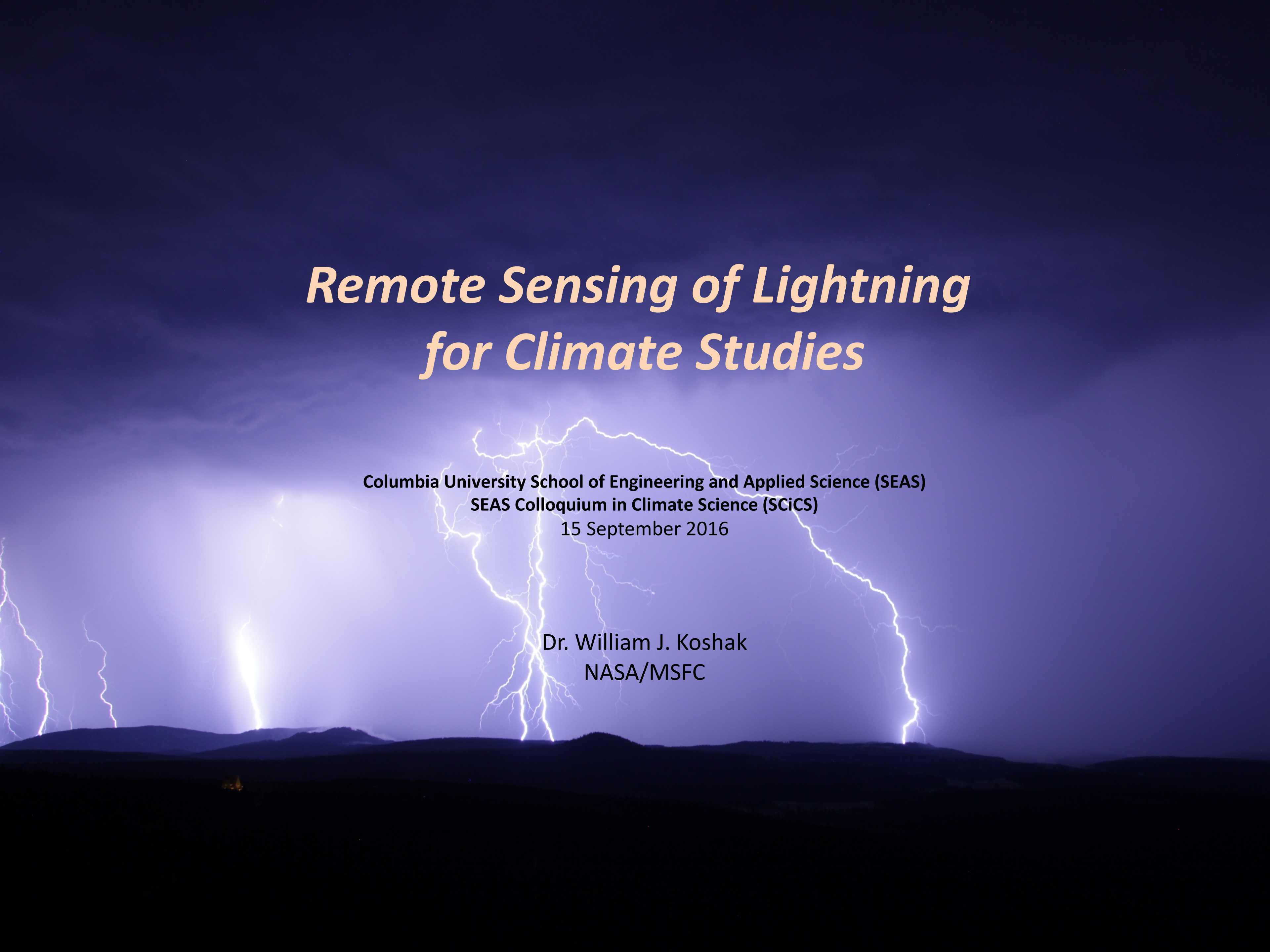


Remote Sensing of Lightning for Climate Studies

Columbia University School of Engineering and Applied Science (SEAS)
SEAS Colloquium in Climate Science (SCiCS)
15 September 2016

Dr. William J. Koshak
NASA/MSFC

Overview

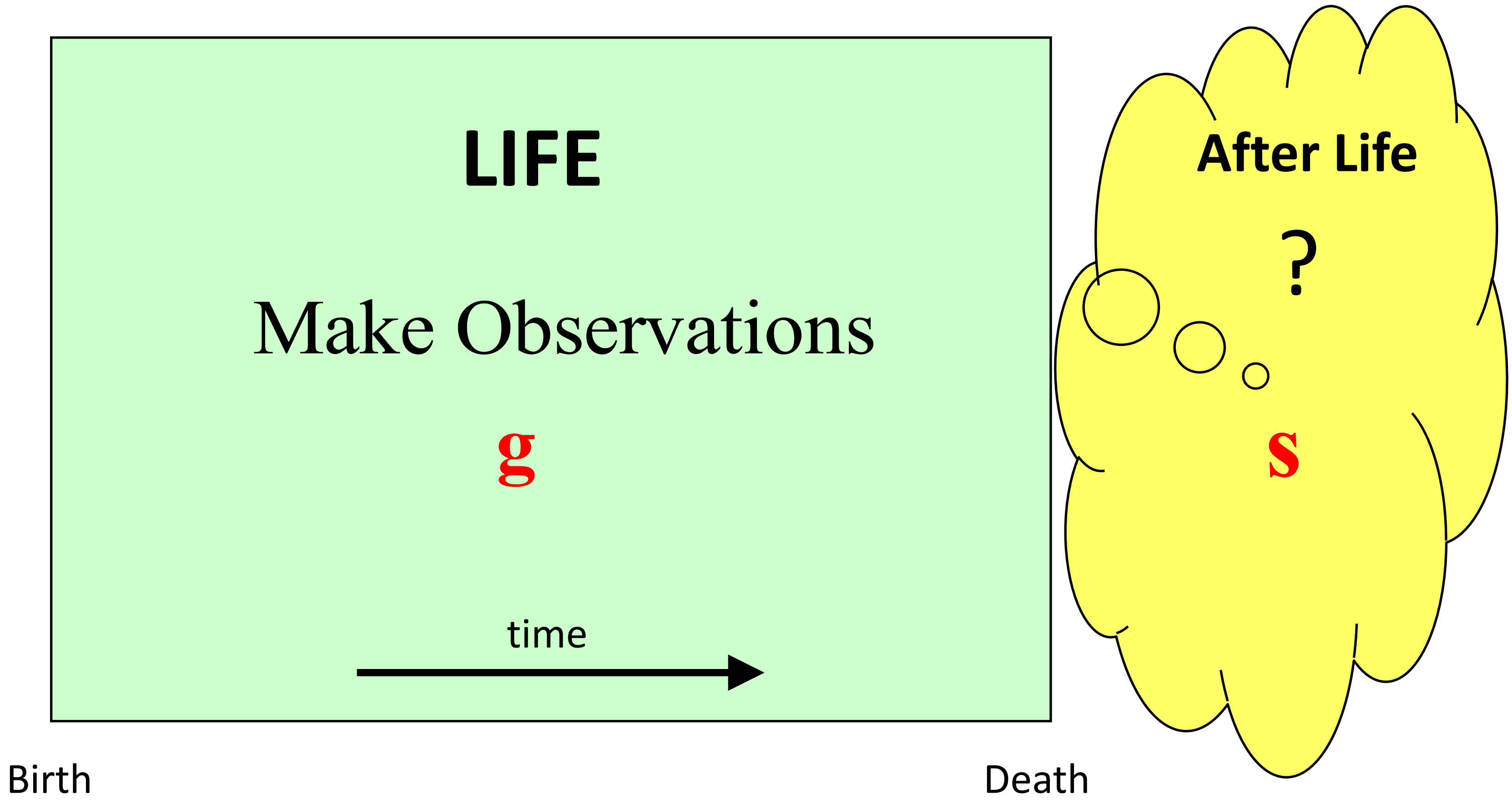
- Inverse Problems
- Lightning Retrievals
- NCA Activities
- Questions


Inverse Problems

First Inversion Scientists

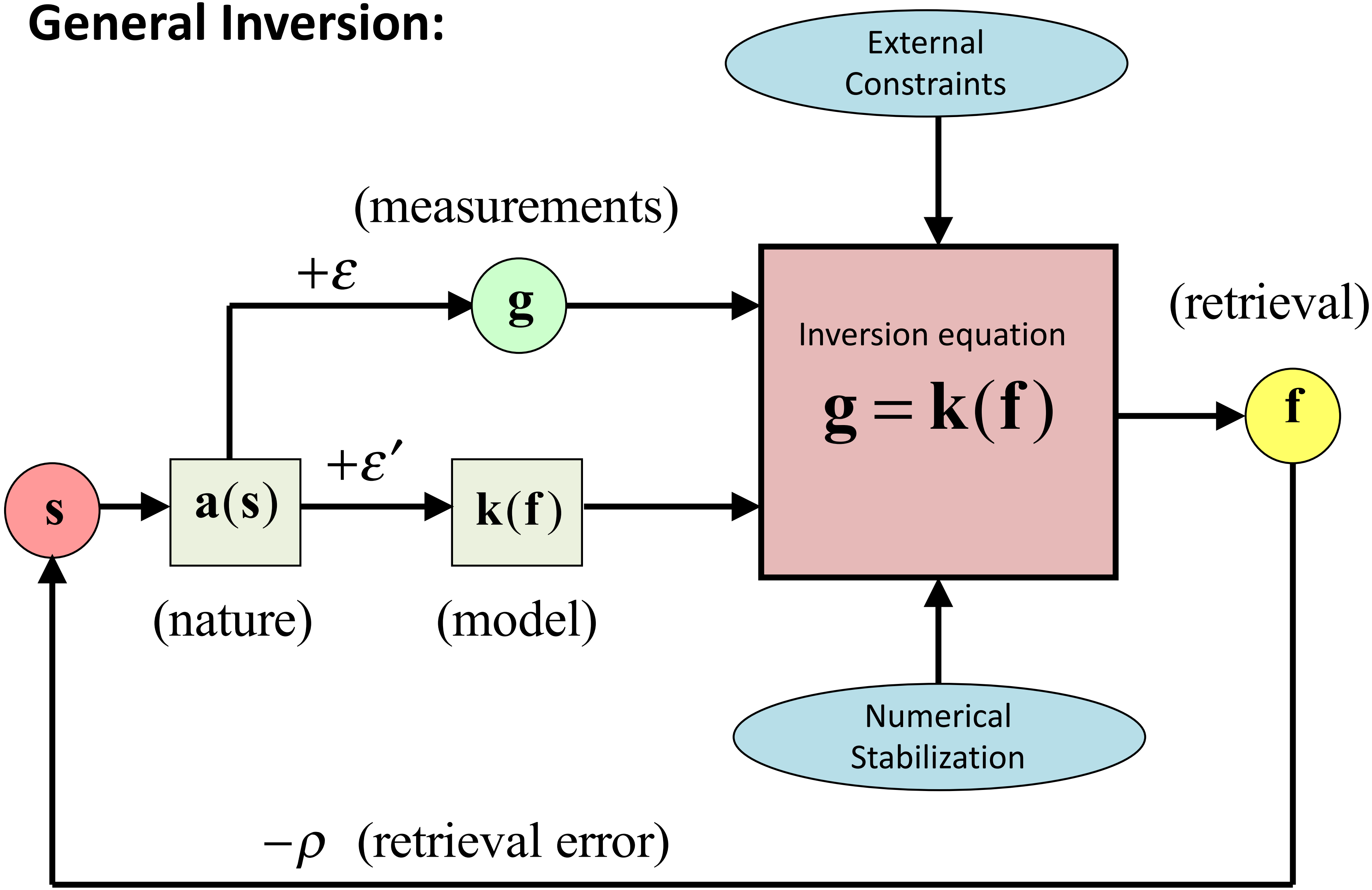
Hunger …
Tracks …
Invert …
Follow? …
Find …
Kill …
Eat !

Everyone is an Inverter !



g(s)

General Inversion:

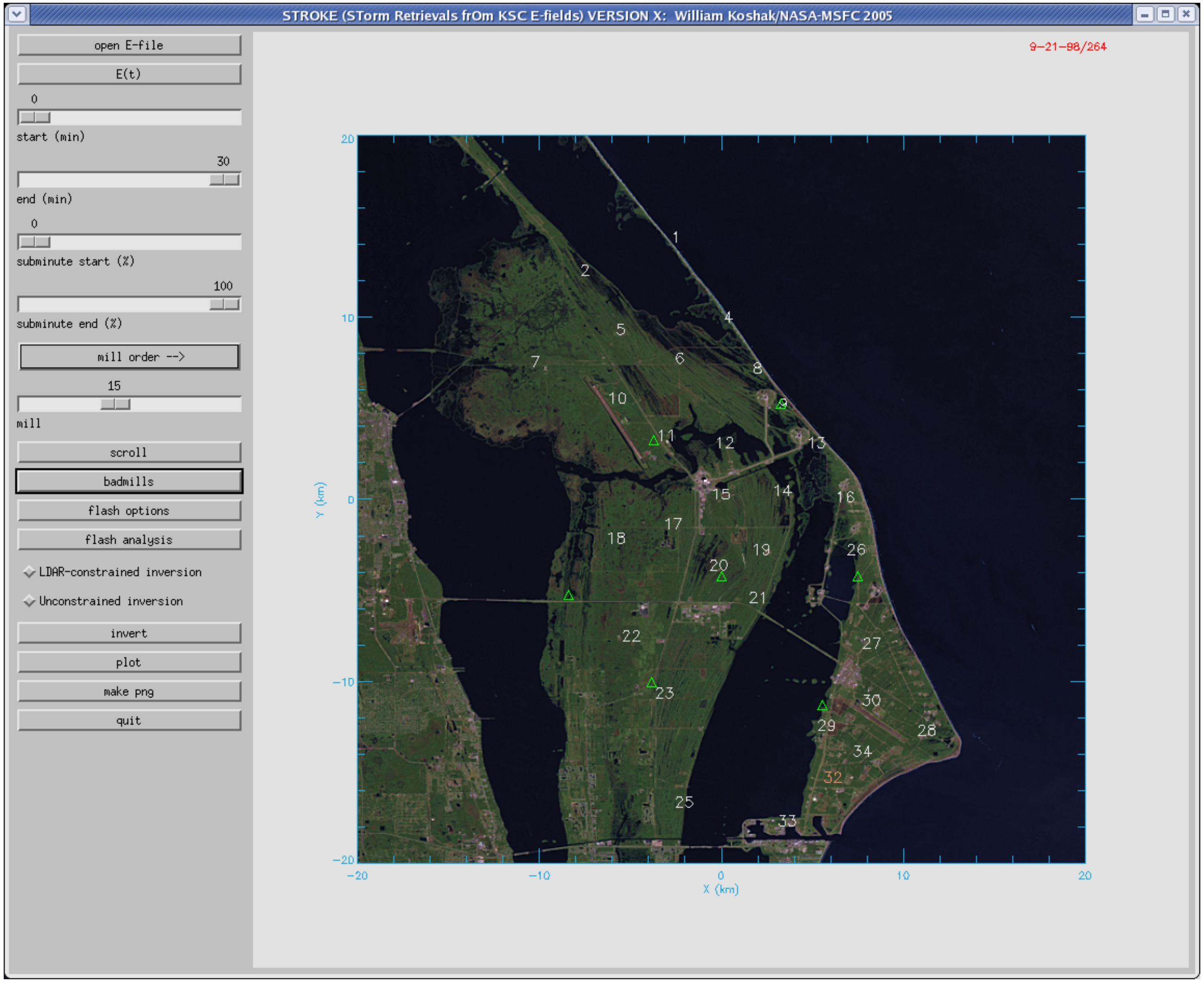



Lightning Retrievals

Sample List

Item	Measurement	Retrieval
Ground-Based		
1	Electrostatic field changes	Charges deposited by Lightning
2	Displacement current	Thundercloud current source
3	VHF time-of-arrival	Channel mapping
4	VLF/LF radiated electric field amplitude, (also Magnetic direction & time-of-arrival)	CG return stroke peak current, (CG strike location)
5	LNOM: VHF time-of-arrival & VLF/LF radiated E	LNOx
In-Situ		
6	Aircraft electric field mill amplitude	Thundercloud electric field *(not discussed further, for brevity)*
Satellite		
7	Maximum Group Area (MGA) in optical	Flash type (CG or cloud flash)
8	Intercepted flash optical energy	LNOx

