Retrieval of Images of Optical Depth of Thin Clouds At Centimeter Scales By High-Resolution Photography from the Surface

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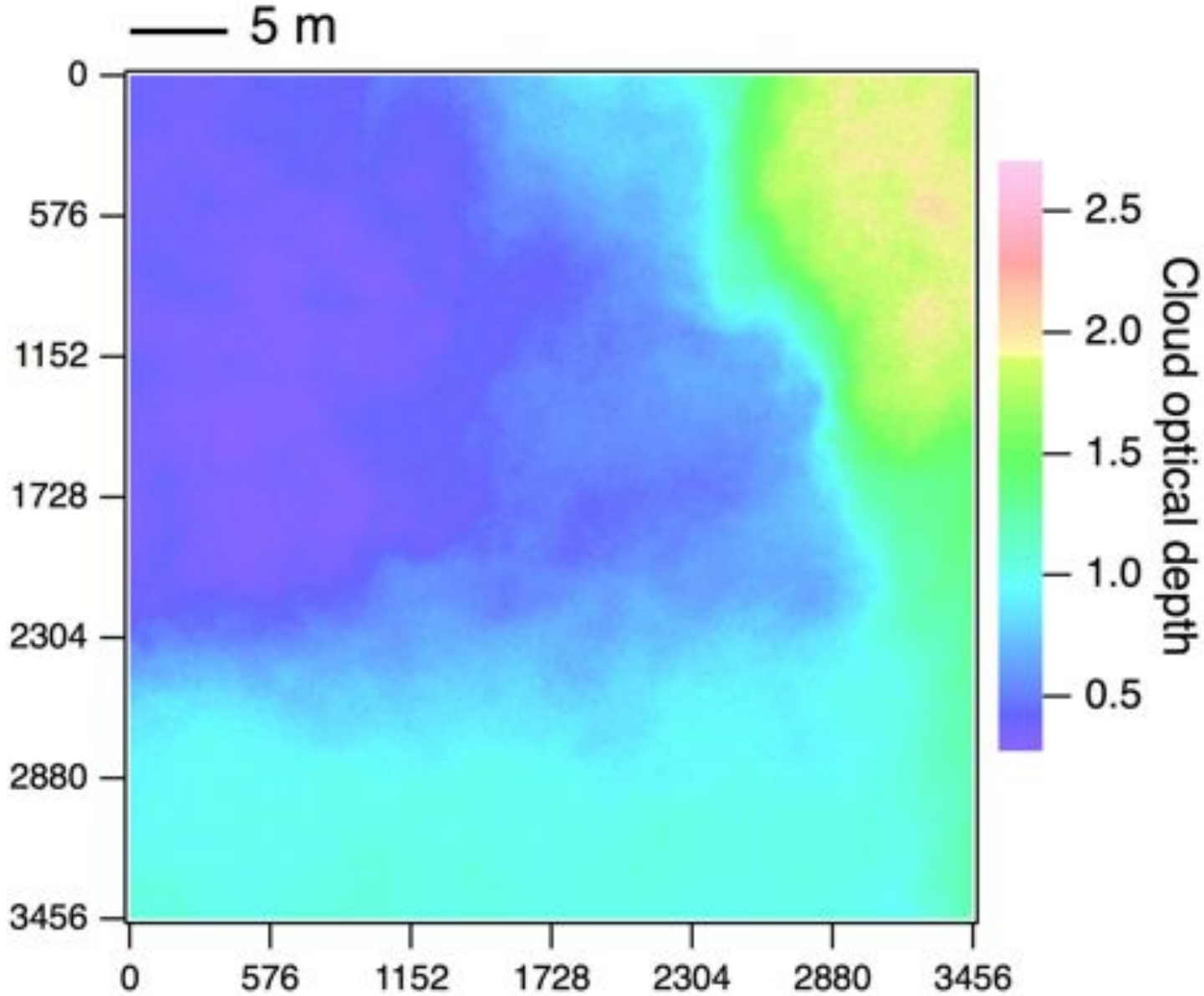
September 15, 2016

www.ecd.bnl.gov/steve

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 FRACTION: CAN IT BE DEFINED, CAN IT BE MEASURED, AND IF WE KNEW IT WOULD IT BE OF ANY USE TO US ANYWAY?

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WHAT IS A CLOUD?

AMS Glossary of Meteorology (2000)

A ***visible aggregate*** of minute water droplets and/or ice particles in the atmosphere above the earth's surface.

Total cloud cover: Fraction of the sky hidden by all ***visible clouds***.

Ramanathan, JGR (ERBE, 1988)

Cloud cover is a ***loosely defined term***.

Koren and Joseph, 2000

The definition of a pixel as cloudy is problem dependent.

Clothiaux, Barker, & Korolev (2005)

Surprisingly, and in spite of the fact that we deal with clouds on a daily basis, to date there is ***no universal definition of a cloud***. . . . Ultimately, the definition of a cloud ***depends on the threshold sensitivity*** of the instruments used.

Potter Stewart (U.S. Supreme Court, 1964)

I shall not today attempt further to define it, but ***I know it when I see it***.

DOE/ER/60085-H1
NCAR/TN-273 + STR
NCAR Technical Notes

Prepared for:
United States Department of Energy

Office of Energy Research
Office of Basic Energy Sciences
Carbon Dioxide Research Division

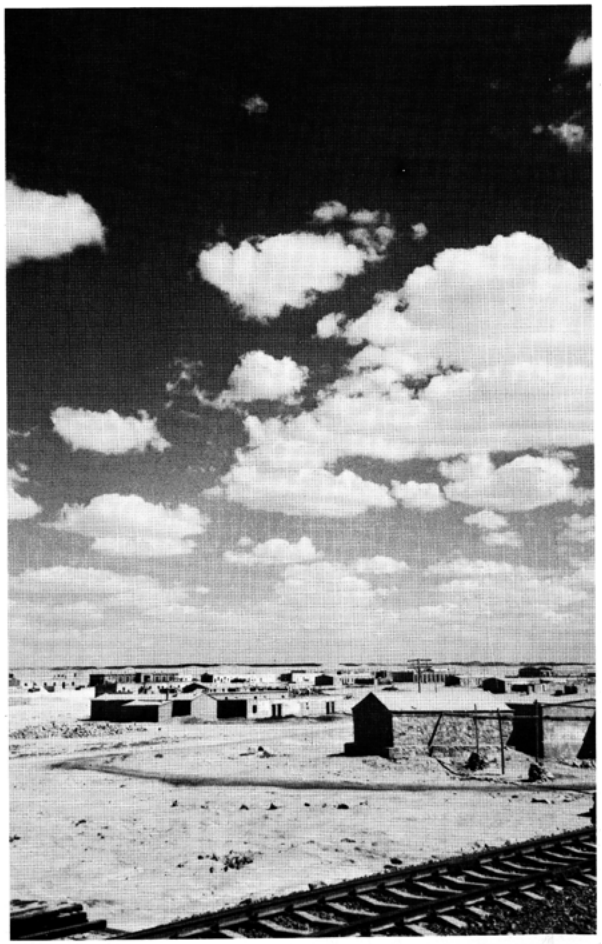
and

National Center for Atmospheric Research
Boulder, Colorado 80307

October 1986

Global Distribution of Total Cloud Cover and Cloud Type Amounts Over Land

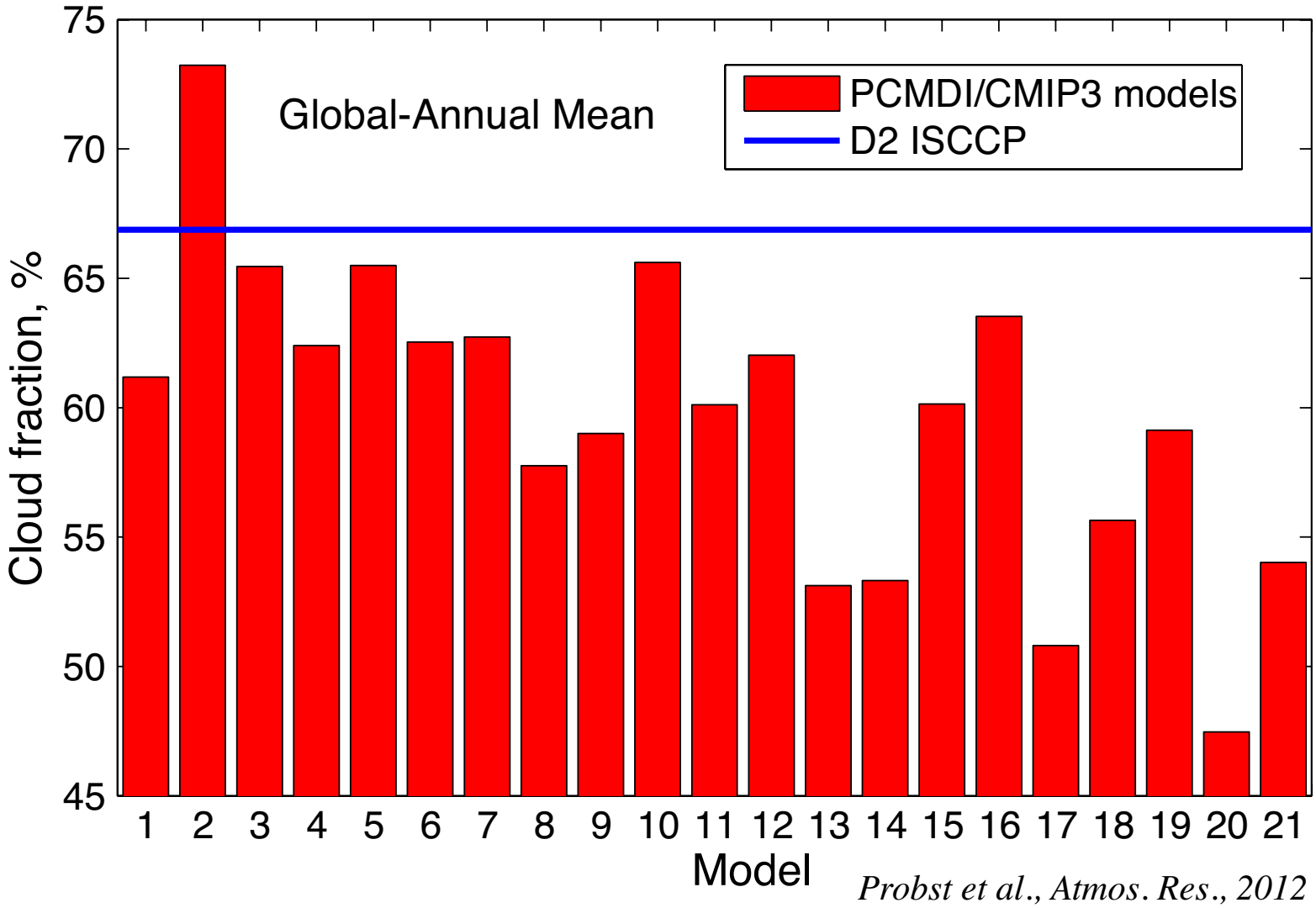
Domain	Observations Millions	Cloud cover %
Land	116	52.4
Ocean	43.3	64.8
Global	159	61.2



