Development of techniques to Calibrate Digital Cameras and Derive Basic and Advanced Visibility Metrics from Digital Imagery

(or back to the future)

John V. Molenar

IMPROVE Steering Committee Meeting

Acadia National Park

7-27-05

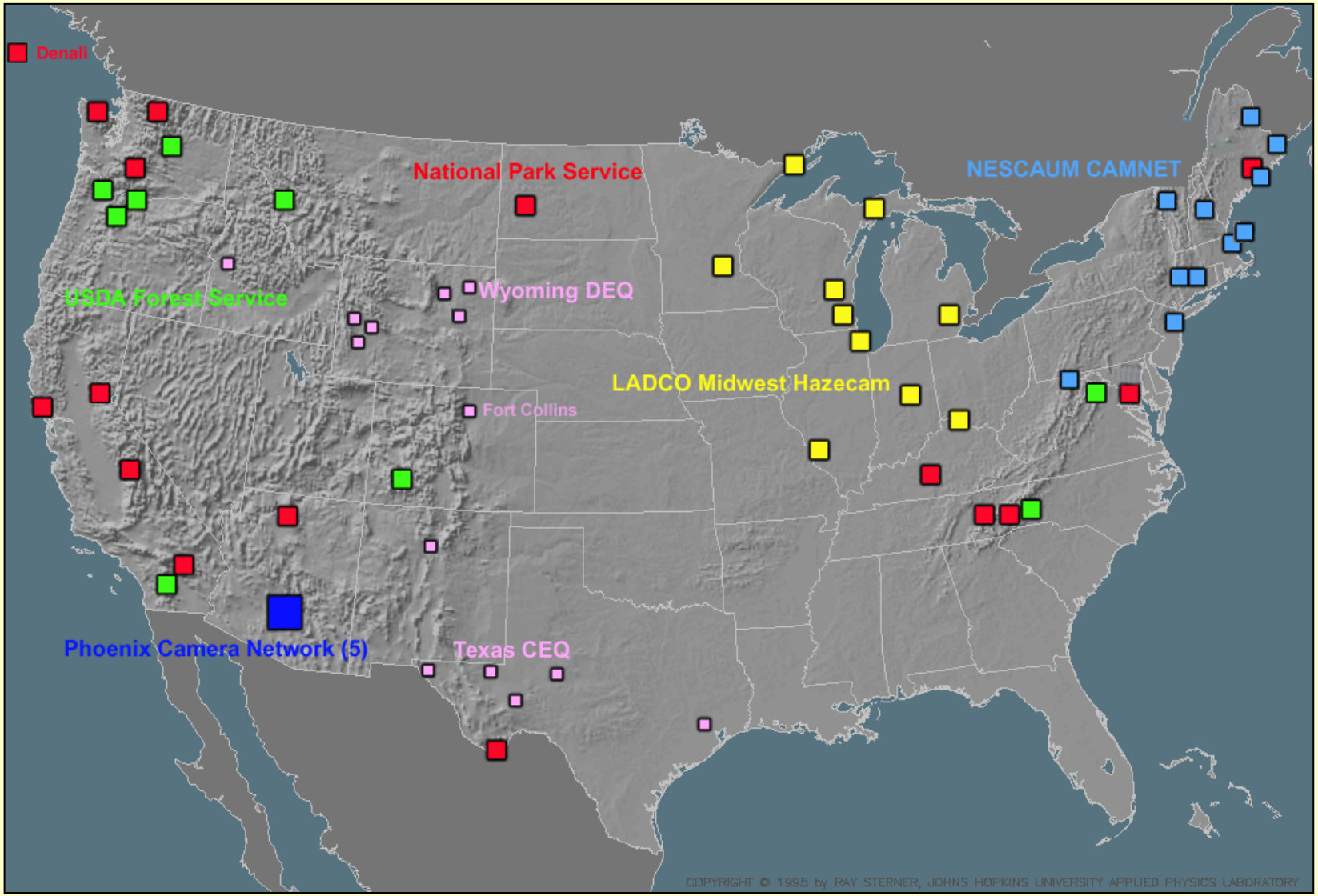
Denali
National Park Service
NESCAUM CAMNET
USDA Forest Service
Wyoming DEQ
LADCO Midwest Hazecam
Fort Collins
Phoenix Camera Network (5)
Texas CEQ
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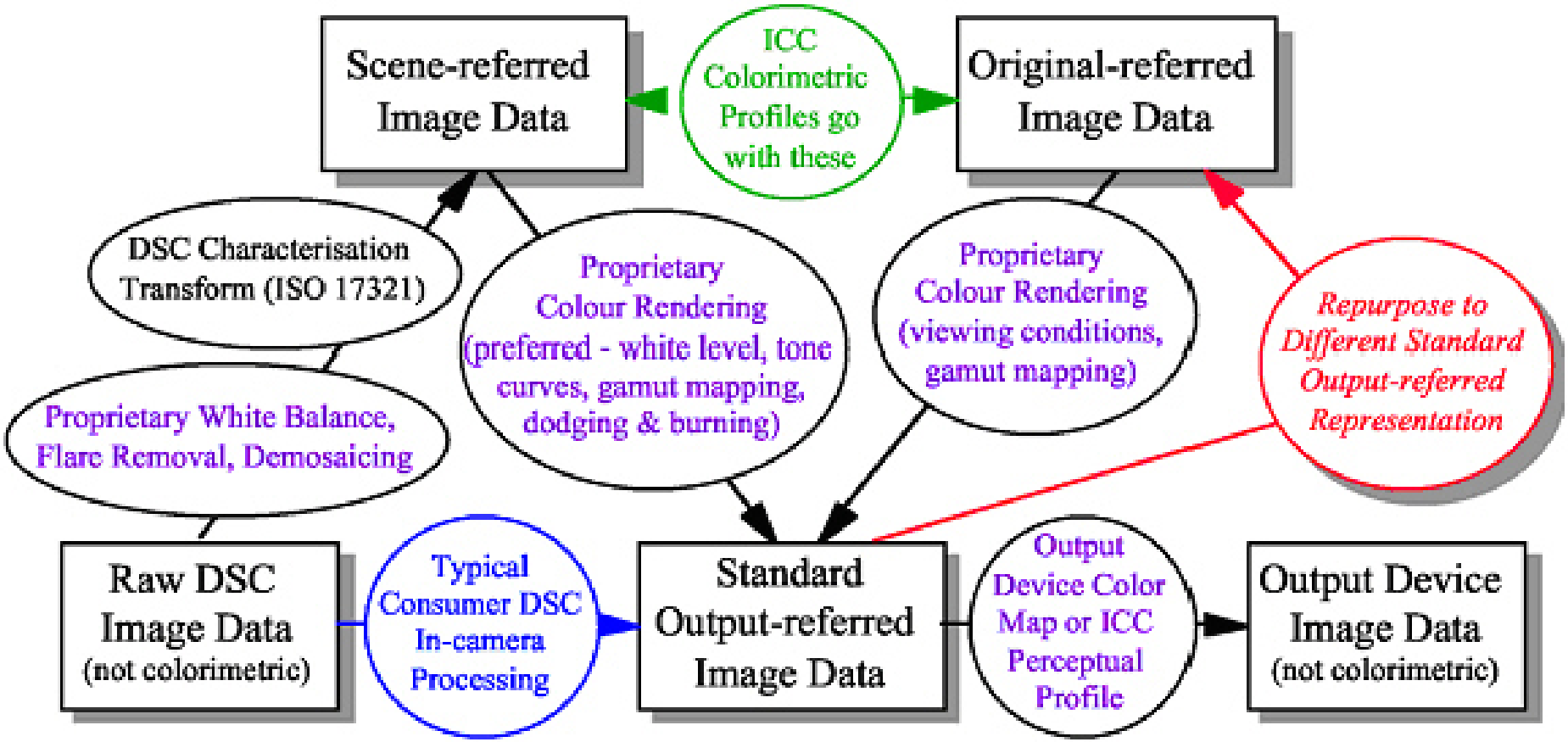
Image Preprocessing

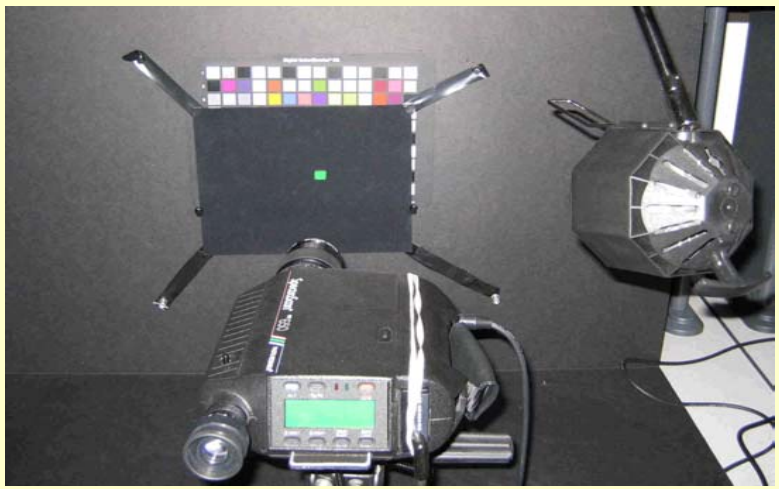
- **Digital Camera Characterization**
- **Image Registration**
- **Clear/Uniform Sky Identification**

