Hurricane Lightning: a new Campaign to Investigate Hurricane Intensification by Using Lightning Observations

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Abstract

Los Alamos National Laboratory (LANL) recently funded a three-year effort to investigate hurricane intensification processes by using lightning observations and hurricane modeling. The objective is to improve the forecast accuracy on rapid hurricane intensification, large-scale transition and reorganization of a multiscale hurricane system by using a model that assimilates knowledge of critical small-scale processes, specifically the eyewall convection provided by a lightning imaging system.

In 2005, LANL's Sferic Array (LASA) showed clearly positive correlation between eyewall lightning activity and the hurricane intensification for Katrina, Rita and Wilma. Since the sensors were not deployed for hurricane study, some of the contributing sensors were as far as 3000 km from hurricane centers, and therefore only limited data were available.

In 2008, we plan to deploy additional LASA sensors in the Gulf region to better cover the hurricane active area. The additional sensors consist of VLF and VHF radio frequency band for each sensor. The VLF band will serve to provide charge moment measurement for individual discharge events, and the VHF band will provide detailed 3D imaging of the lightning structures. Combination of the two simultaneous observations will be used to infer charge structure and charge amount inside a lightning active eyewall. In addition, the VLF band alone will be used to detect, geolocate, and characterize hurricane lightning activity at distances that are beyond the detectable range for VHF. As for the earlier LASA sensors, the full VLF waveform will be captured and recorded for detailed study, and will be used to determine the lightning type, discharge current, and to provide source height for distant impulsive intracloud events. This presentation will report LANL's ongoing and planned hurricane lightning research activity.

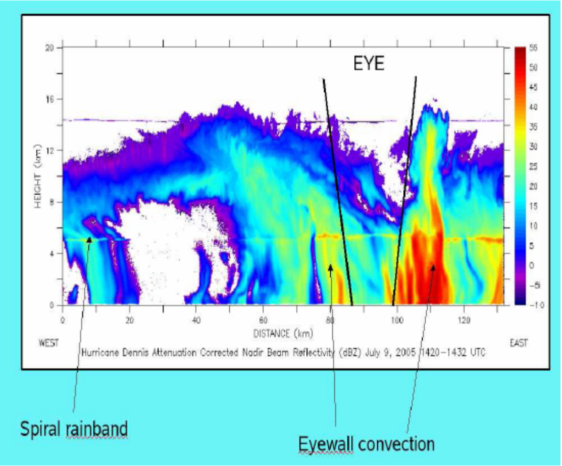
Introduction

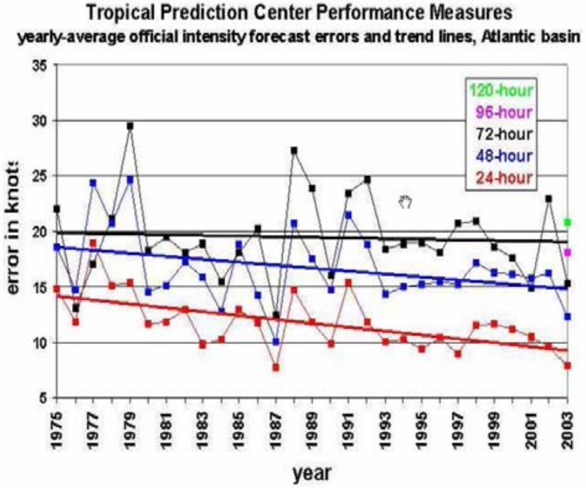
- **NOAA's Hurricane Intensity Research Working Group recommended to achieve a *10 knot improvement in 48-hour intensity forecasts* of hurricane-strength storm in 5 years**
- **However, the hurricane modeling community rapidly approaching the *"limits of predictability"* for model-based intensification forecasts**
  - **Tropical depression is a convectively unstable, vorticity-rich environment with extremely complex and random internal dynamics**
  - **"Vortical Hot Towers" form (10-30 km; 1 hour life), tilt, stretch, and merge. Their cumulative effect is to prime the tropical depression; individually they may trigger rapid intensification**
  - **Individual Vortical Hot Towers will not be accurately predicated by a numerical mode, without new observations and data assimilation**
- **LASA and other observations showed a positive relationship between hurricane intensification and eyewall lightning activity for Katrina, Rita, and Wilma (Shao et al., 2005), suggested that lightning data can be assimilated into model to improve the intensity forecast**

Objectives

- **Perform the first-ever 3-D mapping of convective events in the hurricane eyewall using a new *dual-band* lightning remote-sensing capability developed in LANL**
- **Demonstrate that**
  - **rapid hurricane intensification,**
  - **sudden large-scale transition**
  - **and sudden reorganization of a vastly multiscale systems**

  Can be accurately forecasted using a novel model that assimilates real-time knowledge of critical small-scale processes
- **Achieve the national goal of *10 knot improvement in 48-hour intensity forecasts* in three years.**





