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

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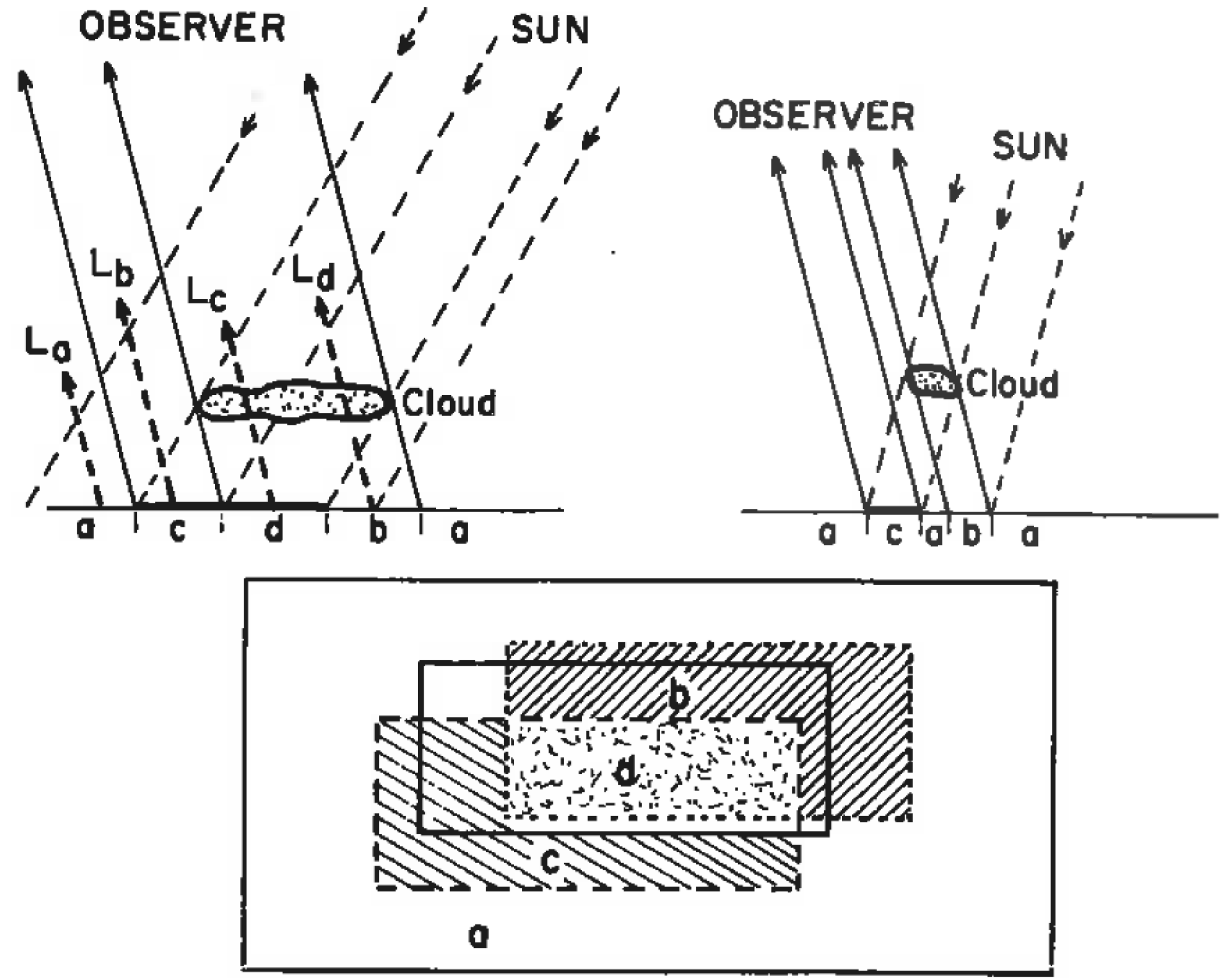
www.ecd.bnl.gov/steve

YORAM'S VIEW OF CLOUDS
Early period

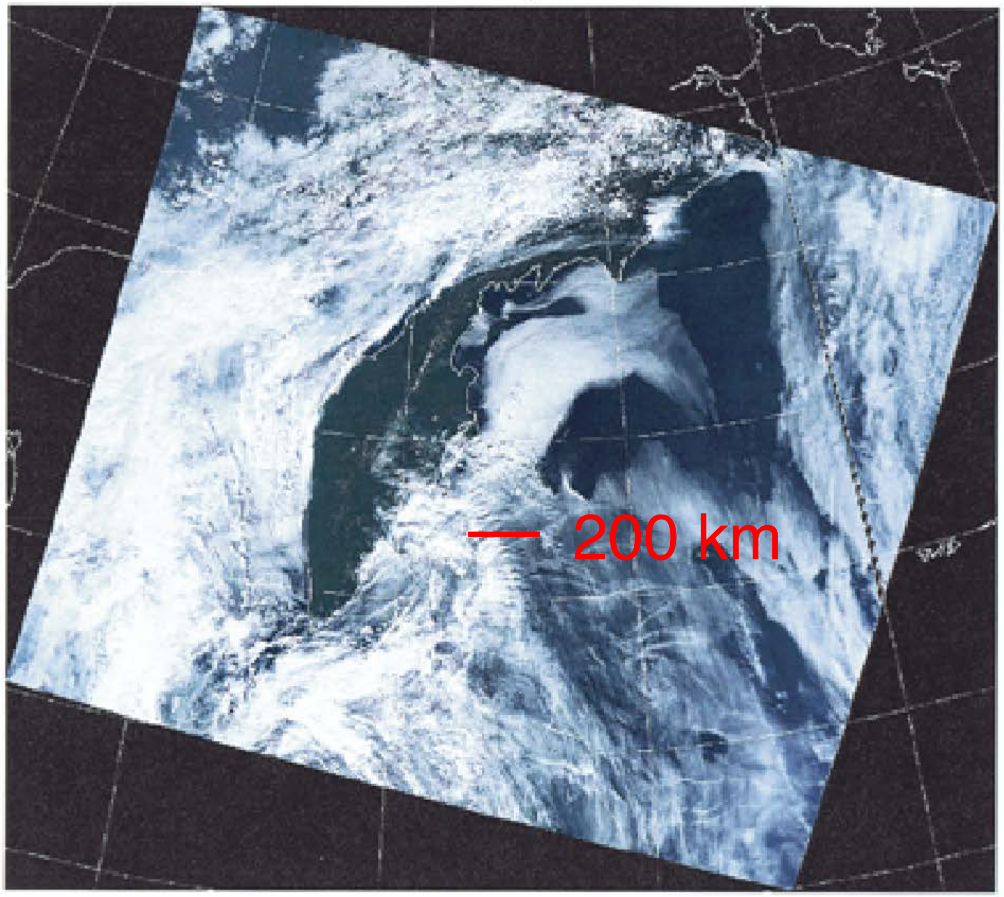


Kaufman, Y. J. (1987). The effect of subpixel clouds on remote sensing. International Journal of Remote Sensing.

YORAM'S VIEW OF CLOUDS
Middle period

R G B

R(0.645, 0.555, 0.469)