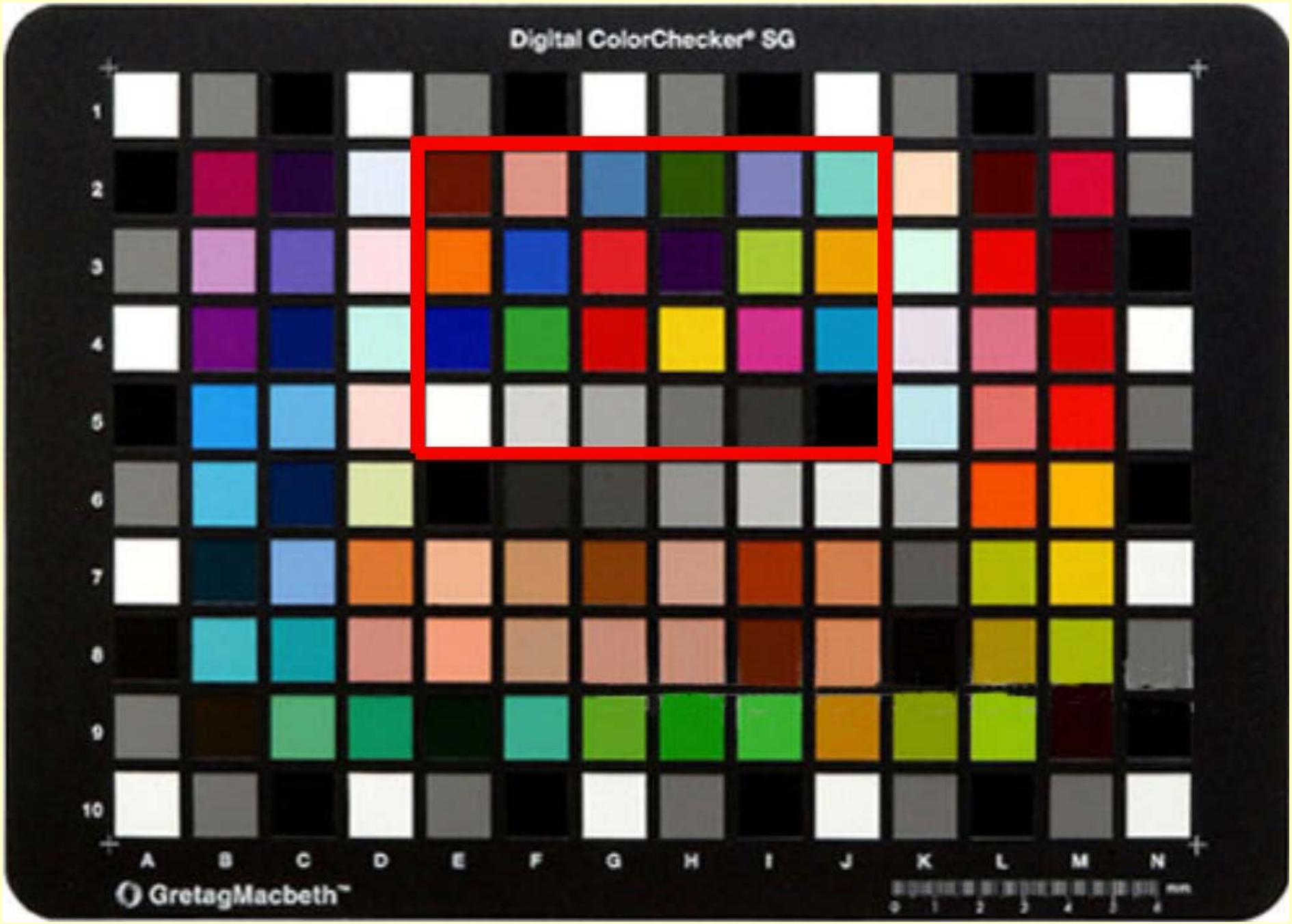


Digital Camera System (DCS) Image Flow

DCS Characterization

- MacBeth Digital ColorChecker SG
- Photo Research 650 Spectroradiometer
- D65 Daylight light source
- Olympus C-730 Digital Camera
- LOTS of TIME




Digital ColorChecker® SG
1
2
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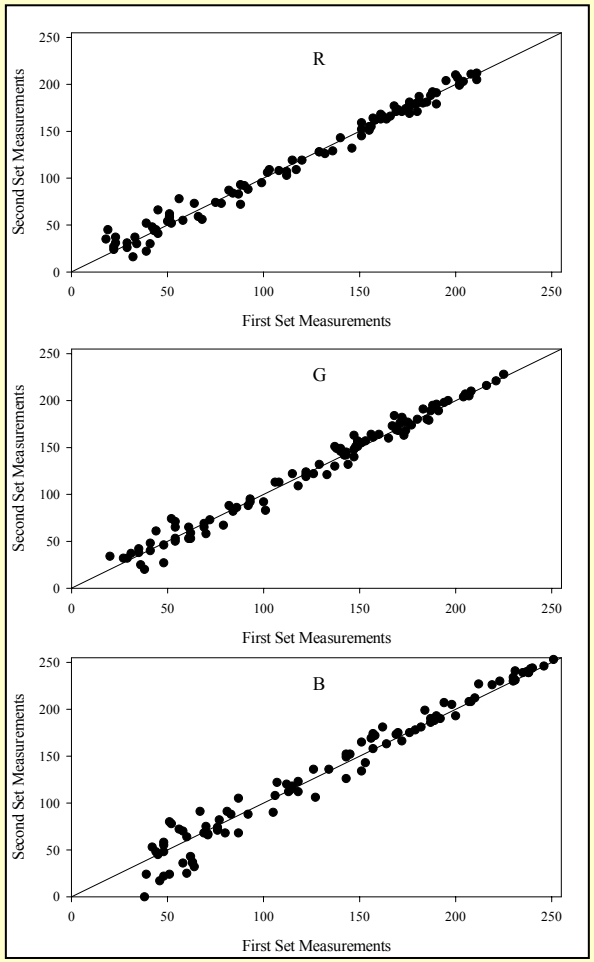
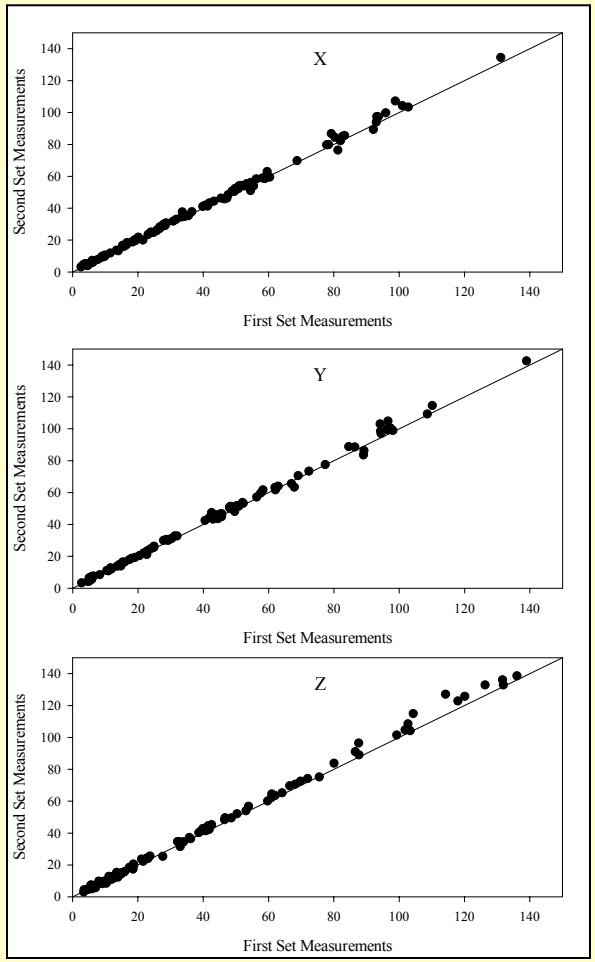
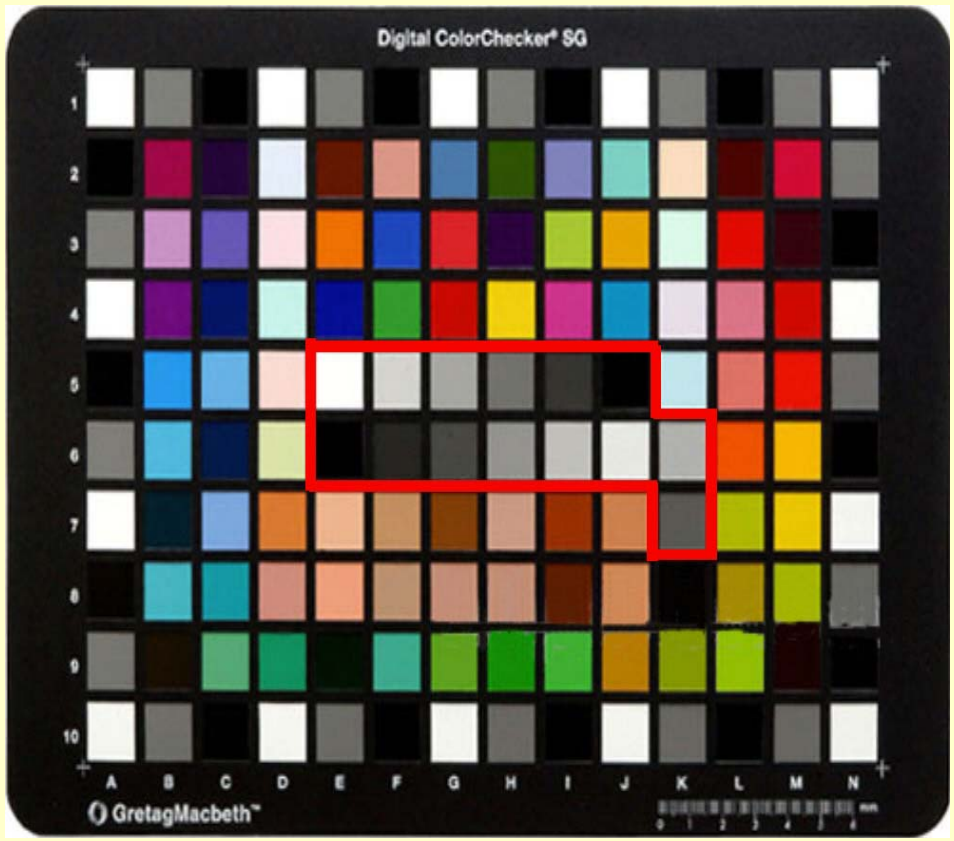
I
J
K
L
M
N
GretagMacbeth™