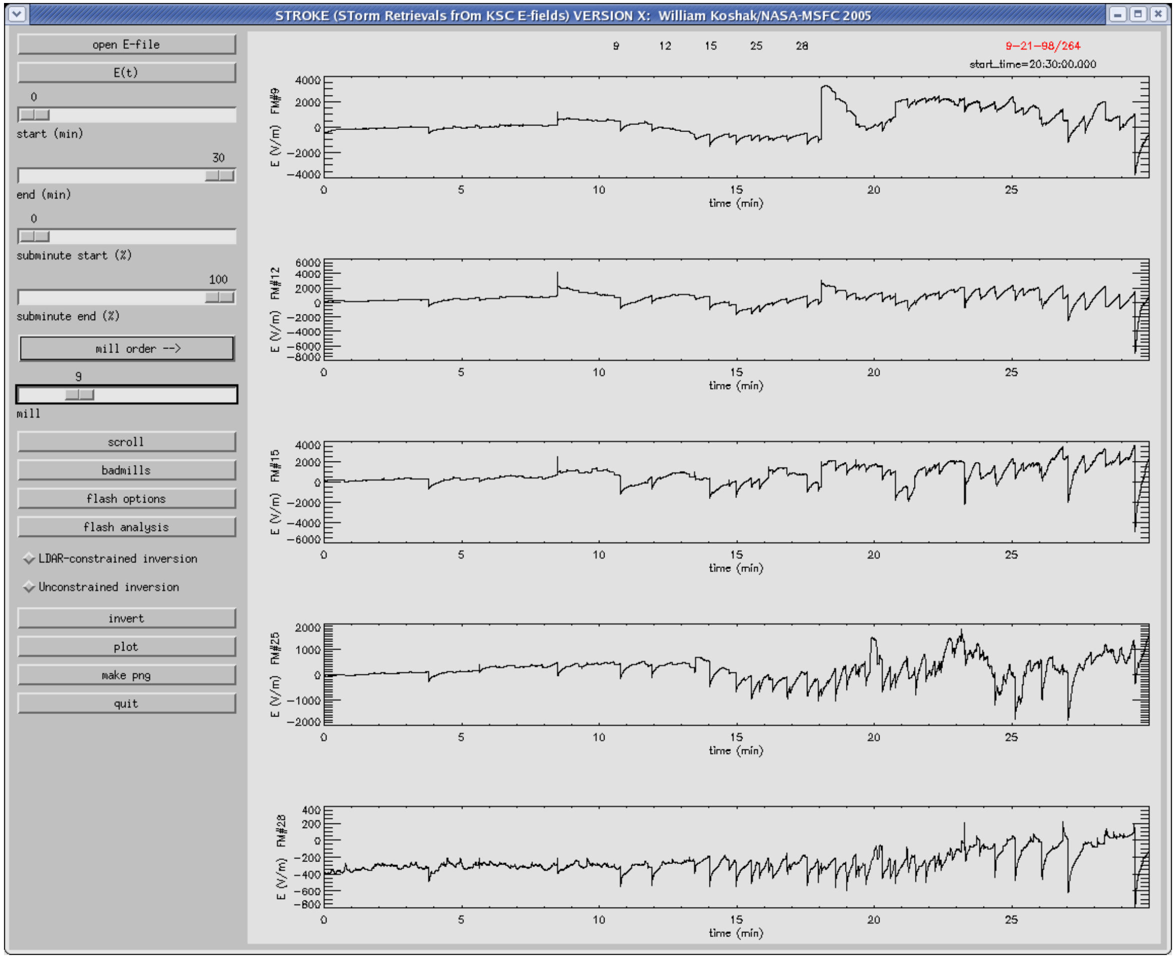
Charge



KSC, FL FIELDMILL NETWORK

W. Koshak, NASA/MSFC ZP11

Charge (cont.)



SURFACE ELECTRIC FIELD

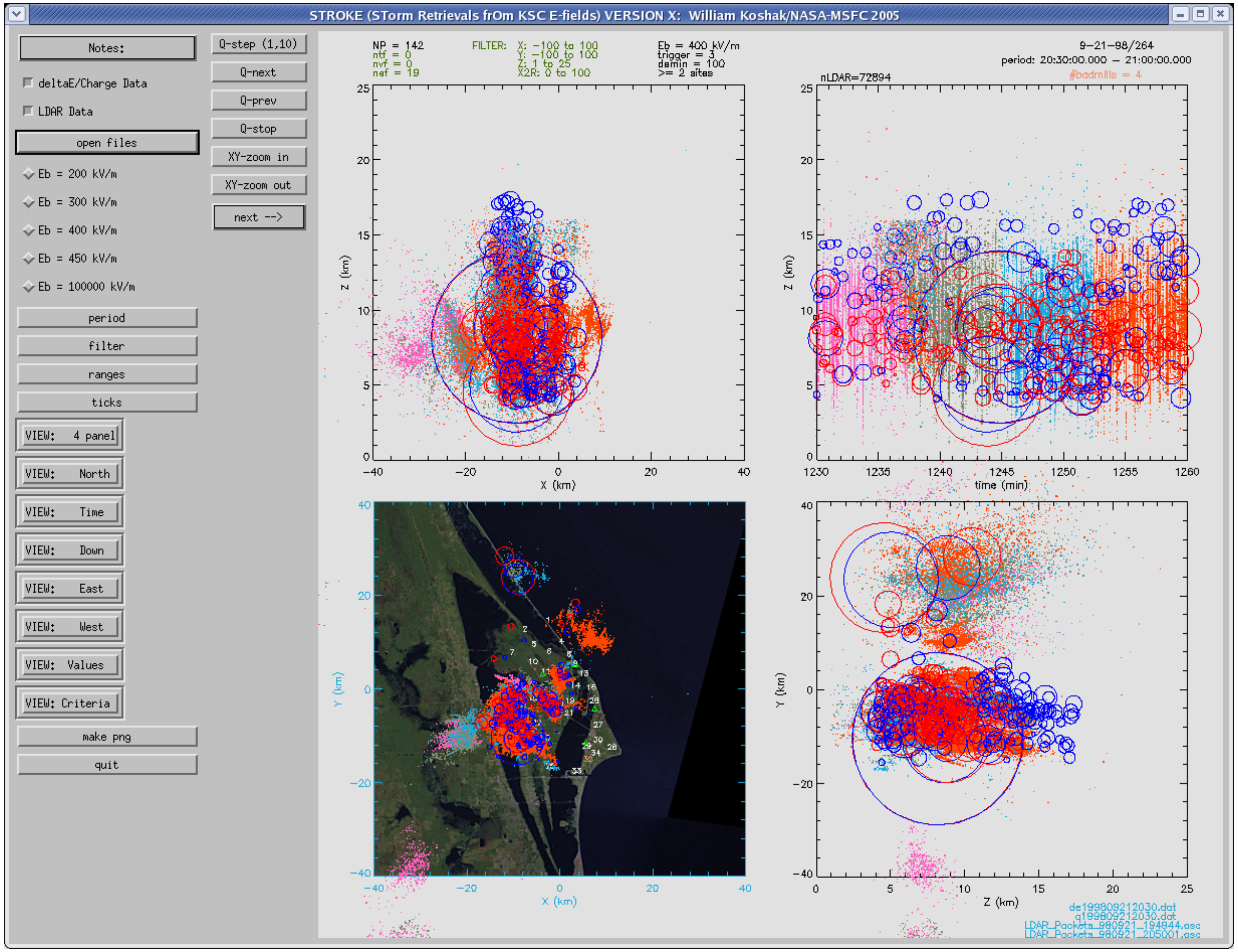
Charge (cont.)

$$\Delta E(x,y) = \int_{UHS} K(x,y,\mathbf{r}')\Delta\rho(\mathbf{r}')dV'$$

Charge (cont.)

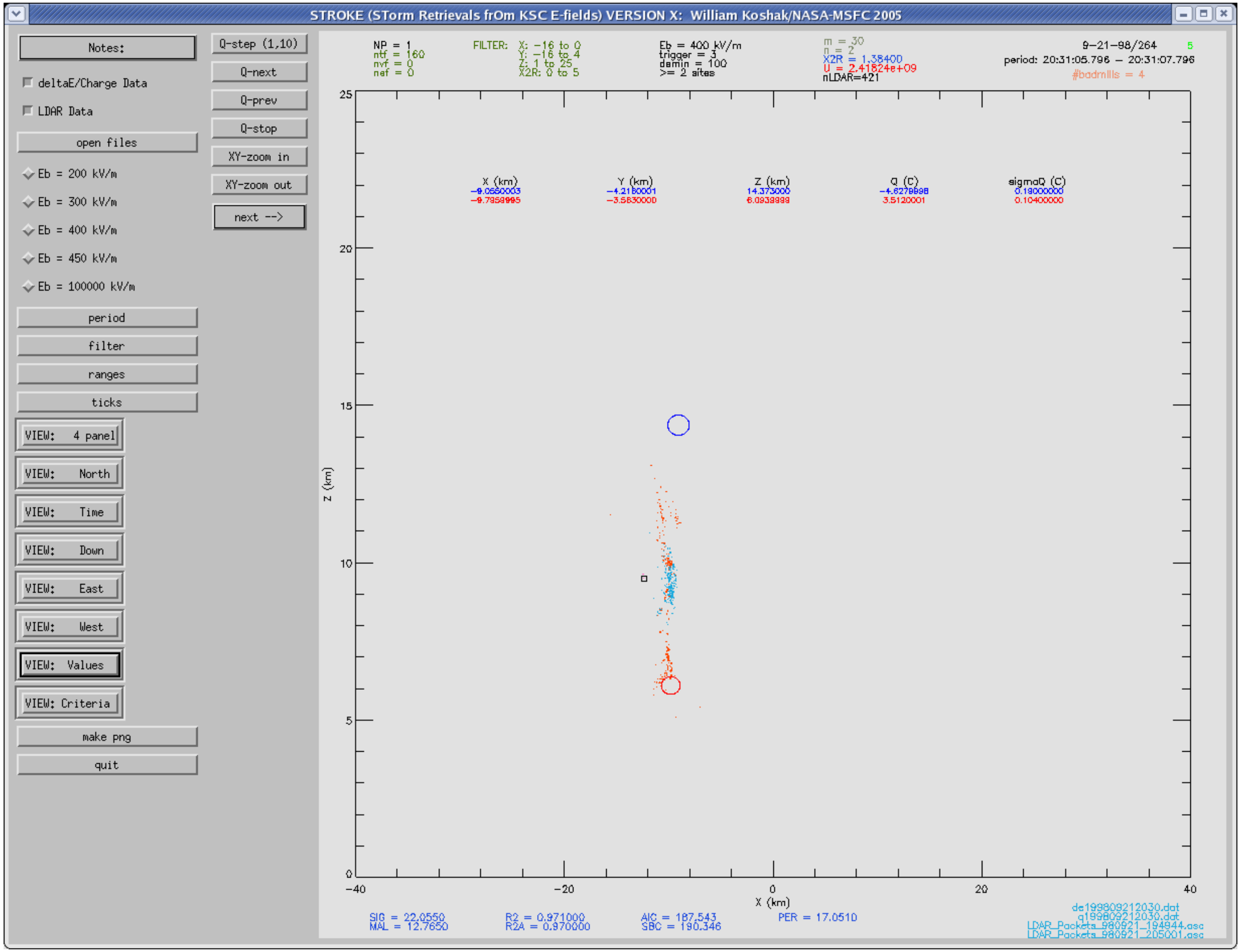
$$\chi^2 = \frac{1}{m-n}\sum_{i=1}^{m}\frac{\left[\Delta E_i - M_i(p_1, \ldots, p_n)\right]^2}{\sigma_i^2}$$

Charge (cont.)



STROKE (STorm Retrievals frOm KSC E-fields) VERSION X: William Koshak/NASA-MSFC 2005
Notes:
deltaE/Charge Data
LDAR Data
open files
Eb = 200 kV/m
Eb = 300 kV/m
Eb = 400 kV/m
Eb = 450 kV/m
Eb = 100000 kV/m
period
filter
ranges
ticks
VIEW: 4 panel
VIEW: North
VIEW: Time
VIEW: Down
VIEW: East
VIEW: West
VIEW: Values
VIEW: Criteria
make png
quit
Q-step (1,10)
Q-next
Q-prev
Q-stop
XY-zoom in
XY-zoom out
next -->
Z (km)
X (km)
time (min)
Y (km)

Charge (cont.)