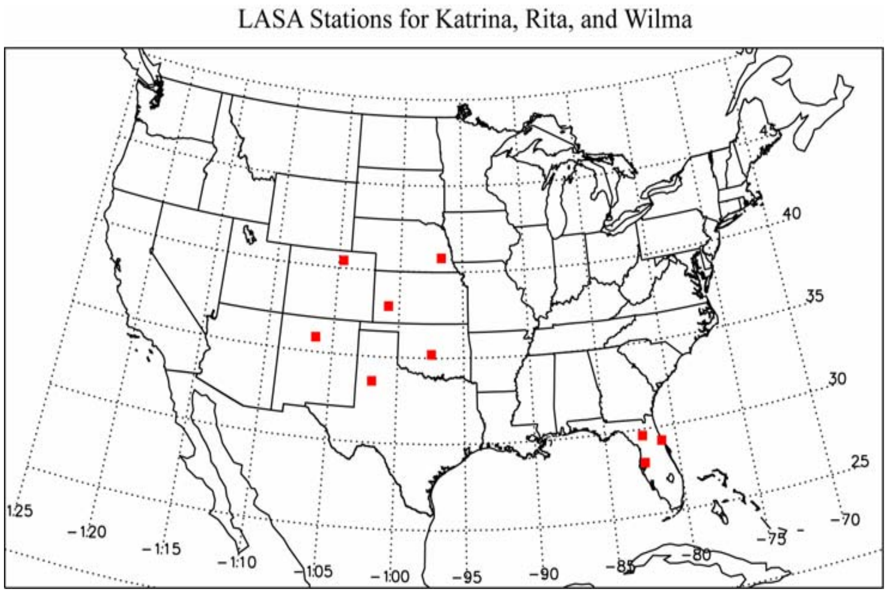
Approaches

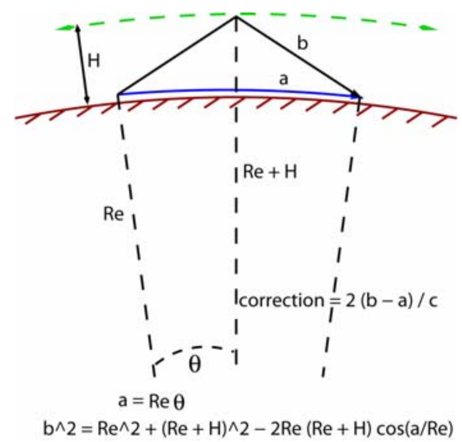
- **Lightning Sensor Array:**
  - Build, deploy and maintain a 3D hurricane lightning mapping system in the Gulf with real-time, 24/7 observational capabilities
- **Hurricane Modeling:**
  - Develop a unique hurricane forecast model that uses assimilated lightning data to accurately predict rapid (re-)intensification cycle
  - Develop the Cloud Electrification Module
  - Develop the Reduced-Order Kalman Filter
  - Perform HIGRAD simulations
  - Integrate all model components
  - Test and evaluate the new model and quantify its improved predictive ability
- **Analysis:**
  - Establish, maintain and analyze a comprehensive database of all LASA observations of hurricane lightning and coincident dropwindsonde, radar, and satellite data

Past LASA observation of Hurricanes Katrina, Rita, and Wilma at VLF/LF

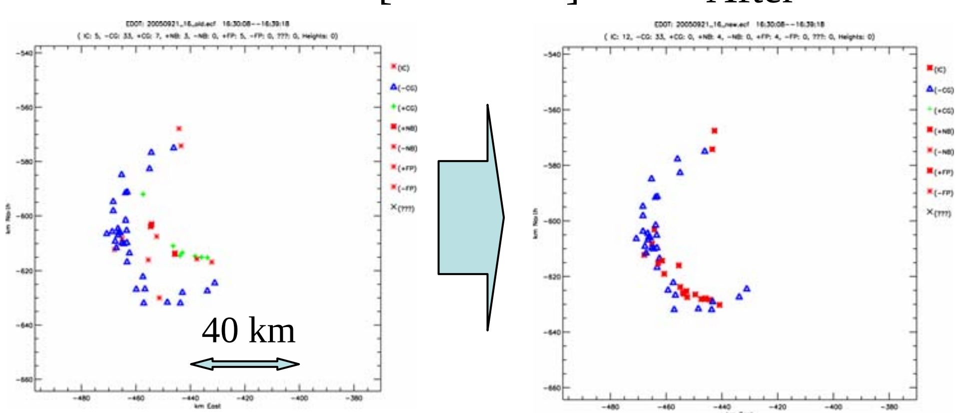
Hurricanes were 10^2-10^3 km from sensors, direct TOA location was inaccurate

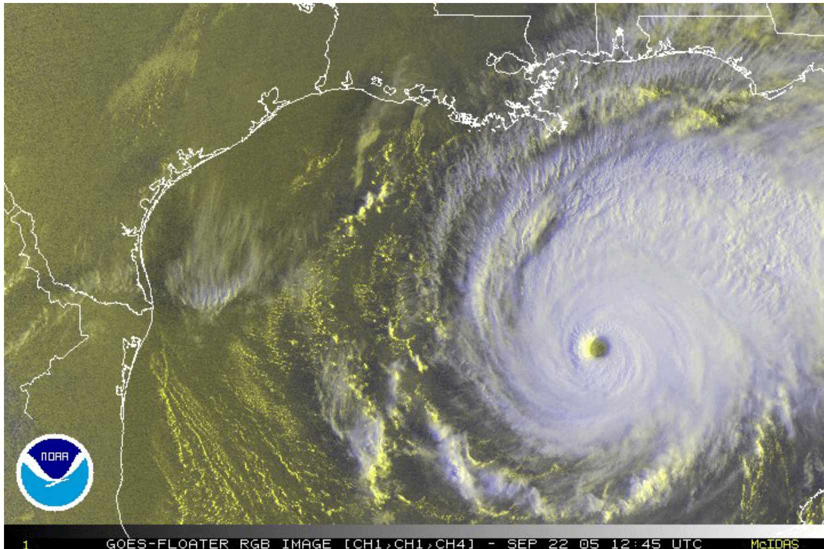
LASA achieves km accuracy after ionospheric correction; ~20 kA sensitivity