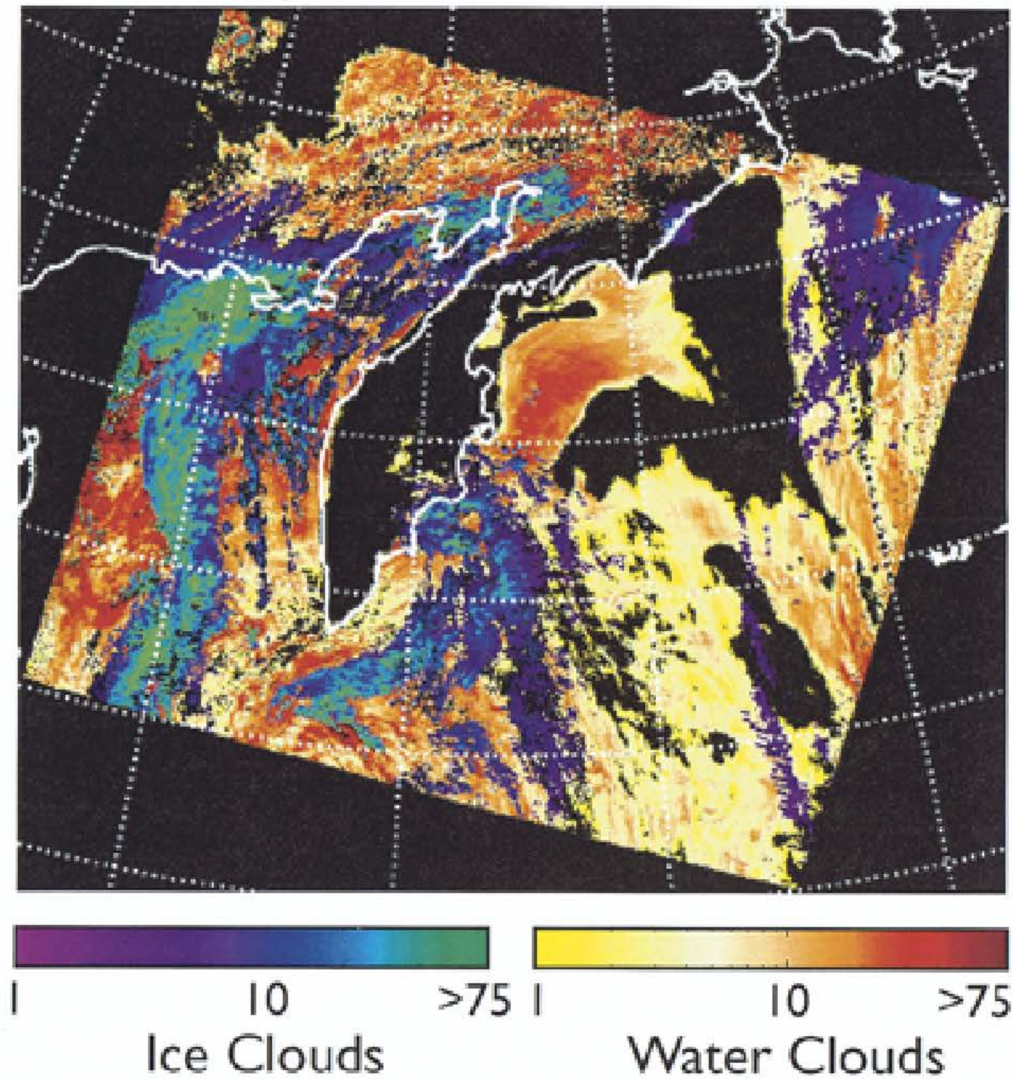


1 pixel = 250 m

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

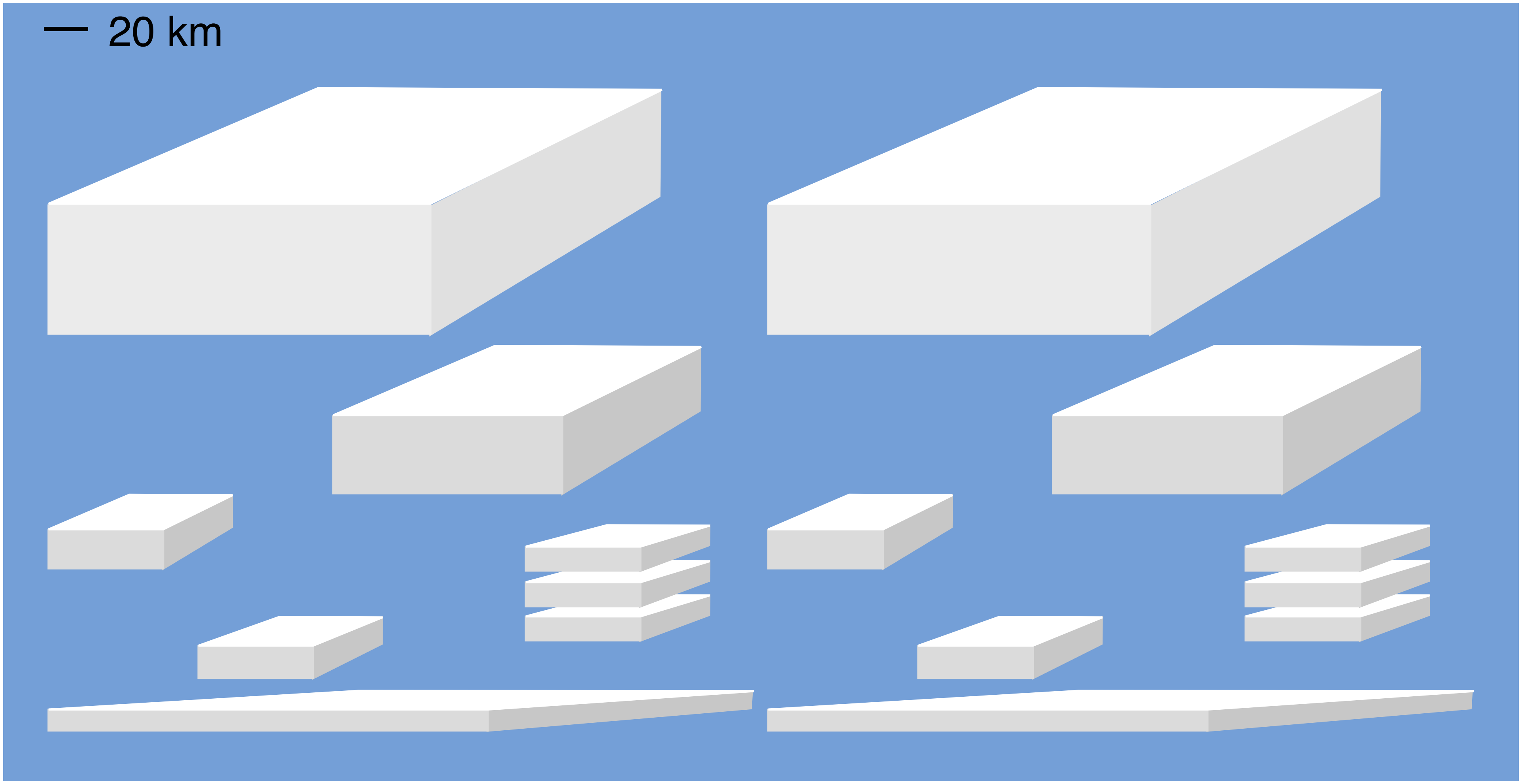
σ_{ext} = extinction coefficient

Cloud Optical Depth



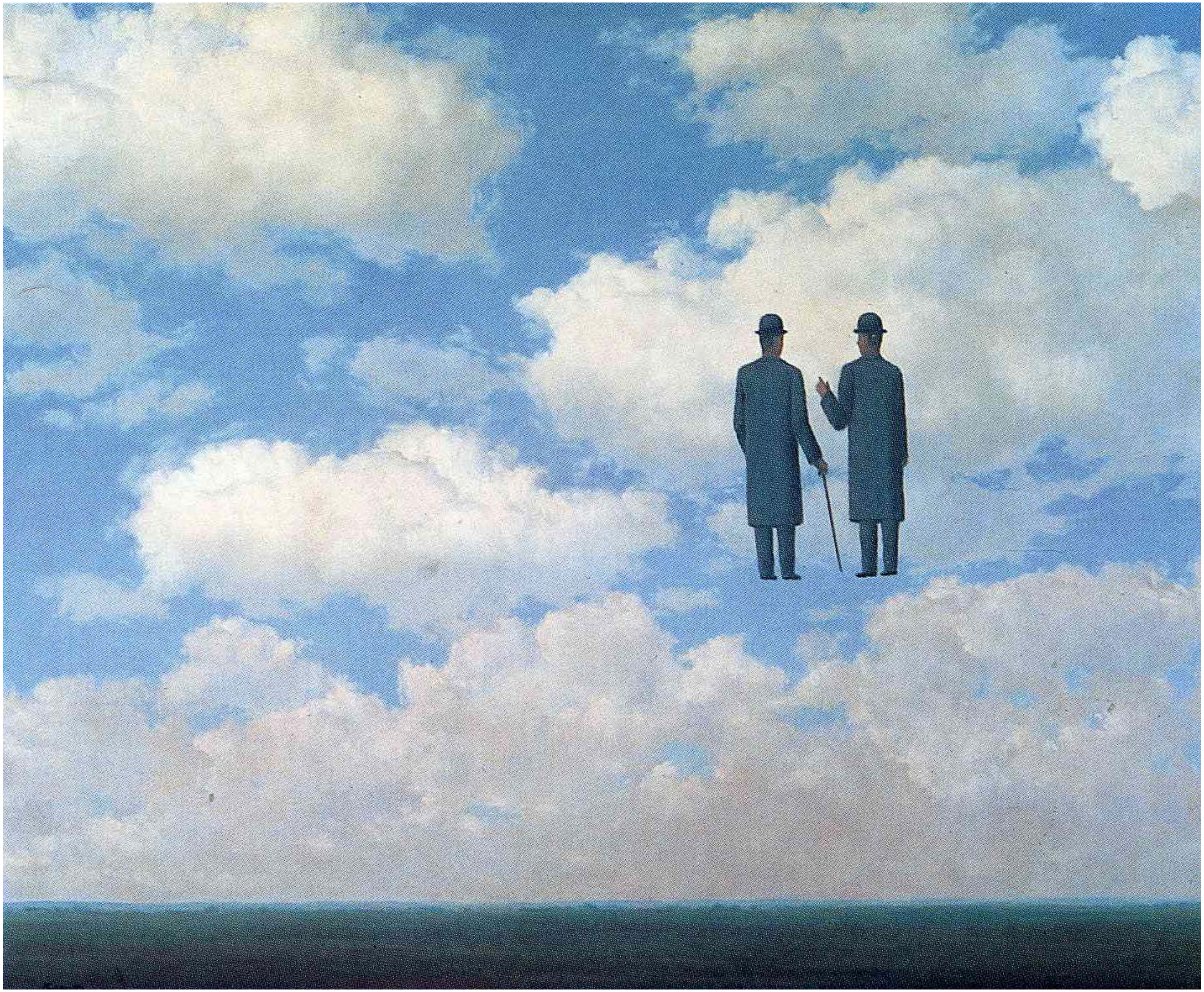
King, M. D., Menzel, W. P., Kaufman, Y. J. et al. (2003). Cloud and aerosol properties, precipitable water, and profiles of temperature and water vapor from MODIS. Geosci. Remote Sensing, IEEE Trans.

A CLIMATE MODELER'S VIEW OF CLOUDS



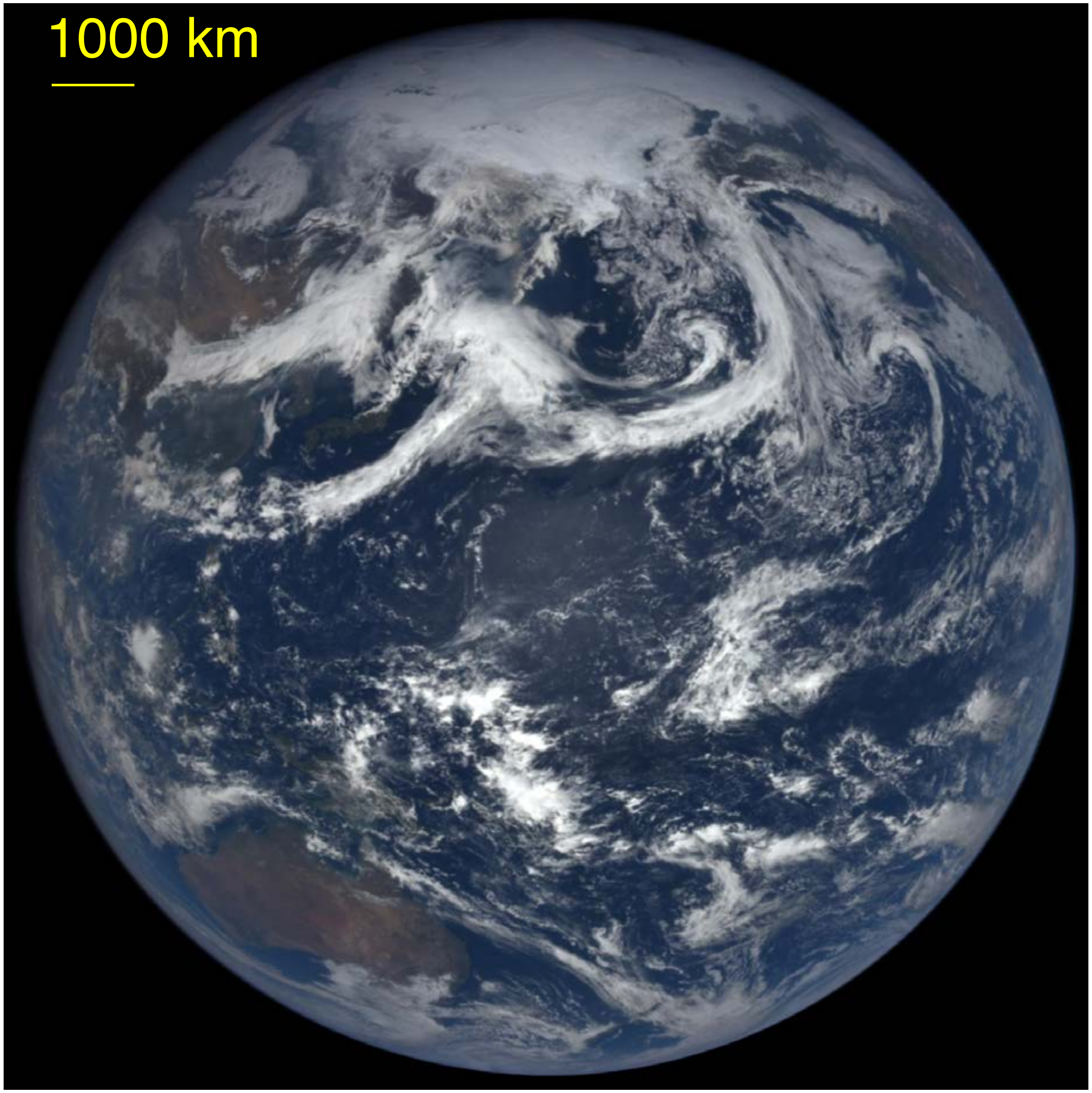
Clouds are represented as rectangular parallelepipeds within grid cells.
A fraction of a grid cell is filled with clouds.
Clouds are stacked with random overlap, or maximum overlap if in adjacent layers.

