

National Aeronautics and
Space Administration



The Next Generation of Lightning Mapping

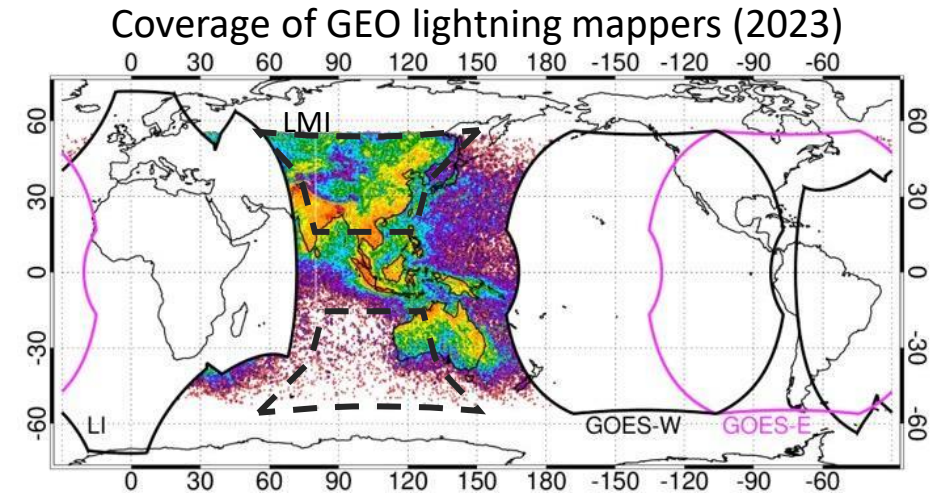
Jackson Remington, Patrick Gatlin, Timothy Lang, Mason Quick:
NASA Marshall Space Flight Center

Sonja Behnke, Harald Edens, Nikhil Pailoor:
Los Alamos National Laboratory

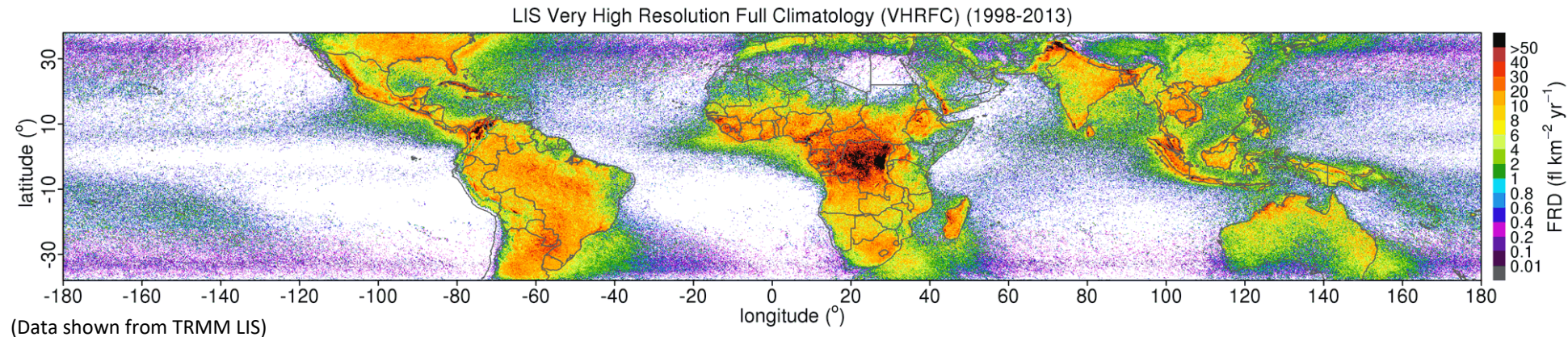
Sarah Stough:
NOAA National Severe Storms Laboratory

Orbital Lightning Mapping

- Optical observation
 - From geostationary or low-Earth orbit
 - Near-infrared (777 nm): hot leader processes
 - Ultraviolet (337 nm): streamer-based processes
- Radio frequency (RF) detection
 - Very high frequency (30-300 MHz)
 - Fast On-orbit Recording of Transient Events (FORTE)
 - Ground-based Lightning Mapping Array (LMA)



Lightning Imaging Sensor (ISS LIS): 2017-2023

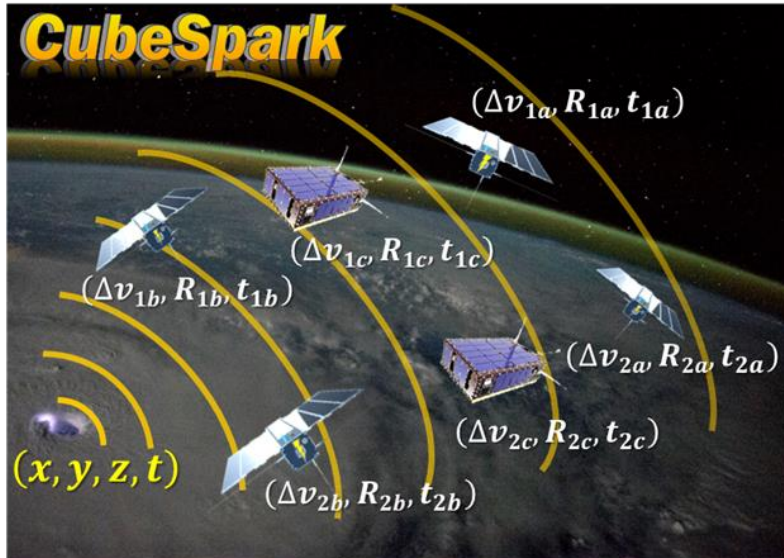


CubeSpark will expand 3-D observations globally

Constellation of small satellites acting as a 3D lightning mapping network in space:

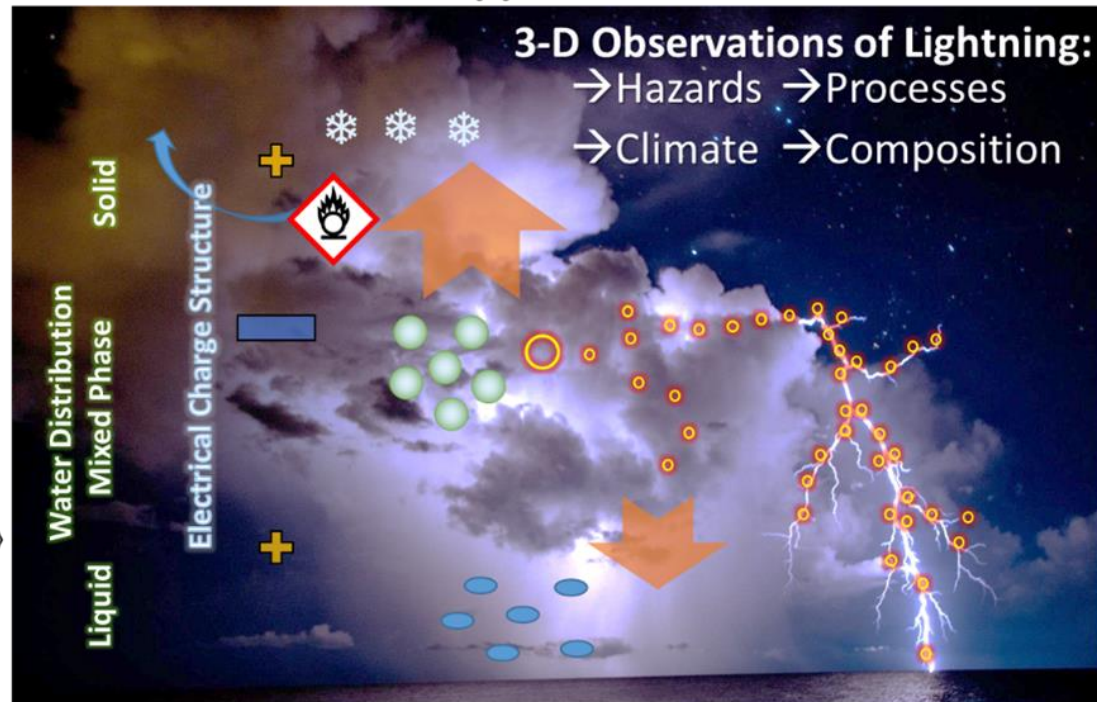
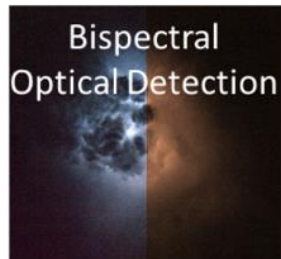
- VHF radio measurements to map lightning structure inside clouds
- Bispectral, high-resolution optical measurements to enhance detection of lightning in severe and anomalous thunderstorms and flashes that extend upward from cloud-top

ESTO
EARTH SCIENCE TECHNOLOGY OFFICE

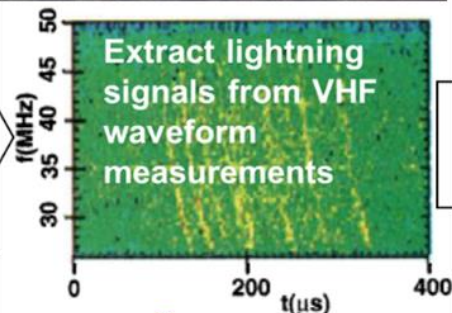


Measurement Concept

Enabled Science and Applications



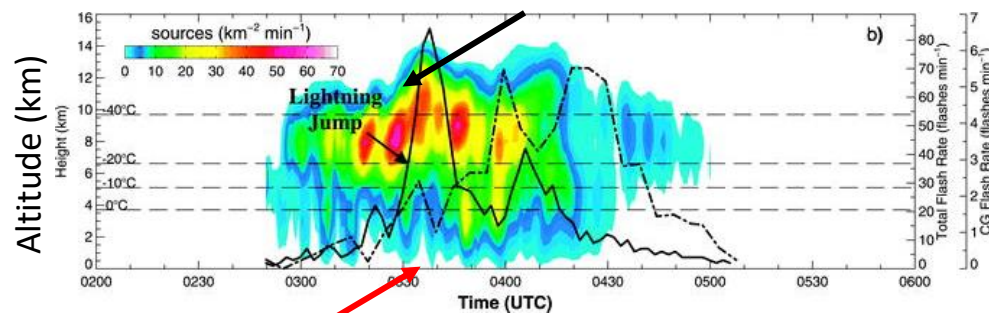
Being designed
at MSFC



Los Alamos
NATIONAL LABORATORY

(Gatlin & Goodman 2010)

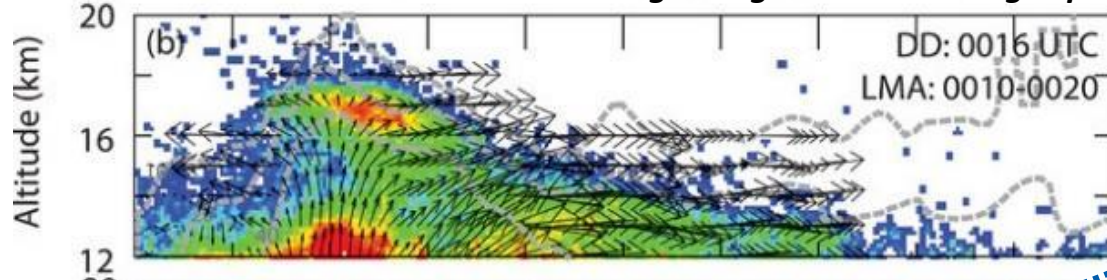
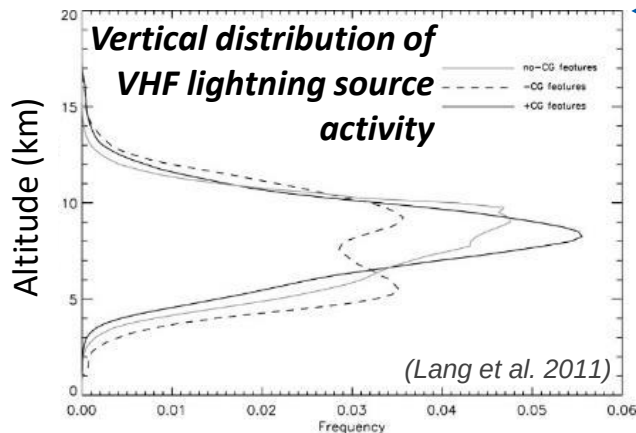
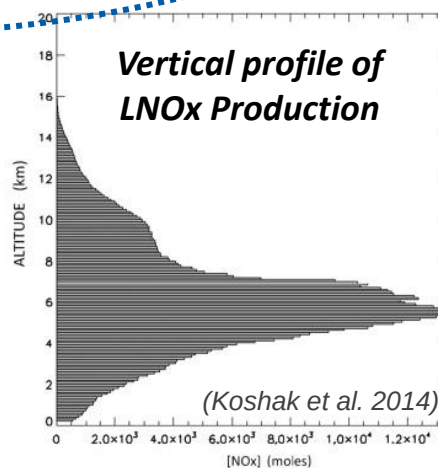
Vertical surge of VHF lightning source density



Damaging hail

(Calhoun et al. 2013)

