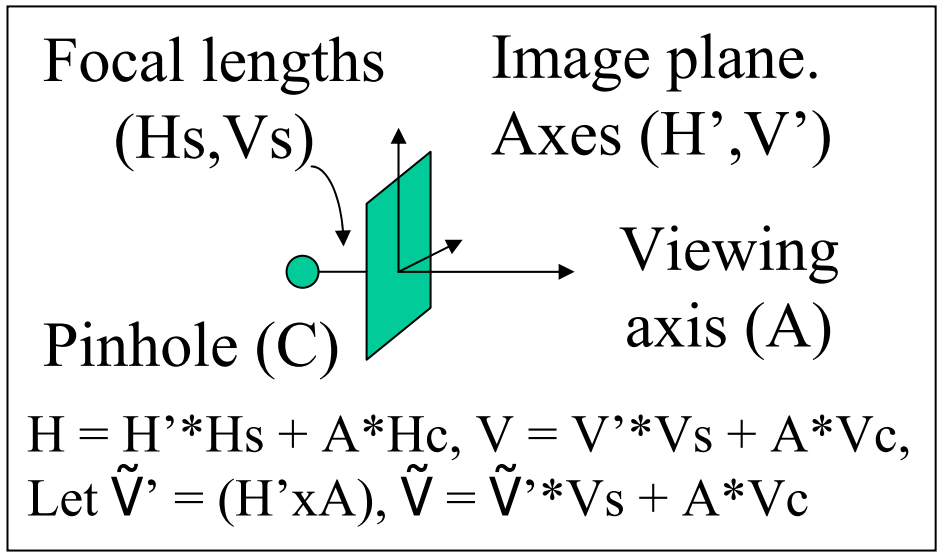
- Fidelity / Performance Options
  - More features: Enough fidelity to test vision algorithms
  - Fewer features: Fast enough for real time simulation

		Benefit		
		High	Moderate	Low
Complexity	Low	Pinhole camera (CAHV) Lighting angle and shadows Pixel noise (shot, readout, …) Vignetting	Global gain, Dark current Fine lens fog/dust, Pixel dropout Saturation, blooming	Pixel response Permanent hot pixels, Single event hot pixels Large detector dust Fast flush & frame transfer noise
	Moderate	Radial lens distortion (CAHVOR) Moving entrance pupil (CAHVORE)	Motion blur Ray tracing specularity, reflectivity, turbulence, transmittance IR camera Large lens dust, Atmosphere fog/dust	Depth of field, focal distance Lens point spread function Color CCD: single chip or multi-chip Wavelength sensitivity Spherical aberration, Chromatic aberration Unsynchronized stereo cameras
	High	Textures with realistic granularity 3D textures (bump maps) @ 5mm cell size Opposition effect		Fixed/repeating pattern noise from EM interference Volatiles on lens, Lens flare, Aliasing, radiosity Cable reflection ghosts, analog antialiasing, pixel jitter

CAHV Camera Model

- Pinhole camera
- Accurate for very small field of view
- H', V' nearly orthogonal





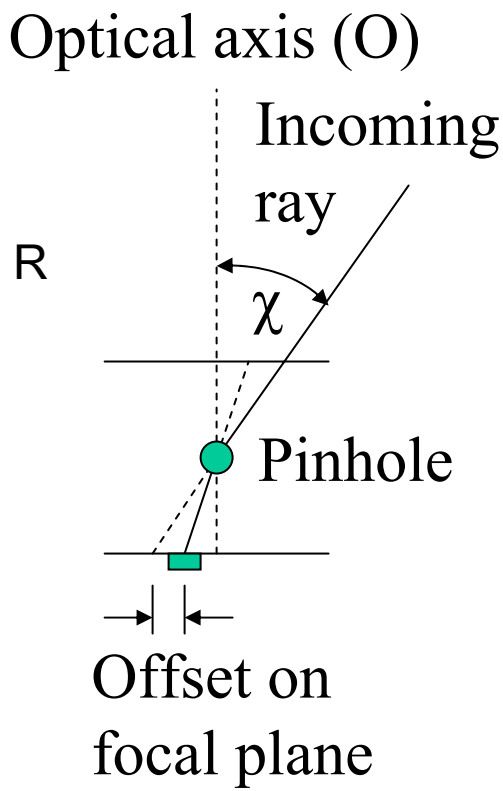
- Render image using OpenGL symmetric, H' ⊥ Ṽ' camera
- Clip CAHṼ subimage

CAHVOR Camera Model

- CAHV + Radial Distortion (O,R)

- Incoming ray at angle χ to optical axis O
- Ray bends at pinhole
  - Component $\perp$ to O scales by $1 + [\ 1 \tan\chi \tan^2\chi\ ] \bullet R$
  - Bent ray projects onto focal plane
  - 1-to-1 mapping of CAHV to CAHVOR pixels

- Render closest CAH$\tilde{V}$ image
  - No O,R; $H' \perp \tilde{V}'$
- For each CAHVOR pixel
  - Calculate equivalent CAH$\tilde{V}$ coordinates
  - Interpolate from CAHV image

