RETRIEVAL OF IMAGES OF OPTICAL DEPTH OF THIN CLOUDS AT CENTIMETER SCALES BY HIGH-RESOLUTION PHOTOGRAPHY FROM THE SURFACE

Stephen E. Schwartz, Dong Huang

Brookhaven National Laboratory, Upton, NY

Daniela Viviana Vladutescu

CUNY New York City College of Technology Brooklyn, NY

AGU FALL MEETING

San Francisco | 12 – 16 December 2016

1 m

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 21 × 29 mrad
(2 × 3 sun diameters)

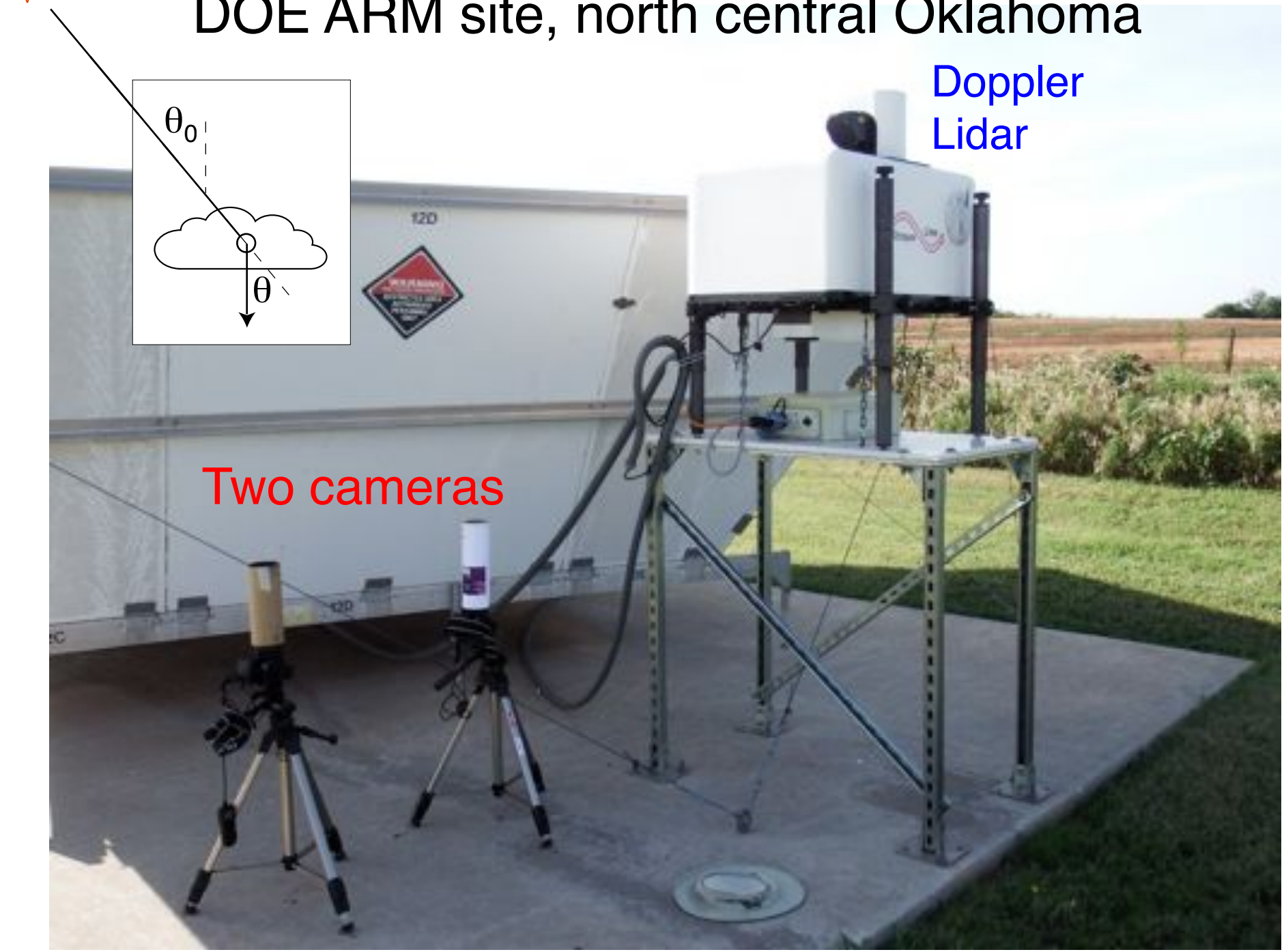
$350

SHORT RANGE CLOUD VARIABILITY

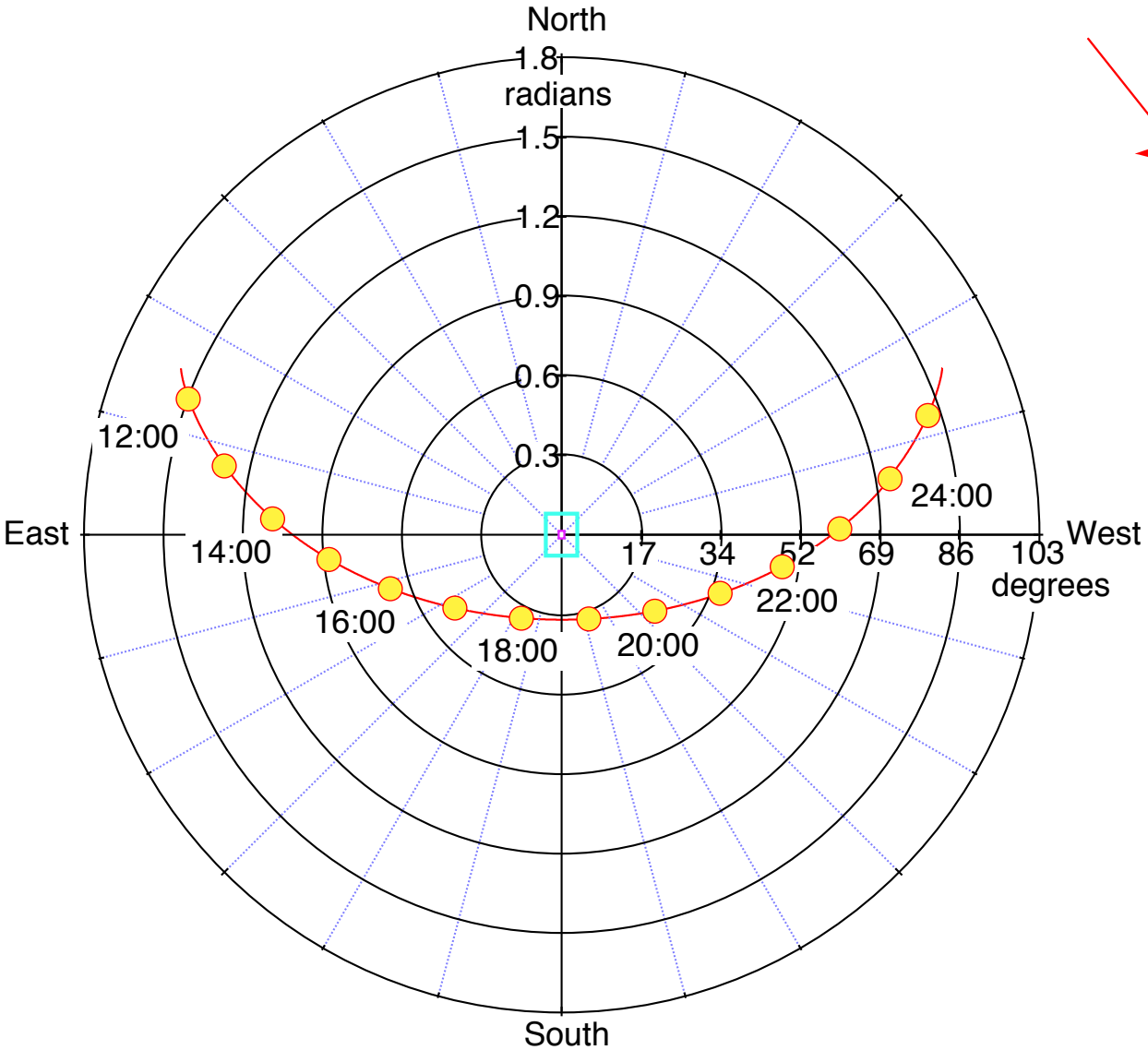
Moon diameter = 9 mrad (0.5°).