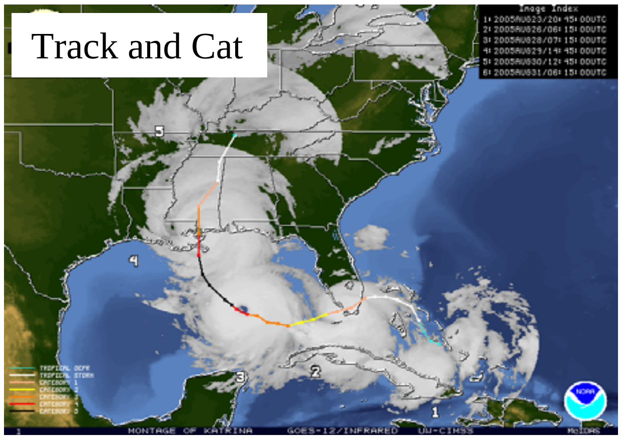
Before [correction] After

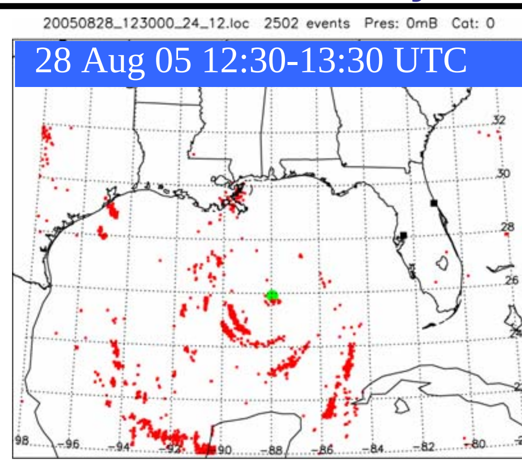


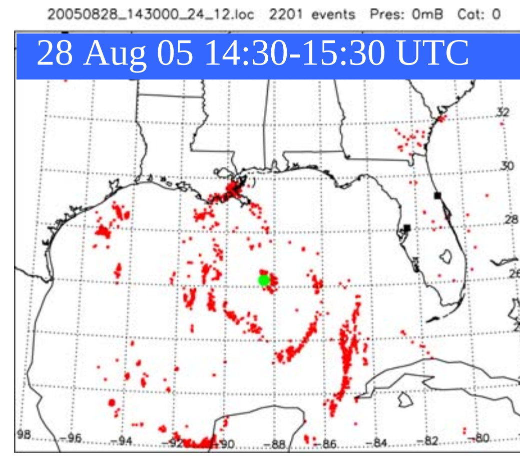


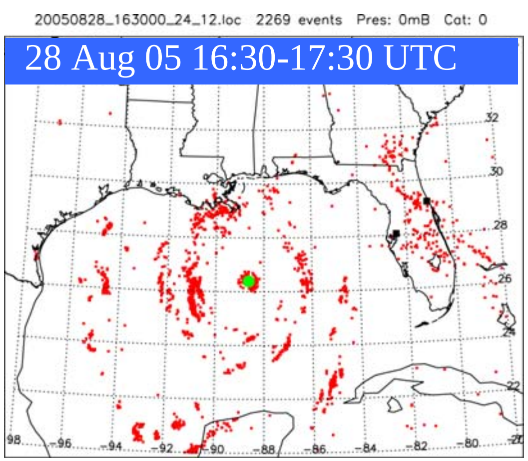
Lightning activities of Katrina

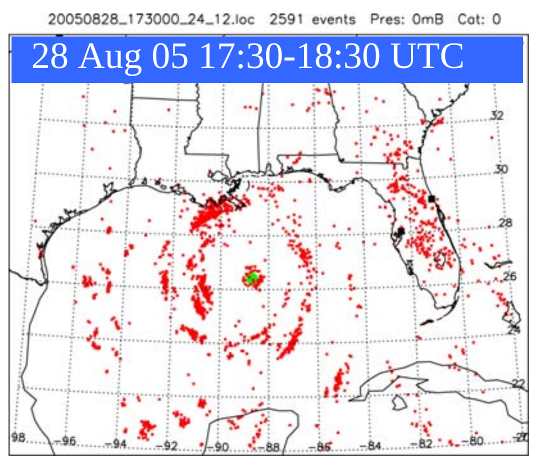
(1) Start to see eye-wall lightning at Cat 4. (2) Eye-wall lightning intensifies as Katrina progresses from Cat 4 to 5; eye-wall lightning deceases when Katrina decays. (3) Unusual high rate of rainband lightning; rainband lightning not associated with Katrina intensity.