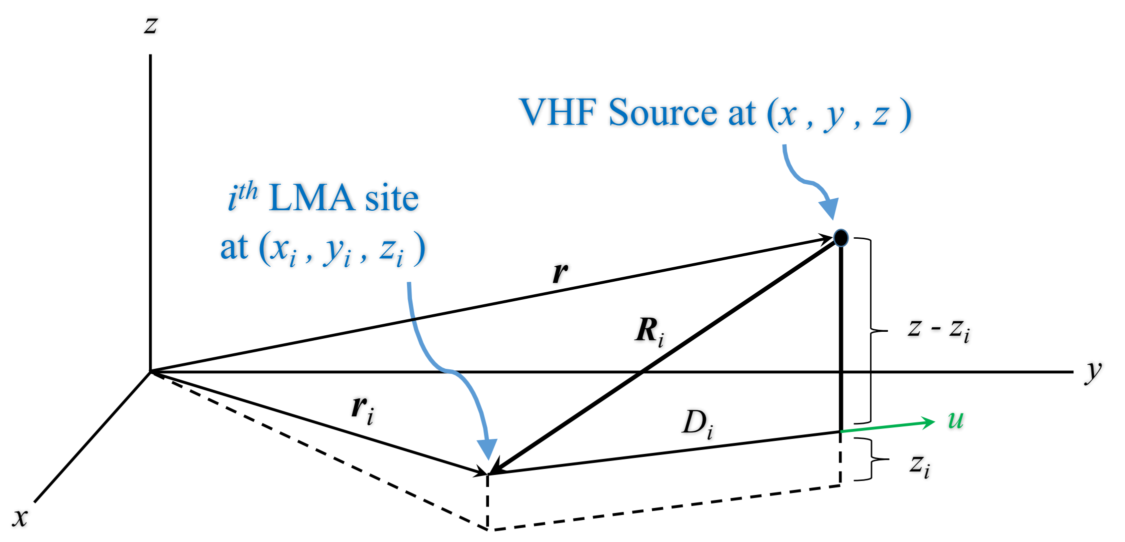


STROKE (STorm Retrievals frOm KSC E-fields) VERSION X: William Koshak/NASA-MSFC 2005
Notes:
deltaE/Charge Data
LDAR Data
open files
Eb = 200 kV/m
Eb = 300 kV/m
Eb = 400 kV/m
Eb = 450 kV/m
Eb = 100000 kV/m
period
filter
ranges
ticks
VIEW: 4 panel
VIEW: North
VIEW: Time
VIEW: Down
VIEW: East
VIEW: West
VIEW: Values
VIEW: Criteria
make png
quit
Q-step (1,10)
Q-next
Q-prev
Q-stop
XY-zoom in
XY-zoom out
next -->
X (km)
Y (km)
Z (km)
Q (C)
sigmaQ (C)
Z (km)
X (km)

Thundercloud Current

$$\frac{\partial E(x,y)}{\partial t} = \int_{UHS} K(x,y,\mathbf{r}') \frac{\partial \rho(\mathbf{r}')}{\partial t} dV'$$

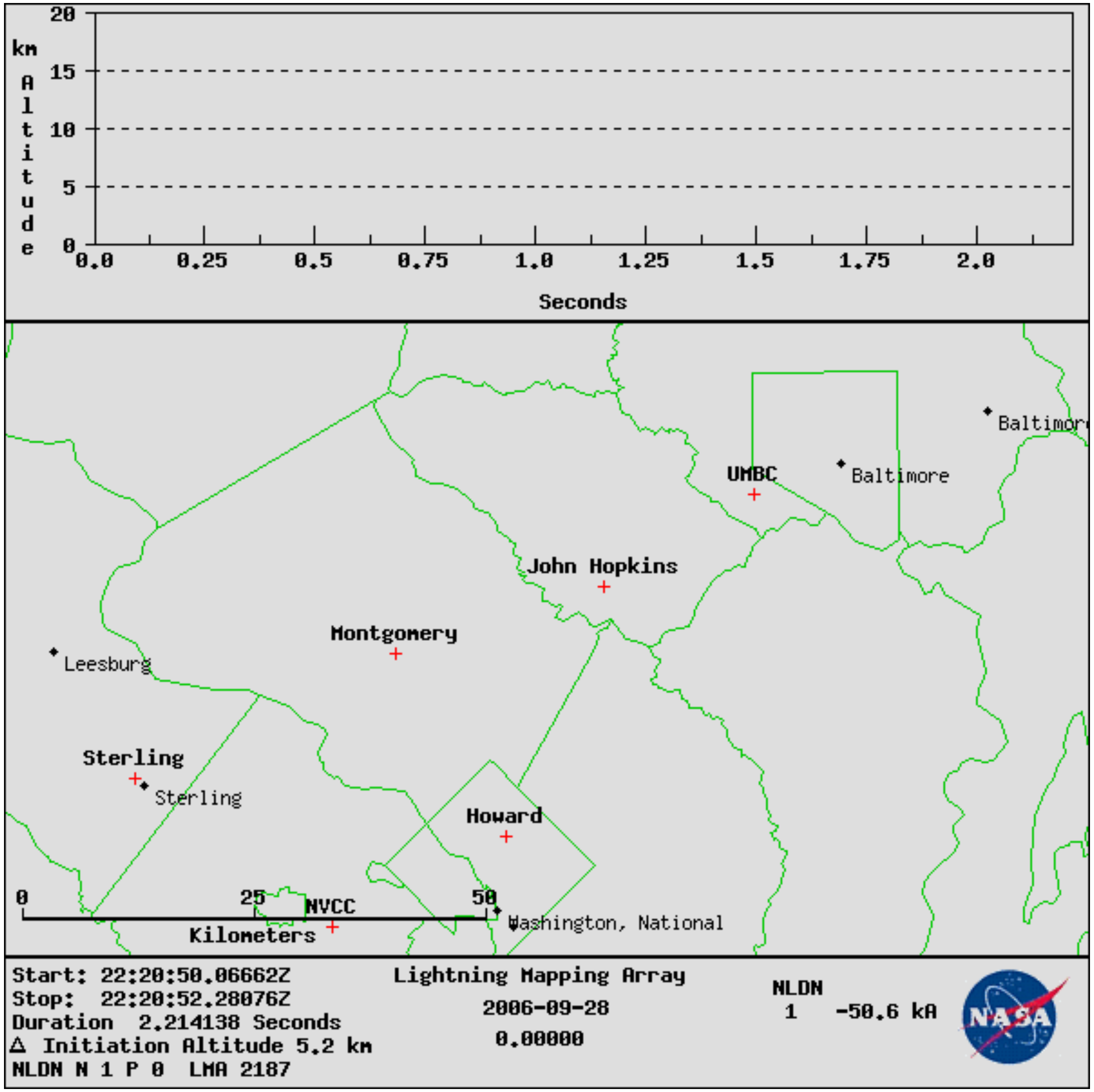
VHF Source



$$\chi^2 = \frac{1}{m-4} \sum_{i=1}^{m} \frac{\left[\tau_i - (t + R_i/c)\right]^2}{\sigma_i^2}$$

DC Area Lightning Discharge- Animation

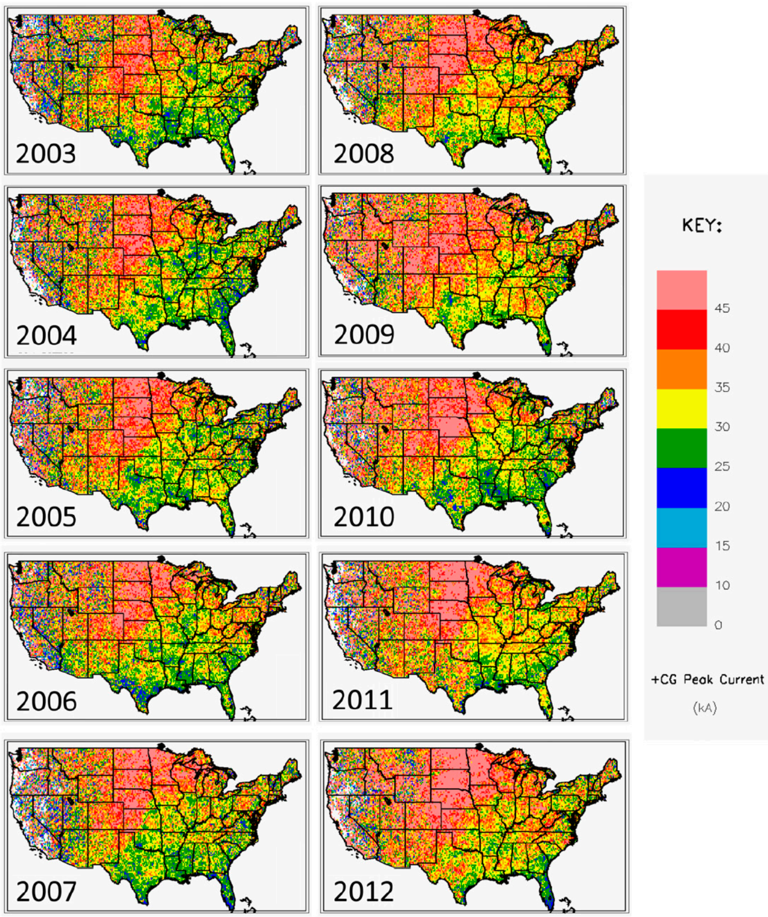
- 2.2 sec hybrid flash
- 50 km horiz extent
- Initiation at 5.2 km
- VHF Sources 2187
- CG strike at 2 s

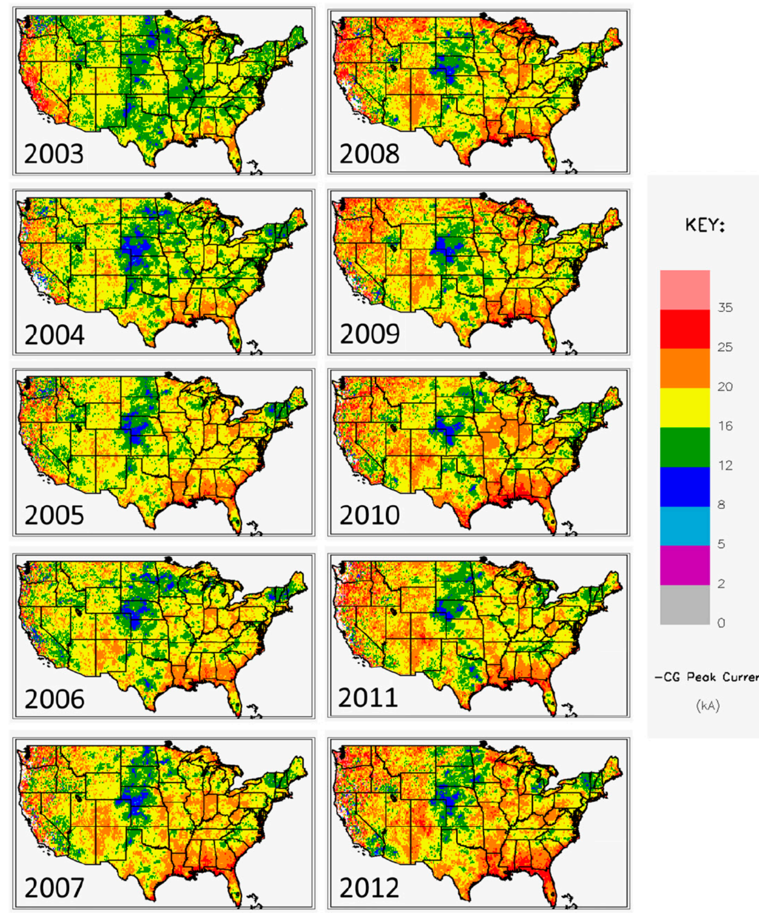


CG Peak Current

$$E_{rad}(t) = -\frac{\mu_o v I(t - D/c)}{2\pi D}$$

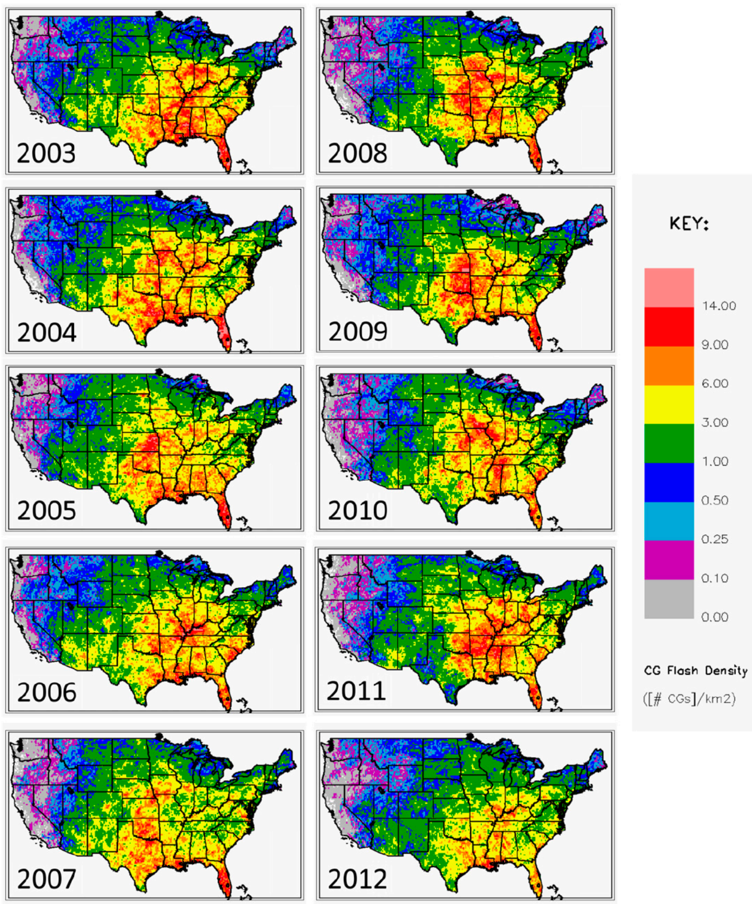
CG Peak Current

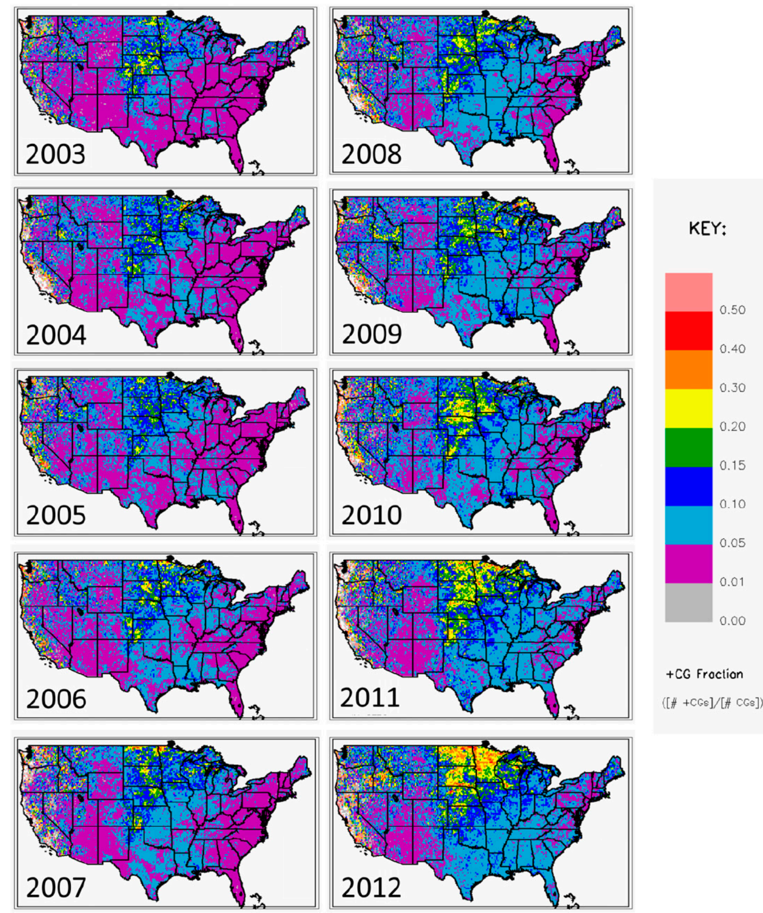




Koshak, W. J., K. L. Cummins, D. E. Buechler, B. Vant-Hull, R. J. Blakeslee, E. R. Williams, H. S. Peterson, 2015: Variability of CONUS Lightning in 2003-12 and Associated Impacts, *J. Appl. Meteorol. Climatology*, **54**, No. 1, 15-41.