Warren, Hahn, London, Chervin, Jenne

GLOBAL CLOUD FRACTION

Comparison of climate models and ISSCP observations

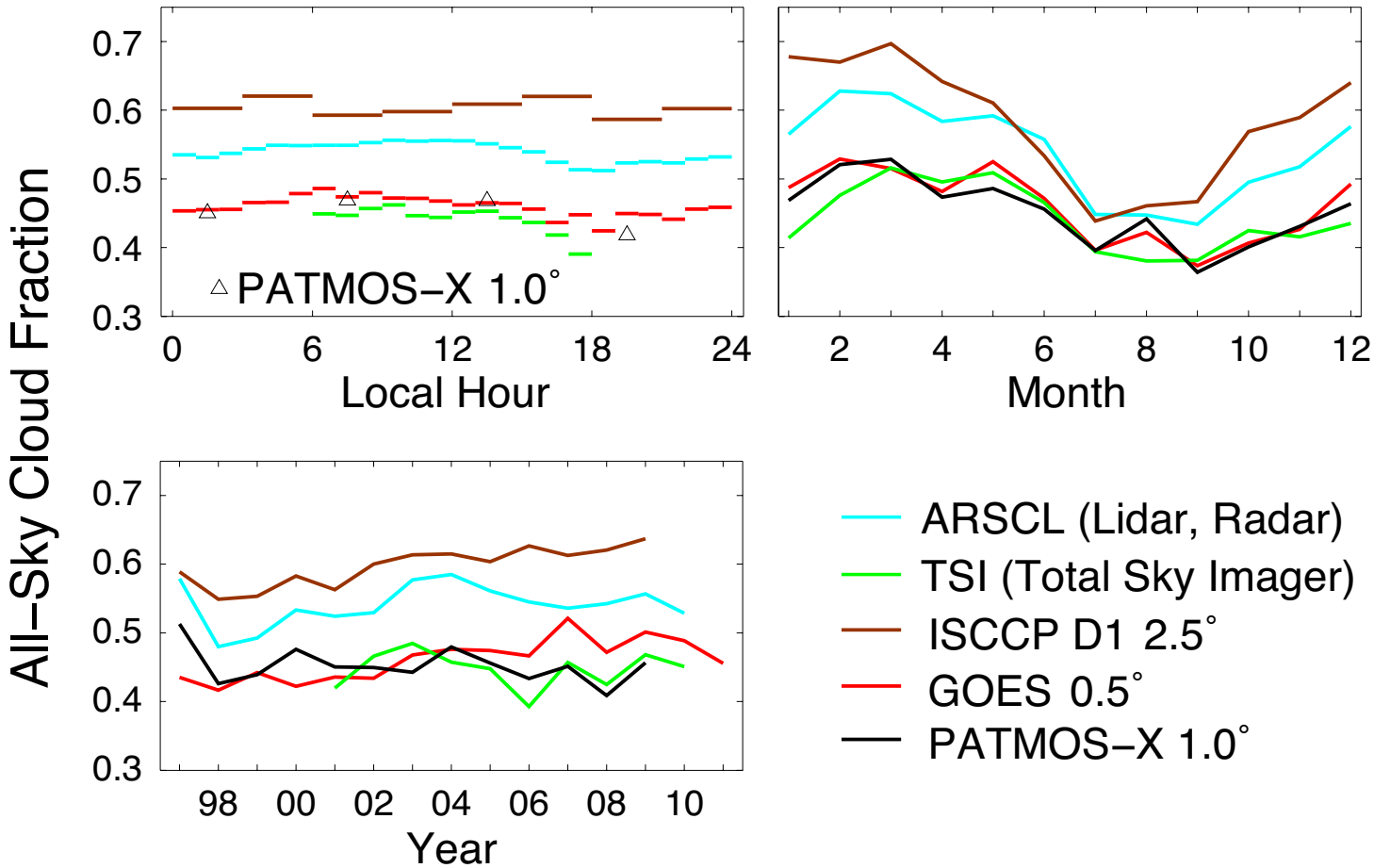


Probst et al., Atmos. Res., 2012

Most climate models exhibit low cloud fraction and compensate with high cloud albedo.

CLOUD FRACTION BY MULTIPLE METHODS

2 Surface, 3 satellite methods at U.S. Southern Great Plains; 10 years data

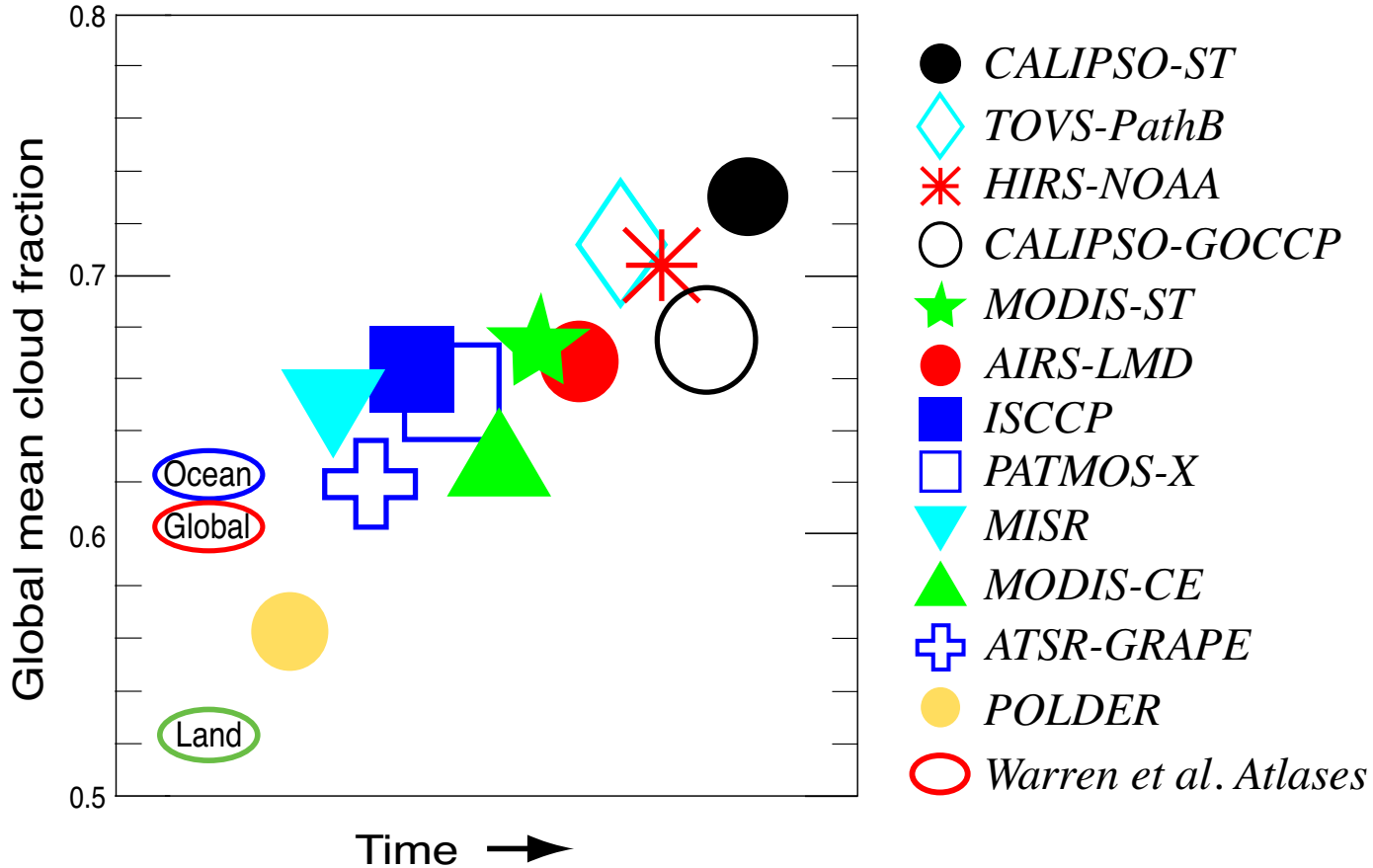


Modified from Wu, Liu, Jensen, Toto, Foster & Long, JGR, 2014

Different methods yield ***substantial systematic differences in the mean***.

Error of 0.1 in cloud fraction is ~ 7 W m^{-2} in shortwave, 4 W m^{-2} in longwave.

MEASUREMENTS OF GLOBAL CLOUD FRACTION



Modified from Stubenrauch, Rossow, ... Ackerman, ... Chepfer, DiGirolamo, ... Winker et al., BAMS, 2013

- For clouds with optical depth > 0.1 global cloud fraction is about 68%.
- Cloud fraction increases to 73% when including subvisible cirrus with optical depth down to 0.01 (e.g. CALIPSO) and decreases to about 56% for clouds with optical depth > 2 (e.g. POLDER).
- Key reasons for differences: ***resolution*** and ***threshold***.

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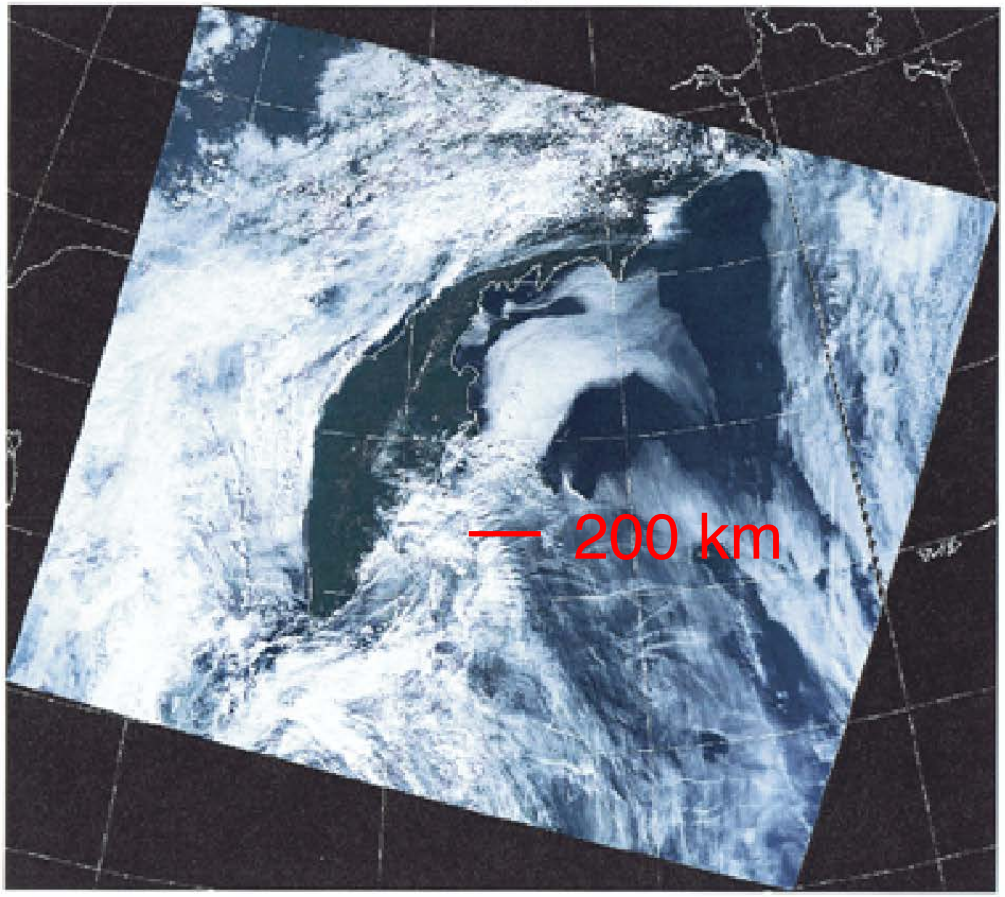
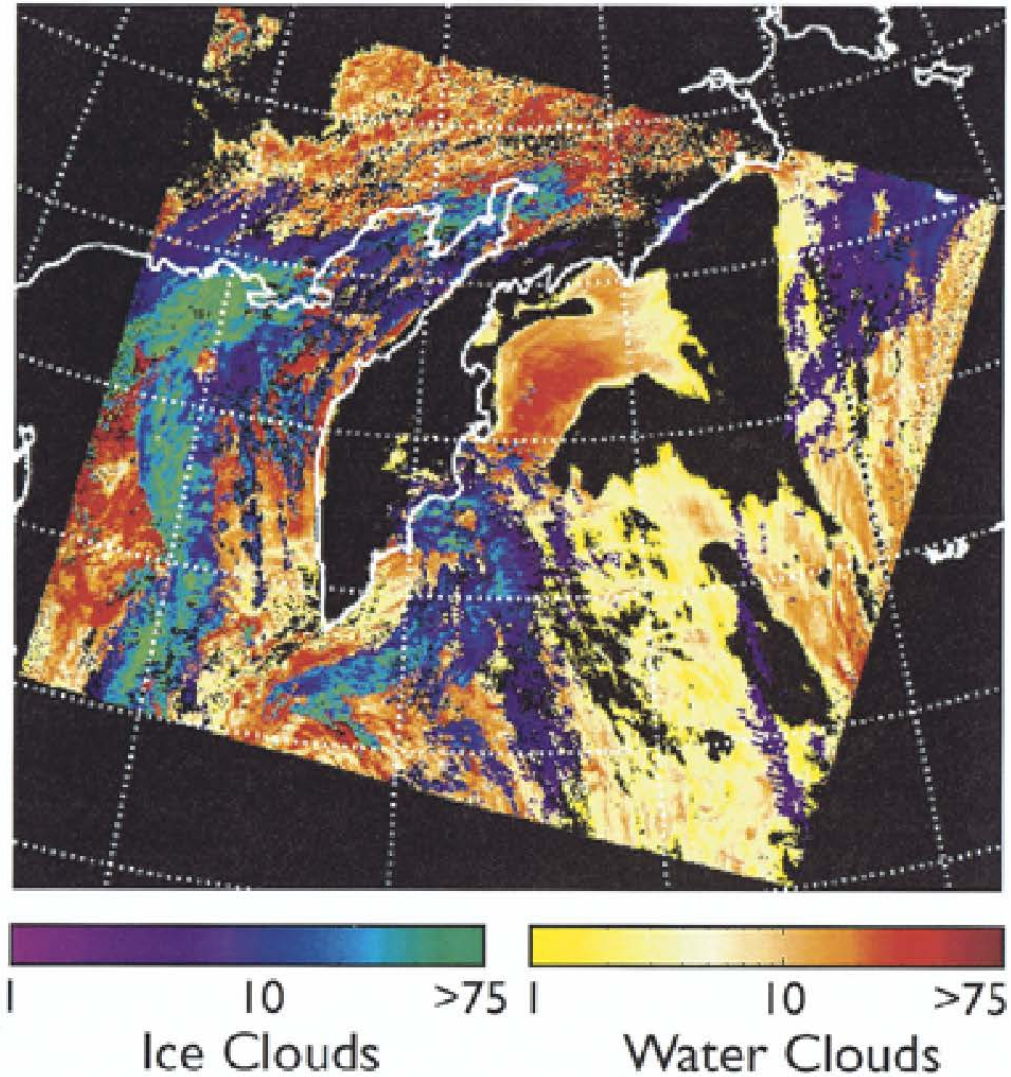
YORAM KAUFMAN'S VIEW OF CLOUDS

R G B

R(0.645, 0.555, 0.469)



Cloud Optical Depth



1 pixel = 250 m

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

σ_{ext} = extinction coefficient

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.