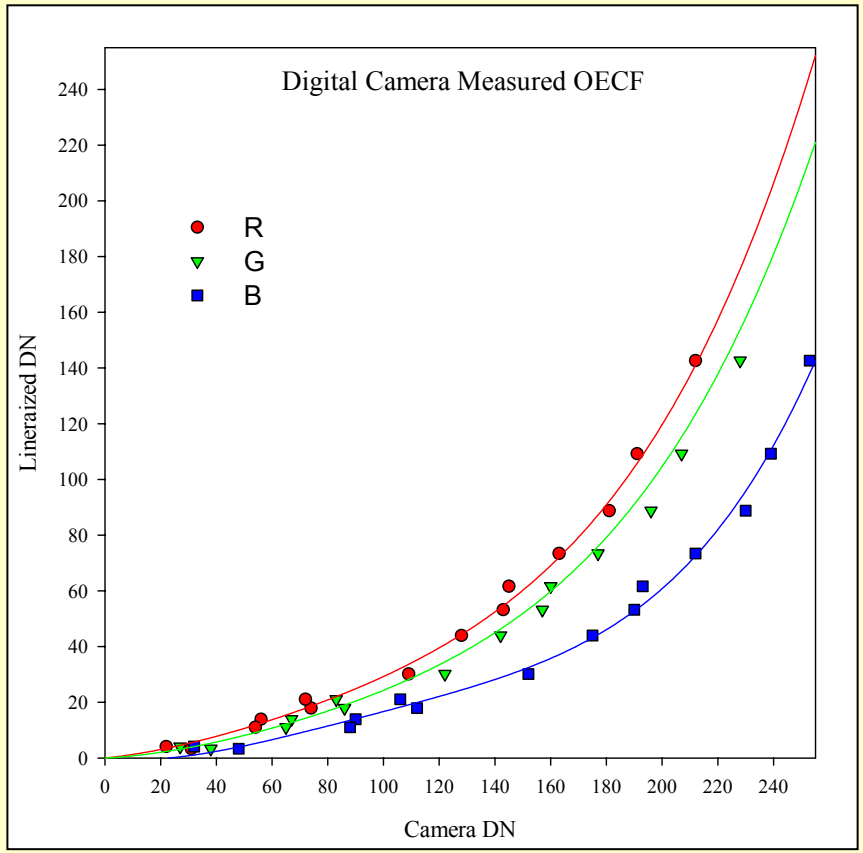
Measurement Repeatability





Opto-electronic Conversion Function





Two sets of measurement triplets from MacBeth CC patches (n=24)
Linearized RGB from digital camera and XYZ from spectroradiometer

$$V = \begin{pmatrix} R1 & G1 & B1 \\ R2 & G2 & B2 \\ . & . & . \\ Rn & Gn & Bn \end{pmatrix} \qquad P = \begin{pmatrix} X1 & Y1 & Z1 \\ X2 & Y2 & Z2 \\ . & . & . \\ Xn & Yn & Zn \end{pmatrix}$$

$$P = AV$$

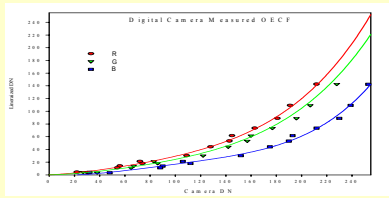
$$A_X = (V^T V)^{-1} (V^T P_X)$$

Polynomial Solutions

- $X = a_1R + a_2G + a_3B$ (3 x 3)
- $X = a_1R + a_2G + a_3R + a_4RG + a_5RB + a_6GB$ (3 x 6)
- $X = a_1R + a_2G + a_3R + a_4RG + a_5RB + a_6GB + a_7R^2 + a_8G^2 + a_9B^2$ (3 x9)
- $X = a_1R + a_2G + a_3R + a_4RG + a_5RB + a_6GB + a_7R^2 + a_8G^2 + a_9B^2 + a_{10}1$ (3 x10)
- $X = a_1R + a_2G + a_3R + a_4RG + a_5RB + a_6GB + a_7R^2 + a_8G^2 + a_9B^2 + a_{10}1 + a_{11}RGB$ (3 x 11)

DCS Characterization

- Measure all 96 patches
- Linearize RGB data with 14 step grayscale
- Calculate coefficients using 24 CC patches for possible polynomials
- Calculate predicted XYZ for all 96 patches
- Convert measured and predicted XYZ to Lab
- Calculate deltaE94 between measured Lab and predicted Lab
- Determine which polynomial has least error



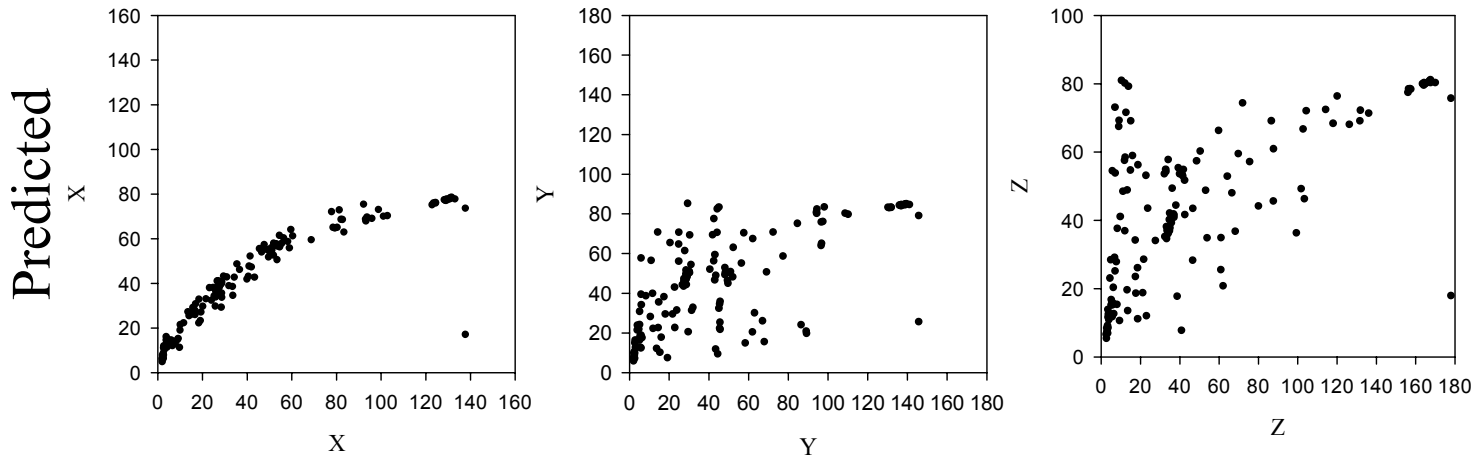
$$A = (N^T N)^{-1} (N^T P)$$

$$(XYZ) = A(RGB)$$

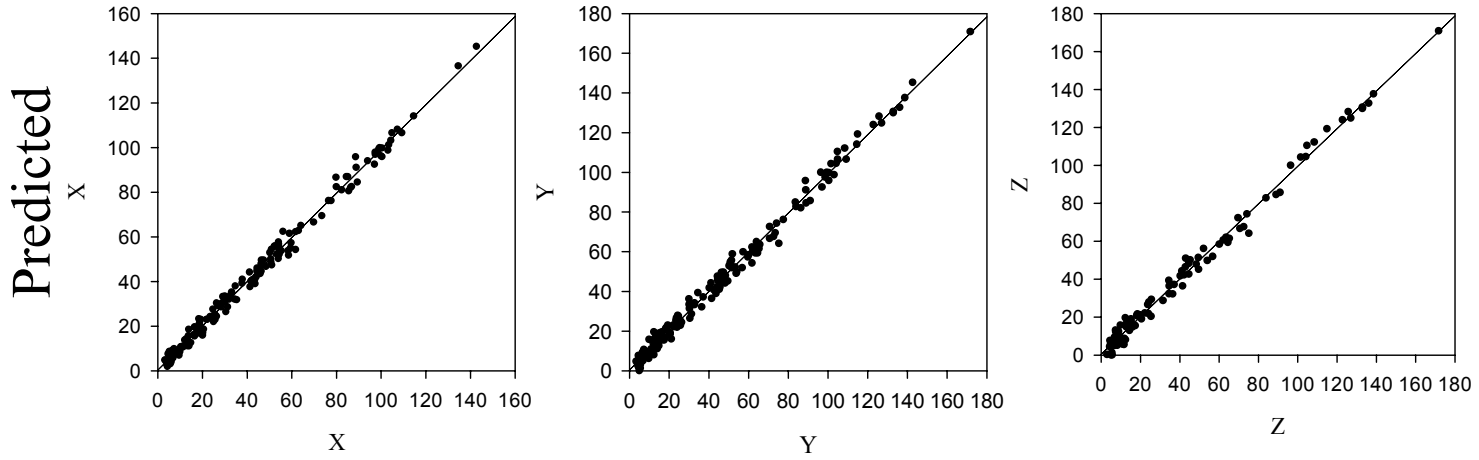
$$(Lab) = B(XYZ)$$

$$deltaE94 = (\Delta L^2/k1 + \Delta a^2/k2 + \Delta b^2/k3)^{1/2}$$

3 x 3 (Linear) Polynomial Regression



3 x 11 Polynomial Regression



deltaE94: Measured vs. Predicted

Coeff.	Avg	Max	Min	White	Mid-Gray	Black
3 x 3	5.2	23.7	0.7	3.3	17.1	2.2
3 x 6	4.4	23.0	0.6	0.6	16.8	2.9
3 x 9	6.4	25.2	0.6	16.7	19.4	2.7
3 x 10	3.7	13.0	0.2	0.2	9.9	1.6
3 x 11	3.8	11.5	0.1	0.1	12.1	1.5

Image Preprocessing

- Digital Camera Characterization
- **Image Registration**
- **Clear/Uniform Sky Identification**

Registration

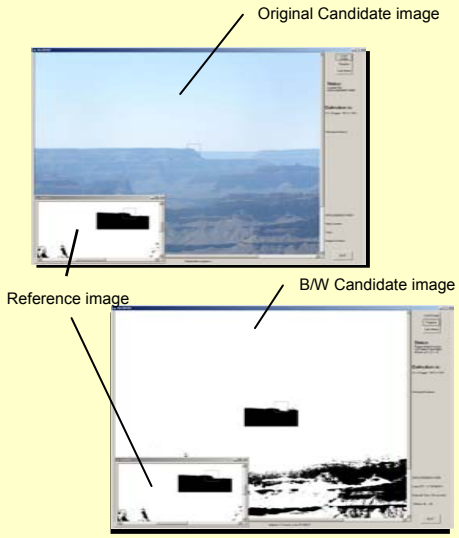
- **Each image is registered to account for camera movement or misalignment. Registered images are necessary for target/sky contrast, as well as other image metrics.**

- **Compares B/W version of candidate image to reference B/W image pixel by pixel. B/W binary comparison is used to eliminate shading and color influences.**

- **Candidate image "walks" one pixel at a time in a spiral pattern until the 50 by 50 pixel test areas in the candidate and reference images have a 98% match.**

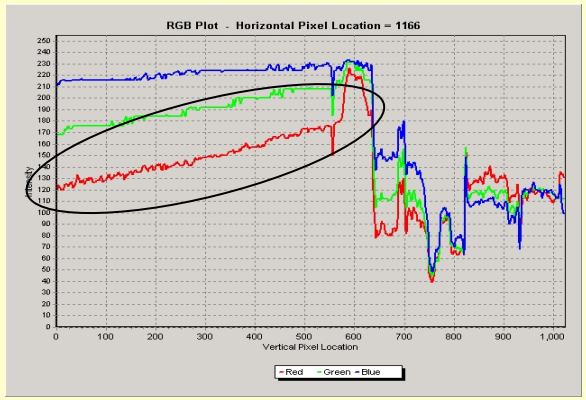
- **Results of registration are horizontal and vertical offsets. They are save in the image database for use by the image metric algorithms. The original images are not affected.**

- **The registration target must be close enough to be visible for all air quality conditions, but be far enough away to minimize parallax float problems (small registration error causing large errors in scene element locations).**



Clear Sky Identification

- Each image is tested for cloud free (clear sky) conditions. Clear sky conditions are necessary for target/sky contrast, as well as other image metrics.
- Five vertical regions are scanned for discontinuities in the red band of the RGB color triplet .
- This technique correctly identifies cloud free images 95% of the time.
- Not possible to determine if images or scenes are completely cloud free because entire sky is not visible.



