Simulations to inform NASA's Future Lightning Missions

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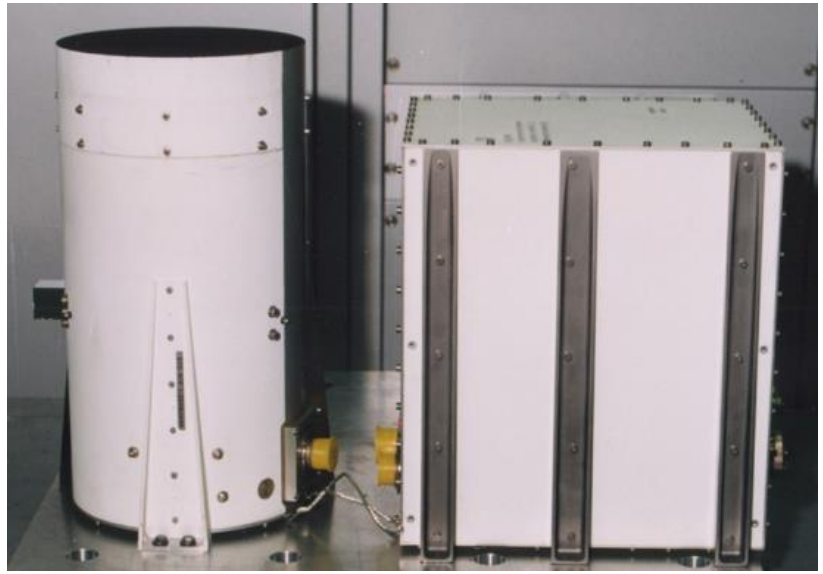
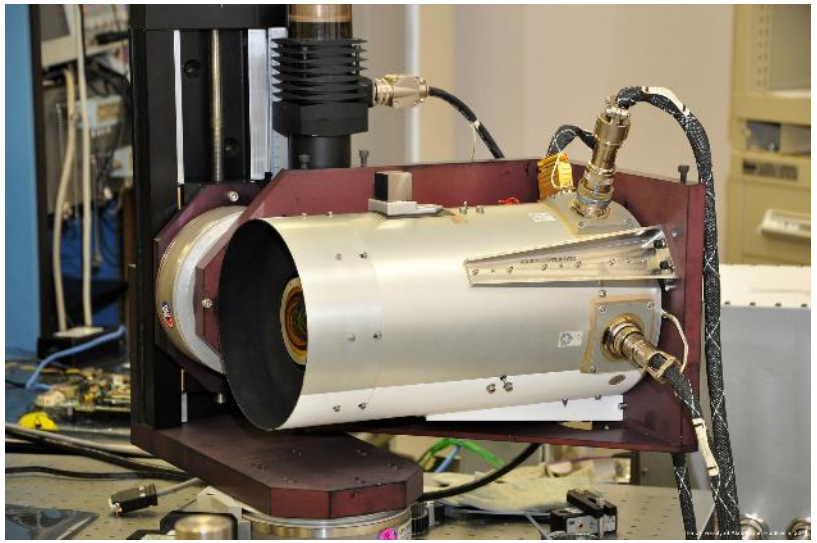
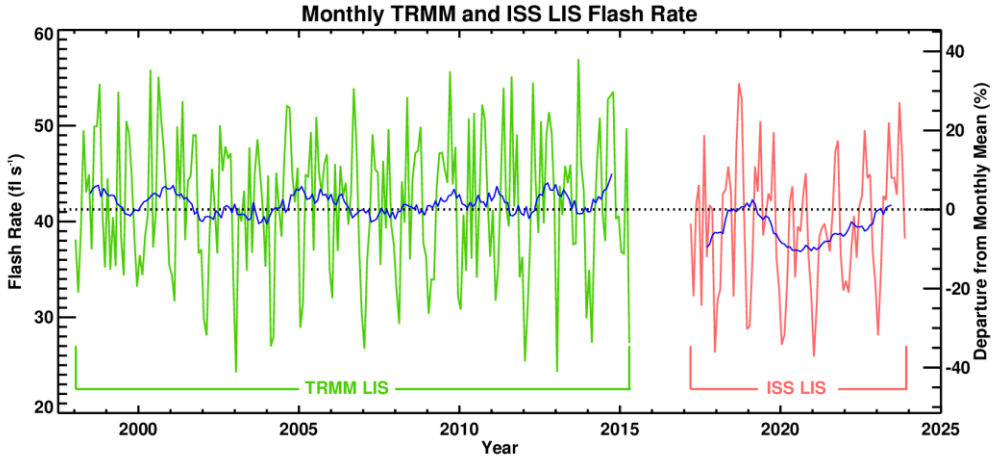
Presentation at Lightning Modeling Grand Challenge Workshop, Albuquerque, NM, April 1-3, 2024

Lightning Imaging Sensor (LIS) decommissioned on November 16, 2023







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3-D monitoring of lightning with optical and VHF sensors in LEO