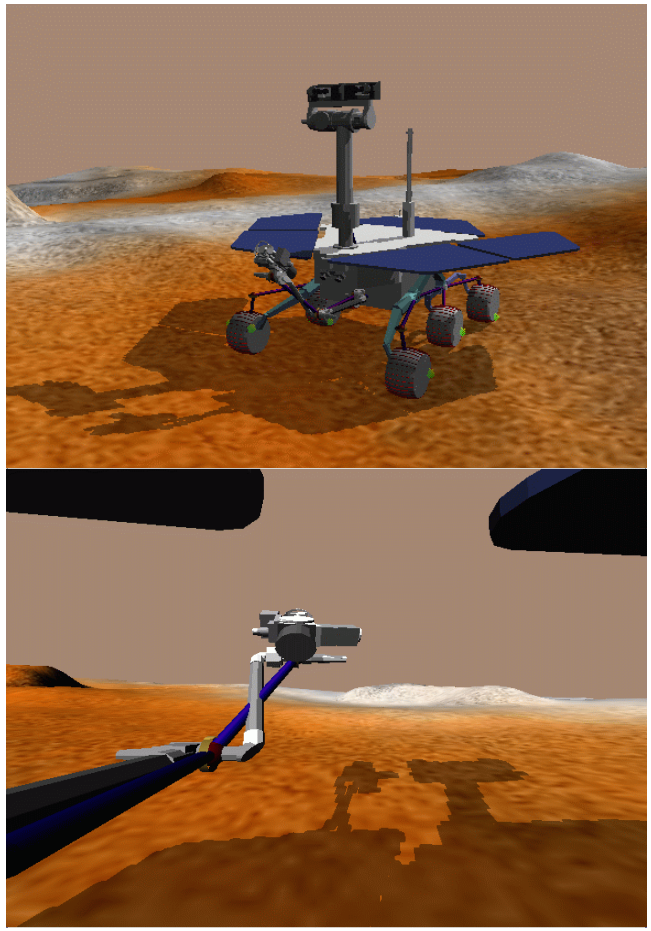


Shadowing

- Shadows impact vision algorithms by adding false edges, reducing contrast, and suggesting nearby obstacles

- Terrain Shadows
  - Render infrequently using POV-RAY
  - Add into surface texture map

- Rover Shadows
  - Rendered every time step
  - On rover and nearby terrain
  - Darken pixels that do not have direct line-of-sight to sun



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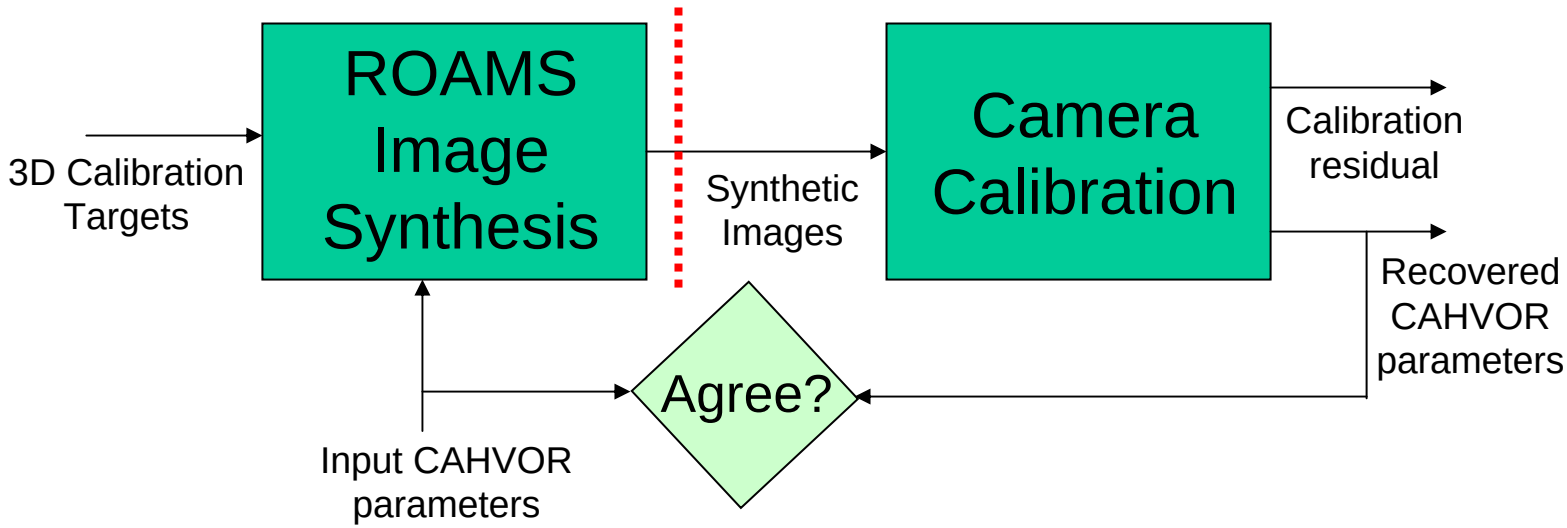
Verification

- Does ROAMS image synthesis accurately apply input CAHVOR model?