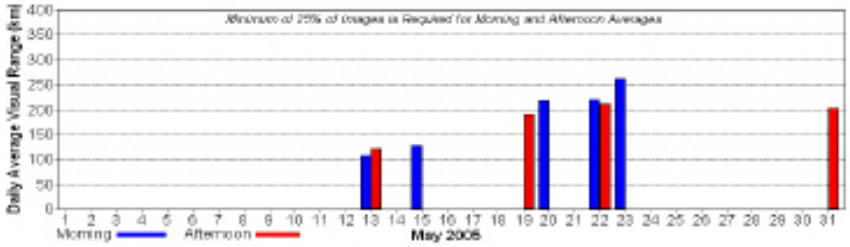
Calculation of Visual Air Quality Metrics

- apparent target (C_r) contrast
- b_{ext} from apparent target contrast
- image difference metrics:
  - pixel-by-pixel deltaE
  - image average deltaE
- image difference metrics based on Human Visual System (HVS) models: S-CIELAB, dcTune, iCAM, others

Standard Automatic Monthly Reports

Grand Canyon National Park

Monthly Image Analysis Report



Images with Minimal Cloud Cover

	Best	Worst
Morning	May 23	May 13
Afternoon	May 22	May 13

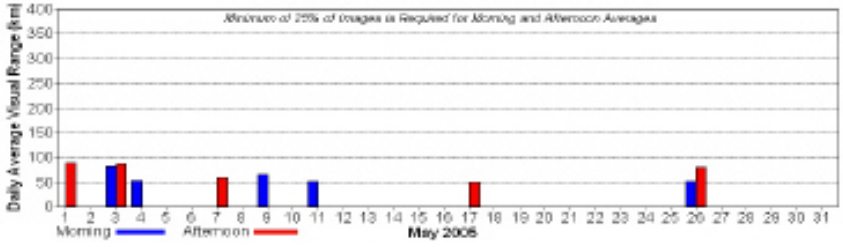
Image Collection Statistics for Morning (9:00 - 10:45 AM) and Afternoon (1:00 - 2:45 PM)

Number of Images Possible (15 minute intervals)	496
Number of Images Captured	438
Number of Images Captured with Minimal Cloud Cover	36
Percent of Images Captured with Minimal Cloud Cover	10%

Notes:

Great Smoky Mtns

Monthly Image Analysis Report



Images with Minimal Cloud Cover

	Best	Worst
Morning	May 3	May 9
Afternoon	May 1	May 17

Image Collection Statistics for Morning (9:00 - 10:45 AM) and Afternoon (1:00 - 2:45 PM)

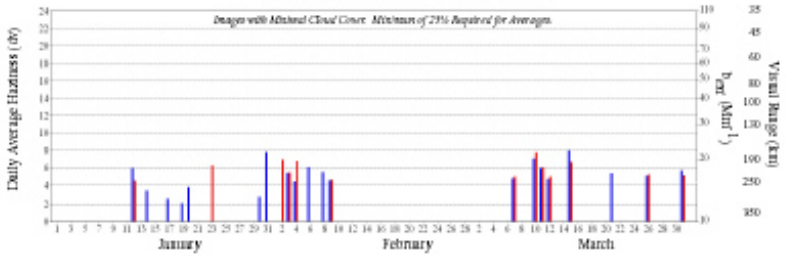
Number of Images Possible (15 minute intervals)	496
Number of Images Captured	468
Number of Images Captured with Minimal Cloud Cover	59
Percent of Images Captured with Minimal Cloud Cover	14%

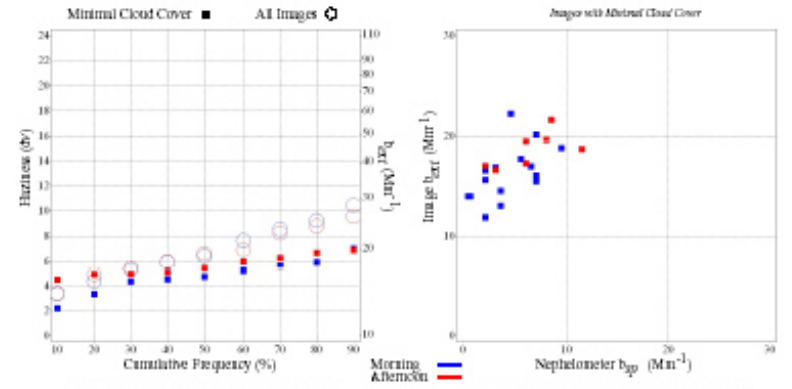
Notes:

Semi-Automatic Quarterly Reports

Grand Canyon National Park

Image Analysis - First Quarter 2005





CUMULATIVE FREQUENCY SUMMARY

Minimal Cloud Cover

%	Morning dv	Morning b_{ext}	Morning VR	Afternoon dv	Afternoon b_{ext}	Afternoon VR
10	2.2	12	313	4.5	16	250
20	3.3	14	280	4.9	16	239
30	4.4	15	253	5.0	16	238
40	4.5	16	248	5.1	17	236
50	4.7	16	244	5.4	17	227
60	5.2	17	233	6.0	18	215
70	5.6	18	223	6.2	19	210
80	5.9	18	216	6.6	19	201
90	7.0	20	194	6.9	20	197

CUMULATIVE FREQUENCY SUMMARY

All Images

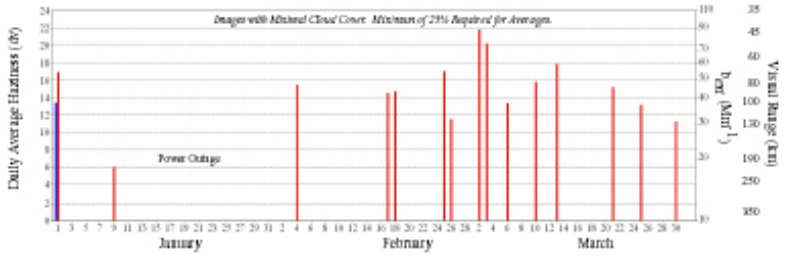
%	Morning dv	Morning b_{ext}	Morning VR	Afternoon dv	Afternoon b_{ext}	Afternoon VR
10	3.3	14	280	3.4	14	278
20	4.4	15	253	4.9	16	239
30	5.3	17	230	5.4	17	227
40	5.9	18	217	6.0	18	216
50	6.4	19	207	6.6	19	202
60	7.6	21	182	6.9	20	197
70	8.5	23	167	8.2	23	172
80	9.2	25	155	8.8	24	163
90	10.4	28	138	9.5	26	151

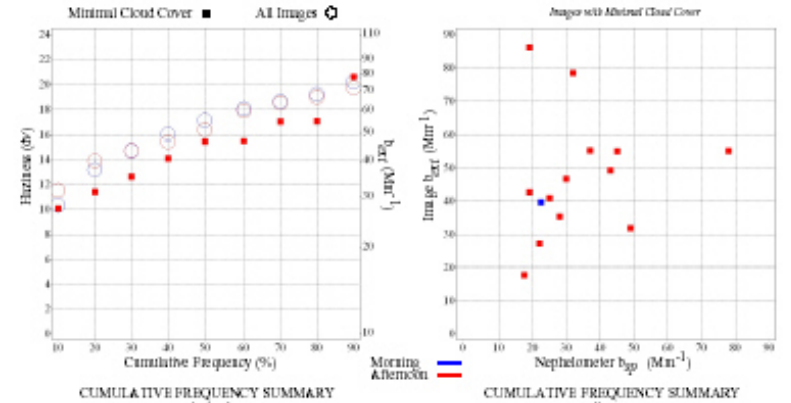
Image Collection Statistics for Morning (9:00 - 10:45 AM) and Afternoon (1:00 - 2:45 PM)

Number of Images Possible (15 minute intervals)	1440
Number of Images Captured	1215
Number of Images Captured with Minimal Cloud Cover	242
Percent of Images Captured with Minimal Cloud Cover	20%

Great Smoky Mtns National Park

Image Analysis - First Quarter 2005





CUMULATIVE FREQUENCY SUMMARY

Minimal Cloud Cover

%	Morning dv	Morning b_{ext}	Morning VR	Afternoon dv	Afternoon b_{ext}	Afternoon VR
10	---	---	---	10.1	27	143
20	---	---	---	11.4	31	125
30	---	---	---	12.6	35	111
40	---	---	---	14.1	41	96
50	---	---	---	15.4	47	84
60	---	---	---	15.5	47	83
70	---	---	---	17.0	55	71
80	---	---	---	17.1	55	71
90	---	---	---	20.6	78	50