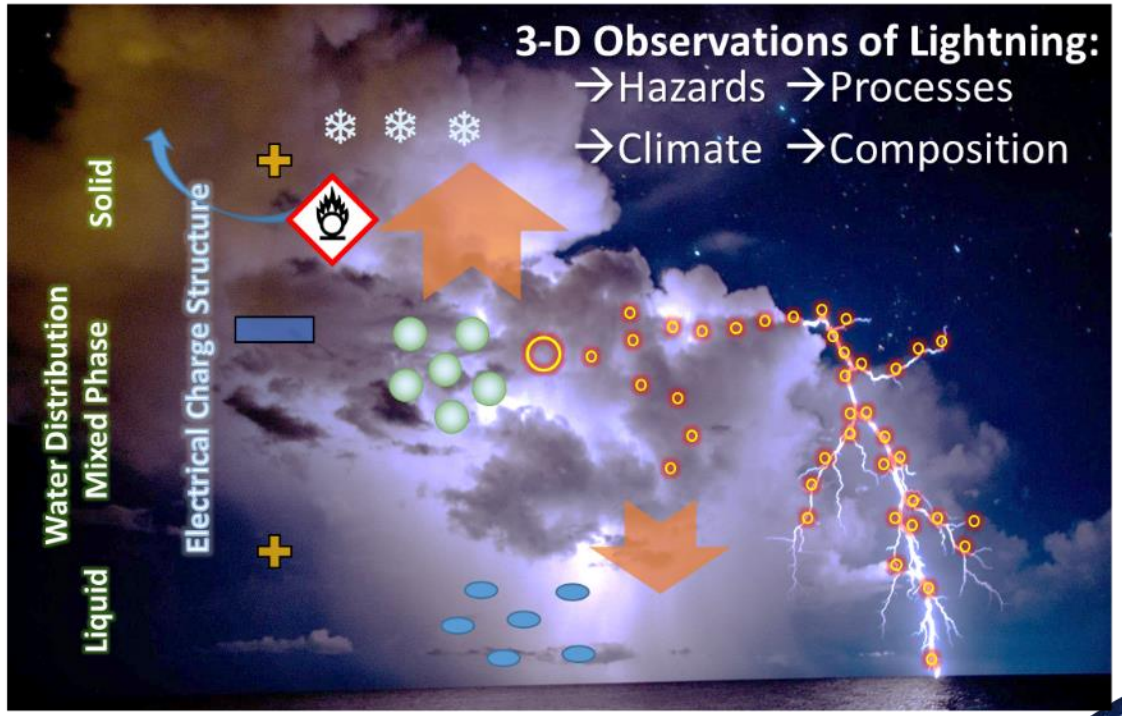
CubeSpark is a constellation of small satellites acting as a 3D lightning mapping network in space:

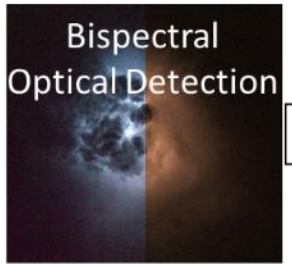
- *VHF radio measurements to map lightning structure inside clouds*
- *Bispectral, high-resolution optical measurements to enhance detection of lightning in severe and anomalous thunderstorms and flashes that extend upward from cloud-top*

Measurement Concept

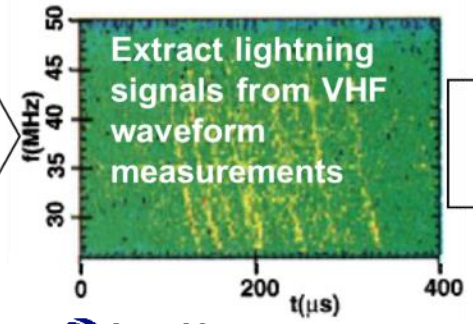
ESTO
EARTH SCIENCE TECHNOLOGY OFFICE

Enabled Science and Applications





CLIDE (MSFC)

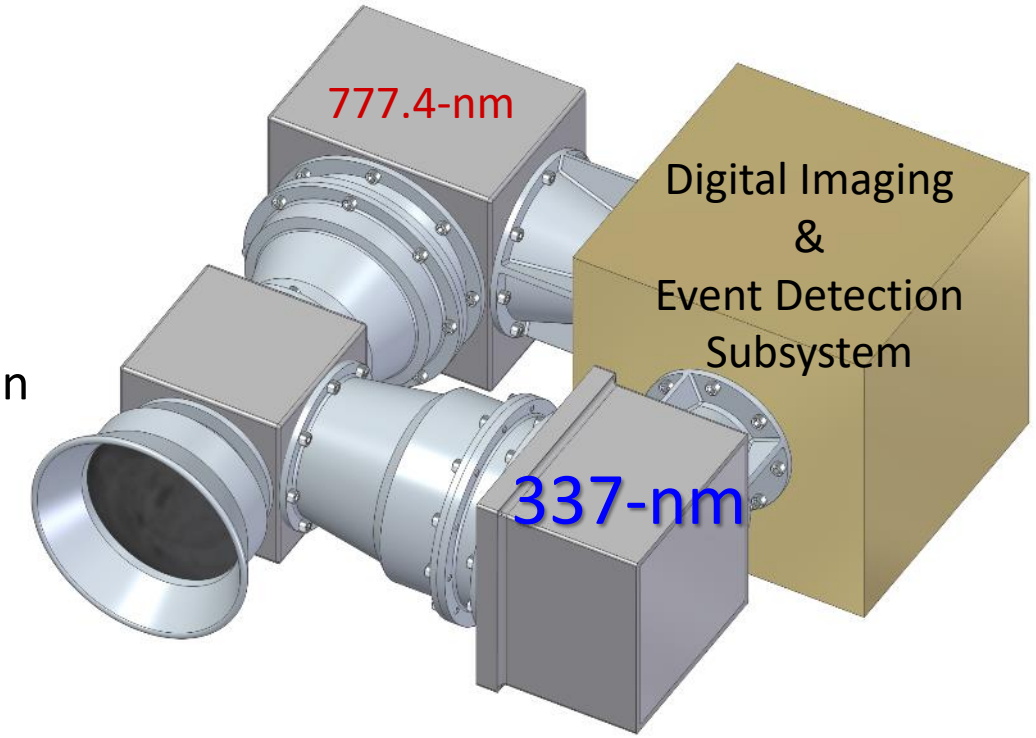


Los Alamos
NATIONAL LABORATORY

CubeSat Lightning Imaging and Detection Experiment (CLIDE)