WHAT AN AUDACIOUS CONCEPT!

To put an imager in space. . .

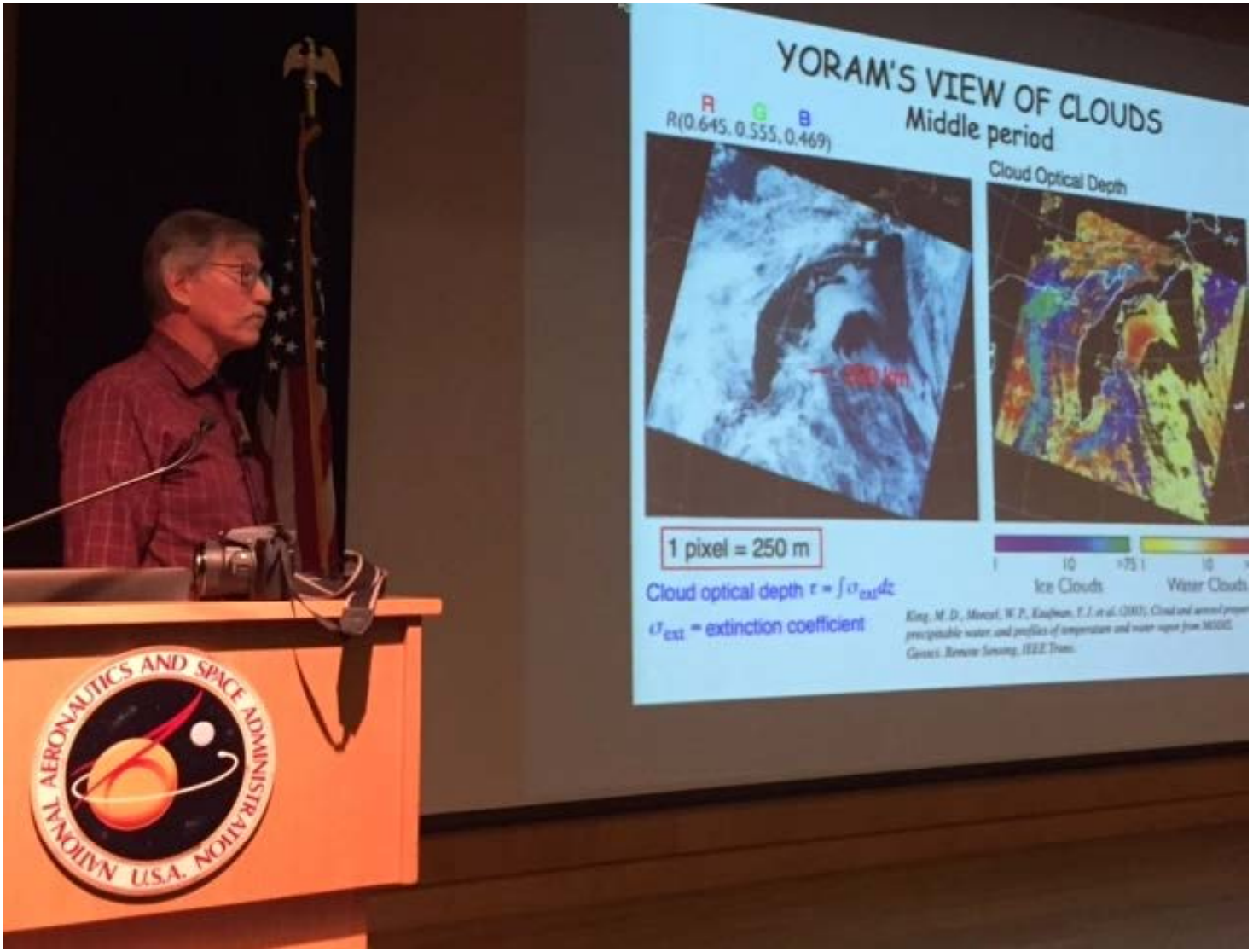
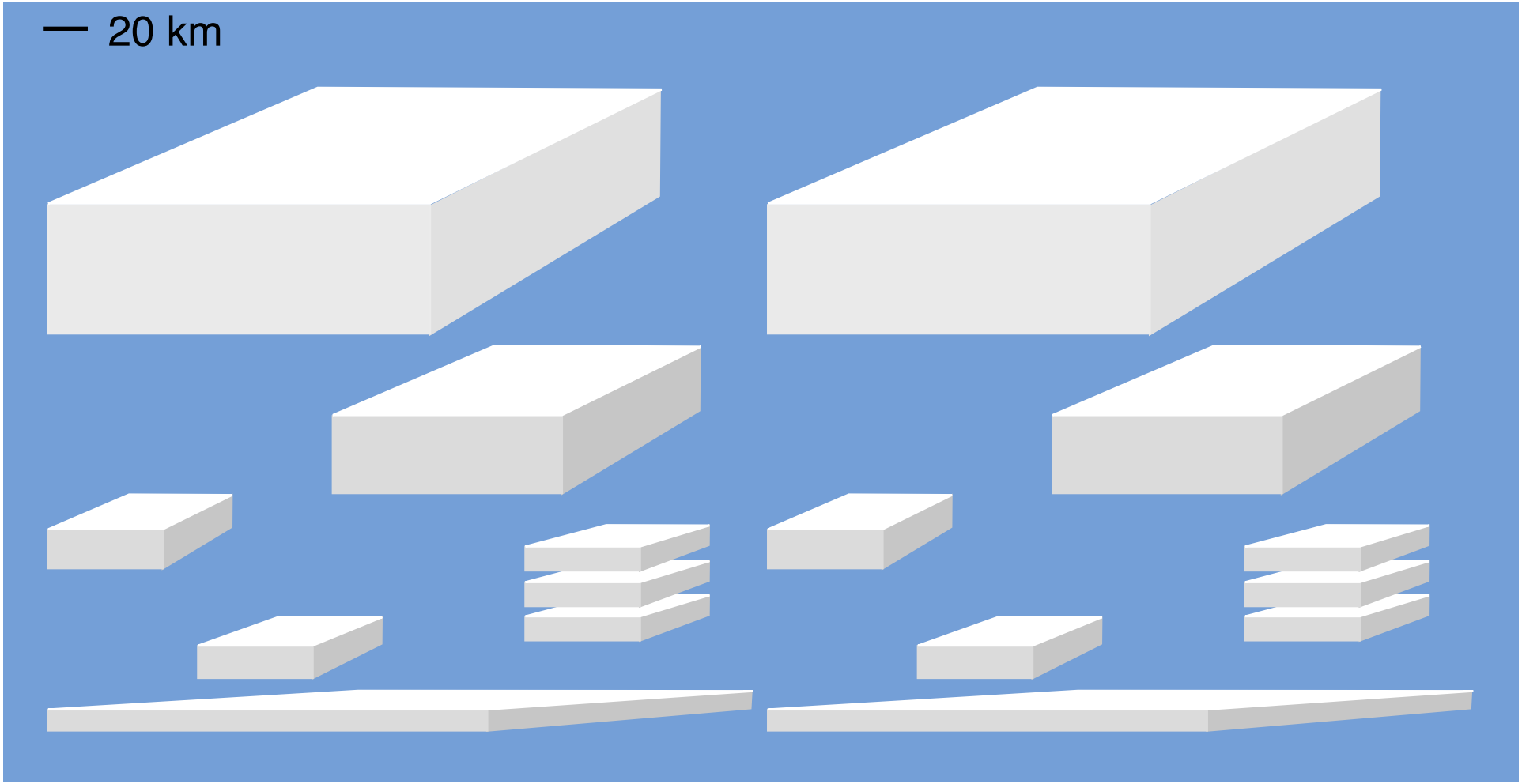


Photo: Rich Kleidman

. . . and invert radiance to obtain cloud optical depth.

A CLIMATE MODELER'S VIEW OF CLOUDS

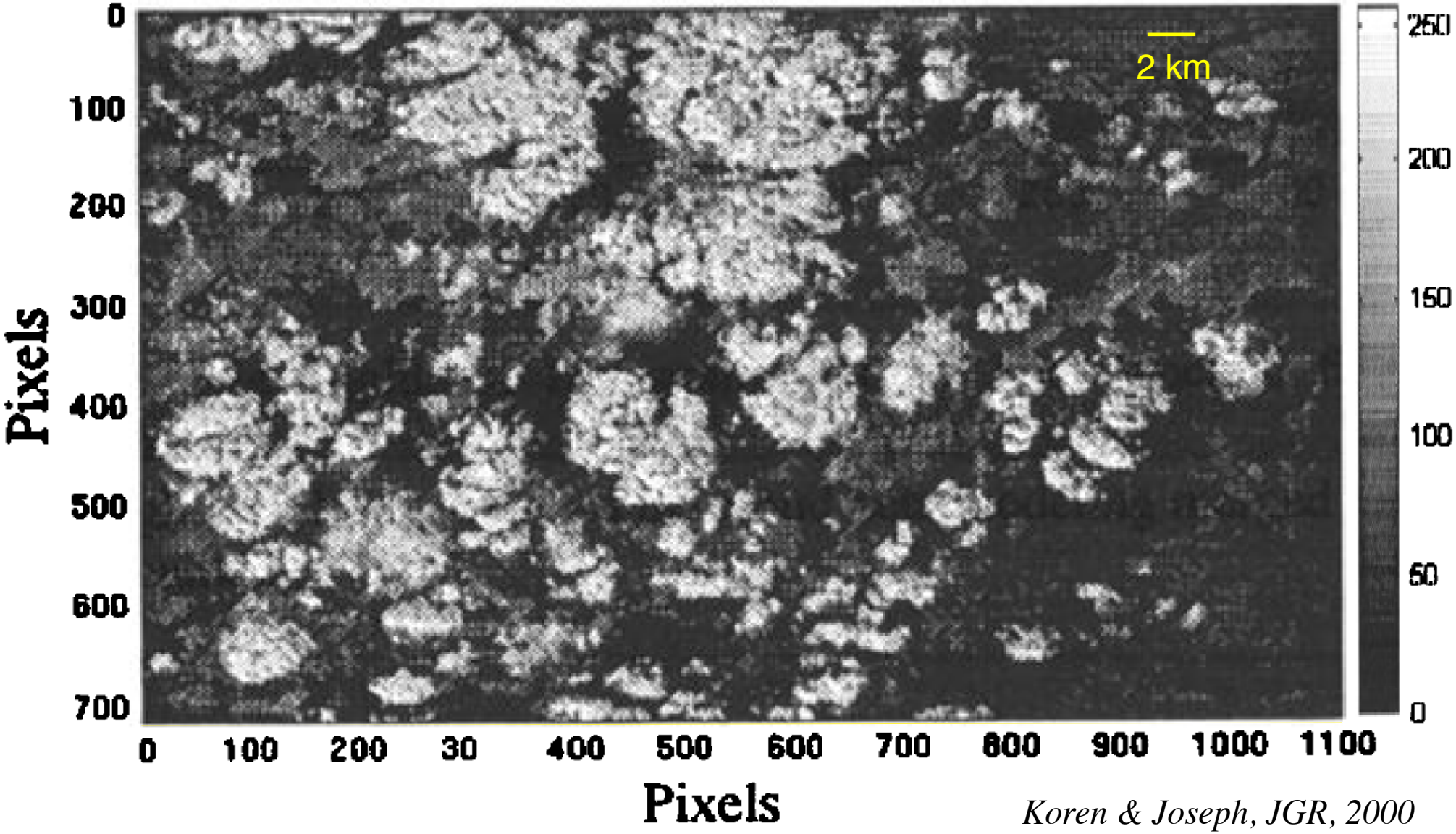


Clouds are represented as rectangular parallelepipeds within grid cells.
A fraction of a grid cell is filled with clouds.
Clouds are stacked with random overlap, or maximum overlap if in adjacent layers.

