Regional Urban X-band Radar Networks
The DFW Metroplex example

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Dense Urban X-band Radar Networks

X-band Radar: an emerging tool for rainfall mapping

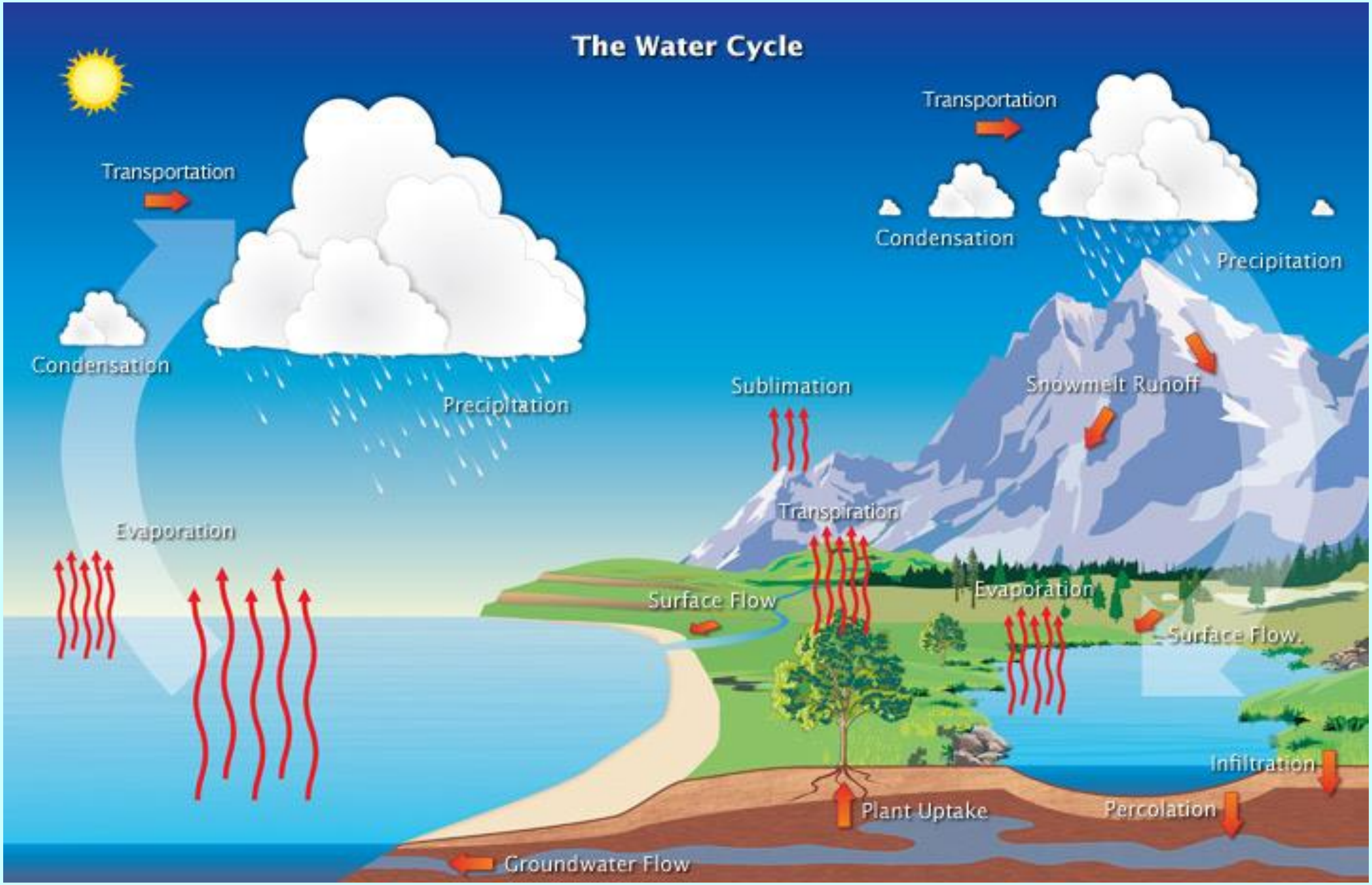
Radar network design and deployment

Observations and products in the presence of floods, hails, and tornadoes

Dense Urban X-band Radar Networks

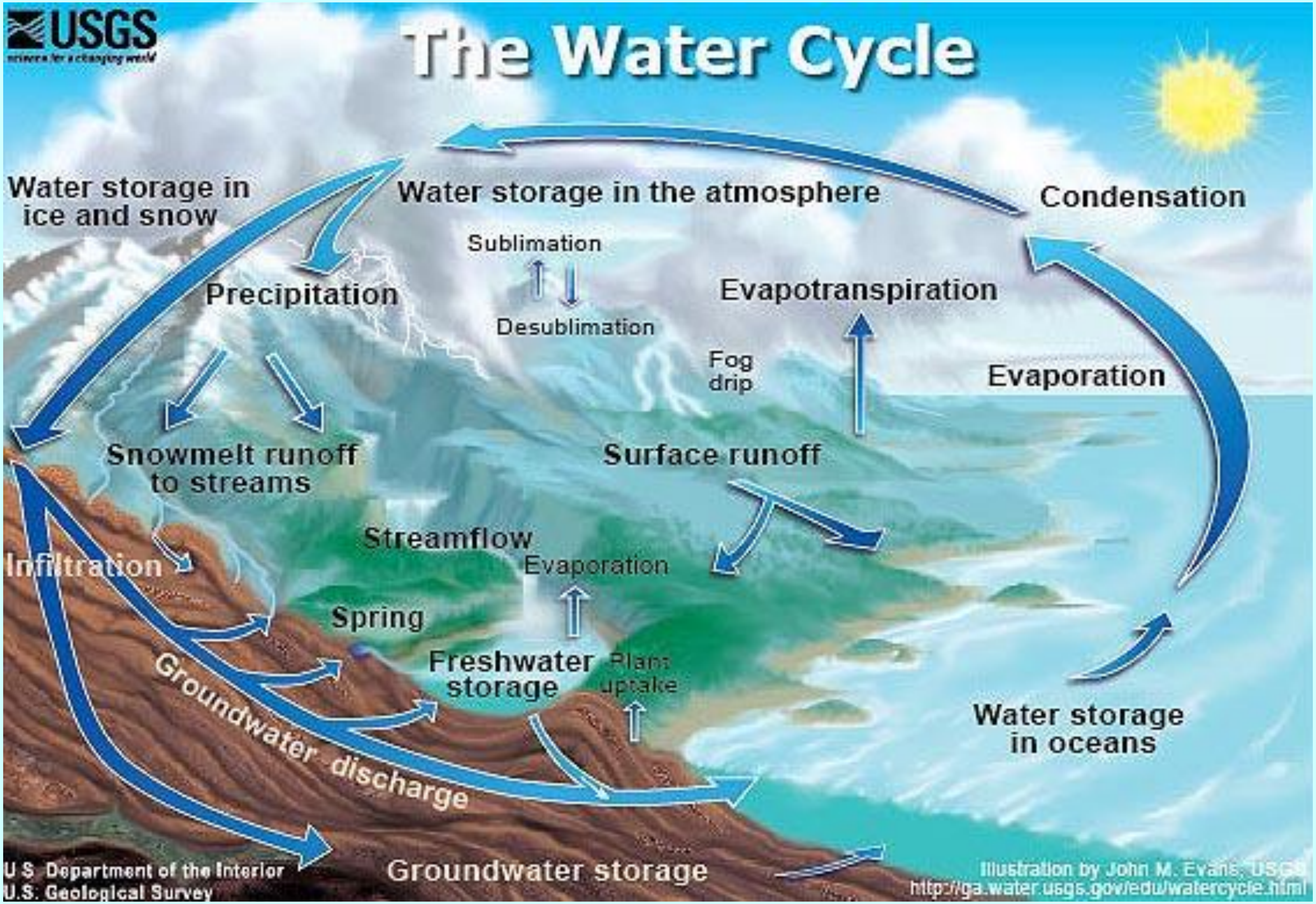
- X-band Radar: an emerging tool for rainfall mapping
- Radar network design and deployment
- Adaptive scan strategy for small radar network
- Attenuation correction for high-freq. observations
- Observations and products in the presence of floods, hails, and tornadoes

The Global Water Cycle



Reference: NOAA

The Global Water Cycle



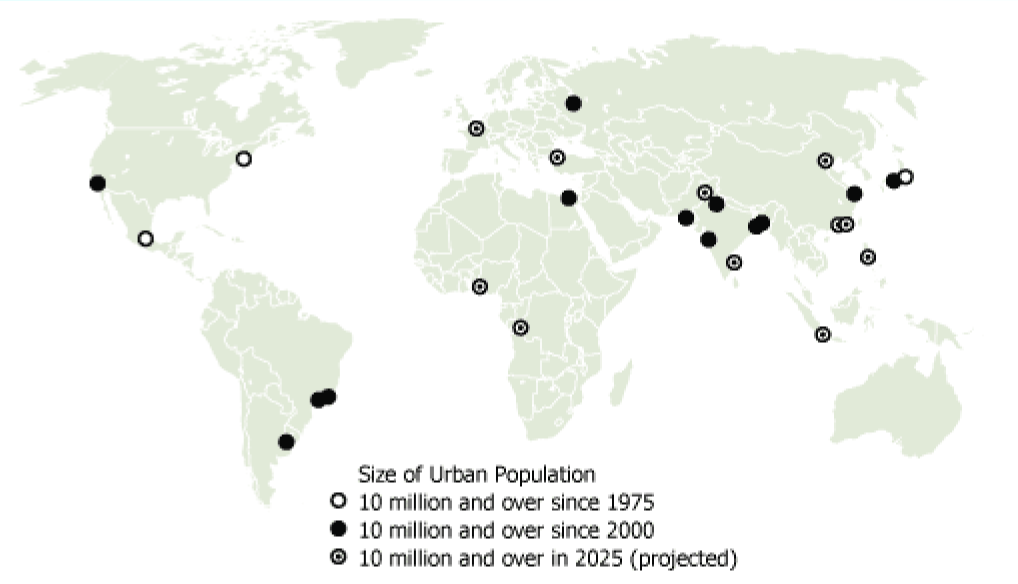
Reference: USGS

Vision

Radars as part of the National Weather and Climate Observation Network, to support forecast and warning operations (data assimilation) as well as, Aviation safety, terminal operations flood mitigation systems and Smart City infrastructure

Introduction

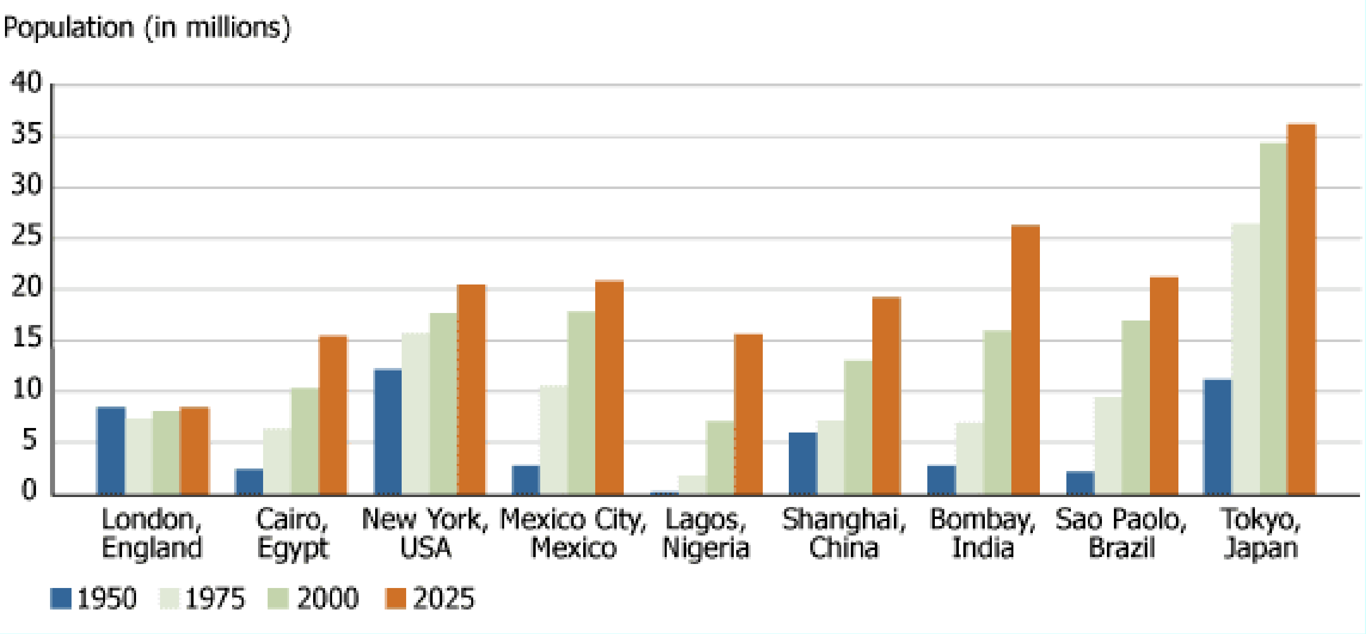
- Since 2008, more than 50% of the world's population is living in cities.
- By 2030 this number will swell to almost 5 billion, with urban growth concentrated in Africa and Asia.



Source: United Nations, *World Urbanization Prospects: The 2007 Revision*.

"The current report shows that two global trends – urbanisation and climate change – have significantly changed the level of risk in numerous countries,"

- Many people will live in the growing number of cities with over 10 million inhabitants, known as megacities.
- As the map "Largest Urban Agglomerations" shows, just three cities had populations of 10 million or more in 1975, one of them in a less developed country. Megacities numbered 16 in 2000.
- By 2025, 27 megacities will exist, 21 in less developed countries.



Source: United Nations, *World Urbanization Prospects: The 2007 Revision*.

The never-ending migration

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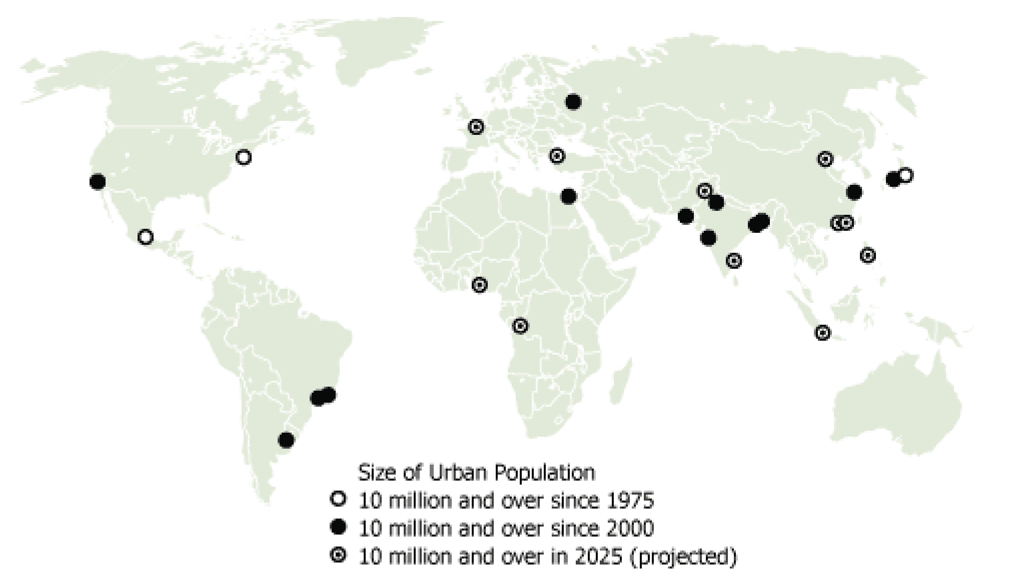


Source: United Nations, *World Urbanization Prospects: The 2007 Revision*.

World Population Moving to Urban Areas

Notes on Urban Population by the UN

Reference: United Nations, World urbanization prospects

As of July 2014, 54 per cent of the world's population lives in urban areas, a proportion that is expected to increase to 66 per cent by 2050.

The urban population of the world has grown rapidly from 746 million in 1950 to 3.9 billion in 2014.

The world's urban population is expected to surpass six billion by 2045.

Mega-cities with more than 10 million people are increasing in number

Sustainable urbanization is key to successful development

Rural populations expected to decrease as urban populations continue to grow

Small cities are numerous and many are growing rapidly

The 2014 revision of the *World Urbanization Prospects* by UN DESA's Population Division notes that the largest urban growth will take place in India, China and Nigeria.

"Managing urban areas has become one of the most important development challenges of the 21st century. Our success or failure in building sustainable cities will be a major factor in the success of the post-2015 UN development agenda"
-John Wilmoth, Director of UN DESA's Population Division.

Global Water Cycle is Accelerating

- The interaction between precipitation and surface run off varies with time and geography.
- Global annual precipitation is on the rise.
- Both natural and human-factor play a role in acceleration of global water cycle.
- Intensifying water cycle will result in increased storm intensity.

Effects of Accelerating Water cycle

"Water is at the heart of both the causes and effects of climate change.“ stated in the National Research Council's report on Research Pathways for the Next Decade (NRC, 1999).

Flooding in Mumbai

Reference: The Leap blog, The absorbers disaster and vulnerability in mumbai

People making their way through a flooded area in Changping District in Beijing

Reference: The Epoch Times

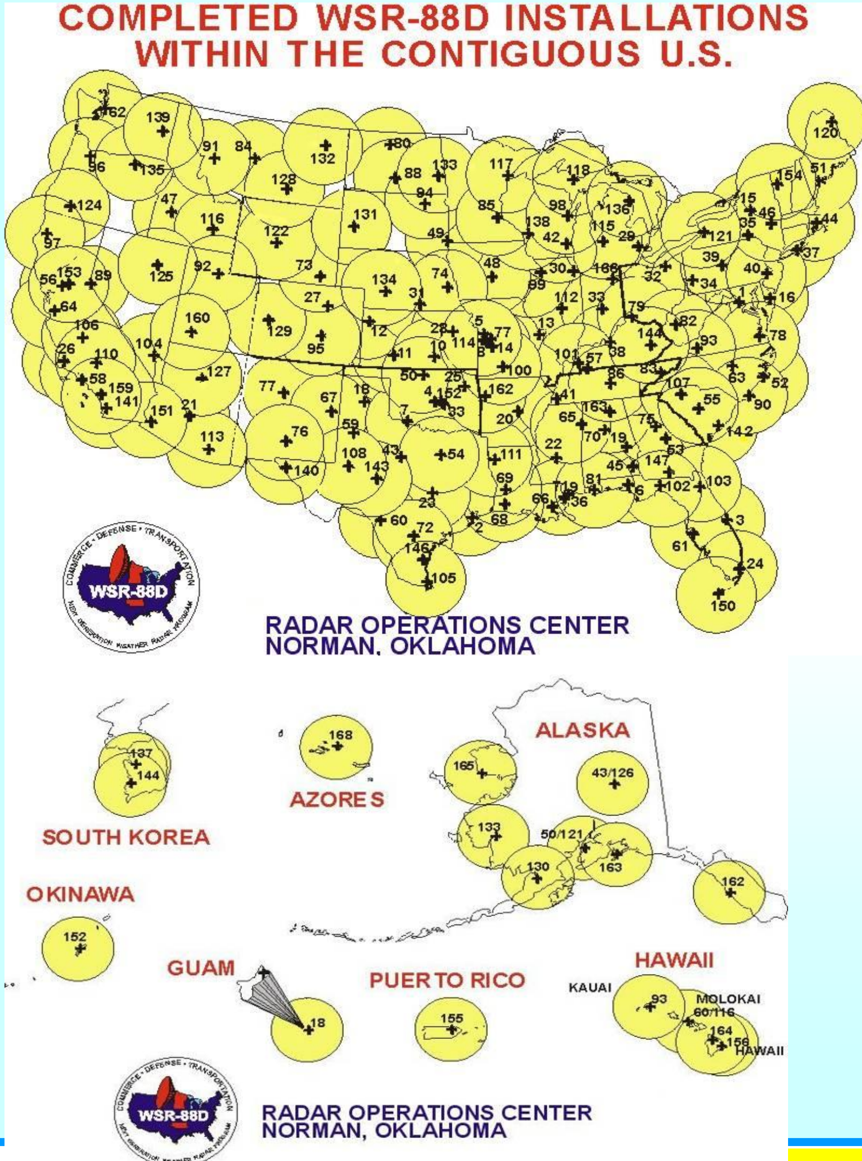
Flooding in Louisiana

Reference: NOAA

Mitigation

- We need to keep an eye on the changes in water level and take necessary actions.
- The urban region's water cycle should be researched to have a better understanding.
- Radar networks serve as an engineering tool to help improve in understanding the water cycle process.