DEPLOYMENT OF CAMERAS AT SGP

DOE ARM site, north central Oklahoma



CAMERA FIELD OF VIEW AND SOLAR EPHEMERIS



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

Wide FOV Camera,
120 x 160 mrad

Sun, angular diameter
0.535° = 9.3 mrad

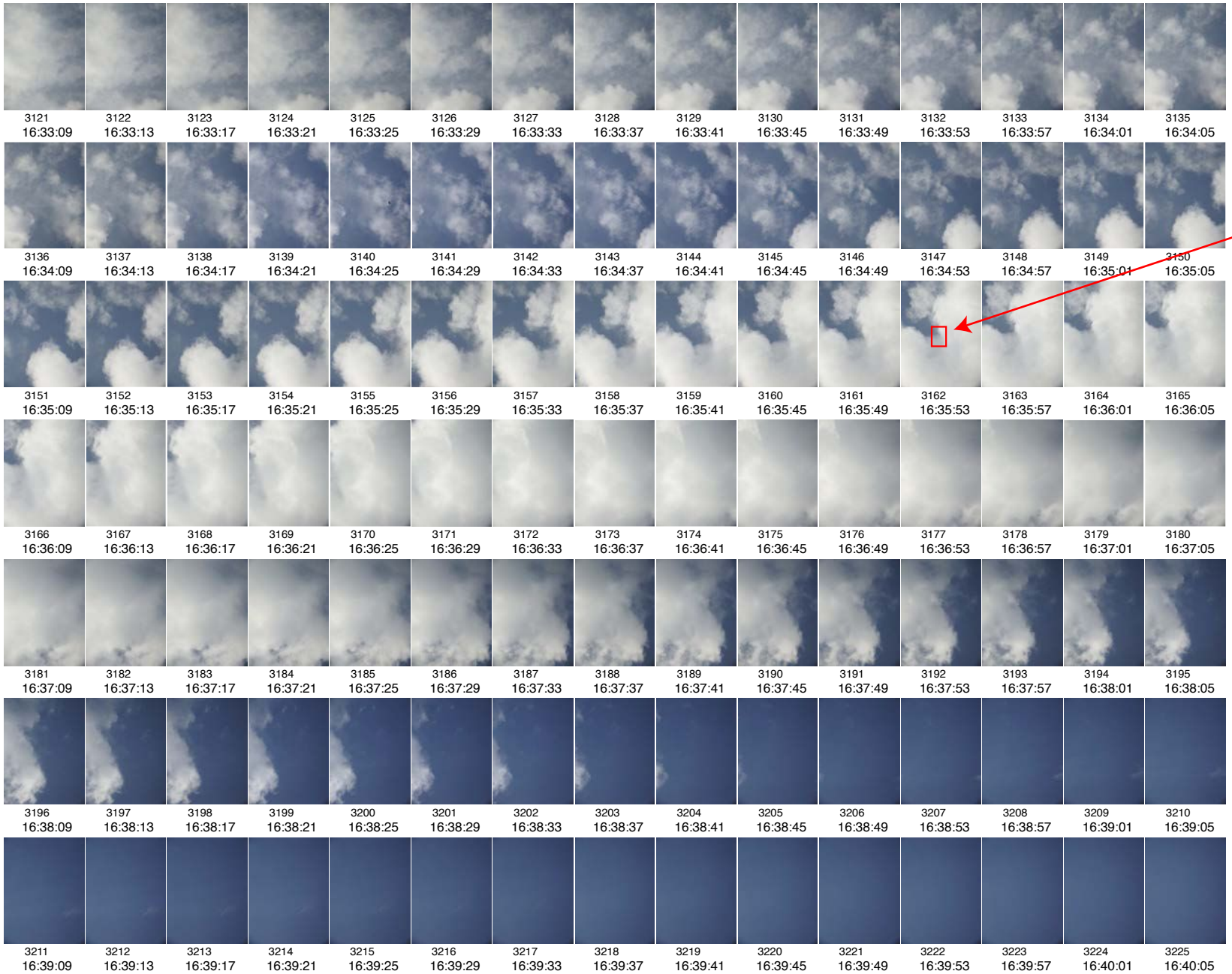