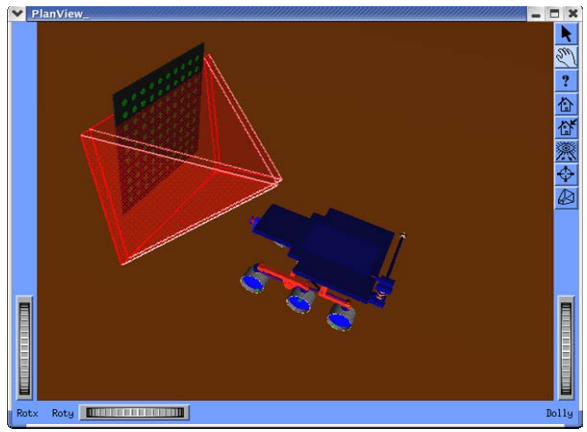
Verification: Cameras

- Tested with 22 assorted cameras

	Rear (bogey) Hazcams	Front (rocker) Hazcams	Navcams	Pancams
Fido	1,2	4,3		
Rocky8	17,18	20,19	21,22	
MER A	5,6	8,7		
MER B	9,10	12,11	15,16	13,14

Verification: Calibration

- Virtual calibration target
- Synthesize images of target
- Record 2D and 3D locations of center of each dot
- Solve for CAHVOR model that best explains 2D and 3D locations
- Iterate to account for radial distortion



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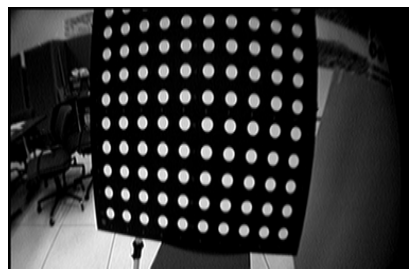

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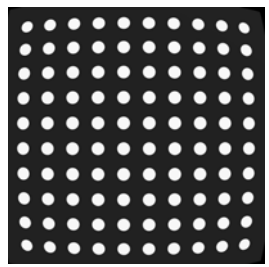

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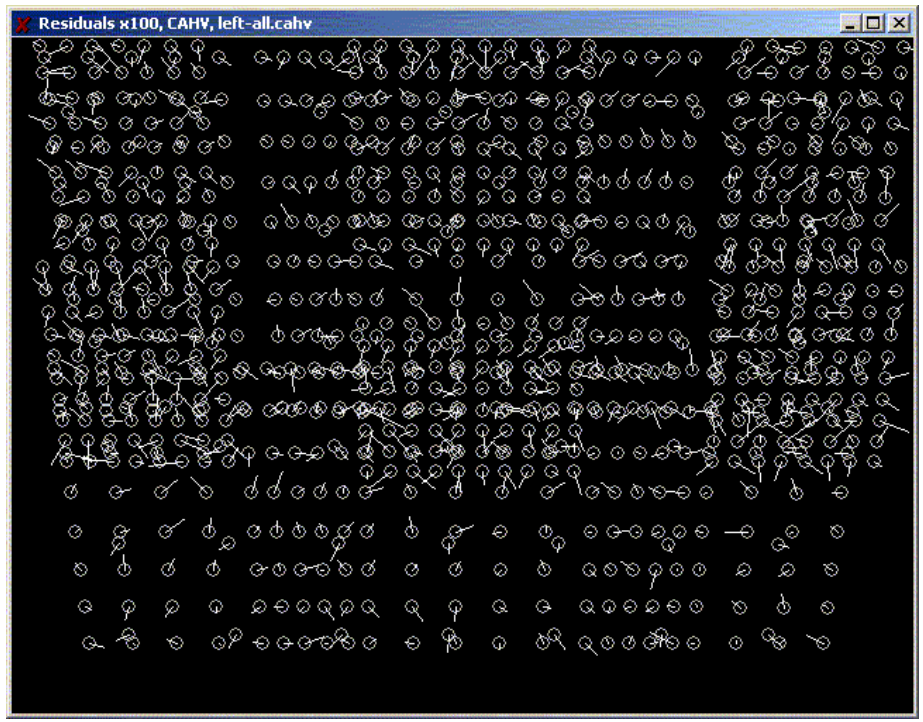
Verification: Residuals

- Measured 2D locations of dots used in calibration
- Vectors point toward 2D locations predicted by CAHVOR + 3D locations
- Good calibration = no pattern, low RMS residual (<0.1 pixel)



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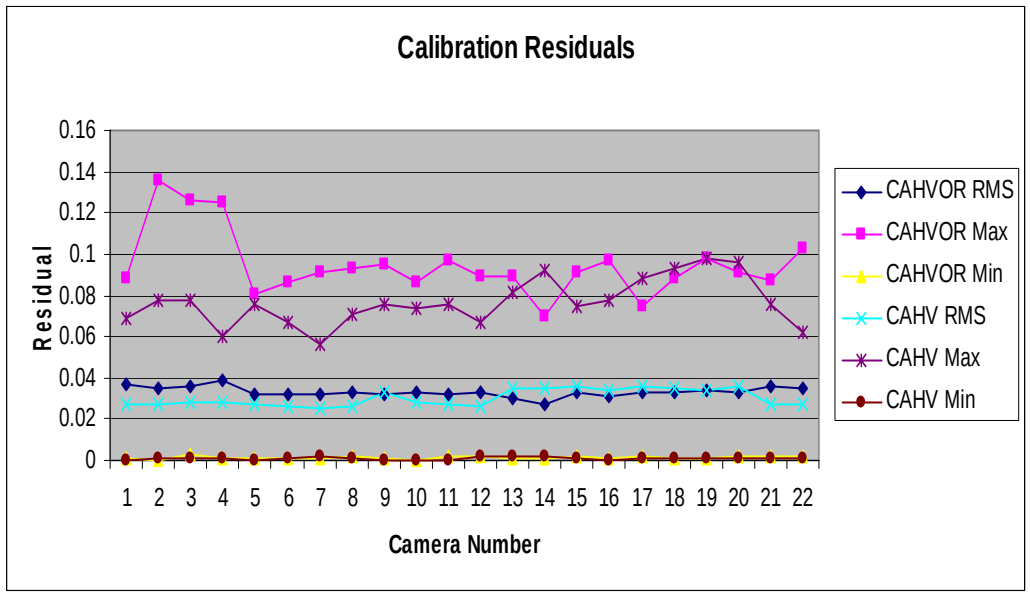
Results: Residual