AN ARTIST'S VIEW OF CLOUDS

Rene Magritte, The Infinite Recognition

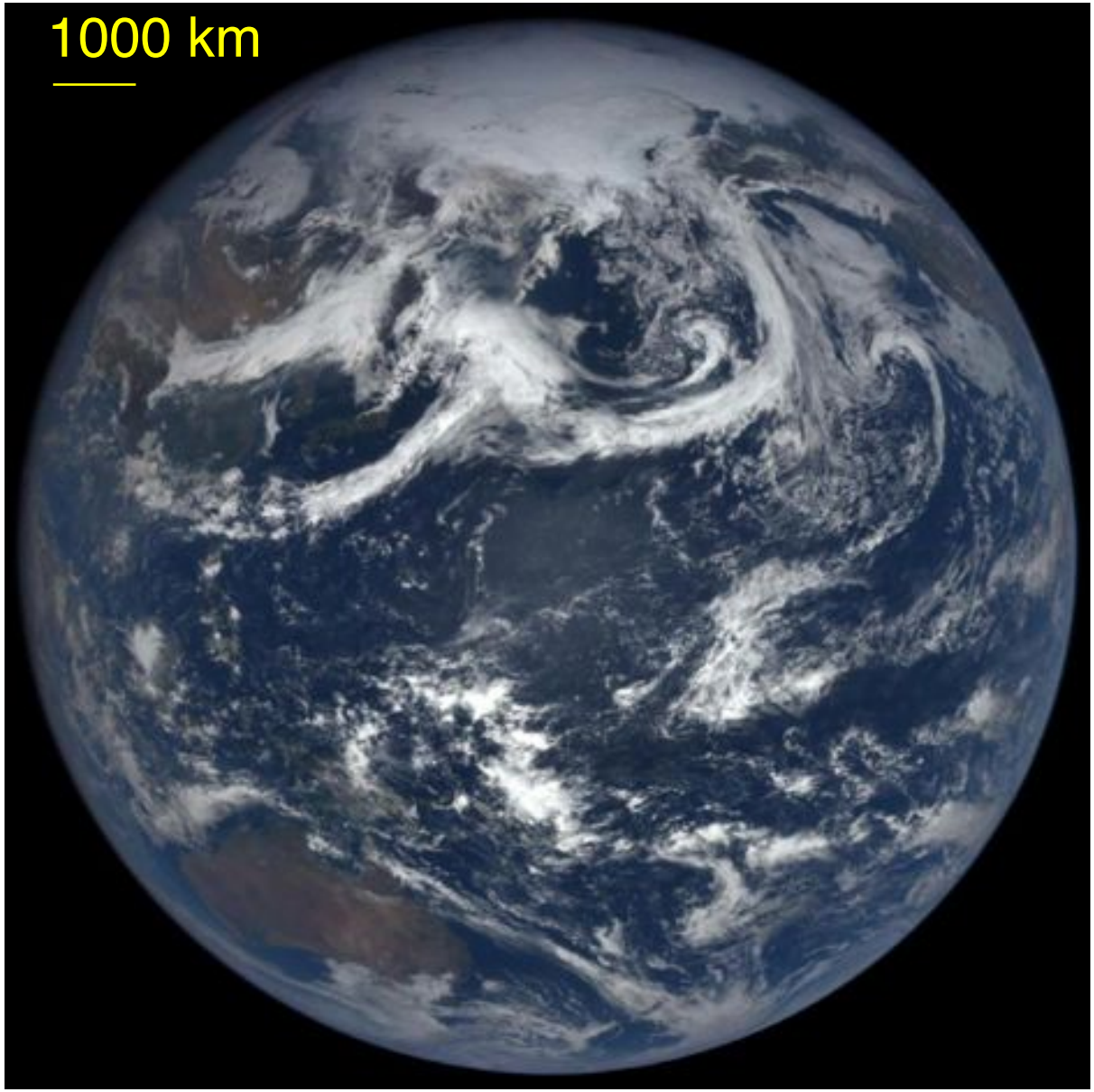
Ilan's View of Clouds (Year 2000)



Koren & Joseph, JGR, 2000

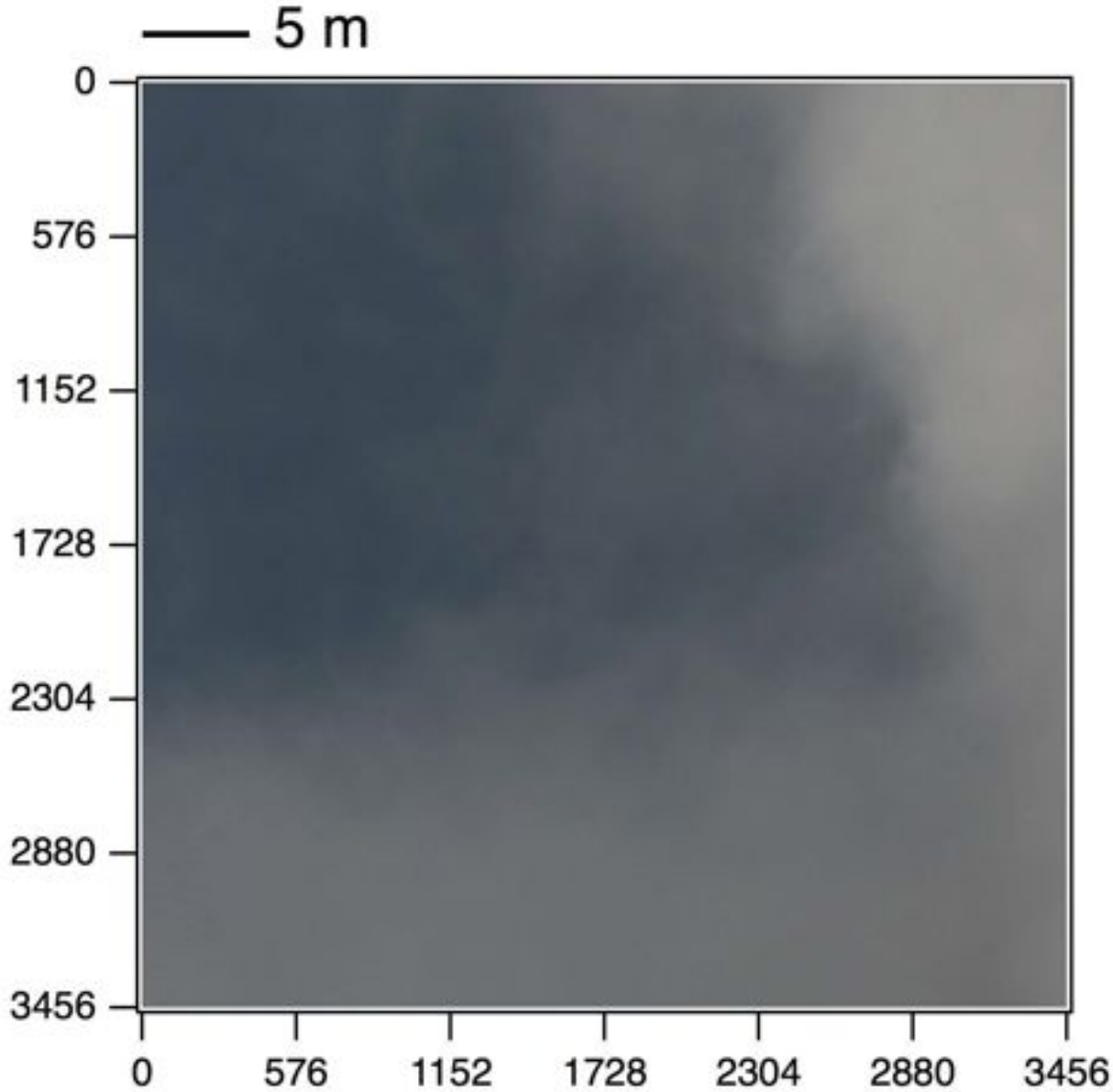
MODIS Airborne Simulator at 20 km. 1 Pixel = 50 m. FOV 55 x 35 km.

DSCOVR-EPIC VIEW OF CLOUDS



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

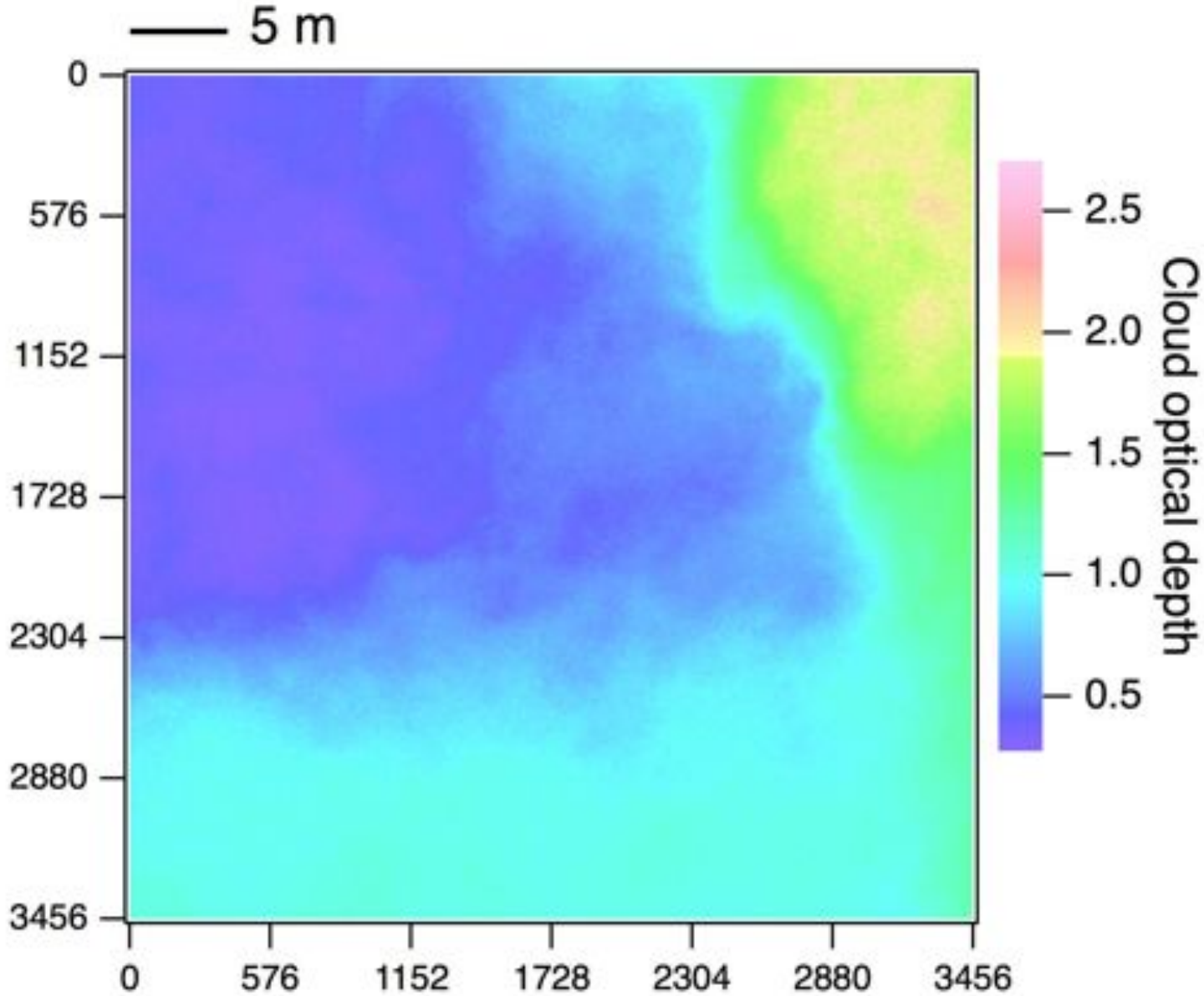
STEVE'S VIEW OF A CLOUD



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



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SOME CONTEXT

These are thin clouds.

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

τ = optical depth; r_e

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

Compare typical precipitable water, 2 cm $\Leftrightarrow$ 2×10^4 g m^{-2}.