- Objective: Improve the detection of small and optically dim lightning flashes that frequent intense thunderstorms
- Dual-wavelength:
  - 777.4-nm (OI multiplet—leaders)
  - 337-nm (N_2 SPS—streamers)
- Digital Imager and Event Detector:
  - CMOS Image Sensor developed for lightning detection
  - 432 x 420 pixel array (<2 km resolution from LEO)
  - 2000 frames per second
  - Enhance QE at 337-nm via backside processing (MBE+AR recipe)
- MSFC designing for use on small satellite missions (e.g., CubeSpark, Bushfire Monitoring)
- Funded by NASA ESTO-IIP21 as Instrument Concept Demo.
- Current TRL: 3

CLIDE Design Concept



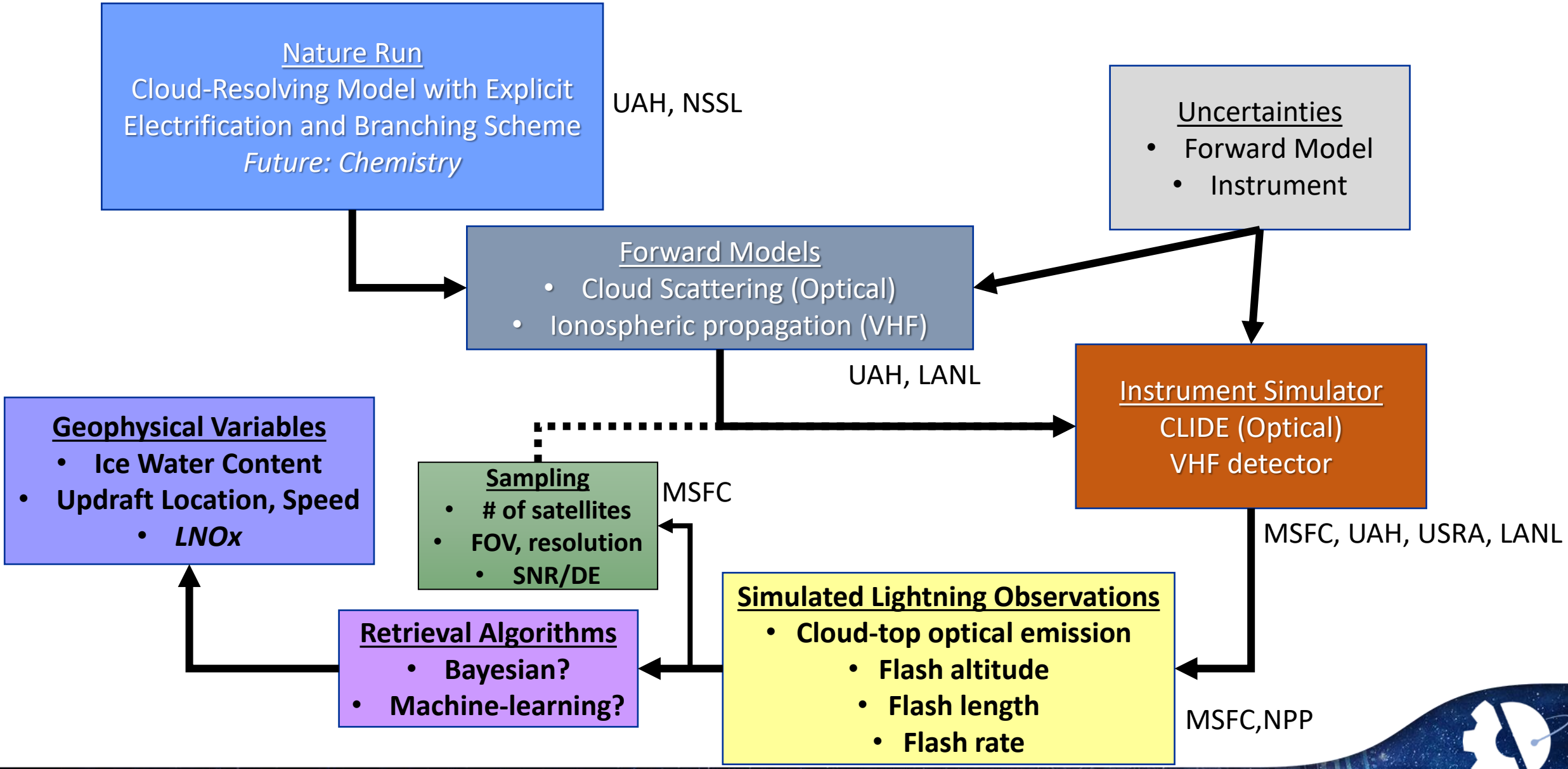
How do we quantify observing requirements for such a mission?

→ Observing System Simulation Experiment (OSSE)

OSSE Examples	Question Asked
Sampling	How often and with what resolution do I need to sample a feature of interest?
Retrieval	How well can the measurement estimate the geophysical variable of interest, including its uncertainties?
Process	What measurements are needed to characterize a process of interest?
Forecast	How much will the new observations improve a weather forecast?
Climate	Do these observations allow us to better constrain climate forcings or response?