- RMS residual ~ 1/30 pixel
- Accurately models CAHV and CAHVOR



Results: Fidelity in C,A,H,V

- Some components recovered well
  - Theta recovered to float precision for CAHVOR and CAHṼ
  - CAHV C and Vs to float precision
  - CAHVOR C (<1mm) and Vs (<0.05%) offsetting errors

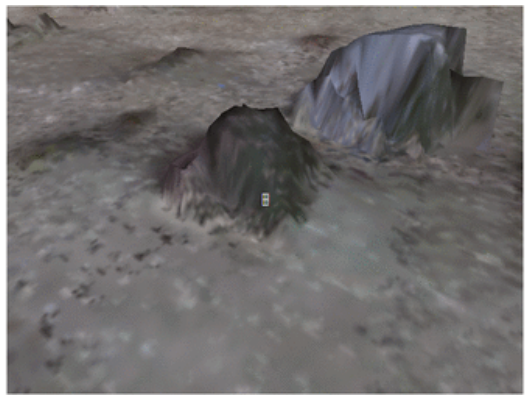
- Some problems caused by two instances of rounding during conversion of CAHV parameters to OpenGL camera parameters
  - Optical center (Hc,Vc) off by 0.5 pixels
  - Axis (A) rotates ~0.01° to compensate for (Hc,Vc) error
  - Hs recovery is erratic but ≤ 0.08%

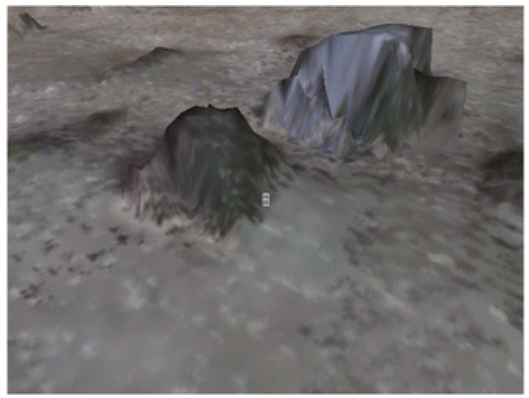
Results: Fidelity in O,R

- Optical axis (O) has noticeable error for fisheye cameras
  - Low distortion MER mast cameras: 0.1° error, ≤ 0.03 pixel offset
  - High distortion FIDO hazcams: 0.05° error, ≤ 0.3 pixel offset
- R recovered well for mast cameras
  - Coupled $Hs*(1+R_0)$ and $Vs*(1+R_0)$ error ≤ 0.02%
  - R_1,R_2 inaccuracy creates error ≤ 0.09 pixels
- R recovery for non-mast cameras
  - $(1+R_0)$ recovered to floating point precision, max offset 0.005 pixels
  - R_1,R_2 inaccuracy < 1%