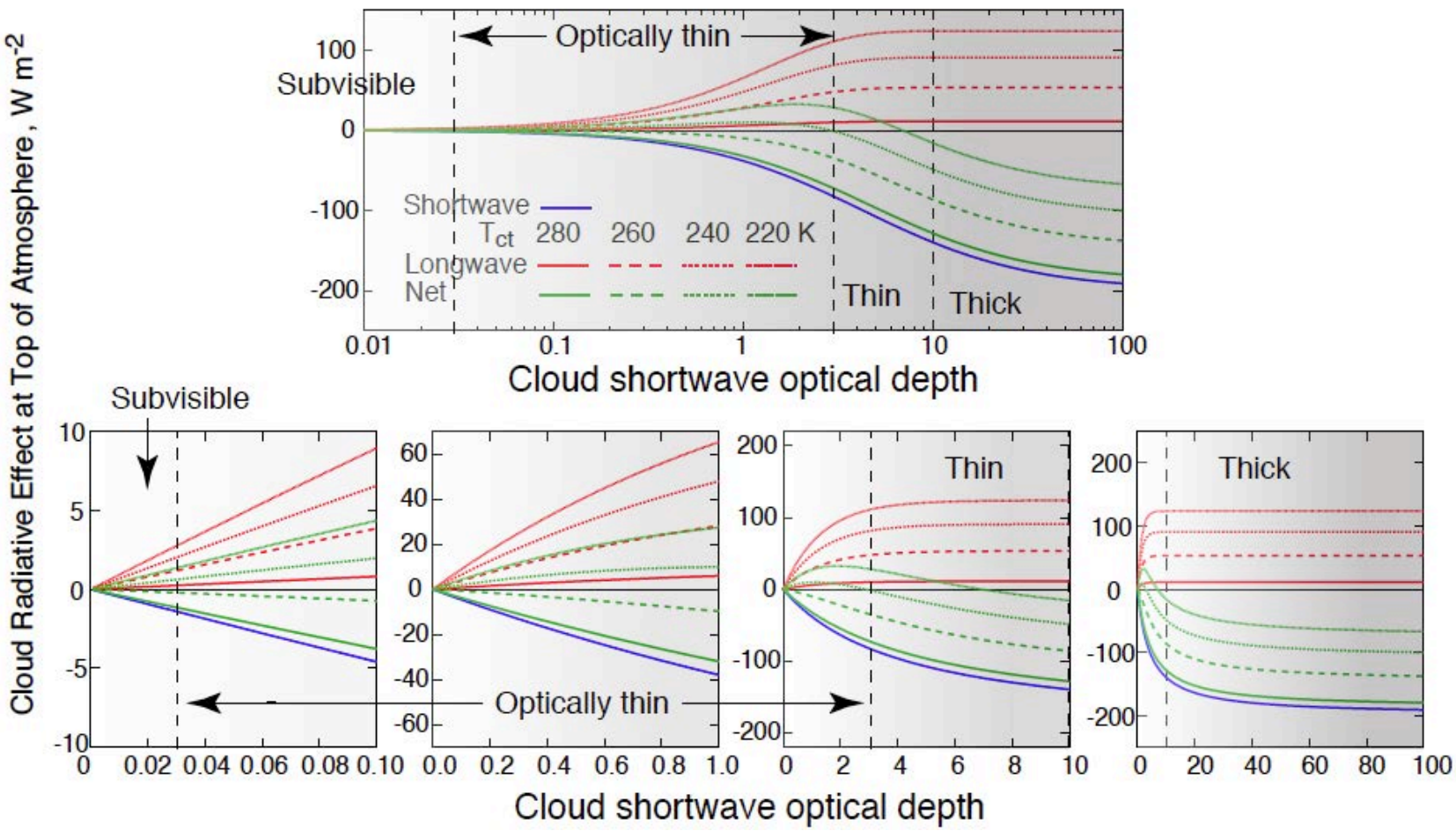
Compare Turner CLOWD (BAMS, 2007), 100 g m^{-2}.

Hard (impossible) to measure by radar, microwave.

These are thin clouds indeed!

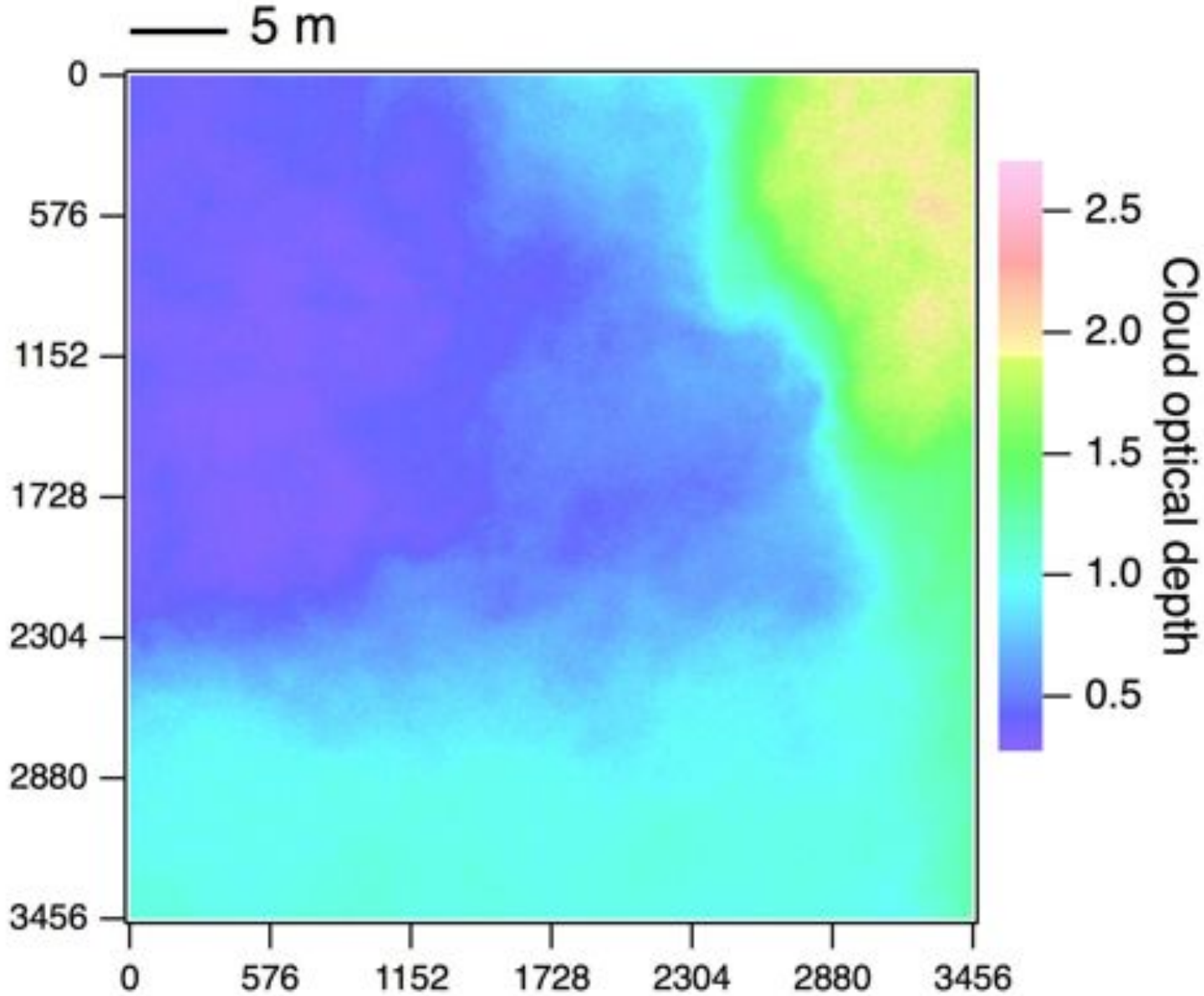
FURTHER CONTEXT

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



Optically thin clouds are radiatively very important!

CLOUD OPTICAL DEPTH



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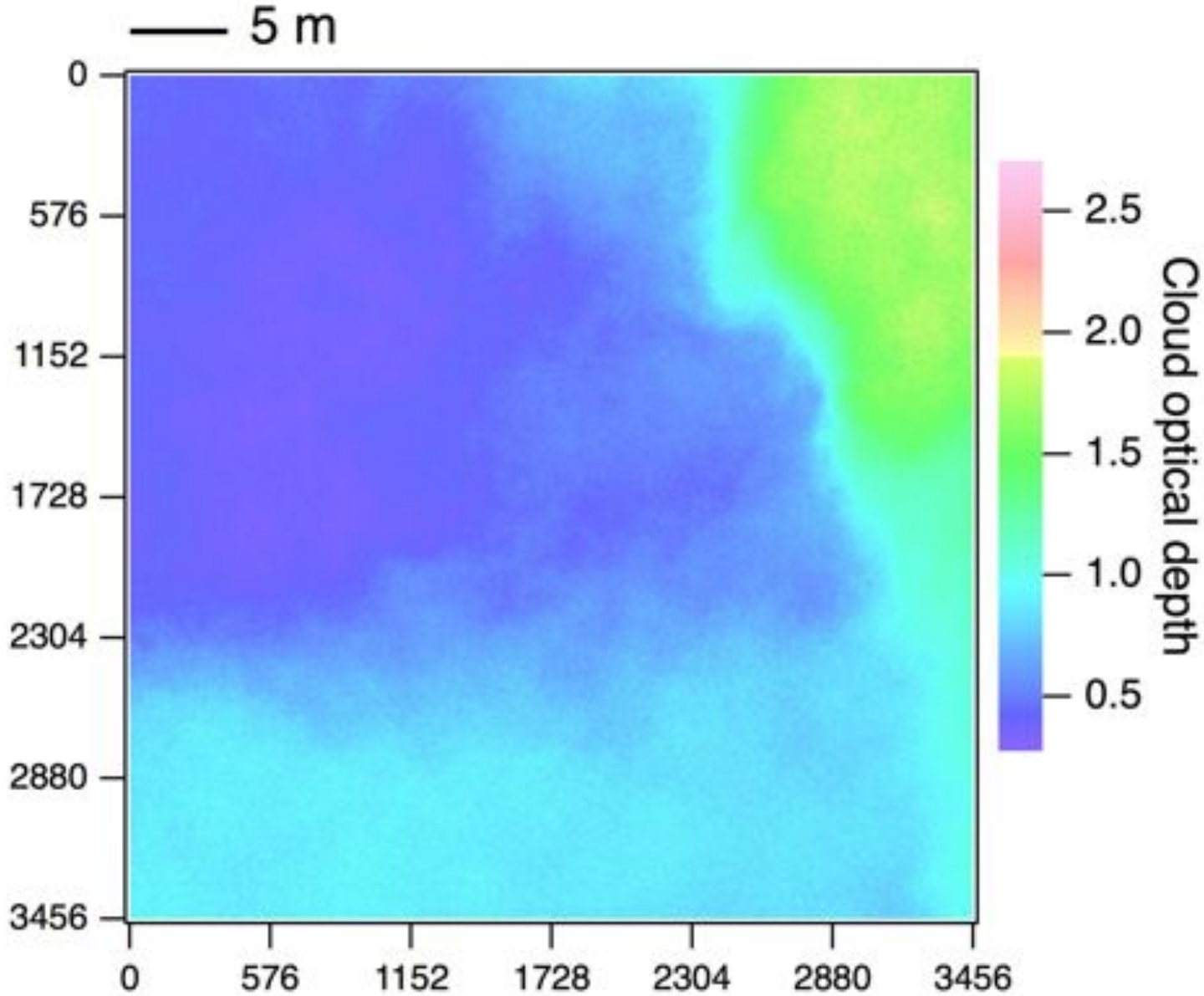
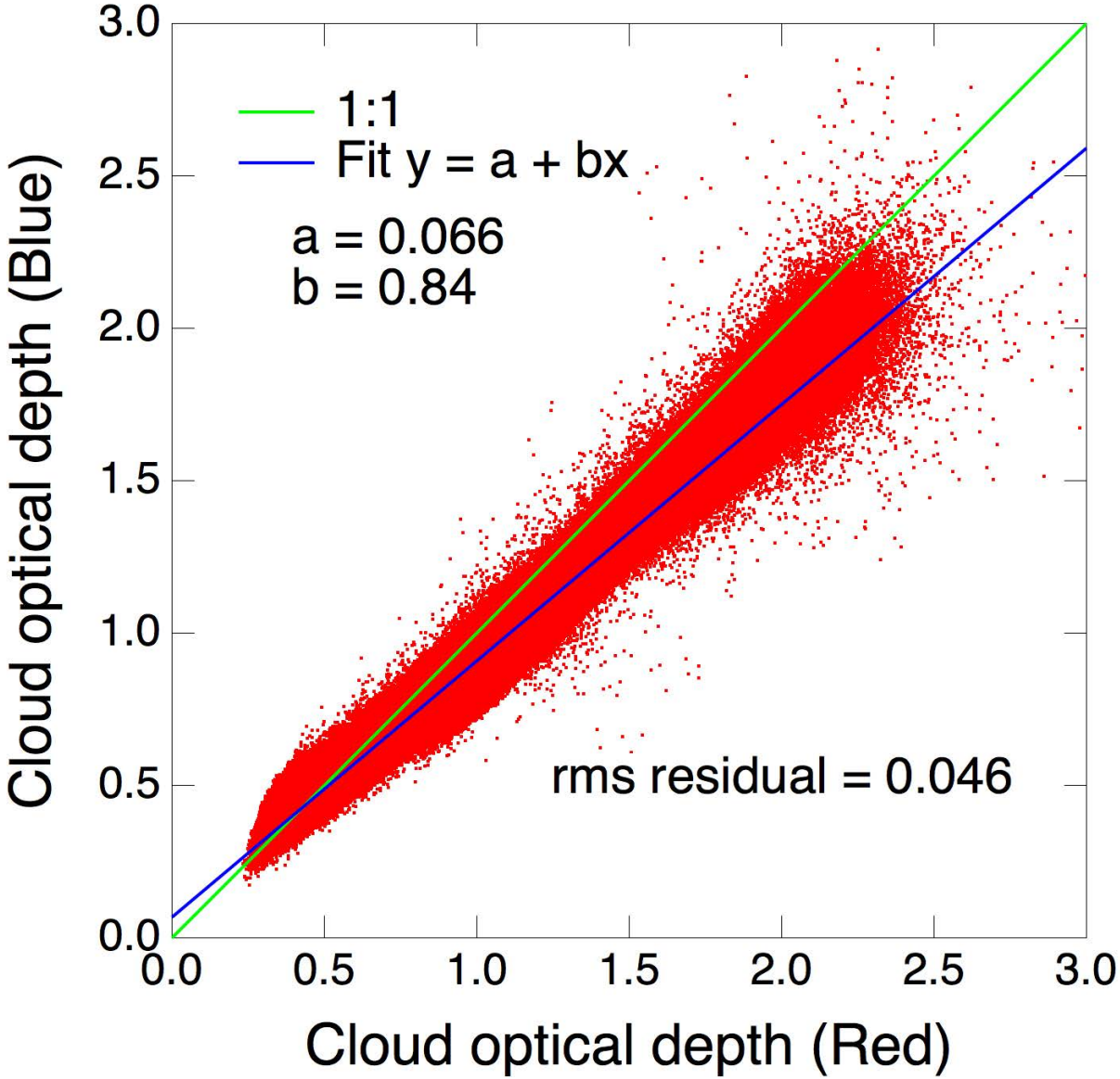
CLOUD OPTICAL DEPTH