Modified from CCP OSSE by D. Posselt (JPL)

Satellite-based Lightning Observing System Simulation Experiment (OSSE)



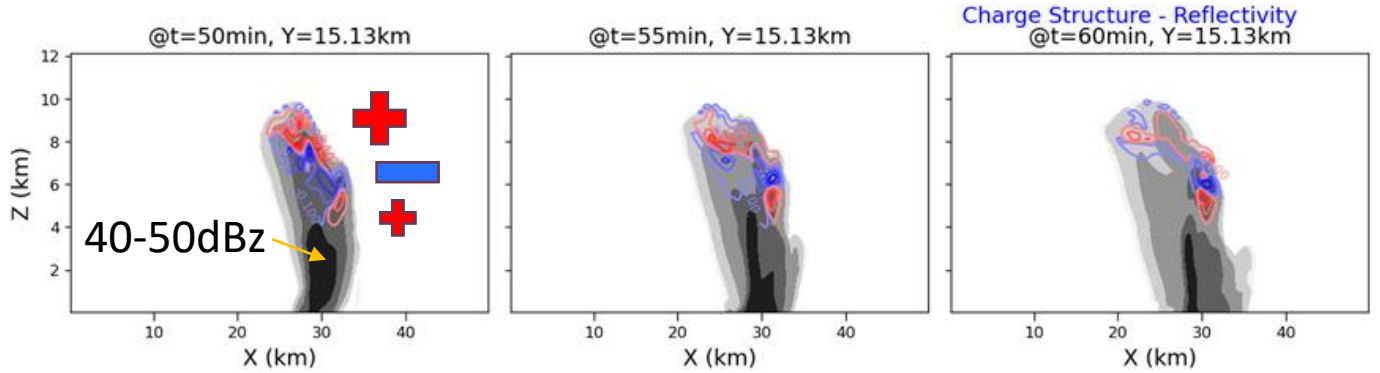
Nature Run: CRM that simulates lightning flash geometry

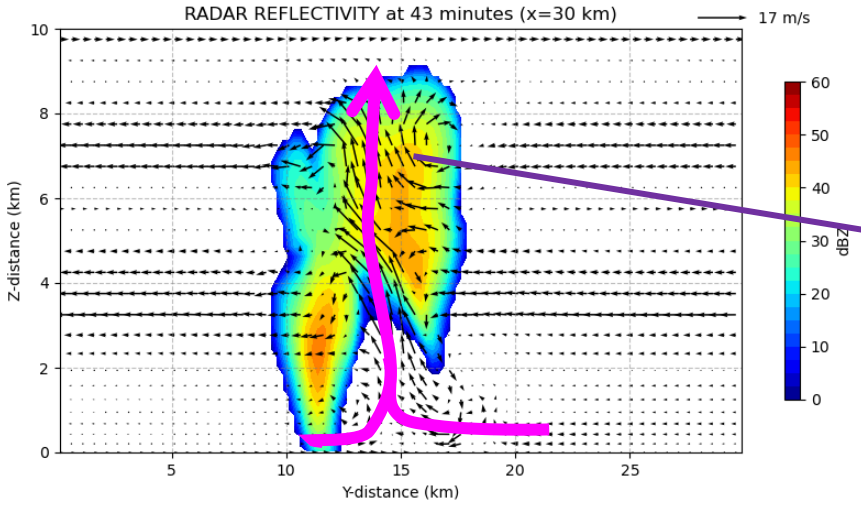
NSSL Collaborative Model for Multiscale Atmospheric Simulation (NCOMMAS; Mansell et al. 2010)

- Non-hydrostatic, convection-allowing model (Wicker & Wilhelmson 1995; Cogniglio et al. 2006)
- 2-moment microphysics (parameterizes q and n for cloud droplets, raindrops, ice crystals, aggregates, graupel; Mansell & Ziegler 2013+)
- Storm electrification scheme (parameterizes ion & hydrometeor charging; Mansell et al., 2005+)
- Discrete breakdown model (parameterizes geometry of lightning channels; Mansell et al., 2002+)

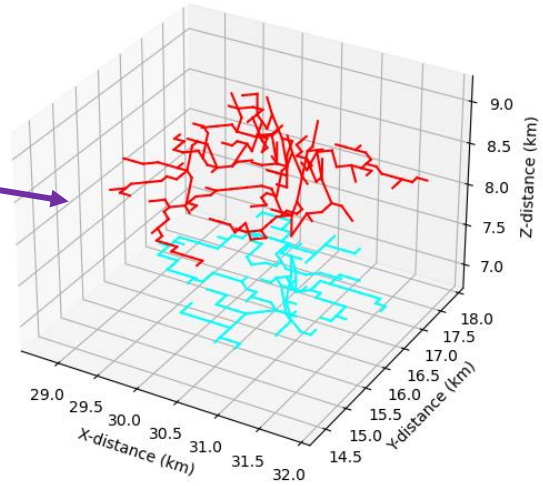
Migrating to GPU and Porting to NU-WRF

Simulation: Florida T-storm on Aug 9, 1991
Domain Size: 50 km x 30 km x 24 km
Grid Spacing: 250 m x 250 m x 100-500 m
Duration: 90 minute
Time Step: 4 sec
Output: 60 sec