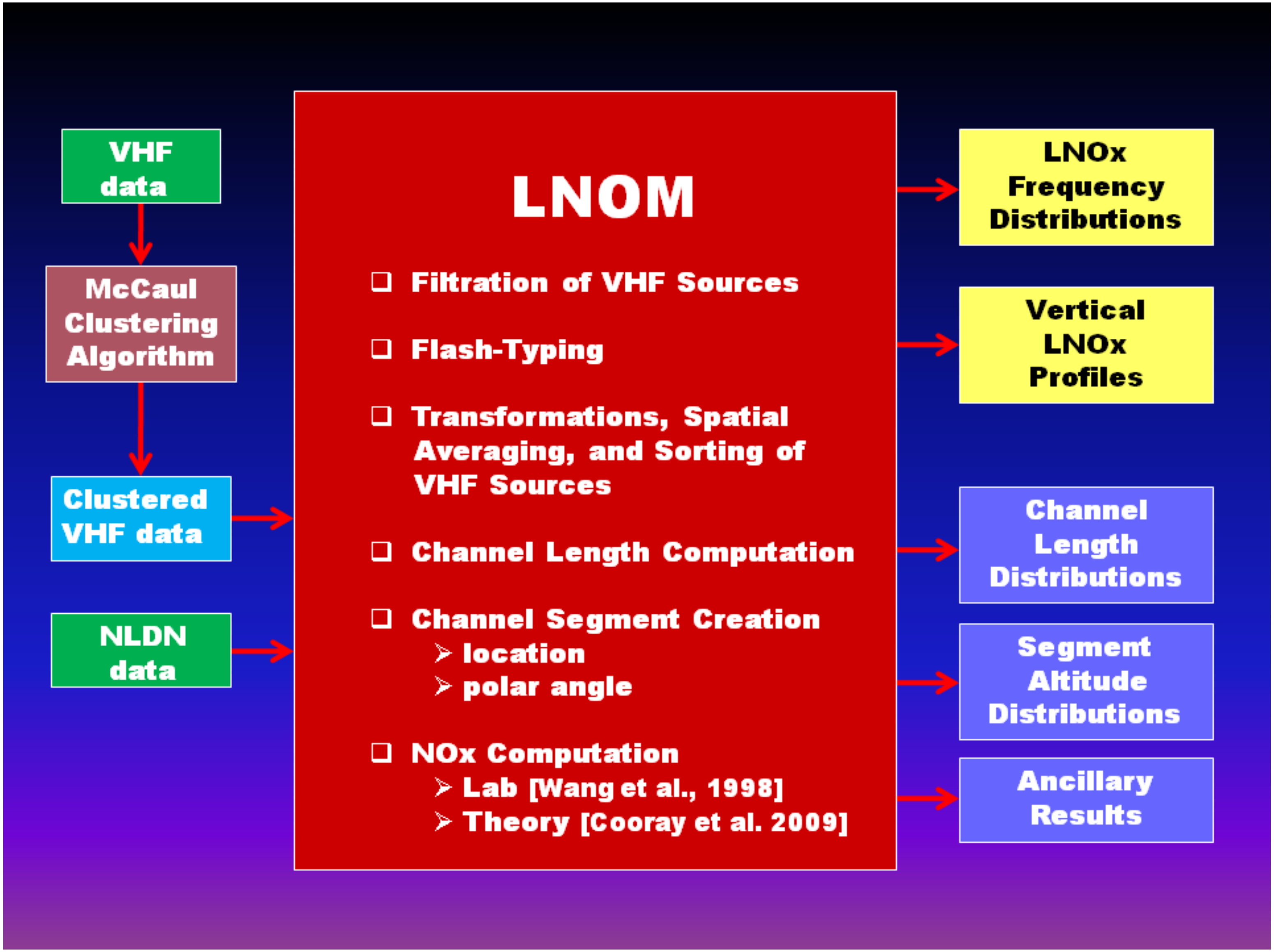
CG Flash Density



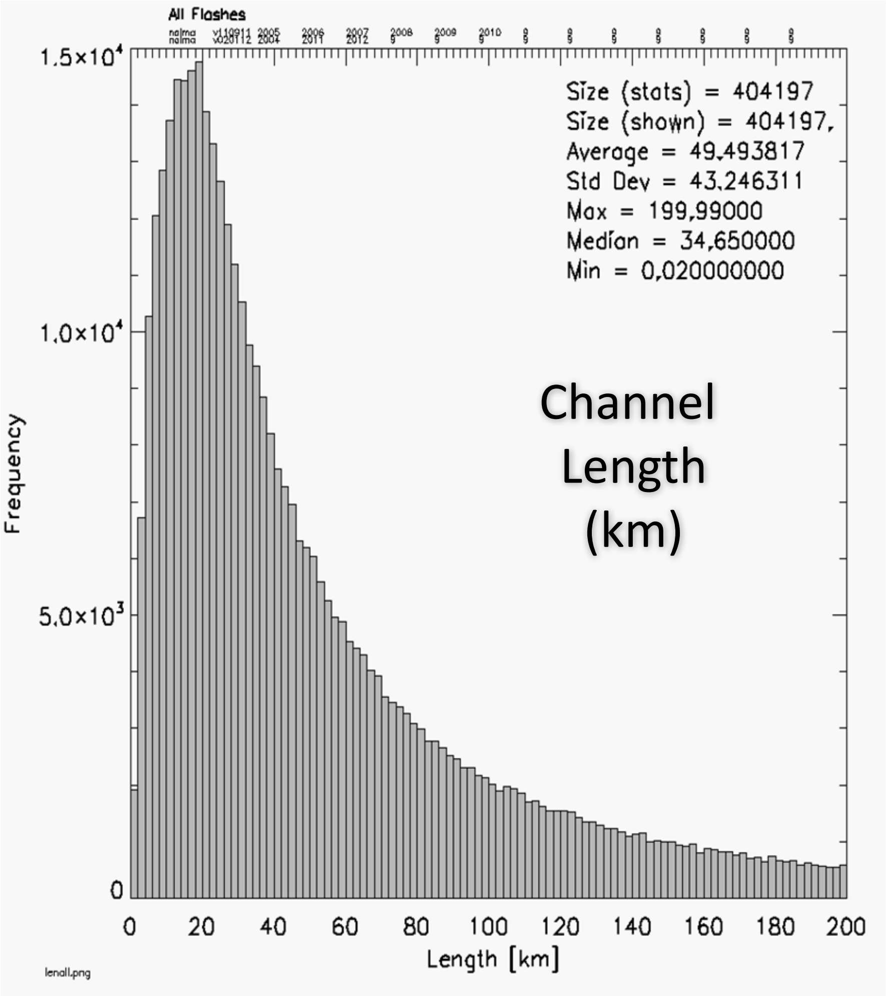


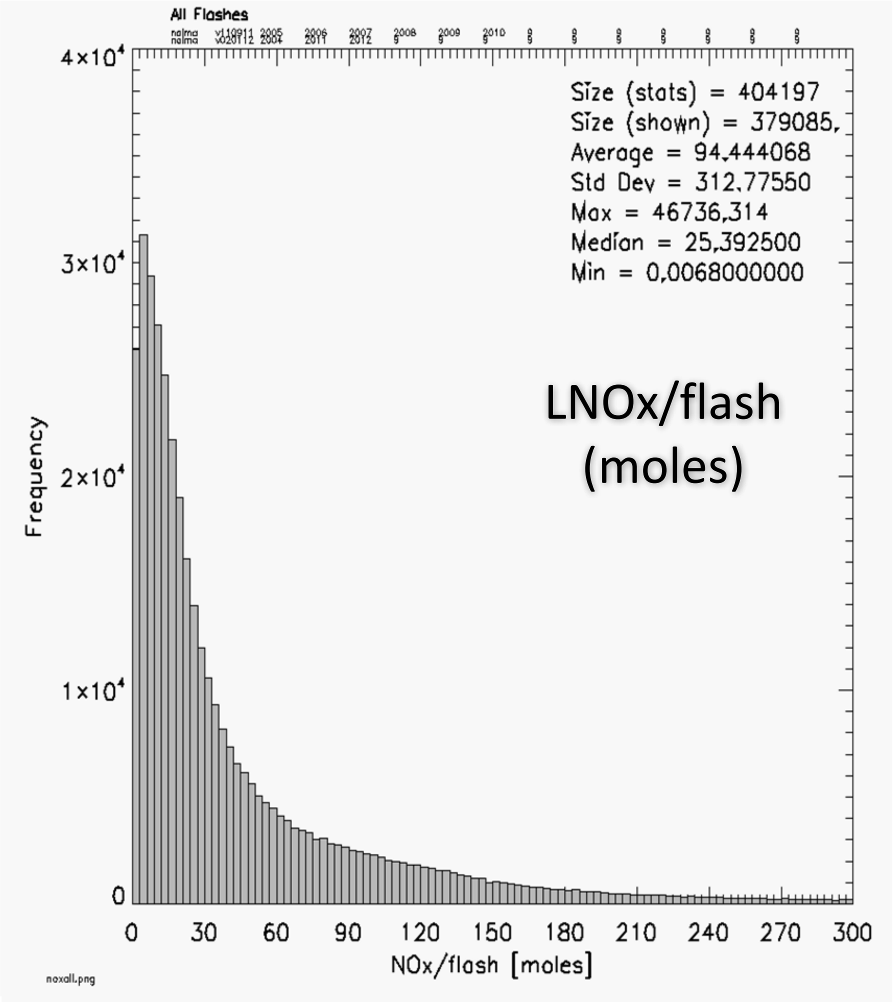
Koshak, W. J., K. L. Cummins, D. E. Buechler, B. Vant-Hull, R. J. Blakeslee, E. R. Williams, H. S. Peterson, 2015: Variability of CONUS Lightning in 2003-12 and Associated Impacts, *J. Appl. Meteorol. Climatology*, **54**, No. 1, 15-41.

MSFC Lightning Nitrogen Oxides Model (LNOM)



MSFC Lightning Nitrogen Oxides Model (LNOM)



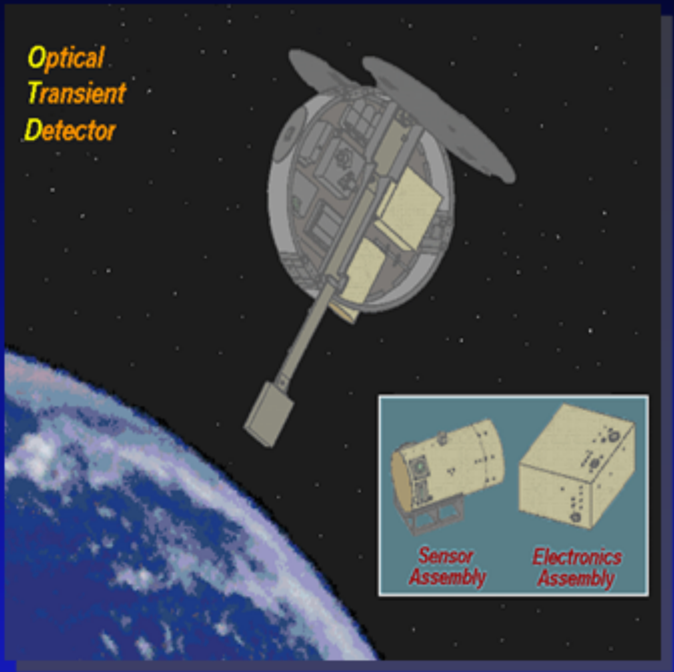


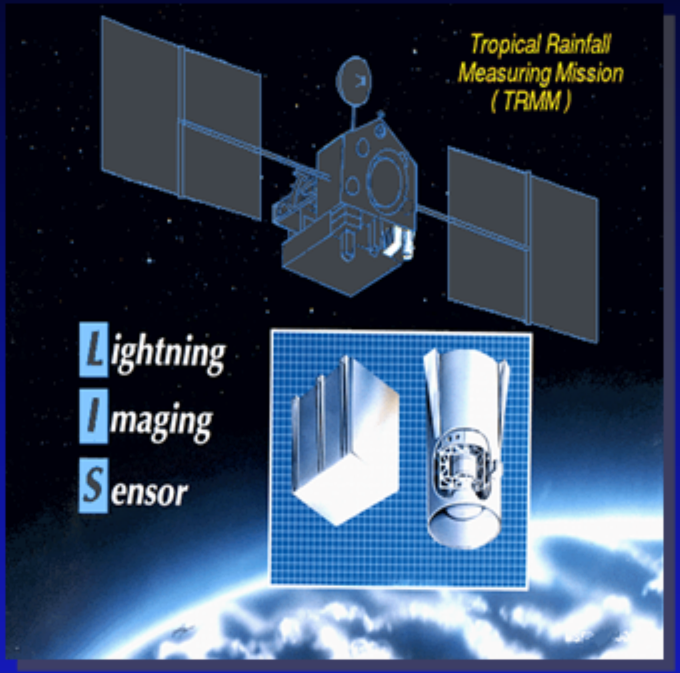
W. Koshak, NASA/MSFC ZP11

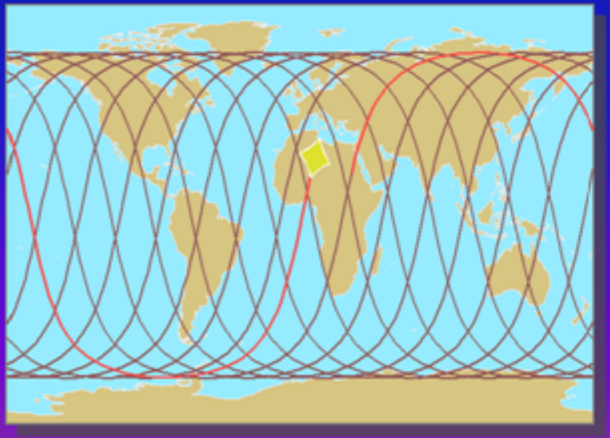
Flash Type (CG or cloud flash)

Space Shuttle Video (STS-48)