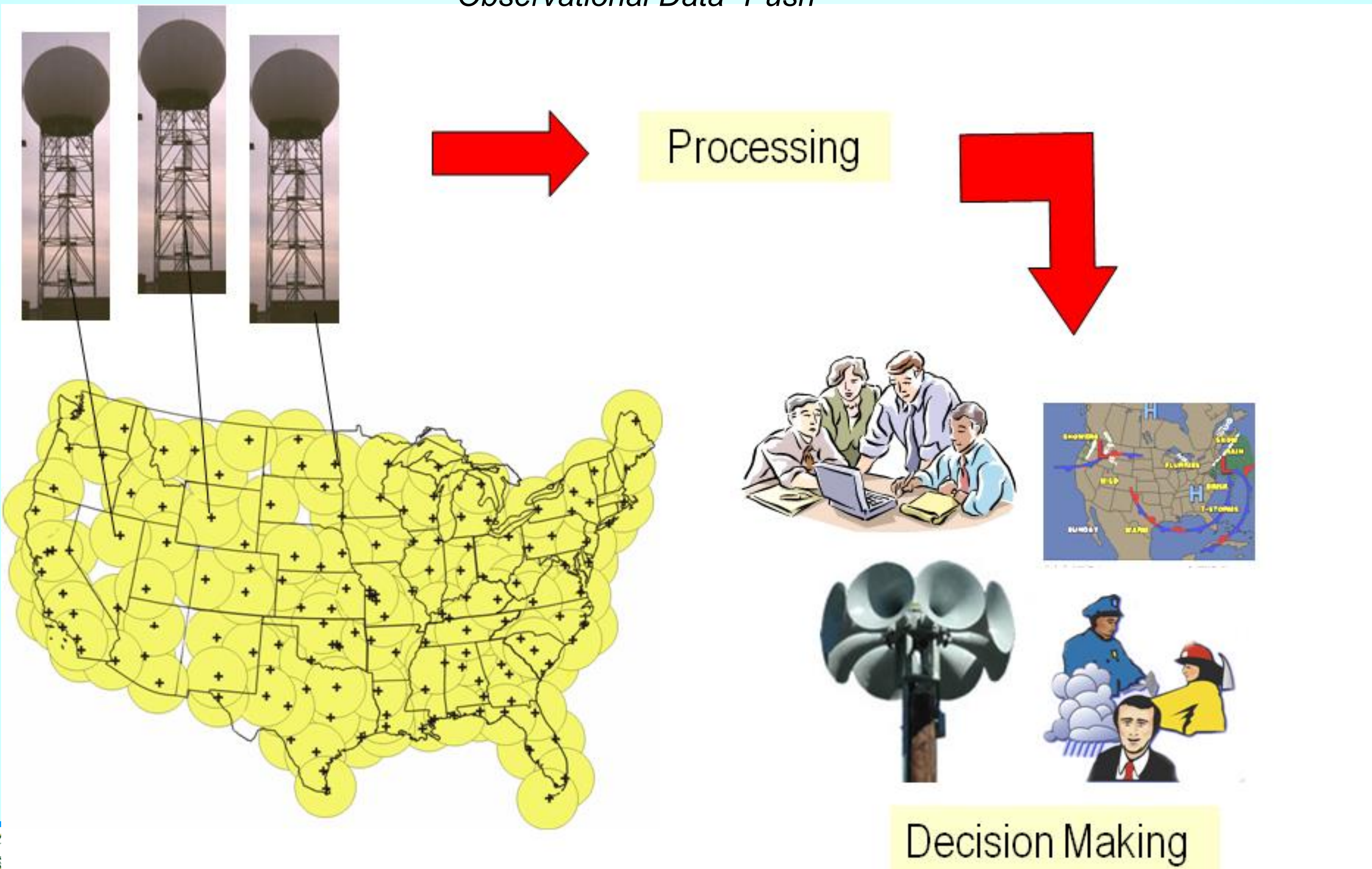
NWS NEXRAD (WSR-88D)



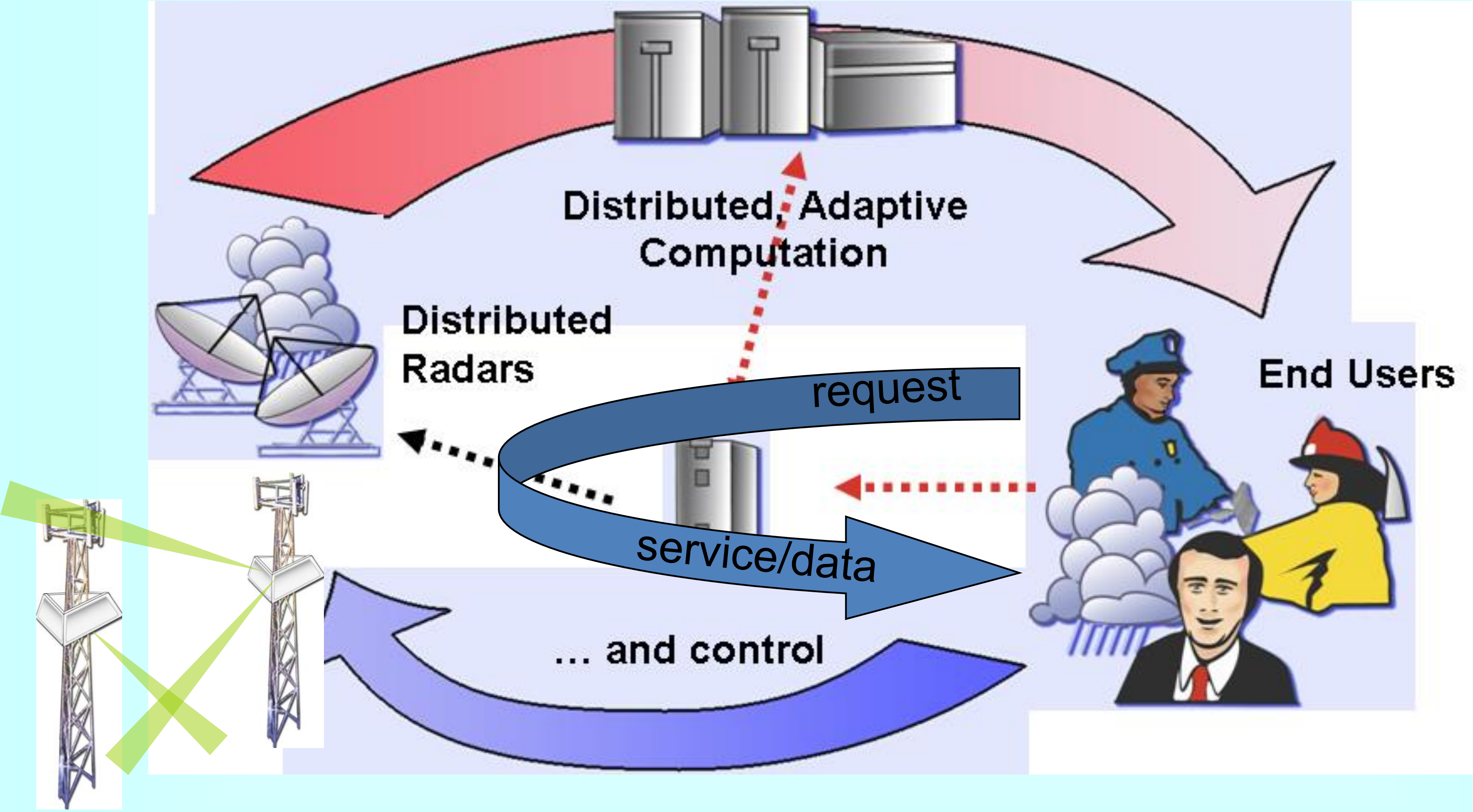
- 160 operational WSR-88D radar systems
- Maximum range:
  - 460 km for reflectivity
  - 230 km for velocity
- 4 volume scan strategies
  - 360^{O} azimuthal sweeps
- S-band
- Dual polarization

Today's Weather Radar Networks

Observational Data "Push"

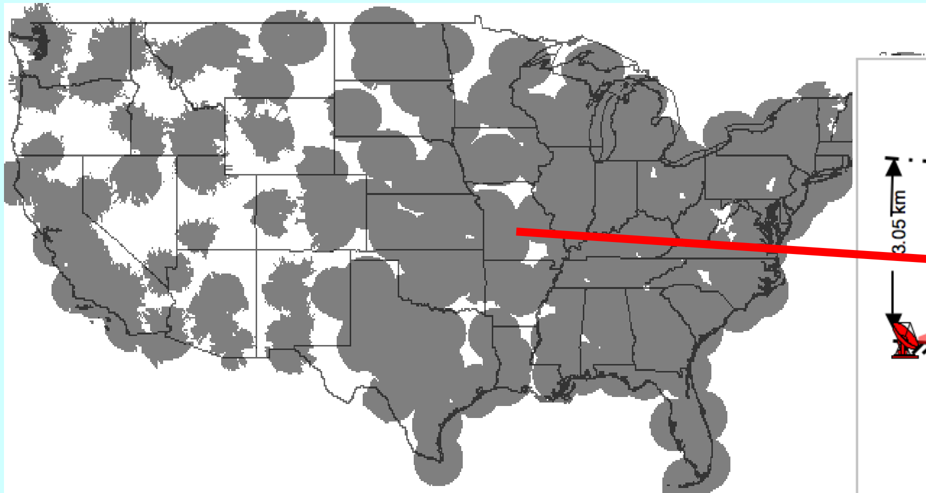


The new Systems

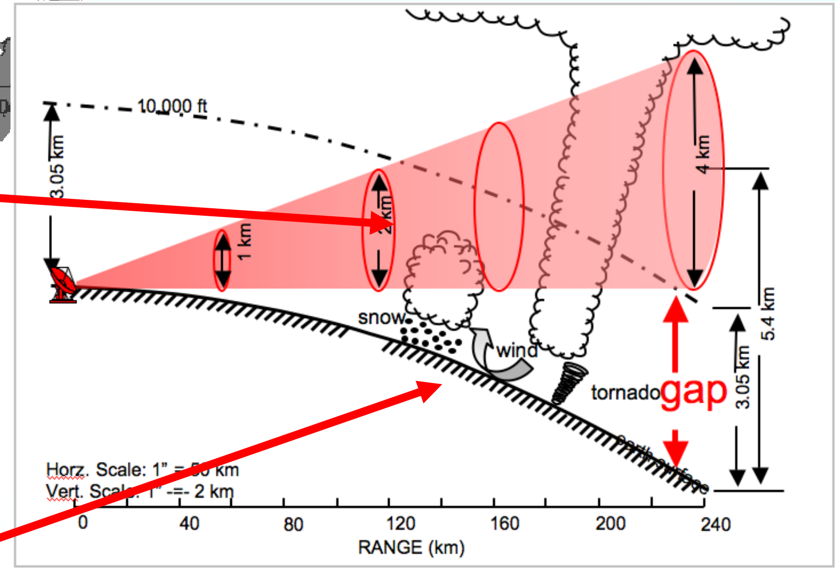


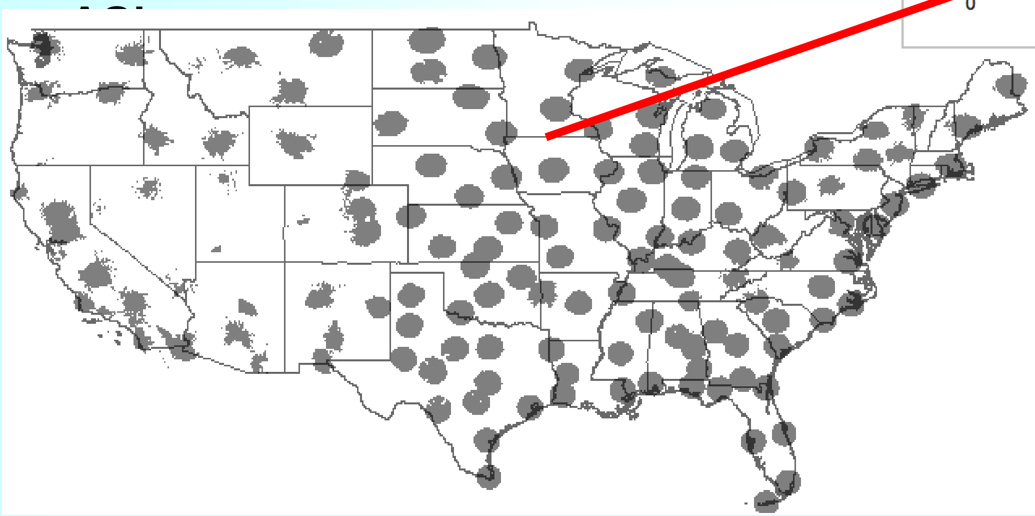
Sample the environment when and where end-user needs are greatest.

CASA Motivation



NEXRAD coverage at 3 km (10,000 ft) AGL.



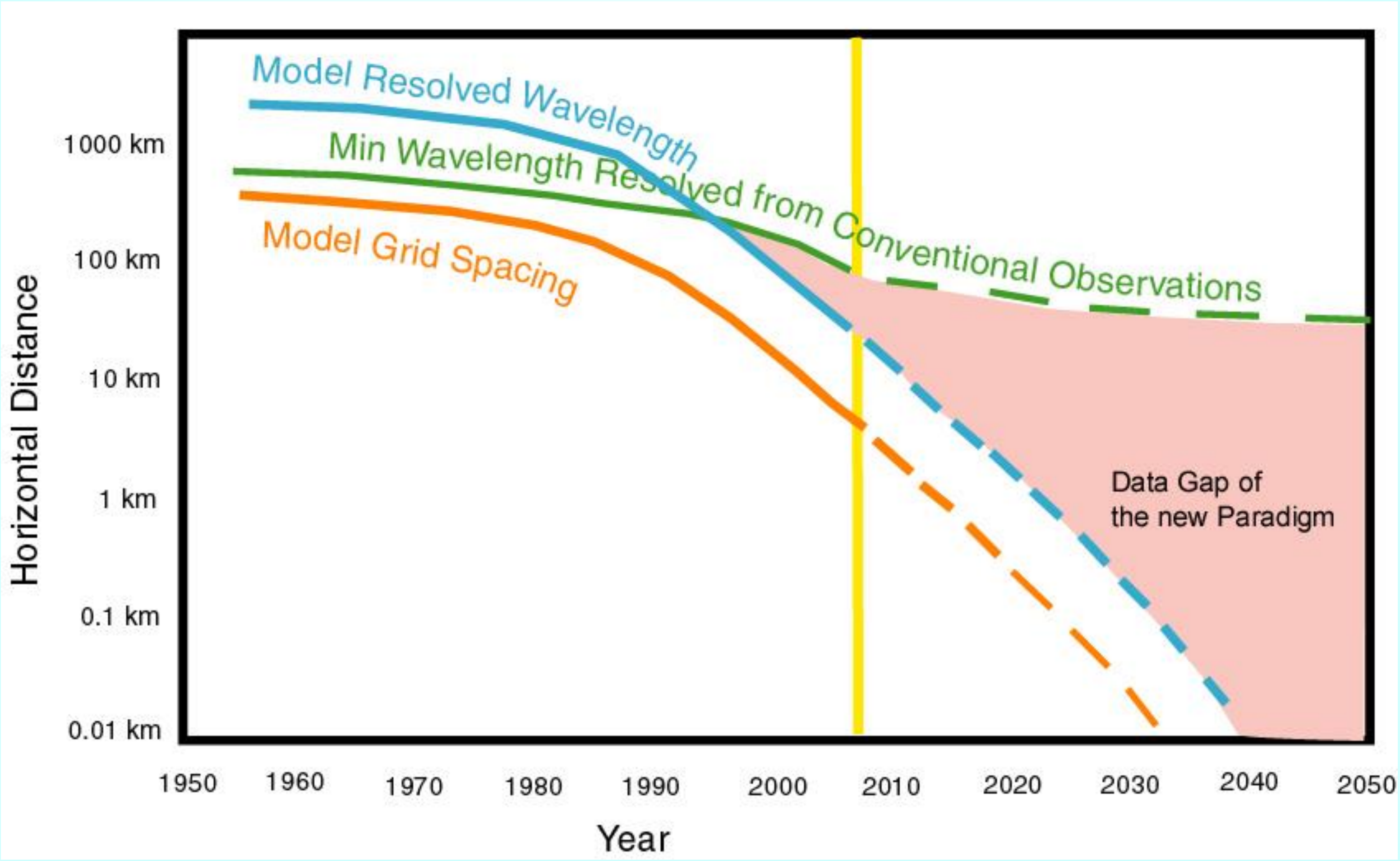


NEXRAD coverage at 1 km (~3200 ft) AGL.

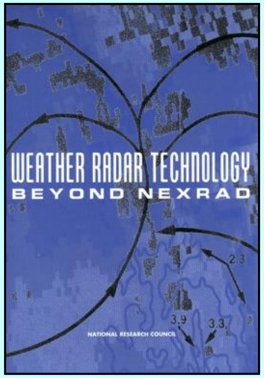
- Radar “Gap”
- Spatial Resolution
- Temporal Resolution
- Radars function autonomously


"CASA RADAR"
ABC News
"World News with
Charles Gibson"
July 25, 2008

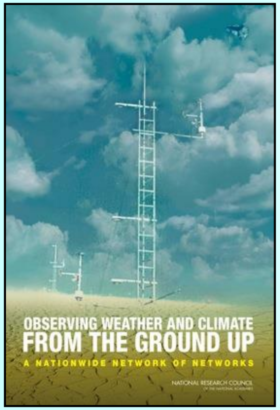
Models and Observations
Can we fill the gap?



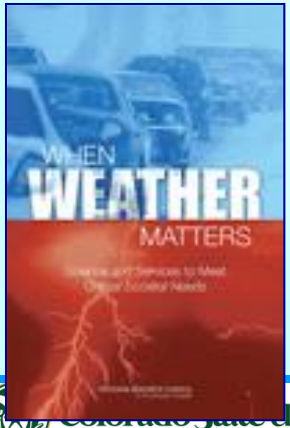
National Academy Reports



Recommendation: "The potential for a network of short-range radar systems to provide enhanced near-surface coverage and supplement (or perhaps replace) a NEXRAD-like network of primary radar installations should be evaluated thoroughly." NRC, 2002



Recommendation: "Emerging technologies for distributed-collaborative-adaptive sensing should be employed by observing networks, especially scanning remote sensors such as radars and lidars." NRC, 2008

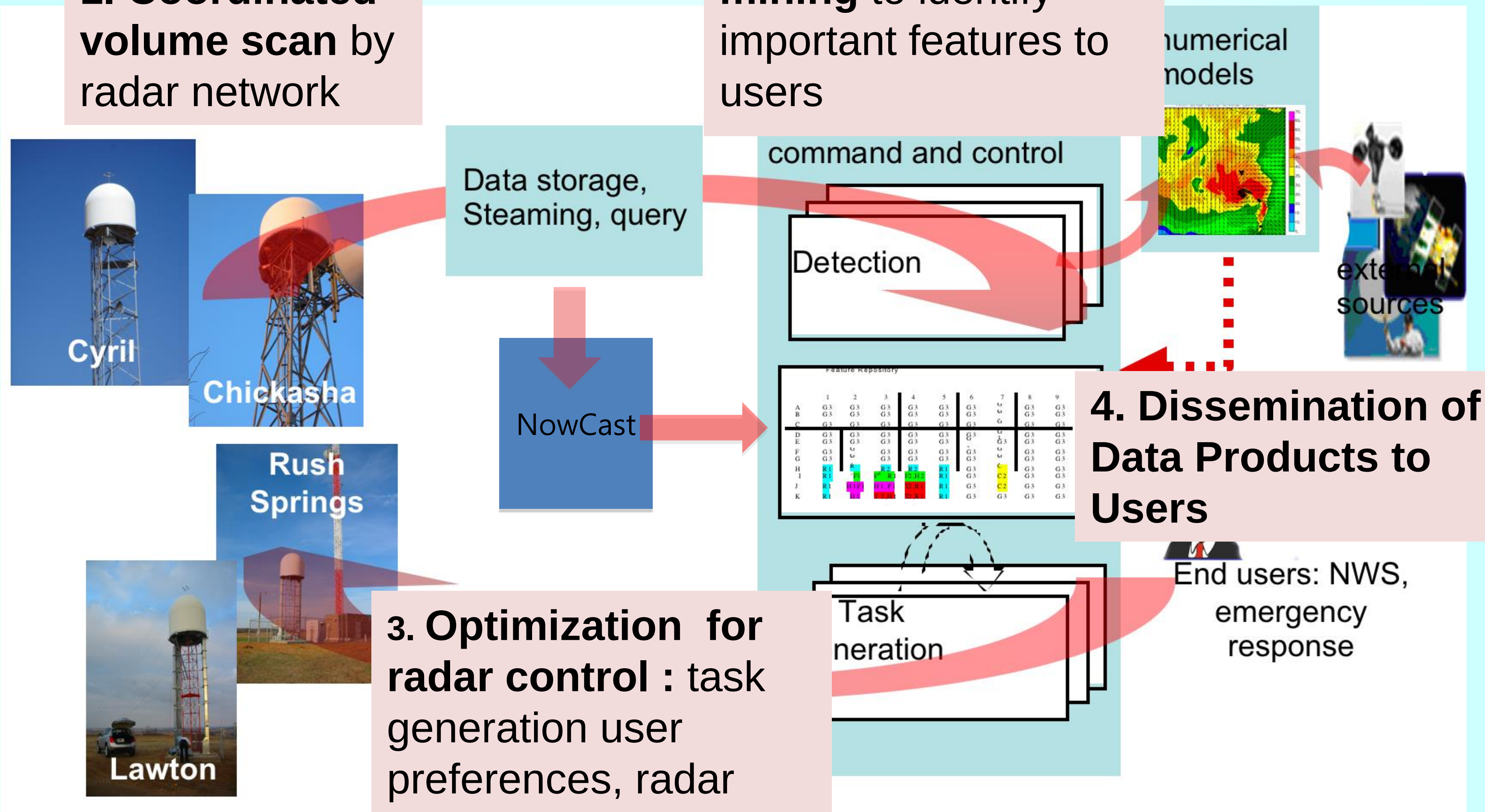


"**…**collaborative and adaptive sensing and related technologies can efficiently enhance the detection and monitoring of adverse weather for hazard mitigation and other applications." NRC, 2010

Where and when user needs are greatest

1. Coordinated volume scan by radar network

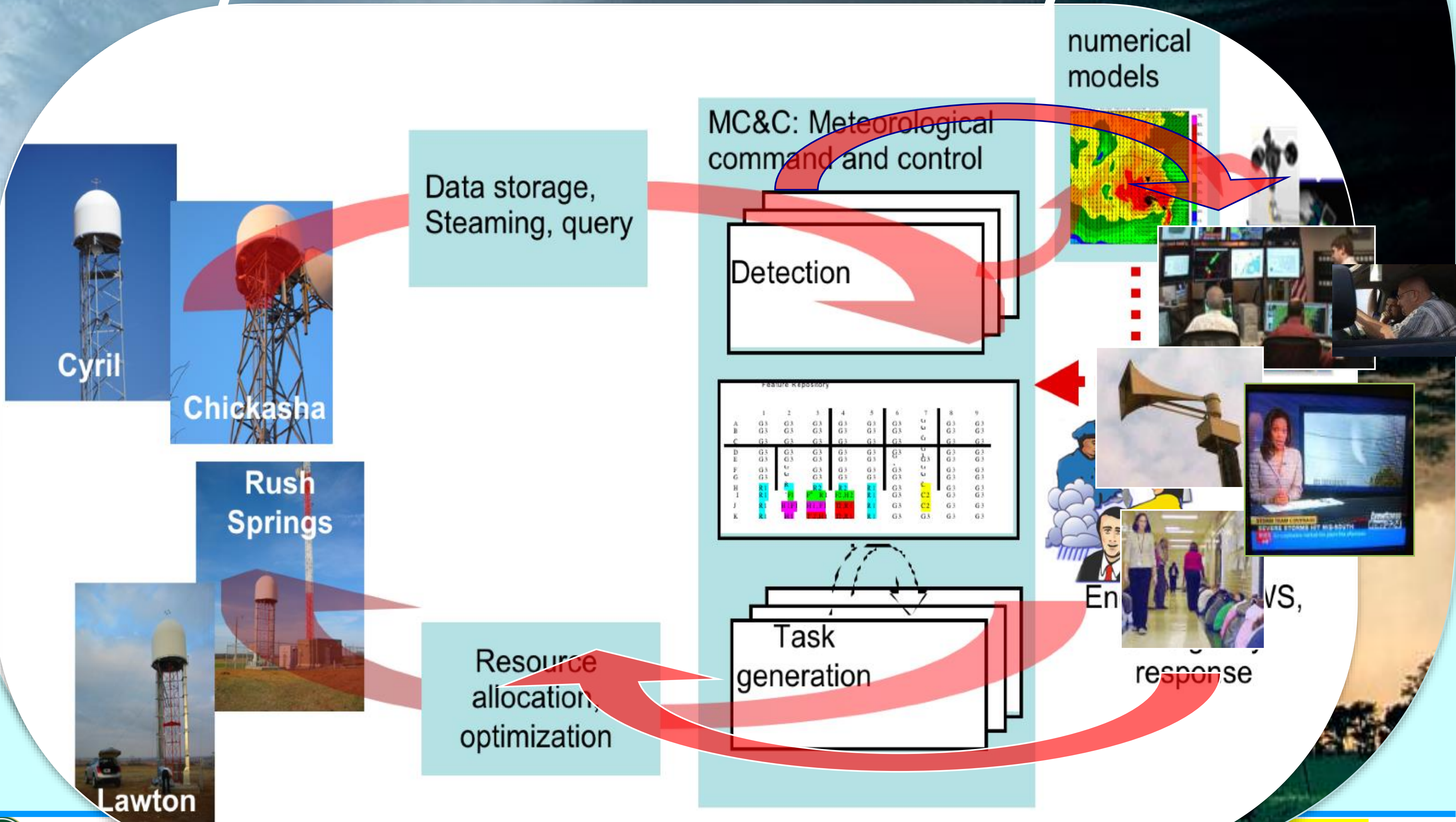
2. **Real time data mining** to identify important features to users



4. Dissemination of Data Products to Users

3. **Optimization for radar control :** task generation user preferences, radar capabilities, meteorological

How can we optimize system operation for the best response?