Lightning in Overshooting Tops



Vertical Observation Empowers Scientific Application

<2 km resolution

Identify severe storm intensification

Determine convective properties

Infer cloud charge structure

<1 km resolution

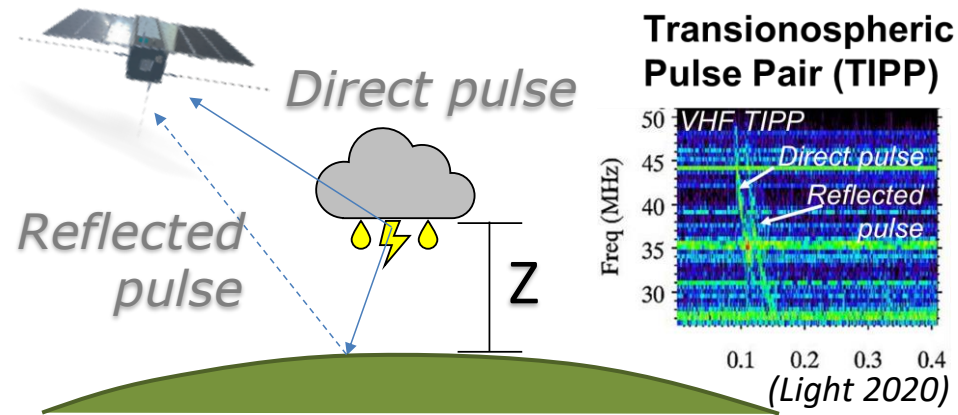
Map channel structure

Model distribution of lightning-produced nitrous oxide (LNOx)

These studies are enabled by 3D lightning observations, limited to regional, ground-based networks (LMA, etc.)

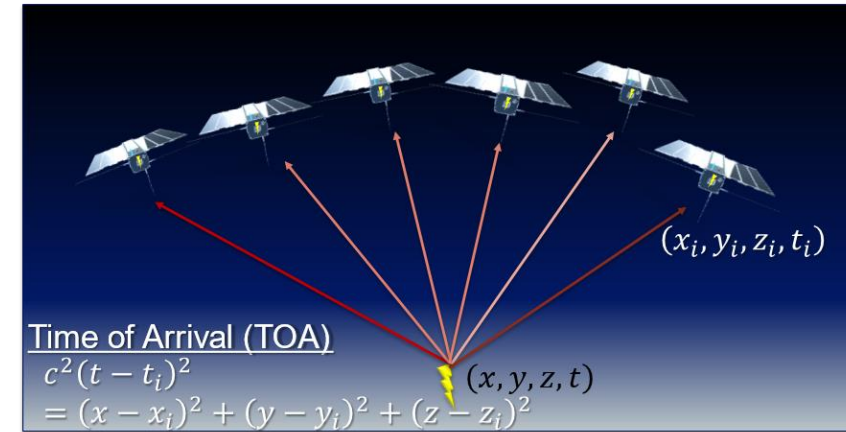
Approaches for spaceborne 3-D geolocation of lightning

Single satellite: TIPP+optical



- RF gives altitude; Optical gives lat/lon
- 3D requires detection of reflected pulses (TIPP) coincident with optical
- Vertical RMS error ~ 300 m ($\sigma_{\text{timing}} = 0.1 \mu\text{s}$)

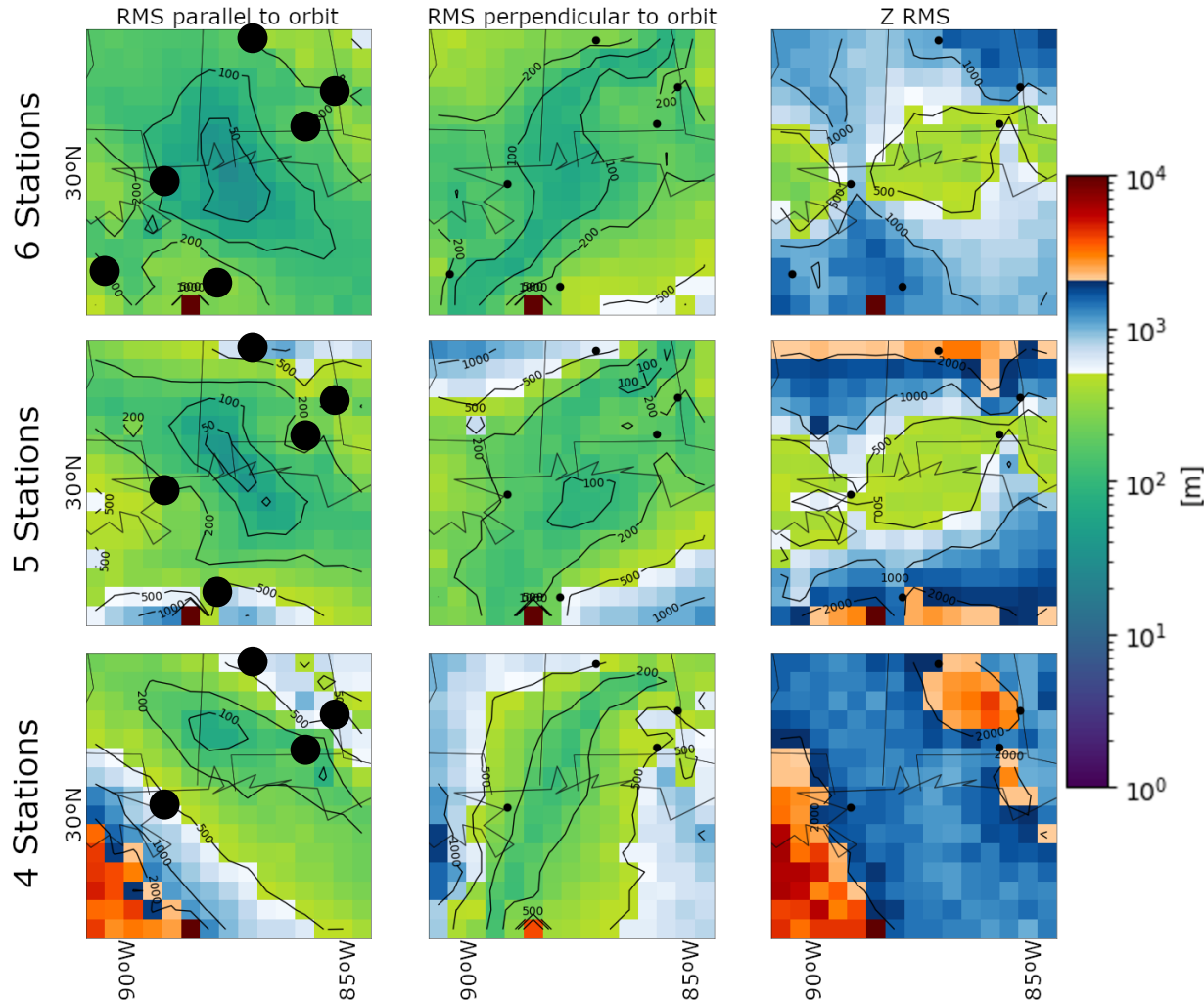
Multi-satellite: Time-of-arrival (TOA)