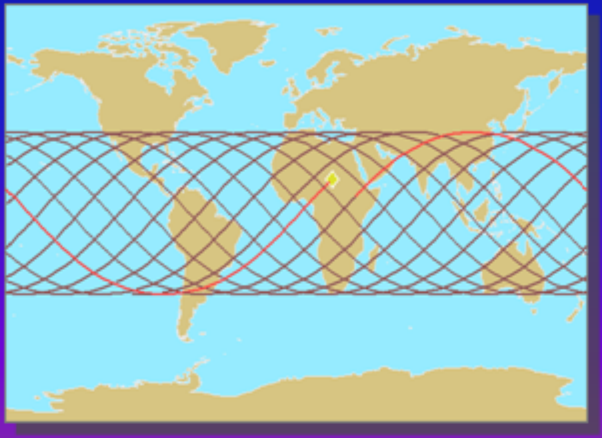
OTD & LIS



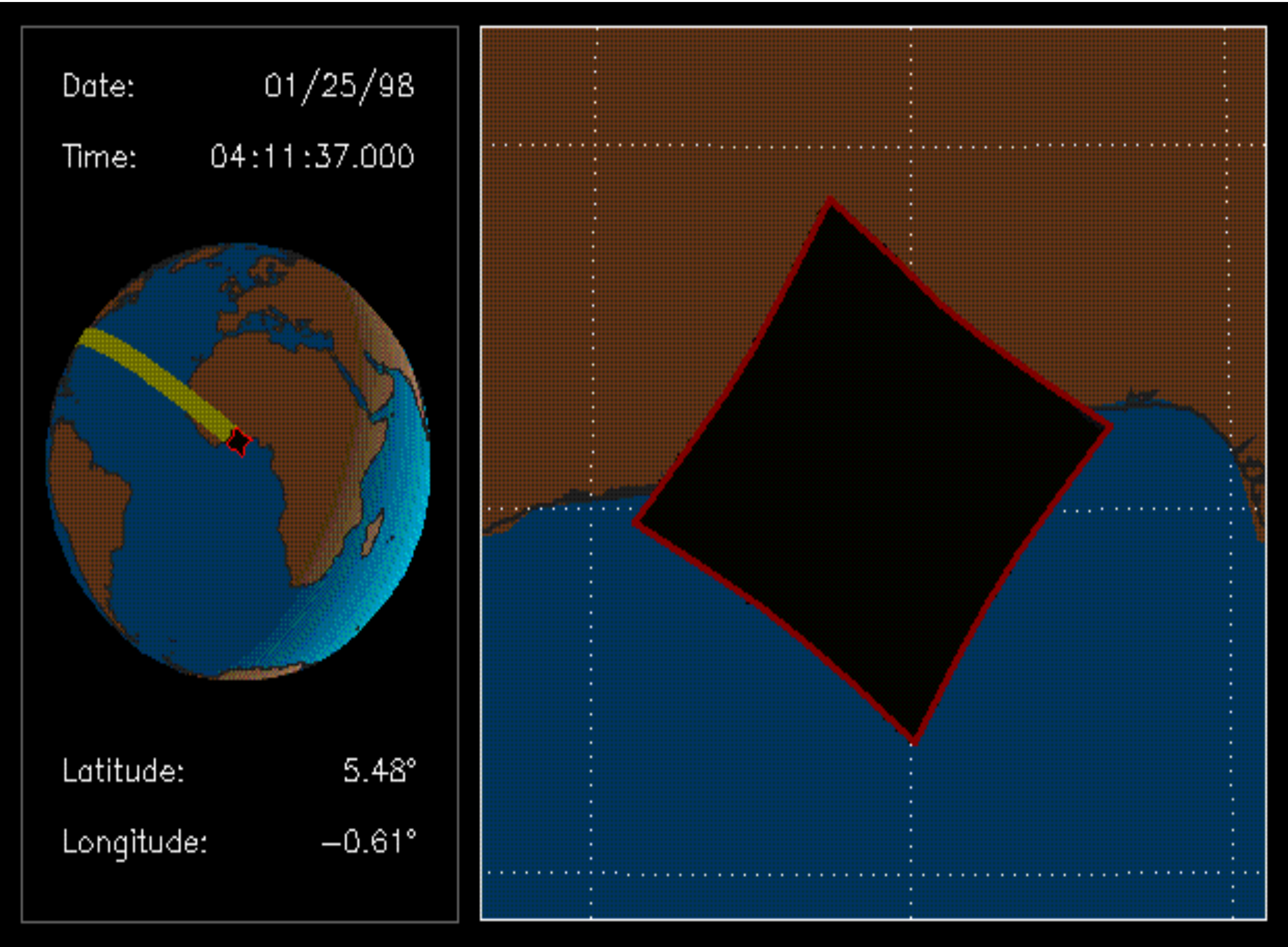




1995-2000

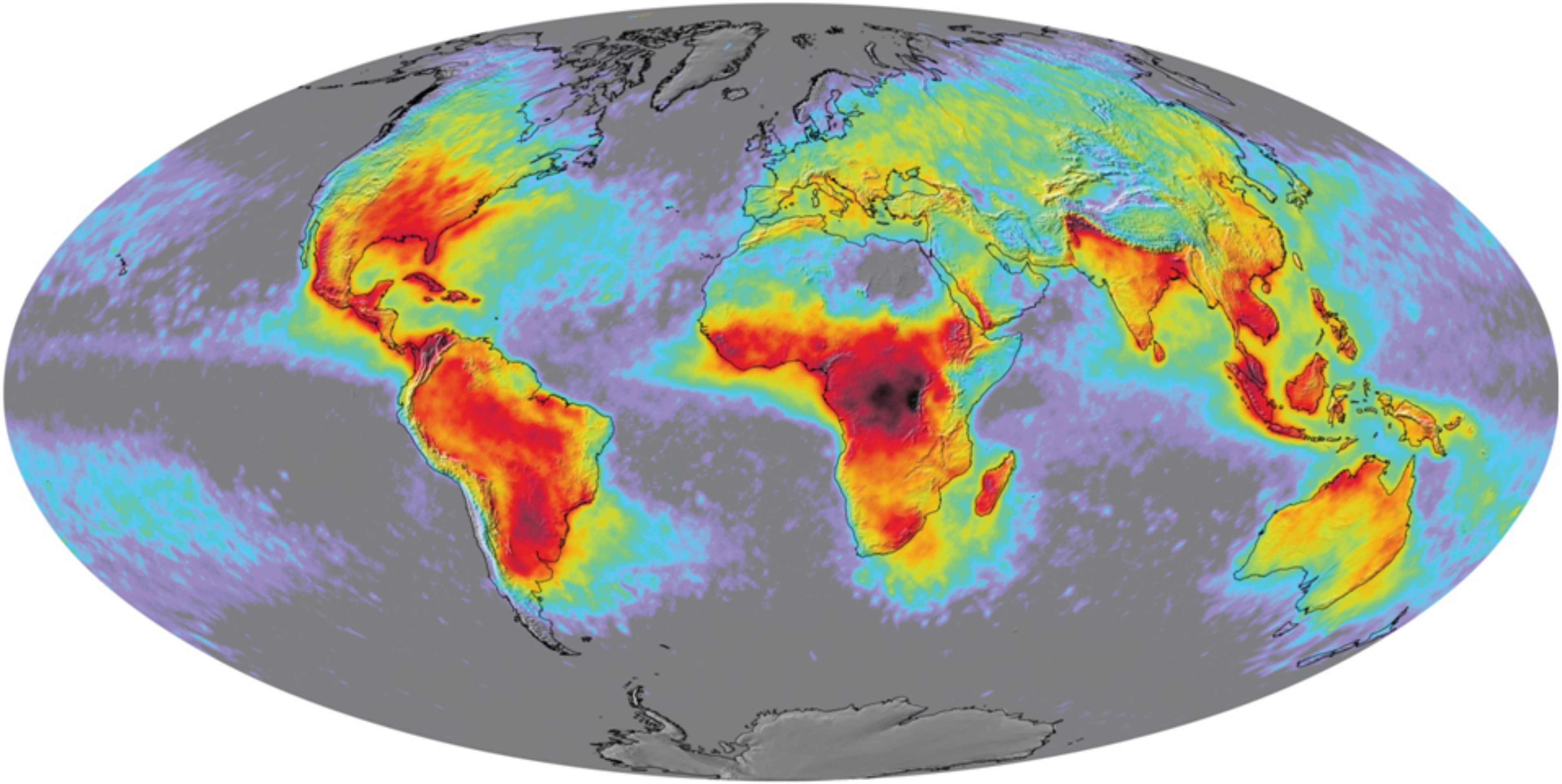


1997-2015



Date: 01/25/98
Time: 04:11:37.000
Latitude: 5.48°
Longitude: −0.61°

Global Distribution of Lightning Activity



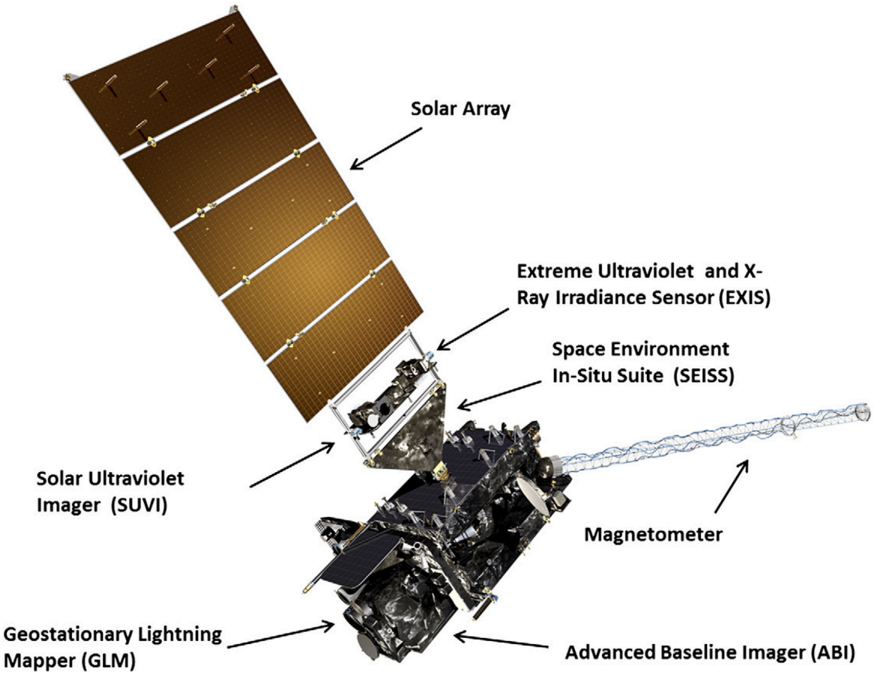
Goodman et al., 2007. Our Changing Planet: The View from Space, M. King, ed., Cambridge University Press

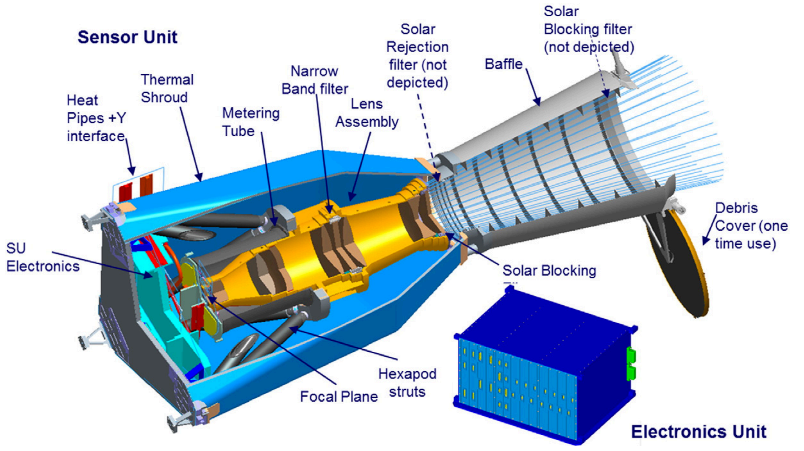
Mean annual global lightning flash rate (flashes km^{-2} yr^{-1}) derived from a combined 8 years from April 1995 to February 2003. (Data from the NASA OTD instrument on the [redacted] OrbView-1 satellite and the LIS instrument on the TRMM satellite.)

GLM Sensor Characteristics

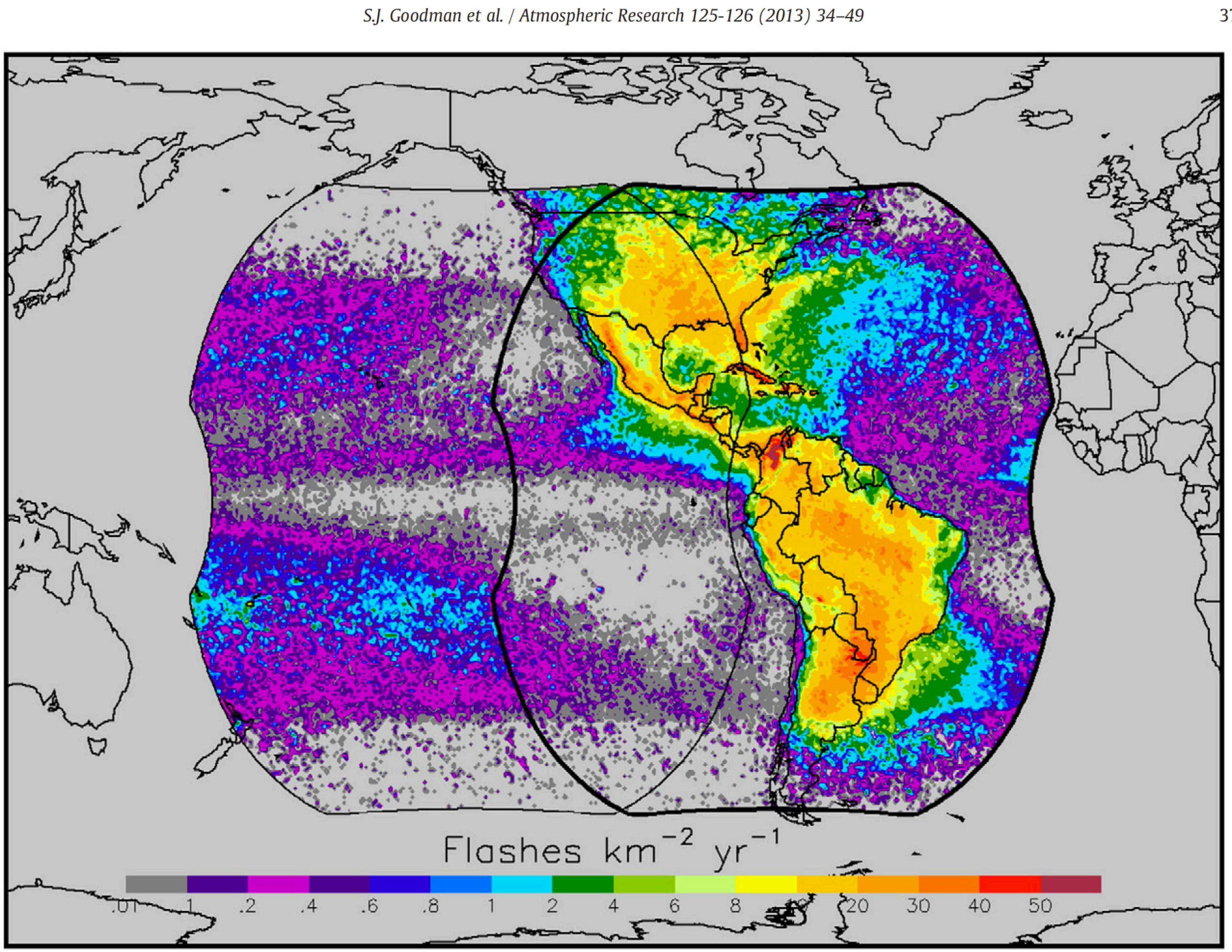
Table 1
GLM performance characteristics.