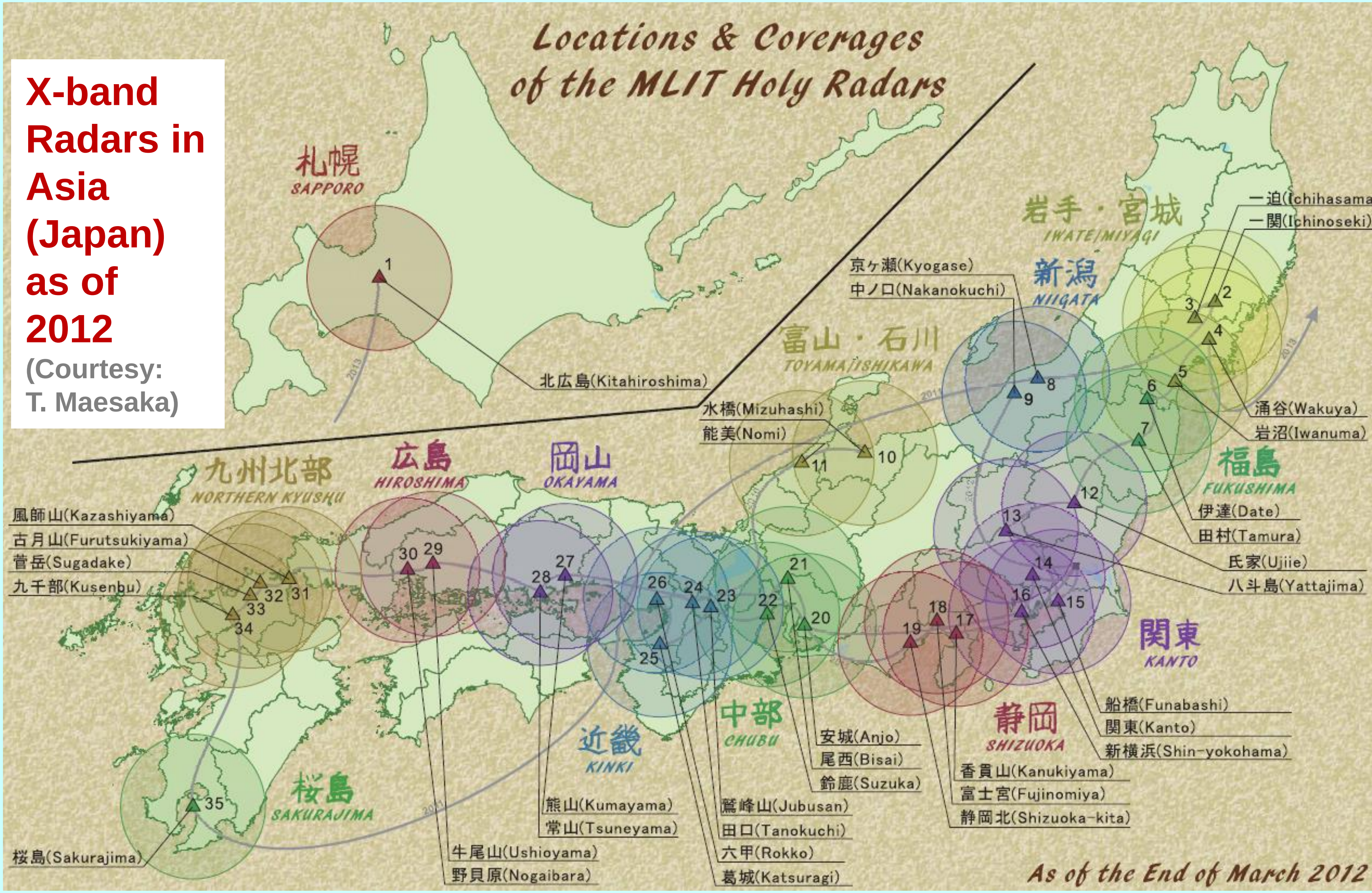
X-band Radar: An Emerging Tool for Rainfall Mapping

CASA Research-to-Operation Testbed in Texas

X-band Radar: An Emerging Tool for Rainfall Mapping

X-band Radars in Asia (Japan) as of 2012

(Courtesy: T. Maesaka)



Background and Objectives

Definition of Flash flood:

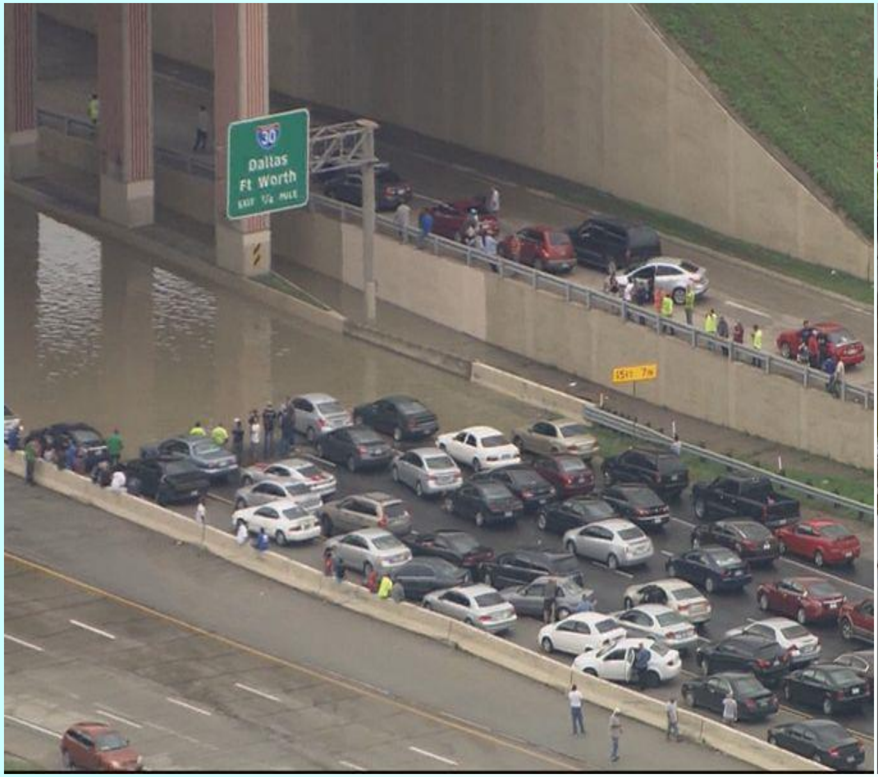
A flood caused by heavy or excessive rainfall in a short period of time, generally less than 6 hours. Flash floods can occur within minutes or a few hours of excessive rainfall.

Urban Flash floods have significant impacts on transportation, infrastructure, and human safety due to urban characteristics such as impervious surface cover and complex drainage systems.

Flash flood (~2hrs rainfall) in DFW area, June 24, 2014.

Real-time, high-resolution rainfall mapping is critical for urban flash flood monitoring and forecasting, and for further ensuring human safety.

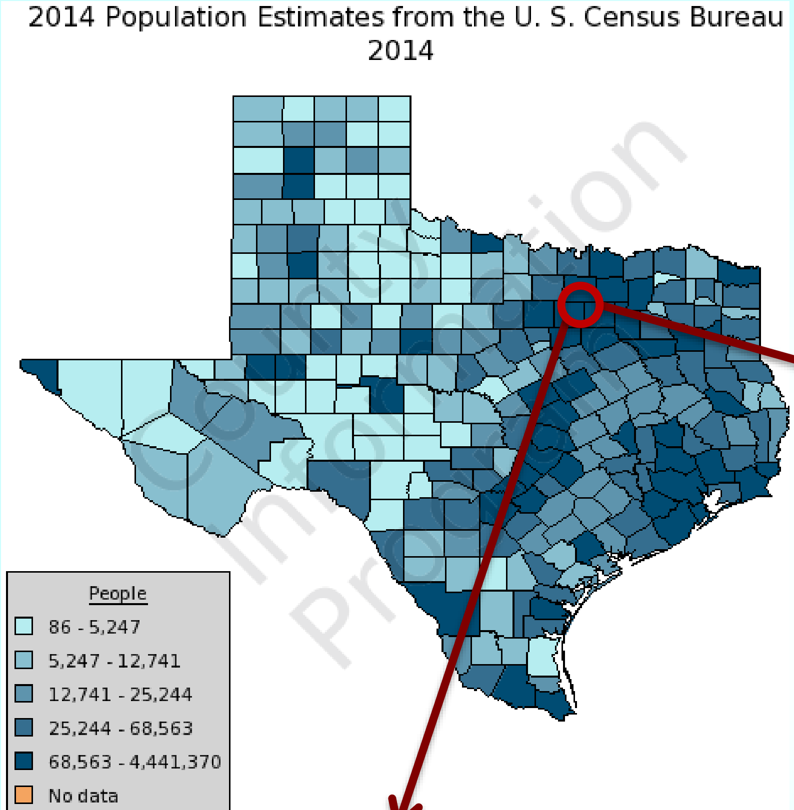
Background and Objectives

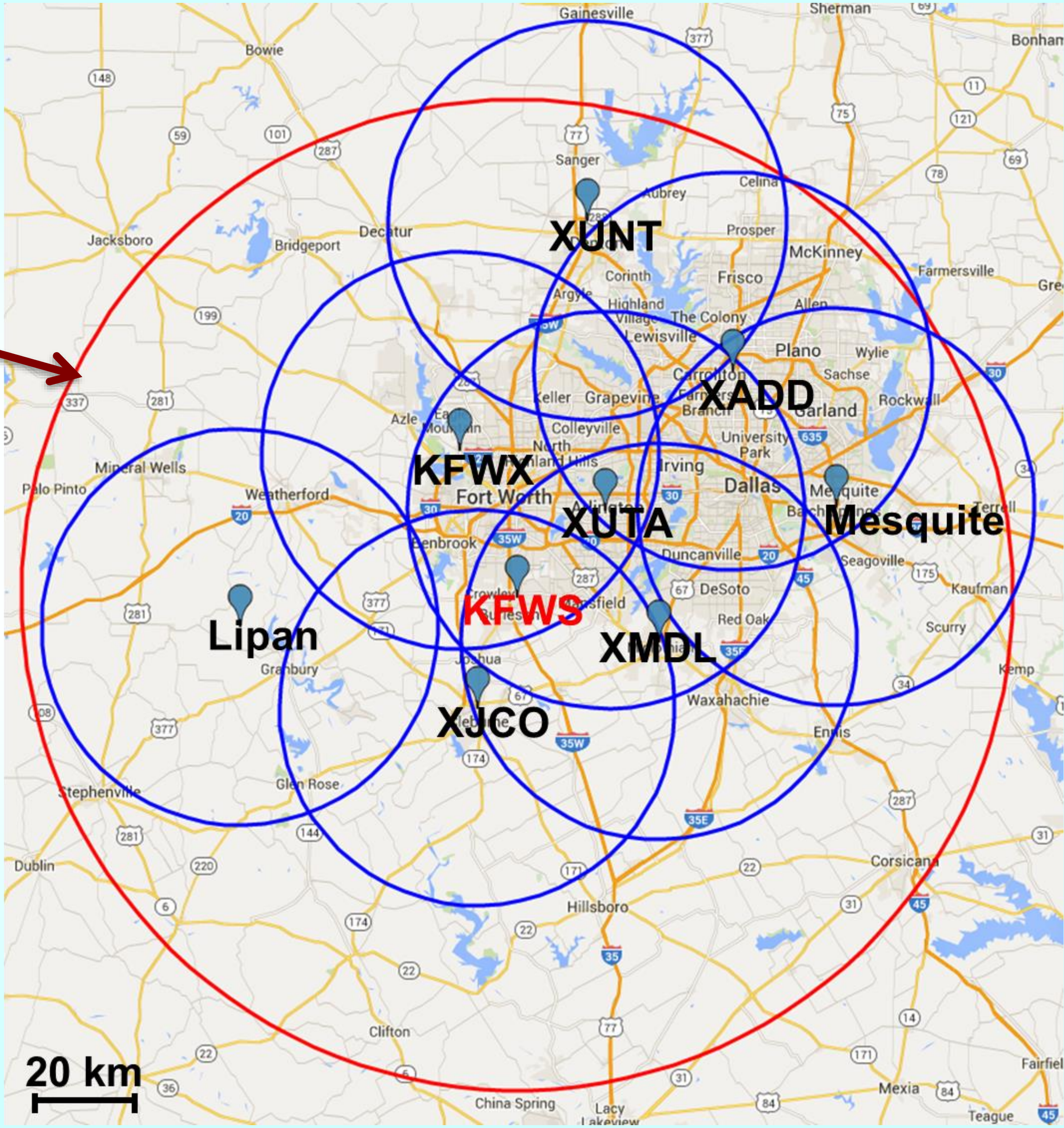


Objectives of this study

- to conduct urban disaster mitigation by deploying X-band dual-polarization radar network.
- to achieve real-time high-resolution quantitative precipitation estimation for urban flooding and hydrologic applications.

CASA DFW Urban Radar Network





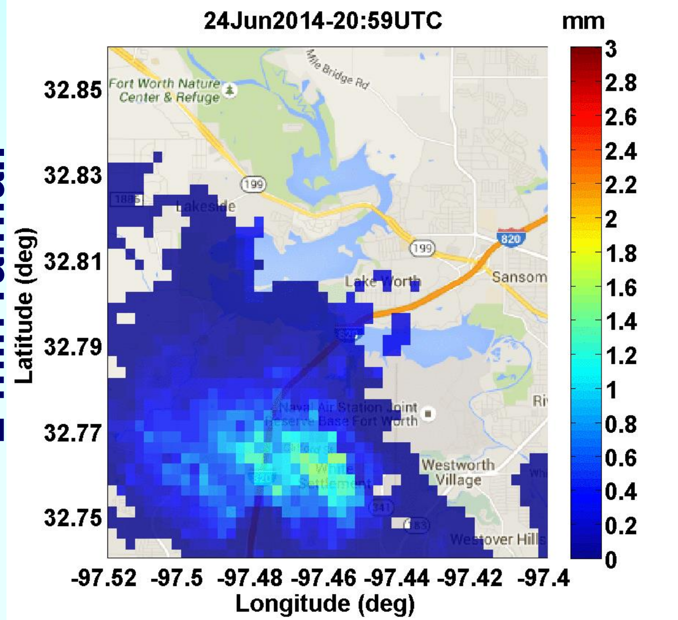
- home to over 6.5 million people
- 4th largest Metroplex in the U.S
- Population growth 25%+
- experiences a wide range of natural weather hazards such as flash flooding and tornado

Sample Rainfall Product and Validation

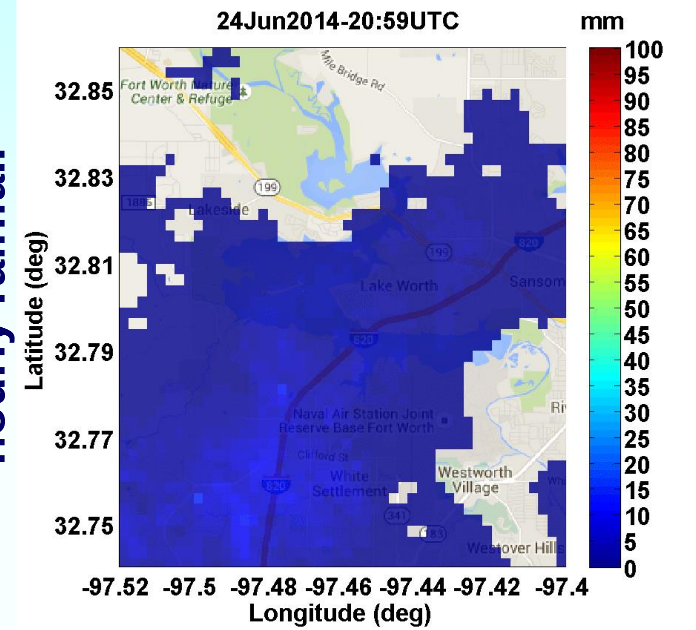
Localized flash flooding on June 24, 2014

- **Domain:** ~10km X 10km
- **Time:** 20:59-22:10UTC
- **Spatial resolution:** 250m X 250m
- **Temporal resolution:** 1 min
- **Peak rain rate** ~200 mm/hr