CUMULATIVE FREQUENCY SUMMARY

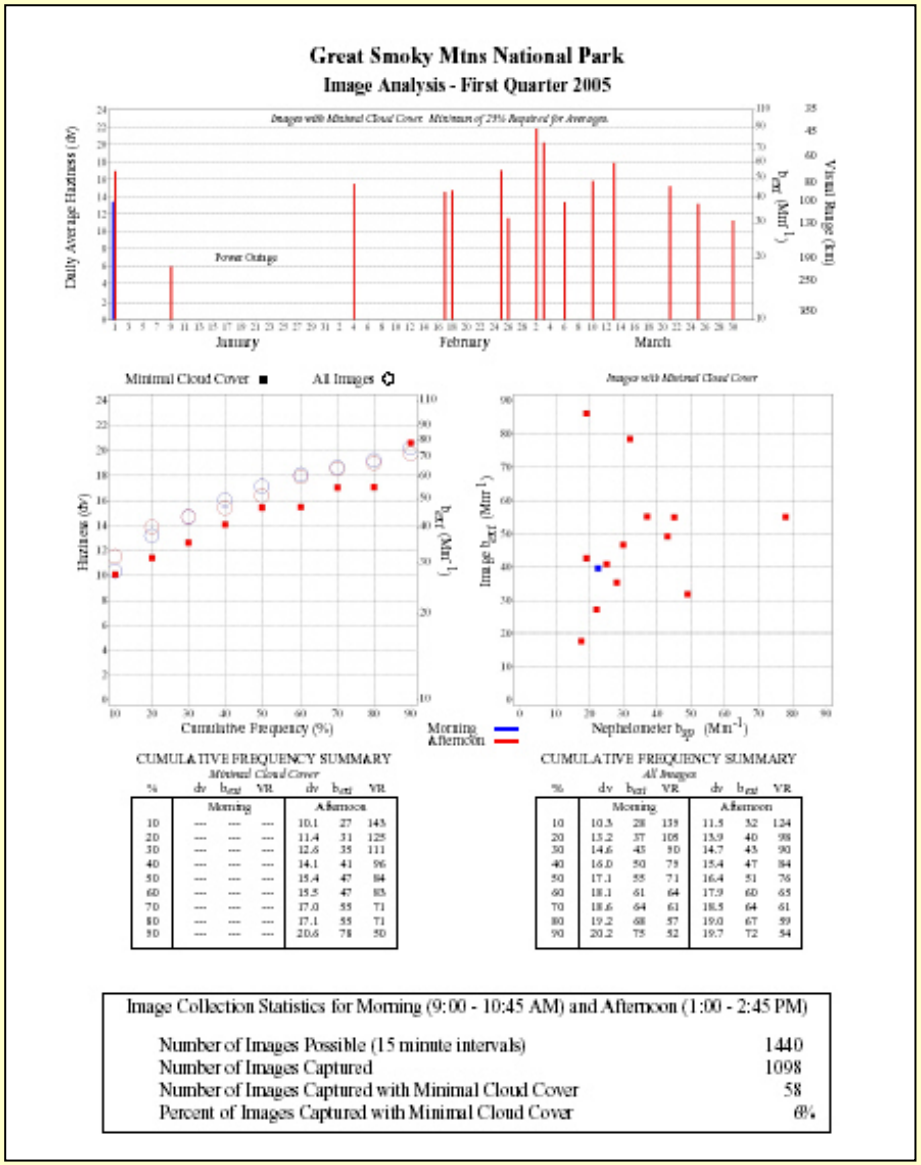
All Images

%	Morning dv	Morning b_{ext}	Morning VR	Afternoon dv	Afternoon b_{ext}	Afternoon VR
10	10.3	28	139	11.5	32	124
20	13.2	37	108	13.9	40	98
30	14.6	43	90	14.7	43	90
40	16.0	50	79	15.4	47	84
50	17.1	55	71	16.4	51	76
60	18.1	61	64	17.9	60	65
70	18.6	64	61	18.5	64	61
80	19.2	68	57	19.0	67	59
90	20.2	75	52	19.7	72	54

Image Collection Statistics for Morning (9:00 - 10:45 AM) and Afternoon (1:00 - 2:45 PM)

Number of Images Possible (15 minute intervals)	1440
Number of Images Captured	1098
Number of Images Captured with Minimal Cloud Cover	58
Percent of Images Captured with Minimal Cloud Cover	6%

Semi-Automatic Quarterly Reports



Great Smoky Mtns National Park
Image Analysis - First Quarter 2005

Images with Minimal Cloud Cover. Minimum of 25% Required for Averages.

Daily Average Haziness (dv) | b_{ext} (Mm^{-1}) | Visual Range (km)

Power Outage

January | February | March

Minimal Cloud Cover ■ All Images ○

Haziness (dv) | b_{ext} (Mm^{-1}) | Cumulative Frequency (%)

Images with Minimal Cloud Cover

Image b_{ext} (Mm^{-1}) | Nephelometer b_{sp} (Mm^{-1})

Morning
Afternoon

CUMULATIVE FREQUENCY SUMMARY
Minimal Cloud Cover

%	Morning dv	Morning b_{ext}	Morning VR	Afternoon dv	Afternoon b_{ext}	Afternoon VR
10	---	---	---	10.1	27	143
20	---	---	---	11.4	31	125
30	---	---	---	12.6	35	111
40	---	---	---	14.1	41	96
50	---	---	---	15.4	47	84
60	---	---	---	15.5	47	83
70	---	---	---	17.0	55	71
80	---	---	---	17.1	55	71
90	---	---	---	20.6	78	50

CUMULATIVE FREQUENCY SUMMARY
All Images

%	Morning dv	Morning b_{ext}	Morning VR	Afternoon dv	Afternoon b_{ext}	Afternoon VR
10	10.3	28	139	11.5	32	124
20	13.2	37	108	13.9	40	98
30	14.6	43	90	14.7	43	90
40	16.0	50	78	15.4	47	84
50	17.1	55	71	16.4	51	76
60	18.1	61	64	17.9	60	65
70	18.6	64	61	18.5	64	61
80	19.2	68	57	19.0	67	59
90	20.2	75	52	19.7	72	54

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Number of Images Captured	1098
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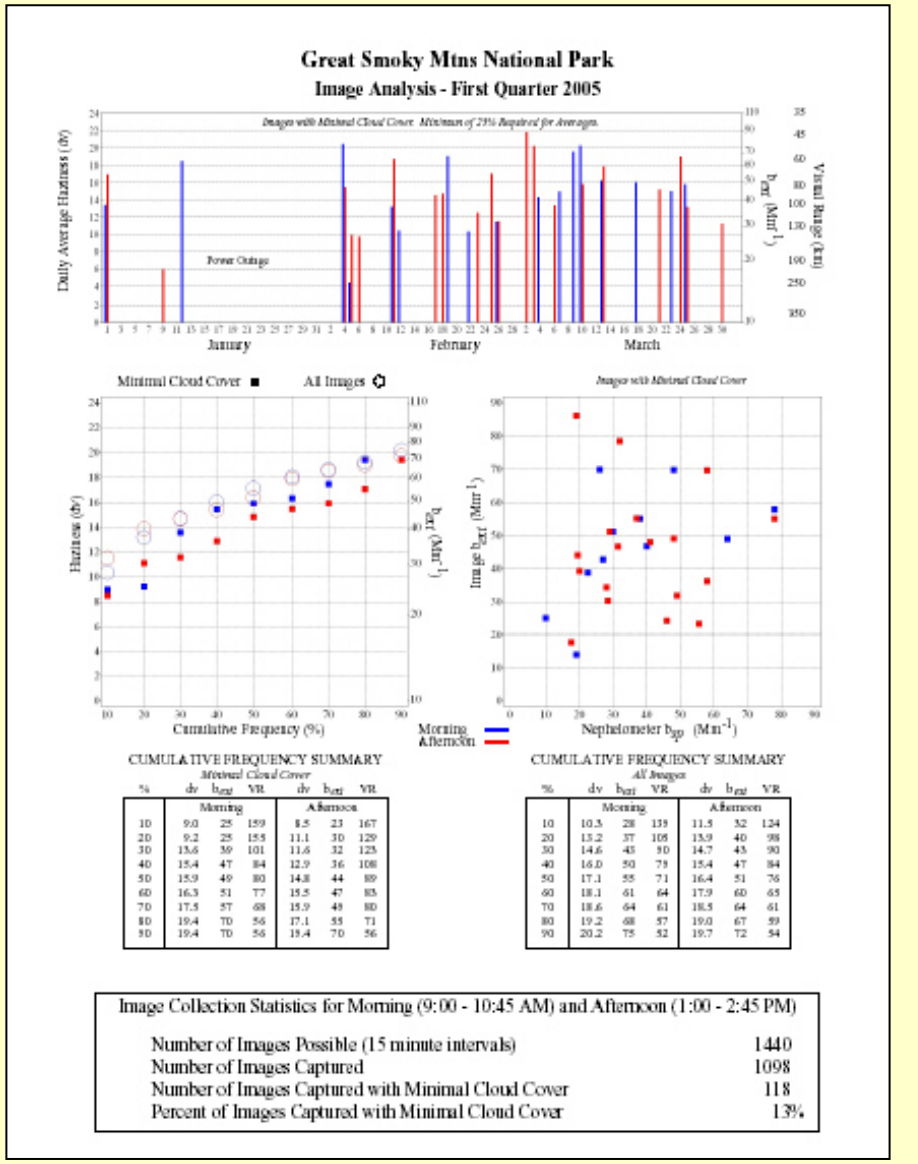
Percent of Images Captured with Minimal Cloud Cover	6%



Great Smoky Mtns National Park
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Images with Minimal Cloud Cover. Minimum of 25% Required for Averages.

Daily Average Haziness (dv) | b_{ext} (Mm^{-1}) | Visual Range (km)

Power Outage

January | February | March

Minimal Cloud Cover ■ All Images ○

Haziness (dv) | b_{ext} (Mm^{-1}) | Cumulative Frequency (%)

Images with Minimal Cloud Cover

Image b_{ext} (Mm^{-1}) | Nephelometer b_{sp} (Mm^{-1})

Morning
Afternoon

CUMULATIVE FREQUENCY SUMMARY
Minimal Cloud Cover

%	Morning dv	Morning b_{ext}	Morning VR	Afternoon dv	Afternoon b_{ext}	Afternoon VR
10	9.0	25	159	8.5	23	167
20	9.2	25	155	11.1	30	129
30	13.6	39	101	11.6	32	123
40	15.4	47	84	12.9	36	108
50	15.9	49	80	14.8	44	89
60	16.3	51	77	15.5	47	83
70	17.5	57	68	15.9	48	80
80	19.4	70	56	17.1	55	71
90	19.4	70	56	19.4	70	56

