# Radiative Forcing Efficiency of a Forest Fire Smoke Plume at the Surface and TOA

John A. Augustine[1], Robert S. Stone[1,2], David Rutan[3], and Ellsworth G. Dutton[1]

[1]Earth System Research Laboratory, Global Monitoring Division, Boulder, CO
[2]Cooperative Institute for Research in Environmental Sciences, University of Colorado
[3]NASA Langley Research Center, A.S.&M., Inc., Hampton, VA

Fourmile Canyon Fire 6 Sept. 2010

# Our focus is to compute the Radiative Forcing Efficiency (RFE) of the smoke aerosol at the Surface and Top of Atmosphere (TOA)

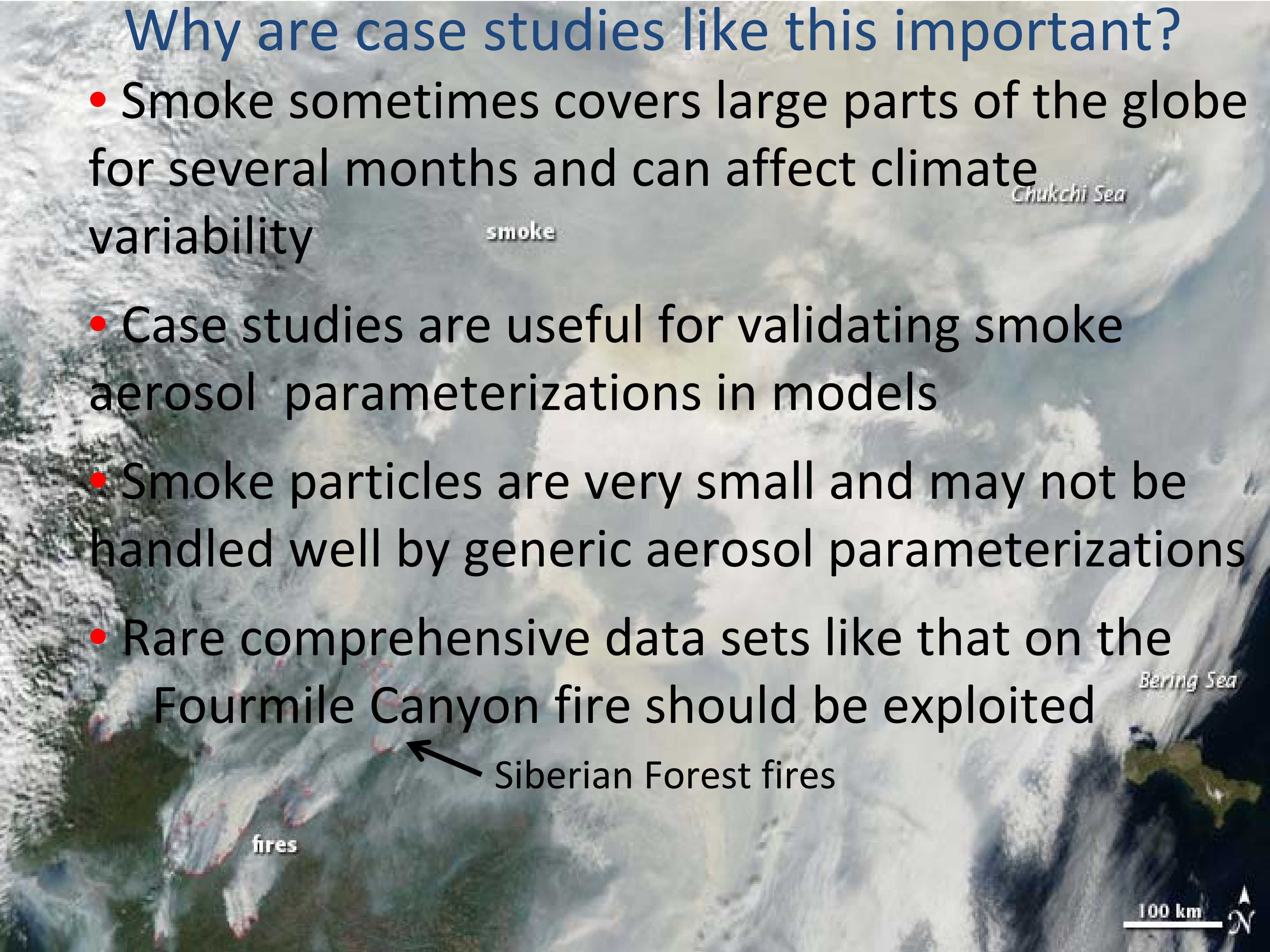
$$RFE = \Delta \text{Total Net Rad/unit } AOD_{500nm}$$