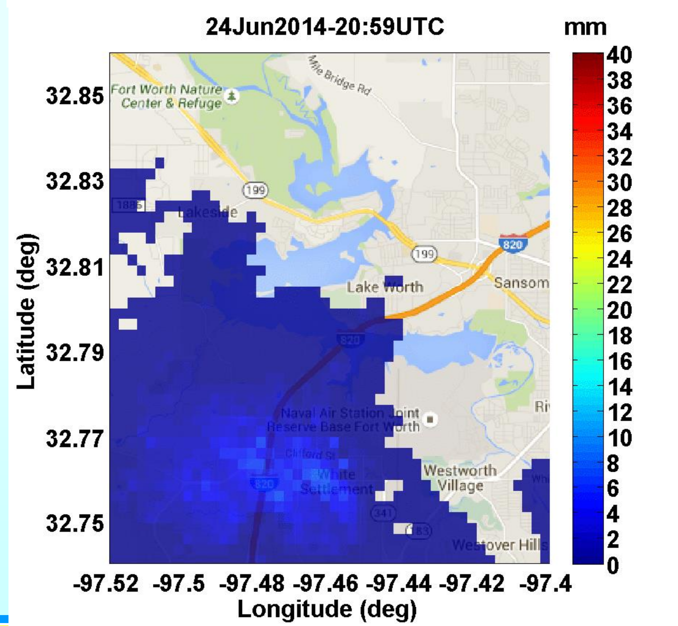
1-min rainfall



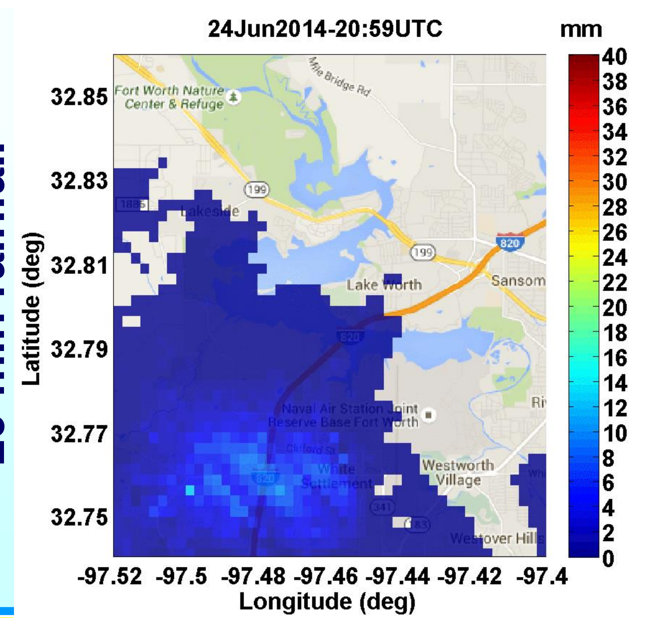
hourly rainfall



5-min rainfall

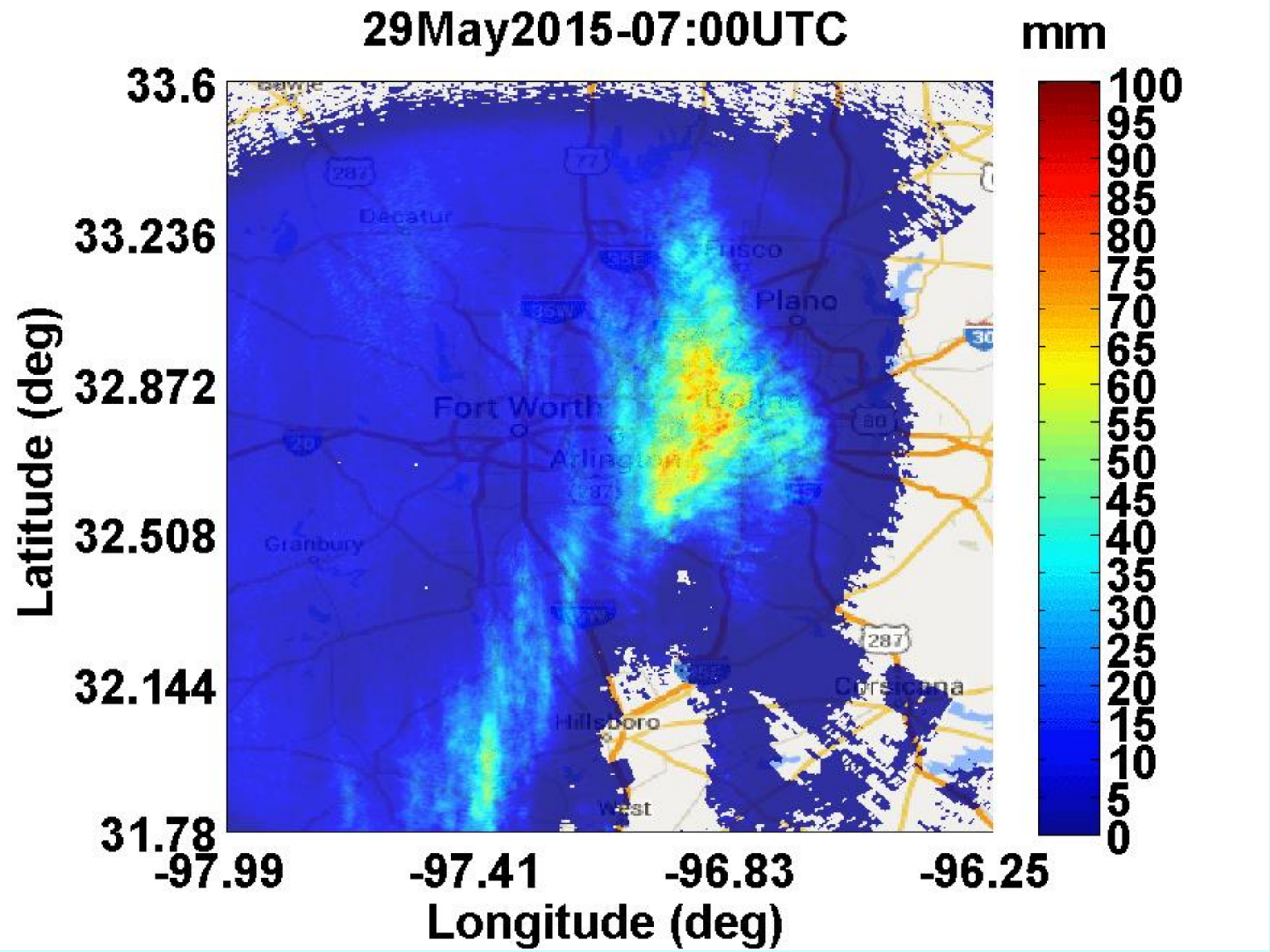


10-min rainfall



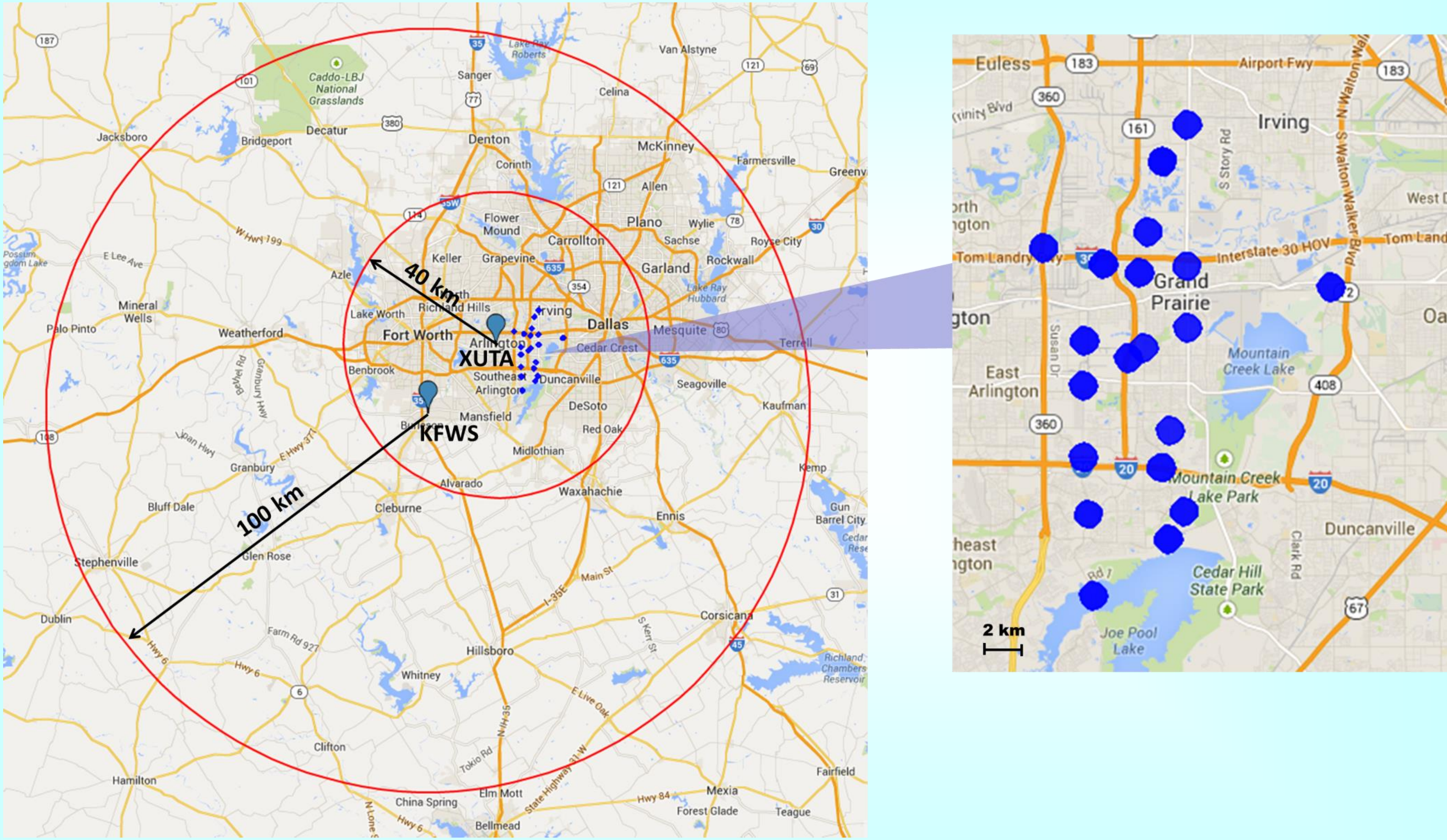
Sample Rainfall Product and Validation

Urban Flash Flood on May 29, 2015



Hourly Rainfall Accumulation: 07:00-09:00UTC

Sample Rainfall Product and Validation



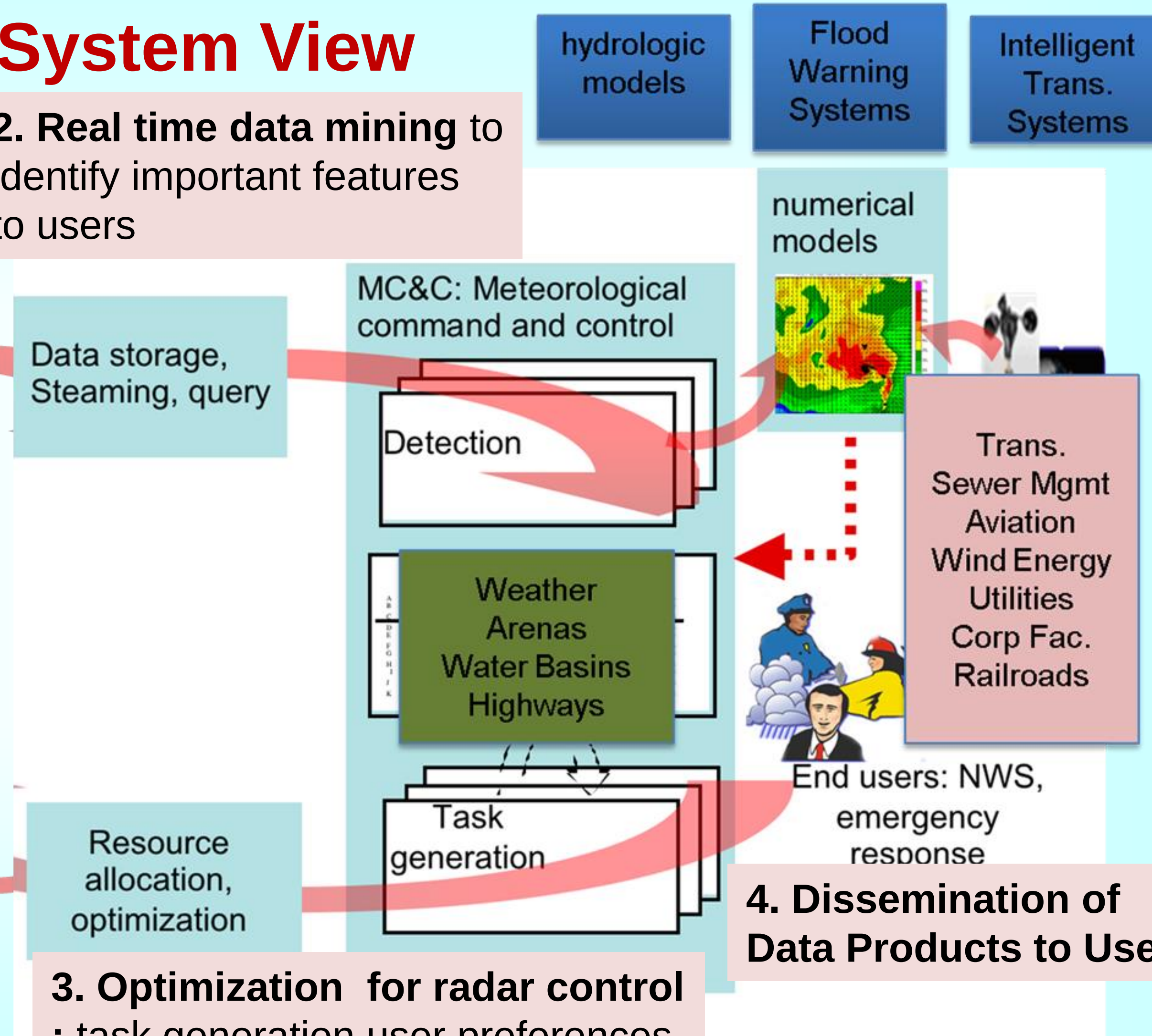
Location of 20 rain gauges in the City of Grand Prairie

Adaptive Scan Strategy for Dense Radar Network

CASA Engineered System View

1. Coordinated volume scan by radar network

2. Real time data mining to identify important features to users

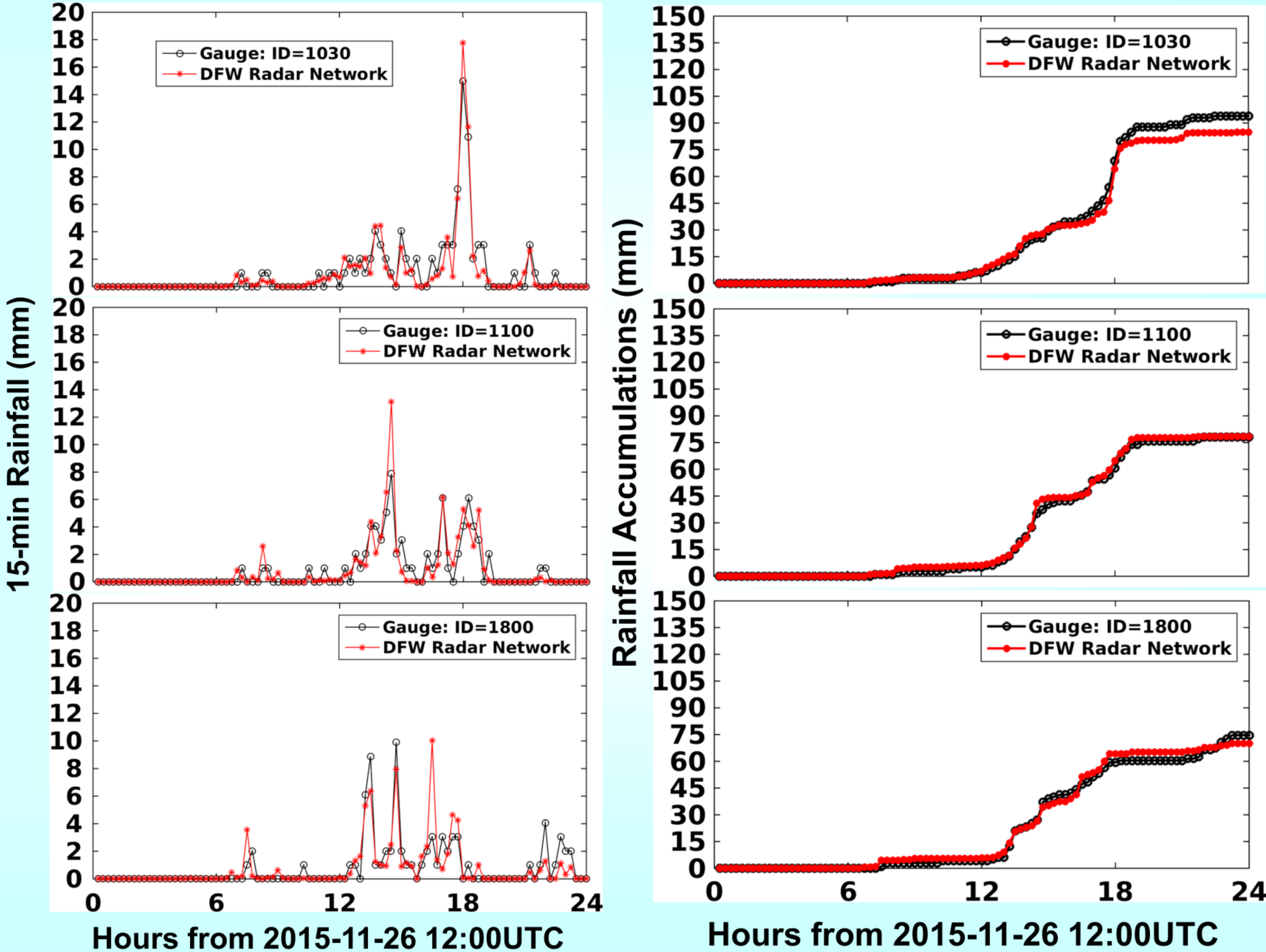


3. Optimization for radar control : task generation user preferences, radar capabilities, meteorological phenomena

4. Dissemination of Data Products to Users

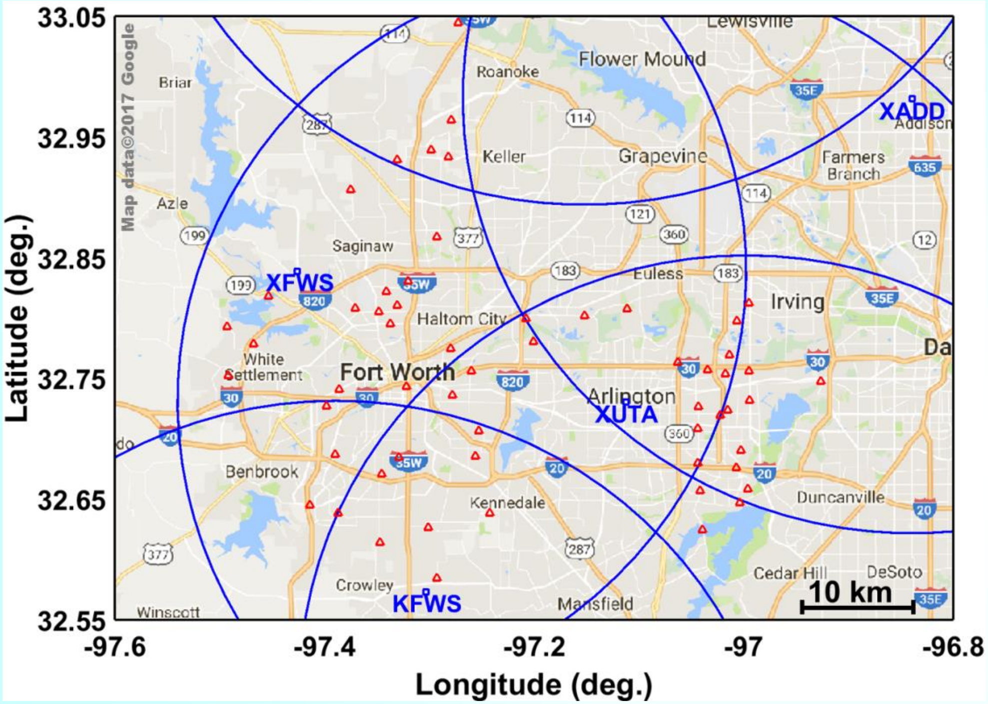
Dense Radar Network to Improve Urban QPE

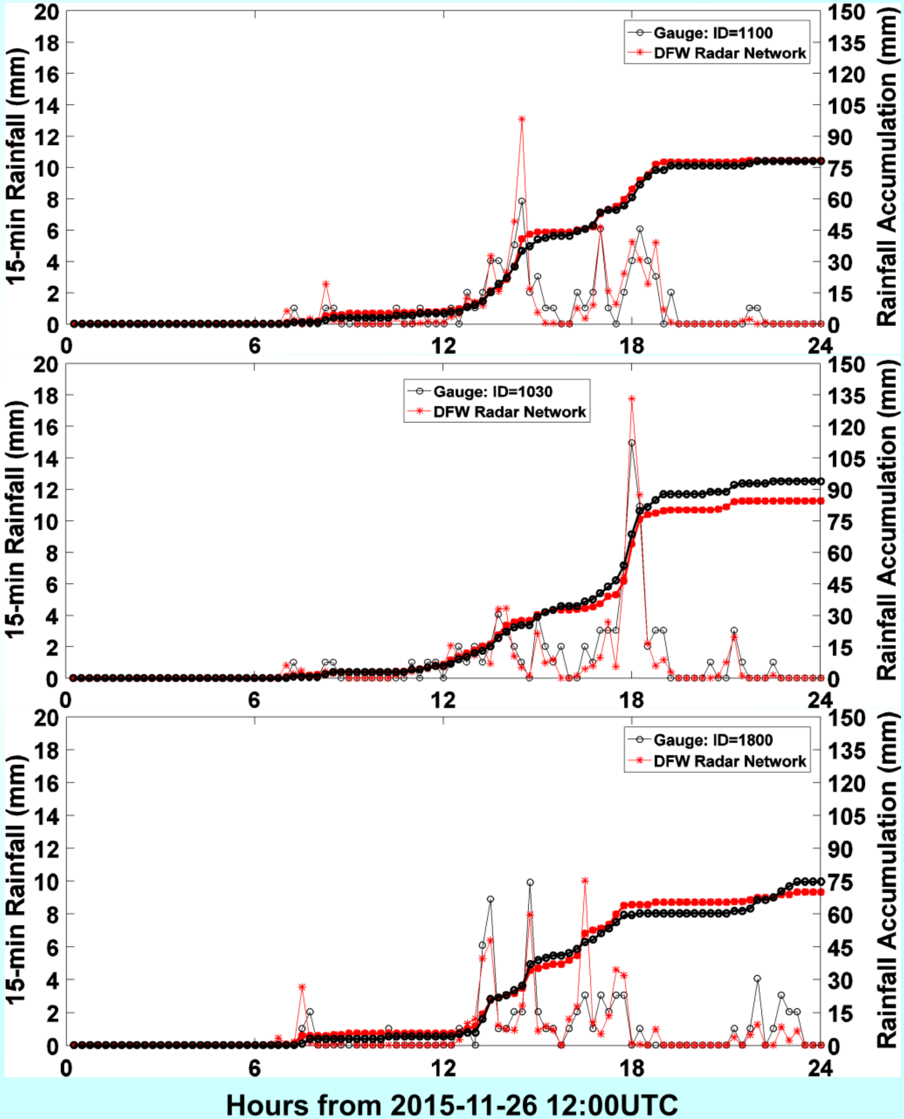
Cross-comparison between DFW Radar QPE and gauge observations



The CASA DFW Dense Urban Radar Network

Validation of high-resolution rainfall products



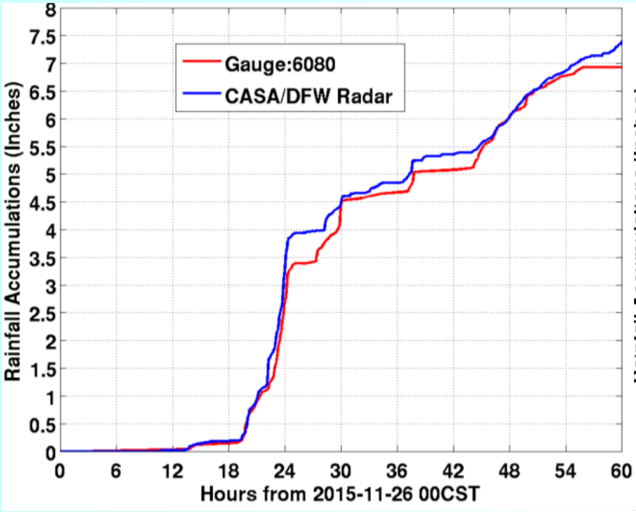


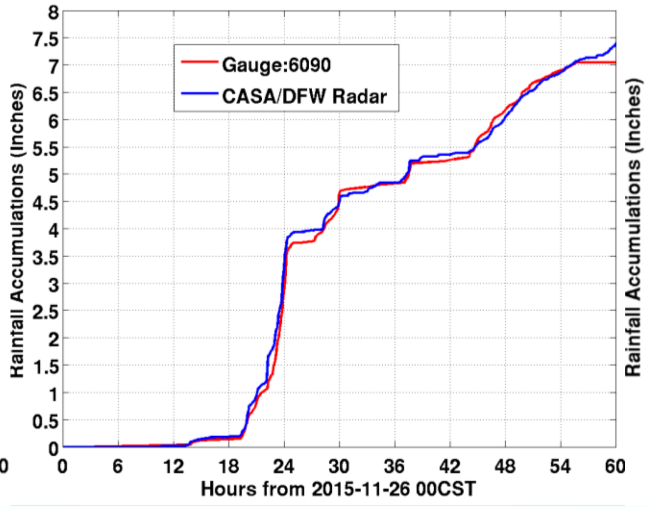
15-min rainfall and rainfall accumulations at sample gauge locations during 2015 Thanksgiving event