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

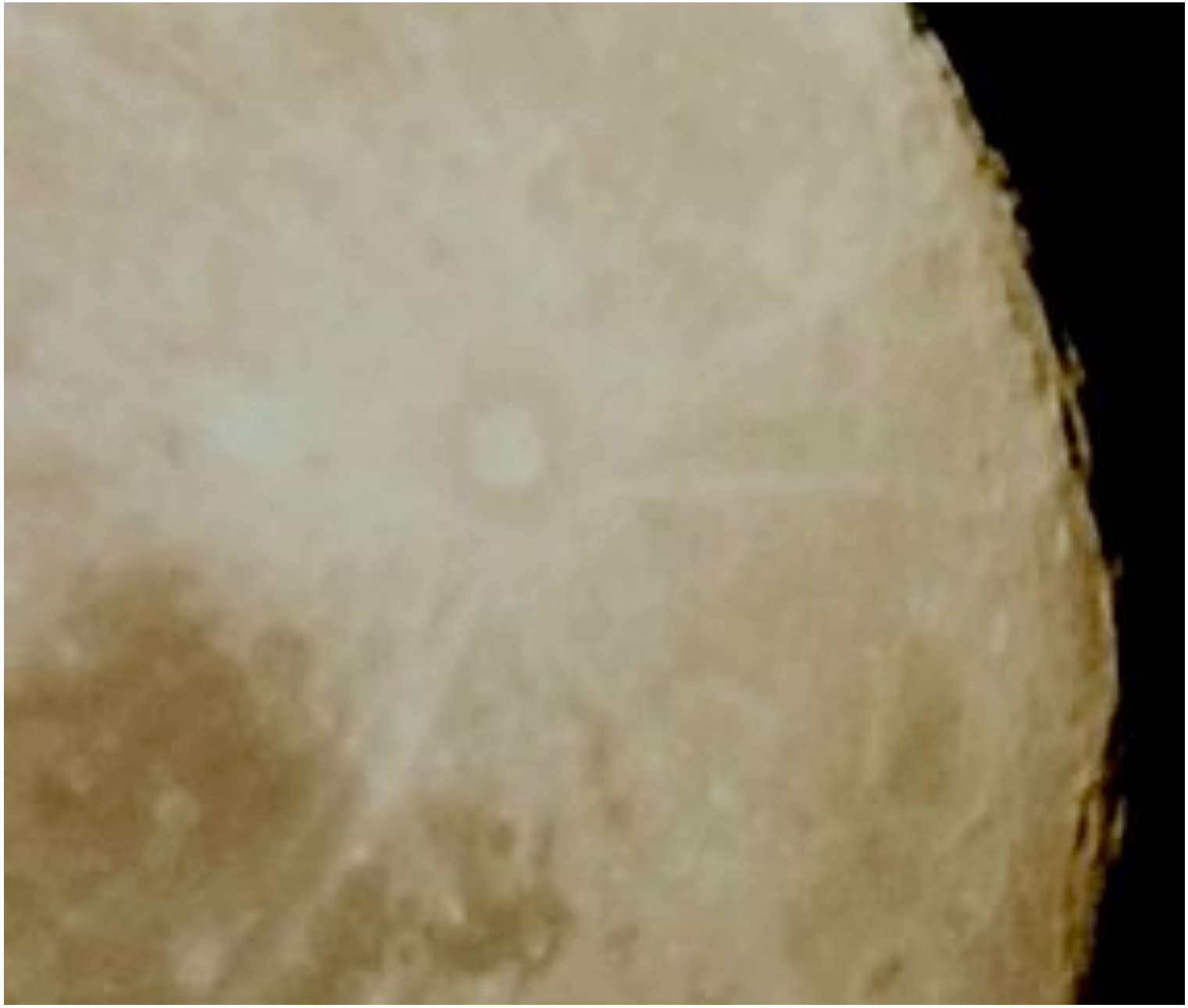
Todd Vorenkamp, B&H Photo, NYC

That's 1.2 meters!

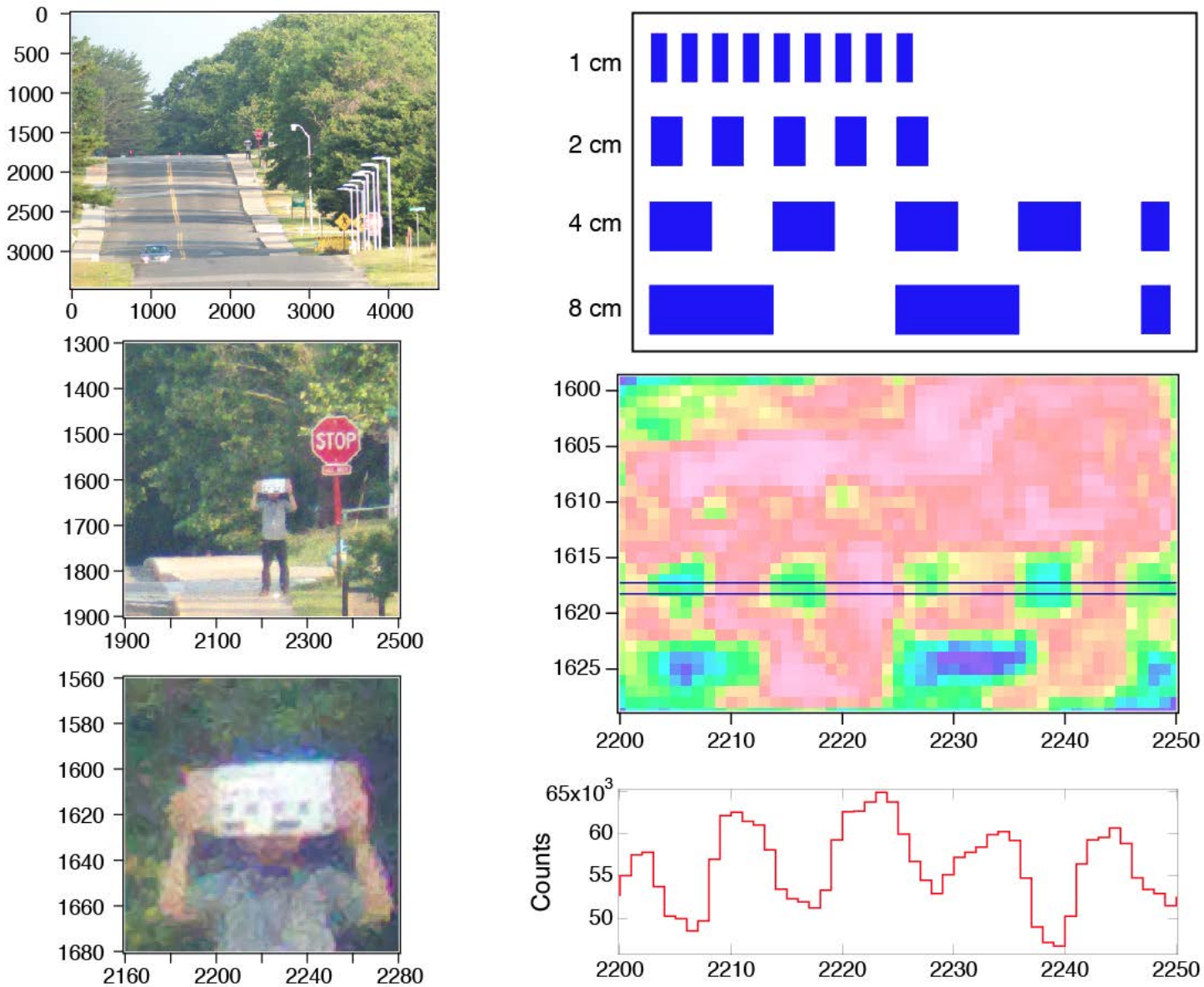
NARROW FIELD OF VIEW

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

HIGH RESOLUTION



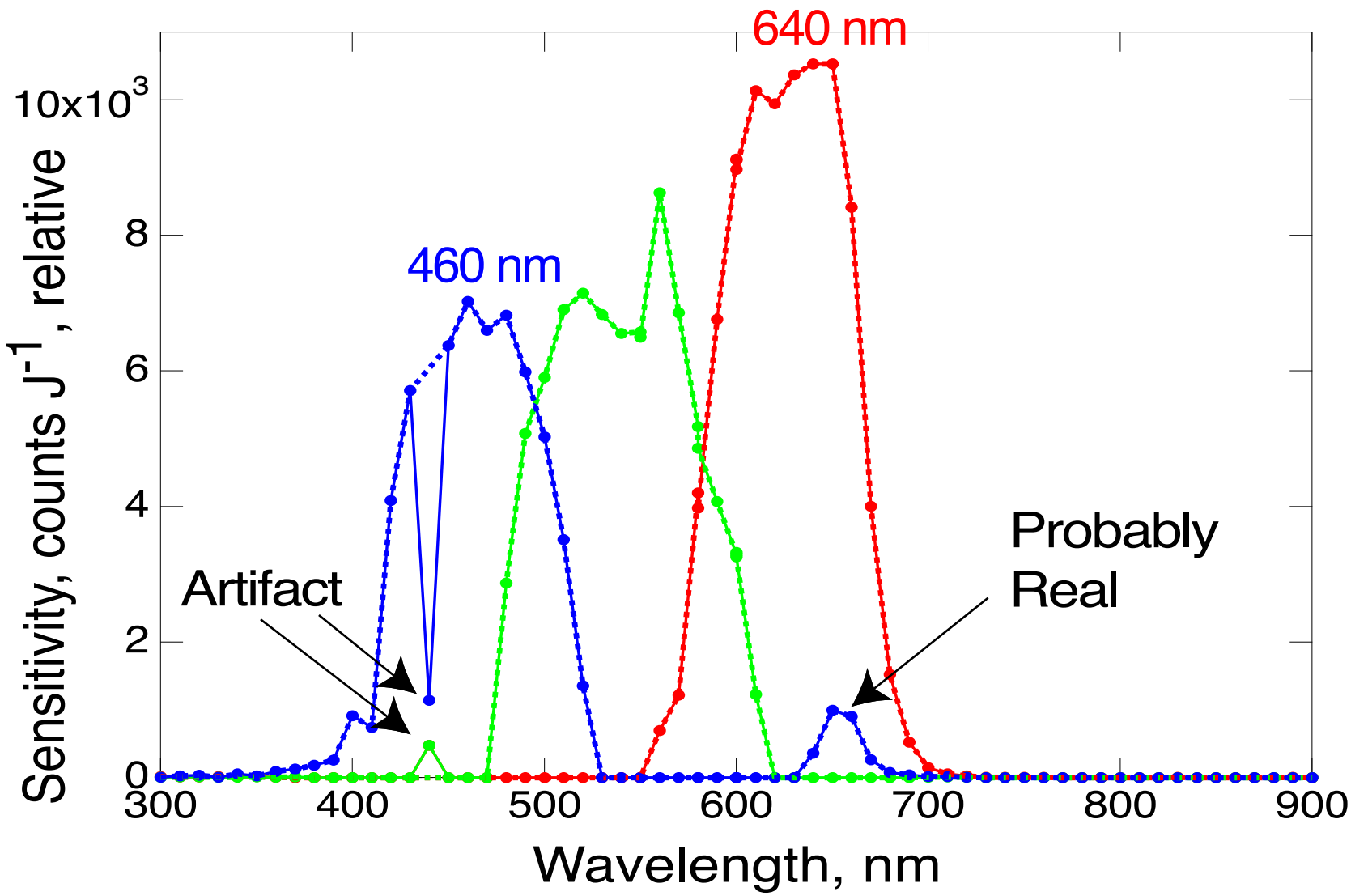
RESOLVING POWER TESTS



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.