Drawn 10 times actual angular dimension

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



Narrow field of view

E

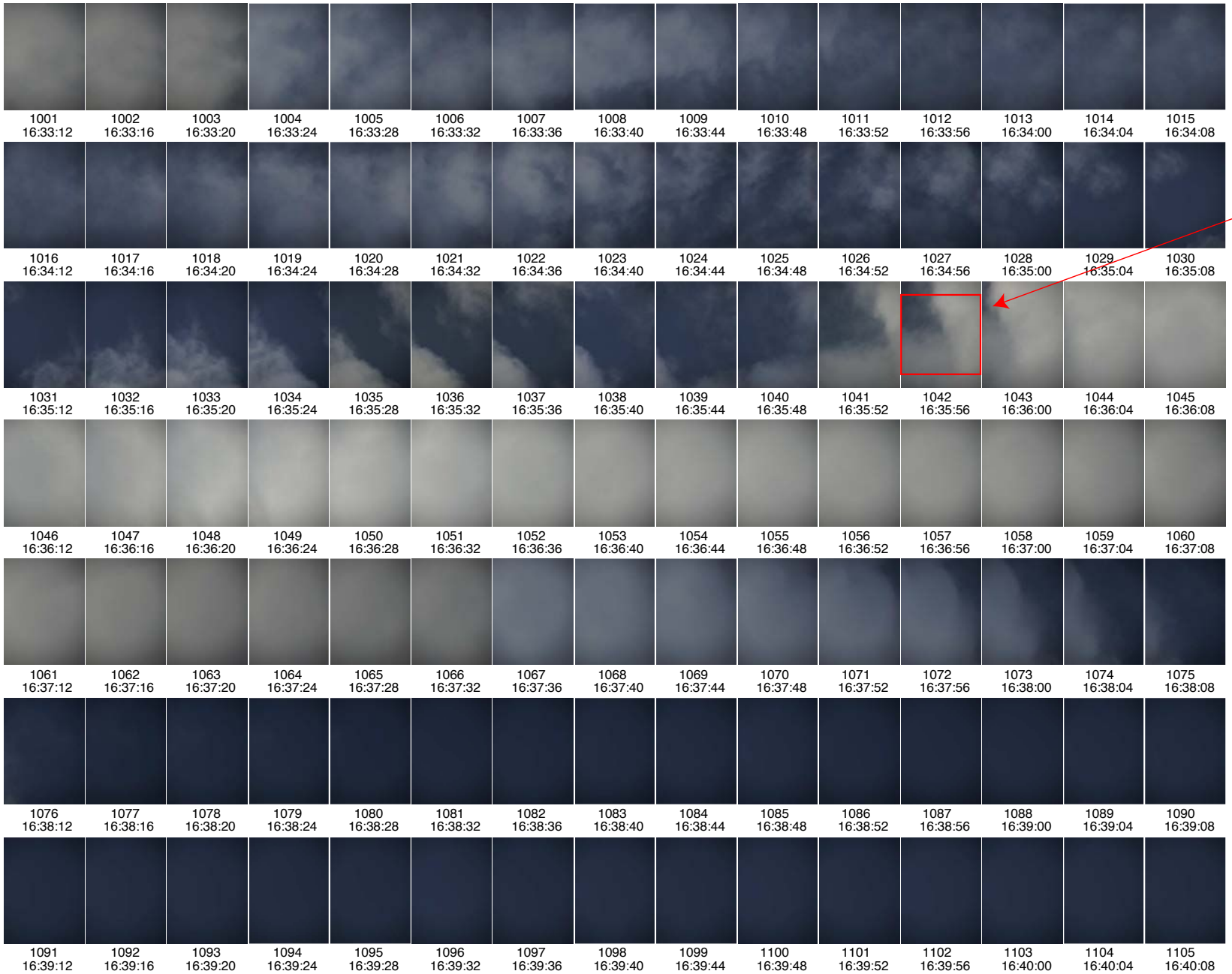
W

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



3456 × 3456 pixels

E

W