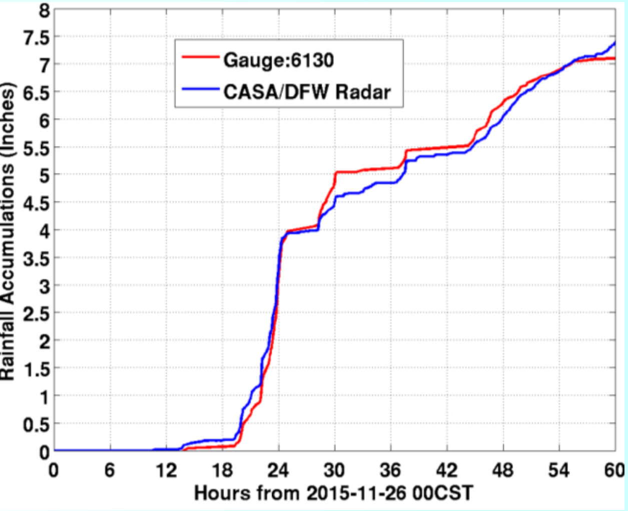
CASA/DFW QPE System

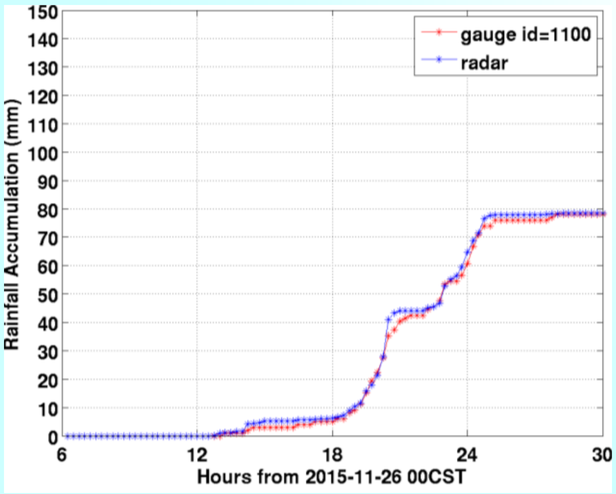
Rainfall accumulations at sample gauge locations

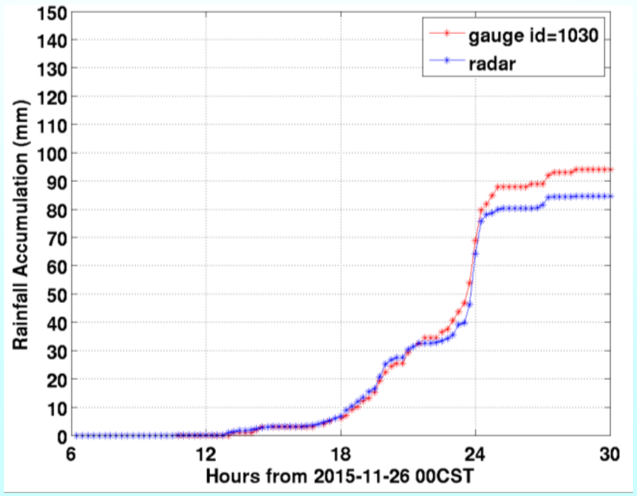
2015 Thanksgiving day event

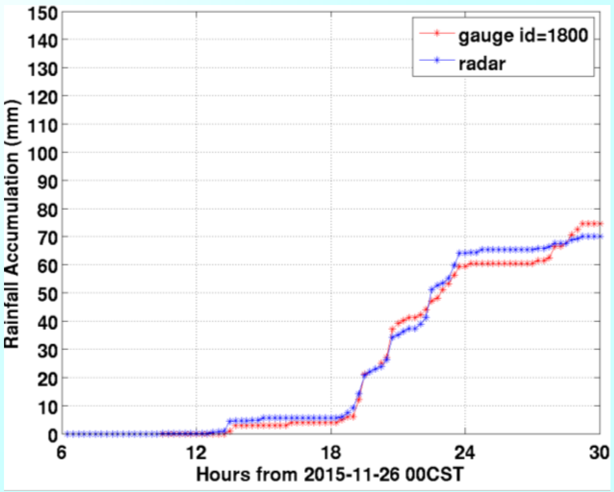






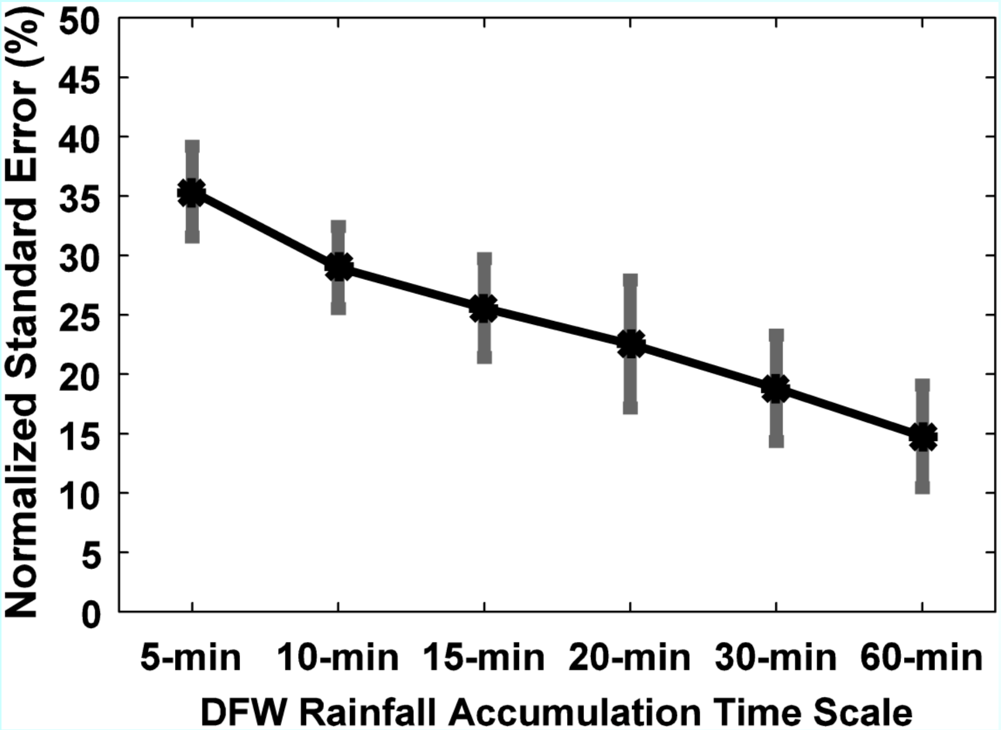


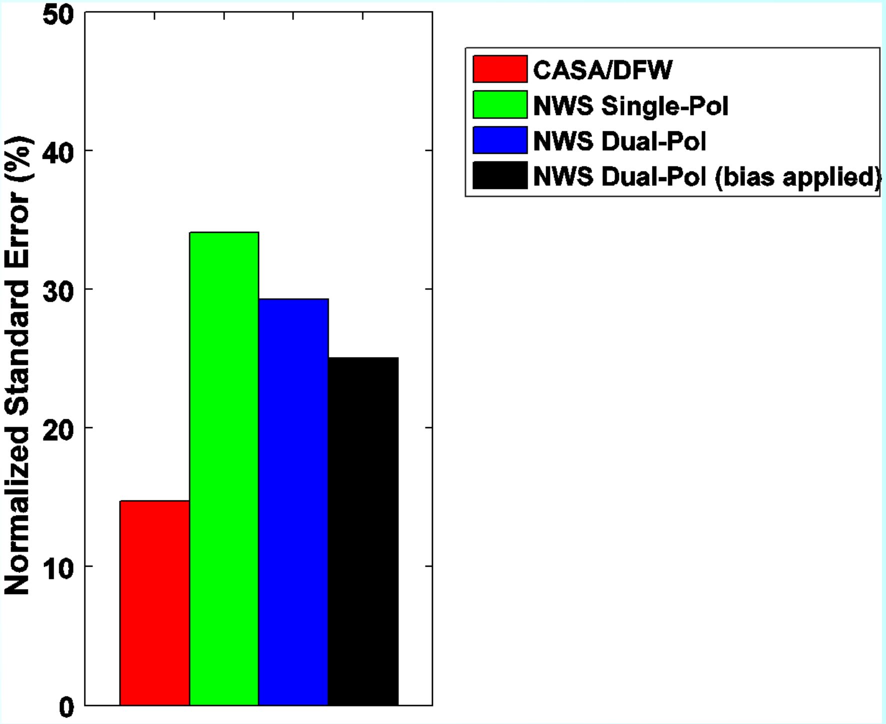




The CASA DFW Dense Urban Radar Network

QPE system performance: $NSE = \frac{<|R_R - R_G|>}{<R_G>}$



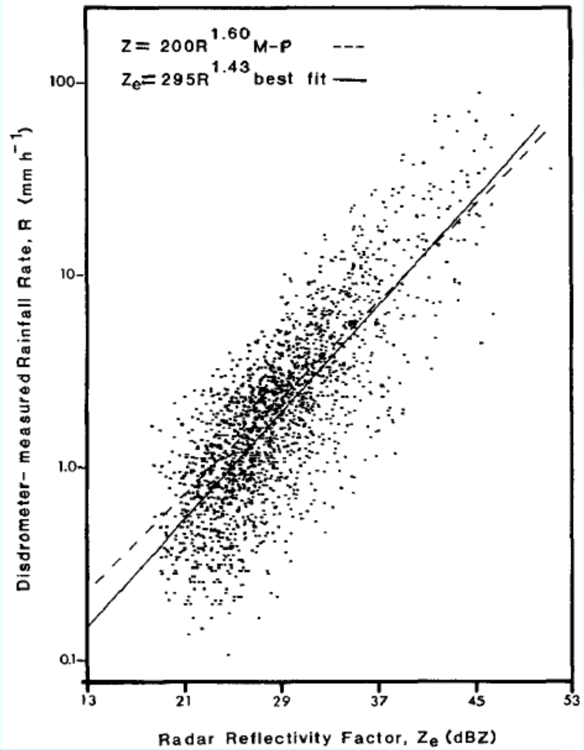


based on all validation gauges

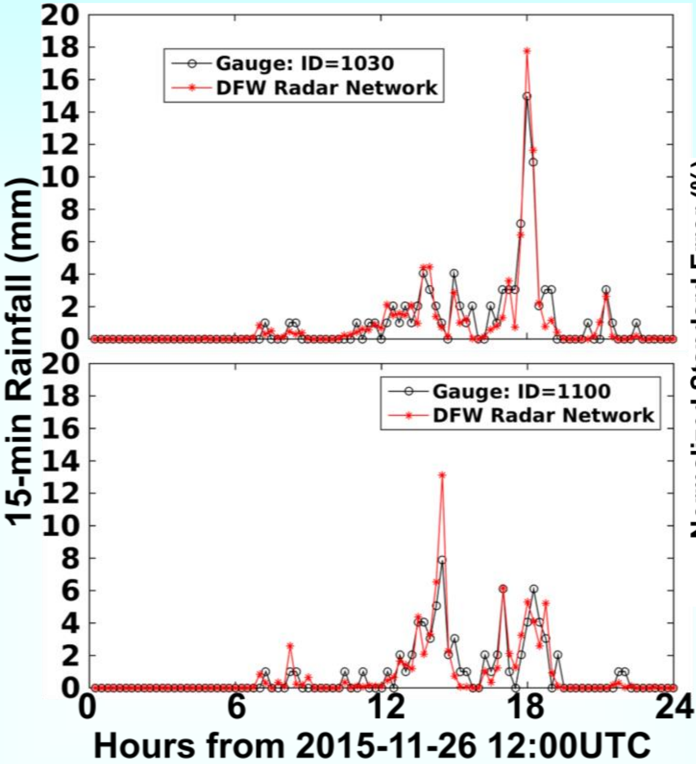
Case Studies

2013-04-18	2013-05-16	2013-06-09
2013-10-27	2014-05-09	2014-07-18
2014-08-18	2015-05-11	2015-05-29
2015-11-26	2015-12-26	

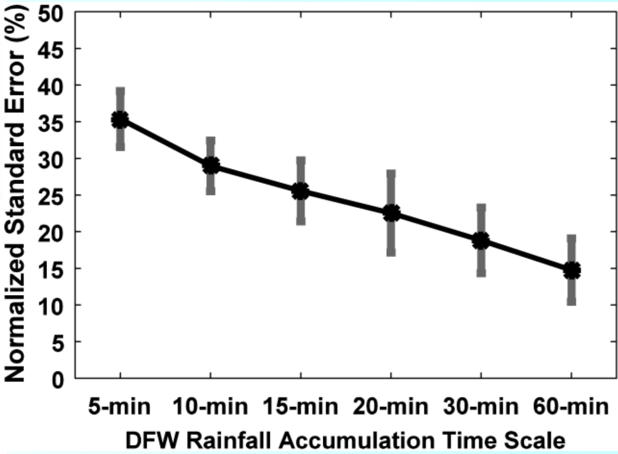
Summary



Scatter plot of radar reflectivity factor vs disdrometer rainfall rate; (Richards and Crozier 1983; Zawadzki, 1984)



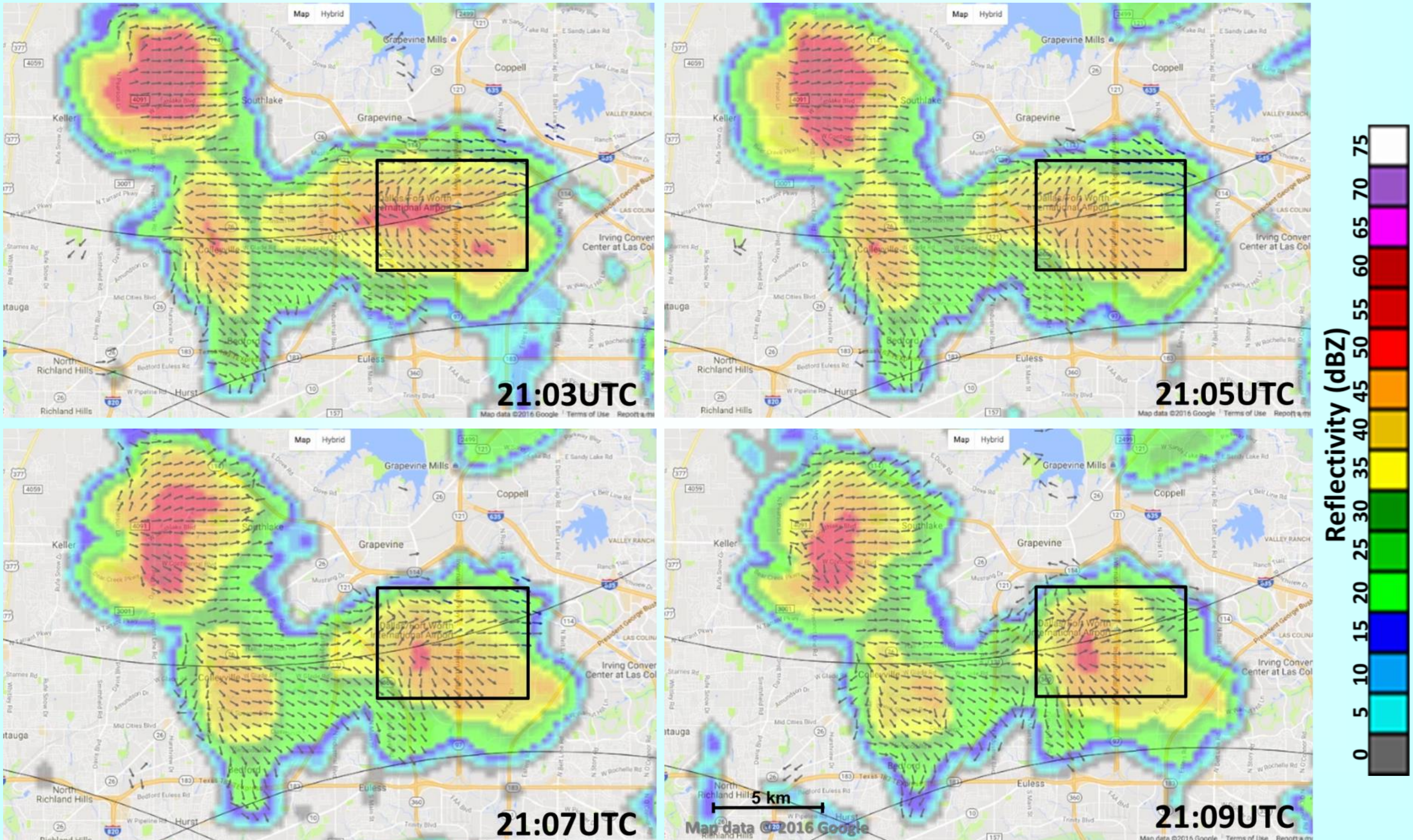
Line traces of 15-min rainfall: DFW radar estimates vs rain gauge measurements



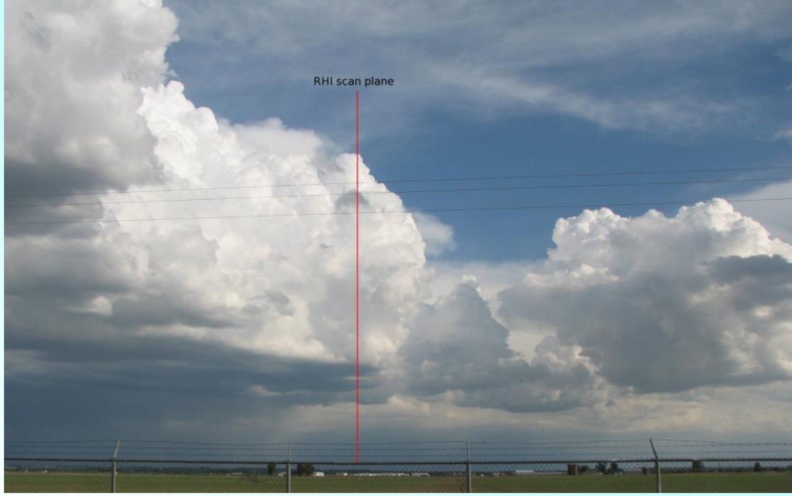
Dense radar network QPE performance

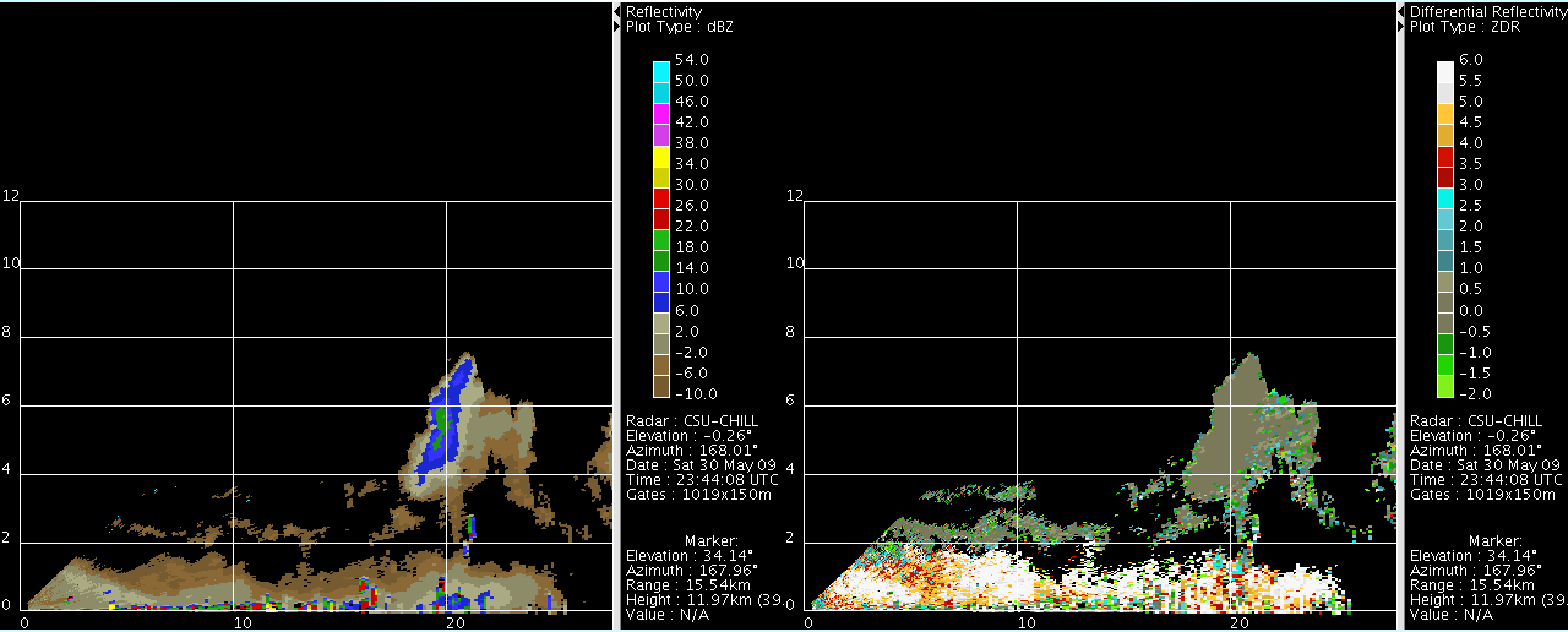
Sample Vector Wind Products

Evolution of downburst over the DFW International Airport region (marked with black rectangle) on August 12, 2016