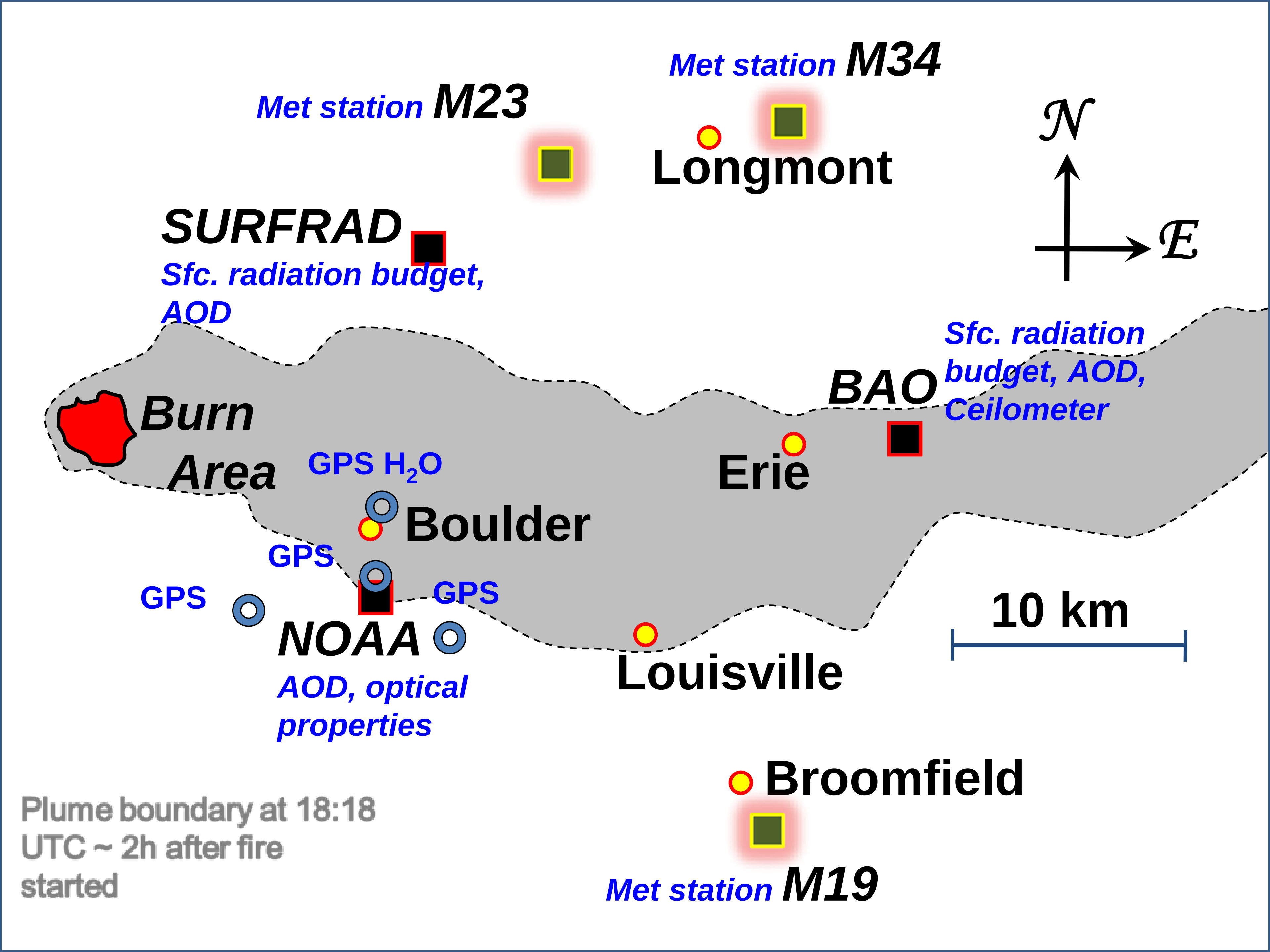
Surface, Atmosphere, and TOA

$$RFE_{atmos} = RFE_{TOA} - RFE_{sfc}$$

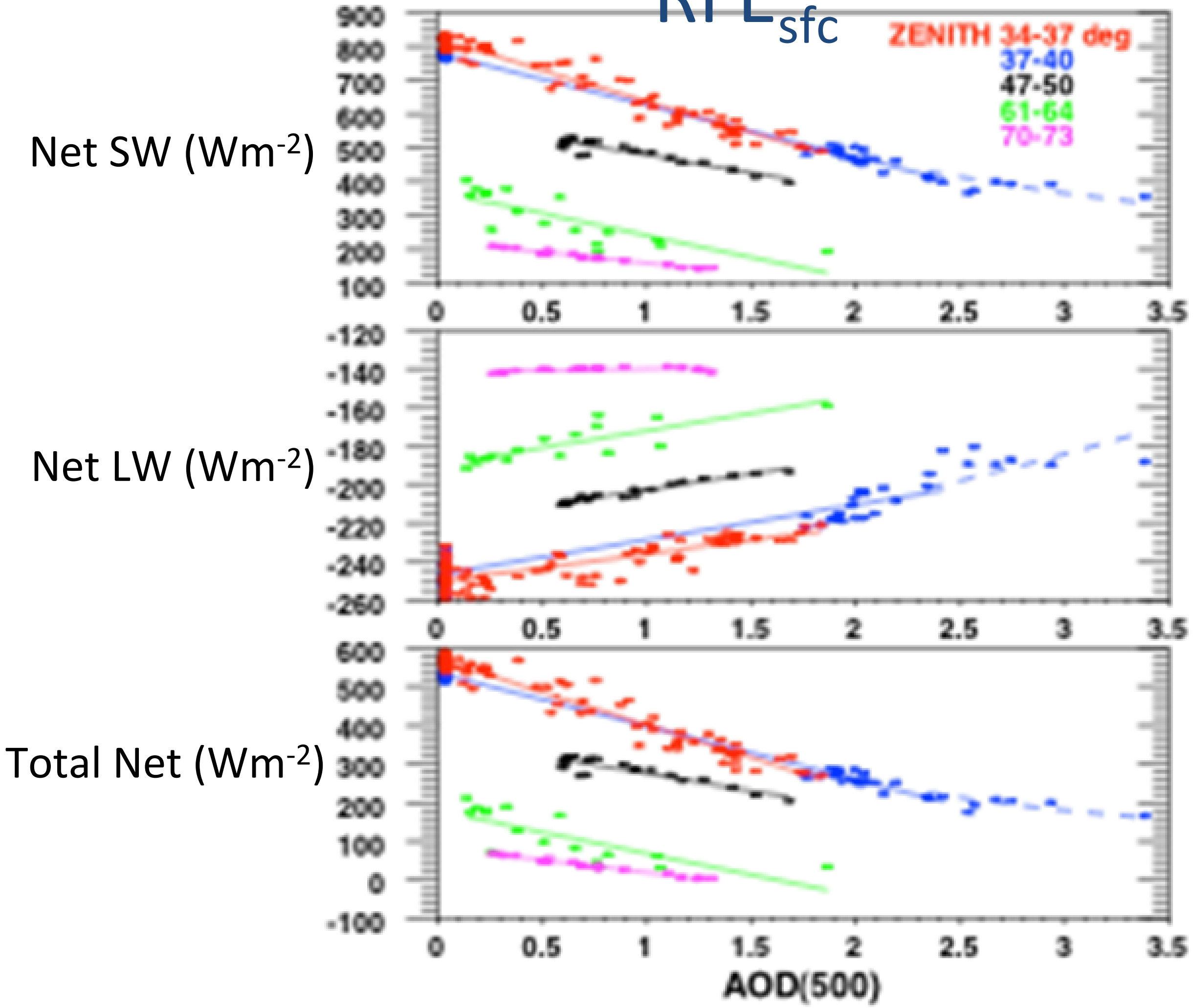
# Why are case studies like this important?

- Smoke sometimes covers large parts of the globe for several months and can affect climate variability
- Case studies are useful for validating smoke aerosol parameterizations in models
- Smoke particles are very small and may not be handled well by generic aerosol parameterizations
- Rare comprehensive data sets like that on the Fourmile Canyon fire should be exploited

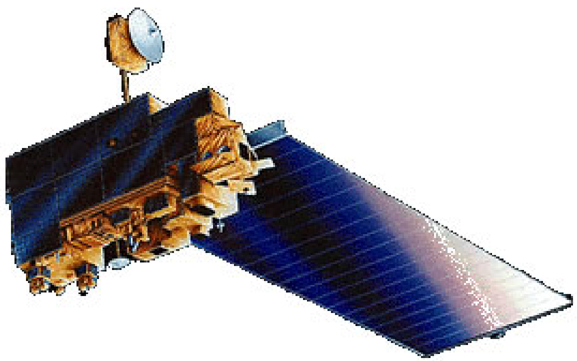



Met station M34
Met station M23
Longmont
$\mathcal{N}$
$\mathcal{E}$
SURFRAD
Sfc. radiation budget, AOD
Sfc. radiation budget, AOD, Ceilometer
BAO
Burn Area
GPS $H_2O$
Erie
Boulder
GPS
GPS
GPS
10 km
NOAA
AOD, optical properties
Louisville
Broomfield
Plume boundary at 18:18 UTC ~ 2h after fire started
Met station M19

# Abundant clear-sky surface measurements throughout the day allowed direct calculation of $RFE_{sfc}$



# TOA – not as easy



1. Satellite observations
   - NASA's Terra and Aqua polar orbiters.
   - First choice CERES broadband imagers
   - Sampling is minimal--1 or 2 passes per day
   - TOA radiative forcing is computed by comparing an aerosol case to a reference case
2. Radiative transfer model

# Available Satellite data

1. CERES SW and IR broadband imagers, 20 km resolution at nadir
2. MODIS 36-channel spectral imager, 1 km resolution at nadir

Problems:

- CERES could not resolve the Fourmile plume
- MODIS could, but NASA does not do a narrowband-to-broadband conversion

# MODIS Spectral radiance to broadband conversion

| Band | Wavelength (nm) | Resolution (m) | Primary Use |
|---|---|---|---|
| 1 | 620–670 | 250m | Land/Cloud/Aerosols Boundaries |
| 2 | 841–876 | 250m | |
| 3 | 459–479 | 500m | Land/Cloud/Aerosols Properties |
| 4 | 545–565 | 500m | |
| 5 | 1230–1250 | 500m | |
| 6 | 1628–1652 | 500m | |
| 7 | 2105–2155 | 500m | |
| 8 | 405–420 | 1000m | Ocean Color/ Phytoplankton/ Biogeochemistry |
| 9 | 438–448 | 1000m | |
| 10 | 483–493 | 1000m | |
| 11 | 526–536 | 1000m | |
| 12 | 546–556 | 1000m | |
| 13 | 662–672 | 1000m | |
| 14 | 673–683 | 1000m | |
| 15 | 743–753 | 1000m | |
| 16 | 862–877 | 1000m | |
| 17 | 890–920 | 1000m | Atmospheric Water Vapor |
| 18 | 931–941 | 1000m | |
| 19 | 915–965 | 1000m | |

+ 17 more (3660 – 14385 nm)

Tang et al. [2006], *JGR* used 159,000 MODTRAN runs to produce a linear model that converts the the first 7 spectral channel reflectances ($\rho$) to SW broadband reflectance (r)

RMS error = 0.01

$$r = b_0 + \rho_1 b_1 + \rho_2 b_2 + \rho_3 b_3 + \rho_4 b_4 + \rho_5 b_5 + \rho_6 b_6 + \rho_7 b_7$$