Application: Stereo

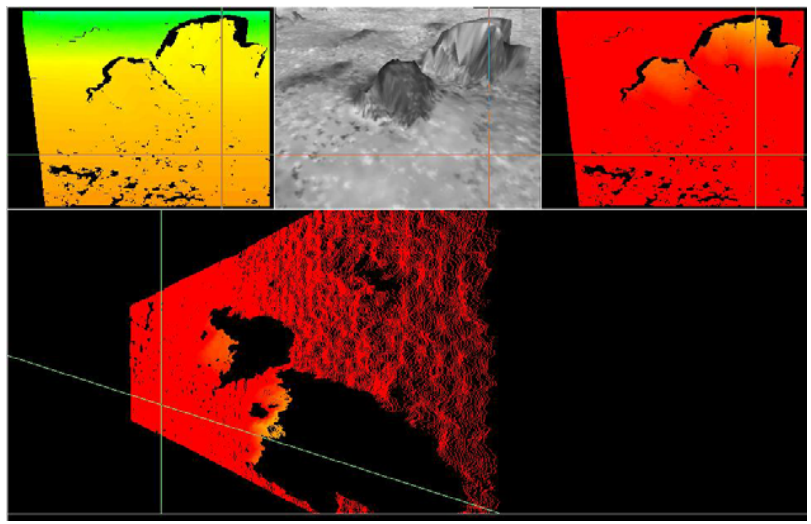
Left Camera Image





Right Camera Image

Stereo output coded by distance

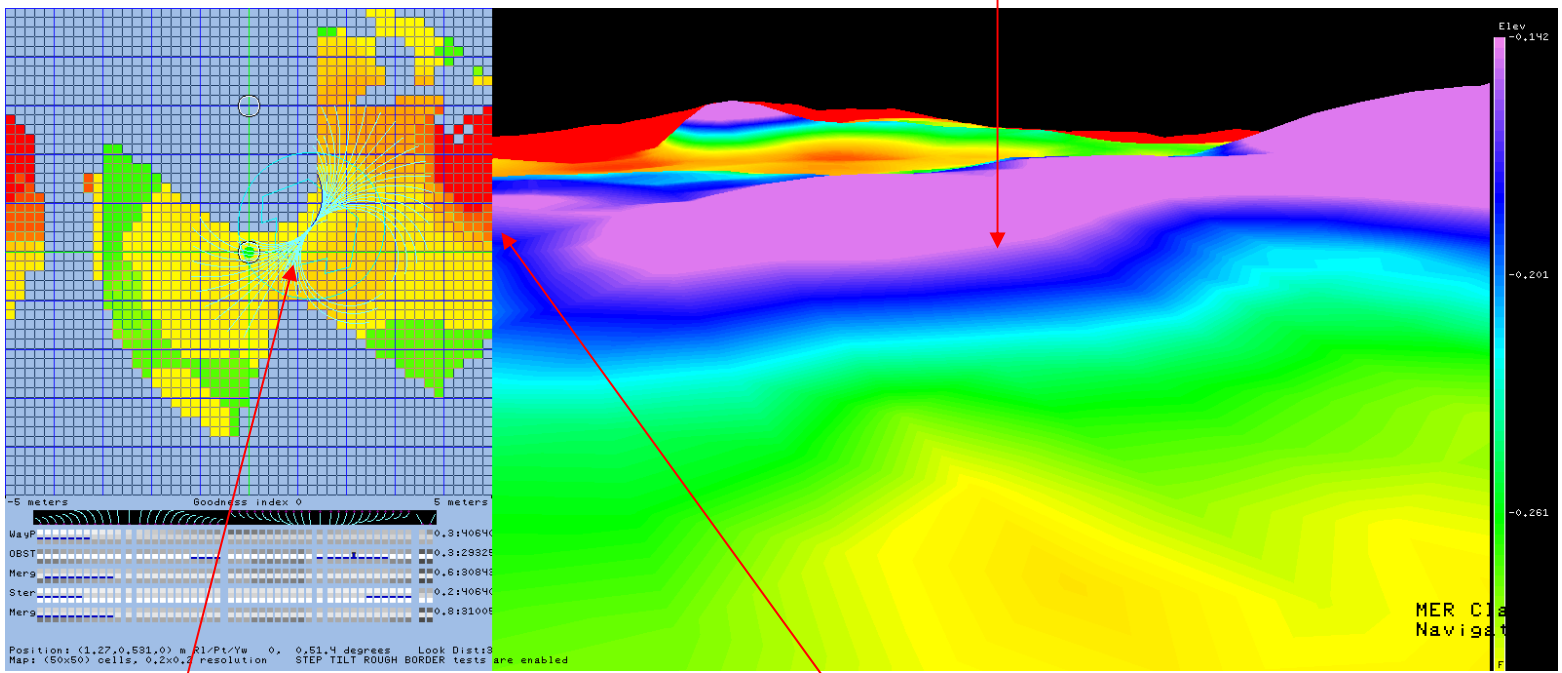


Stereo output coded by elevation

Stereo output overhead view

Application: GESTALT (MER Autonomous Navigation)

Use ROAMS-generated range image to compute elevation



Elevation changes indicate obstacles

Arc left to avoid obstacle

Repeat at each new location

Conclusions

- ROAMS provides CAHV and CAHVOR image synthesis
- Very low calibration residuals show that images adhere to CAHV and CAHVOR models
- Some small differences between input models and the models actually used