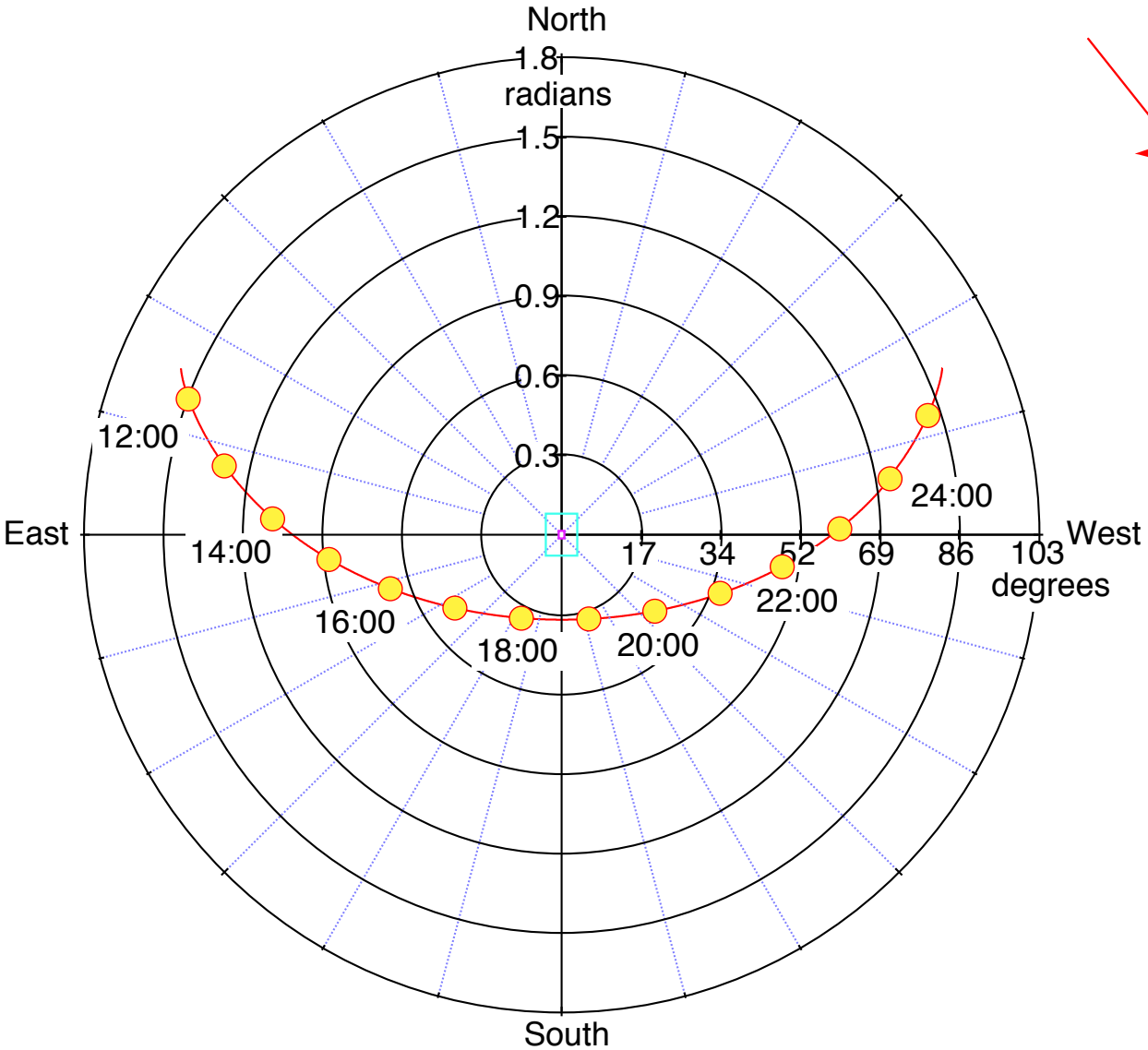
WHAT A GREAT CAMERA!

SHORT RANGE CLOUD VARIABILITY

Moon diameter = 9 mrad.

DEPLOYMENT OF CAMERAS AT SGP

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

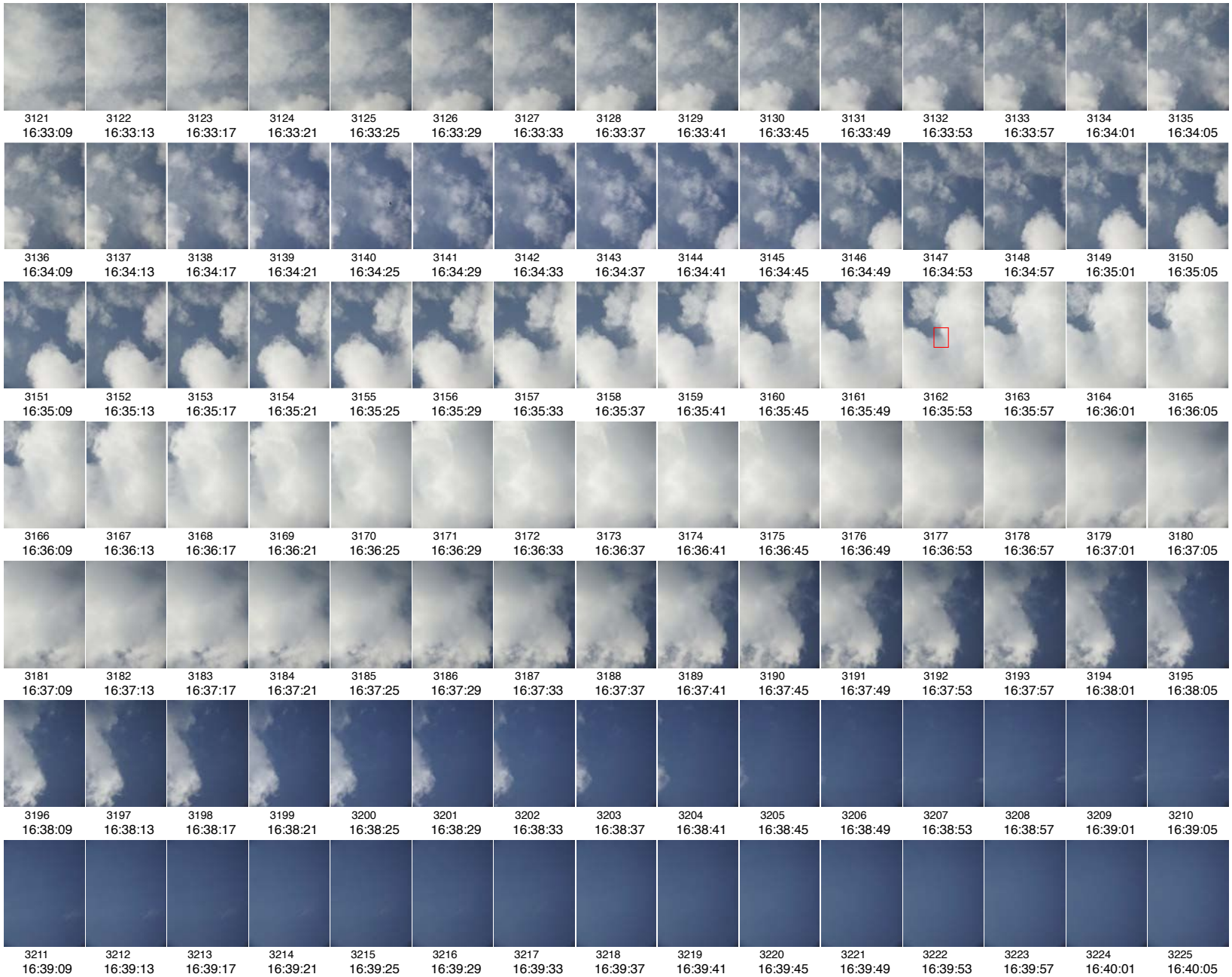
SGP, Oklahoma
2015-07-31
Times are UTC
Local sun time: UTC - 6.5 h

Measurements are hyper local!