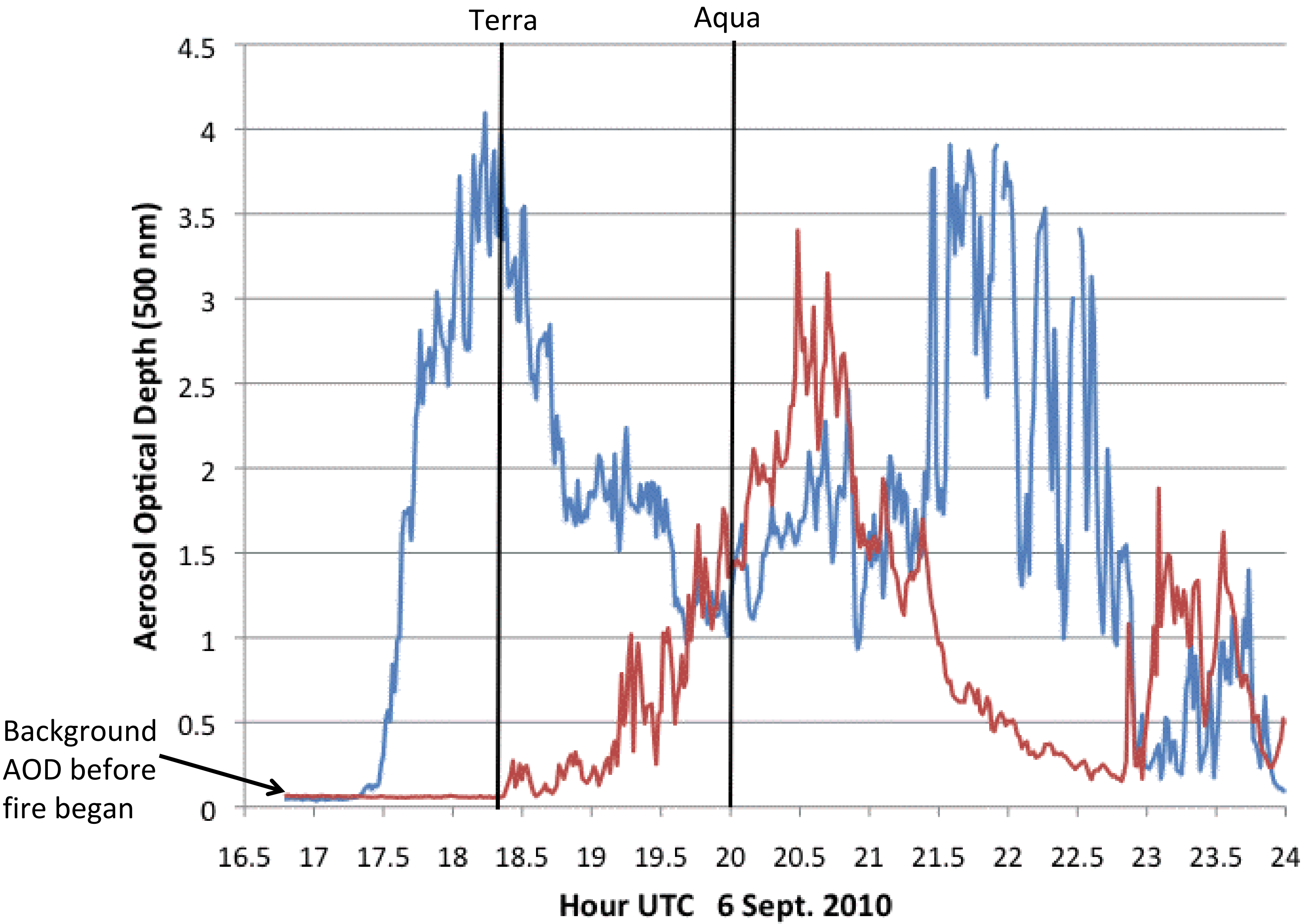
where:

$$b_i = c1_i + [c2_i/(1+\exp((1/\cos(VZA)-c3_i/c4_i))$$

$$\rho_i = \pi L_i d^2/Eo_i \cos(SZA)$$

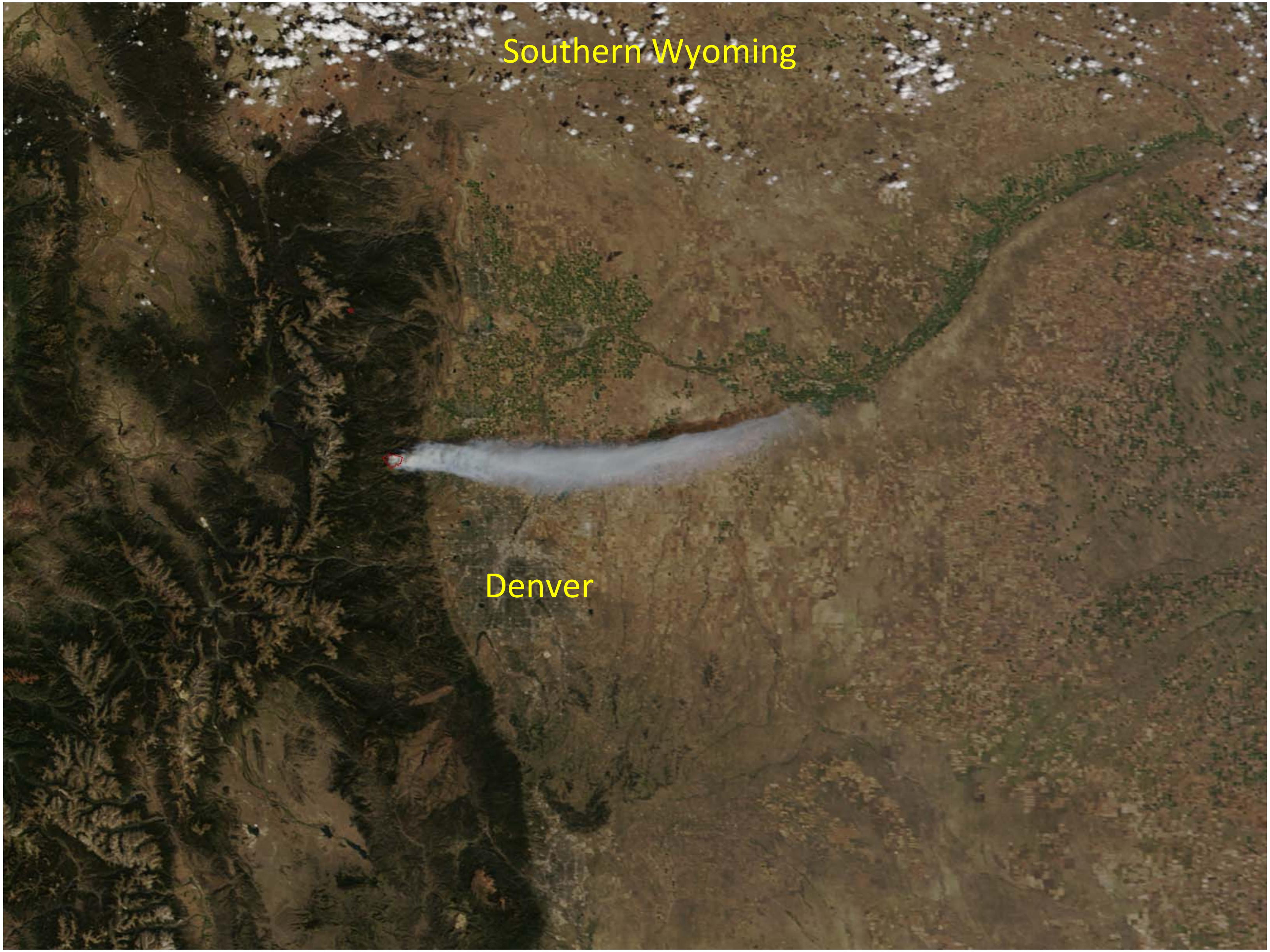
$L_i$ is the measured upwelling radiance for channel i