AN ARTIST'S VIEW OF CLOUDS



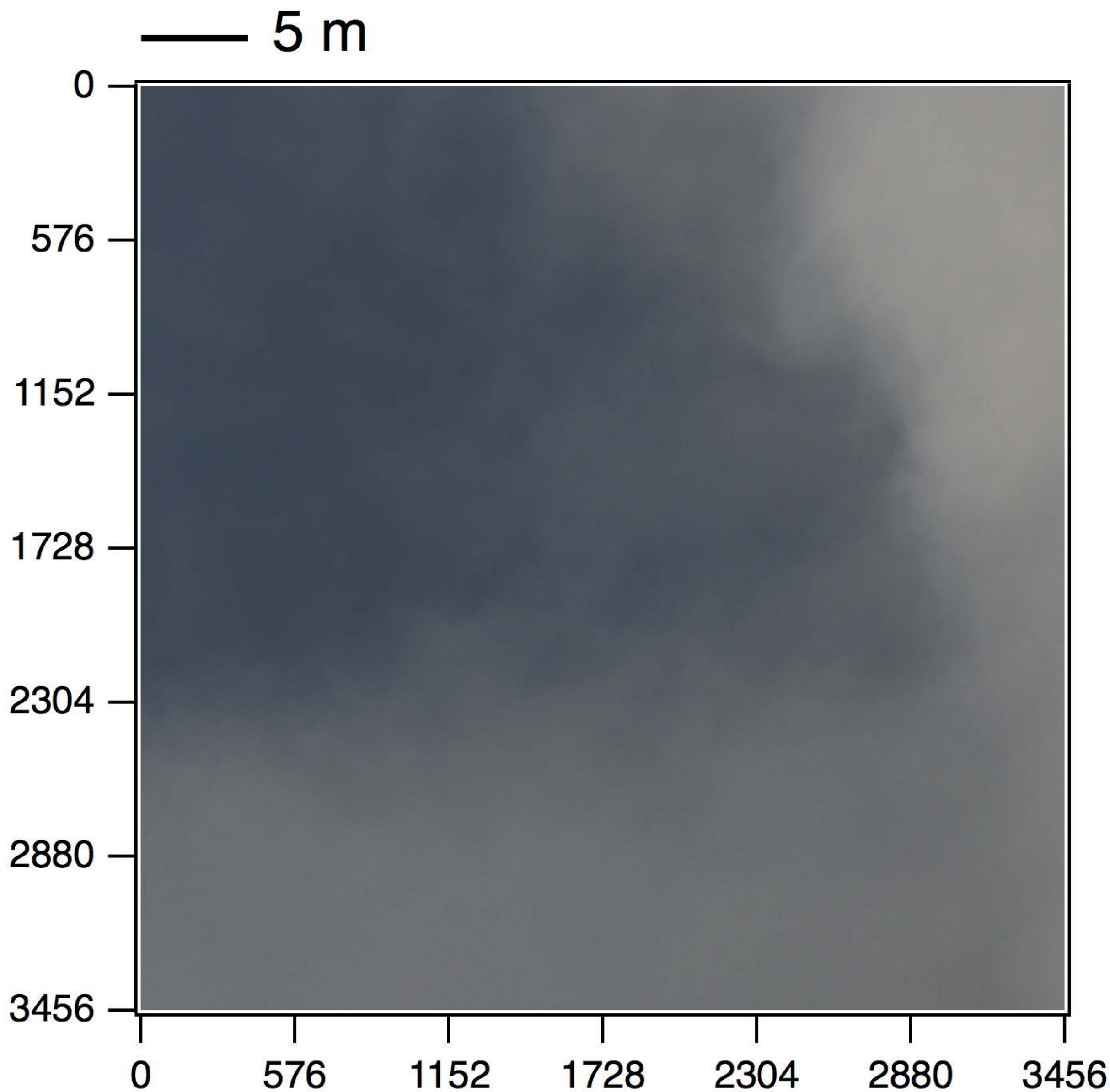
Rene Magritte, The Infinite Recognition

DSCOVR-EPIC VIEW OF CLOUDS



RGB image. 4 M pixel. One pixel = 5.2 μrad = 8 km at nadir.

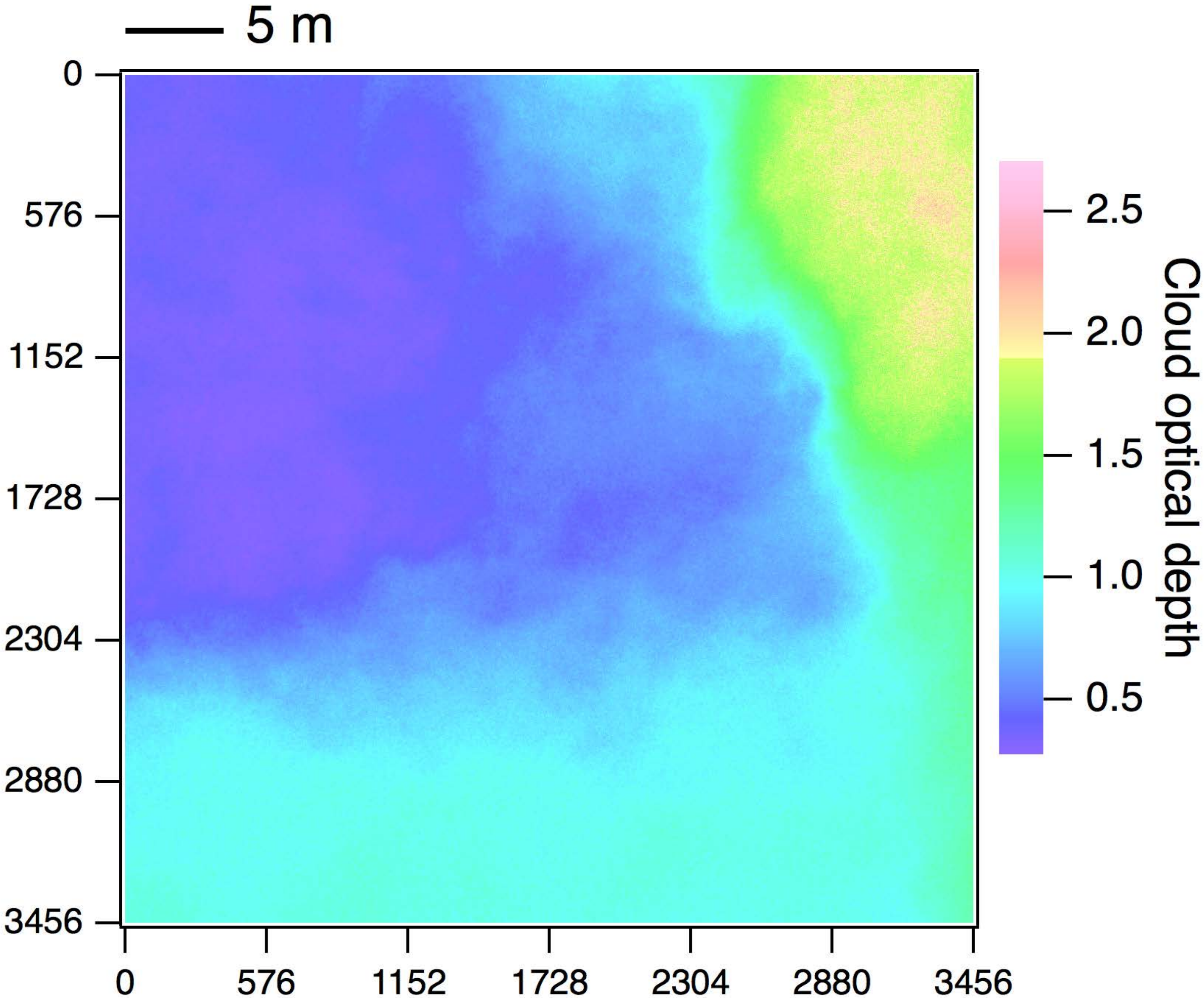
STEVE'S VIEW OF A CLOUD



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

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

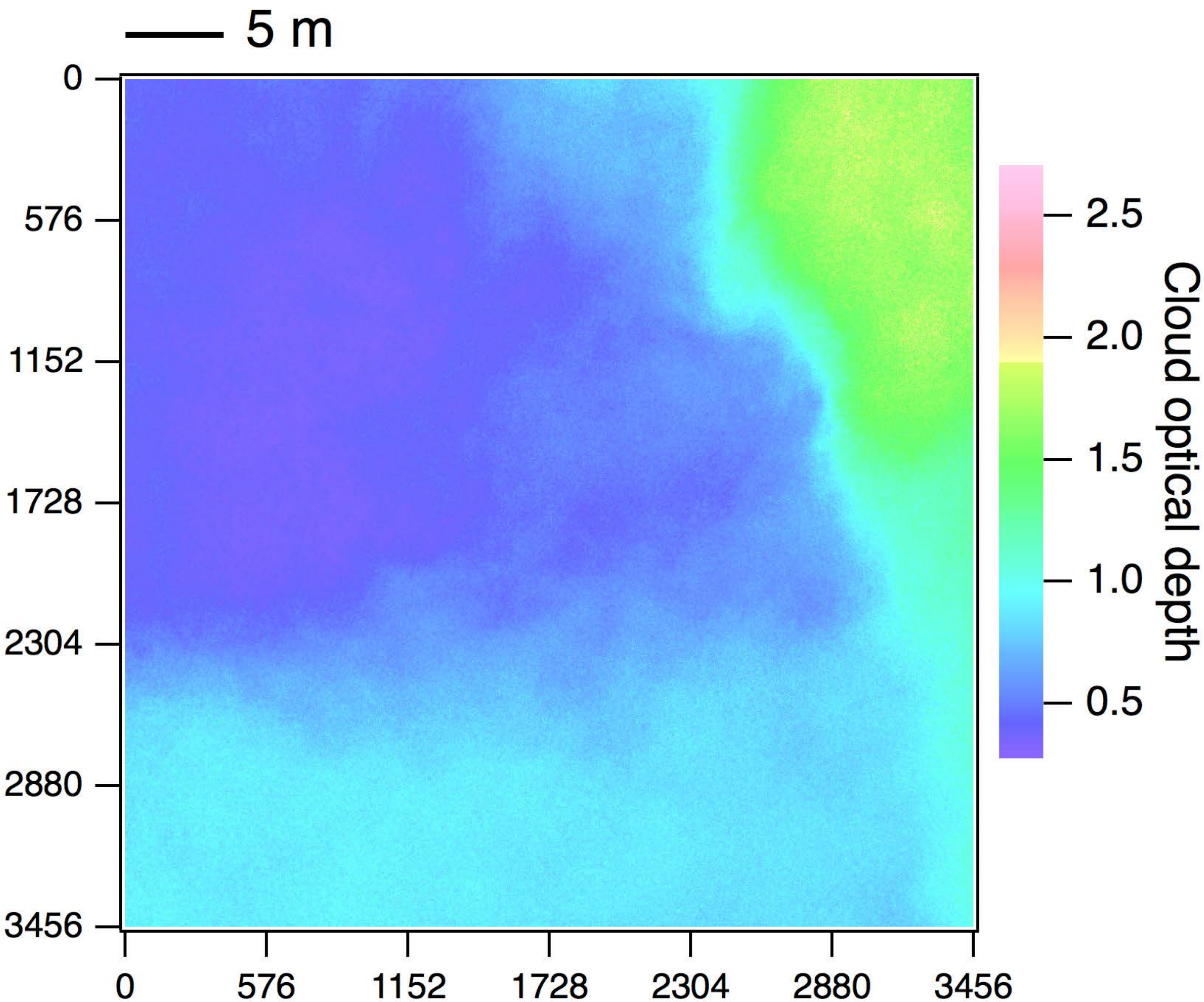
CLOUD OPTICAL DEPTH



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

Cloud optical depth determined from blue channel of RGB image.
12 million independent determinations of COD from single image.

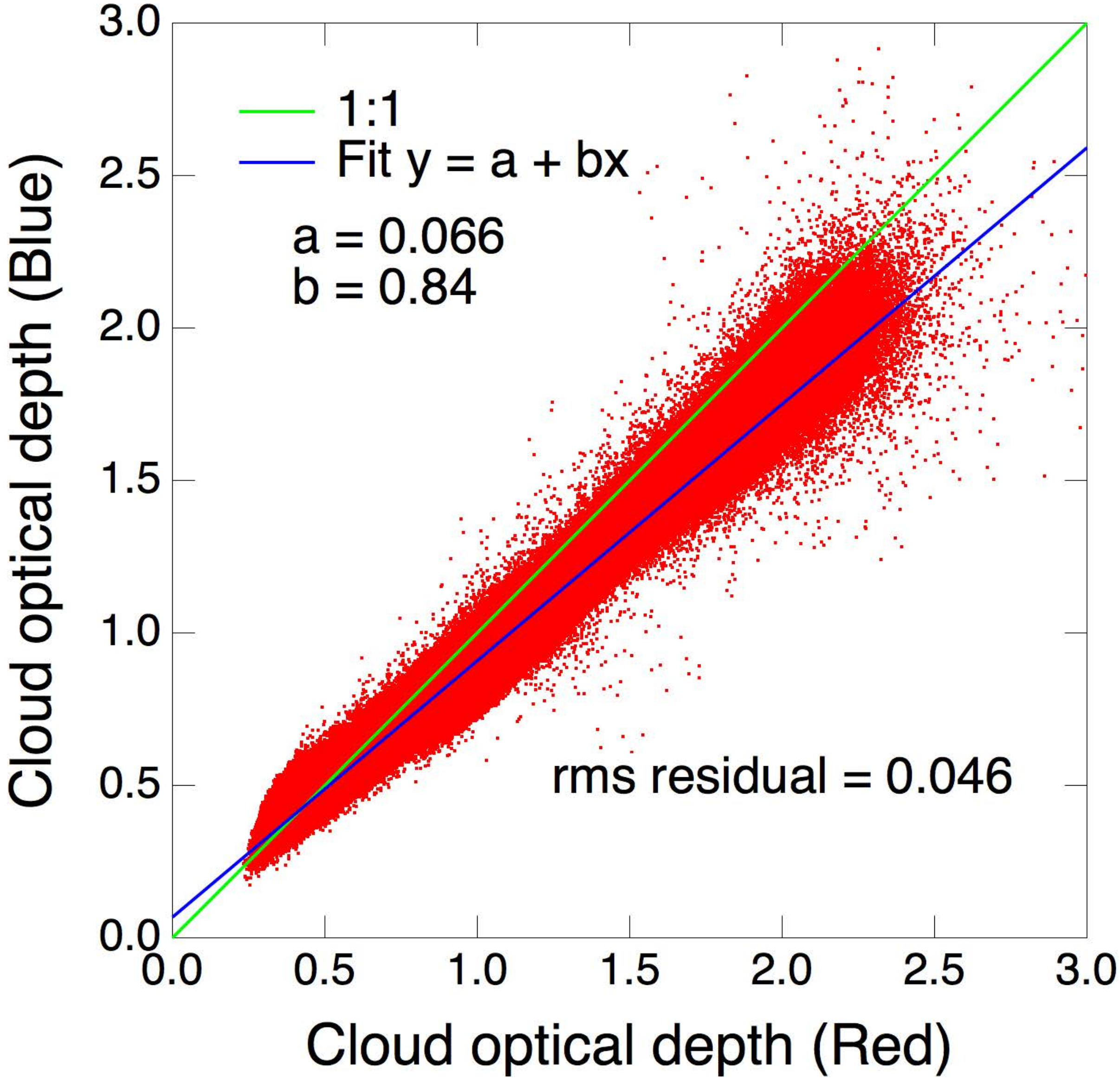
CLOUD OPTICAL DEPTH



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

Cloud optical depth determined from red channel of RGB image.
Differs slightly from COD determined from blue channel.