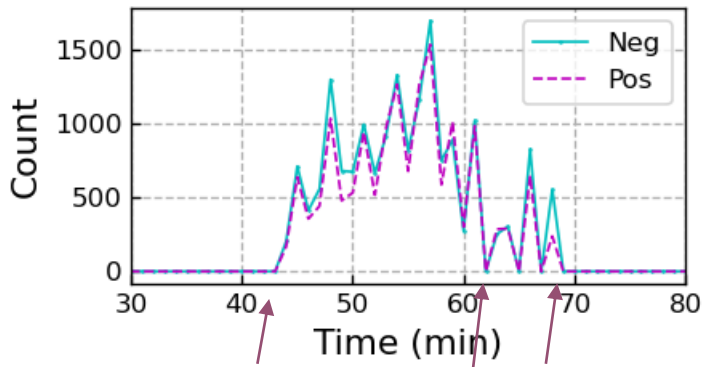




Simulated Lightning Flash Structure



Simulated flash segments

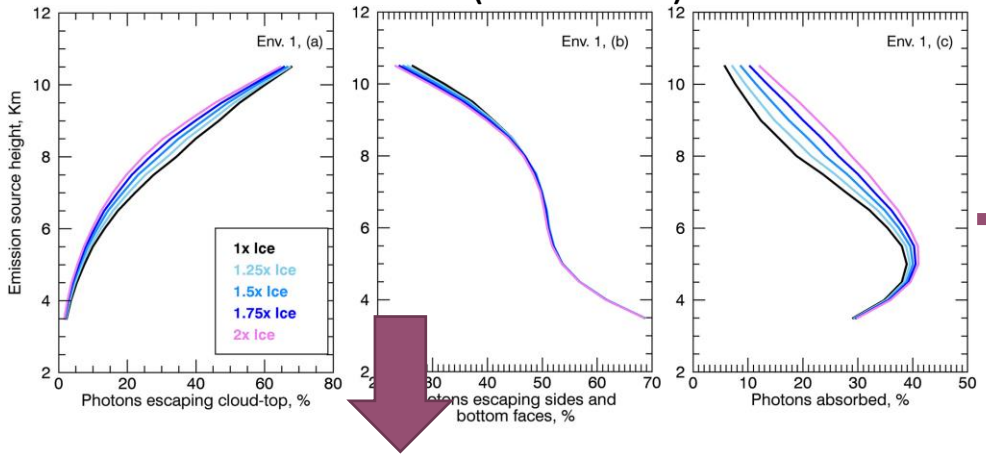


Forward Models: Cloud-top Optical Emission

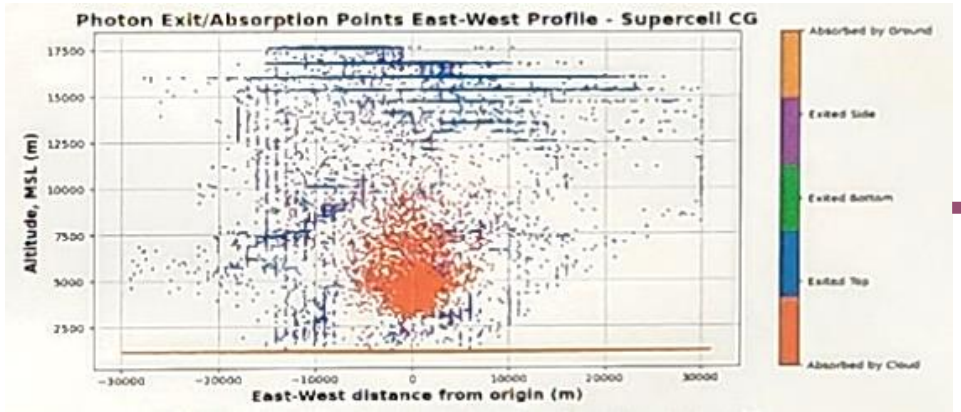
Monte Carlo Photon Pathway Model

- Simulates light emitted by lightning channel (line source)
- Lightning radiative transfer model: Thomson & Krider (1982); Koshak et al. (1994); Light et al. (2001)
- Photon extinction by inhomogeneous environment: Brunner & Bitzer (2020)

1-D Photon Extinction (1-D cloud)

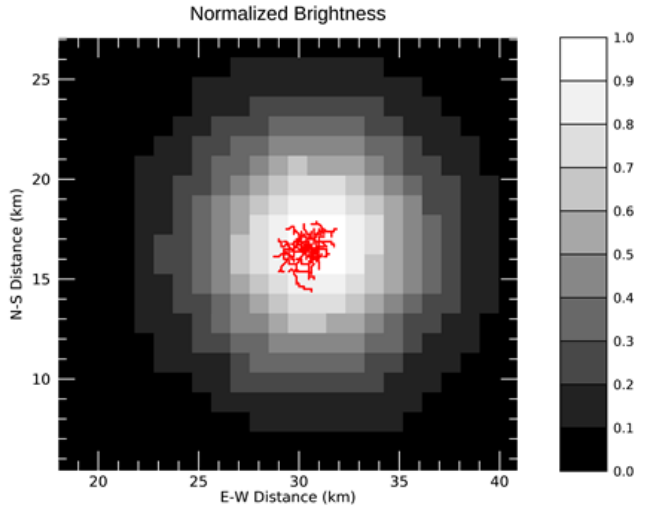


3-D Photon Extinction Model



(e.g., Wolff et al. AirForce 2023 AGU poster)

Cloud-top optical emission at 777.4-nm
Simulated lightning flash from Nature Run



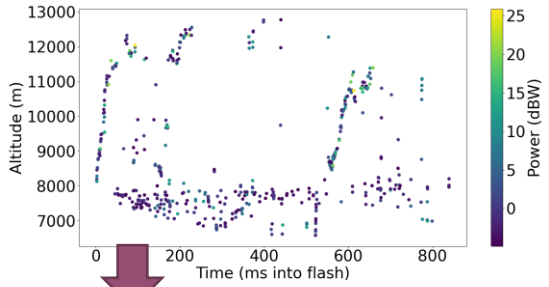
Example:
r = 10 µm
$N_T = 10^8/m^3$
z_{CT} = 12-km

J. Burchfield (UAH)

Forward Models: Ionospheric propagation of VHF signal

Los Alamos National Lab VHF signal propagation model

- Simulates propagation of RF wave through ionosphere
- Accounts for polarization of wave and ionospheric dispersive effects on it

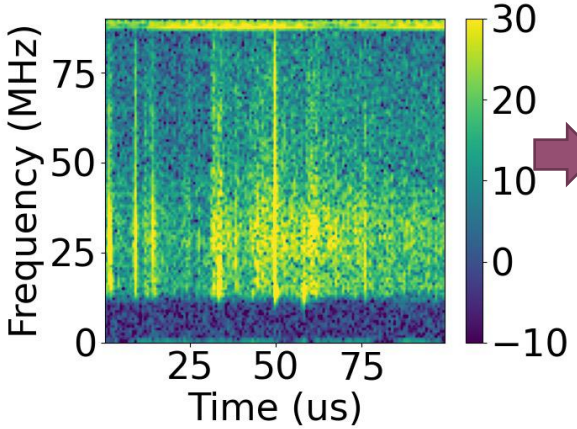


LMA depiction of flash corresponding to VHF interferometric measurements used for this simulation