CCD imager	1372 × 1300 pixels
FOV (across)	Full disk
Pixel FOV (nadir)	8 km
Pixel FOV (corner)	14 km
Wavelength	777.4 nm
Frame rate	2 ms
Downlink data rate	7.7 mbps
Product latency	<20 s
Total mass	125 kg
Average operational power	405 W
Volume (height, width, depth)	149 cm × 63.5 cm × 65.8 cm





GLM FOV (137°W West Park, 75°W East Park)



ISS/LIS Sensor Details

Field-of-View (FOV)	80º × 80º	Measurement Accuracy	
Pixel IFOV (nadir)	4 km	location	1 pixel
Interference Filter		intensity	10 %
wavelength	777.4 nm	time	tag at frame rate
bandwidth	1 nm	Dimensions	
Detection Threshold	4.7 μJ/ m² sr	sensor unit	7.8 x 14.6 in (20 ×x 37 cm)
Signal to Noise Ratio	6	electronics unit	12.2 × 8 .7 x 10.6 in (31 × 22 x 27 cm)
CCD Array Size	128 x 128 pixels	interface unit	9.8 × 2.4 x 13.8 in (25 × 6 x 35 cm)
Dynamic Range	> 100	Weight	55 lbs (25 kg)
Detection Efficiency	~ 90 %	Power	35 W
False Event Rate	< 5 %	Telemetry Data Rate	8 kilobytes/second

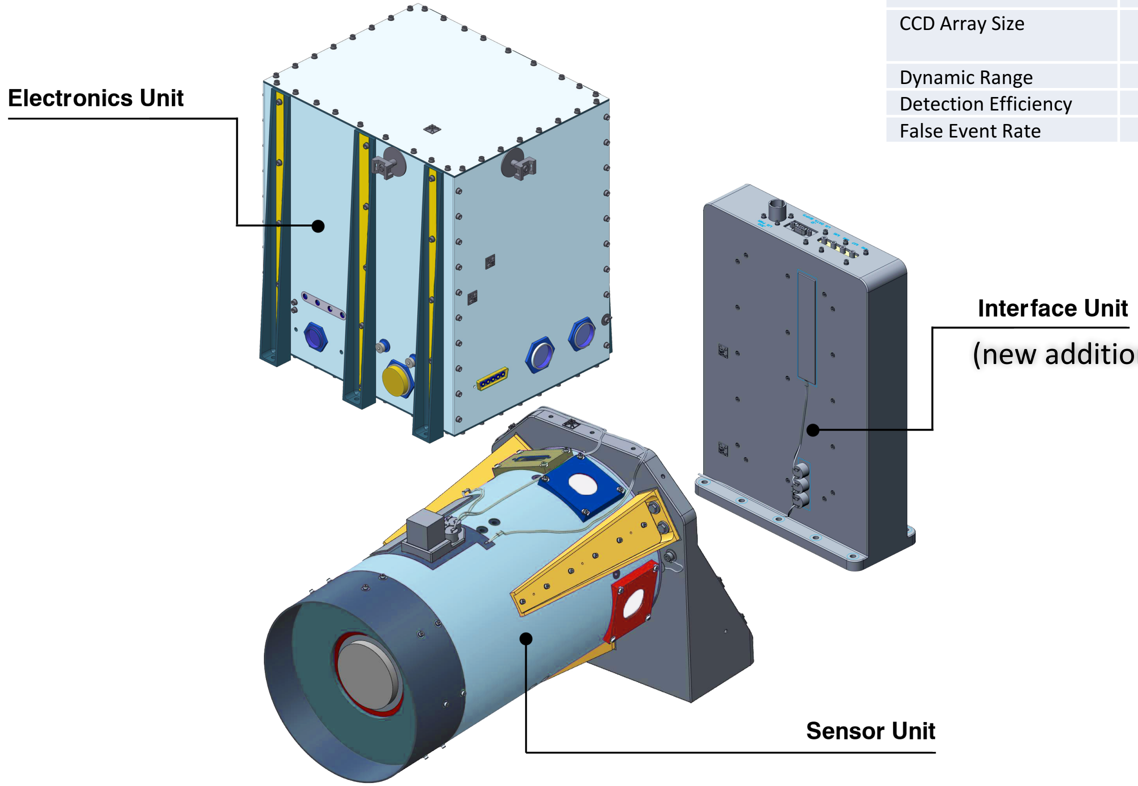
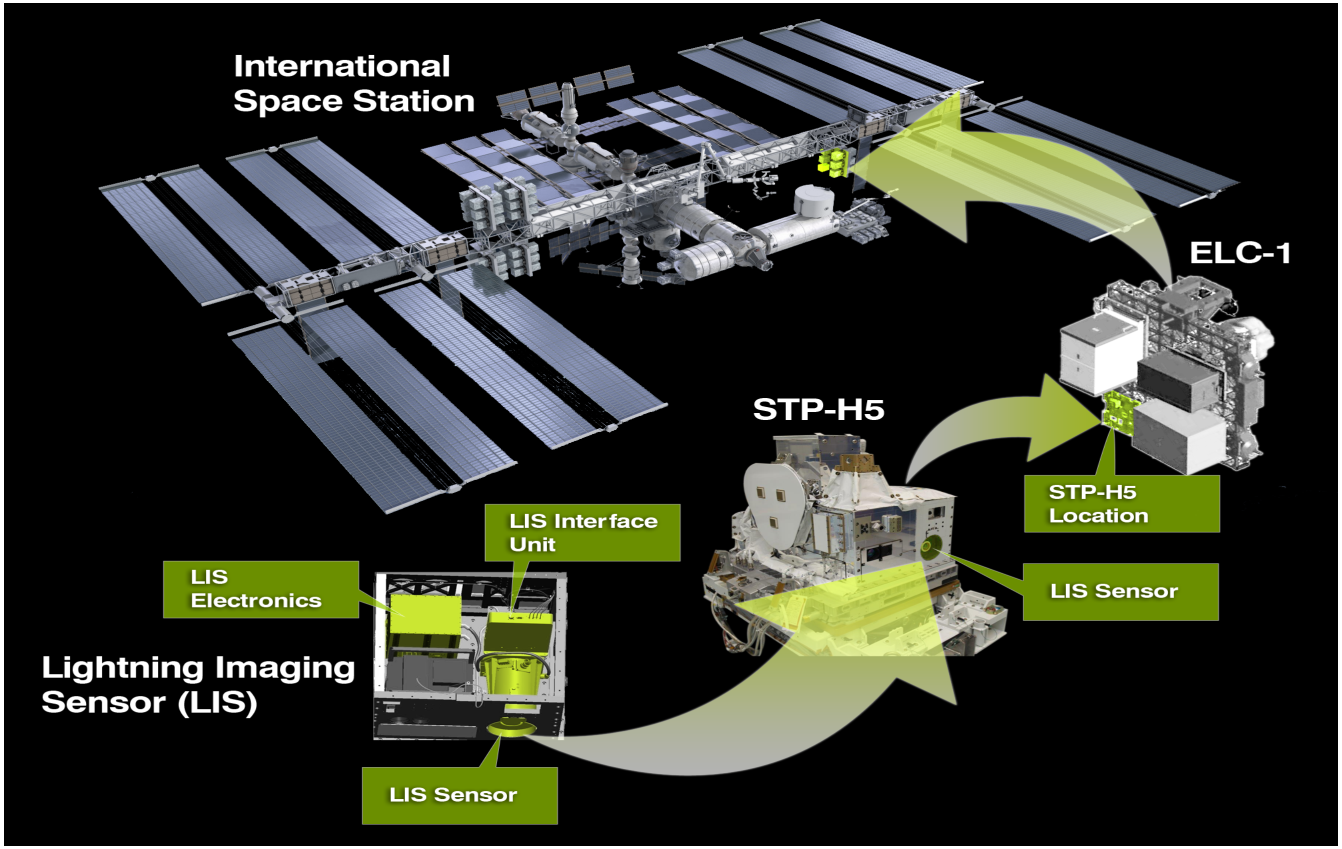


Image credit: NASA and UAH

Installation of LIS Spare on ISS



LIS hardware is installed within the STP-H5 payload, which is installed on ELC-1 in a nadir viewing position.

Image credit: NASA and UAH

Summary Timeline

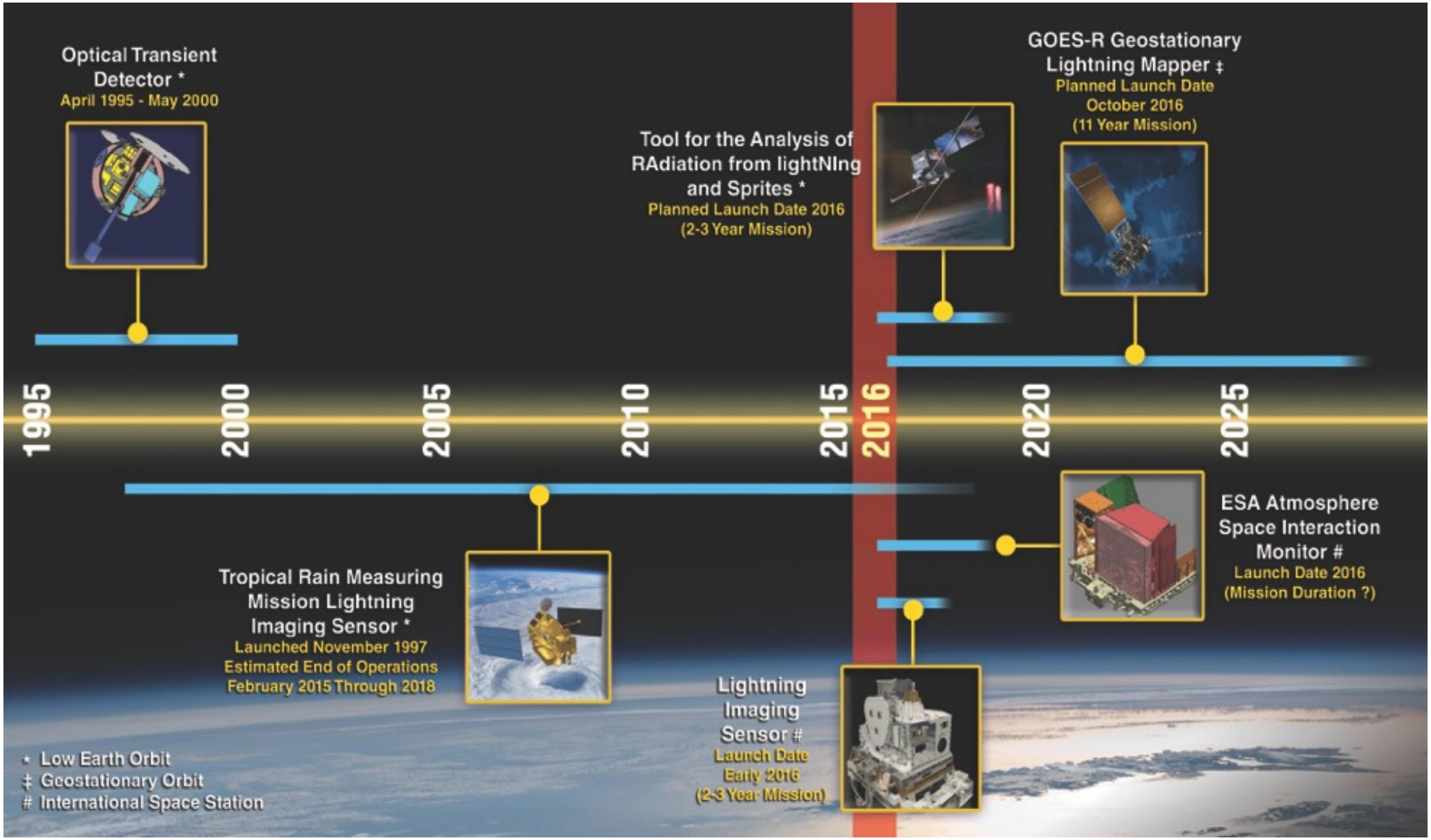
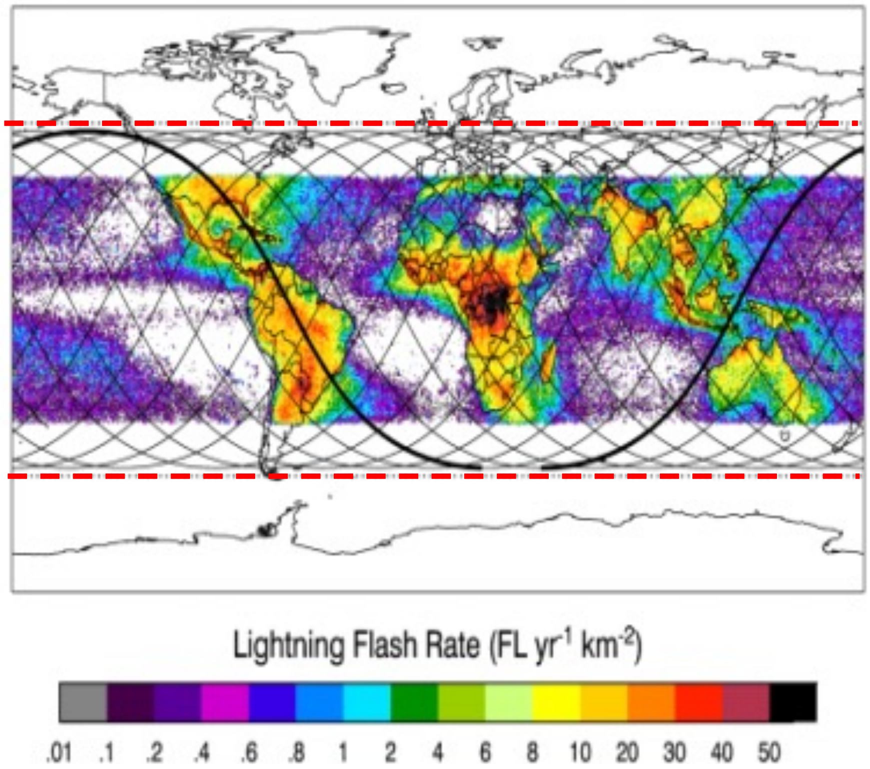