High time resolution RHI scans through a developing thunderstorm: 30 May 2009

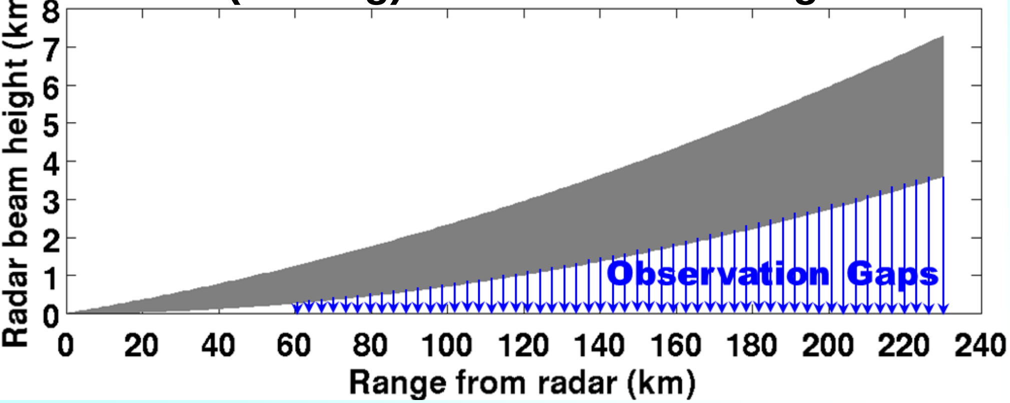


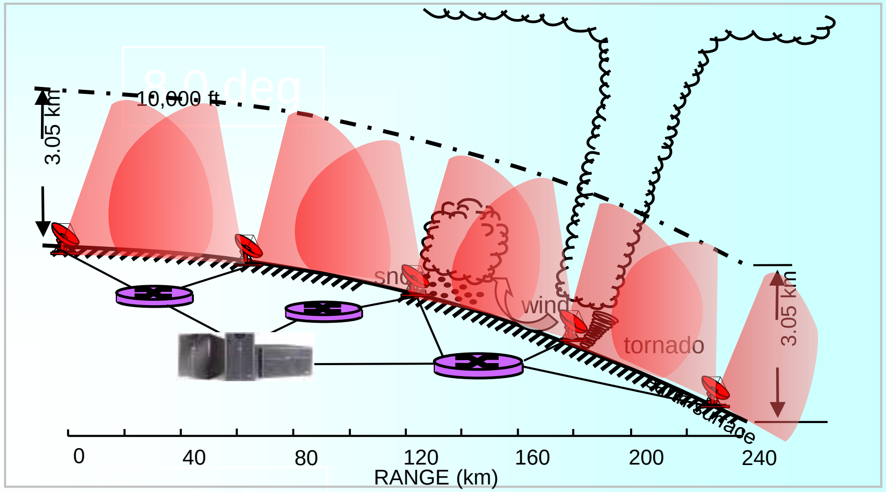


X-band Radar: An Emerging Tool for Rainfall Mapping

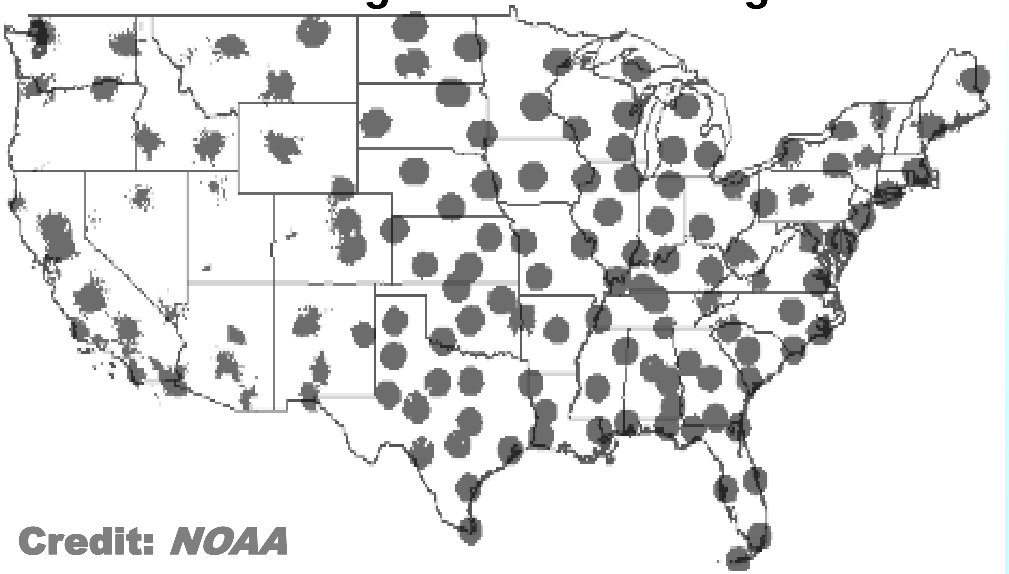
Coverage Limitations of WSR-88DP Radar Network

Lowest (0.5-deg) NEXRAD beam height

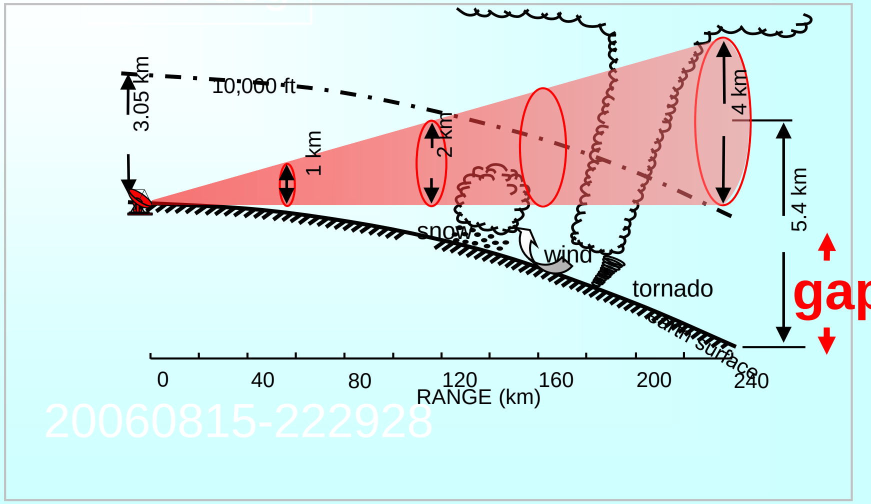




NEXRAD coverage at 1 km above ground level



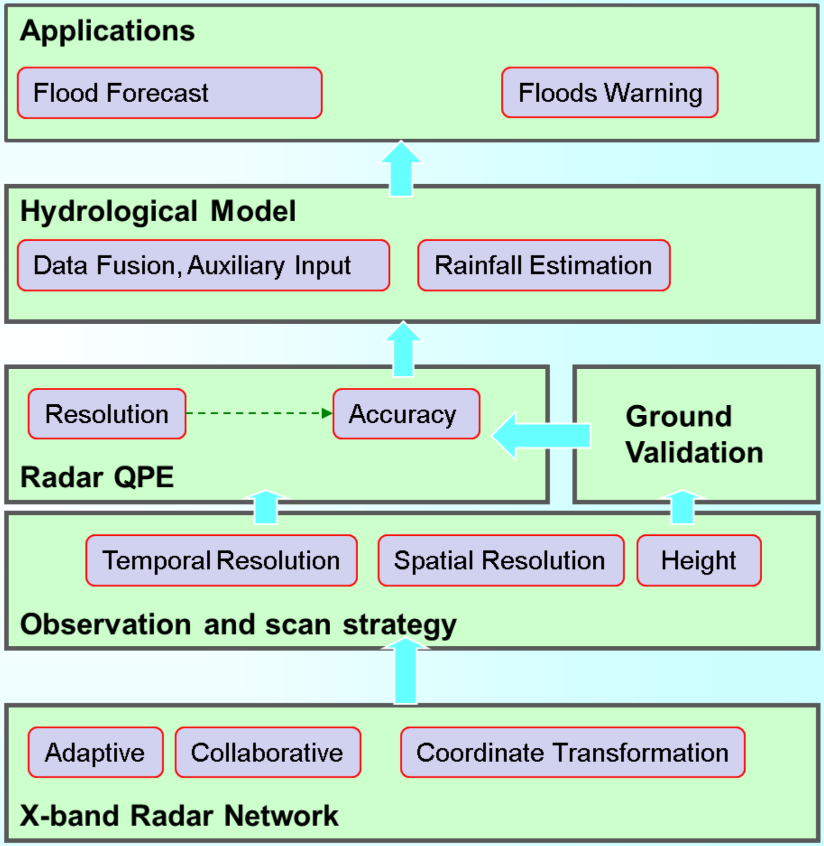
Credit: *NOAA*



X-band Radar: An Emerging Tool for Rainfall Mapping

X-band radar has great potential for QPE

- Serve as "gap filling" radars in operational networks
  - *Produce high resolution QPE for hydrological applications in both urban and rural (watershed-scale) regions*
- Networks of X-band systems will play increasing role in operational QPE



Functional architecture of urban floods monitoring system integrated into an X-band radar network

- **Advantages** of X-band systems
  - *portability*
  - *increased sensitivity to phase estimator of rainfall (Kdp)*
- **Disadvantages** of X-band systems
  - *attenuation in heavy rain*
  - *typically cover a smaller area than S-band*

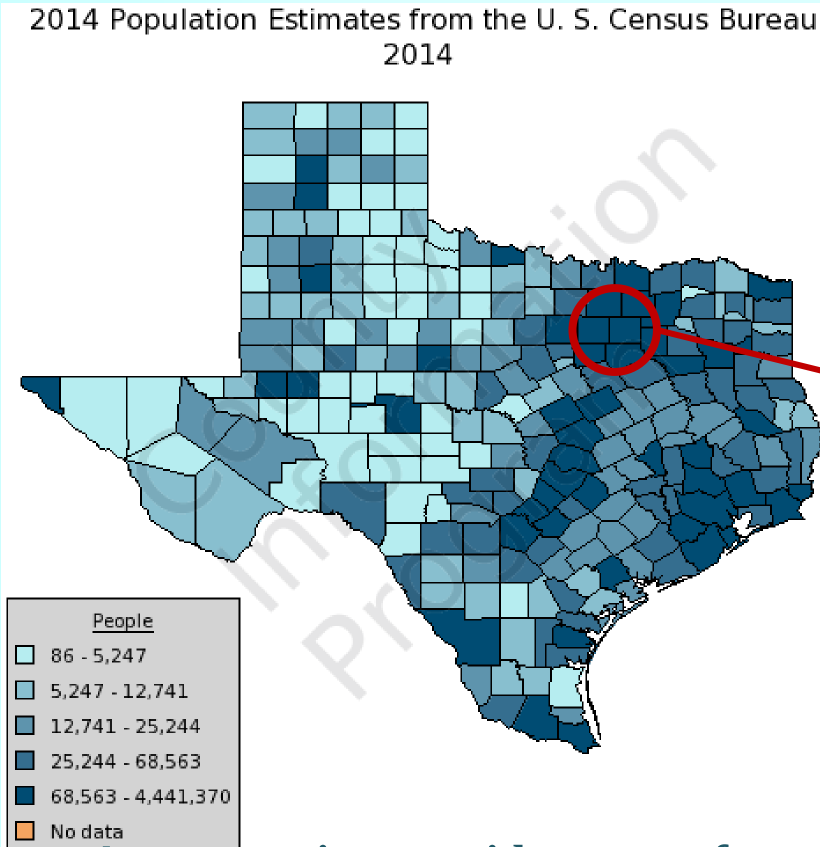
X-band Radar: An Emerging Tool for Rainfall Mapping

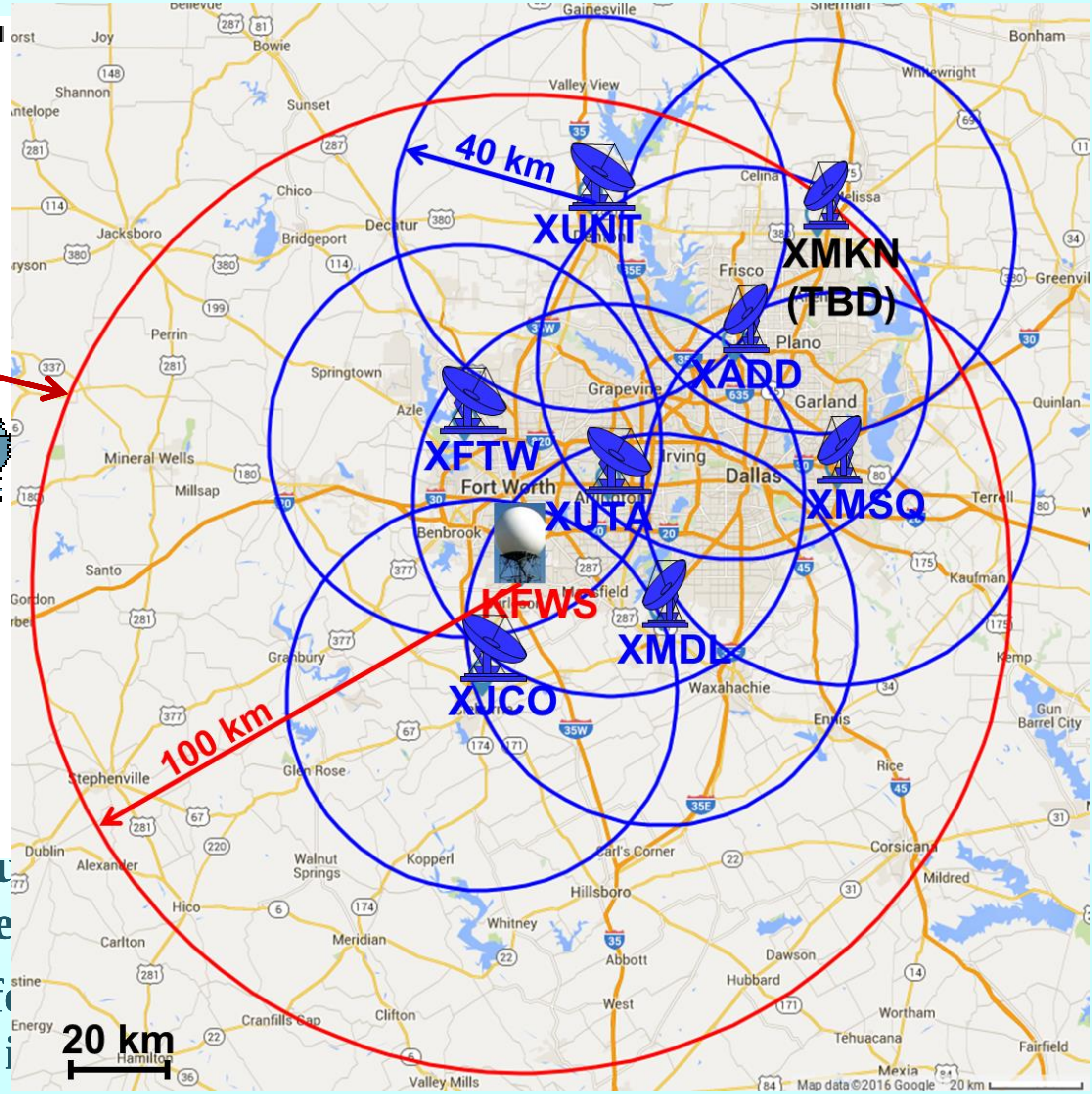
CASA Background

Specification Comparison (CASA X-band Radar vs. NEXRAD)		
	CASA Radar	WSR-88DP
Transmitter	Magnetron	Klystron
Peak power	8.0 kw	750 kw
Average power	12 w	300-1300 w
Pulse width	660-1000 ns	1600-4500 ns
Frequency	9.41GHz	2.7-3.0 GHz
Antenna size	1.2 m	8.5 m
Antenna gain	41 dB	45.5 dB
beam width	1.8 deg.	0.925 deg.
Range res.	60 m	250 m (super res.)
Scan update	< 1 min	5-6 mins

X-band Radar: An Emerging Tool for Rainfall Mapping

CASA Research-to-Operation Testbed in Texas

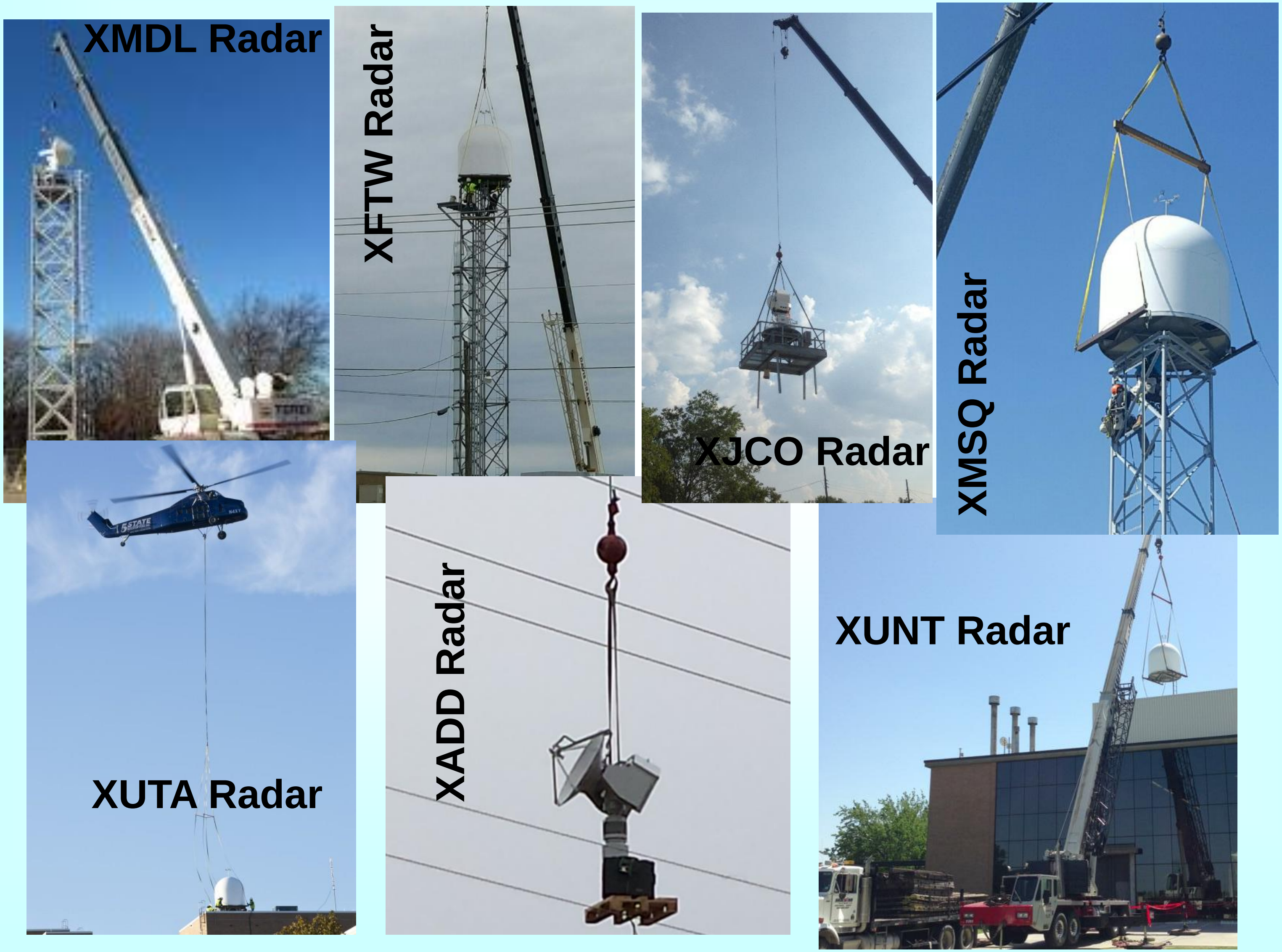




- Area experiences wide range of natu hazards (e.g., flooding and tornadoe
- Radar network initially developed fo hazards monitoring and mitigation i populated urban environment

X-band Radar: An Emerging Tool for Rainfall Mapping

CASA Research-to-Operation Testbed in Texas



Dense Urban X-band Radar Networks

- X-band Radar: an emerging tool for rainfall mapping
- Radar network design and deployment
- Adaptive scan strategy for small radar network
- Attenuation correction for high-freq. observations
- Observations and products in the presence of floods, hails, and tornadoes

Dense Urban X-band Radar Networks

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Adaptive Scan Strategy for Dense Radar Network