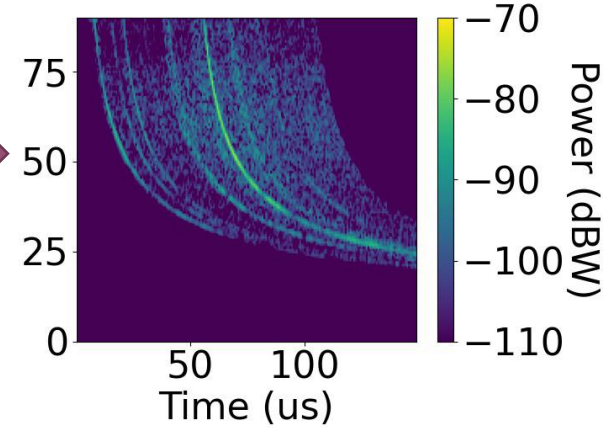
Instrument Simulator: VHF Lightning Detector

- Noise estimates to compute SNR obtained from FORTE mission data (Burr et al., 2004)

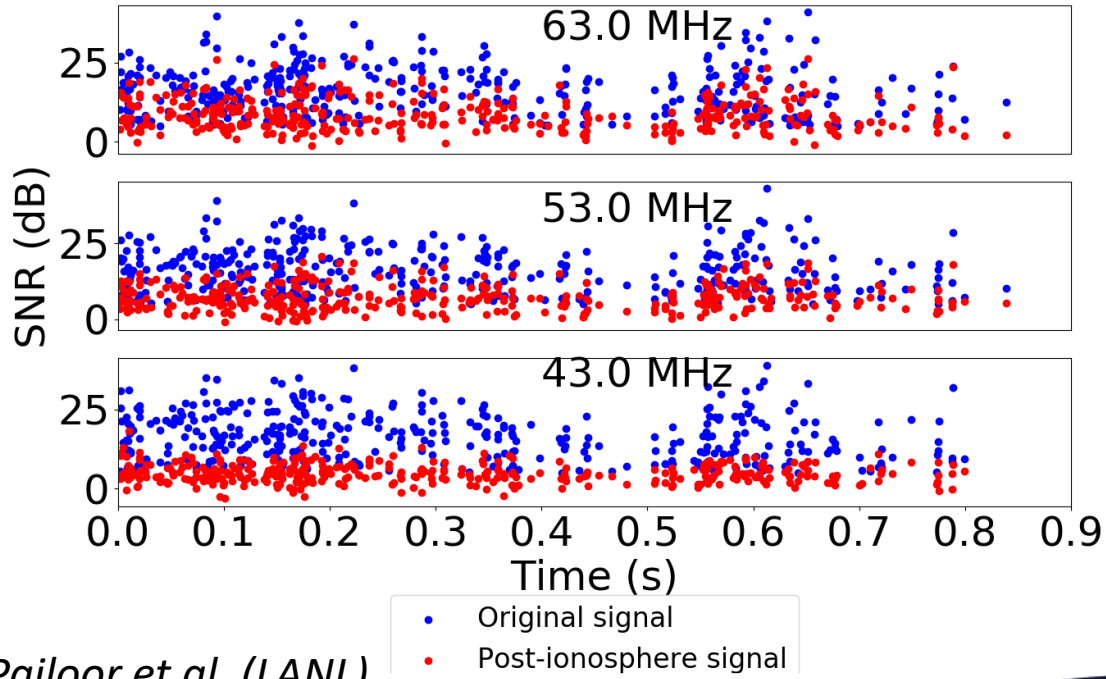
Pre-ionosphere impulses



Impulses dispersed by ionosphere



SNR at 530-km altitude (gets at detection capability)



Results presented at AGU2023 by N. Pailoor et al. (LANL)

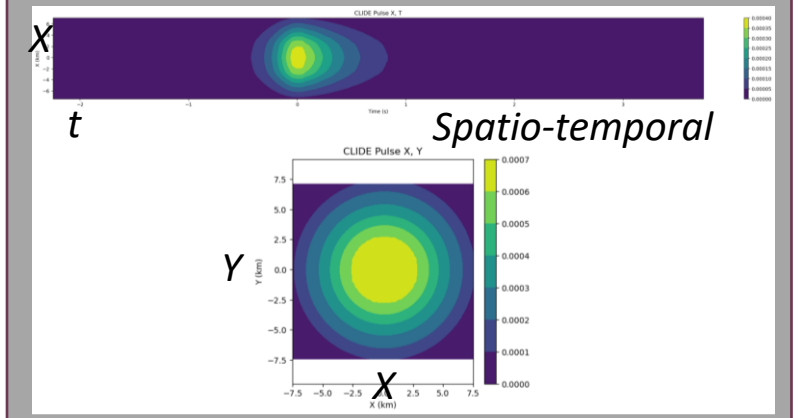
Instrument Simulator: Optical Lightning Mapper (e.g., CLIDE)

Optical Lightning Mapper model

Simulated Lightning Source → optics model → sensor model → Event Detection Logic → L0 data product