- Doesn't rely on reflected pulse for 3D
- Optical can be used to reduce number of VHF detections required for 3D retrieval
- Vertical RMS error $< 1\text{-}2$ km

VHF-Based Time of Arrival (TOA)

Solution RMS Errors (Rotated): Varying # of Stations
timing err: 1e-7 s ; configuration2



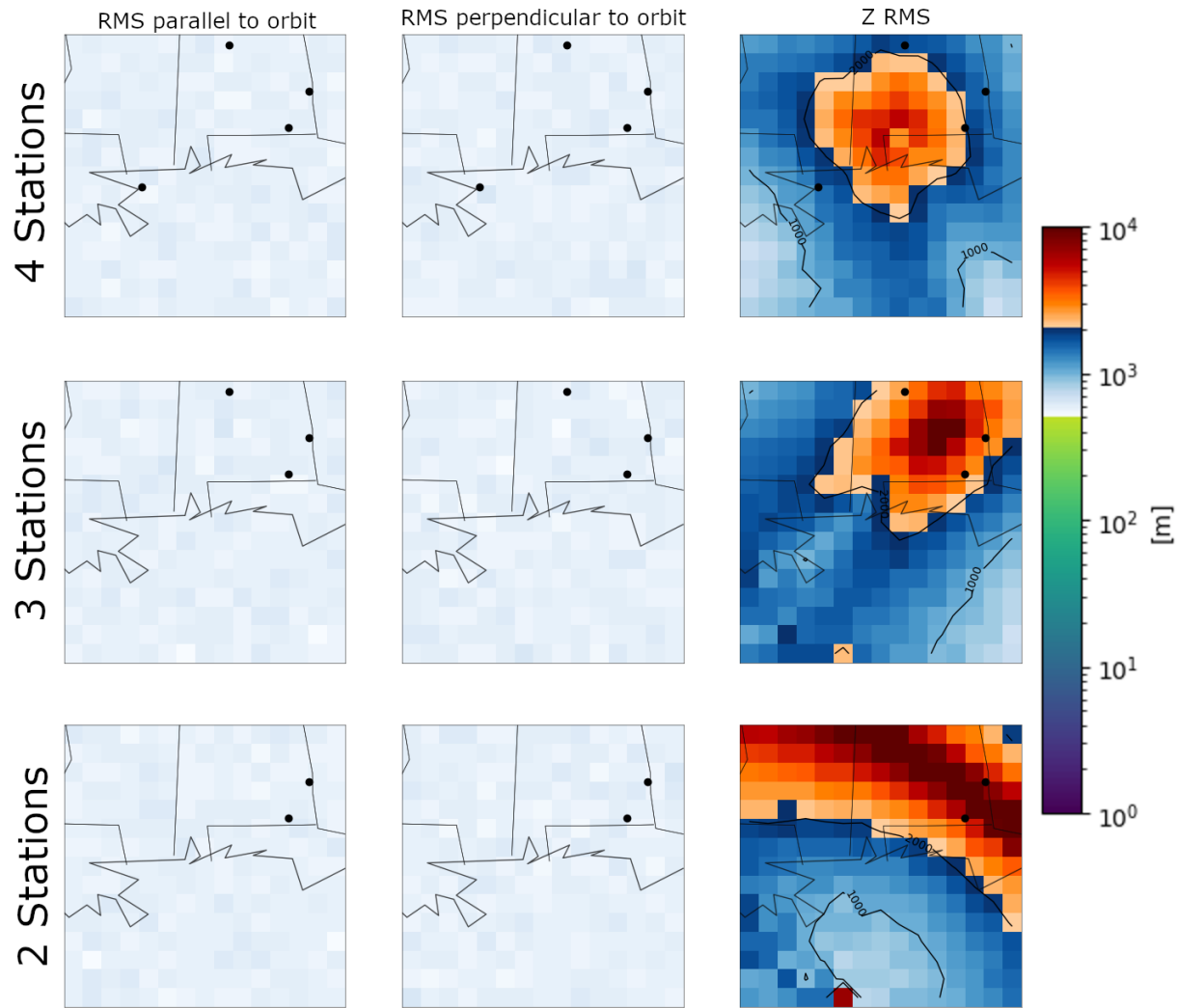
Test location at mid-latitudes (30.2° N, 92.3° W)

RMS errors in x' , y' , z :

- 6 satellites:
 - 160 m, 210 m, **850 m**
 - ~60% coverage with 3D resolution <1 km
- 5 satellites
 - 290 m, 330 m, **1100 m**
 - ~44% coverage with 3D resolution <1 km
- 4 satellites
 - 760 m, 500 m, **2000 m**
 - 0% coverage with 3D resolution <1 km
 - ~75% coverage with 3D resolution <2 km

Optically-Constrained TOA

Test location at mid-latitudes (30.2° N, 92.3° W)