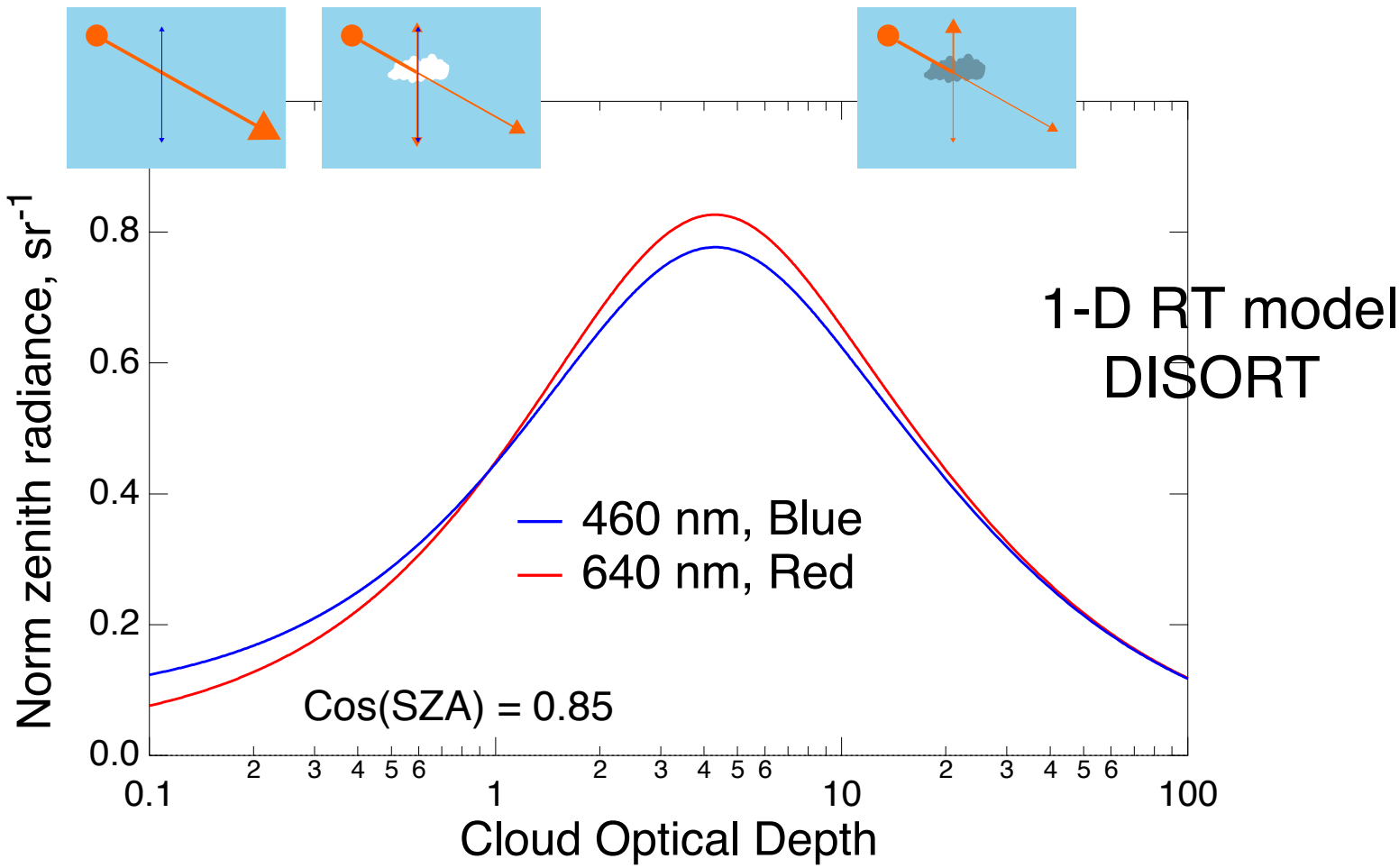
S

1 Photo every 4 s. Image is ~21 × 29 mrad = ~40 × 60 m @ 2 km.

ZENITH RADIANCE DEPENDENCE ON COD

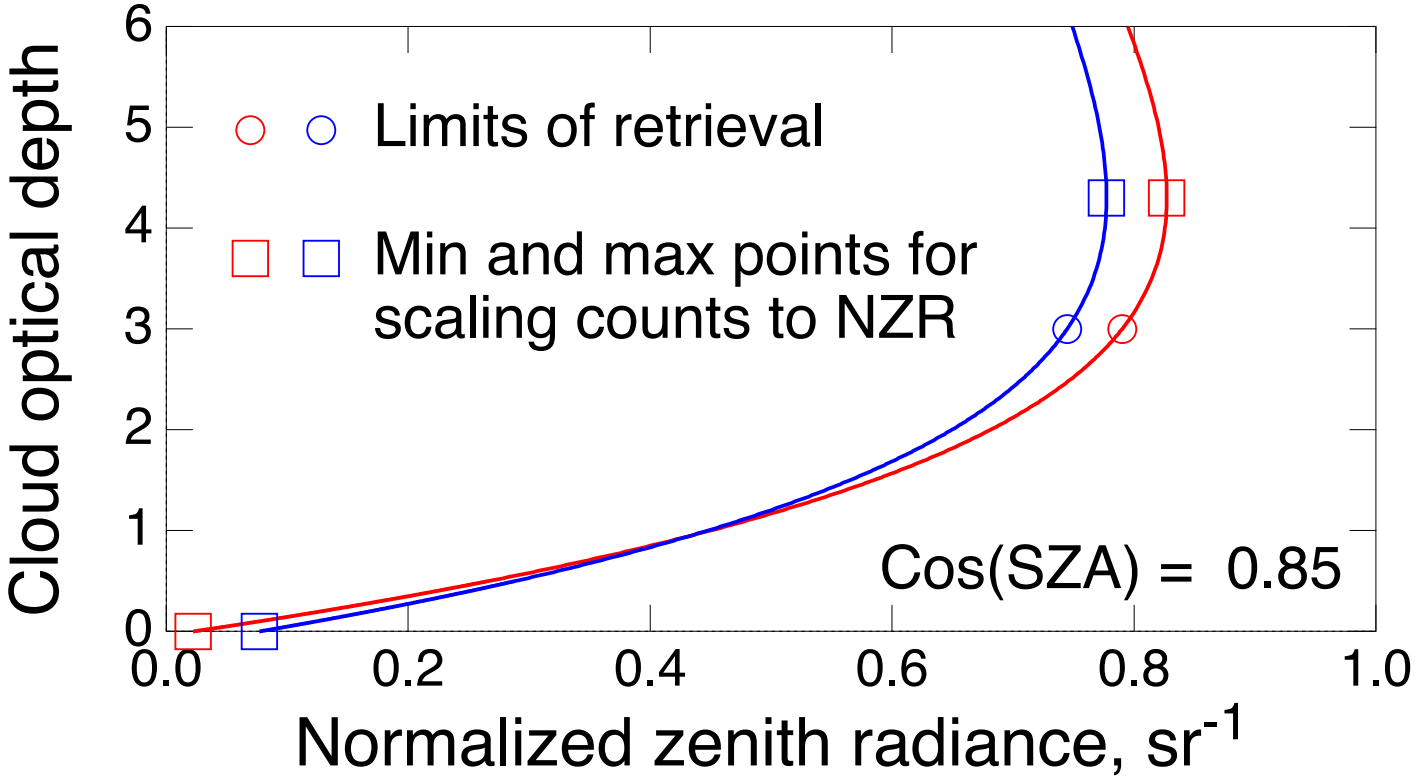
Normalized zenith radiance: Zenith radiance per hemispheric TOA solar irradiance