7 MINUTES IN OKLAHOMA, WIDE FIELD OF VIEW CAMERA

N

E



W

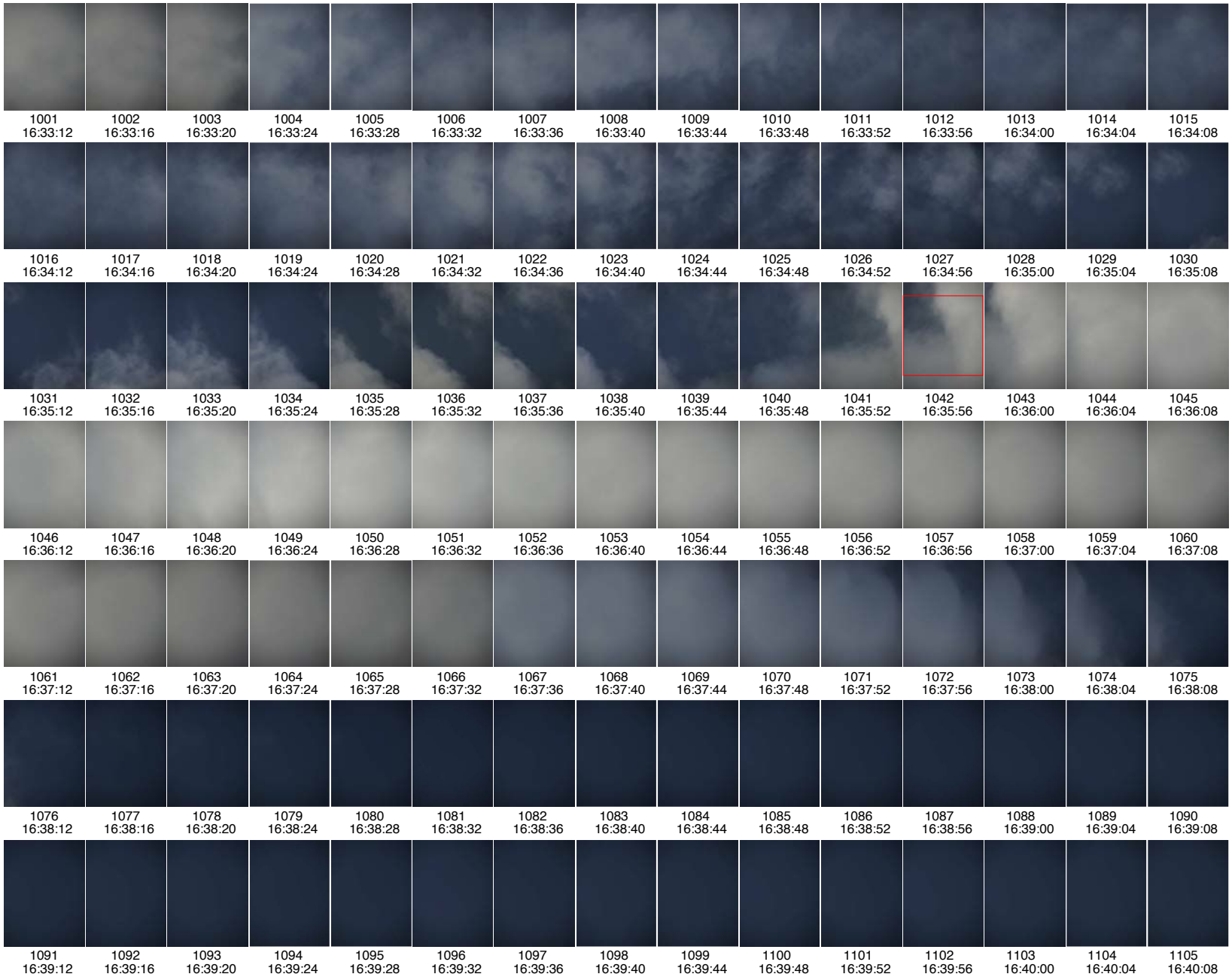
S

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

7 MINUTES IN OKLAHOMA, NARROW FIELD OF VIEW CAMERA

N

E



W

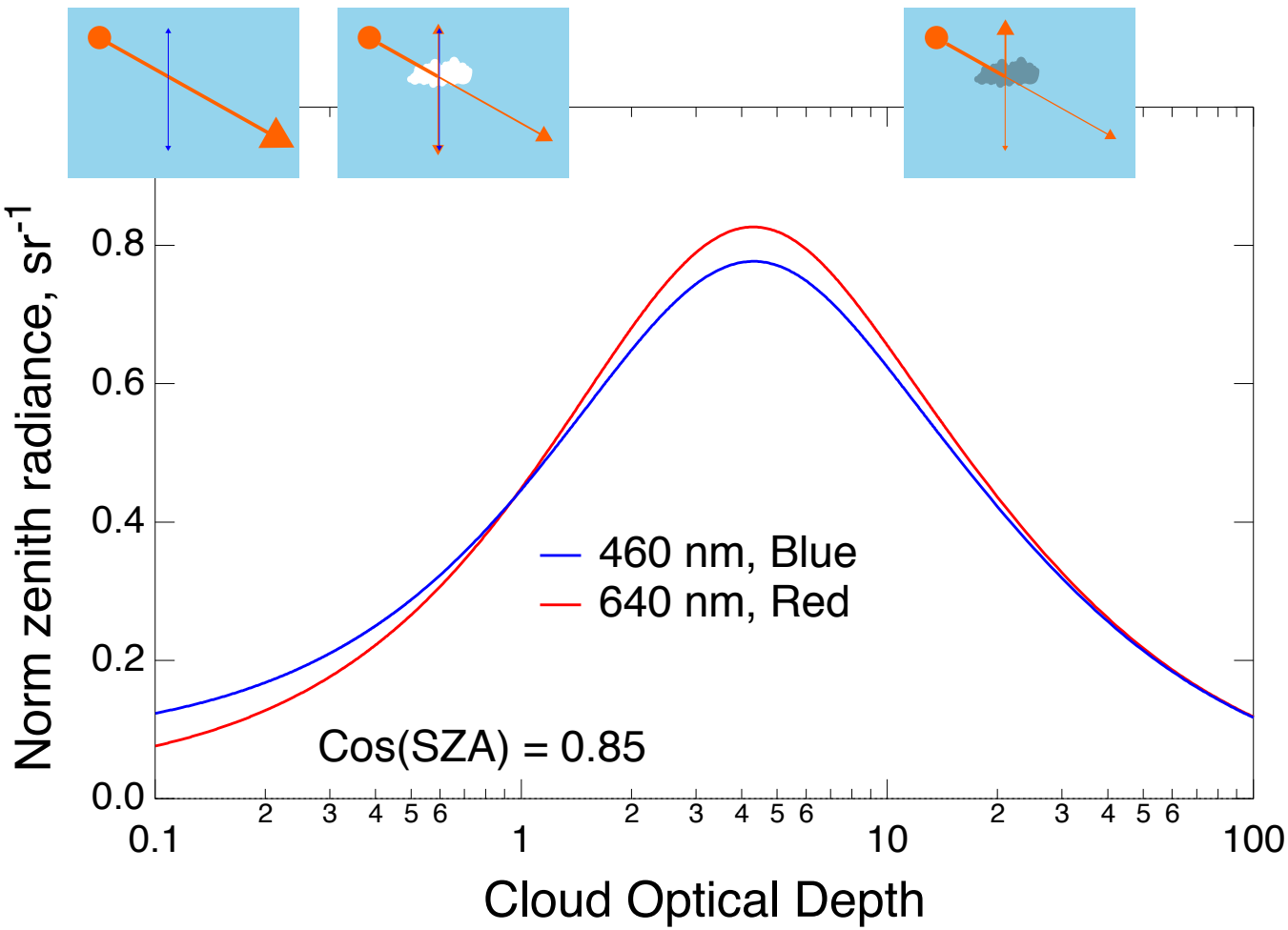
S

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

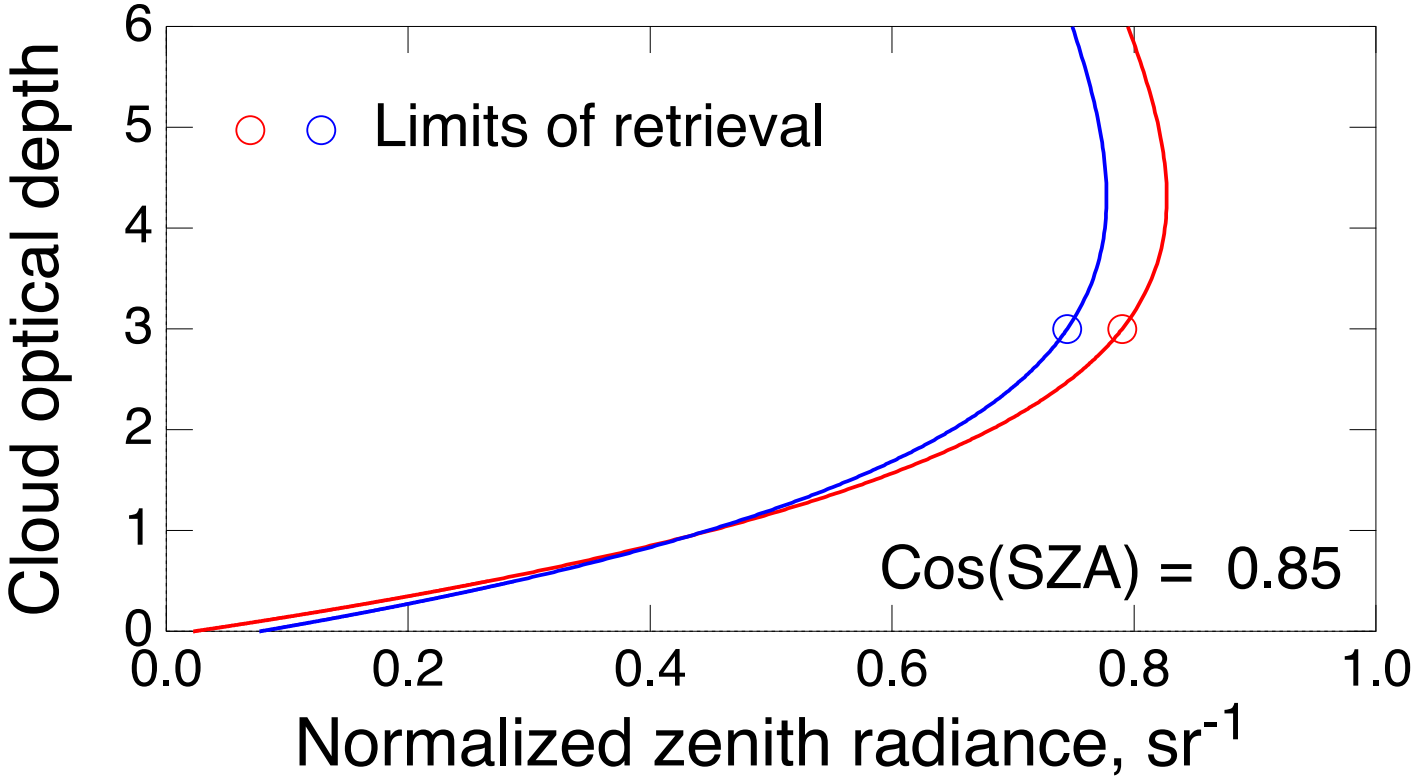


In absence of cloud, Rayleigh scattering only, low zenith radiance.

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***.

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.

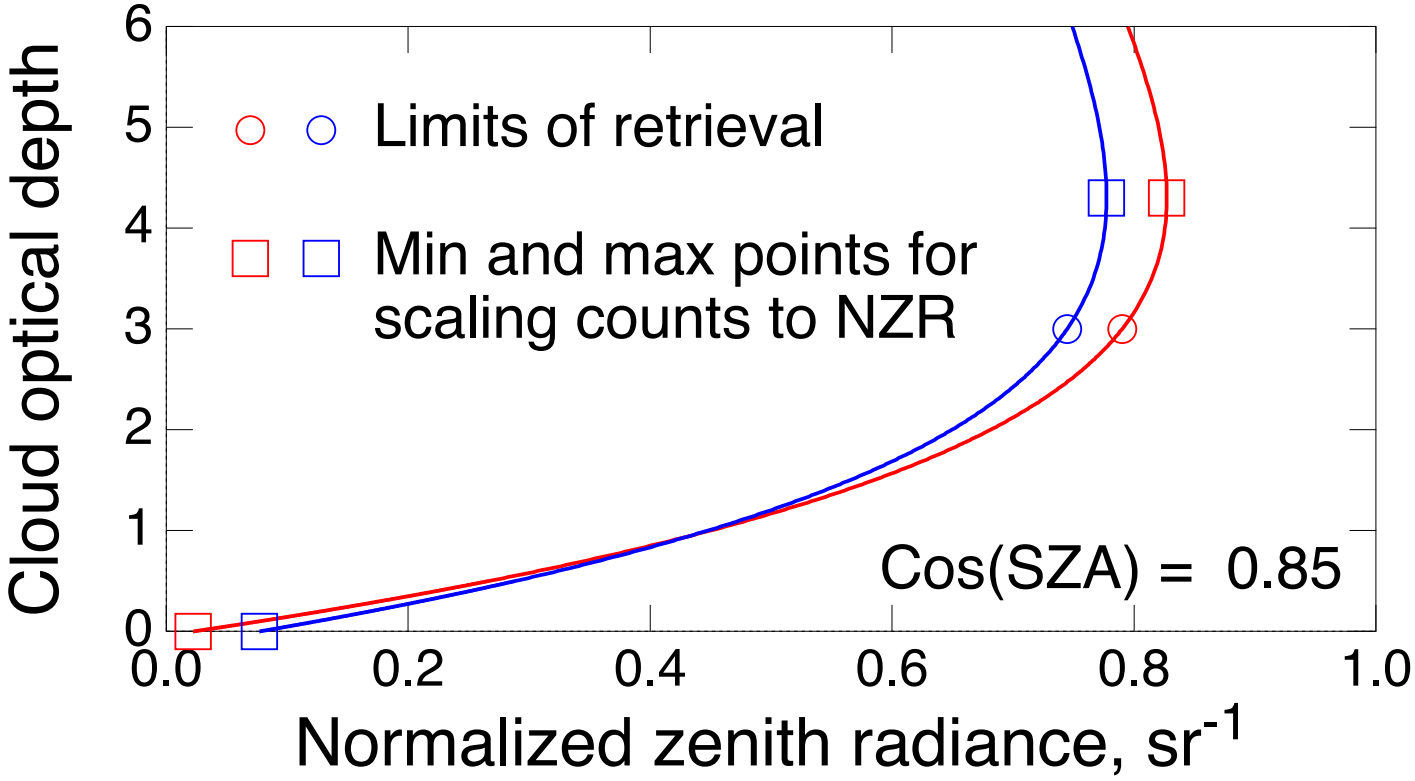
Calibration on Dark and Bright scenes permits ***determination of NZR, COD, Cloud albedo at native resolution of images.***

Concerns:

Aerosol contribution to nominal "Rayleigh" signal.

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

COD DEPENDENCE ON ZENITH RADIANCE



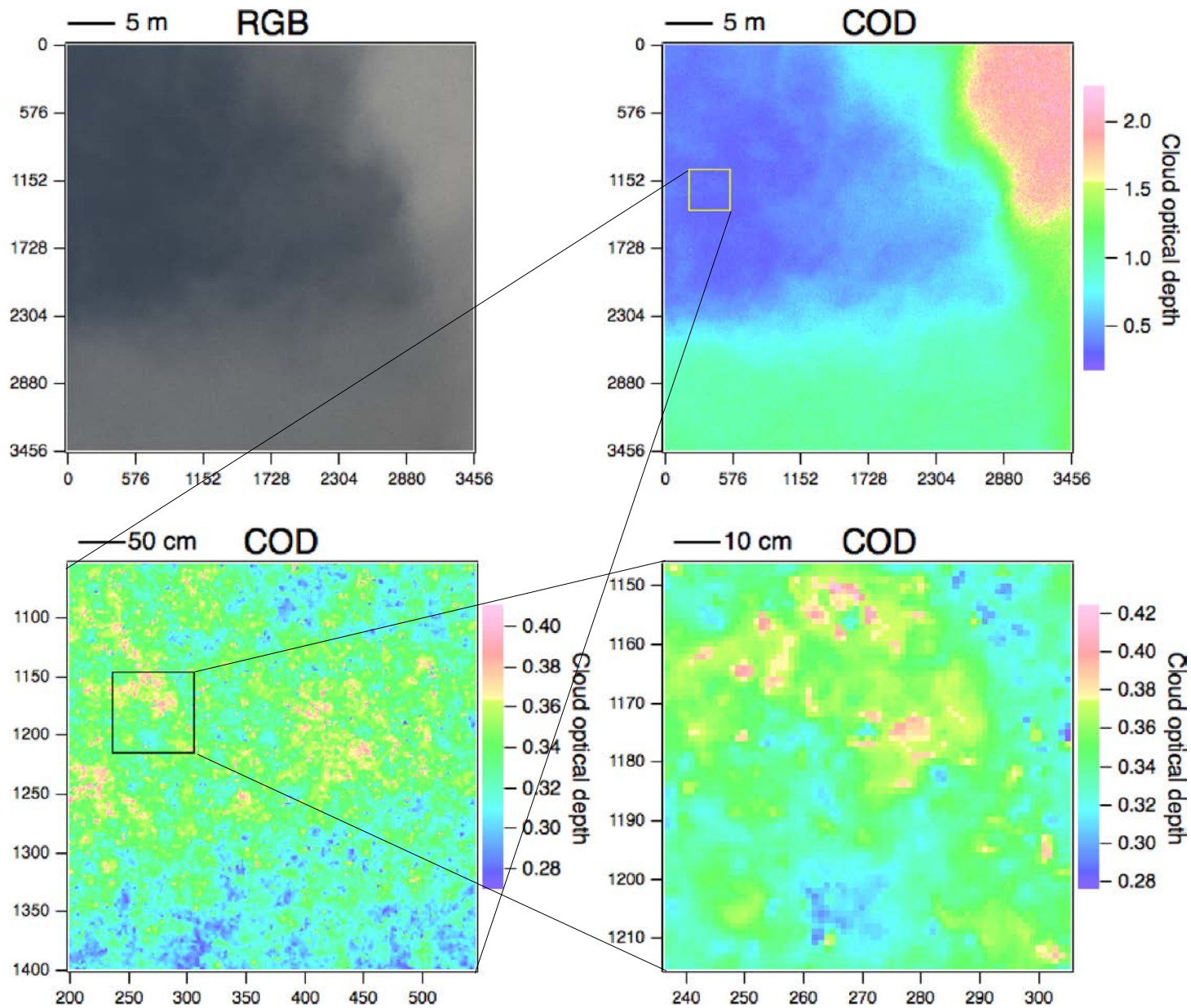
Dependence of NZR on COD is inverted to obtain COD from NZR.

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.

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.