COMPARE COD DETERMINATIONS



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

Compare CODs from red and blue channels of RGB image.
Agreement within 15% at higher COD.

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

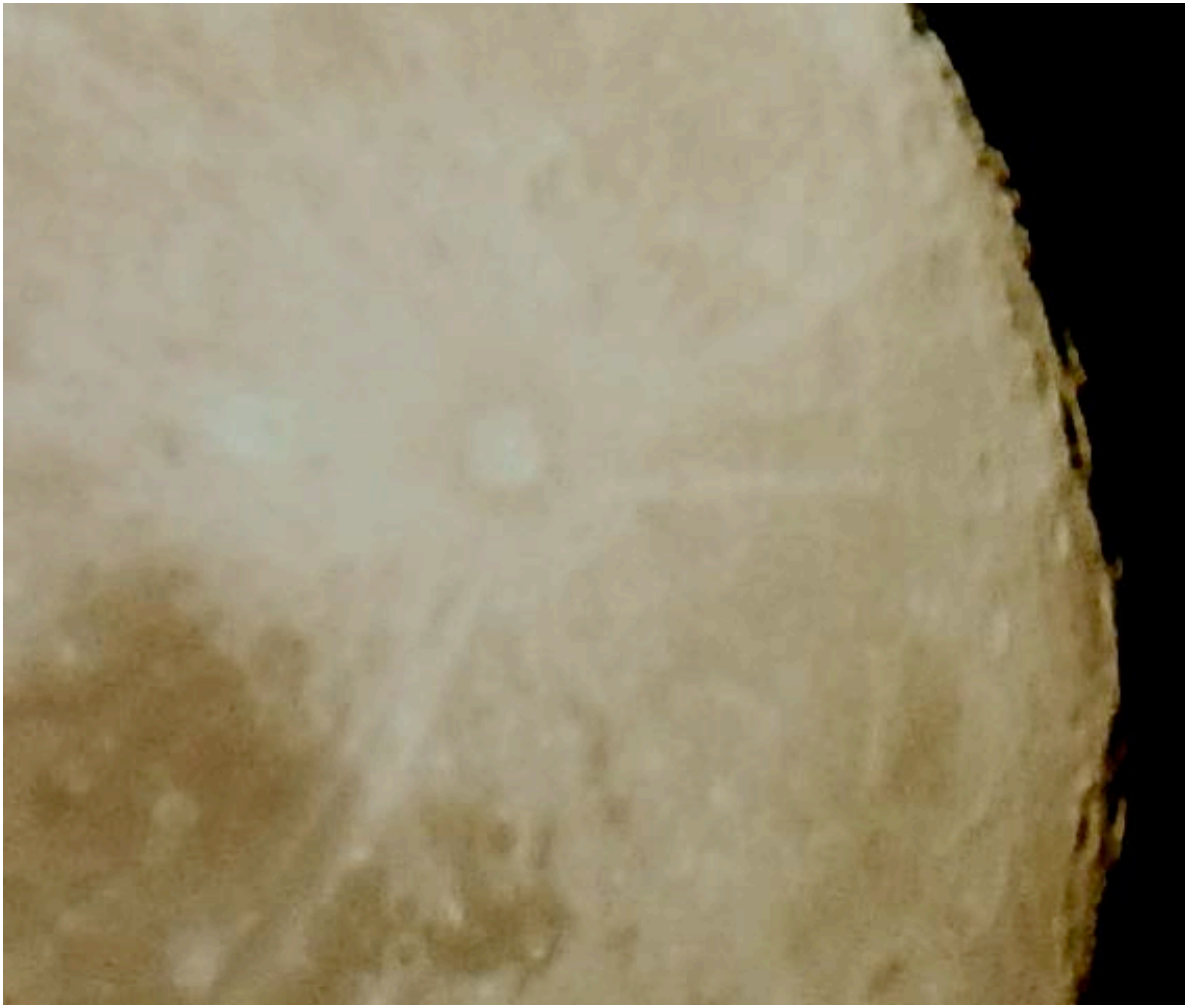
Todd Vorenkamp, B&H Photo, NYC

That's 1.2 meters!

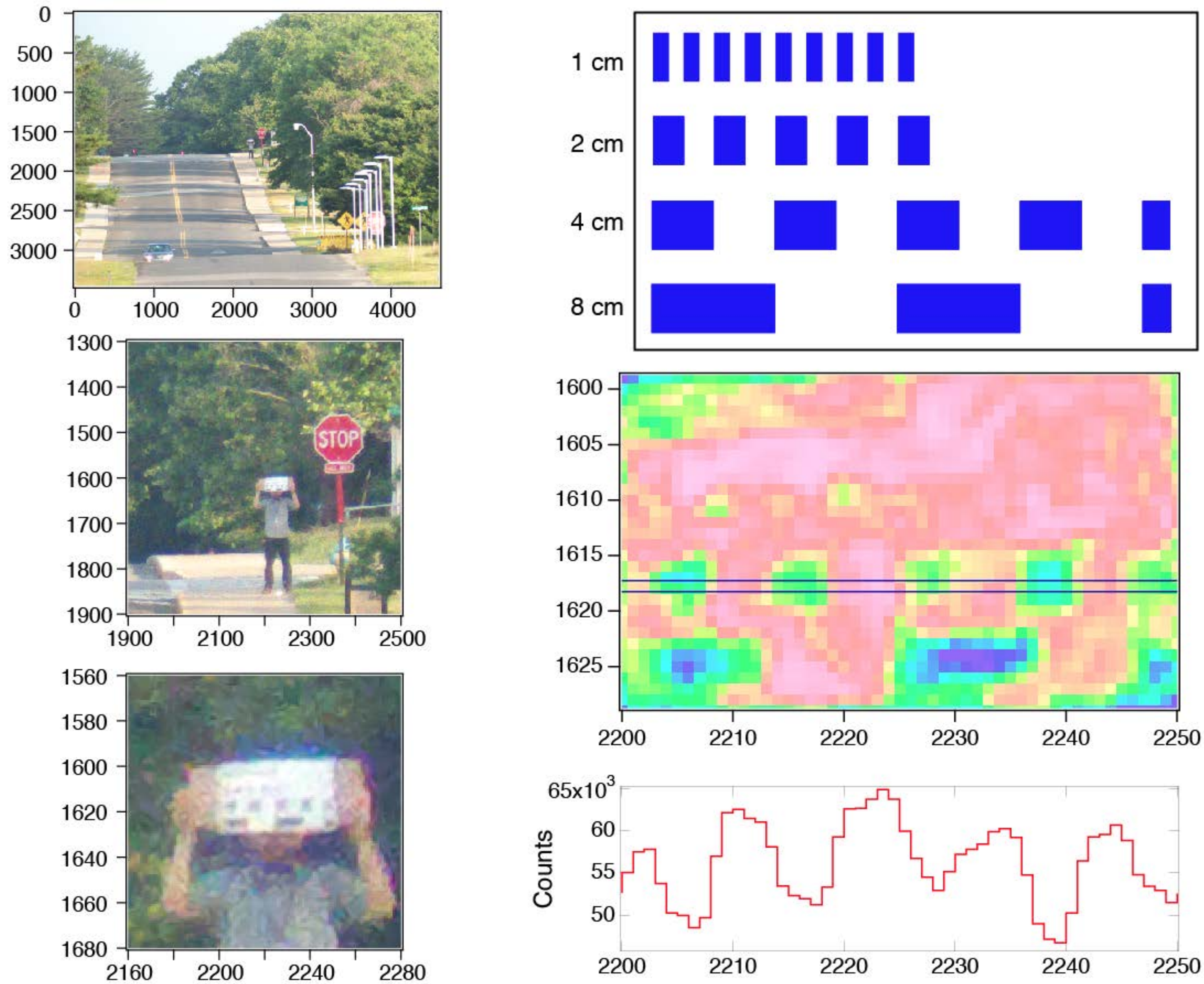
NARROW FIELD OF VIEW

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

HIGH RESOLUTION



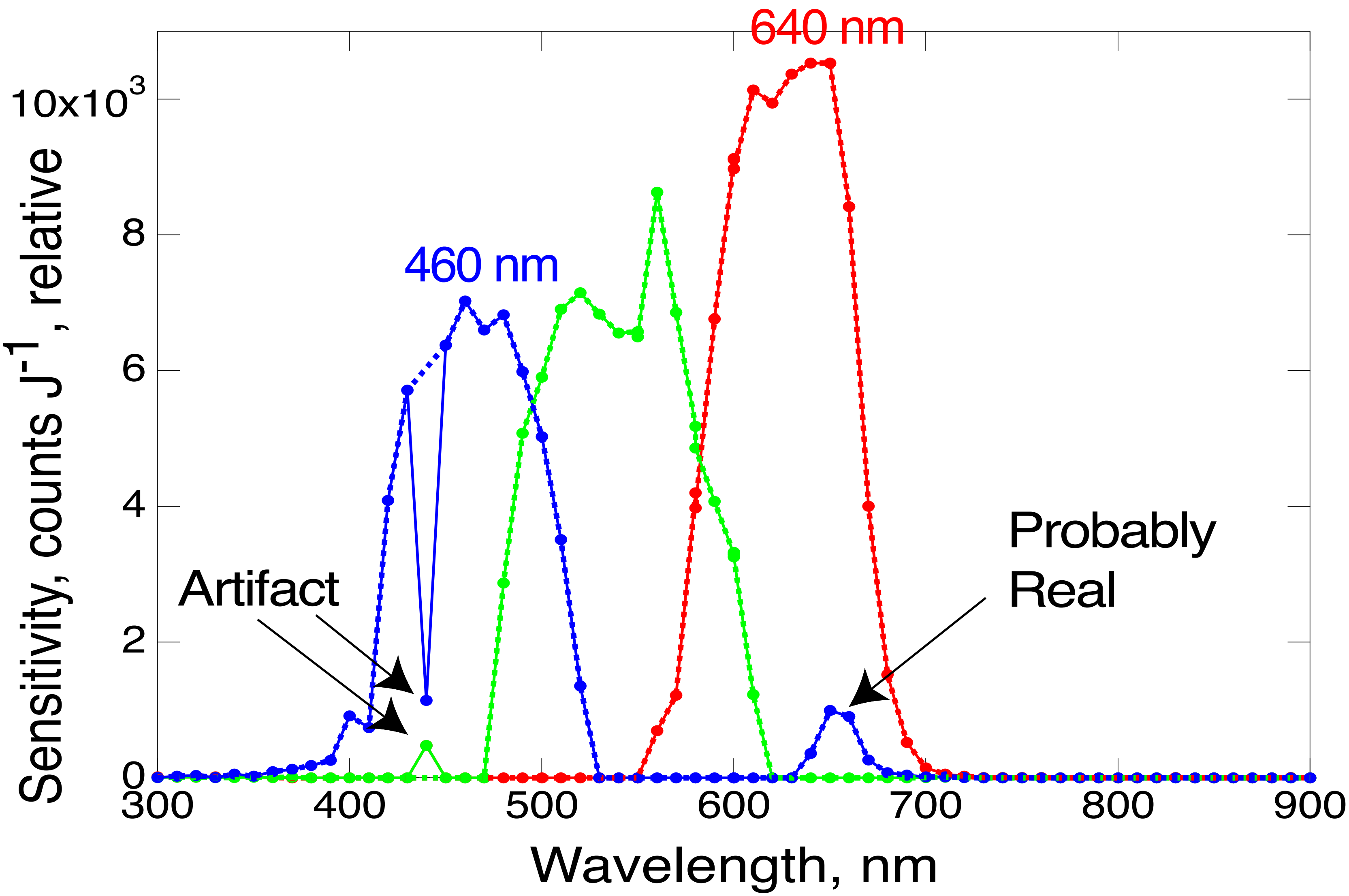
RESOLVING POWER TESTS



Resolves 2 cm blocks at 1 km.