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



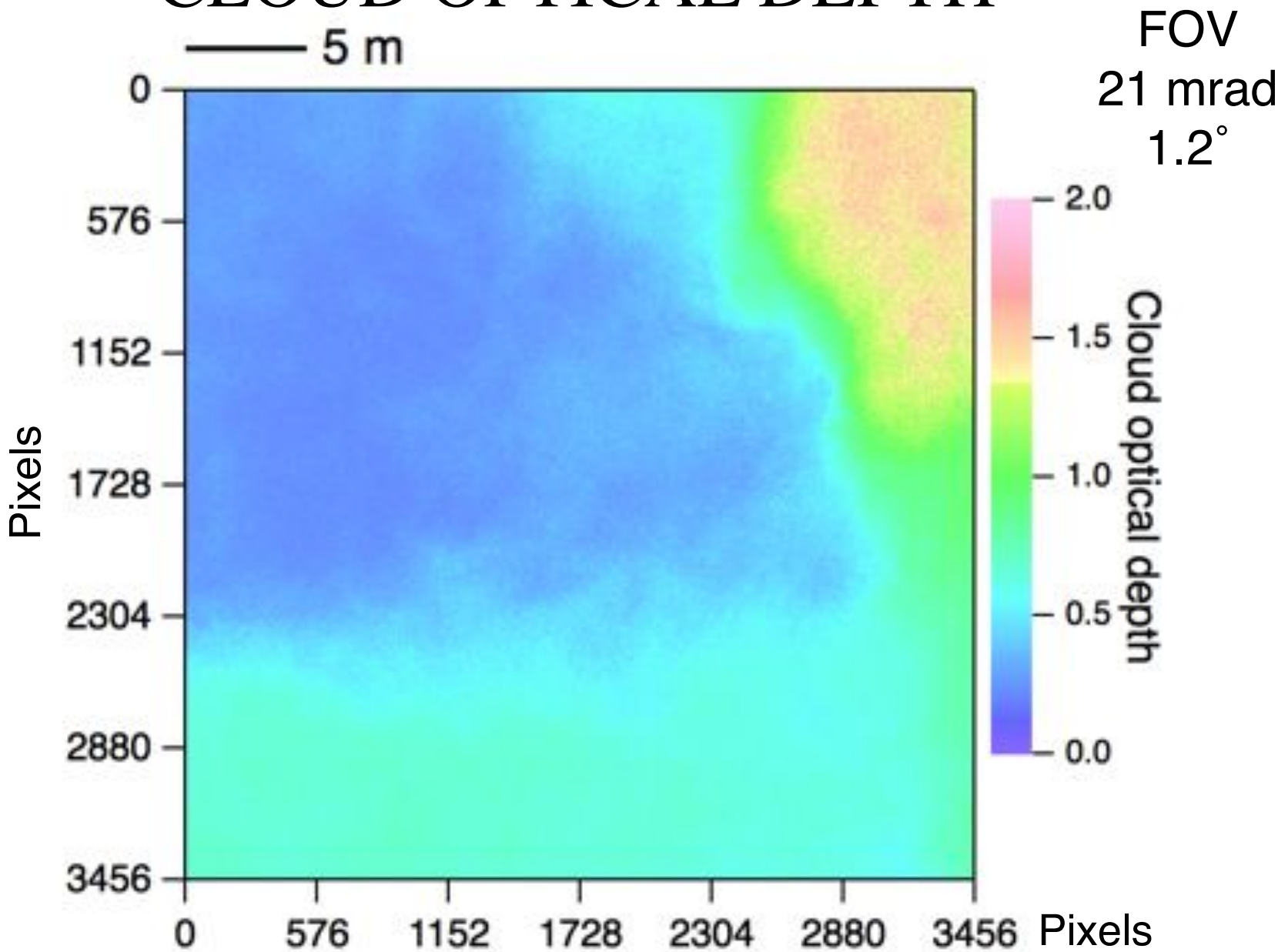
Dependence of NZR on COD is inverted to obtain COD from NZR.

Inversion is valid only for COD $\lesssim$ 3. Must establish COD < 3.

The inversion is applied to yield COD on ***pixel-by-pixel basis***.

Minima and maxima permit scaling counts to NZR in each channel.