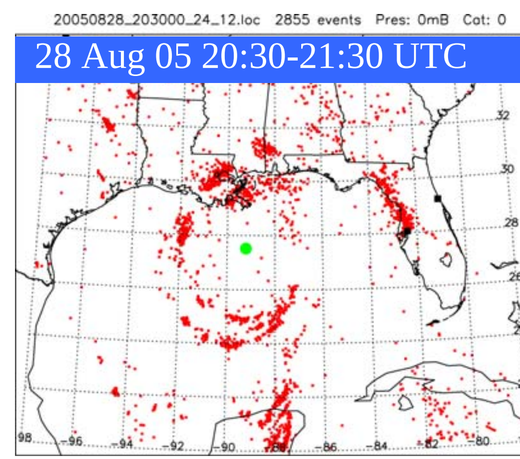








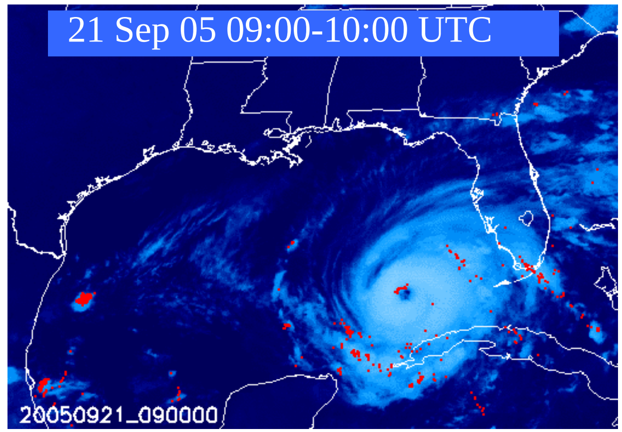


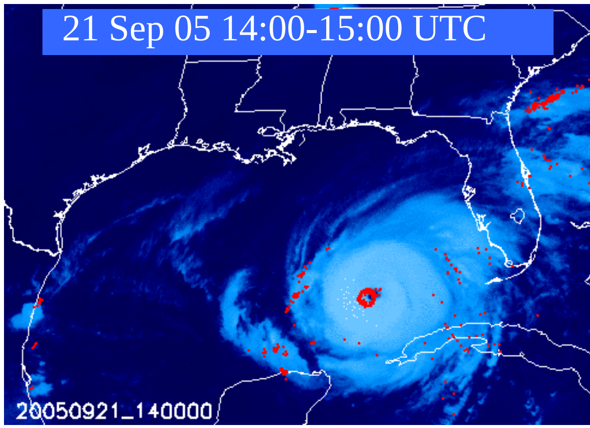


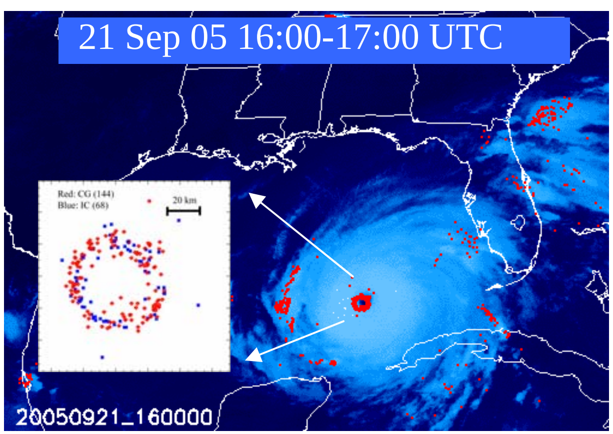
Shao et al., Eos, 86, 42, 18 Oct. 2005

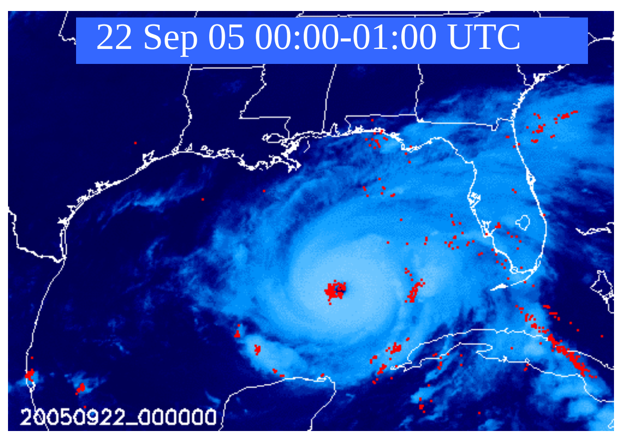
Lightning activities of Rita

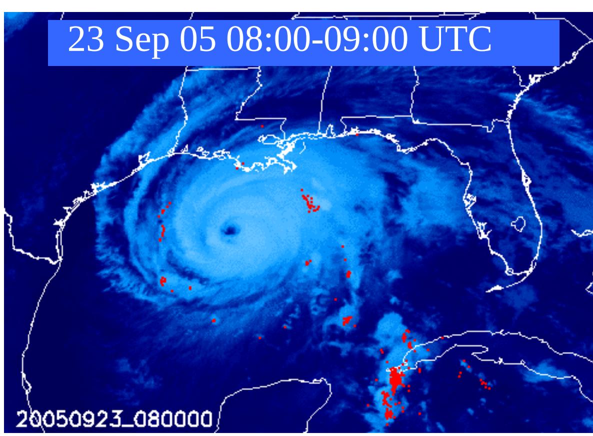
(1) Start to see eye-wall lightning at Cat 3. (2) Eye-wall lightning intensifies as Rita progresses from Cat 3 to 5; eye-wall lightning deceases when rita decays. (3) "Normal" rate of rainband lightning. (4) Rita intensified from Cat 3 to 5 much faster than Katrina, and produced much more eye-wall lightning.