# Surface AOD measurements at BAO and SURFRAD (TBL)



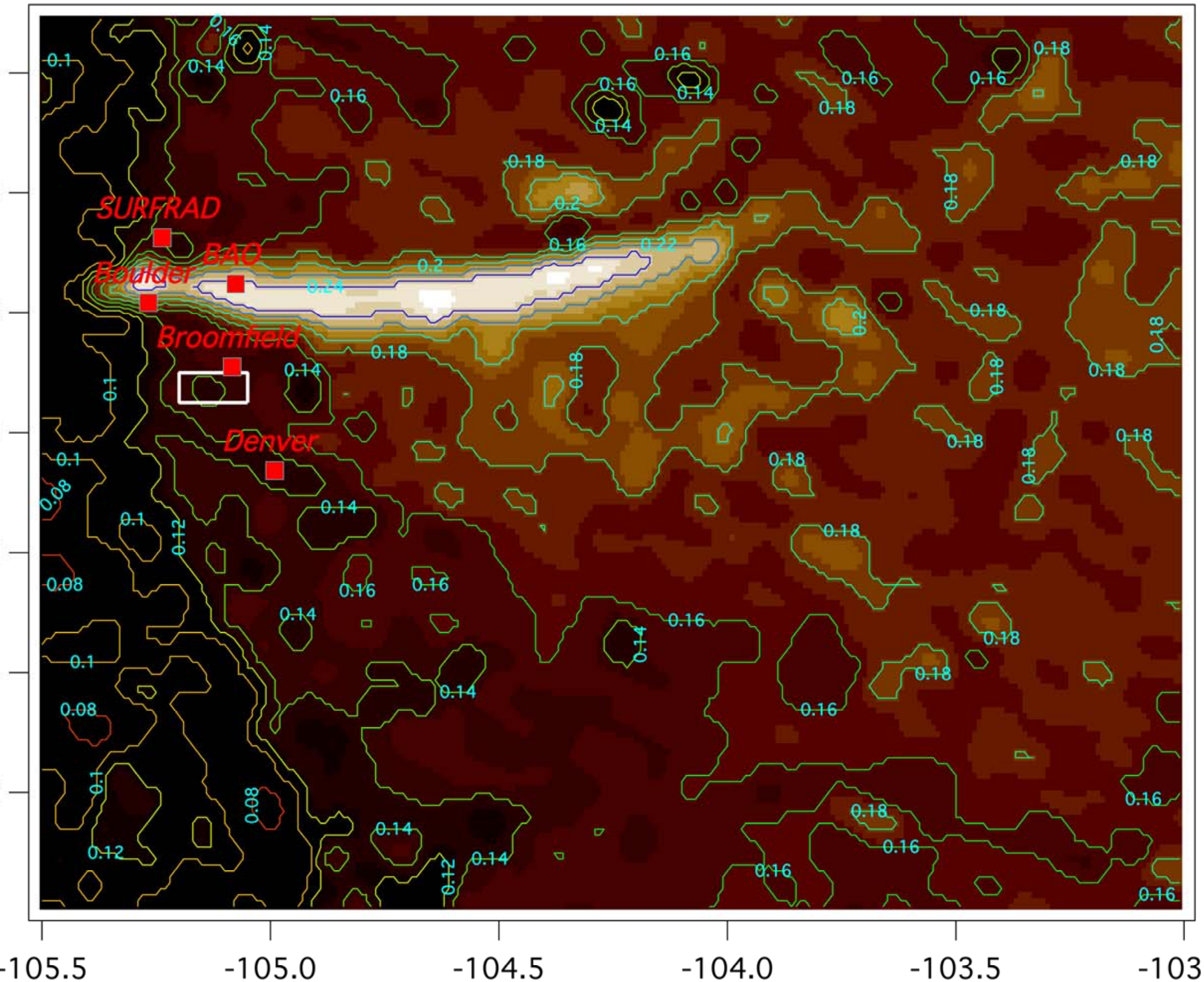
# NASA Terra MODIS imager

## 1820 UTC, ~ 2 hours after the fire started



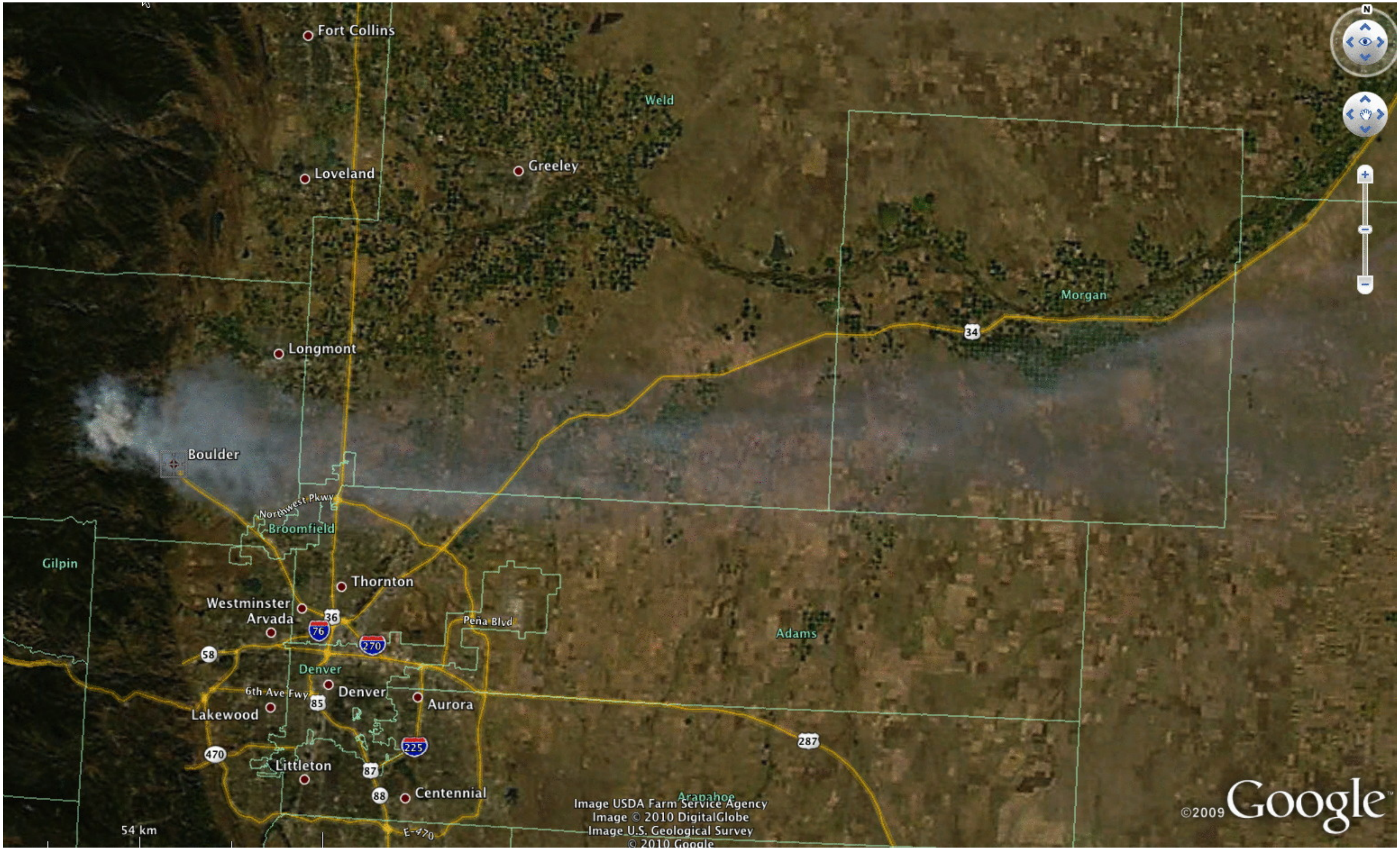
# Terra broadband reflectance 6 Sept. 2010, 1820 UTC