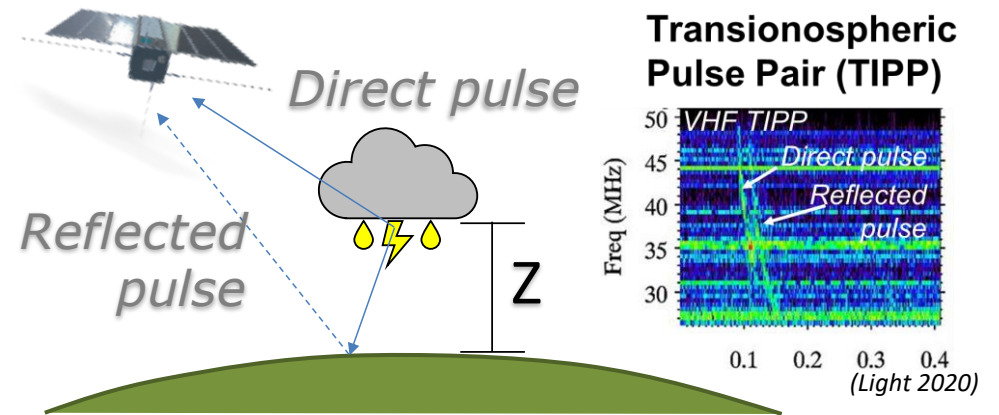
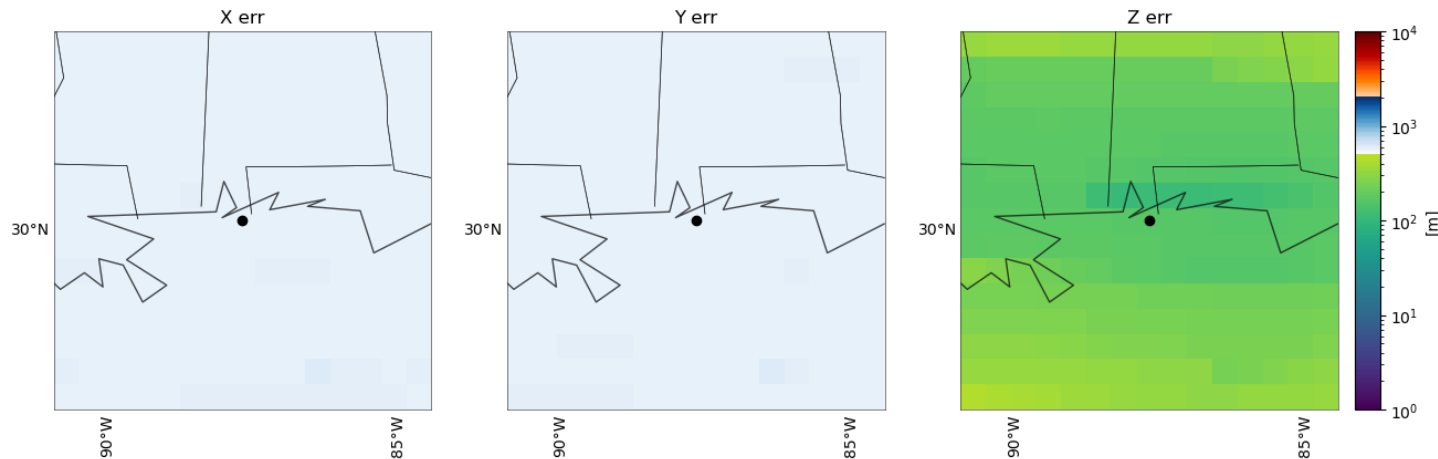


RMS errors in x' , y' , z :

- 4 satellites:
 - 580 m, 580 m, **1700 m**
 - ~13% coverage with 3D resolution <1 km
- 3 satellites
 - 580 m, 580 m, **1900 m**
 - ~10% coverage with 3D resolution <1 km
- 2 satellites
 - 580 m, 580 m, **3800 m**
 - ~10% coverage with 3D resolution <1 km

Single-Satellite Reflected Pulse Method

- Requires optical constraint and reflected VHF emission
 - 12-32% of VHF sources
 - Horizontal position given by optical imager (x, y)
 - Altitude and time given by direct and reflected pulses (z, t)



RMS errors in x, y, z :

- 580 m, 580 m, **300 m**
- ~100% coverage with 3D resolution <1 km

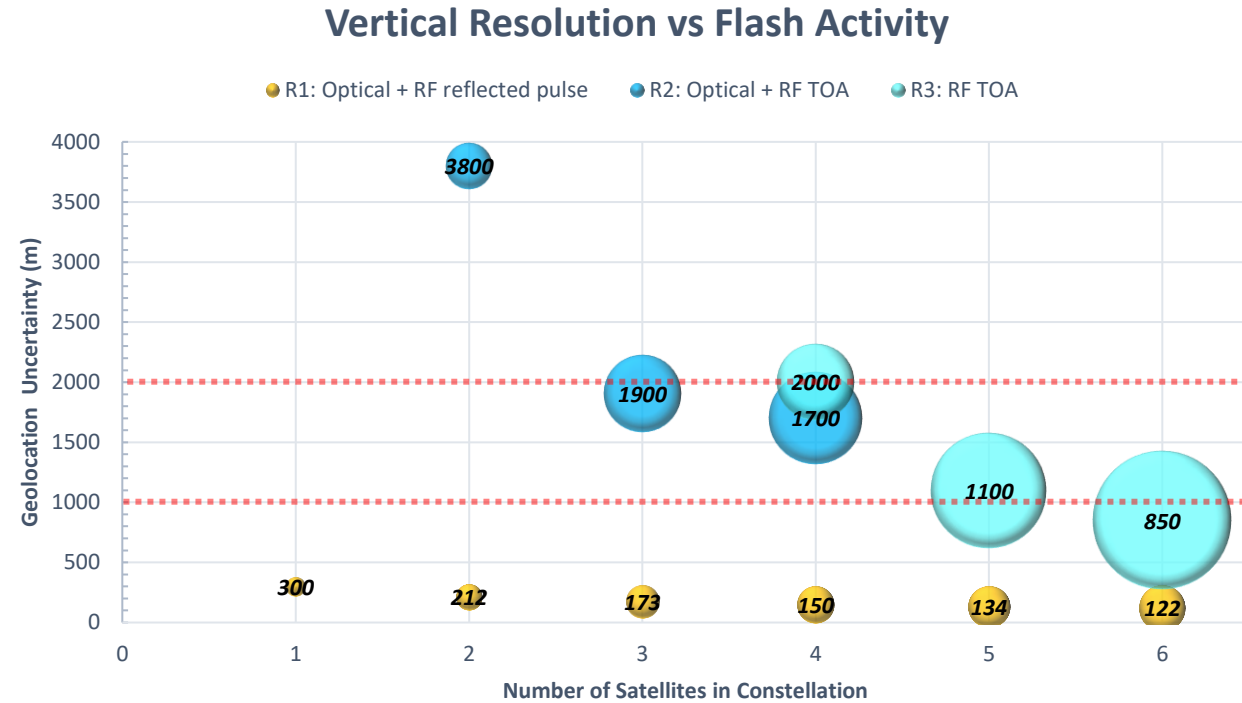
Results and Limitations

Geometric Error Sources:

- **Pure-VHF** TOA is viable using 5 or more satellites
- **Optically-constrained** TOA is viable using 3 or more satellites
- Single-satellite method always viable
- Using ionospheric electron density 30 TECU (10^{16} electrons/m²)
- Instrumental timing error $\sigma = 0.1 \mu\text{s}$

Detection Efficiency?

