Characterization of Clouds at Sub-Meter Scales by High Resolution Photography from the Surface

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YORAM'S VIEW OF CLOUDS
Middle period

Cloud optical depth $\tau = \int \sigma_{\text{ext}} dz$

$\sigma_{\text{ext}} = $ extinction coefficient

Clouds are represented as rectangular parallelepipeds within grid cells. A fraction of a grid cell is filled with clouds. Clouds are stacked with random overlap, or maximum overlap if in adjacent layers.
AN ARTIST'S VIEW OF CLOUDS

Rene Magritte, The Infinite Recognition
DSCOVR-EPIC VIEW OF CLOUDS

RGB image. 4 M pixel. One pixel = 5.2 μrad = 8 km at nadir.
RGB image obtained with zenith-pointing digital camera at surface. 12 M pixel, 16-bit. **One pixel = 6 μrad = 12 mm** at cloud height 2 km
Cloud optical depth determined from blue channel of RGB image. 12 million independent determinations of COD from single image.
Cloud optical depth determined from red channel of RGB image. Differs slightly from COD determined from blue channel.
Compare COD determinations from red and blue channels of RGB image. Agreement within 15% at higher COD.

**Equation:**

fit $y = a + bx$

- $a = 0.066$
- $b = 0.84$

**Root-Mean-Square Residual:**

$0.046$

**ARM SGP site, 2016-0731, 16:35:52 UTC (10:05:52 local sun time)**
HIGH RESOLUTION IMAGER

Fujifilm FinePix S1
16 Megapixels, 3456 × 4608
3 Color, RGB, 16 bit
1200 mm focal length
(35 mm equiv)
1 Pixel = 6 μrad
FOV 22 × 29 mrad
(2 × 3 sun diameters)
$350
1200 mm EQUIVALENT FOCAL LENGTH

That's 1.2 meters!

Todd Vorenkamp, B&H Photo, NYC
NARROW FIELD OF VIEW

29 × 22 mrad ≈ 3 × 2 sun (or moon) diameters, 29 × 22 m at 1 km
RESOLVING POWER TESTS

Resolves 2 cm blocks at 1 km.
Line trace is 1 pixel wide across 4 cm blocks
SPECTRAL SENSITIVITY CALIBRATION OF RGB CHANNELS

Cameras calibrated with XeHg arc lamp, integrating sphere, NIST calibrated photodiode.
Measurements are *hypospectral!* We use just red and blue channels.
CAMERA FIELD OF VIEW AND SOLAR EPHEMERIS

Narrow FOV Camera, 22 x 29 mrad = 2 x 3 sun diameters

Wide FOV Camera, 120 x 160 mrad

Sun, angular diameter 0.535° = 9.3 mrad

Drawn 10 times actual angular dimension

SGP, Oklahoma
2015-07-31
Times are UTC
Local sun time: UTC - 6.5 h

Measurements are hyper local!
DEPLOYMENT OF CAMERAS AT SGP
7 MINUTES IN OKLAHOMA, WIDE FIELD OF VIEW CAMERA

1 Photo every 4 s. Image is \(\sim 120 \times 160\) mrad = \(\sim 240 \times 320\) m @ 2 km.
7 MINUTES IN OKLAHOMA, NARROW FIELD OF VIEW CAMERA

1 Photo every 4 s. Image is $\sim 20 \times 30$ mrad = $\sim 40 \times 60$ m @ 2 km.
ZENITH RADIANCE DEPENDENCE ON COD

Normalized zenith radiance: Zenith radiance per hemispheric TOA solar irradiance

Unit: $W \, m^{-2} \, nm^{-1} \, sr^{-1} / W \, m^{-2} \, nm^{-1} = sr^{-1}$

Downwelling radiance is low in absence of clouds; increases with increasing cloud optical depth, reaches a peak, and then decreases.

Why?
ZENITH RADIANCE DEPENDENCE ON COD

Normalized zenith radiance: Zenith radiance per hemispheric TOA solar irradiance

Unit: $W \text{ m}^{-2} \text{ nm}^{-1} \text{ sr}^{-1} / W \text{ m}^{-2} \text{ nm}^{-1} = \text{ sr}^{-1}$

In absence of cloud, Rayleigh scattering only, low zenith radiance.
At low COD normalized zenith radiance _increases_ with increasing COD.
At higher COD normalized zenith radiance _decreases_ with increasing COD.
Dependence of NZR on COD is inverted to obtain COD from NZR. Inversion is valid only for COD $\leq 3$. Must establish COD $< 3$. The inversion is applied to yield COD on *pixel-by-pixel basis*. Minima and maxima permit scaling counts to NZR in each channel.
CALIBRATION APPROACHES

Need to calibrate counts in Red and Blue channels to Radiance.

• Absolute calibration (calibrated lamp or radiometer accounting for geometric effects).
• Field transfer from calibrated zenith radiometer.
• Radiation transfer calculations:
  Two point calibration of NZR using minimum (Rayleigh) radiance and maximum (Bright Cloud) radiance.

Calibration on Dark and Bright scenes permits determination of NZR, COD, Cloud albedo at native resolution of images.

Concerns:

Aerosol contribution to nominal “Rayleigh” signal.
Dependence on assumptions in RT calculations such as 1-D plane parallel; cloud drop asymmetry parameter.
Organized structure is present down to 10 cm scale.
STRENGTHS AND ADVANTAGES

High resolution: 6 µrad nominal; 20 µrad actual.

Large number of independent measurements: 12 million nominal.

High dynamic range: 16 bit.

Black background of outer space: No surface influence (to first order); Rayleigh radiance is exactly calculable.

Readily available data acquisition hardware and image processing software.

Low cost.

Lots of data!
WEAKNESSES AND LIMITATIONS

Two-dimensional only.
Daytime only.
Hyperlocal.
Hypospectral (but 2 channels may be enough).
Limited to COD $\leq 3$ (but we see a path forward).

*Lots of data!*
SUMMARY

High resolution digital photography from the surface presents an unprecedented view of cloud structure.

Resolution is 3 to 5 orders of magnitude higher than existing approaches.

Radiance and optical depth of thin clouds are retrieved pixel-by-pixel from digital camera images at resolution of ~4 cm for cloud at 2 km.

Cloud radiance and optical depth exhibit rich spatial structure, for example order of magnitude variation over 40 m × 40 m domain.

Variation in radiance on scales down to ~10 cm is attributed to variation in cloud optical depth.