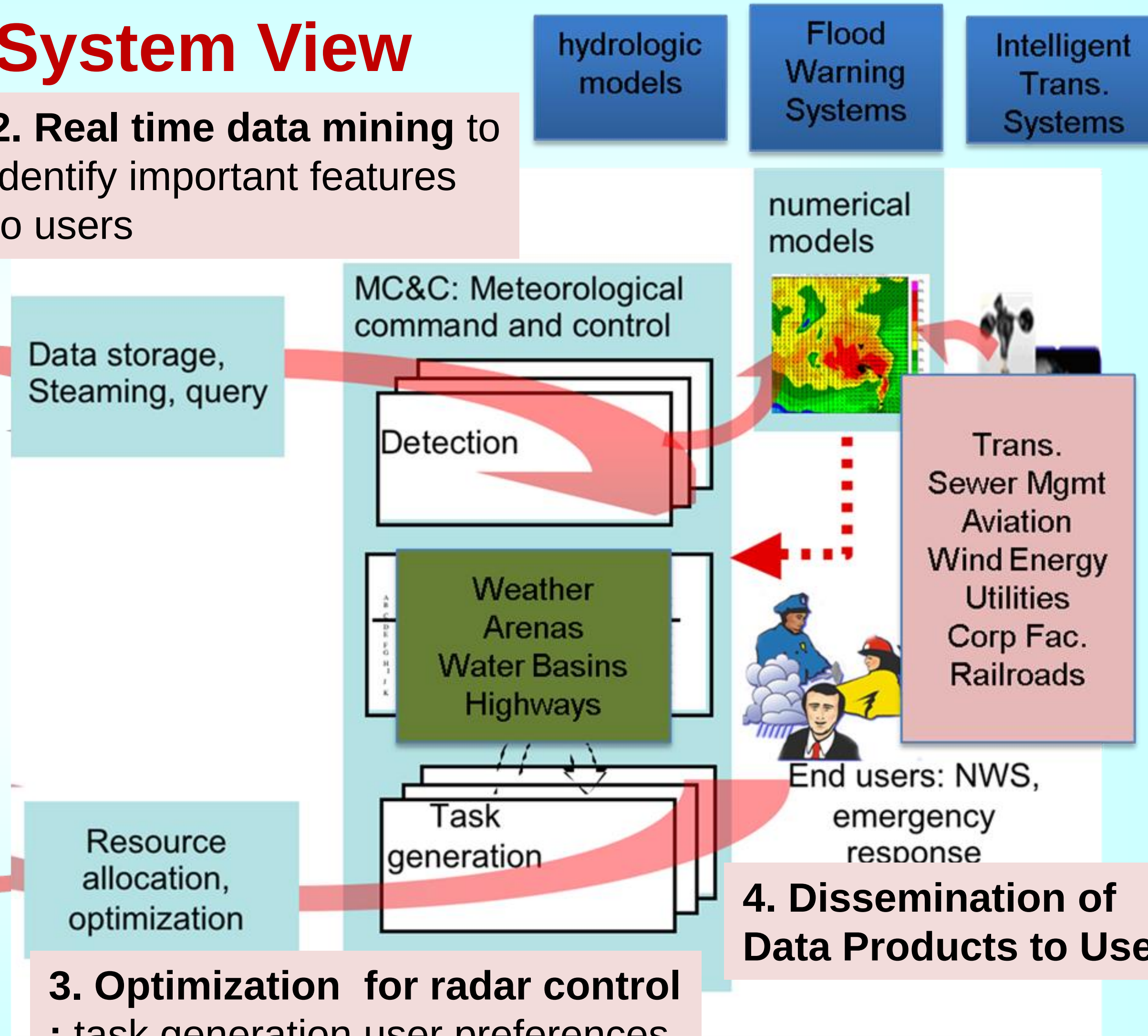
CASA Engineered System View

1. Coordinated volume scan by radar network

2. Real time data mining to identify important features to users

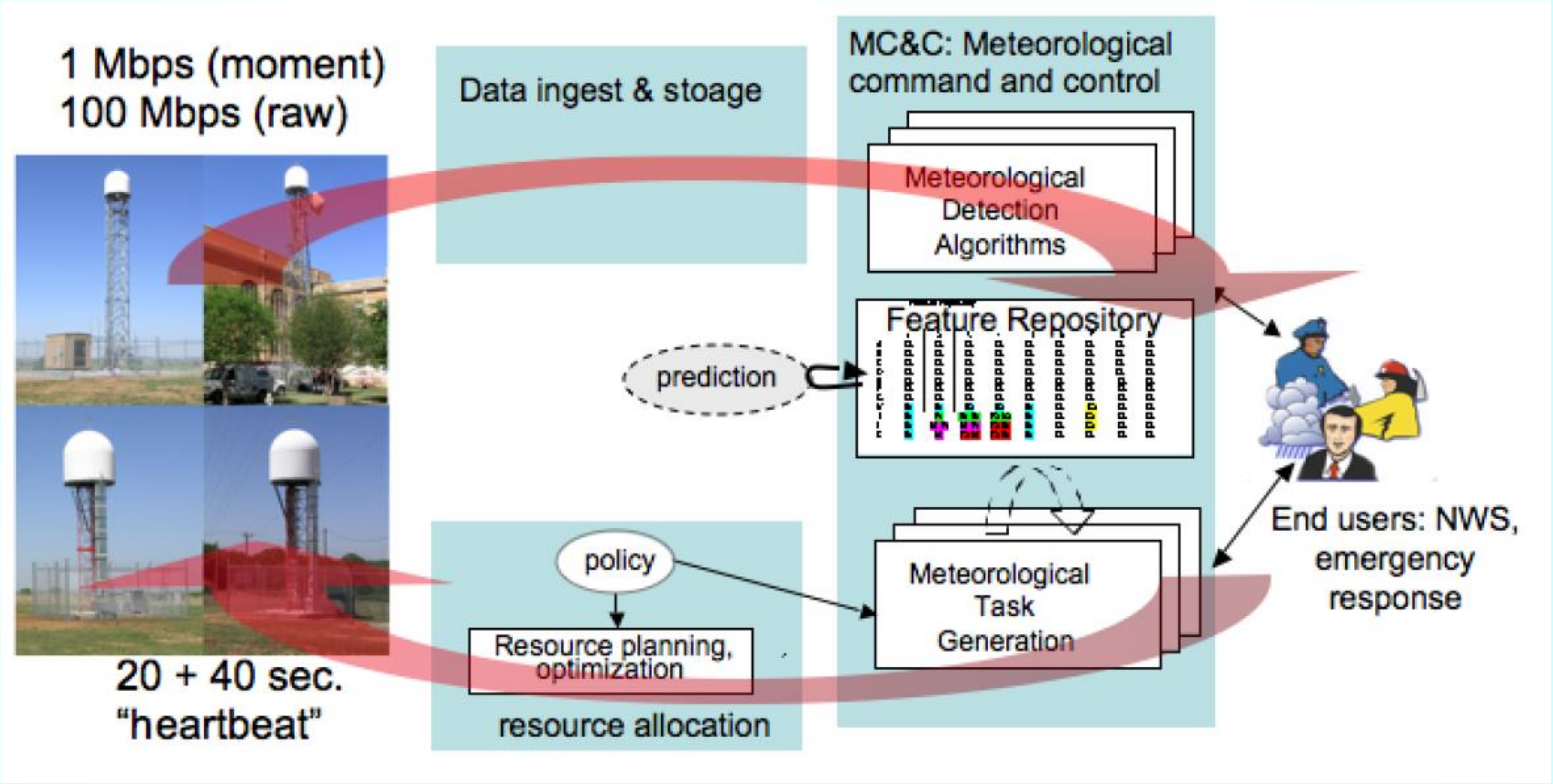
**3. Optimization for radar control : ** task generation user preferences, radar capabilities, meteorological phenomena

4. Dissemination of Data Products to Users



Adaptive Scan Strategy for Dense Radar Network

MCC: Meteorological Command & Control

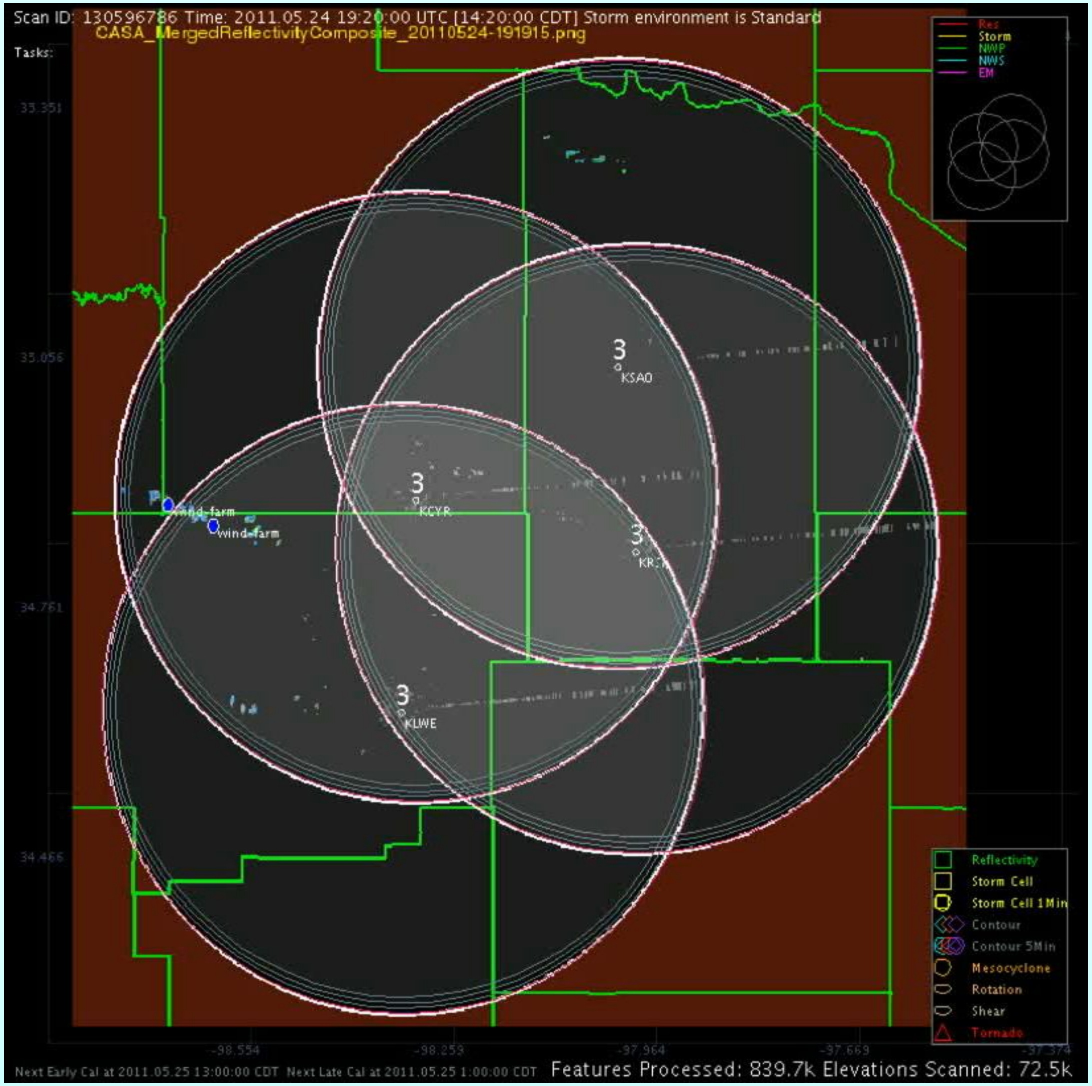


Overall MC&C architecture

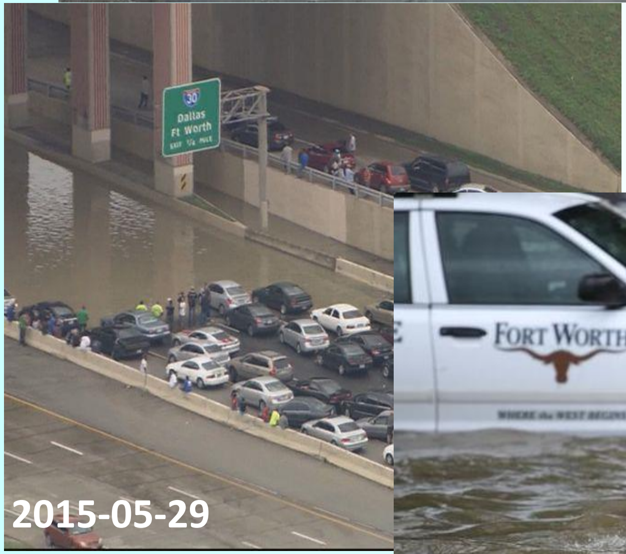
MCC: Meteorological Command & Control

CASA Smart Radar Scans

2011-05-24



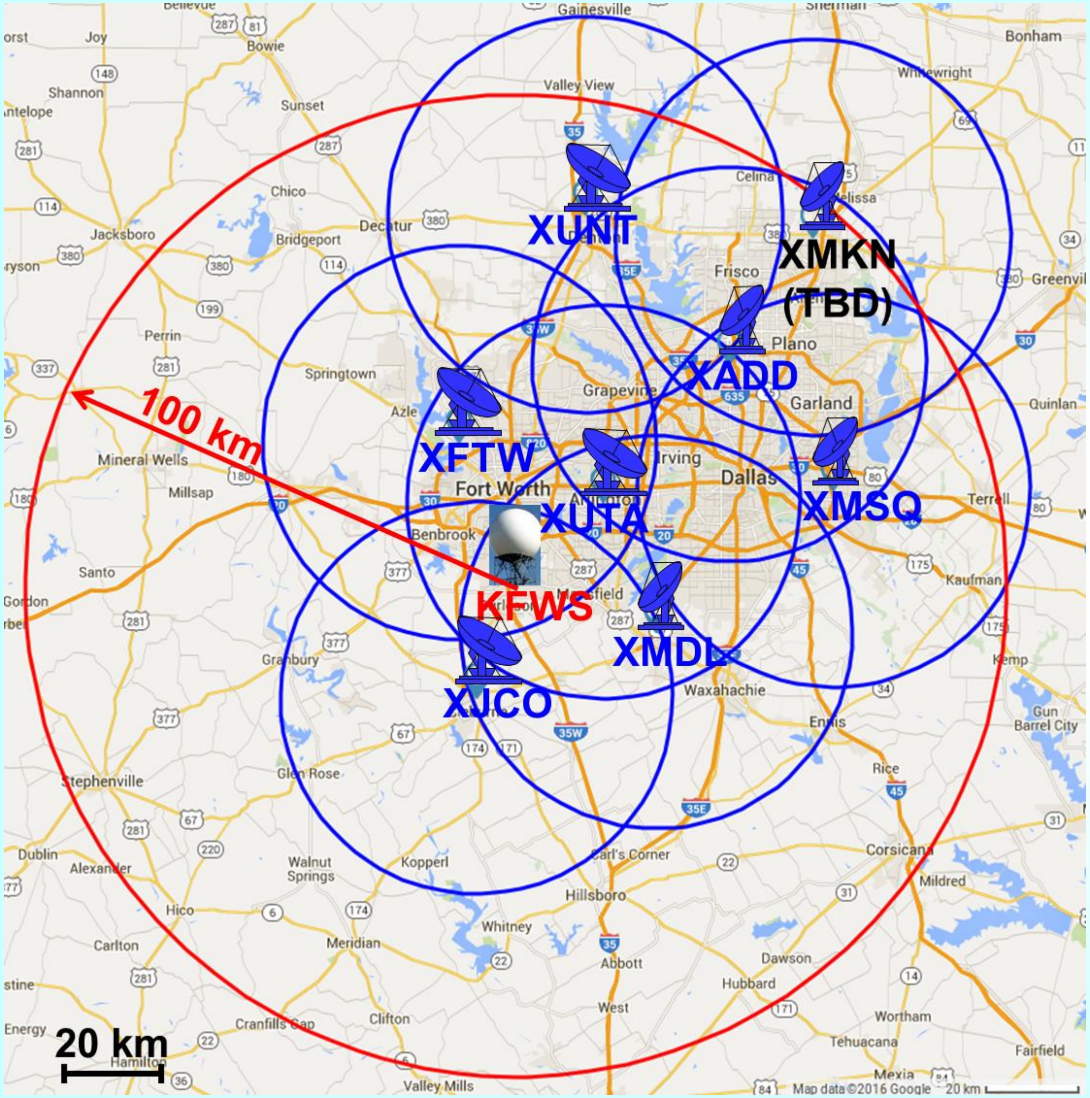
Severe Weather Events in DFW Metropolitan Area



2015 is the wettest year on record for DFW (since 1898).

Tornado Damage during 2015 Christmas

Severe Weather Events in DFW Metropolitan Area



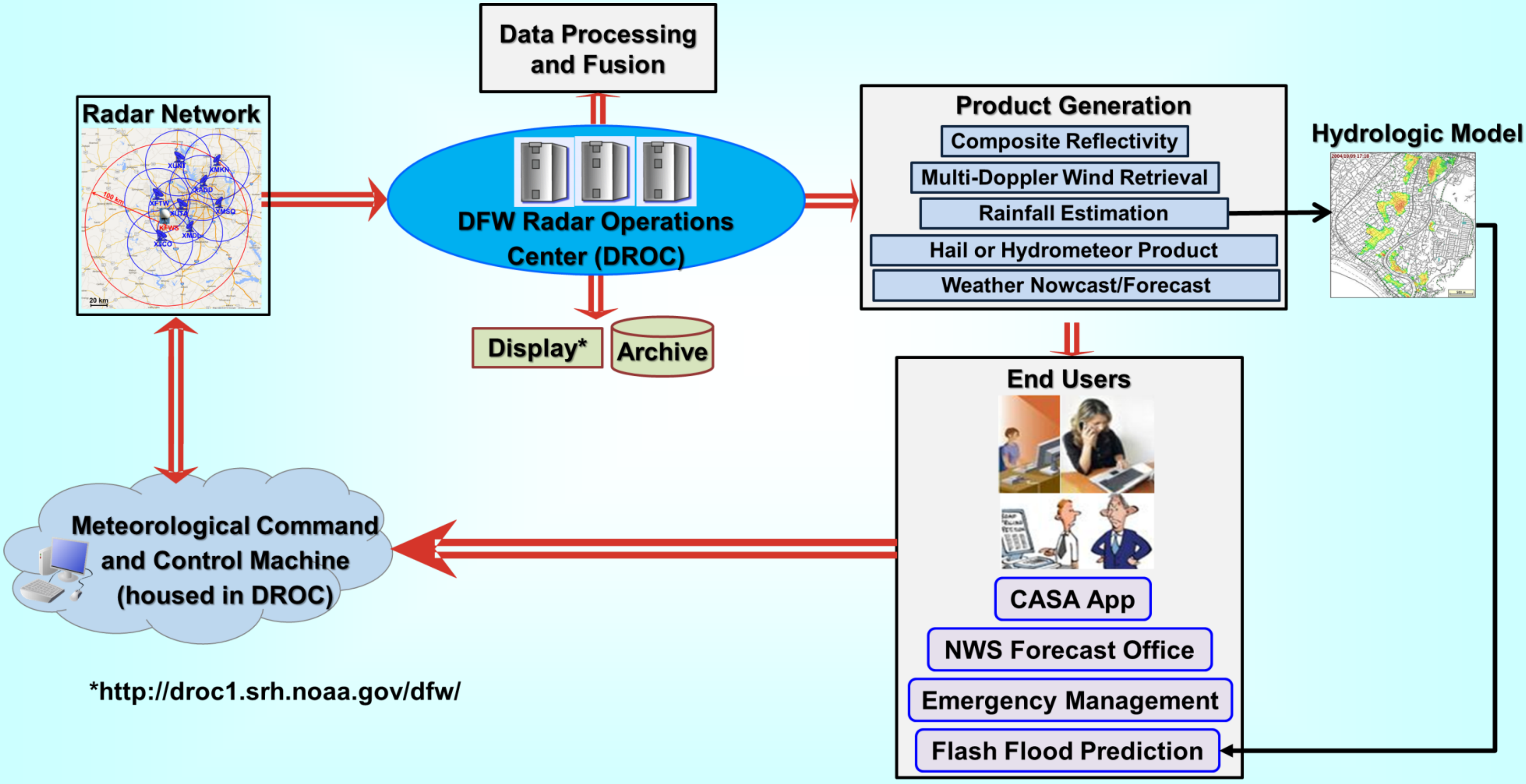
Objectives:

- Develop high-resolution, two- and three-dimensional mapping of current atmospheric conditions for hazardous weather detection and mitigation.
- Demonstrate the value of a dense network of dual-polarization X-band radars to existing sensors and assess optimal combinations of different observing systems.
- Create impacts-based, neighborhood-scale warnings and forecasts in real-time for benefit of the public safety and economy.
- Comprehensive study of dense urban radar network early warning benefits
- Develop models for federal/municipal/private partnerships to introduce new observation technologies for on-going operational and interdisciplinary weather system research.

Research-to-Operation topics include but not limited to:

- Quantitative precipitation estimation (QPE) and forecast (QPF)
- Urban flash flood and hydrologic modelling
- Hydrometeor identification and hail detection
- 3-D multiple Doppler wind retrieval

Real-Time System Architecture for CASA DFW Urban Radar Network

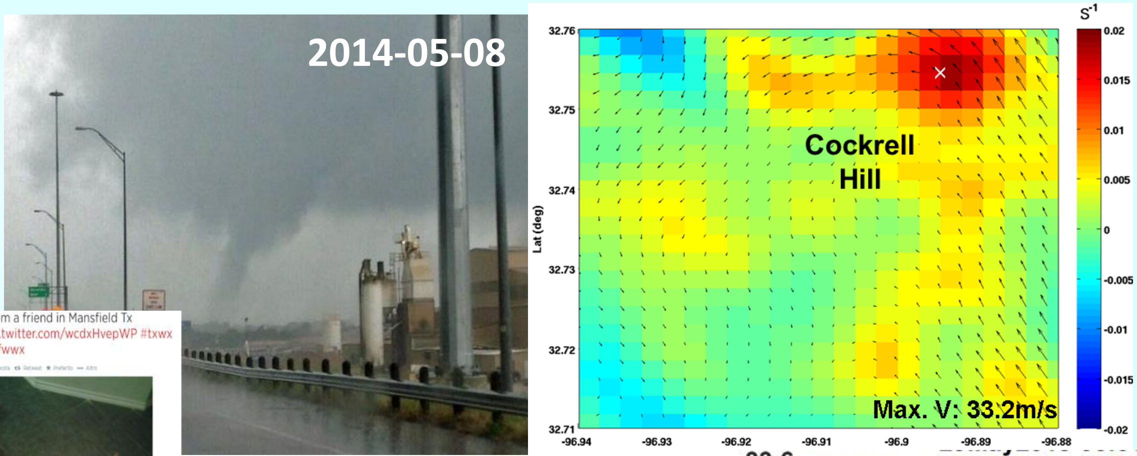


*http://droc1.srh.noaa.gov/dfw/

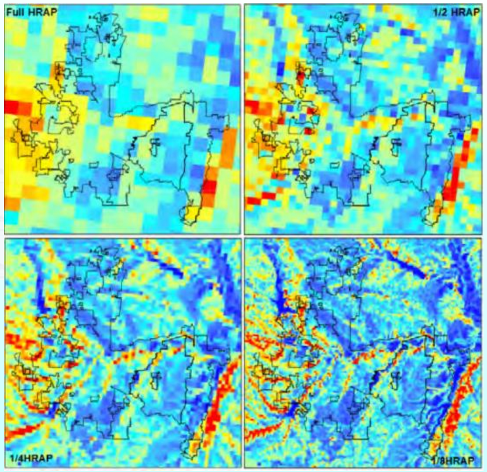
The CASA DFW Dense Urban Radar Network

Selected Real-time Products

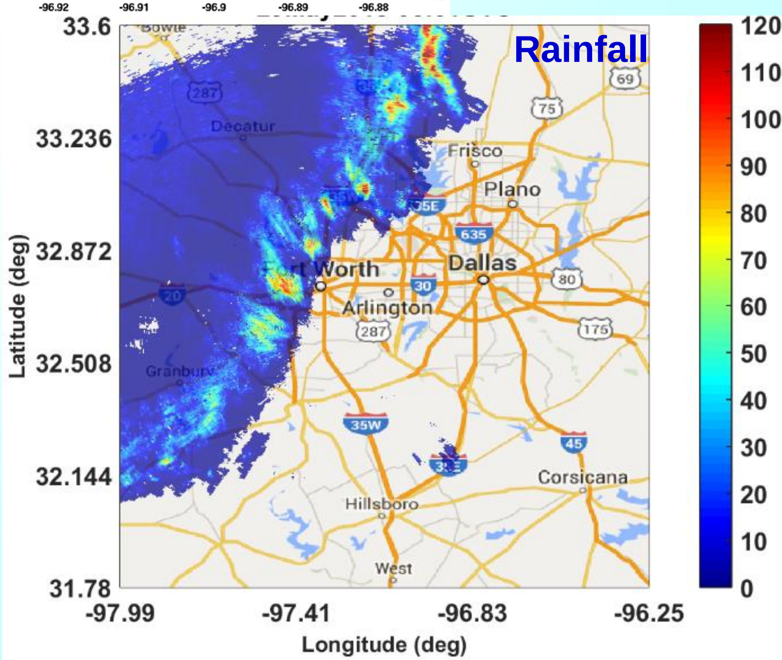
Multiple Doppler Vector Winds (Tornado/Downburst Detection)