Image credit: NASA and UAH

Higher Latitude Coverage

Max ISS latitude 54.33 degrees

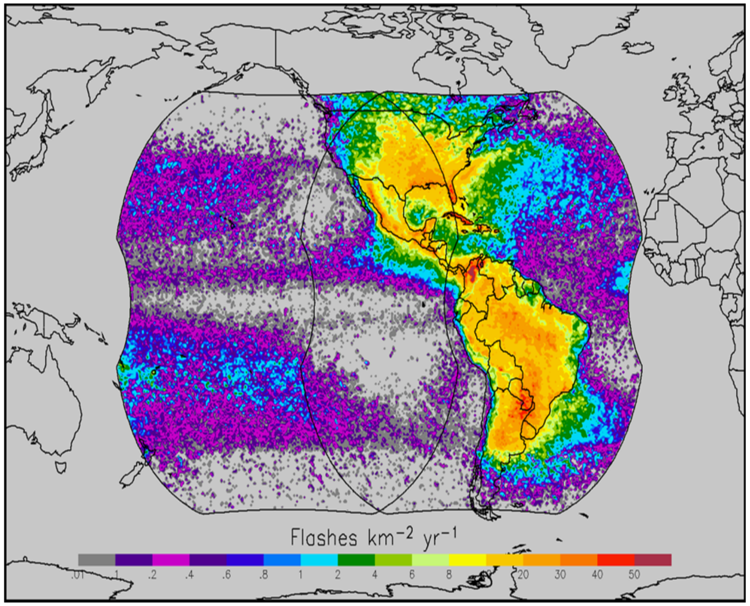
TRMM/LIS



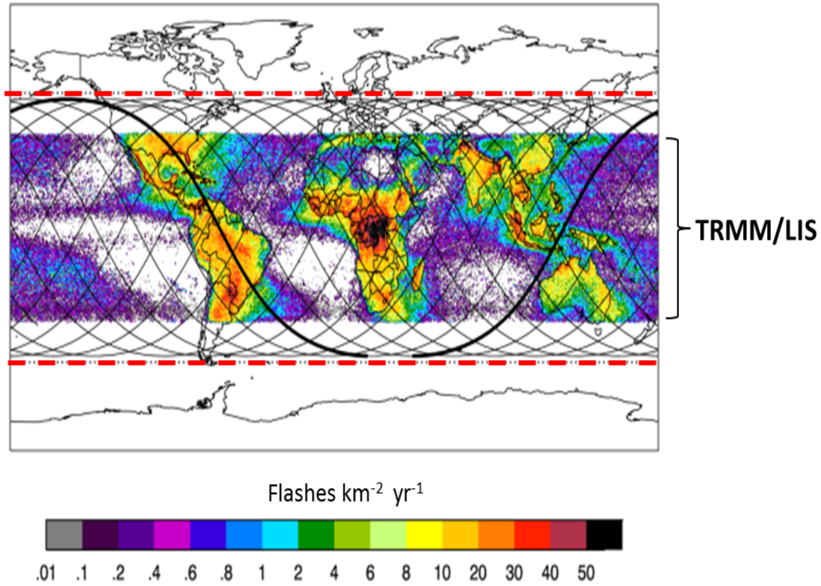
	TRMM/LIS	ISS/LIS
Fraction of Earth Area Seen	62%	81%
Fraction of Worldwide Lightning Seen	90%	98%

Comparison of FOVs

GLM (east & west park options)



ISS/LIS (red-dotted)



Flash Type (CG or cloud flash)

$$\alpha_r = \frac{(\mathbf{m}-\mathbf{b})^T(\mathbf{a}-\mathbf{b})}{(\mathbf{a}-\mathbf{b})^2}$$

$$\mathbf{g}_r = \mathbf{m} + (1-\alpha_r)(\mathbf{a}-\mathbf{b})$$

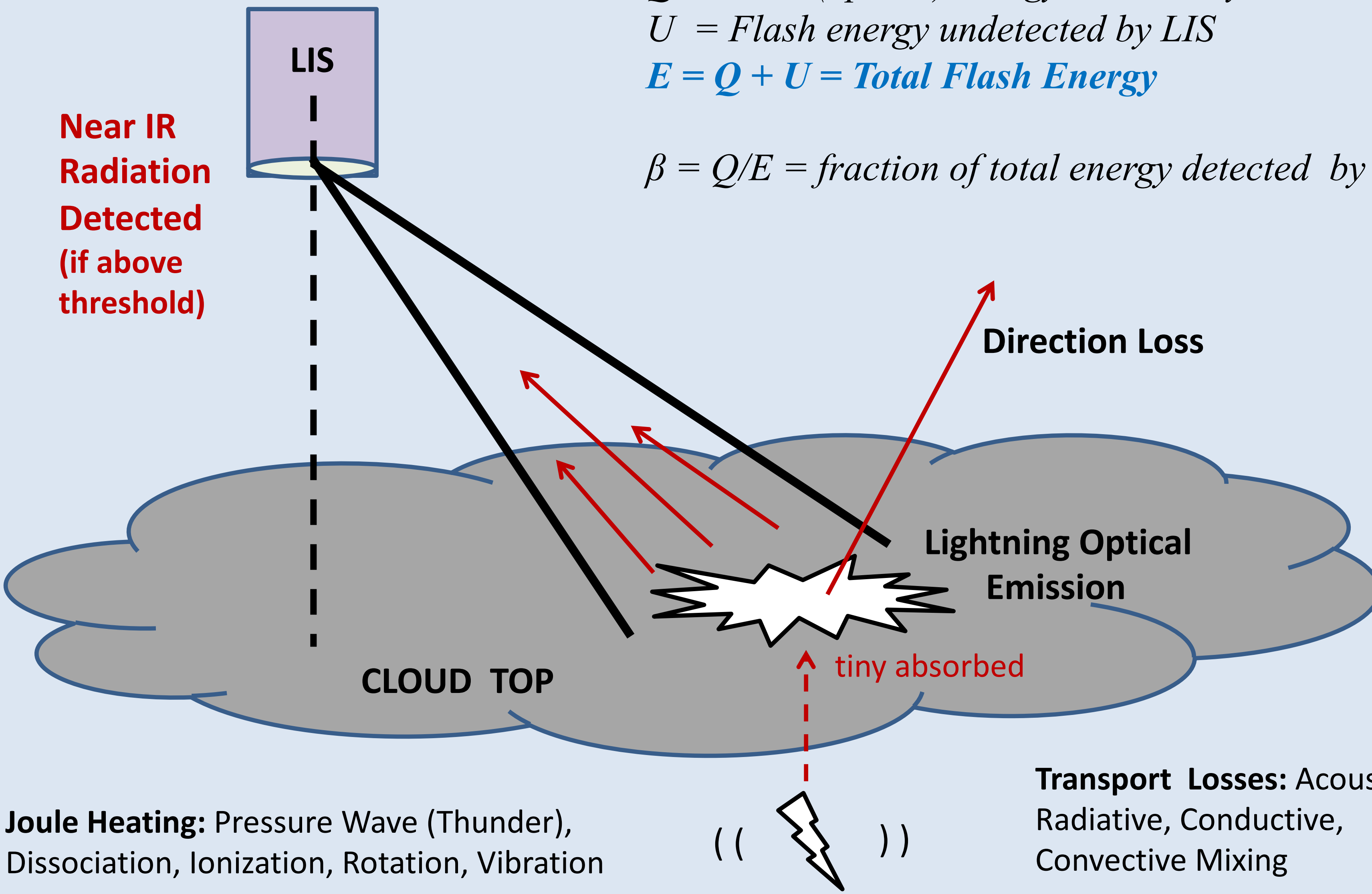
$$\mathbf{c}_r = \mathbf{m} - \alpha_r(\mathbf{a}-\mathbf{b})$$

$$P_{gr}(x) = \frac{\alpha_r g_r(x)}{\alpha_r g_r(x) + (1-\alpha_r)c_r(x)} = \begin{cases} > 0.5 \Rightarrow \text{ CG} \\ \leqslant 0.5 \Rightarrow \text{ cloud flash} \end{cases}$$

LNOx

Q = Flash (optical) energy detected by LIS
U = Flash energy undetected by LIS
E = Q + U = Total Flash Energy

β = Q/E = fraction of total energy detected by LIS



Joule Heating: Pressure Wave (Thunder), Dissociation, Ionization, Rotation, Vibration

Transport Losses: Acoustical, Radiative, Conductive, Convective Mixing

LNOx

$$\text{LNOx Production} = \underbrace{\frac{Y}{N_A}}_{\text{[moles/Joule]}} \underbrace{\frac{Q}{\beta}}_{\text{[Joules/flash]}}$$

[moles/flash]

β = Q/E = fraction of total energy detected by LIS
~ 1.8675×10^{-19} implies 250 moles/fl on average in 1998.

Y = Thermo-chemical Yield = 10^{17} molecules/Joule

N_A = Avogadro's Constant = 6.022×10^{23} molecules/mole

LNOx

XV International Conference on Atmospheric Electricity, 15-20 June 2014, Norman, Oklahoma, U.S.A.

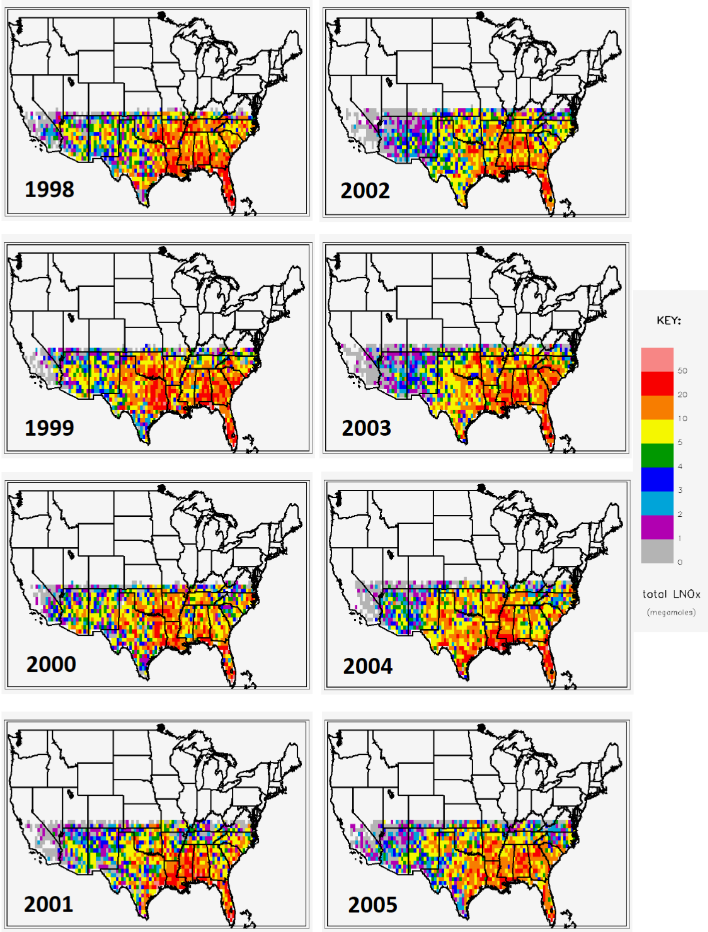


Figure 1: LIS-inferred LNOx production (megamoles) for the period 1998-2005.

XV International Conference on Atmospheric Electricity, 15-20 June 2014, Norman, Oklahoma, U.S.A.