- Source powers decoupled from these simulations
- What does a real flash look like when reconstructed?
 - (in progress)

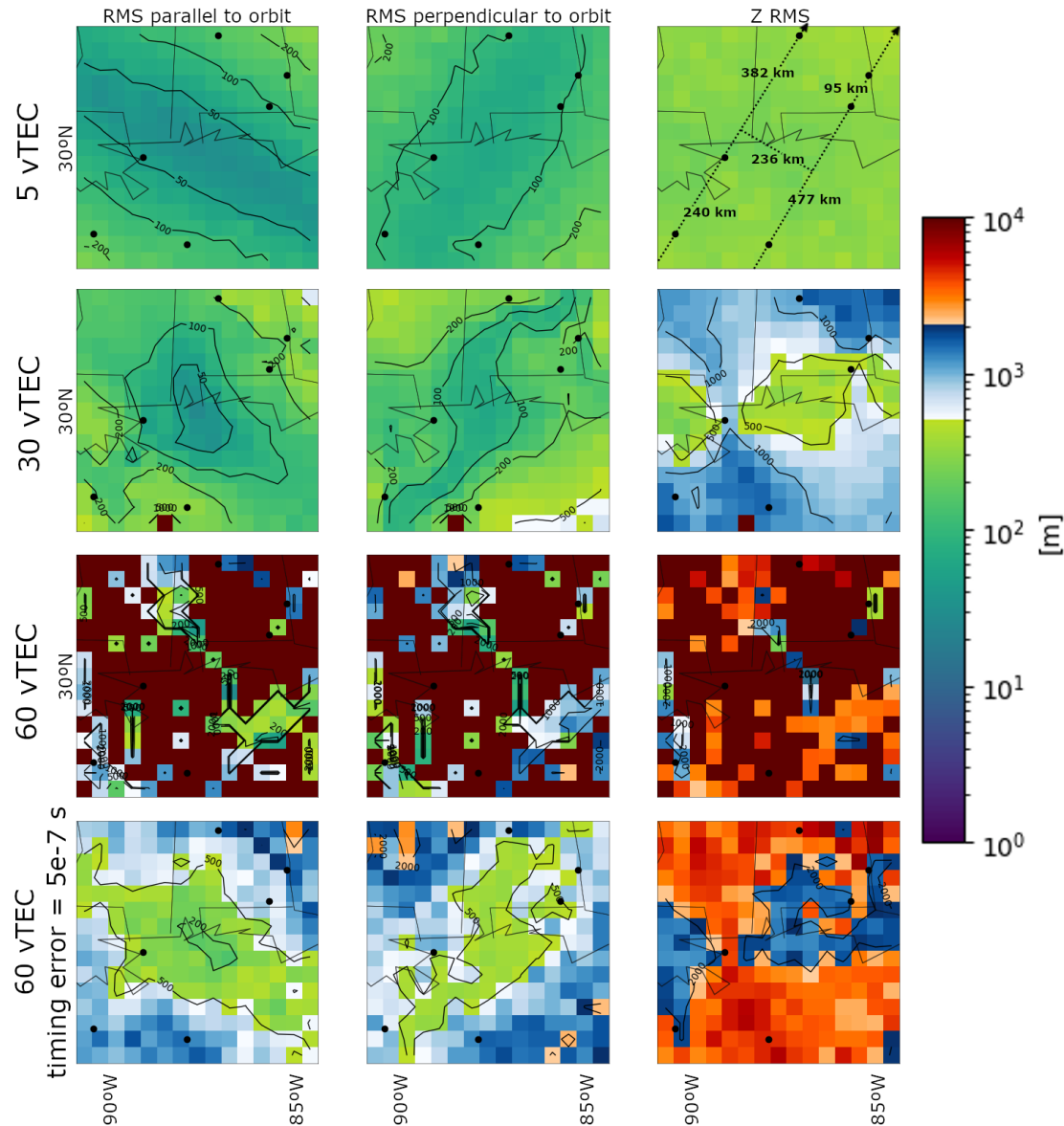


- Size represents relative number of well-resolved sources (approx.)

Ionospheric Total Electron Count (TEC)

RMS errors in x' , y' , z :

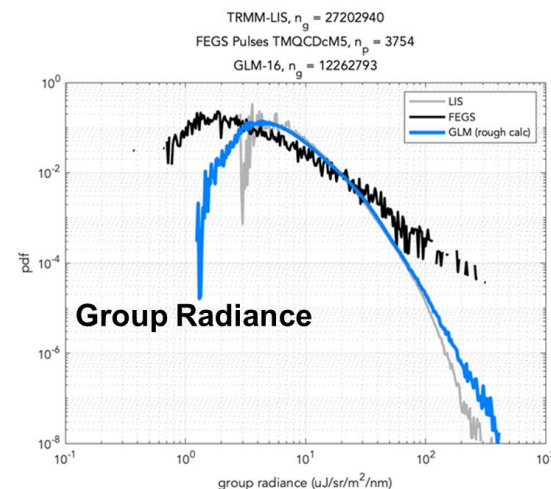
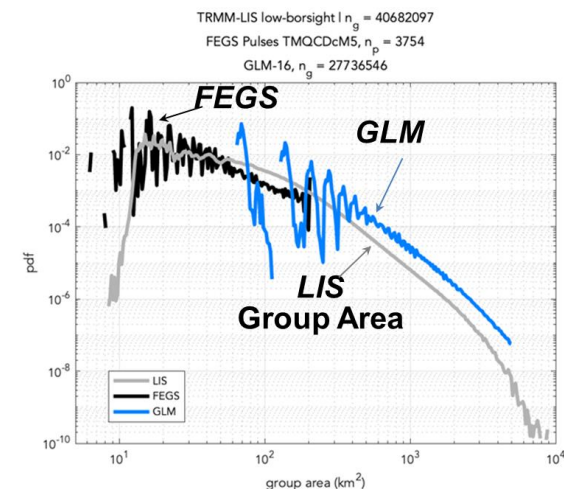
- 5 TECU:
 - 85 m, 110 m, **290 m**
 - 100% coverage with 3D resolution <1 km
- 30 TECU
 - 160 m, 210 m, **850 m**
 - ~60% coverage with 3D resolution <1 km
- 60 TECU
 - Poor algorithm convergence rates
- 60 TECU (relaxed timing)
 - 720 m, 870 m, **2700 m**
 - 0% coverage with 3D resolution <1 km
 - ~30% coverage with 3D resolution <2 km



Detecting Optically Small and Faint Flashes

The CubeSat Lightning Imaging and Detection Experiment (CLIDE) sensor is being developed for use by CubeSpark:

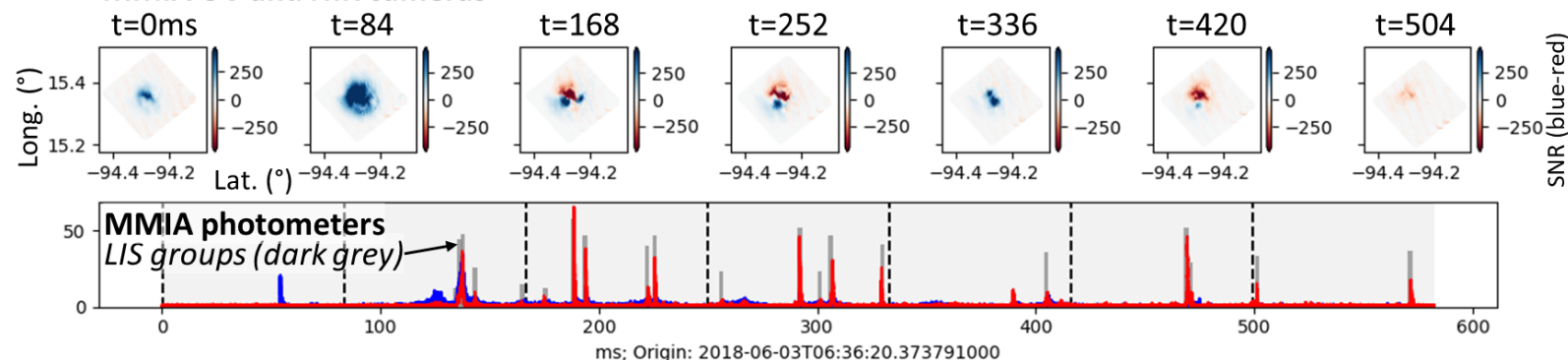
- Increased horizontal resolution improves detection of smaller flashes
- Increased sensitivity improves detection of dimmer flashes
- CLIDE will have an ultraviolet imager (337 nm) for detecting cool (streamer) processes that may not be detectable at standard 777 nm (hot leaders)



Comparison of ASIM and LIS on ISS:

MMIA UV and NIR cameras

MMIA 2018-06-03T06:36:20.290591000 id:14343



ALOFT data analysis (underway)
will tell us more about spectral
fingerprint of lightning

Summary of Results

- Using **pure-VHF** TOA, expected vertical accuracy is:

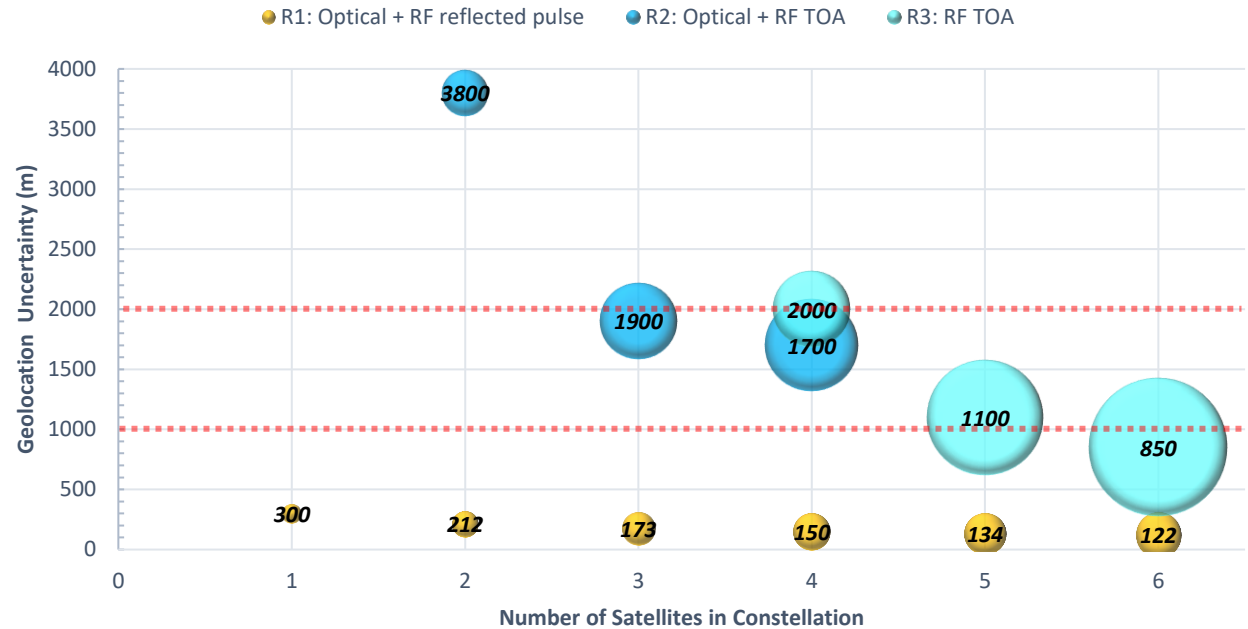
- **850 m using 6 satellites**
- **1,100 m using 5 satellites**
- <5 satellites unreliable

- Using **optically-constrained** TOA, expected vertical accuracy is:

- **1,700 m using 4 satellites**
- **1,900 m using 3 satellites**
- <3 satellites unreliable

- High resolution 3D lightning geolocation would represent a significant advancement in fields beyond lightning from meteorology to climate modeling.
- Storm charge layers can be inferred with vertical accuracy <2 km, lightning structure may be resolved with accuracy <1 km
 - (with caveats of detection efficiency)

Vertical Resolution vs Flash Activity



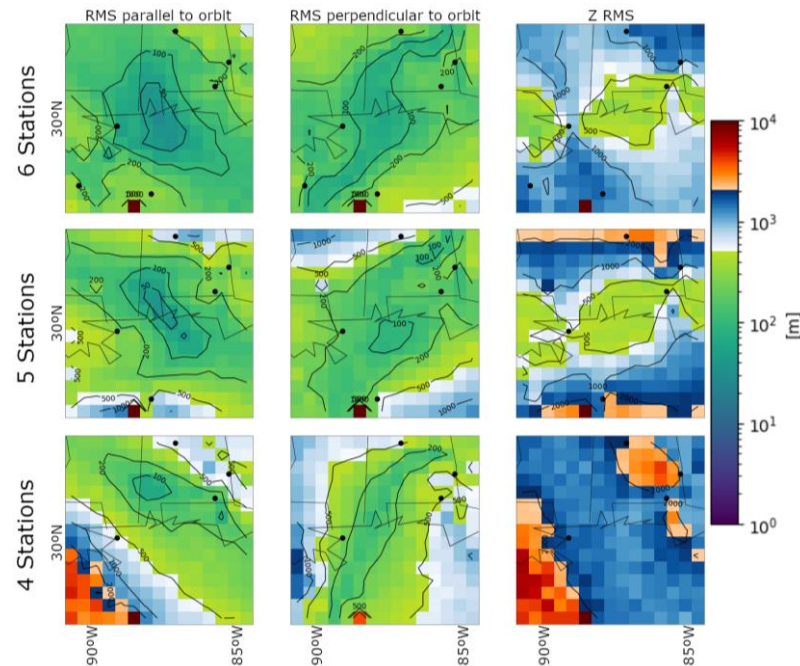
- Size represents relative number of well-resolved sources (approx.)

The background of the slide is a cosmic scene. The top half features a dark blue space with a bright blue nebula on the right and numerous small, distant stars. The bottom half is a gradient of orange and yellow, also filled with stars. A light blue horizontal band runs across the middle, containing the word 'Supplementary'.