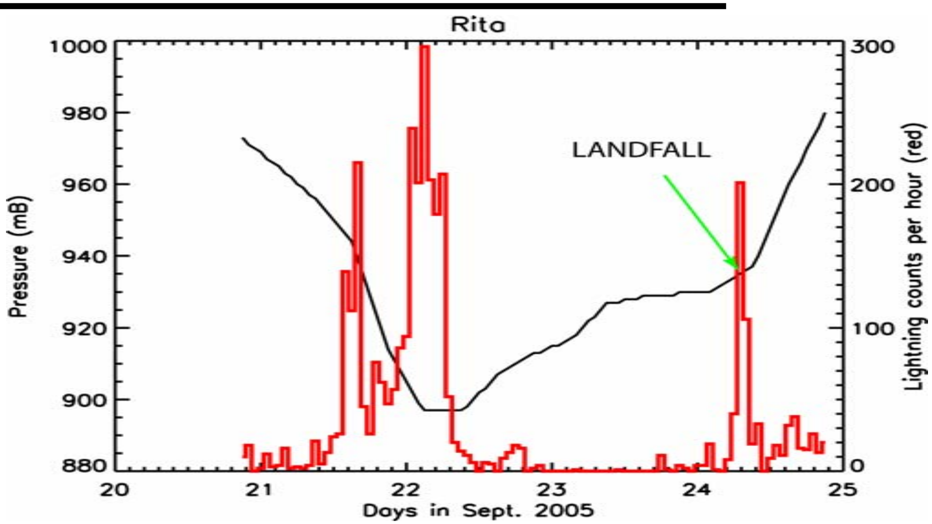


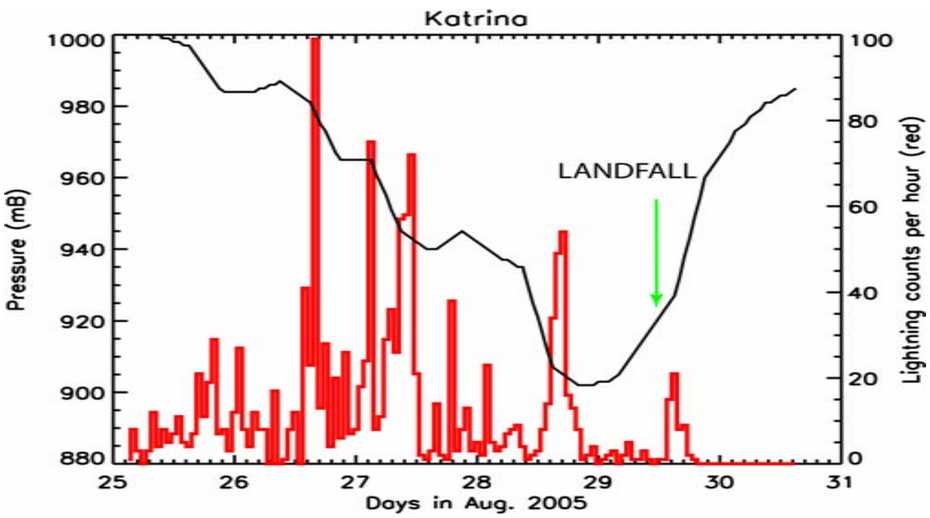
Shao et al., Eos, 86, 42, 18 Oct. 2005

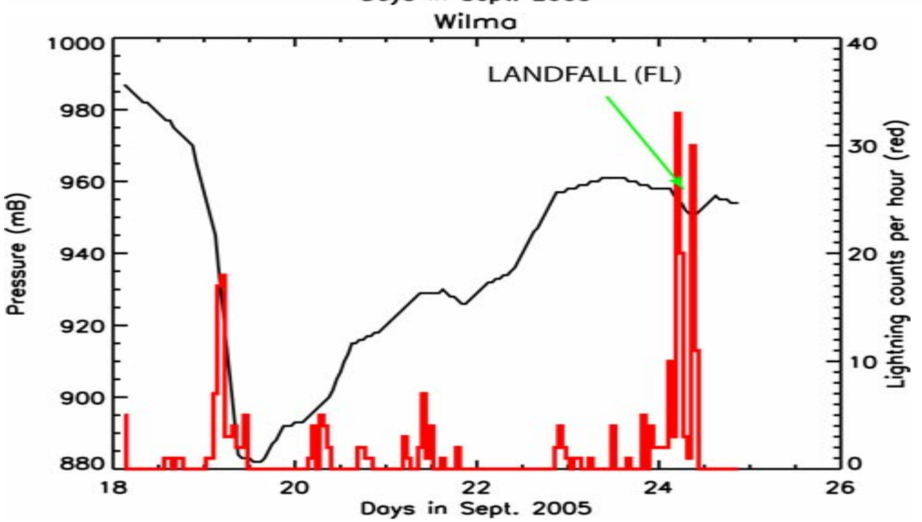
Eyewall lightning detected at stage of hurricane intensification and at times of landfall. Little eye-wall lightning while hurricane decays