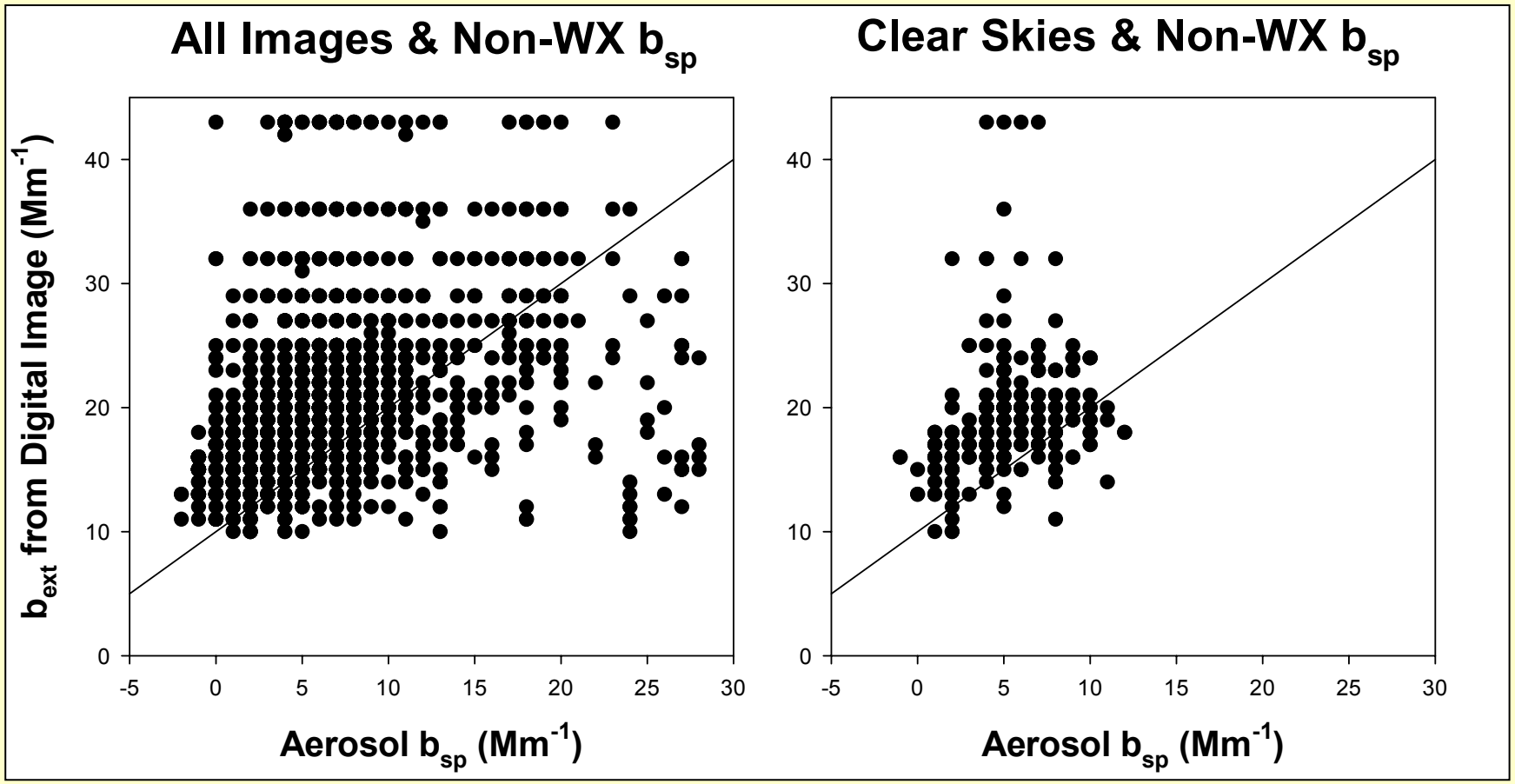
CUMULATIVE FREQUENCY SUMMARY
All Images

%	Morning dv	Morning b_{ext}	Morning VR	Afternoon dv	Afternoon b_{ext}	Afternoon VR
10	10.3	28	139	11.5	32	124
20	13.2	37	108	13.9	40	98
30	14.6	43	90	14.7	43	90
40	16.0	50	78	15.4	47	84
50	17.1	55	71	16.4	51	76
60	18.1	61	64	17.9	60	65
70	18.6	64	61	18.5	64	61
80	19.2	68	57	19.0	67	59
90	20.2	75	52	19.7	72	54

Image Collection Statistics for Morning (9:00 - 10:45 AM) and Afternoon (1:00 - 2:45 PM)

Number of Images Possible (15 minute intervals)	1440
Number of Images Captured	1098
Number of Images Captured with Minimal Cloud Cover	118
Percent of Images Captured with Minimal Cloud Cover	13%

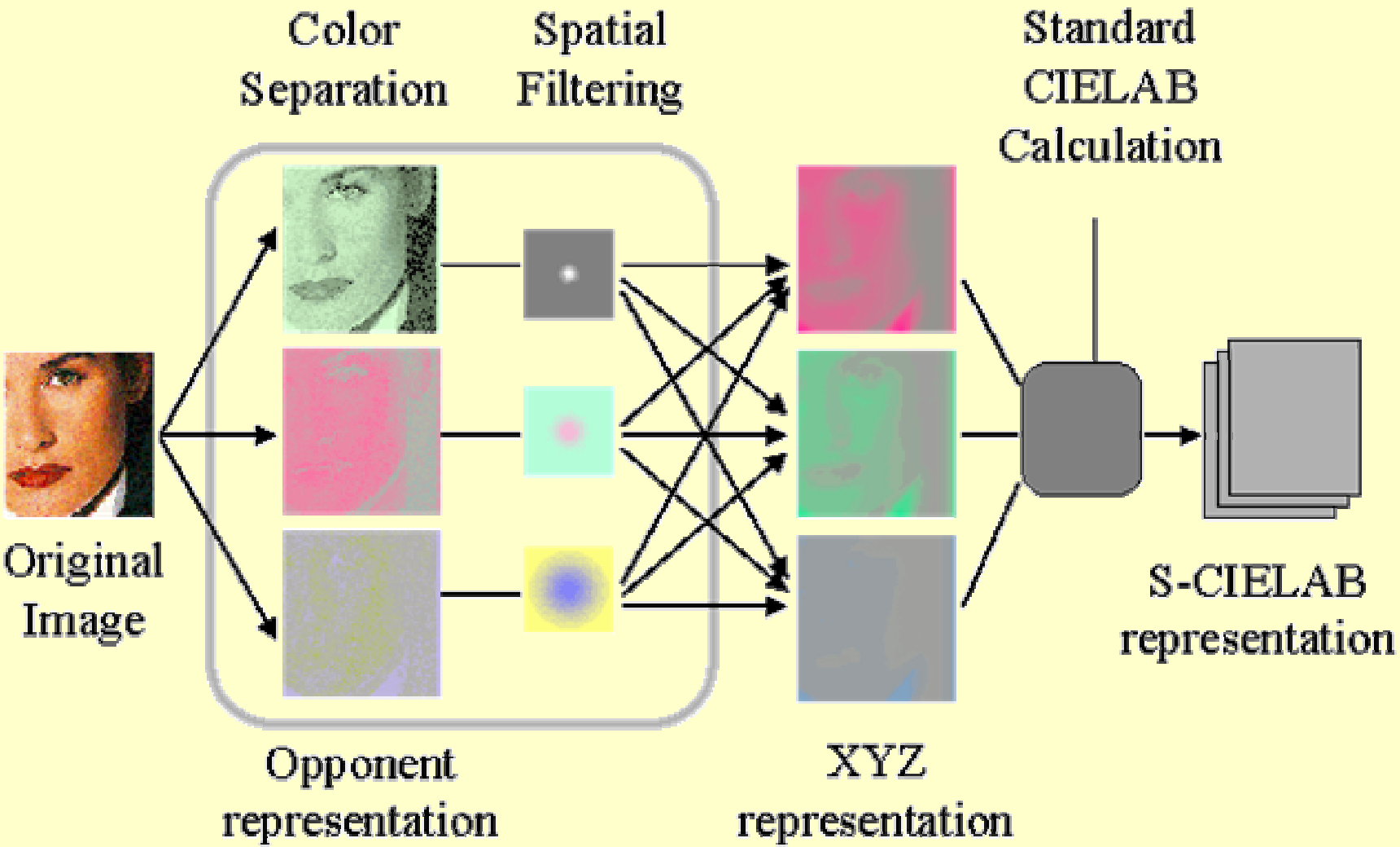
Grand Canyon National Park
b_{ext} from Digital Images vs. b_{sp} from Nephelometer
1/1/2005 – 6/8/2005



Calculation of Visual Air Quality Metrics

- apparent target (C_r) contrast
- b_{ext} from apparent target contrast
- image difference metrics:
  - pixel-by-pixel deltaE
  - image average deltaE
- image difference metrics based on Human Visual System (HVS) models: S-CIELAB, dcTune, iCAM, Sarnoff, and MANY others

S-CIELAB Model



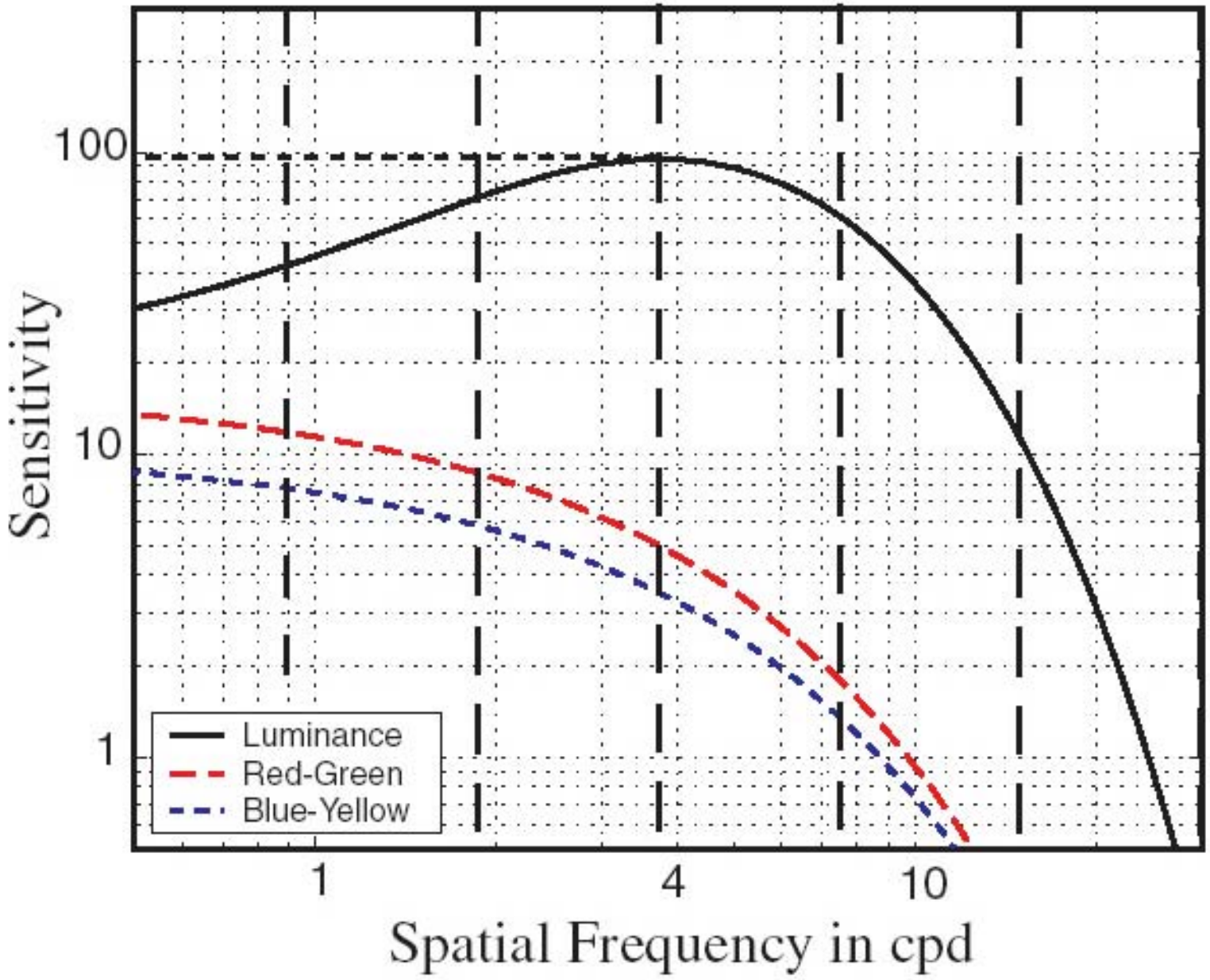

100
10
1
Sensitivity
Luminance
Red-Green
Blue-Yellow
1
4
10
Spatial Frequency in cpd