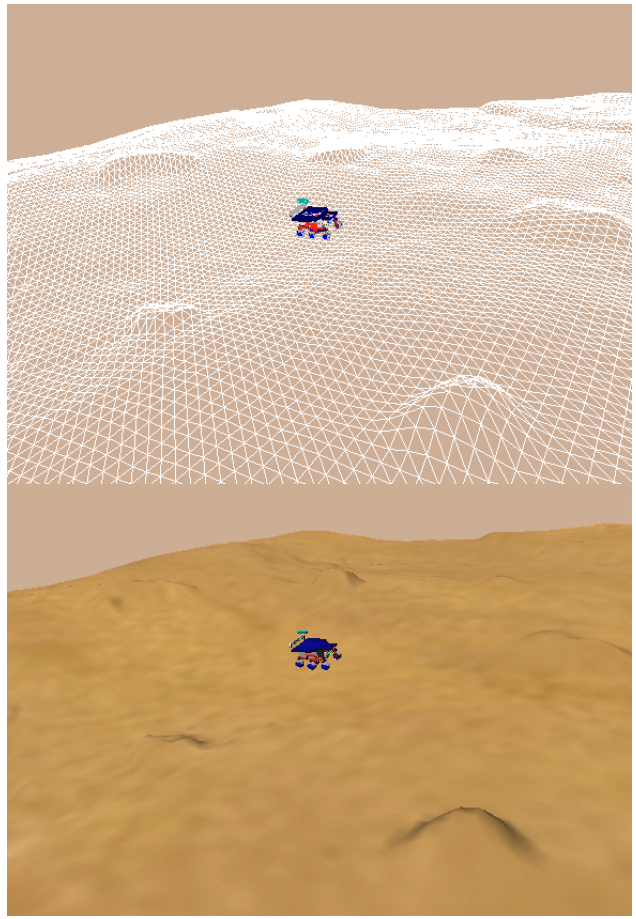
Future Directions

- Implement CAHVORE model
  - Simple CAVHORE (world @ distance=1m)
  - Full CAHVORE (use data from range map)
- Compensate for two instances of rounding in conversion to OpenGL camera
  - Should eliminate most error in Hc, Vc, Hs, and A
- CAHV imaging with non-orthogonal image plane axes
  - Render orthogonalized CAH$\tilde{V}$, then warp to CAHV
  - Same process as used for CAHVOR

Backup Slides

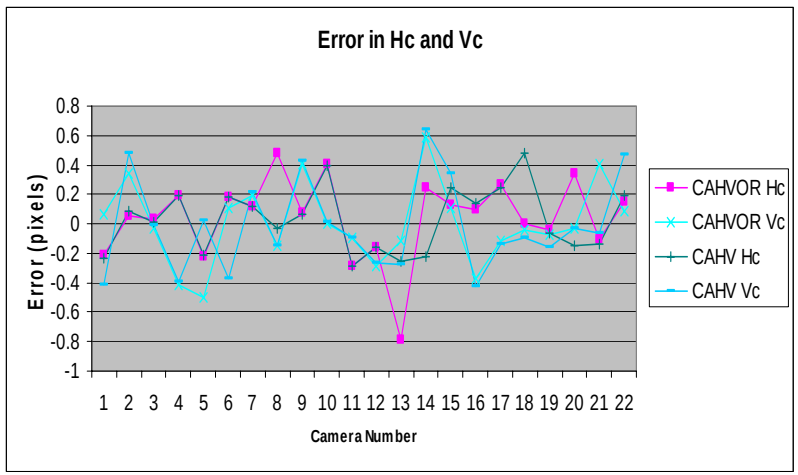
Terrain Modeling: SimScape

- 2.5D Height map
  - Analytical function
  - or data file
- Texture map
  - User specified
  - Arbitrary granularity
- Fast, OpenGL polygon rendering, pinhole camera



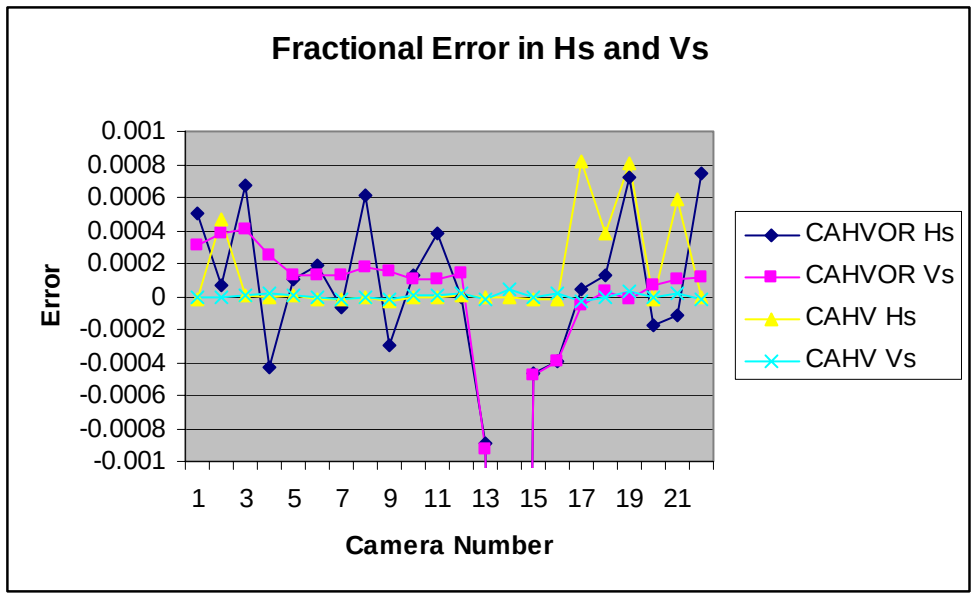
Results: Optical Center

- (Hc,Vc) off by ½ pixel
- Caused by rounding during conversion to OpenGL camera



Results: Focal Lengths

- CAHV Vs well modeled
- CAHVOR Vs error ≤ 0.04% (0.1 pixel) except in underconstrained cameras 13-16
- Hs has significant errors due to rounding in conversion to OpenGL params