RMS=0.01

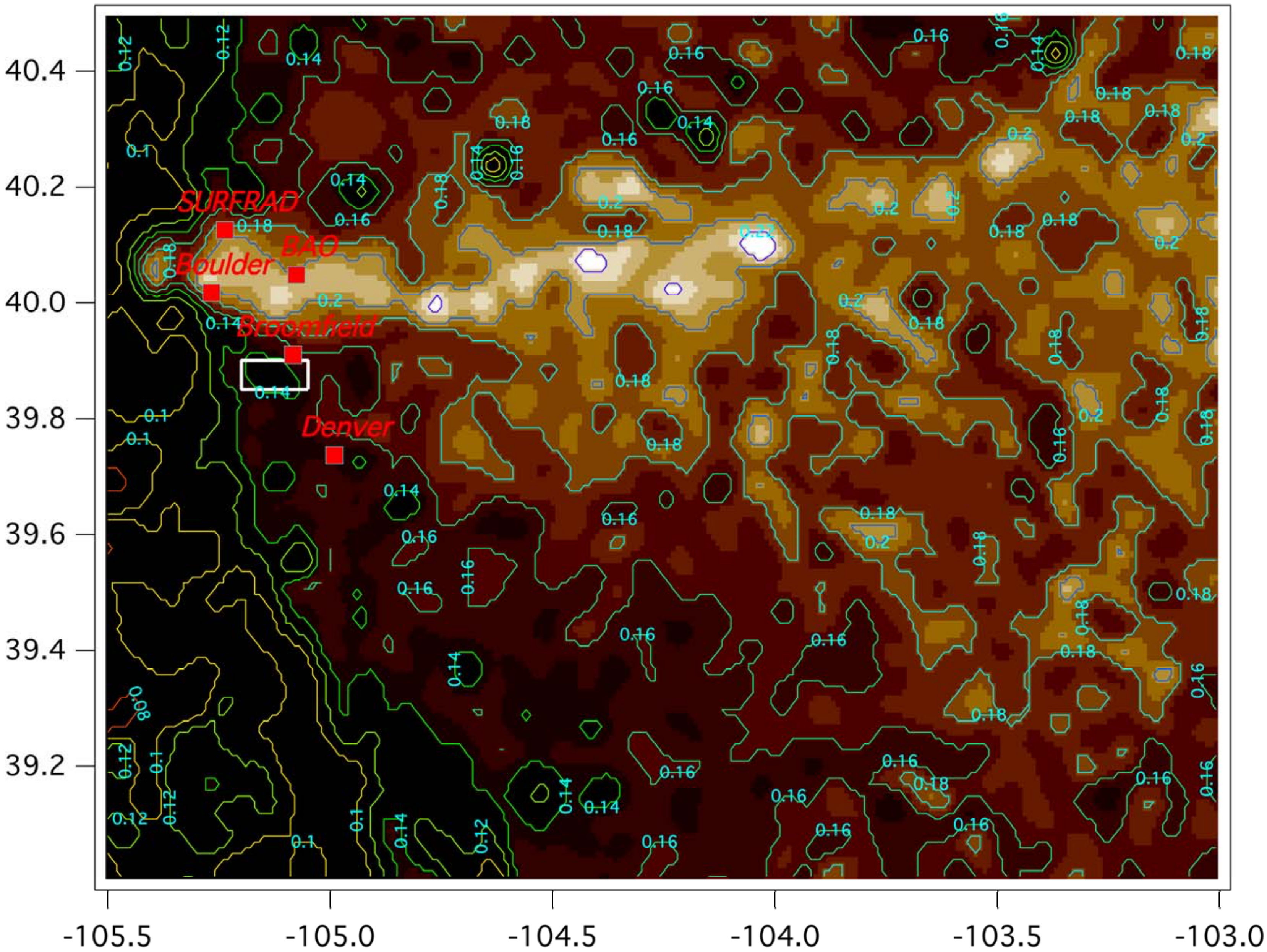


# NASA Aqua MODIS imager

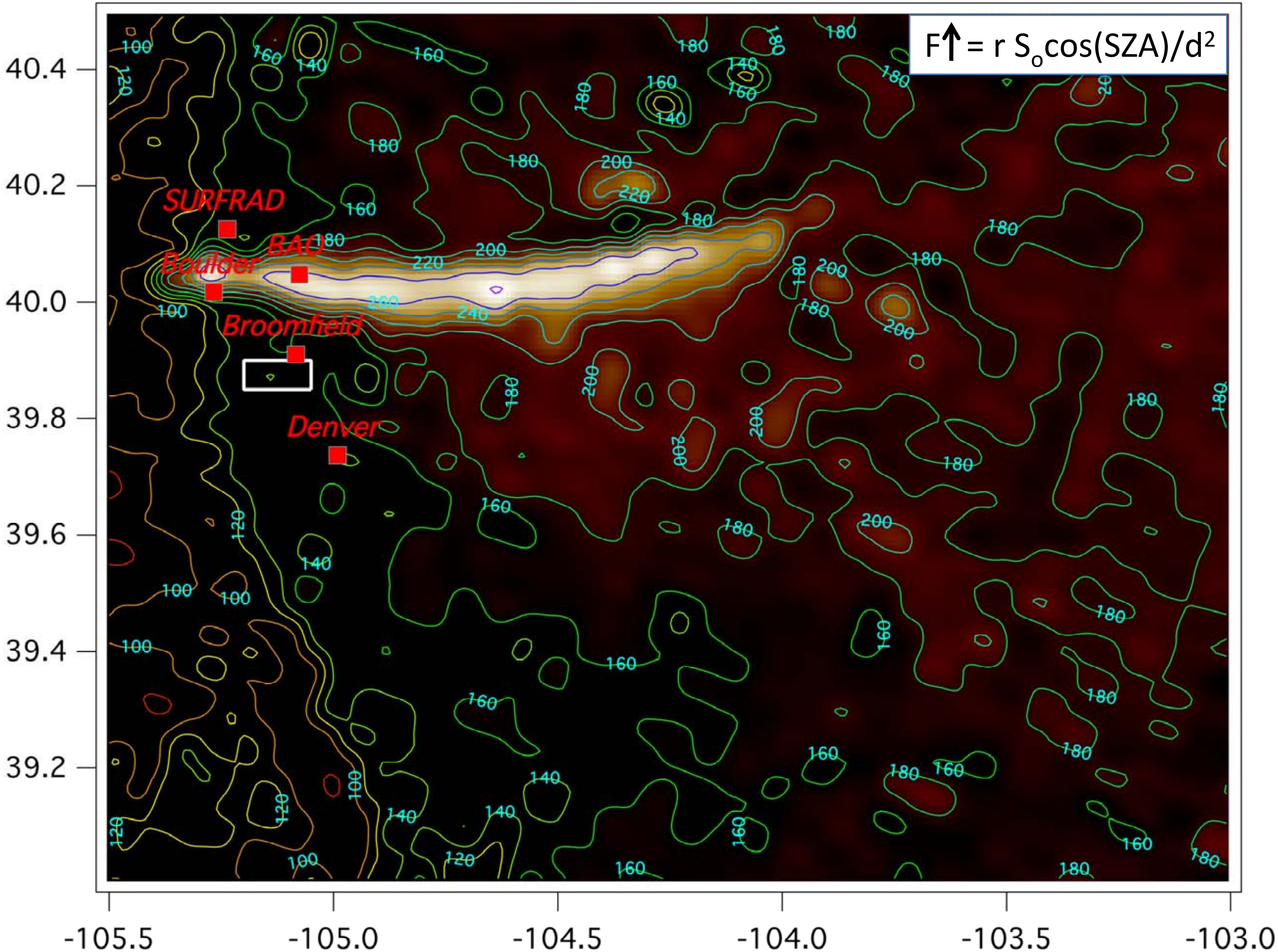
## 2000 UTC, ~ 3.5 hours after the fire started



# Aqua broadband reflectance 6 Sept. 2010, 2000 UTC



# Terra broadband TOA SW flux 6 Sept. 2010, 1820 L



# Calculations of SW Radiative Forcing

SW forcing is dominant -- can be 20 times greater than LW forcing

$$\text{Net SW}_{TOA} = [1361 * \cos(SZA)/d^2] - SW\uparrow_{TOA} \text{ (satellite)}$$

$$RF_{TOA} = \text{Net SW}_{TOA} \text{ (plume)} - \text{Net SW}_{TOA} \text{ (ref. area)}$$