Red: LASA hourly eye-wall lightning rate
Black: NOAA hurricane center pressure

Lower pressure -> stronger hurricane

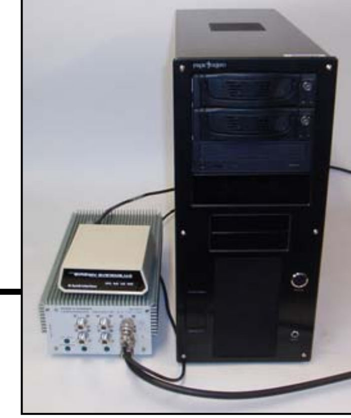






New LASA sensor for the campaign

Active monopole antenna, dual-band observation



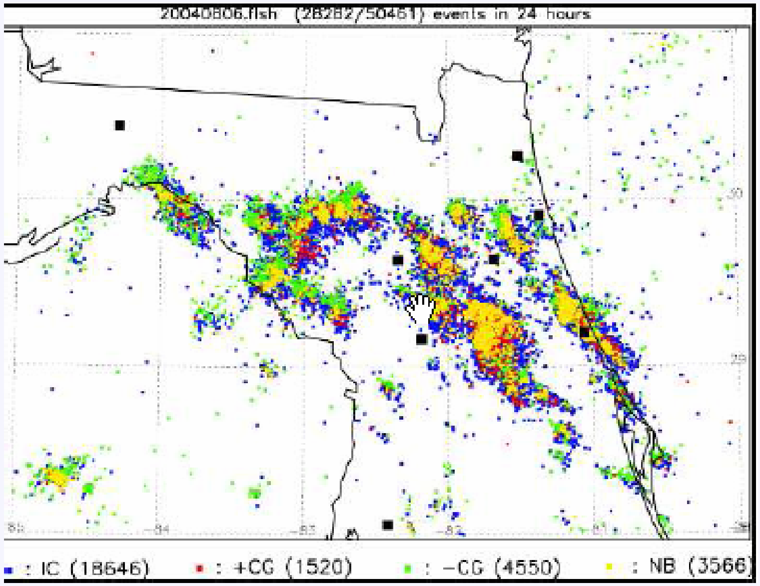
	Low band: (10 – 500 kHz)	High band (63/3 or 69/3 MHz)
Sampling rate	1 MHz	10 MHz
Digital resolution	15 bit	12 bit
Triggering	Software, noise-riding	Software, noise-riding
Dead time	Zero	Zero
Real-time data	Trigger time	Peak time and amplitude
Delayed data	Full E-field waveform	Power waveform at 1 μs resolution
Time resolution	1 μs	100 ns
Data transfer	Internet	Internet

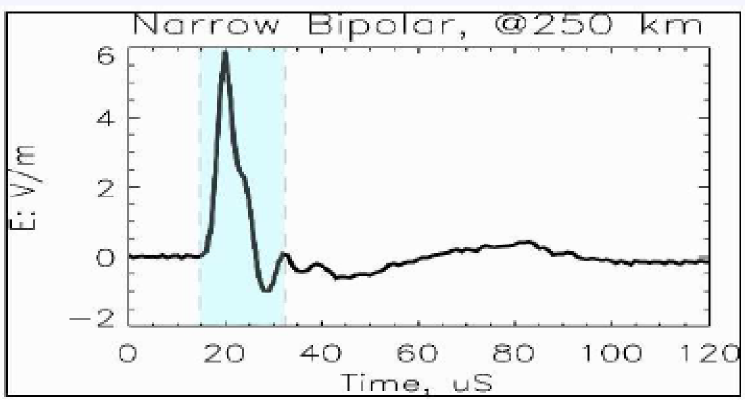
Planned LASA deployment in 2008

- **Dual-band sensors**, provides detailed 3D map within ~400 km
- **Low-band sensors**, provides 2D map and lightning types over Gulf and Caribbean regions

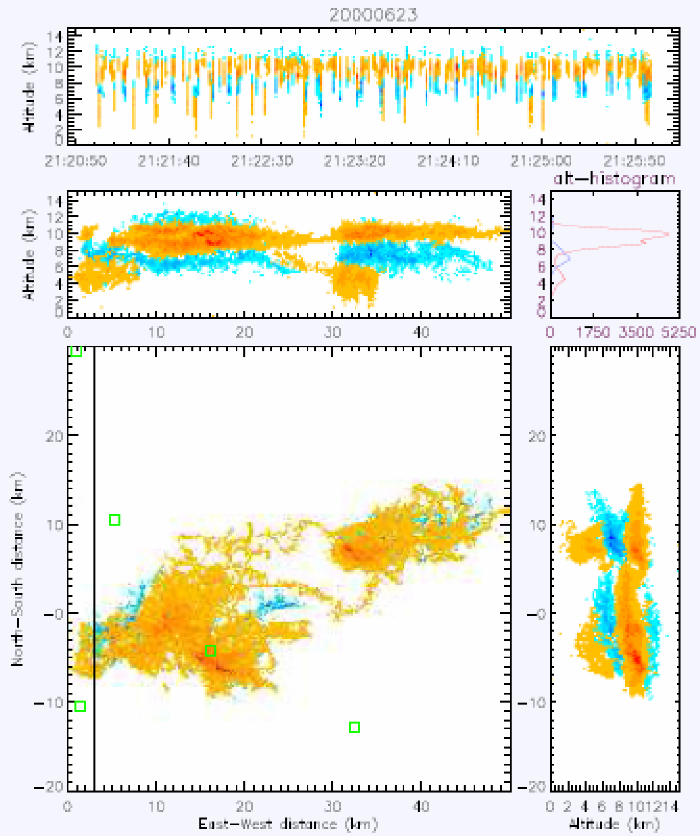
VHF provides detailed 3-D map around the dense array
VLF/LF provides associated field changes
Combination of the two provides charge transfer