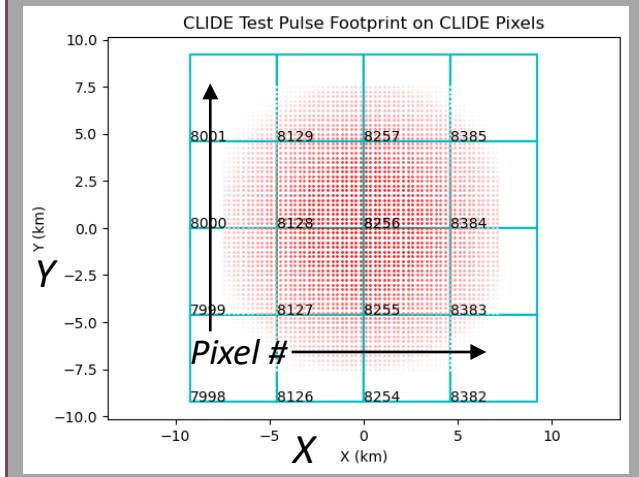
Optics Model

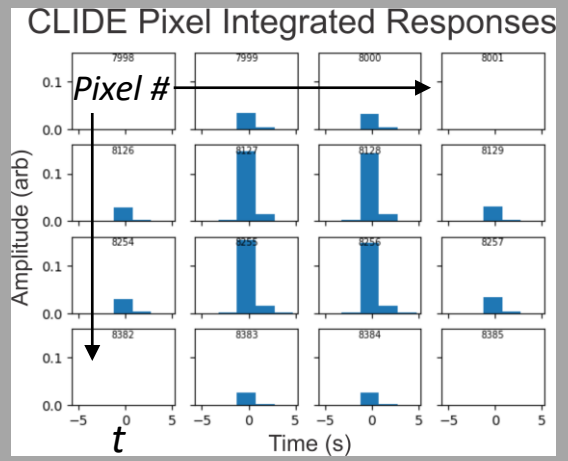
Simulates cloud-top optical emissions imaged at optical focal plane