$$RF_{sfc} = AOD_{500} * RFE_{SW} \text{ (from Stone et al. 2011)}$$

$$RF_{atmos} = RF_{TOA} - RF_{sfc}$$

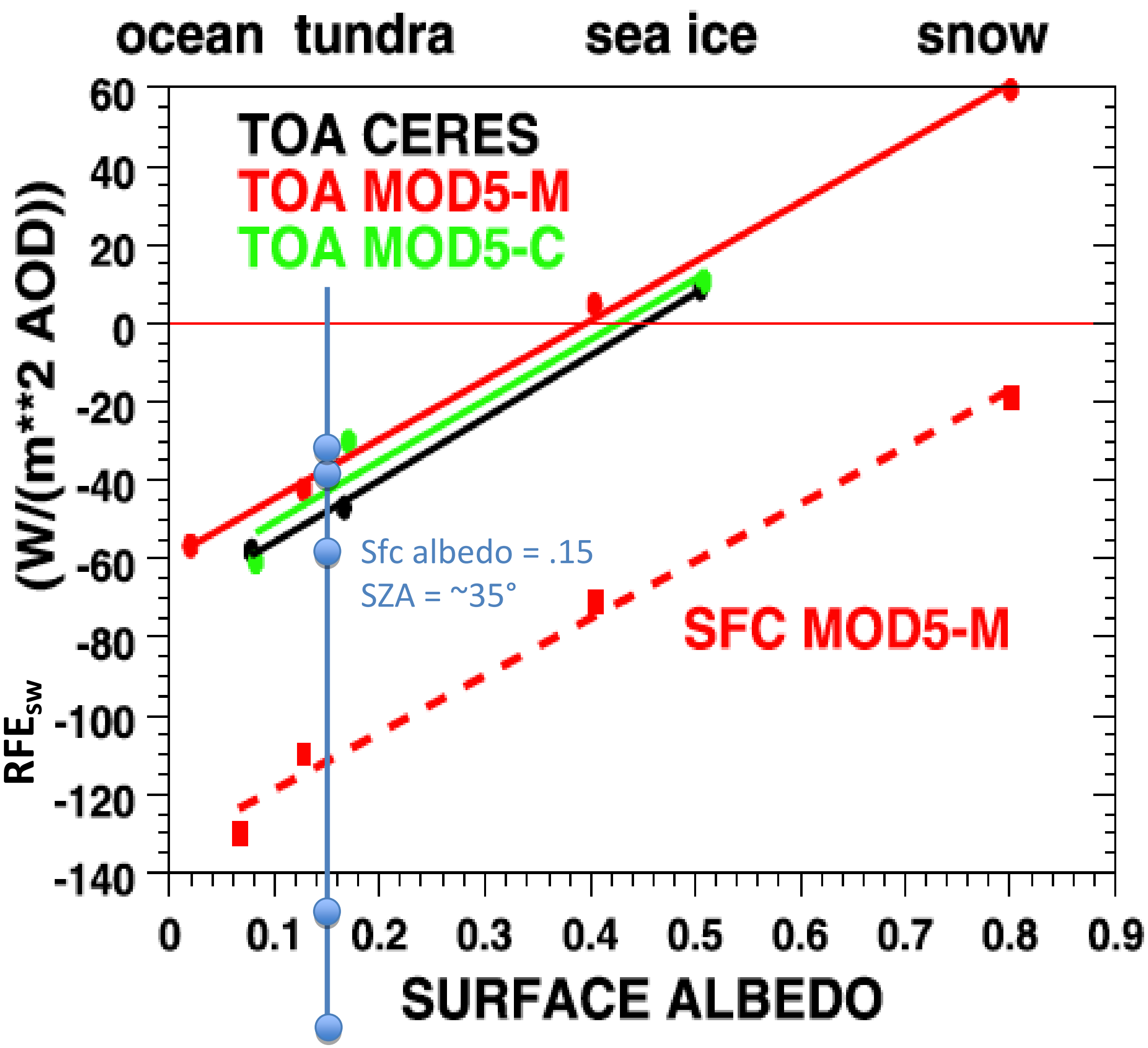
# RF Results (θ ~ 35°)

| | | $AOD_{500}$ | Sfc $RF_{sw}$ | TOA $RF_{sw}$ | Atmos. $RF_{sw}$ | Atmos. heating (°K/day) |
|---|---|---|---|---|---|---|
| Terra | SURFRAD 1820 UTC | 0.060 (-1 min.)<br>0.057<br>0.058 (+1 min.) | | -0.6 $Wm^{-2}$ | | |
| | BAO 1820 UTC | 3.38<br>3.37<br>3.97 | -512 $Wm^{-2}$ (±5%) | -113 $Wm^{-2}$ (±6%) | +399 $Wm^{-2}$ (±7.5%) | → 12.6 |
| Aqua | SURFRAD 2000 UTC | 1.36<br>1.37<br>1.45 | -255 $Wm^{-2}$ | -58 $Wm^{-2}$ | +197 $Wm^{-2}$ | → 8.4 |
| | BAO 2000 UTC | 1.01<br>1.23<br>1.33 | -187 $Wm^{-2}$ | -75 $Wm^{-2}$ | +112 $Wm^{-2}$ | → 6.5 |

↓ 5°C cooling measured at surface

# RFE Results ($\theta$ ~ 35°)

| | | $AOD_{500}$ | Sfc $RFE_{sw}$ | TOA $RFE_{sw}$ | Atmos. $RFE_{sw}$ |
|---|---|---|---|---|---|
| Terra | SURFRAD 1820 UTC | 0.060 (-1 min.)<br>0.057<br>0.058 (+1 min.) | | 0 $Wm^{-2}$/AOD | |
| | BAO 1820 UTC | 3.38<br>3.37<br>3.97 | -152 $Wm^{-2}$/AOD (±5%) | -34 $Wm^{-2}$/AOD (±6%) | +118 $Wm^{-2}$/AOD (±7.5%) |
| Aqua | SURFRAD 2000 UTC | 1.36<br>1.37<br>1.45 | -186 $Wm^{-2}$/AOD | -42 $Wm^{-2}$/AOD | +143 $Wm^{-2}$/AOD |
| | BAO 2000 UTC | 1.01<br>1.23<br>1.33 | -152 $Wm^{-2}$/AOD | -61 $Wm^{-2}$/AOD | +91 $Wm^{-2}$/AOD |




SZA = 50°, From *JGR*, Stone et al. 2008

# Summary

- MODIS SW spectral to broadband conversion algorithm gives reasonable results at TOA

- TOA aerosol radiative forcing computed from MODIS-based broadband SW fluxes consistent with similar empirical and model case study results

# Plans

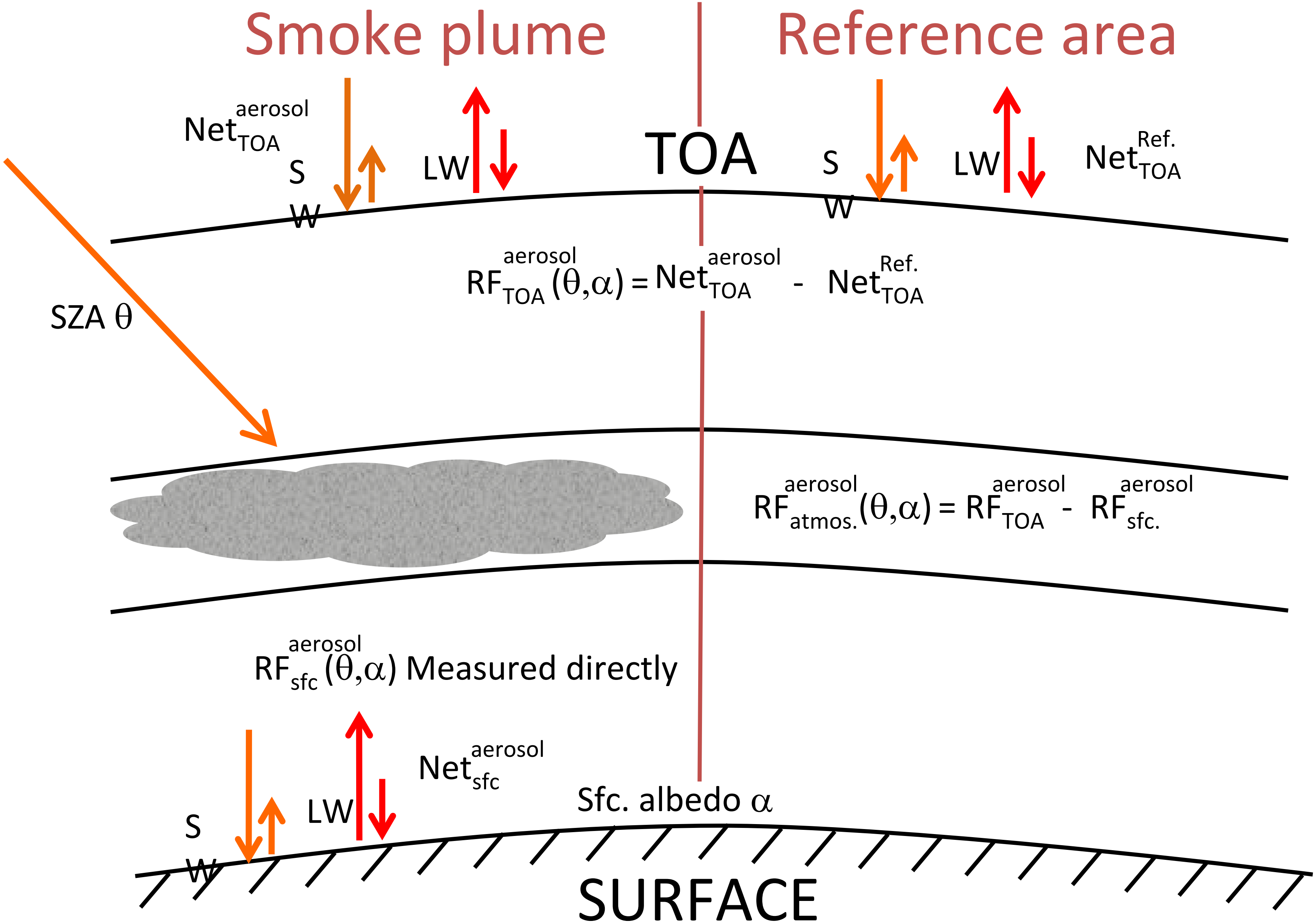
- Model observed surface radiation fluxes with MODTRAN using the actual particle size distribution as measured by CSD, measured spectral albedo, aerosol microphysics, etc.