LASA VLF



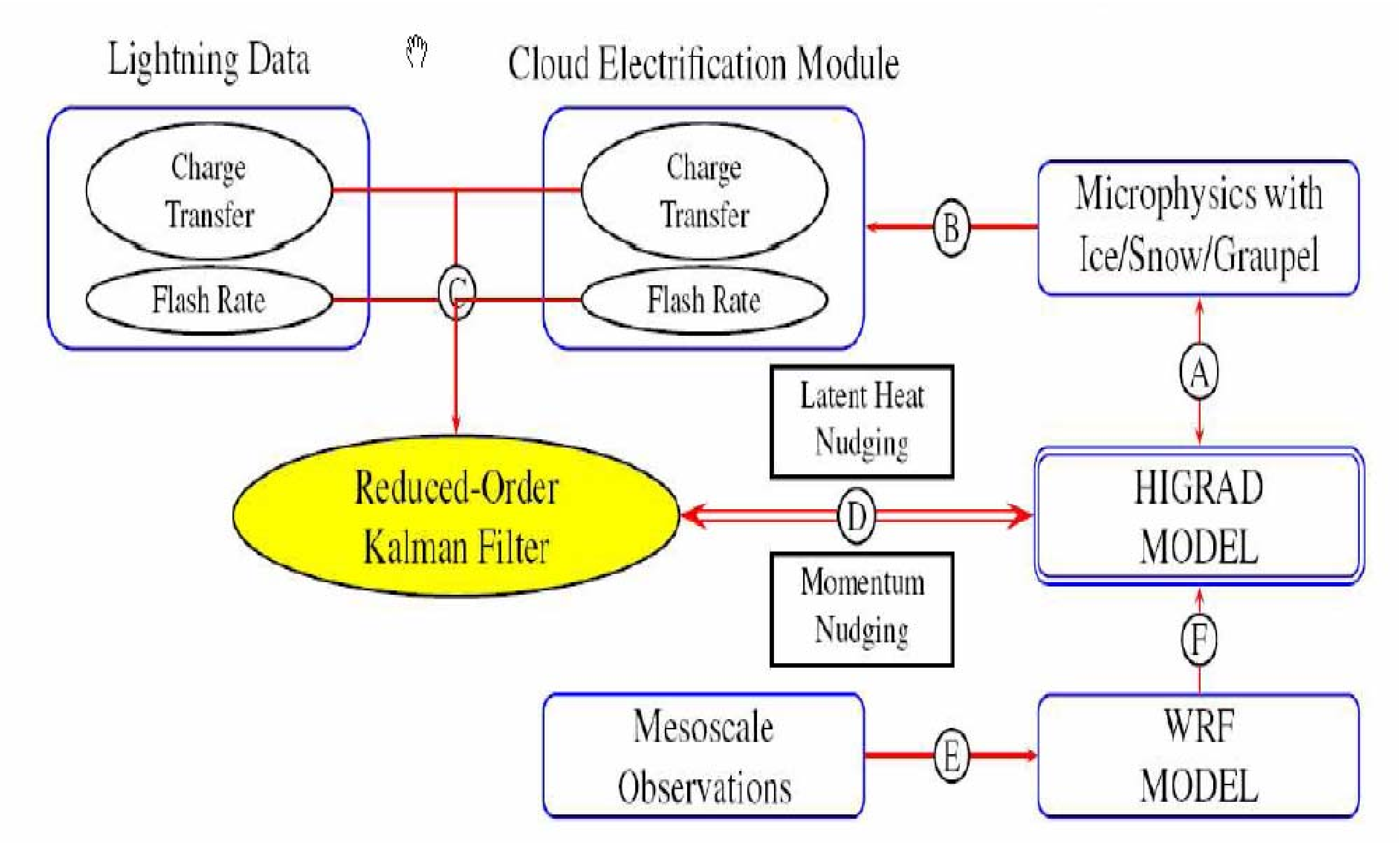


VHF (from NM Tech LMA system)



Charge transfer can be calculated
from new dual VHF–VLF.

A new model approach using lightning observations



Using Kalman filter to assimilate lightning observation to the hurricane model

We use an **Extended Kalman Filter** (EKF) to assimilate LASA lightning data into the LANL hurricane forecast model.