Line trace is 1 pixel wide across 4 cm blocks

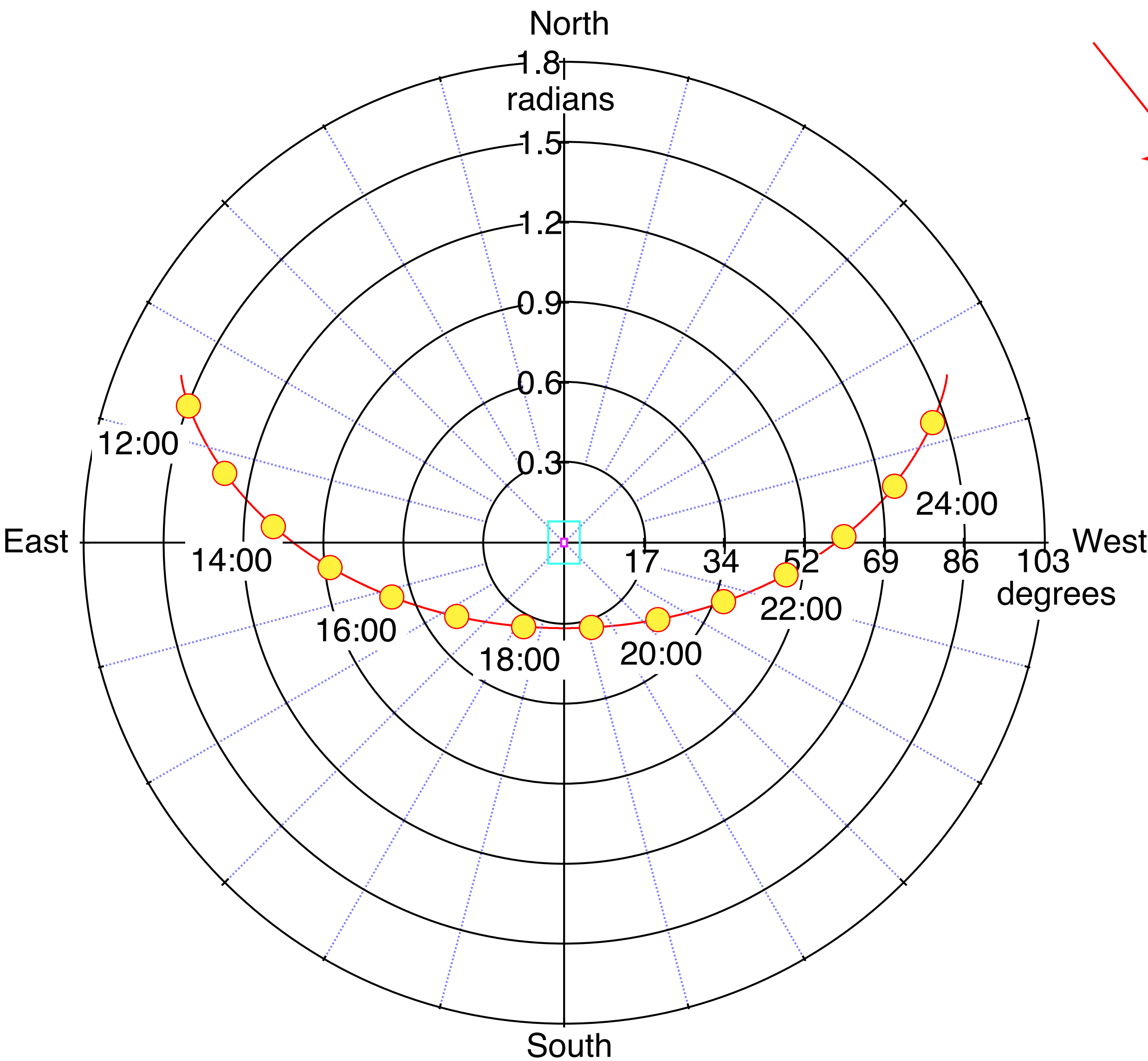
SPECTRAL SENSITIVITY CALIBRATION OF RGB CHANNELS



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

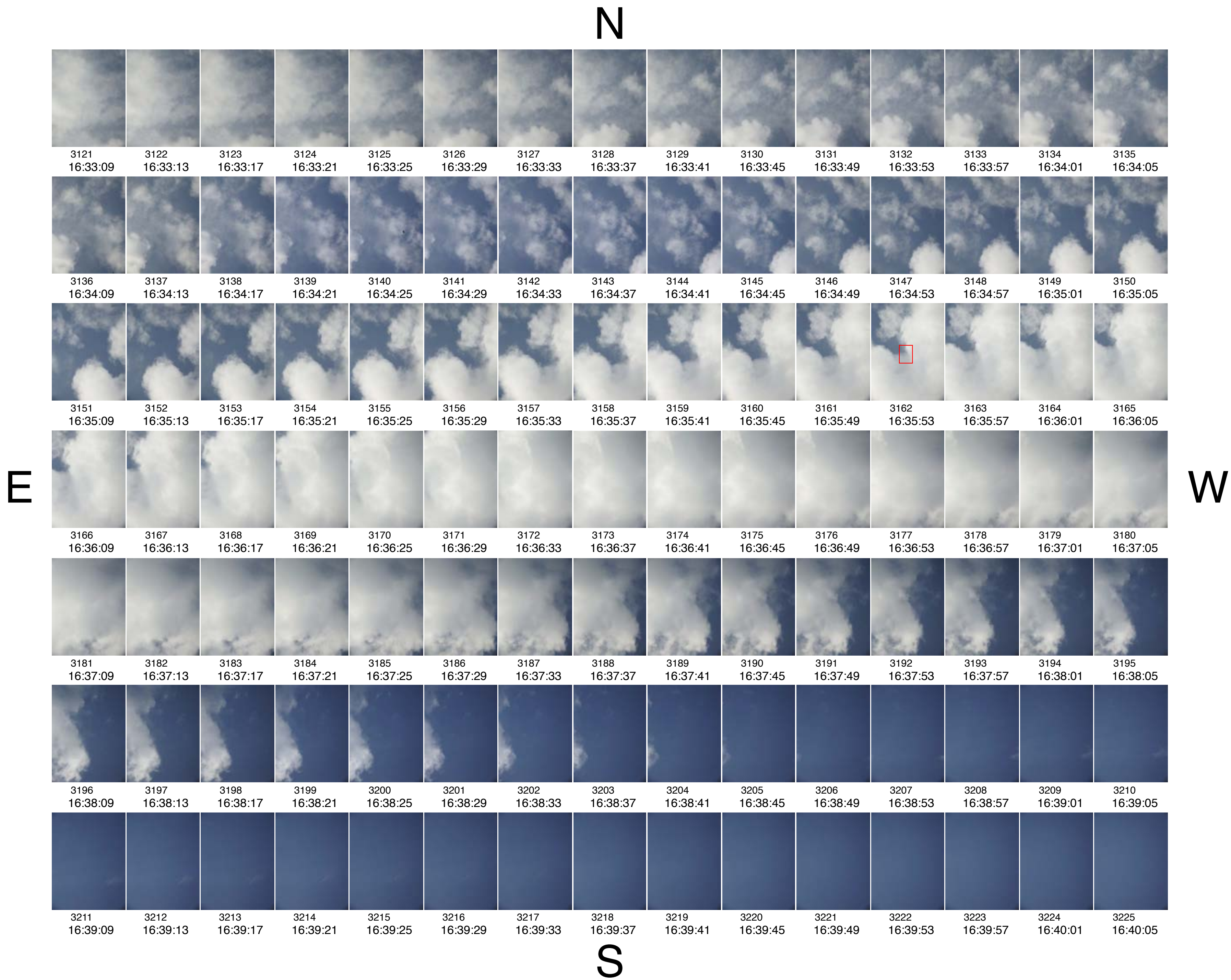
Drawn 10 times actual angular dimension

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

Measurements are hyper local!