- Model the TOA SW fluxes at the BAO and SURFRAD locations to validate the satellite-based results and expand TOA calculations to the entire day

- Use MODTRAN to estimate LW TOA radiative forcing of the smoke aerosol

END

Questions?



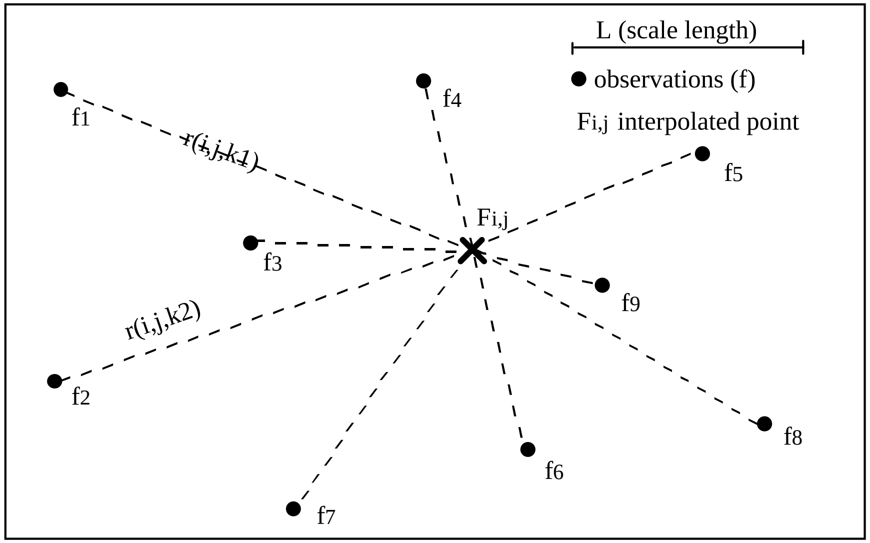
Smoke plume
Reference area
$Net_{TOA}^{aerosol}$
SW
LW
TOA
SW
LW
$Net_{TOA}^{Ref.}$
$RF_{TOA}^{aerosol}(\theta,\alpha) = Net_{TOA}^{aerosol} - Net_{TOA}^{Ref.}$
SZA θ
$RF_{atmos.}^{aerosol}(\theta,\alpha) = RF_{TOA}^{aerosol} - RF_{sfc.}^{aerosol}$
$RF_{sfc}^{aerosol}(\theta,\alpha)$ Measured directly
$Net_{sfc}^{aerosol}$
SW
LW
Sfc. albedo α
SURFACE

# Analytic Approximation method of Caracena (1987) used to interpolate to a 0.1 km grid

$$\langle F_{i,j} \rangle = \sum_{k=1}^{N} w_{i,j,k} \frac{f_k}{N_{i,j}},$$ Weighted sum

$$where: N_{i,j} = \sum_{l-1}^{N} w_{i,j,k}$$

Gaussian weights are used: $$w_{i,j,k} = \exp\left\{ -\frac{\left| r_{i,j,k} \right|^2}{L^2} \right\}$$




To effect three more passes of analyzing and removing residuals, the above equation becomes:

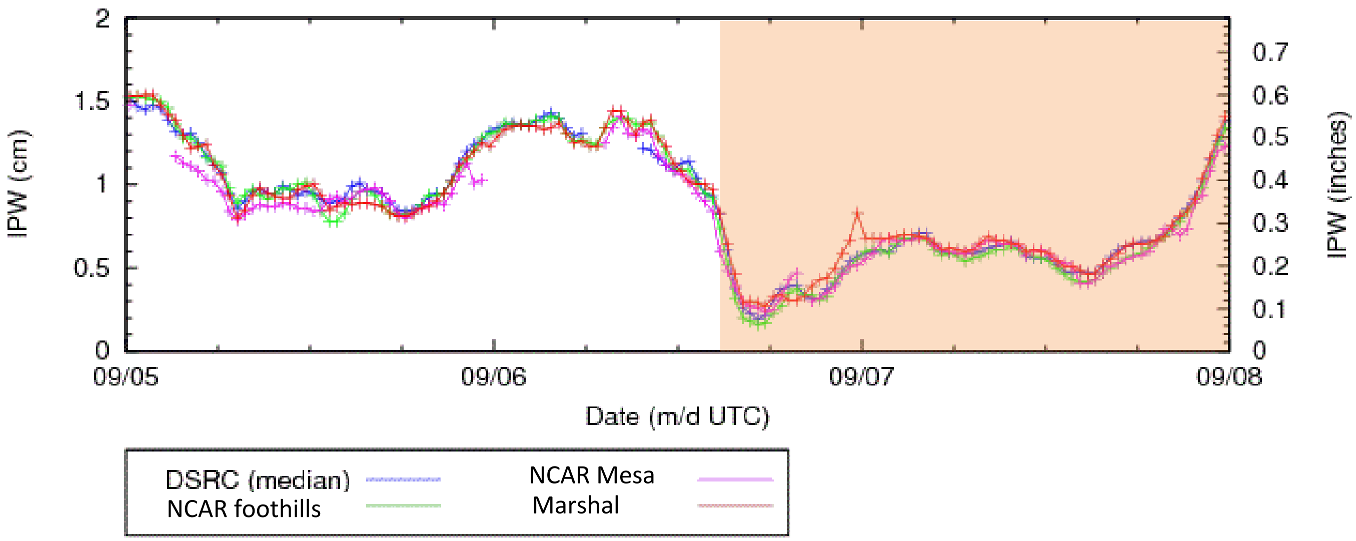
$$\langle F_{i,j} \rangle^{(4)} = \sum_{k=1}^{N} w_{i,j,k} \frac{\left(4I - 6W + 4W^2 - W^3\right) f_k}{N_{i,j}}$$ Weighted sum with residuals removed in three successive passes

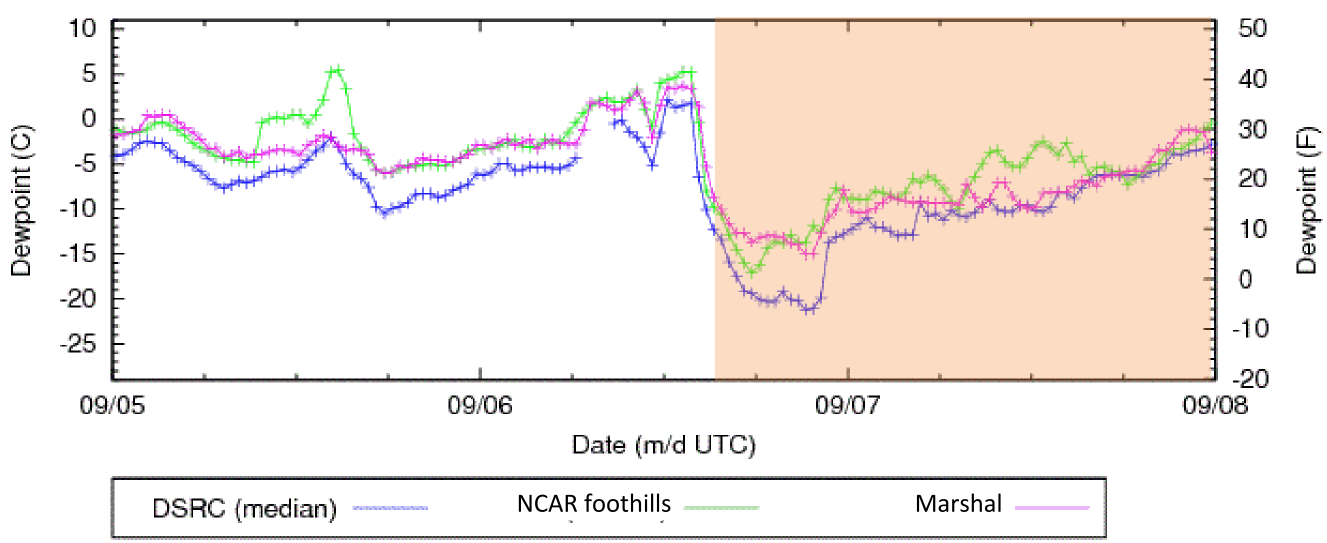
$where: W = crossweight\ matrix$

$and: I = Identity\ matrix$

# GPS water vapor data

(Courtesy of Seth Gutman)