CLIDE Sensor Model

Simulates pixelated image observed by sensor

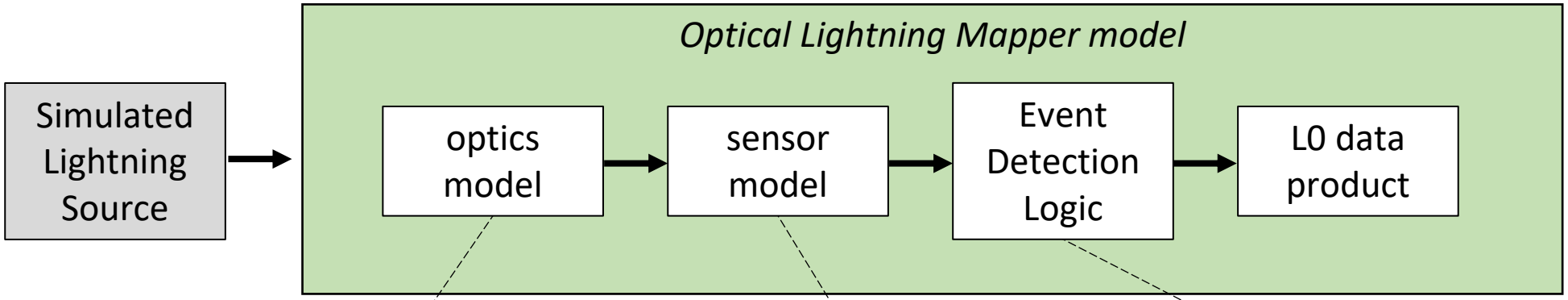


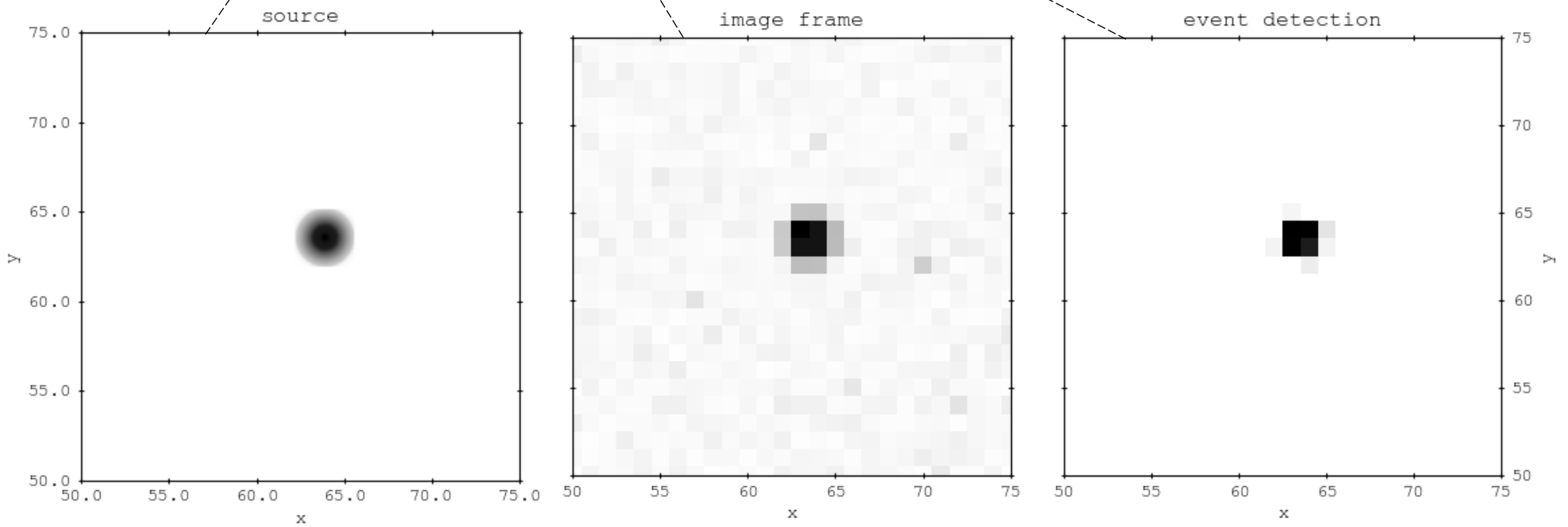


Event Detection Simulator

M. Quick (MSFC); D. Mach (USRA)

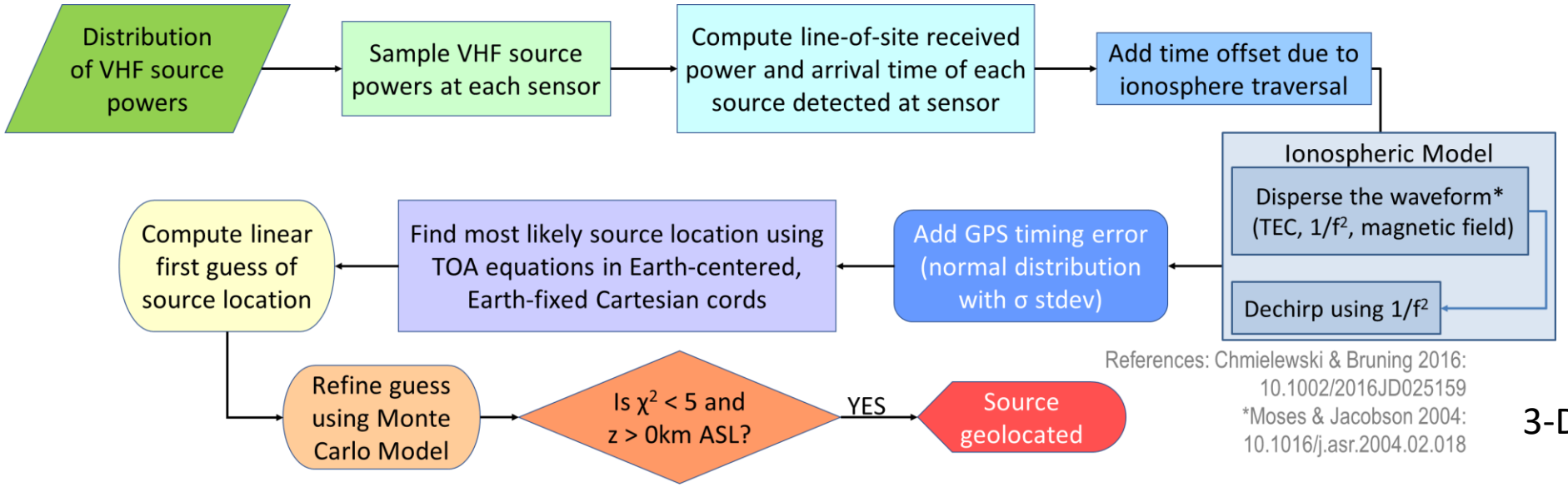
Example: Optical Lightning Event Detector





M. Quick (MSFC); D. Mach (USRA)

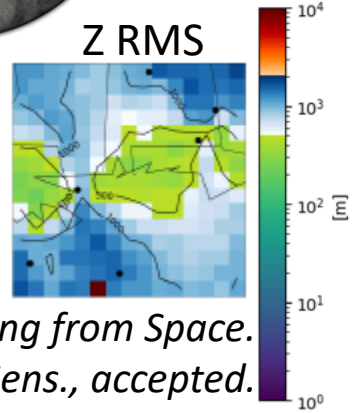
Simulated Observations: VHF Lightning Mapping from Space (e.g., CubeSpark)



References: Chmielewski & Bruning 2016: 10.1002/2016JD025159
*Moses & Jacobson 2004: 10.1016/j.asr.2004.02.018

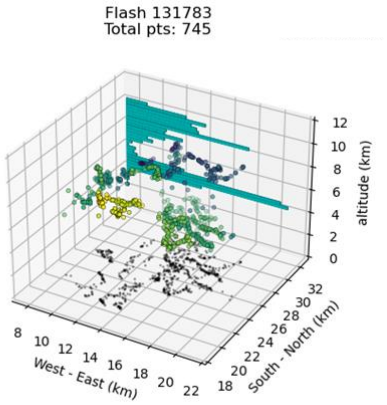
Z RMS

6-satellites
30 vTEC
3-D RMS error
< 1-2 km



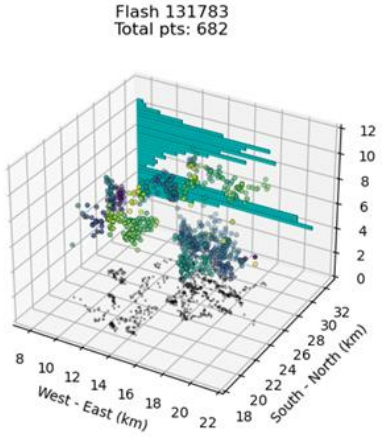
Remington et al., 2024: Simulated Feasibility of 3D Lightning Mapping from Space. IEEE Trans. Geosci. Rem. Sens., accepted.

VHF sources from lightning (e.g., LMA or Nature Run)

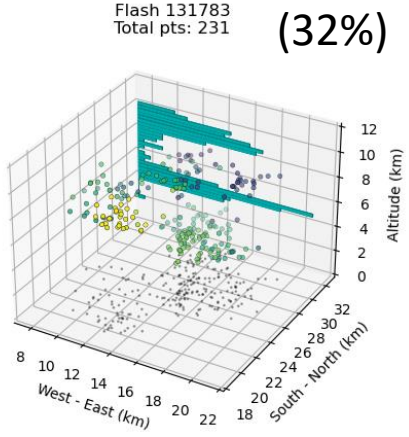


Simulated 3D Spaceborne Observation

Multi-satellite RF TOA



Single-sat: TIPP+optical (32%)



Simulated 3D Flash Geometry