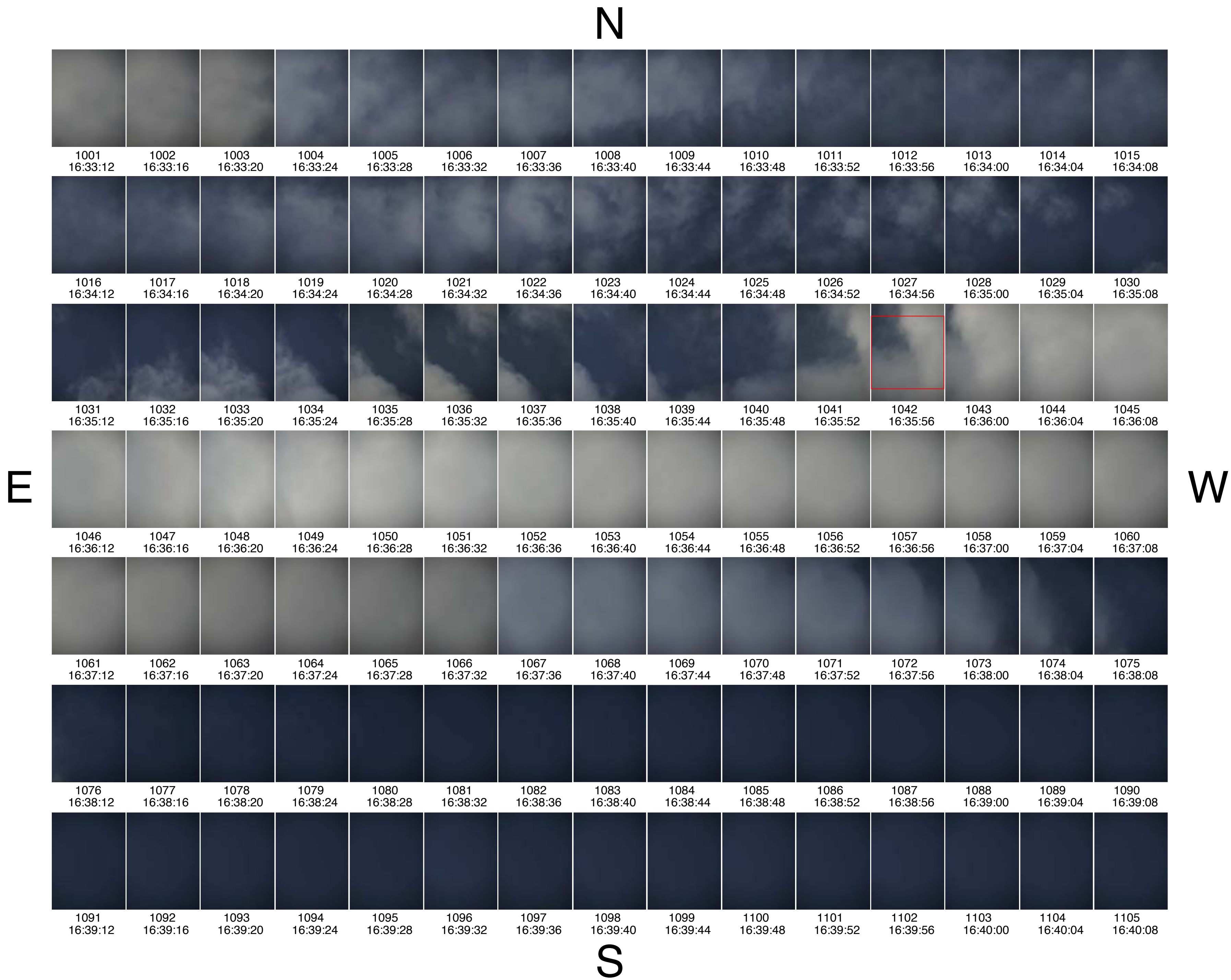
DEPLOYMENT OF CAMERAS AT SGP

7 MINUTES IN OKLAHOMA, WIDE FIELD OF VIEW CAMERA



1 Photo every 4 s. Image is ~120 × 160 mrad = ~240 × 320 m @ 2 km.

7 MINUTES IN OKLAHOMA, NARROW FIELD OF VIEW CAMERA

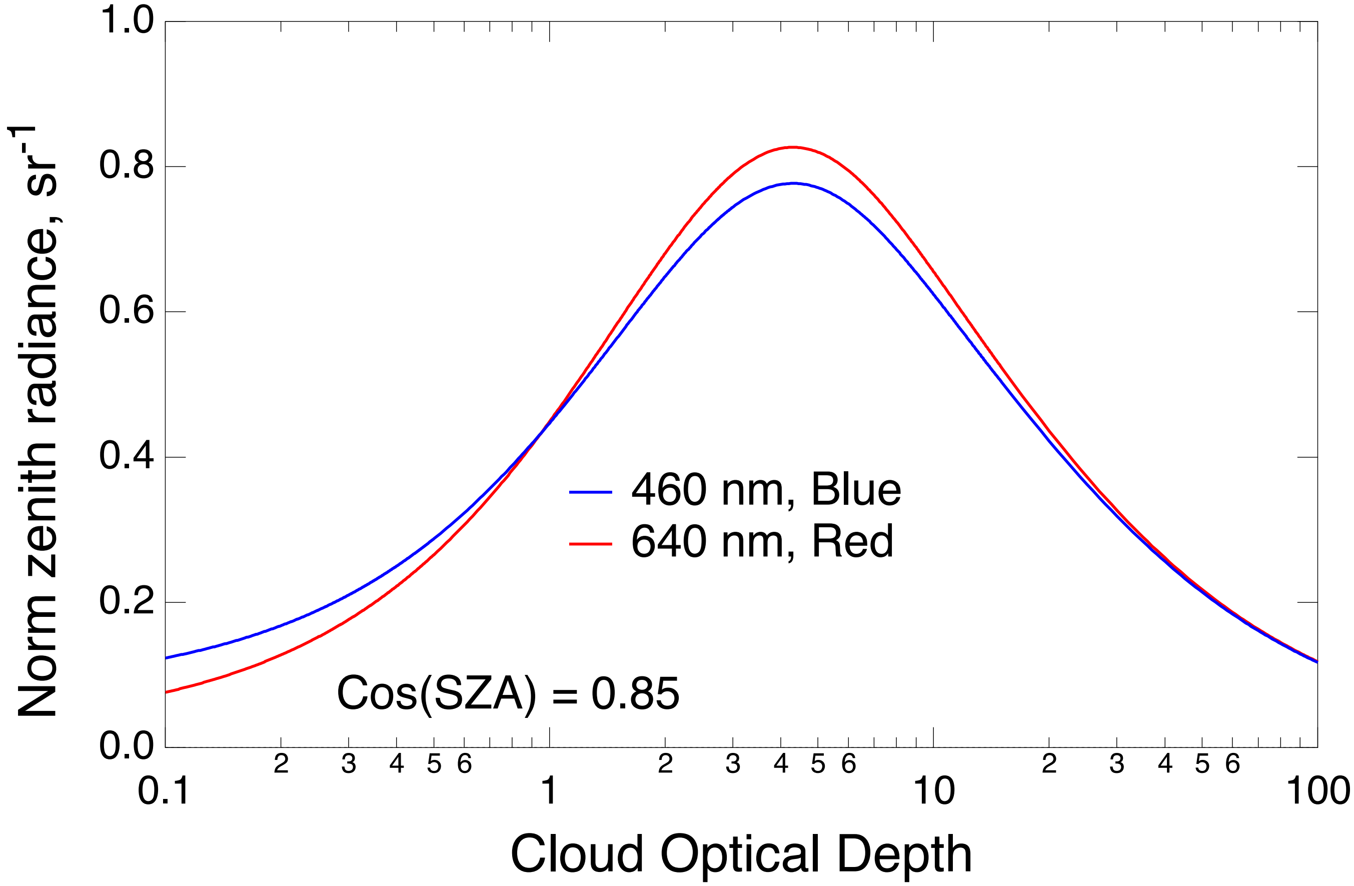


1 Photo every 4 s. Image is ~20 × 30 mrad = ~40 × 60 m @ 2 km.

ZENITH RADIANCE DEPENDENCE ON COD

Normalized zenith radiance: Zenith radiance per hemispheric TOA solar irradiance

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



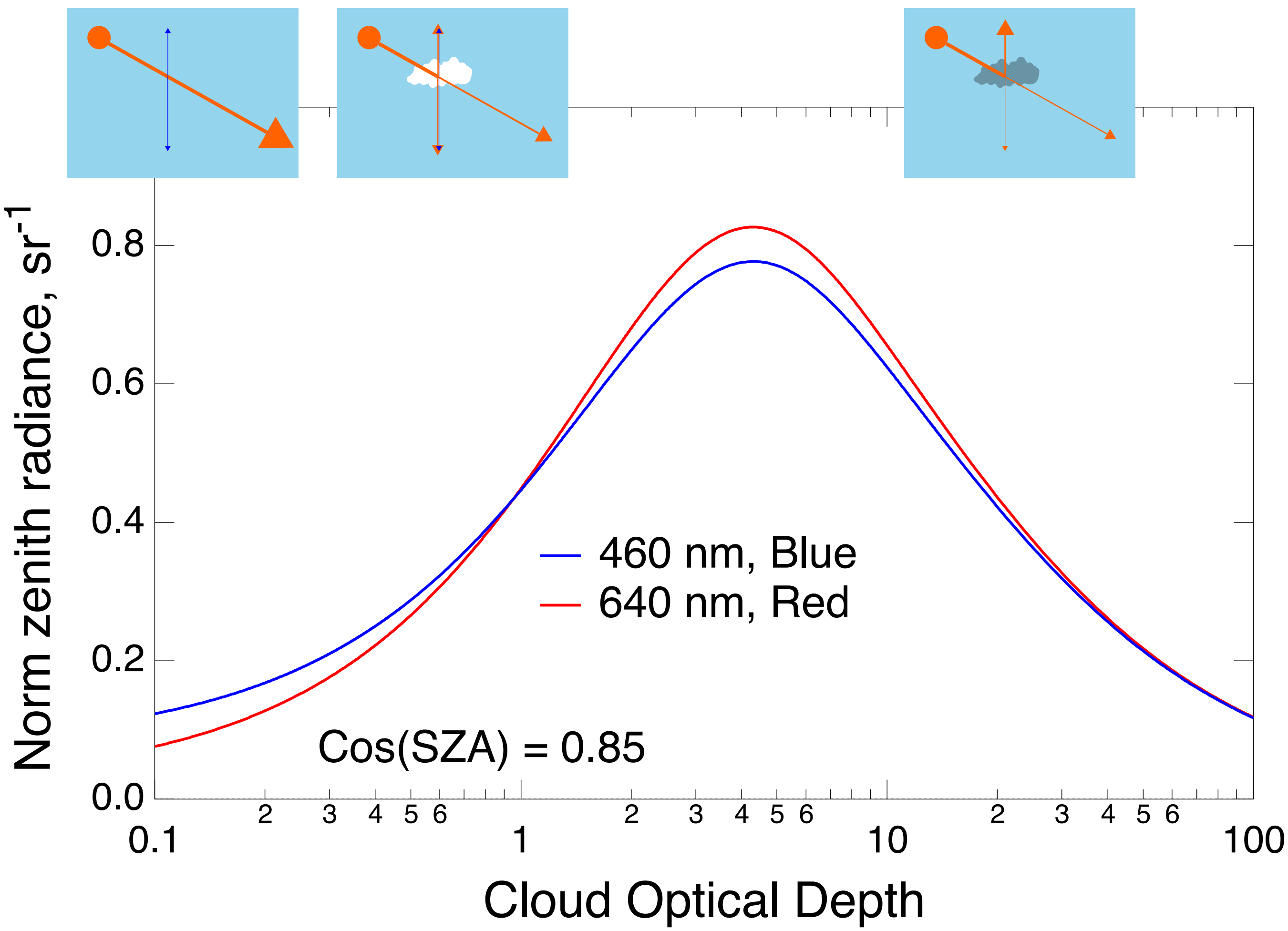
Downwelling radiance is low in absence of clouds; increases with increasing cloud optical depth, reaches a peak, and then decreases.

Why?

ZENITH RADIANCE DEPENDENCE ON COD

Normalized zenith radiance: Zenith radiance per hemispheric TOA solar irradiance

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

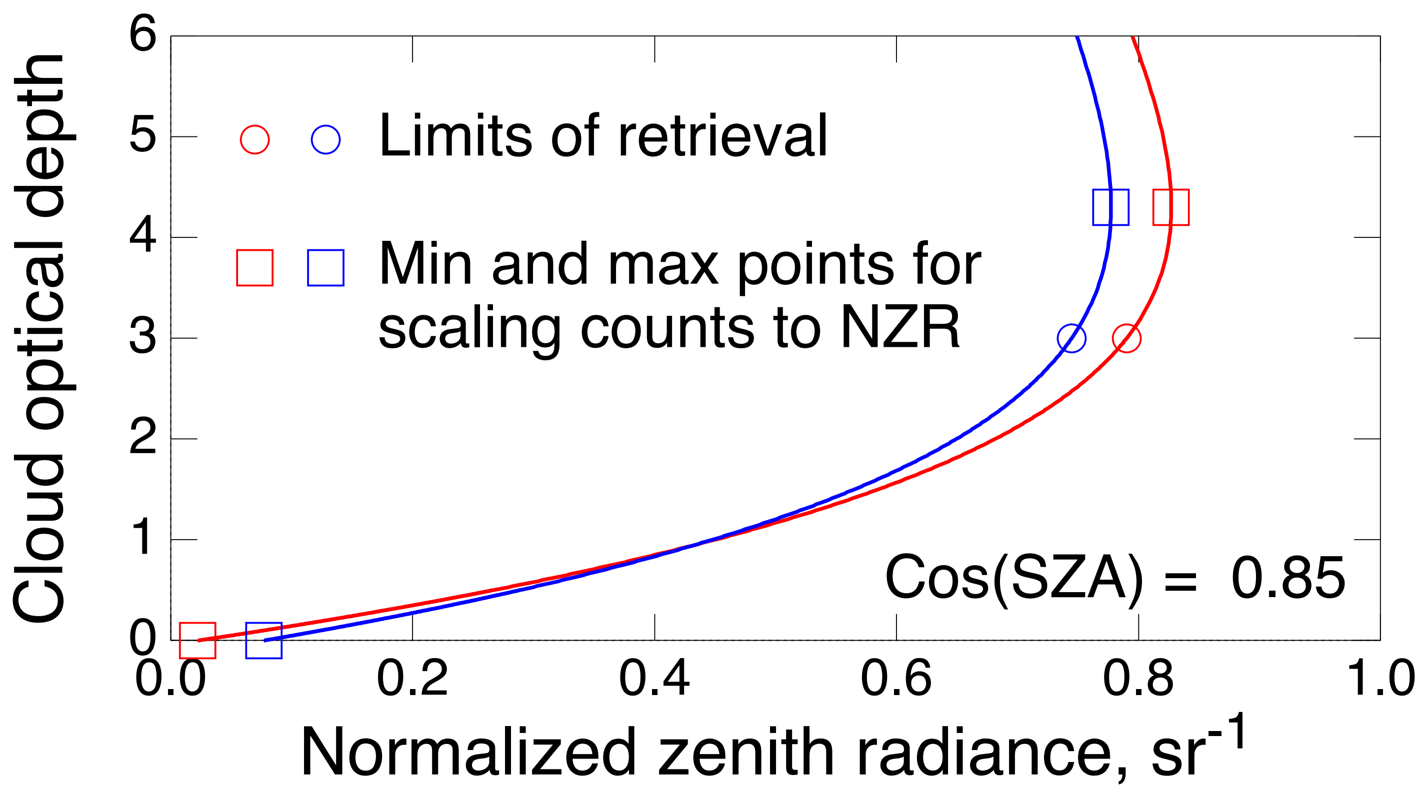


In absence of cloud, Rayleigh scattering only, low zenith radiance.