# Radiative Forcing Efficiency ($RFE_x$) valid for sfc. Albedo of 0.15

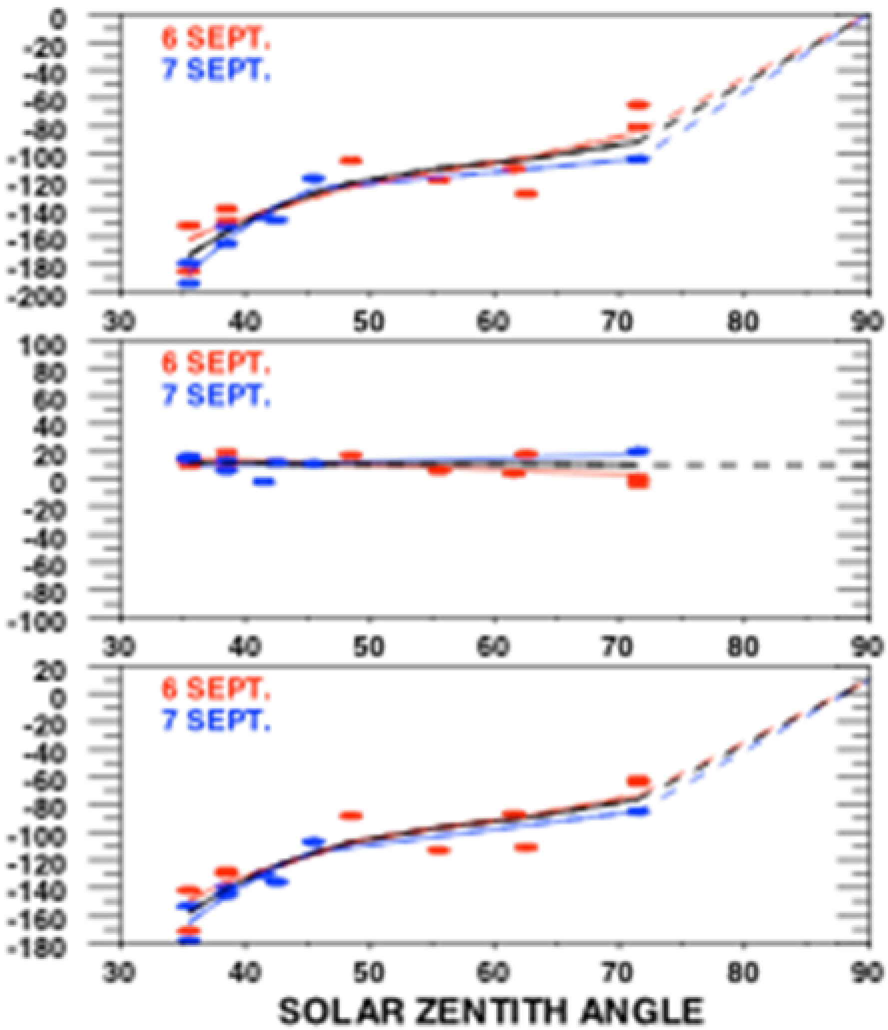
$RFE_{sw}$ $Wm^{-2}/AOD_{500}$

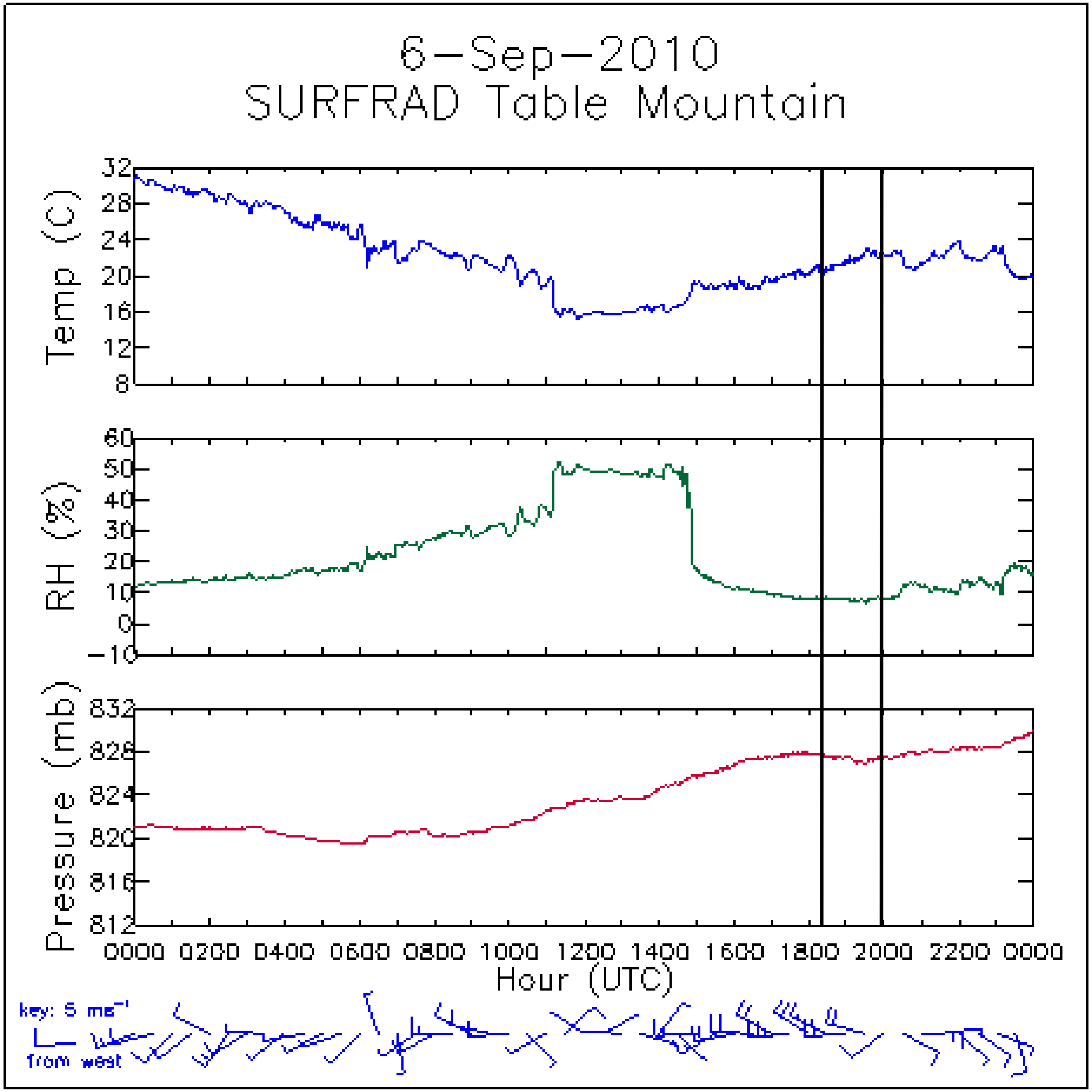
-194 to 0 $Wm^{-2}/AOD_{500}$
In the daytime

$RFE_{Lw}$ $Wm^{-2}/AOD_{500}$

+10 $Wm^{-2}/AOD_{500}$
Day and night

$RFE_{all\ wave}$ $Wm^{-2}/AOD_{500}$





6-Sep-2010
SURFRAD Table Mountain
Temp (C)
32
28
24
20
16
12
8
RH (%)
60
50
40
30
20
10
0
-10
Pressure (mb)
832
828
824
820
816
812
0000 0200 0400 0600 0800 1000 1200 1400 1600 1800 2000 2200 0000
Hour (UTC)
key: 5 ms⁻¹
from west

# Terra coverage 18:18:43 to 18:19:24 UTC (41 sec.)