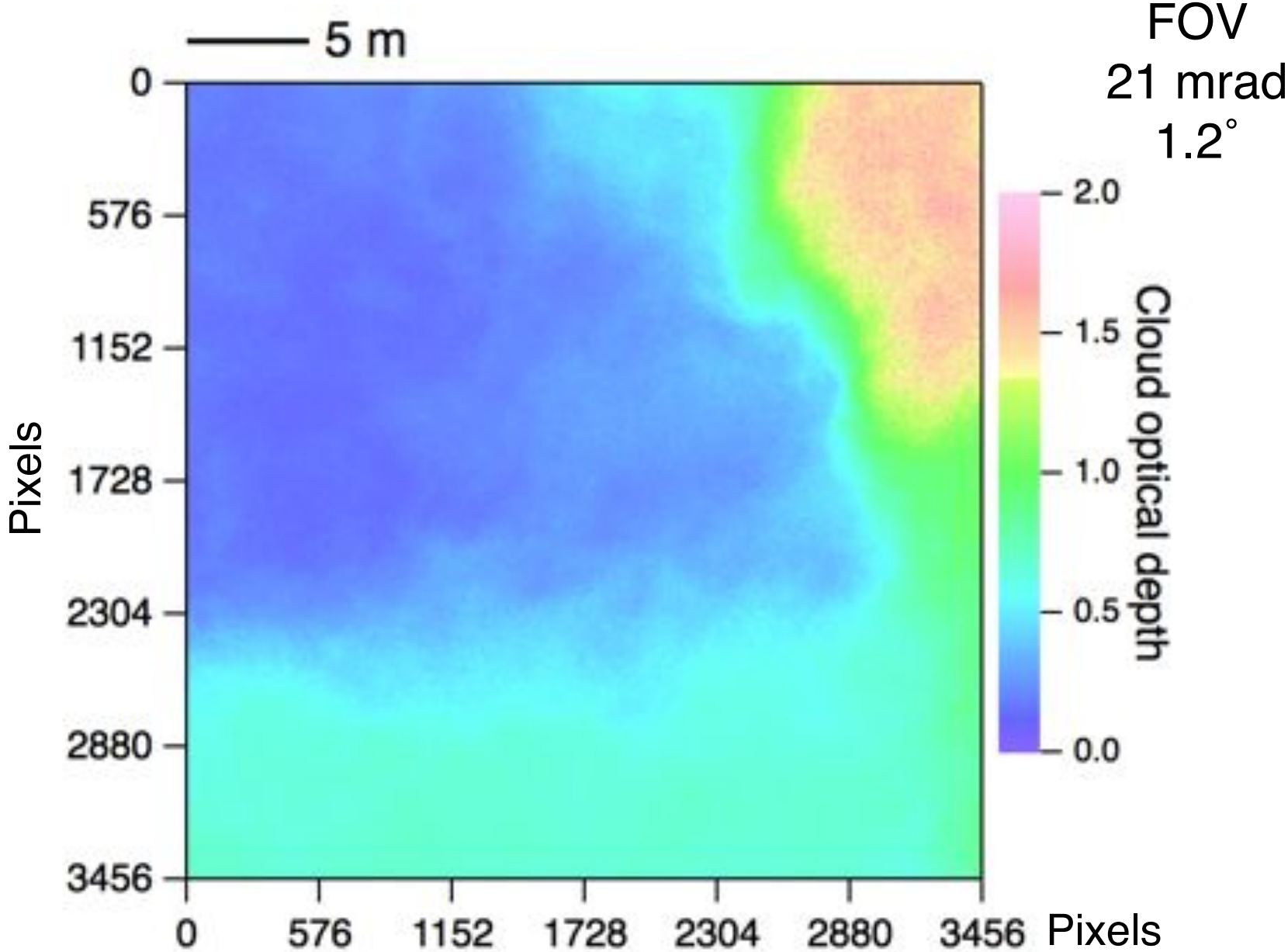
CLOUD OPTICAL DEPTH



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.
3 million independent determinations of COD from single image.

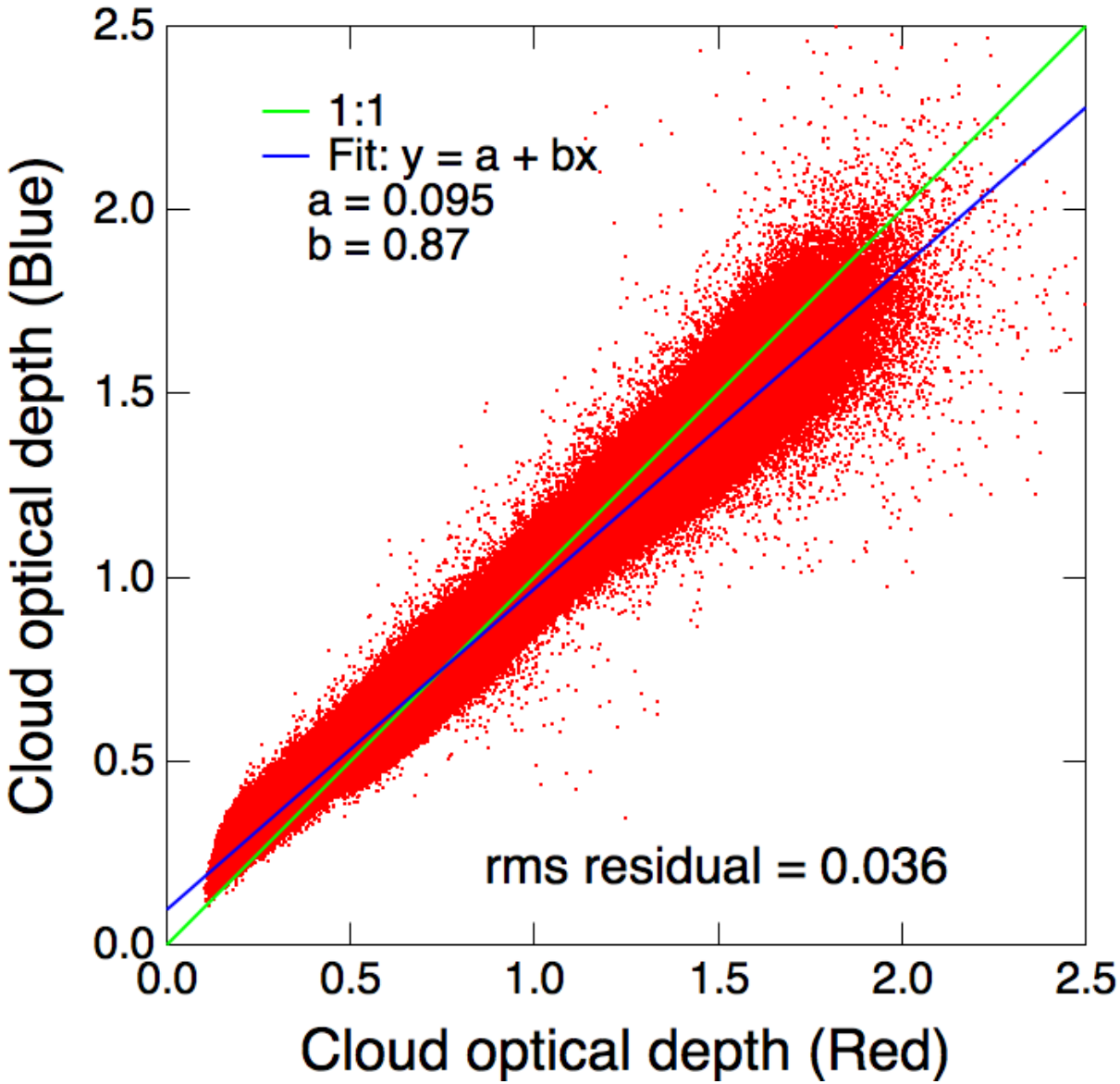
CLOUD OPTICAL DEPTH



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.
3 million independent determinations of COD from single image.