Supplementary

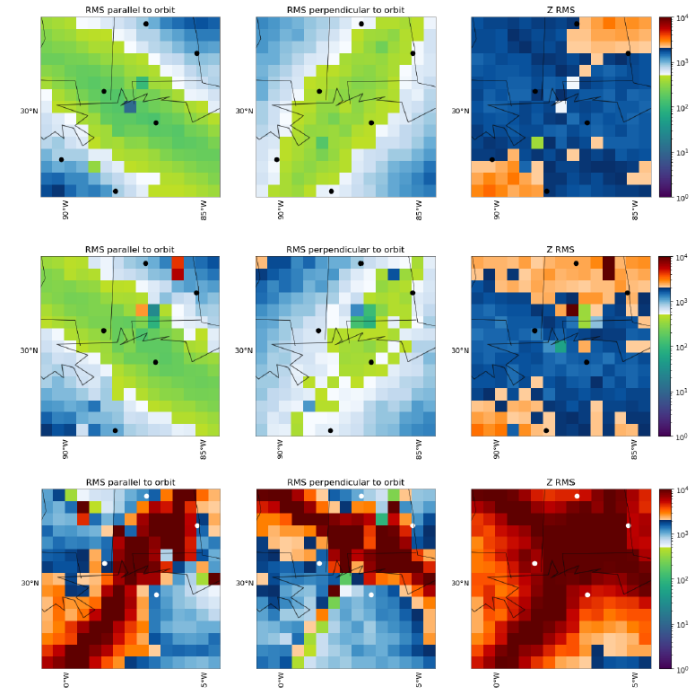
Instrumental Timing Error

$$\sigma_{\text{timing}} = 0.1 \mu\text{s}$$



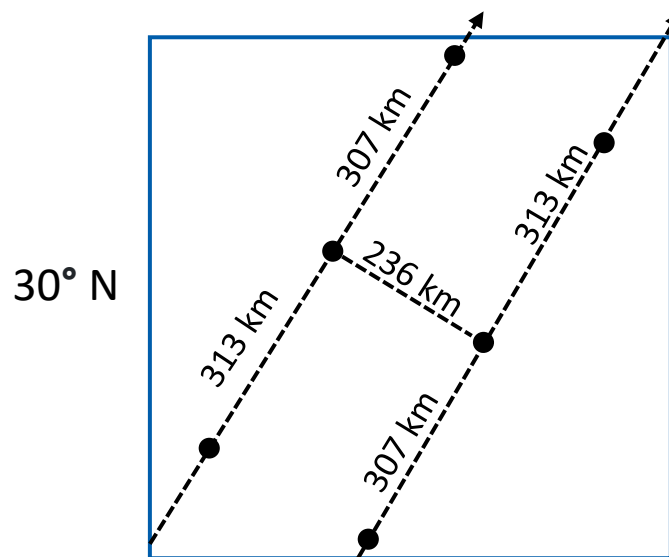
- 6 satellites:
 - **~ 0.2 km** horizontal error
 - **~ 0.9 km** vertical error
- 5 satellites
 - **~ 0.3 km** horizontal error
 - **~ 1.1 km** vertical error
- 4 satellites
 - **~ 0.6 km** horizontal error
 - **~ 2.0 km** vertical error

$$\sigma_{\text{timing}} = 0.5 \mu\text{s}$$

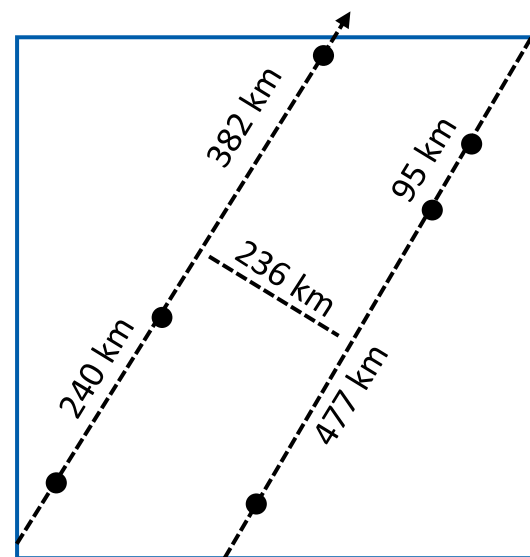


- 6 satellites:
 - **~ 0.7 km** horizontal error
 - **~ 1.5 km** vertical error
- 5 satellites
 - **~ 0.8 km** horizontal error
 - **~ 1.6 km** vertical error
- 4 satellites
 - **>> 5 km** error
 - Not feasible

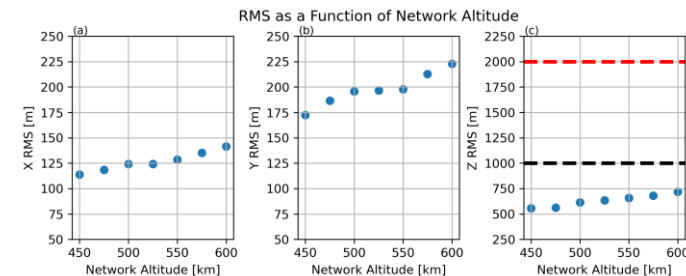
CubeSpark Constellation Design



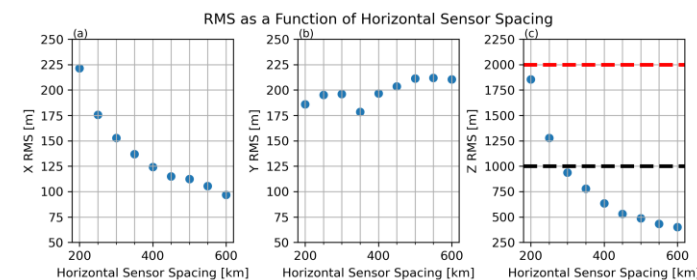
Original configuration



Shifted to avoid
baseline symmetry



Altitude:
525 km



Average separation:
300 km

CubeSat Lightning Imaging and Detection Experiment (CLIDE)

- Purpose: To detect small and optically dim lightning flashes that frequent intense thunderstorms
- Specifications:
 - Center wavelengths: 777.4 ± 0.5 nm; 337 ± 1 nm
 - Spectral bandwidth: ≤ 1 nm FWHM
 - 60 x 60 deg FOV (≥ 90 -sec storm observation time)
 - ≤ 2 -km spatial resolution
 - < 1 -ms temporal resolution
 - Event detection threshold: $\leq 2 \mu J m^{-2} sr^{-1}$
- Being designed for use on small satellite missions like CubeSpark
 - Includes a more compact optics design to reduce size, weight, and cost of telescope
 - Uses faster and higher resolution CMOS detectors with new AI-based storm detection and dynamic sampling strategy