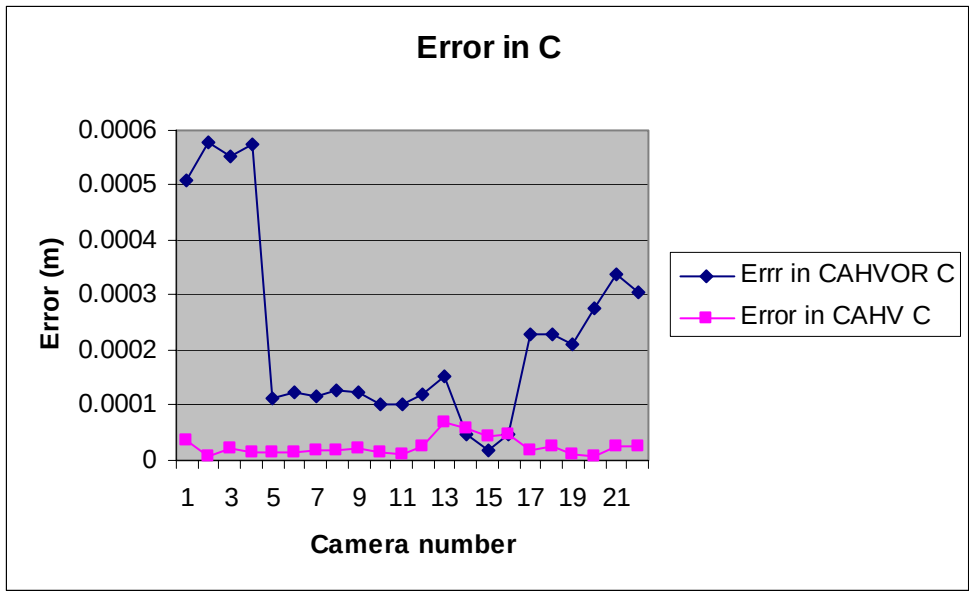
Results: Orthogonal Axes

- Real camera image plane axes are nearly orthogonal
  - $\Theta \approx 90°$
- Calibration may adjust this to minimize residual
  - Typically, $89.9° \leq \Theta \leq 90.1°$
- ROAMS CAHV imaging requires orthogonal axes
  - Replaces input with orthogonalized $CAH\tilde{V}$
- For imagery synthesized using CAHVOR and $CAH\tilde{V}$ models, calibration recovers Θ accurately to floating point precision

Camera Position

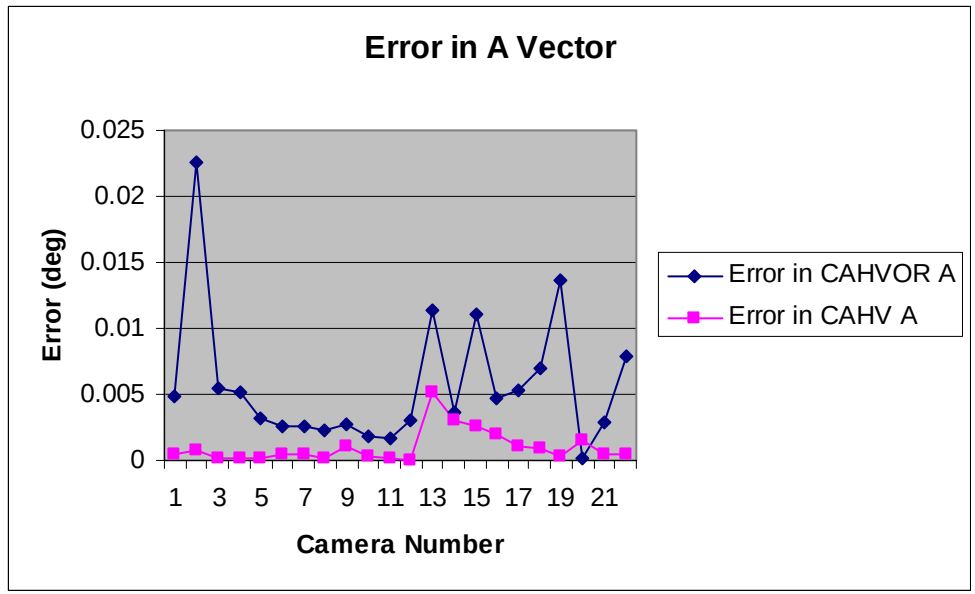
- CAHV C accurate to floating point precision

- CAHVOR
  - Error is along viewing axis
  - Compensates almost exactly for error in Vs



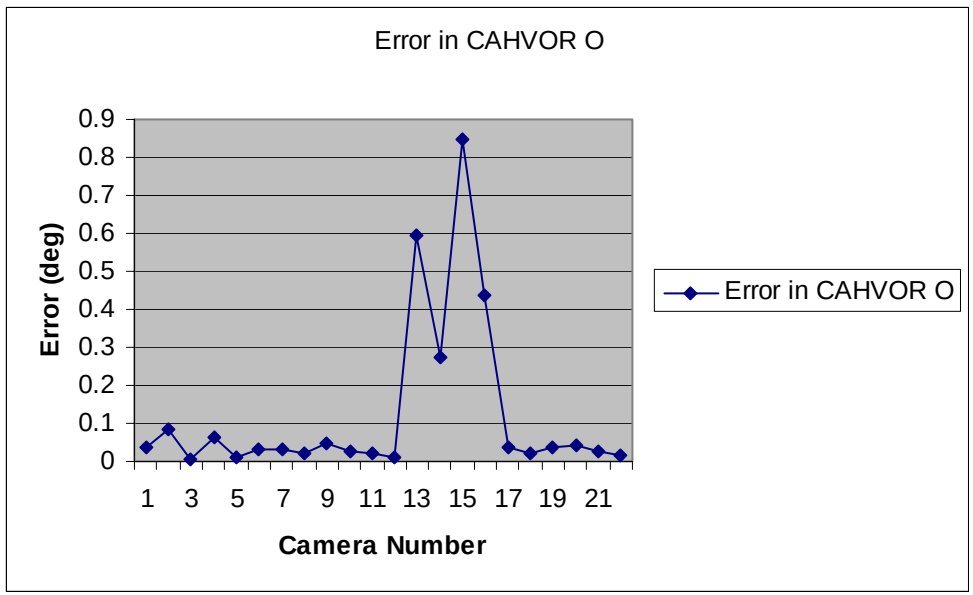
Results: Pointing Axis

- Most error compensates for error in (Hc,Vc)
- A few cameras have another, mystery error source