COMPARE COD DETERMINATIONS

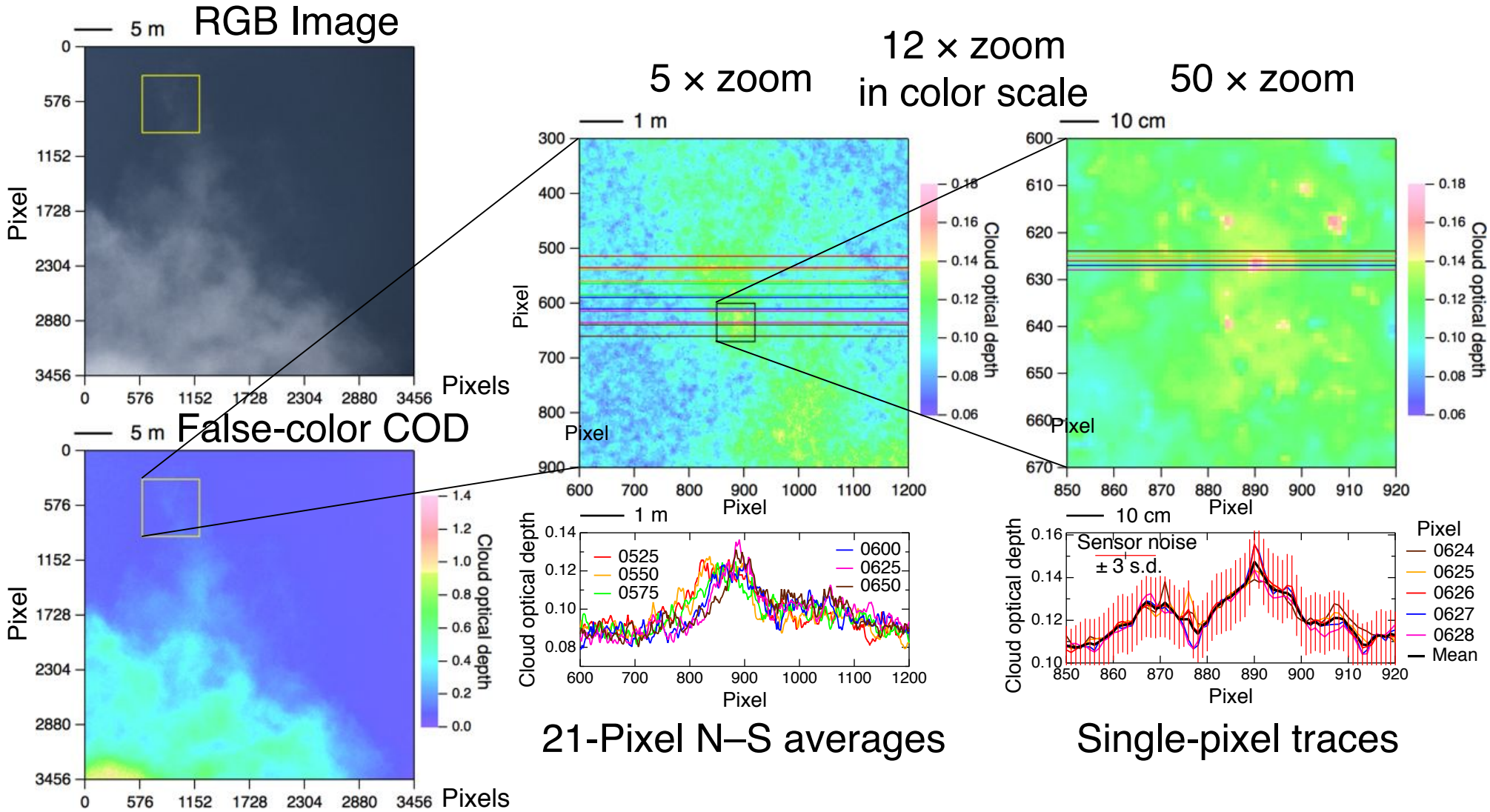


ARM SGP site, 2016-0731, 16:35:52 UTC (10:05:52 local sun time)

Compare CODs from red and blue channels of RGB image.
Agreement within 0.1 at low COD, 15% at higher COD.

SPATIAL VARIATION OF CLOUD OPTICAL DEPTH

Zoom in on thin cloud; examine line traces



Cloud optical depth varies coherently over ***distances as short as 10 cm***.

Single pixel noise = 0.05 COD, 1 s.d. (increases with increasing COD).

STRENGTHS AND ADVANTAGES

Images!

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!

1 m

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!

50 cm

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 ***quantitatively*** attributed to variation in cloud optical depth.

50 cm

LOTS TO DO

- Examine spatial variation on many scales; examine autocorrelation, fractal properties, etc.
- Extend to cirrus; extend to optically thicker clouds.
- Examine temporal changes in COD after accounting for translation.
- Relate observations to the "too few, too bright" problem.
- ***Put the final nail in the coffin of cloud fraction***.

- Determine whether short range variations can be used to remotely sense vertical motion?
- Go off zenith to examine vertical structure obliquely.
- We have lots of unanalyzed images; ***we welcome collaborations***.
- Get a camera and start taking photos!