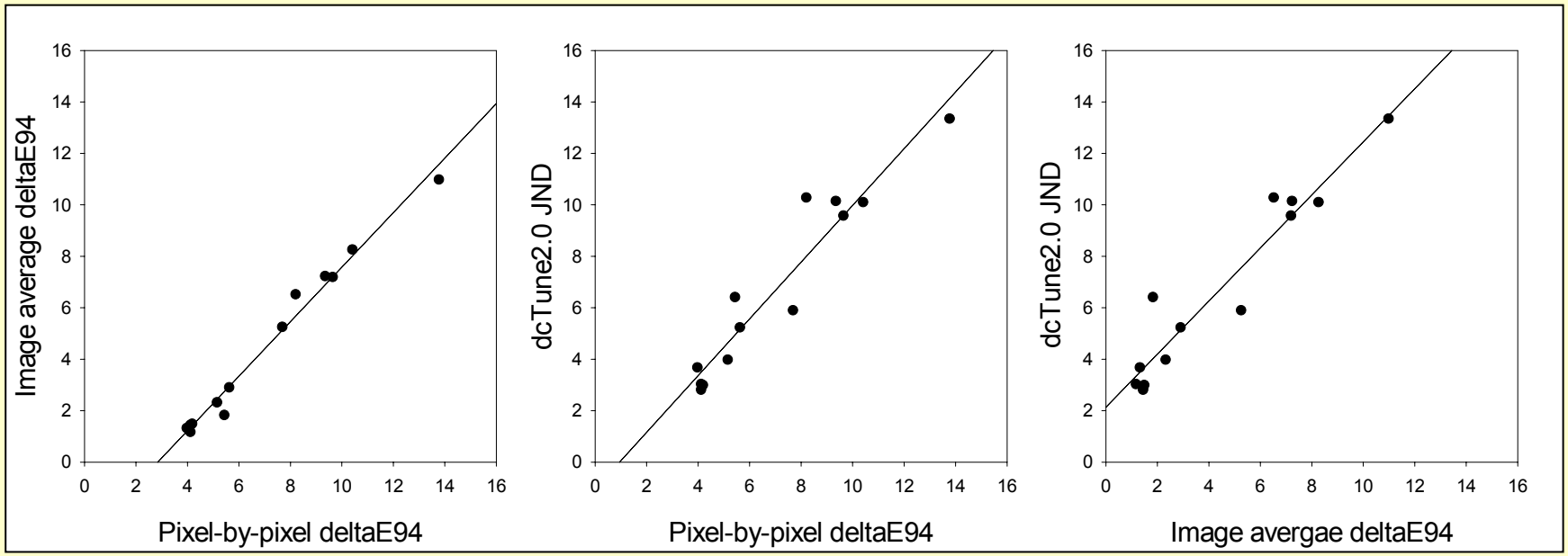
Image Modulation Depth

$$I_{m(rgb)} = \frac{1}{(n-1)\overline{E_{(rgb)}}}\left[\sum_{i=1}^{n}(E_{i(rgb)} - \overline{E_{(rgb)}})^2\right]^{1/2}$$