At low COD normalized zenith radiance ***increases*** with increasing COD.

At higher COD normalized zenith radiance ***decreases*** with increasing COD.

COD DEPENDENCE ON ZENITH RADIANCE



Dependence of NZR on COD is inverted to obtain COD from NZR.

Inversion is valid only for COD $\lesssim$ 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.

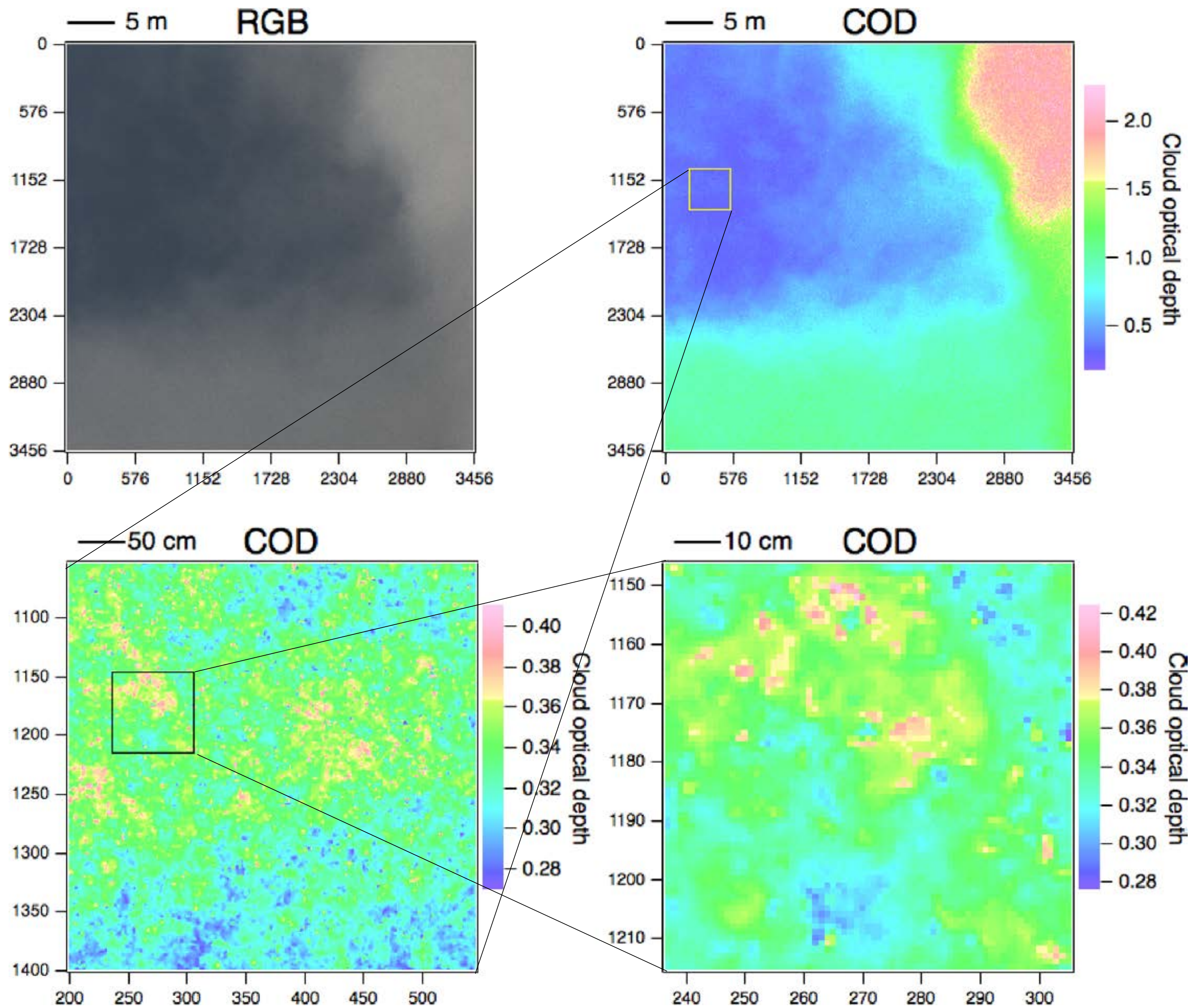
Calibration on Dark and Bright scenes permits ***determination of NZR, COD, Cloud albedo at native resolution of images.***

Concerns:

Aerosol contribution to nominal "Rayleigh" signal.

Dependence on assumptions in RT calculations such as 1-D plane parallel; cloud drop asymmetry parameter.

ZOOMING IN



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 $\lesssim 3$ (but we see a path forward).

Lots of data!

SUMMARY

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

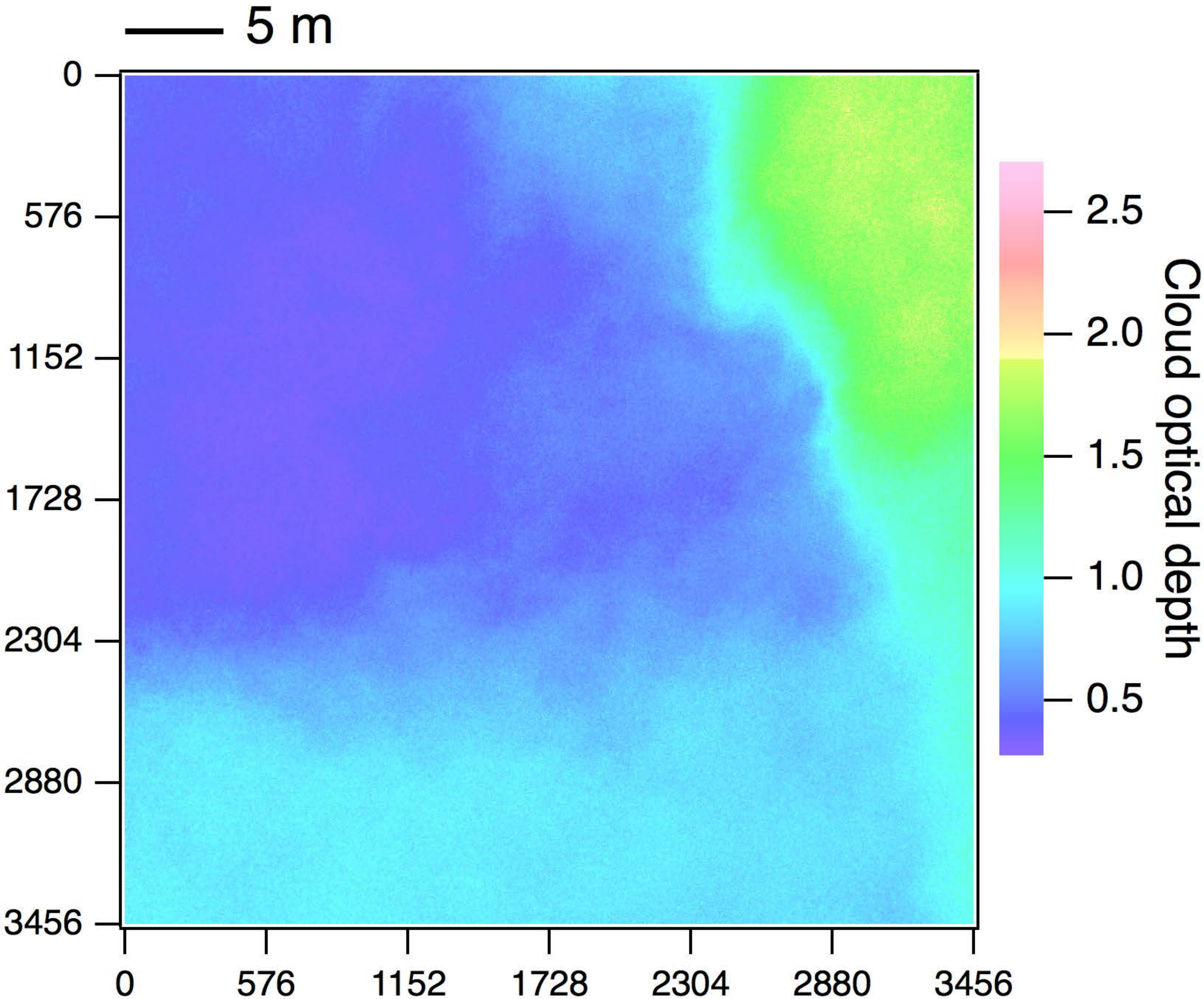
Resolution is 3 to 5 orders of magnitude higher than existing approaches.

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.

STEVE'S VIEW OF A CLOUD



SOME CONTEXT

These are thin clouds.

Liquid water path: $L = (2/3) r_e \tau$

τ = optical depth; r_e = effective radius

For $\tau = 1$ and $r_e = 6$ μm, $L = 4$ μm ⇔ 4 g m^{-2}.

Compare typical precipitable water, 2 cm.

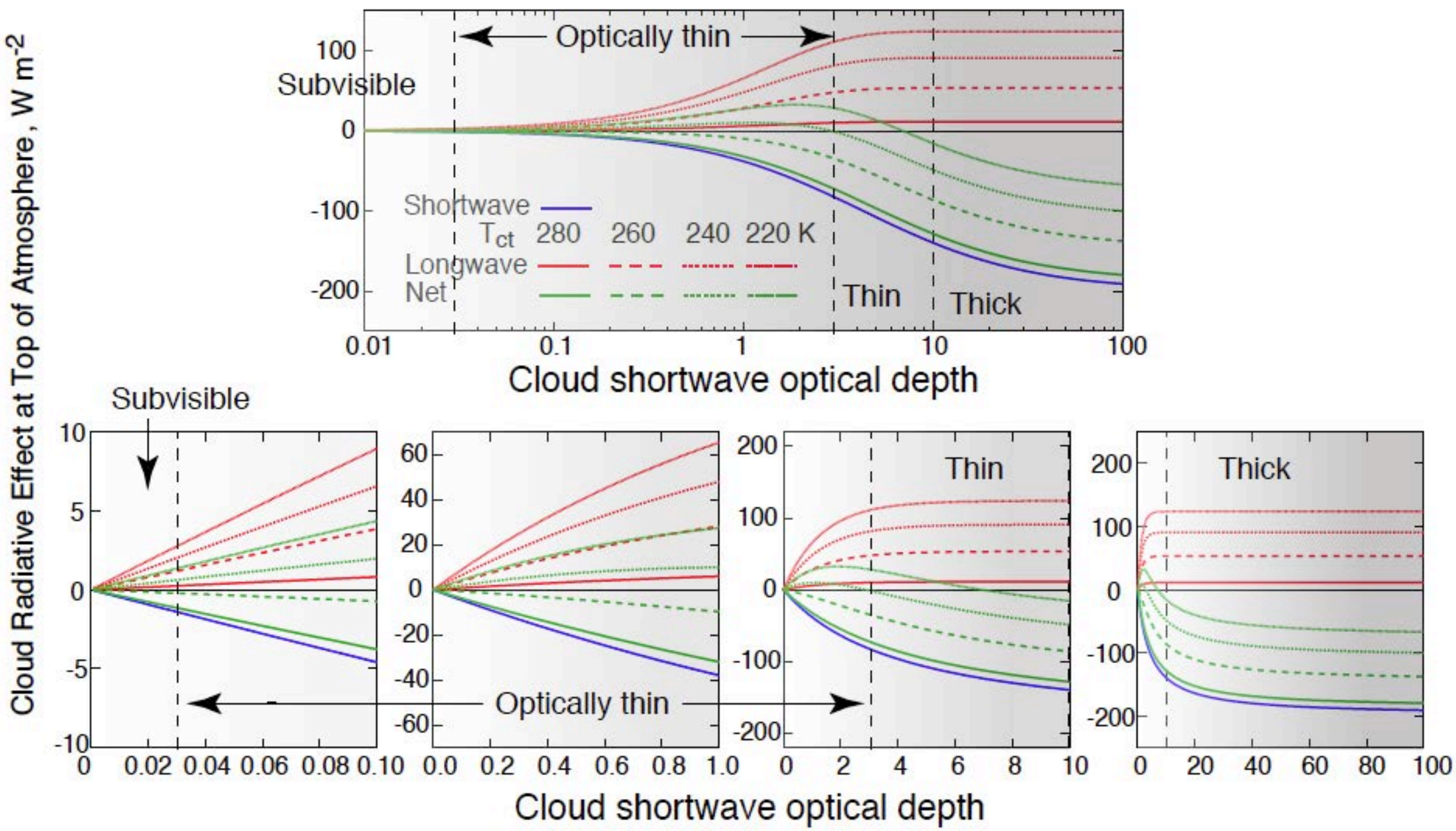
Compare Turner CLOWD, 100 g m^{-2}.