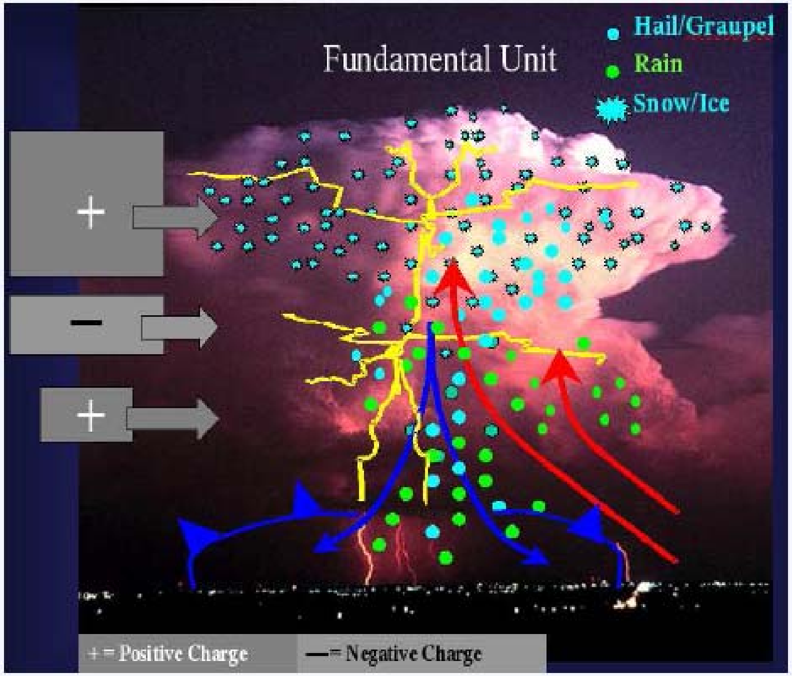
$$
\begin{aligned}
\boldsymbol{X}_{opt} &= \text{Optimal Prediction } \textbf{with Data Assimilation} \\
\boldsymbol{X}_{pred} &= \text{Model Forecast} \\
\boldsymbol{Y}_{obs} &= \text{Lightning Observations} \\
\mathcal{H}(\boldsymbol{X}_{opt}) &= \text{Model Predicted Lightning}
\end{aligned}
$$

EKF allows observation of non-state-variables $\boldsymbol{Y}_{obs}$ to influence optimal state-variables $\boldsymbol{X}_{opt}$ via minimization of a global cost function J.

$$
\begin{aligned}
J &= \frac{1}{2}\left[\boldsymbol{X}_{pred} - \boldsymbol{X}_{opt}\right]^T \left[\boldsymbol{X}_{pred} - \boldsymbol{X}_{opt}\right] / \text{Model\_Err\_Covar}(X_i, X_j) \\
&\quad + \frac{1}{2}\left[\boldsymbol{Y}_{obs} - \mathcal{H}(\boldsymbol{X}_{opt})\right]^T \left[\boldsymbol{Y}_{obs} - \mathcal{H}(\boldsymbol{X}_{opt})\right] / \text{Obs\_Err\_Covar}(Y_i, Y_j)
\end{aligned}
$$

Lightning data assimilation

$$
\begin{aligned}
\overline{w'T'} &> 0 \\
\overline{\rho'_{ice} w'} &> 0 \\
\overline{\rho'_{rain} w'} &< 0 \\
\overline{(\text{charge}) w'} (top) &> 0 \\
\overline{(\text{charge}) w'} (bottom) &< 0 \\
\overline{(\text{flash rate}) \rho_{graupel}} &> 0 \\
\overline{(\text{flash rate}) w'} &> 0
\end{aligned}
$$



$$
\begin{aligned}
J &= \frac{1}{2}\left[\boldsymbol{X}_{pred} - \boldsymbol{X}_{opt}\right]^T \left[\boldsymbol{X}_{pred} - \boldsymbol{X}_{opt}\right] / \text{Model\_Err\_Covar}(X_i, X_j) \\
&+ \frac{1}{2}\left[\boldsymbol{Y}_{obs} - \mathcal{H}(\boldsymbol{X}_{opt})\right]^T \left[\boldsymbol{Y}_{obs} - \mathcal{H}(\boldsymbol{X}_{opt})\right] / \text{Obs\_Err\_Covar}(Y_i, Y_j)
\end{aligned}
$$

Project timelines

- 2008
  - — Deploy dual-band LASA sensors near New Orleans with one station on oil rig
  - — Deploy low-band LASA sensor around Gulf and Caribbean regions
  - — Develop a working electrification module
  - — Develop a new data assimilation framework
  - — Develop the new hurricane forecast model
- 2009
  - — Deploy more dual-band LASA sensors on oil rigs to extend the array southward
  - — Improve and complete electrification module based on 2008 study
  - — Improve and complete data assimilation algorithm
  - — Improve and complete the new hurricane forecast model
- 2010
  - — Comprehensive analysis and evaluation of the new technique (observations, data assimilation, and models)
  - — Deliver a complete forecast package to the community

Conclusion

- **A three-year (2008-2010) campaign is funded in LANL to investigate hurricane intensification by assimilating real-time, 24/7 lightning observation with a new hurricane forecast model**
- **An addition array of new, dual-band (VLF/LF, VHF) lightning sensors will be deployed in the Gulf region for detailed 3D eyewall lightning mapping, lightning type classification, lightning current and charge moment and charge transfer observations**
- **A Reduced-Order Kalman Filter will be developed to assimilate the lightning data to the hurricane intensity forecast model**
- **A cloud electrification module will be developed for the data assimilation**
- **The objective of this campaign is to achieve the national goal of *10 knot improvement in 48-hour intensity forecasts***