$$ModDepth = \left(I_{m(r)}^2 + I_{m(g)}^2 + I_{m(b)}^2\right)^{1/2}$$

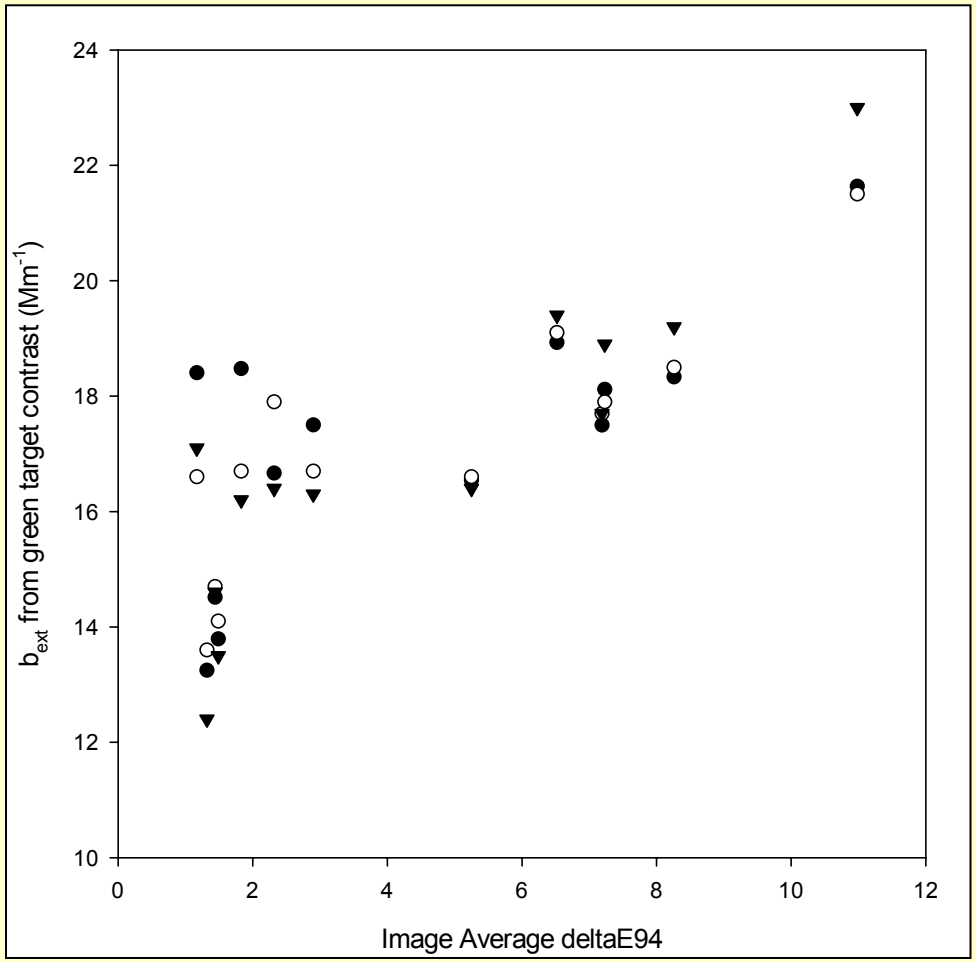
GRCA 1500 hrs Image Analysis

deltaE94 & dcTune JND

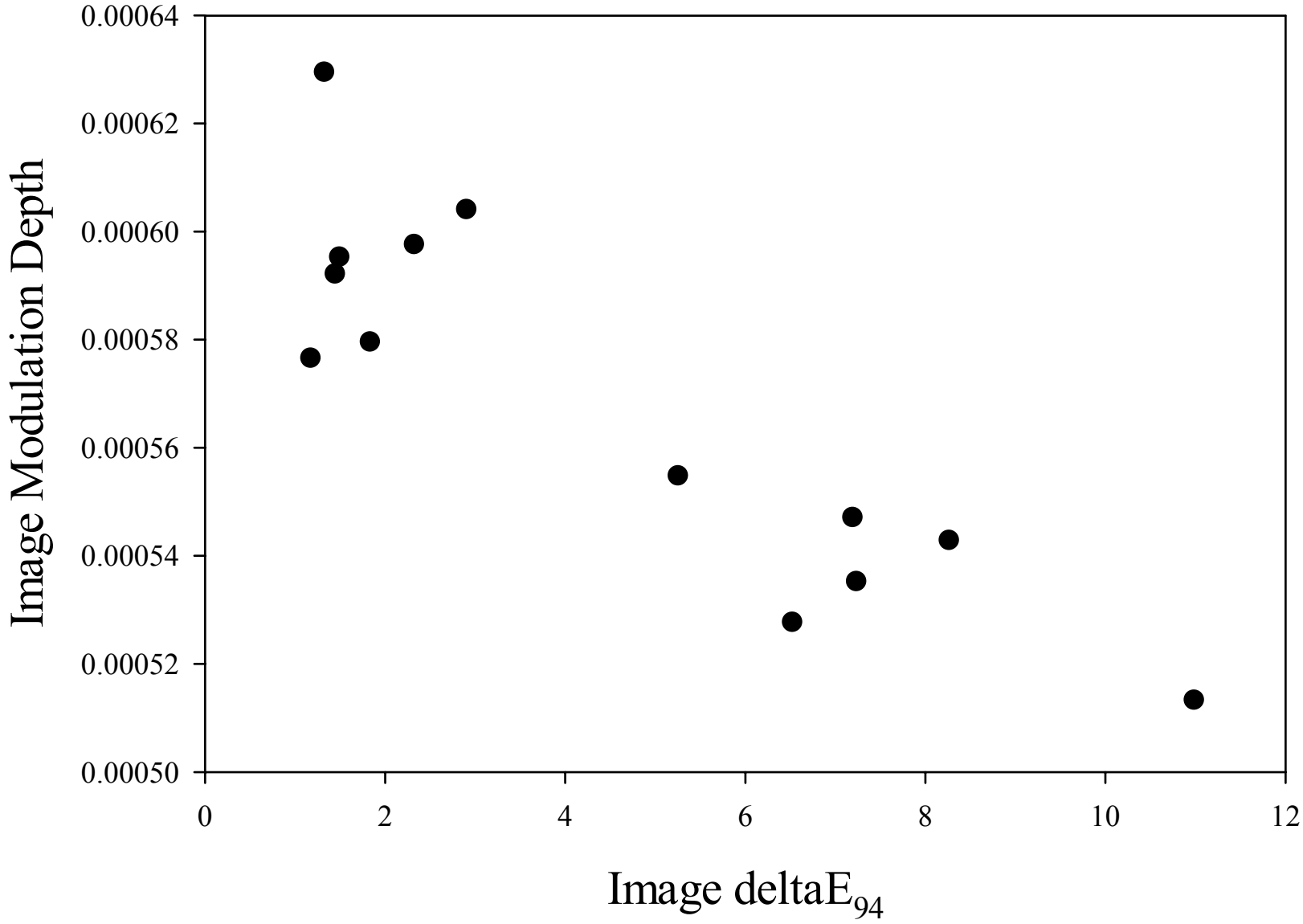


GRCA 1500 hrs Image Analysis

b_{ext} from target contrast vs. Image Average deltaE94

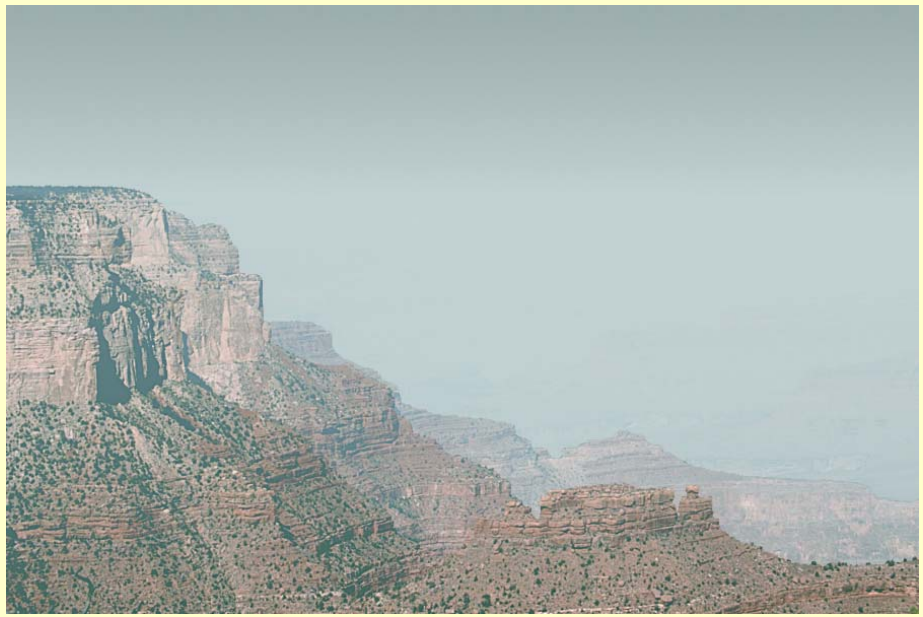


GRCA 1500 Images

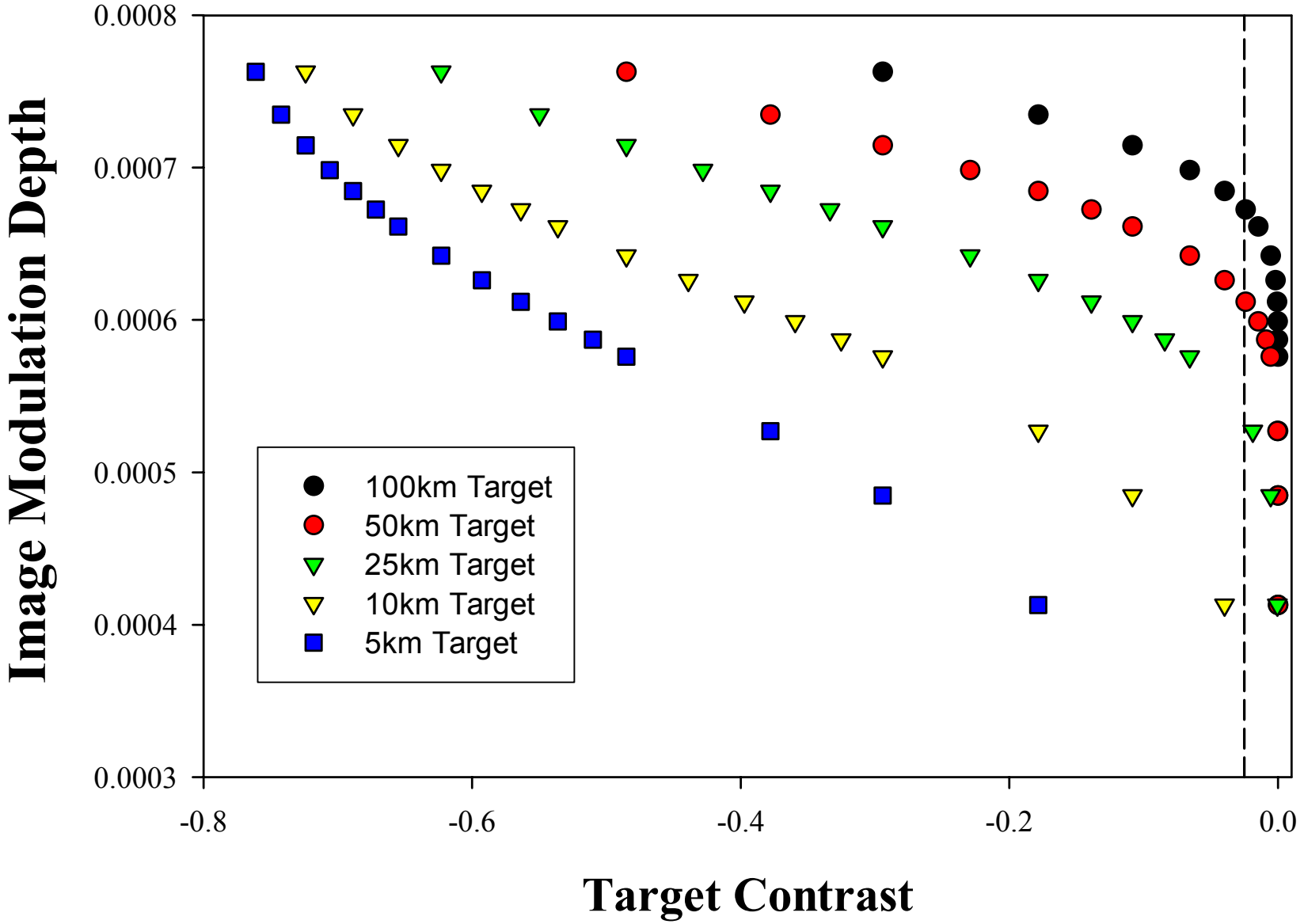


1

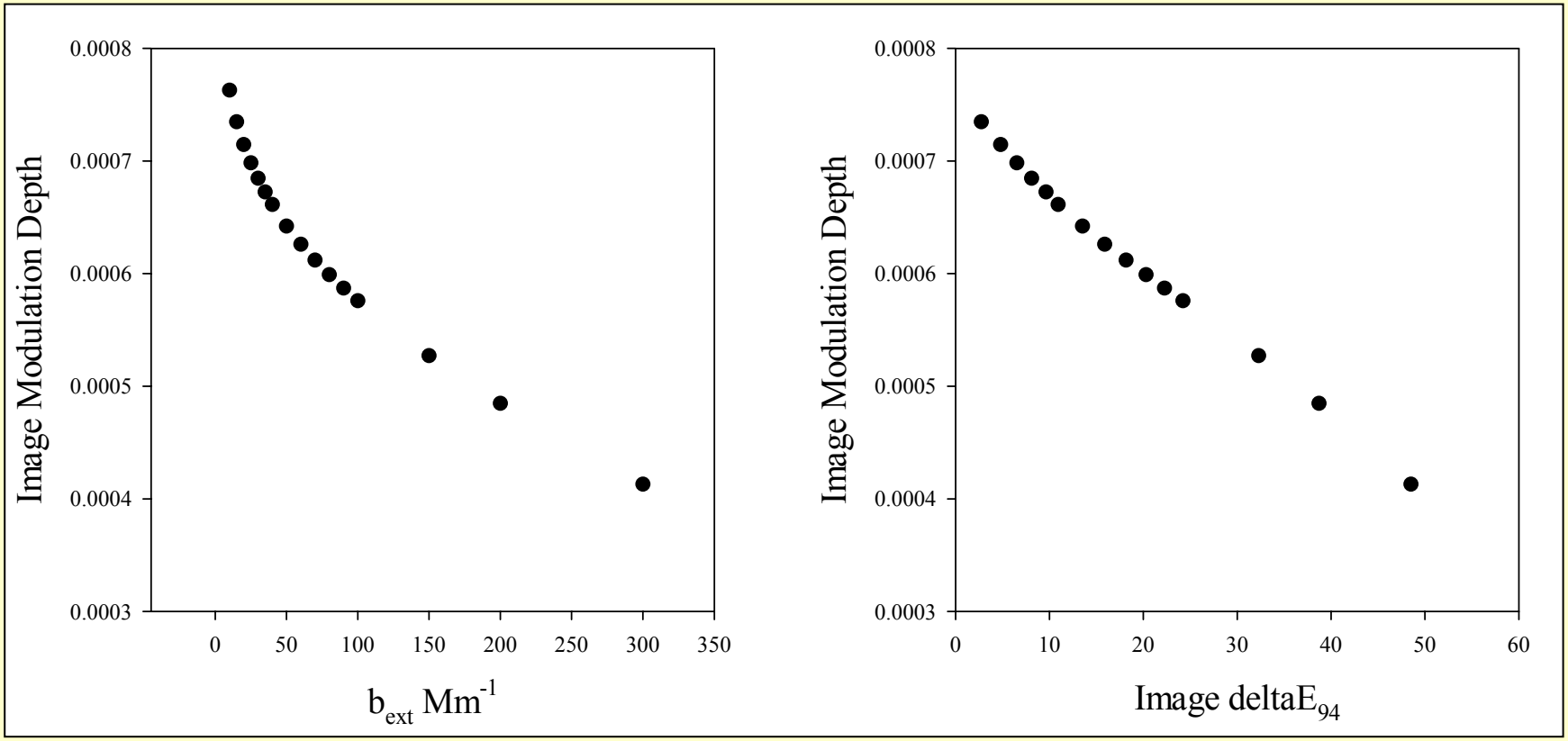
14



GRCA WinHaze Images



GRCA WinHaze Images



Current Status

- Digital images can be automatically registered, and categorized for further analyses
- Digital cameras can be reasonably characterized allowing the calculation of various image metrics
- Tests indicate that for “clear sky” images these various metrics can be related to onsite optical measurements

Current Status

- Operational at Grand Canyon NP, Great Smoky Mountains NP, and Phoenix, AZ providing Automatic Monthly and Semi-automatic Quarterly summaries of b_{ext} and Visual Range

- Is available for other locations depending on funding by clients

On going (ARS Funded) Work

- Automate characterization hardware
- Examine and include flare and image plane uniformity corrections
- Test various digital cameras by characterizing the systems, take simultaneous images of scenic vistas, calculate and compare visual air quality metrics calculated from different cameras for same scene
- Development of additional data products