Hard (impossible) to measure by radar, microwave.

These are thin clouds indeed!

FURTHER CONTEXT

24-Hour average cloud radiative effect at equinox At midlatitude site



Optically thin clouds are radiatively very important!

ADDENDUM

CLOUD FRACTION

Cloud fraction is conventionally defined as the ***fraction of a given area that is covered by cloud***.

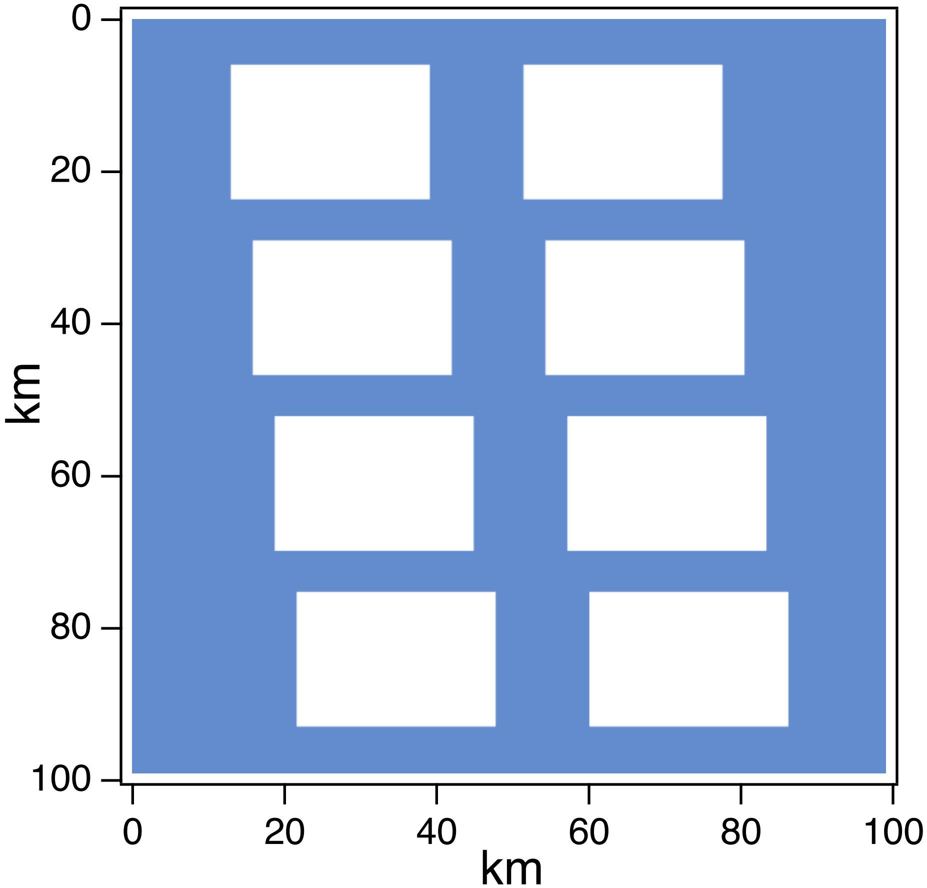
This definition inherently requires a threshold and a criterion:

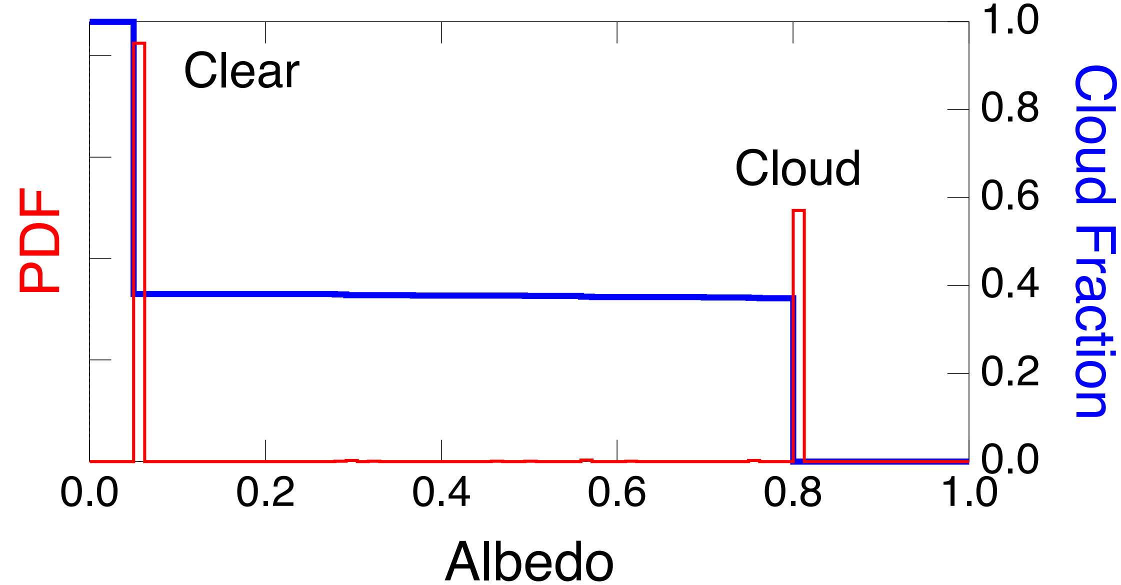
> Is the threshold exceeded ***on average*** in a pixel, or ***anywhere*** in the pixel?

Areal cloud fraction is ***inherently dependent on threshold, resolution, and criterion***.

CLIMATE MODELER'S VIEW OF CLOUDS

Plan View

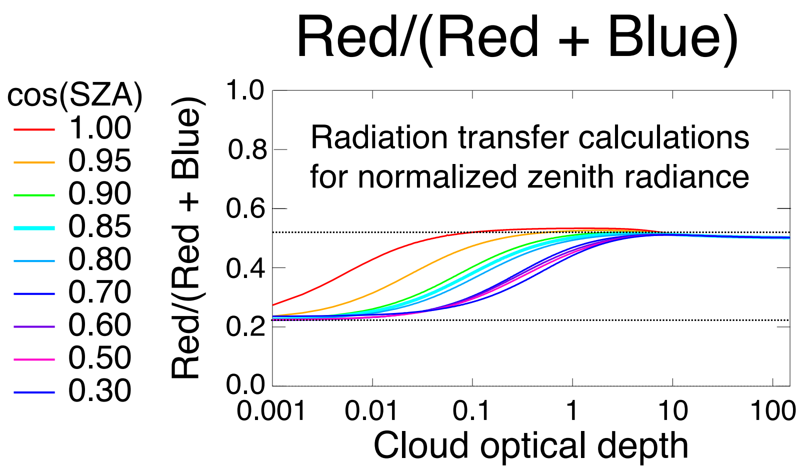


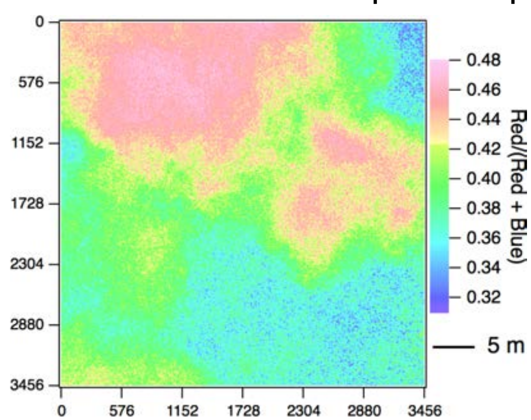


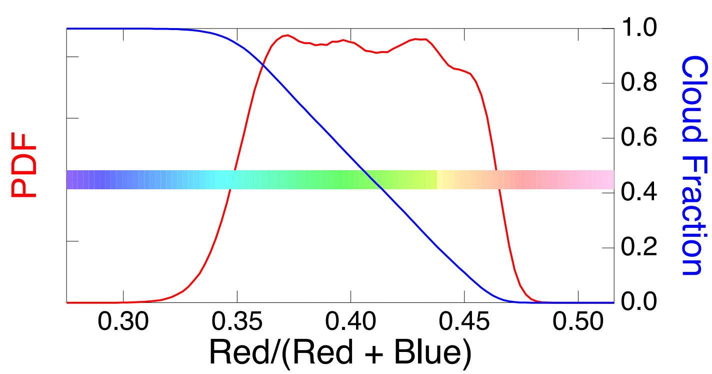
Clouds are represented as rectangular parallelepipeds within grid cells.
A fraction f of grid cell is filled with clouds.
Cloud and clear regions are clearly distinguished.
Cloud region has high albedo; clear region has low albedo.
Scene albedo is weighted average: $A = fA_{cld} + (1-f)A_{clr}$

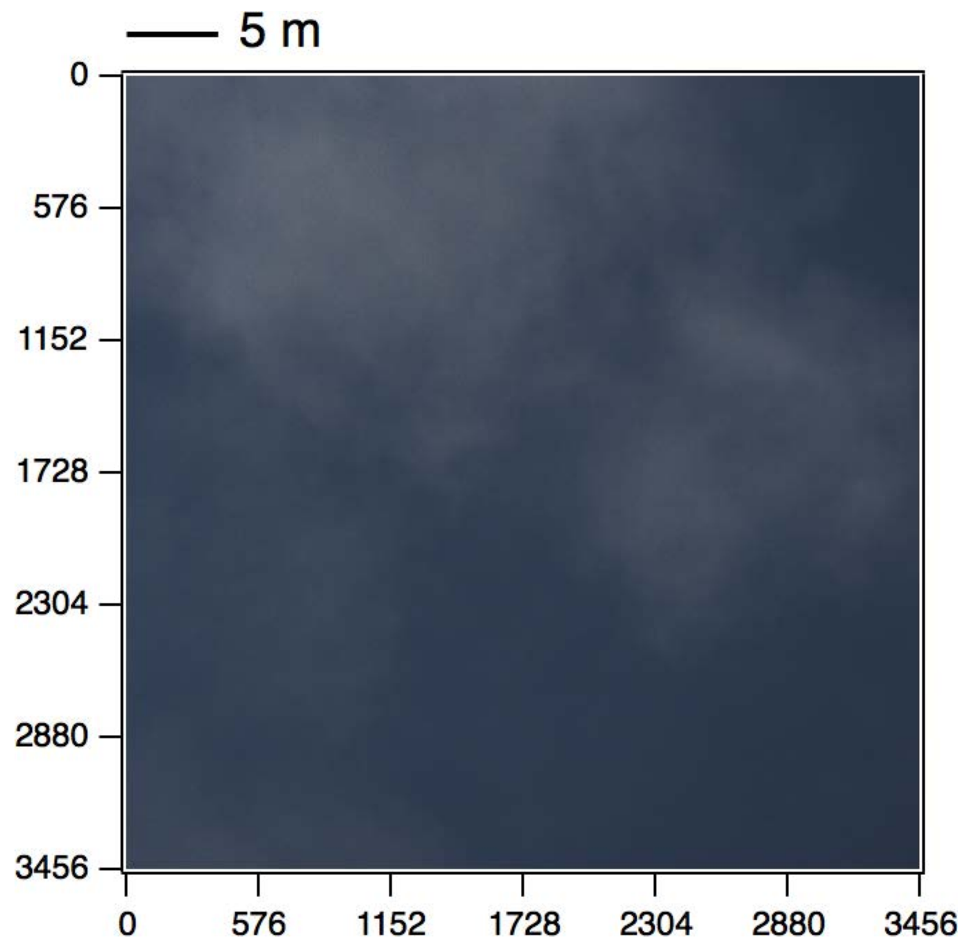
RED/(RED + BLUE)

A widely used discriminant to distinguish cloud-free and cloudy sky









For this cloud, and quite commonly, there is no unique break point.

RADIATIVE CLOUD FRACTION

A local intensive measure of cloud contribution to zenith radiance, scaled from 0 to 1

Red/(Red + Blue) → Radiative cloud fraction