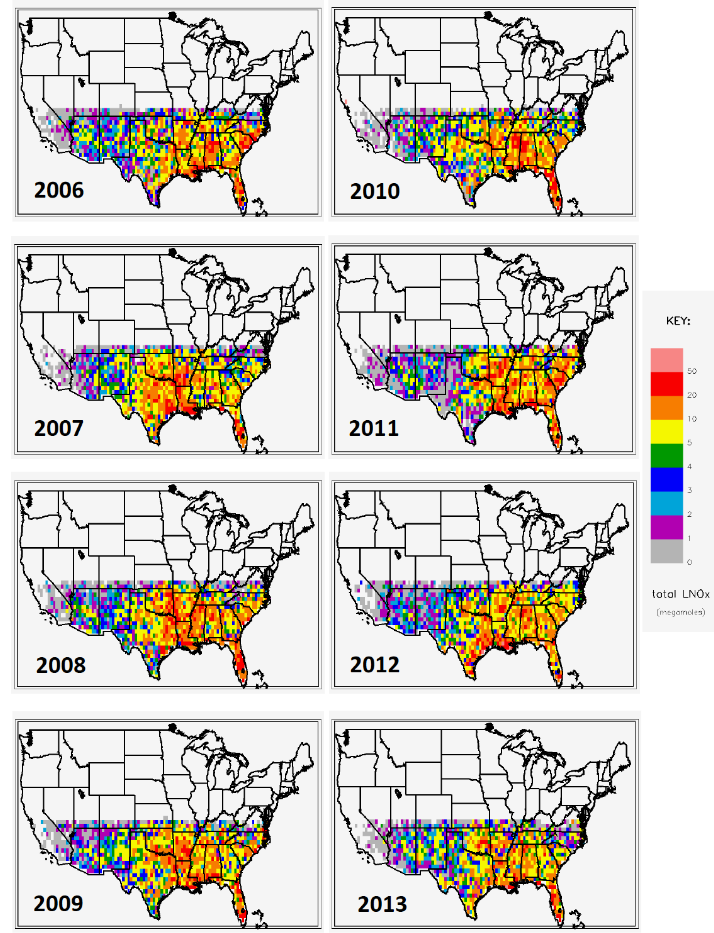
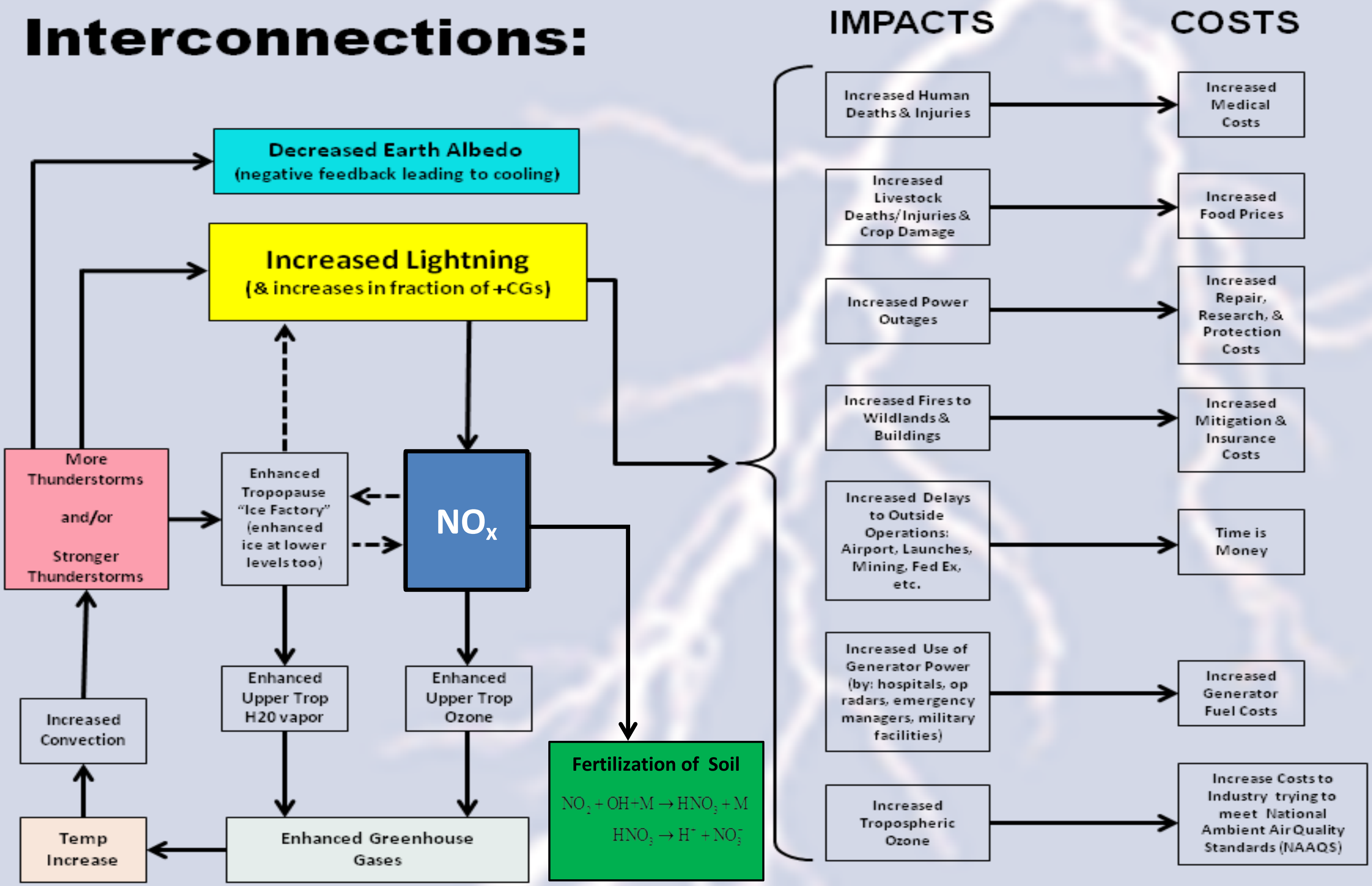
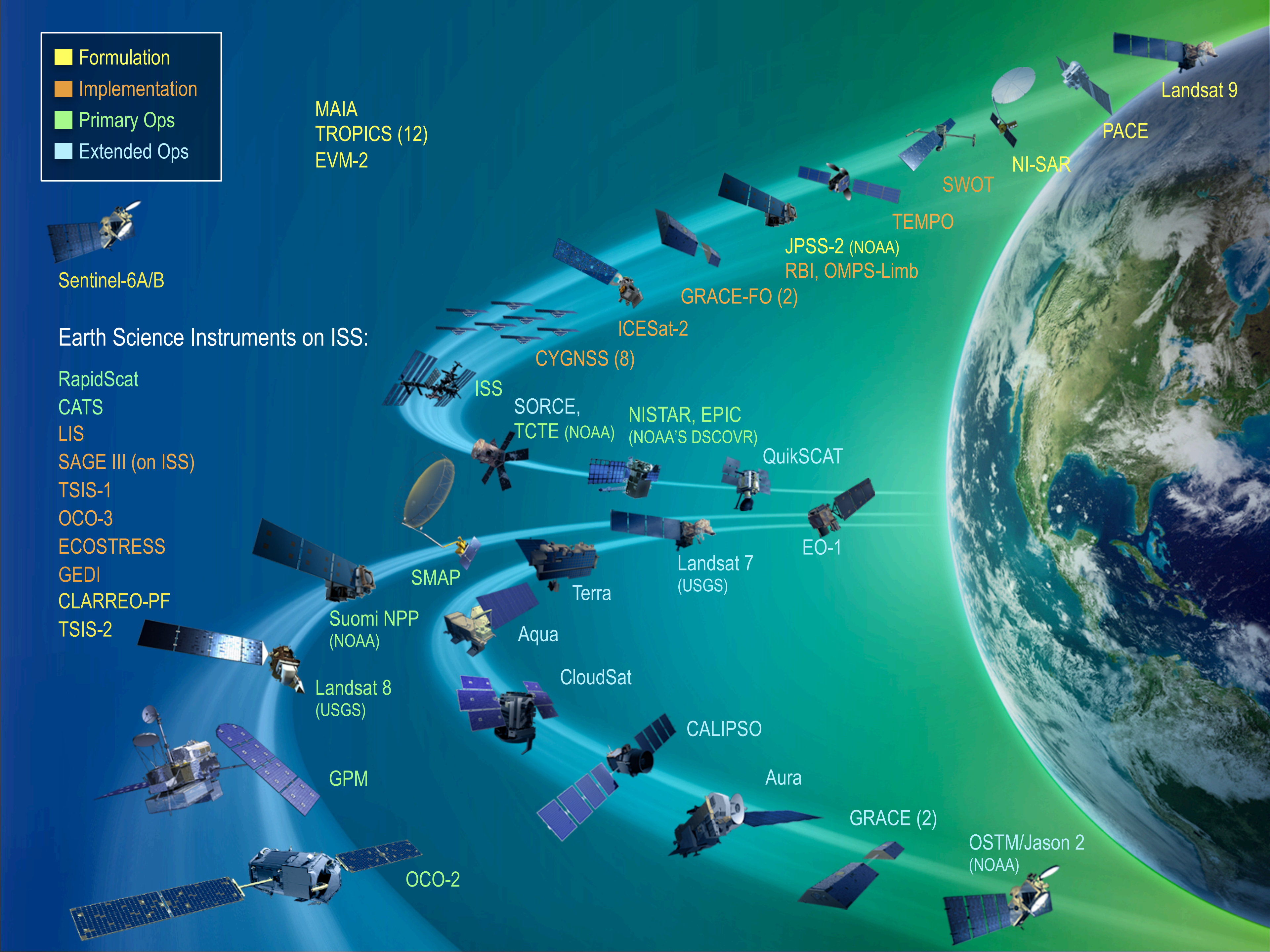


Figure 2: LIS-inferred LNOx production (megamoles) for the period 2006-2013.

NCA Activities

IMPORTANCE OF LNOx

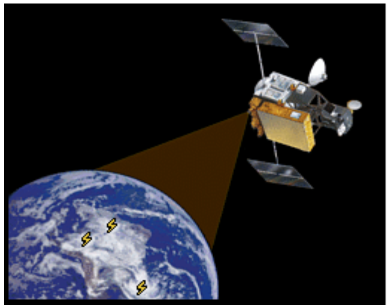


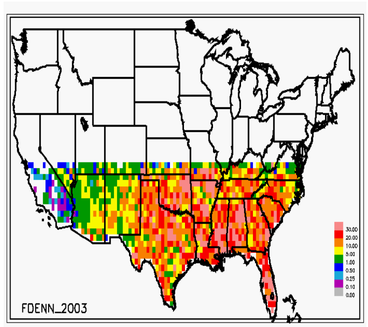


Formulation
Implementation
Primary Ops
Extended Ops
MAIA
TROPICS (12)
EVM-2
Landsat 9
PACE
NI-SAR
SWOT
TEMPO
JPSS-2 (NOAA)
RBI, OMPS-Limb
GRACE-FO (2)
ICESat-2
CYGNSS (8)
Sentinel-6A/B
Earth Science Instruments on ISS:
RapidScat
CATS
LIS
SAGE III (on ISS)
TSIS-1
OCO-3
ECOSTRESS
GEDI
CLARREO-PF
TSIS-2
ISS
SORCE,
TCTE (NOAA)
NISTAR, EPIC
(NOAA'S DSCOVR)
QuikSCAT
EO-1
Landsat 7
(USGS)
Terra
SMAP
Suomi NPP
(NOAA)
Aqua
Landsat 8
(USGS)
CloudSat
CALIPSO
GPM
Aura
GRACE (2)
OSTM/Jason 2
(NOAA)
OCO-2

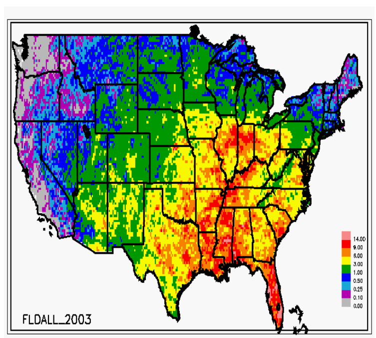
National Climate Assessment

TRMM/LIS





National cloud-to-ground (CG) network



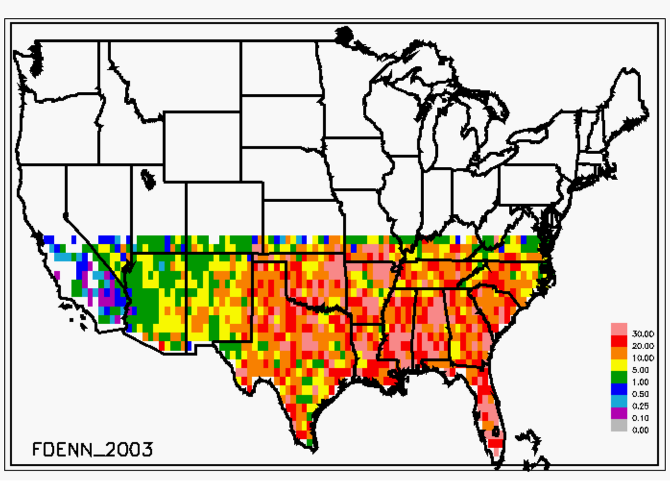
Period	NLDN	LIS (Raw)	LIS (DE & VT Corrected)
2003-2007	25,204,345.80	92,655.00	46,997,805.40
2008-2012	21,986,578.80	92,659.40	47,175,192.40
Percent Change	-12.77%	0.005%	0.38%

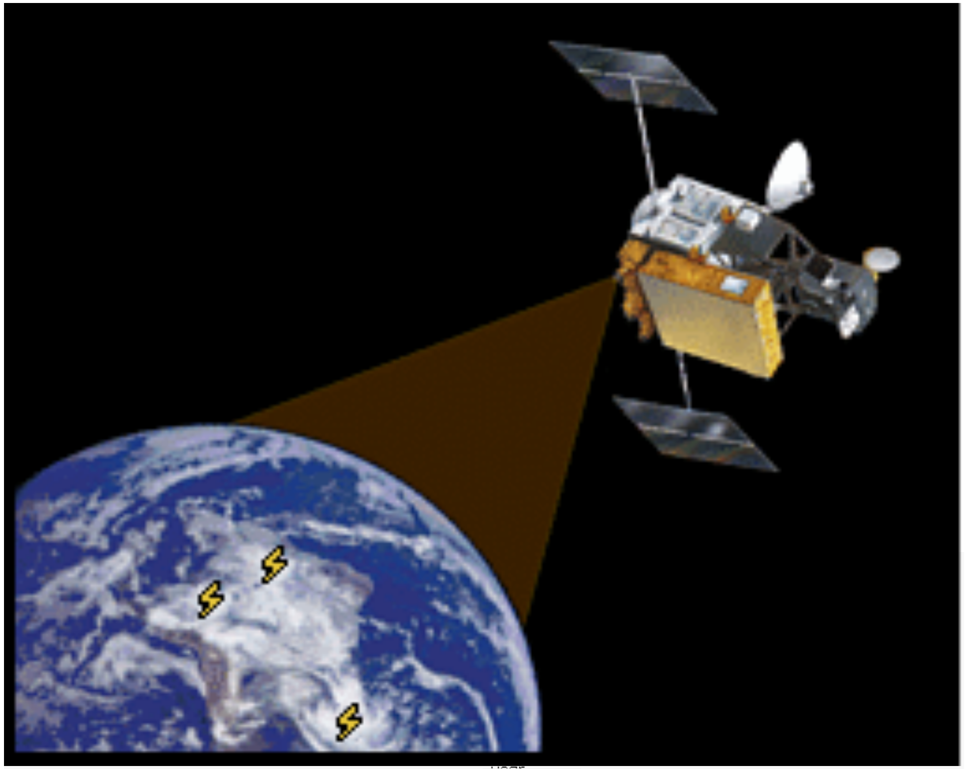
Koshak, W. J., K. L. Cummins, D. E. Buechler, B. Vant-Hull, R. J. Blakeslee, E. R. Williams, H. S. Peterson, 2015: Variability of CONUS Lightning in 2003-12 and Associated Impacts, *J. Appl. Meteorol. Climatology*, **54**, No. 1, 15-41.

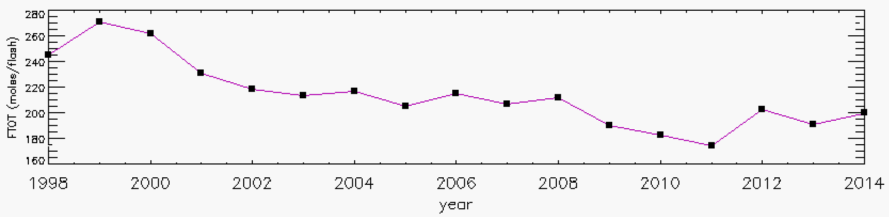
National Climate Assessment

- Lightning Nitrogen Oxides (LNOx) affect greenhouse gases & hence climate.
- Use Space-Based Flash Optical Data
- Optical → Flash Energy → Flash LNOx Production

TRMM/LIS Flash Density







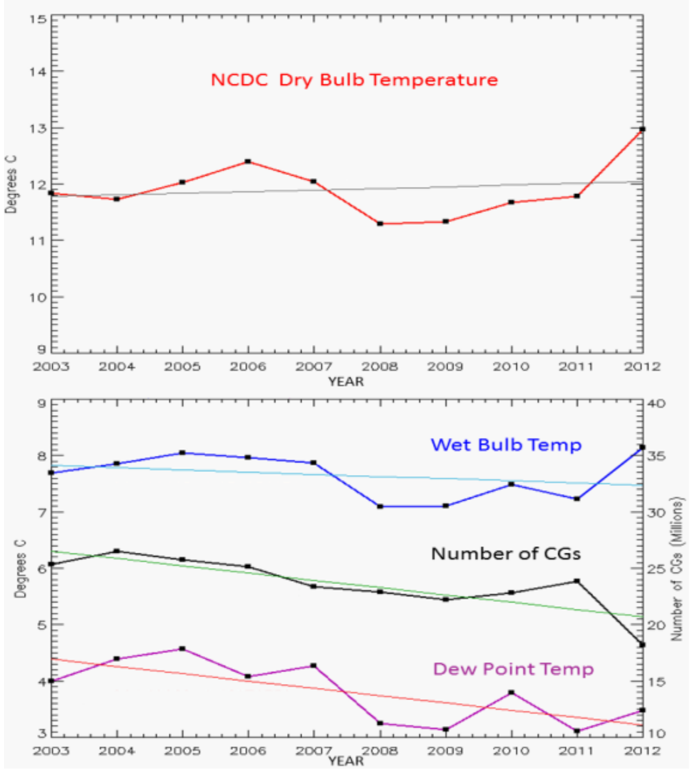
TRMM/LIS: LNOx trended downward, but upward more recently

National Climate Assessment

- Co-evolution of temperature, lightning, & adverse lightning-caused impacts for the decade 2003-2012 using total of 25 lightning indicators:
  - **Cloud-to-Ground (CG) lightning count <u>dropped</u> by 12.8%**
    (there were small changes in peak current and # strokes/CG)
  - Dry bulb temp trends up, but **wet bulb** <u>trends downward</u>
    (lightning needs heat & moisture!)
  - CG-caused deaths, injuries, wildfires <u>dropped</u>, but crop & property damage <u>increased</u>.
  - +CG fraction (a severe Wx marker) trends <u>upward</u>
  - **LIS total lightning <u>remarkably constant</u> (increased by 0.38%).**
    (total lightning evidently less sensitive to wet bulb temp)

- We find a +18% change in CG count per +1°C change in average CONUS wet bulb temp. This is close to the recent result of 12% per °C found in Romps et al. (2014).

- **LIS-detected flash optical energies have trended <u>downward</u> over the lifetime of LIS, but upward more recently.**



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Questions