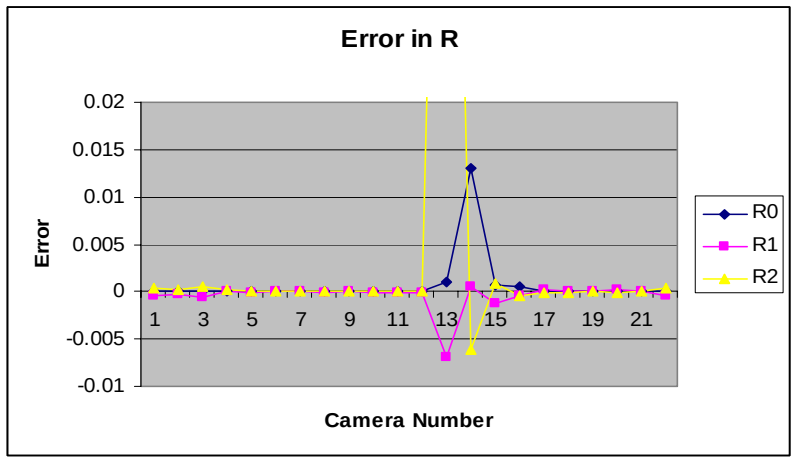
Results: Optical Axis

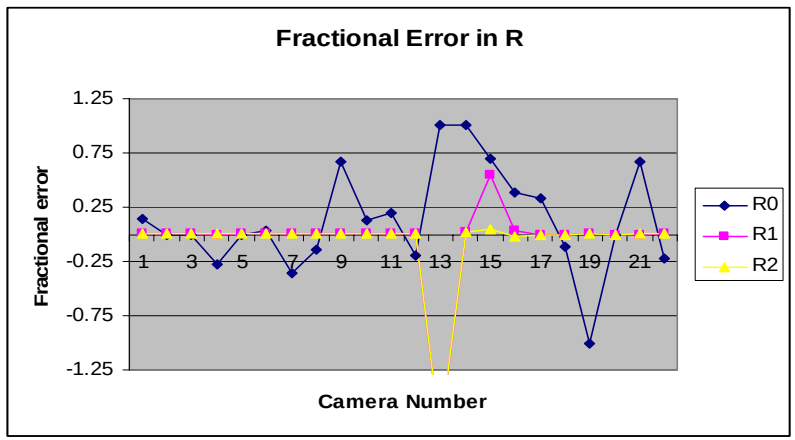
- Cameras 13-16 have low distortion
  - Optical axis is difficult to identify
  - Camera 15 incorrect O causes ≤ 0.03 pixel error
- Camera 2 has high distortion
  - Error ≤ 0.3 pixels



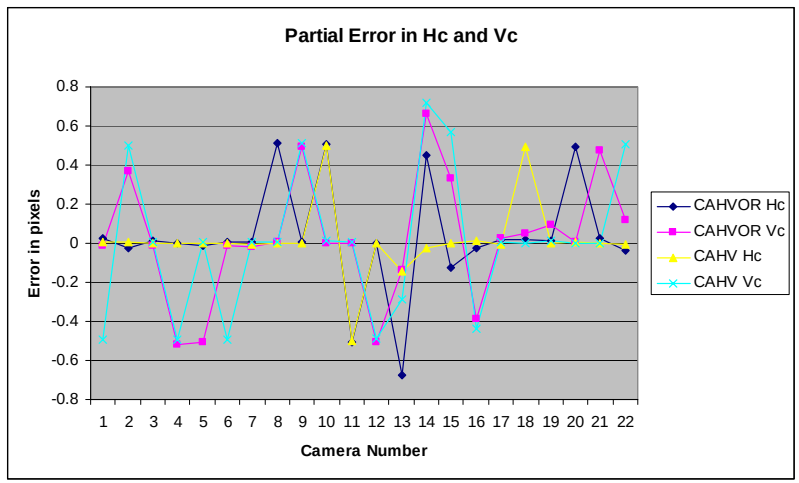
Results: Radial Distortion

- MER mast cameras
  - Low distortion
  - Hs and Vs couple to $(1+R_0)$
  - $Hs*(1+R_0)$ and $Vs*(1+R_0)$ error ≤ 0.02%
  - R_1,R_2 inaccuracy creates error ≤ 0.09 pixels
- Non-mast cameras
  - Distortion $\propto (1+R_0)$
  - Recovered to float precision
  - Creates error ≤ 0.005 pixels
  - R_1,R_2 inaccuracy < 1%





Results: Optical Center

- When input (Hc,Vc) are rounded to nearest half pixel, error in recovered is approximately 0.0 or ± 0.5

- Problem is certainly rounding, but is not quite solved yet