Hail Detection



Runoff/Streamflow

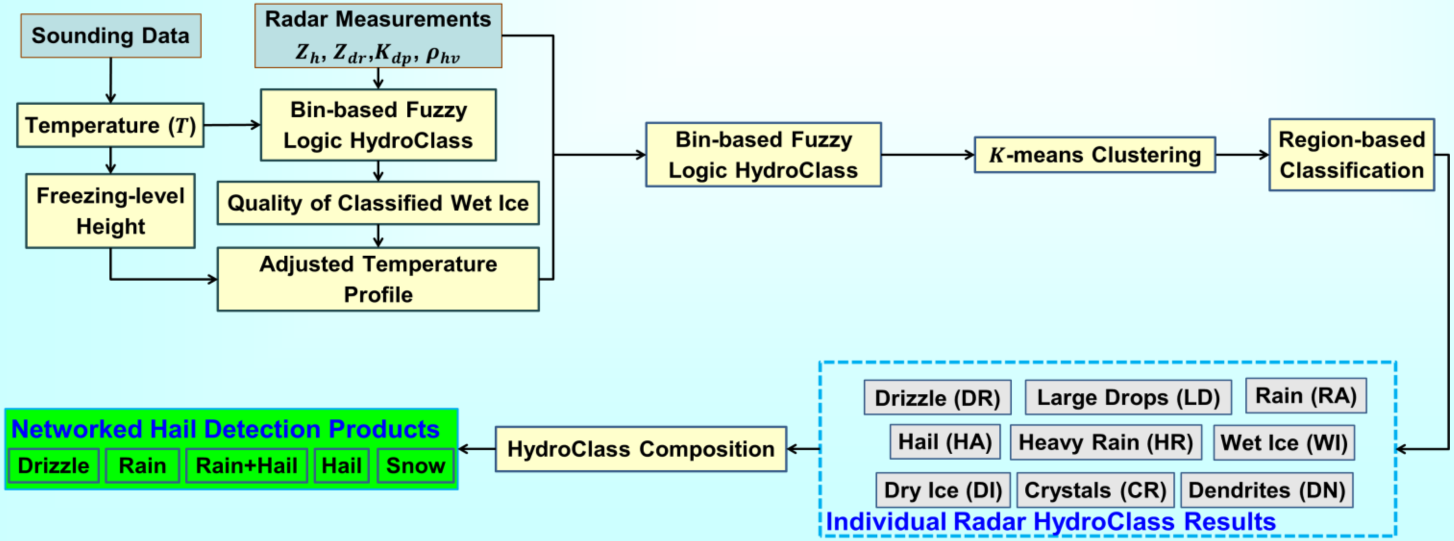


The CASA DFW Dense Urban Radar Network

Classification of different precipitation types

Classification in 4 steps

1) Freezing level adjustment
   - optimization based on the quality of the *wet ice* identifications (melting layer)
2) Bin-based classification
3) Cluster-based classification
   - cluster analysis with contiguity term and a penalty constraint
4) Region-based classification
   - Performed over connected regions

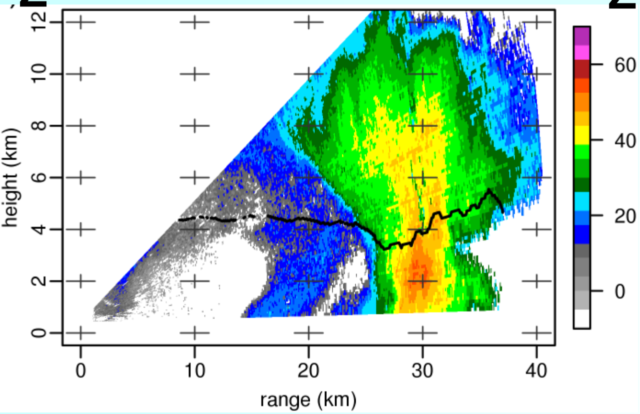


Real-time operational product for easy interpretation

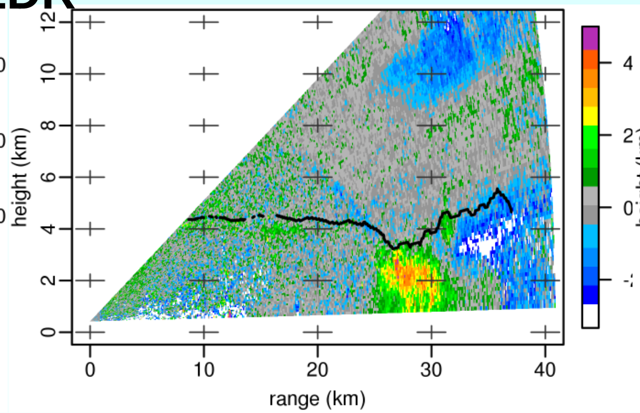
The CASA DFW Dense Urban Radar Network

Classification of different precipitation types

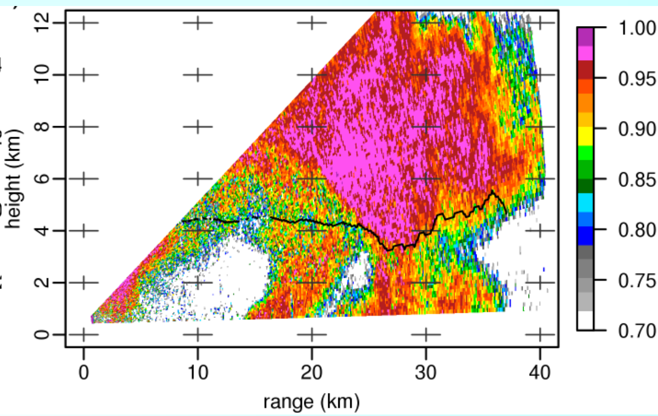
Z



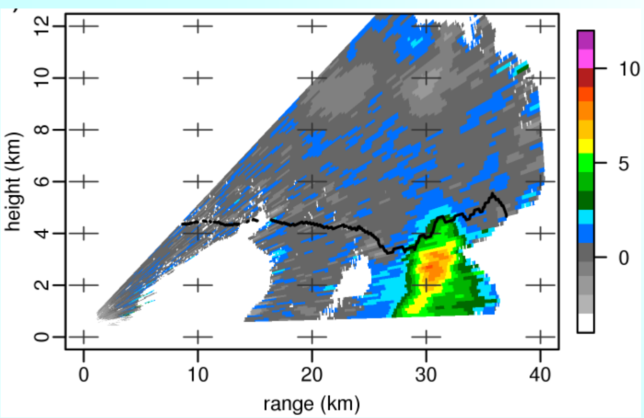
ZDR



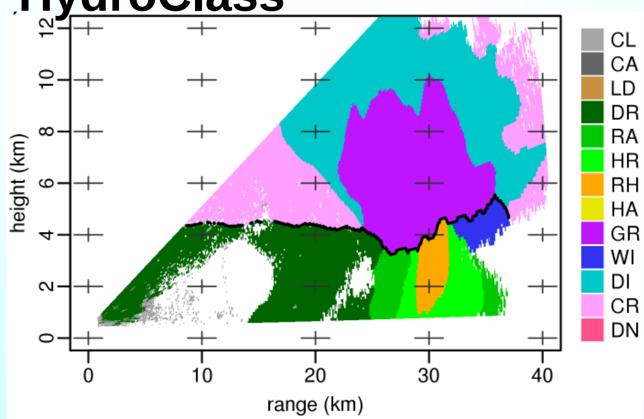
RhoHV



KDP



HydroClass

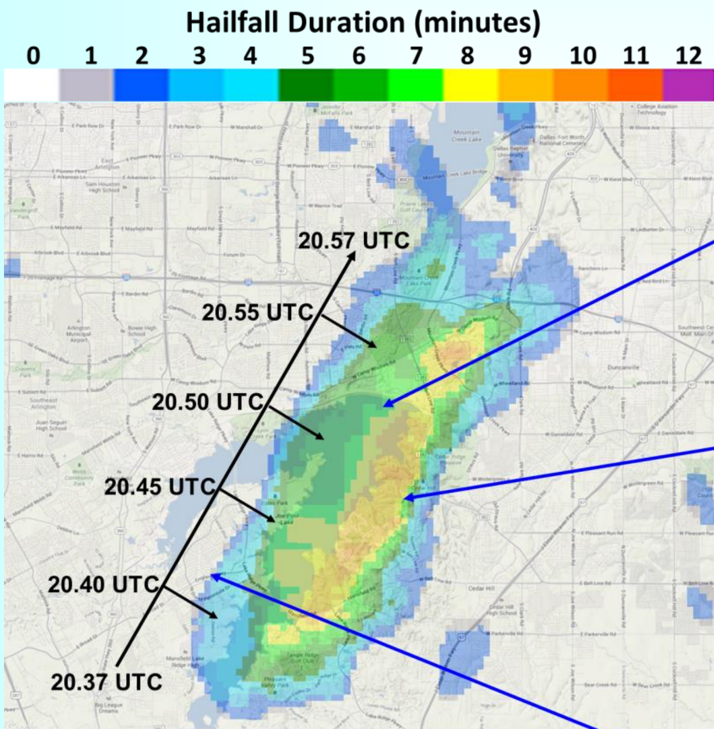


CL: CLUTTER
CA: CLEAR_AIR
LD: LARGE_DROPS
DR: DRIZZLE
RA: RAIN
HR: HEAVY_RAIN
RH: RAIN_HAIL
HA: HAIL
GR: GRAUPEL
WI: WET_SNOW
DI: DRY_SNOW
CR: CRYSTALS
DN: DENDRITES

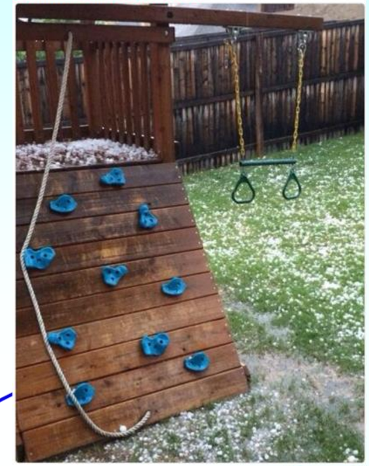
Sample Observations and Results from CASA IP1 testbed (KCYR radar) at 04:14UTC, May 20, 2011

The CASA DFW Dense Urban Radar Network

Hail path over Joe Pool Lake on May 12, 2014



pic.twitter.com/QiAXWiAKvy



James Jennings
@jennings9701
Follow
@TxStormChasers Quarter size hail near Joe Pool Lake in Grand Prairie.
2:48 PM - May 12, 2014

pic.twitter.com/LHLcKJogrN

Quinton Browder
@Qbrowder
Follow
@wfaaweathertoo hail in Grand Prairie near Joe Pool Lake
2:43 PM - May 12, 2014

Patrick @PatmanSays · 12 mag
@TxStormChasers @BeeManDerek where did that hit?
Dettagli

Patrick @PatmanSays · 12 mag
@TxStormChasers @BeeManDerek like what part of Mansfield ?
Dettagli

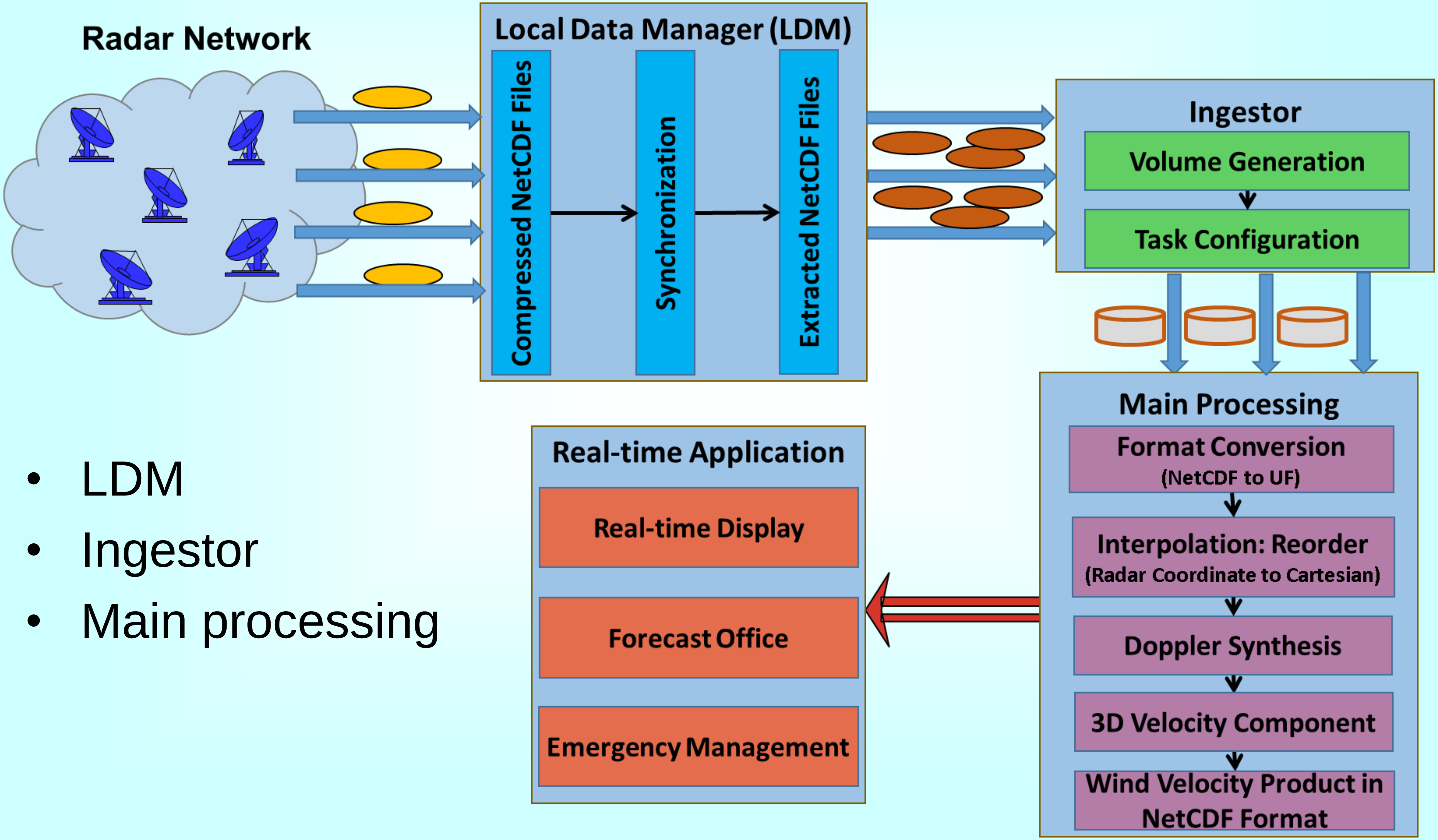
Texas Storm Chasers @TxStormChasers · 12 mag
@PatmanSays @BeeManDerek Likely very near Joe Pool Lake.
Dettagli

pic.twitter.com/wcdxHvepWP

Derek
@BeeManDerek
Follow
@TxStormChasers From a friend in Mansfield Tx
3:01 PM - May 12, 2014

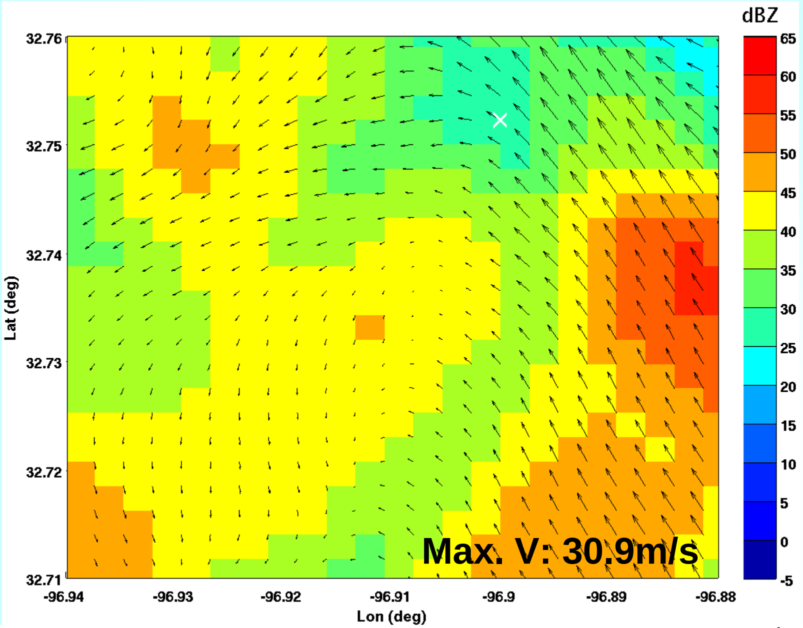
The CASA DFW Dense Urban Radar Network

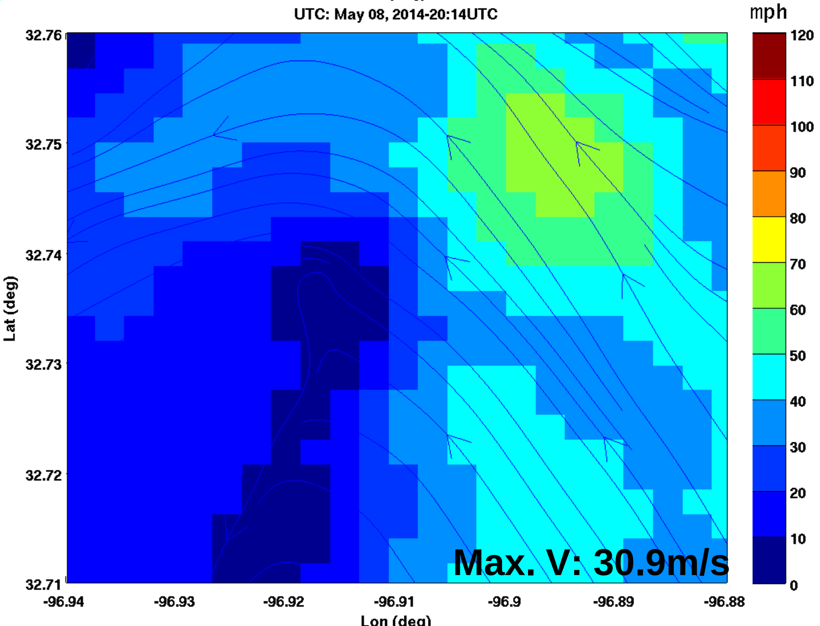
Tornado Detection and High-wind Retrieval System



- LDM
- Ingestor
- Main processing

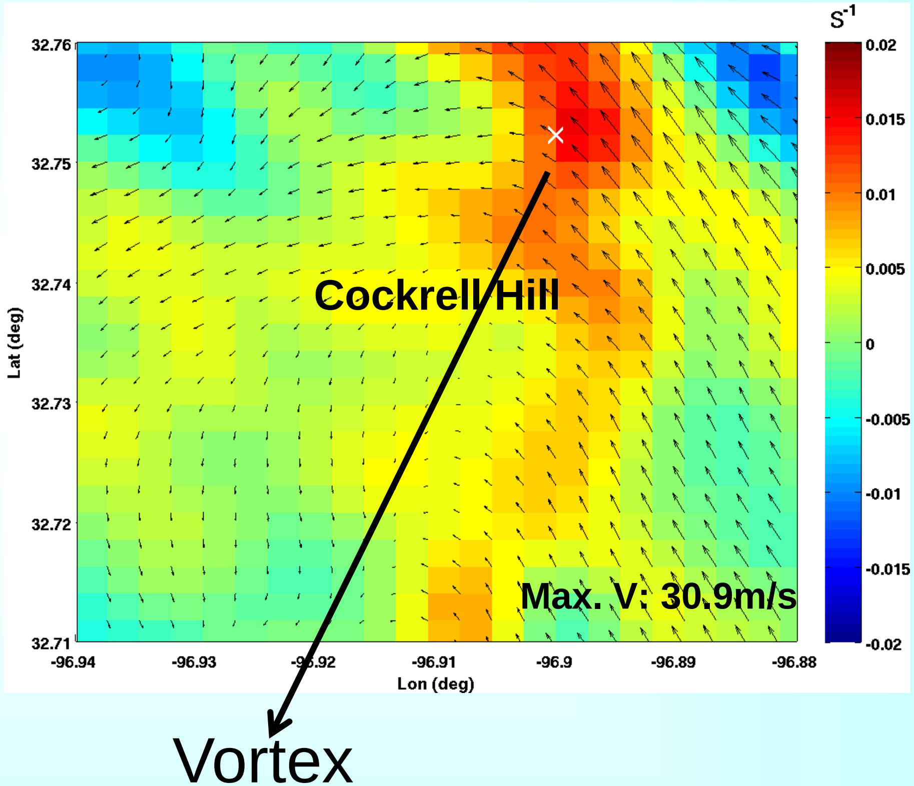
The CASA DFW Dense Urban Radar Network





Sample Observations of Tornado

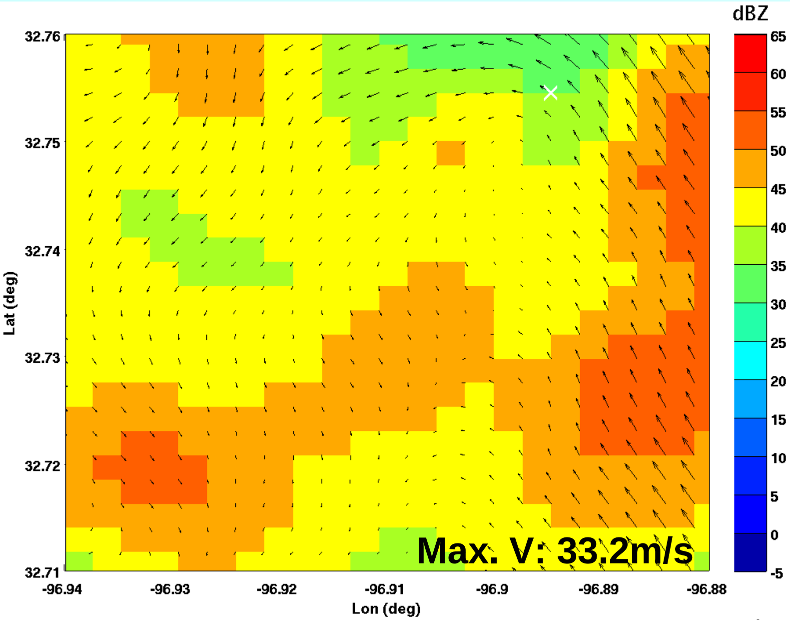
Vorticity $\vec{\omega} = \nabla \times \vec{V}$, the curl (rotation) of the flow vector velocity $\vec{V}$

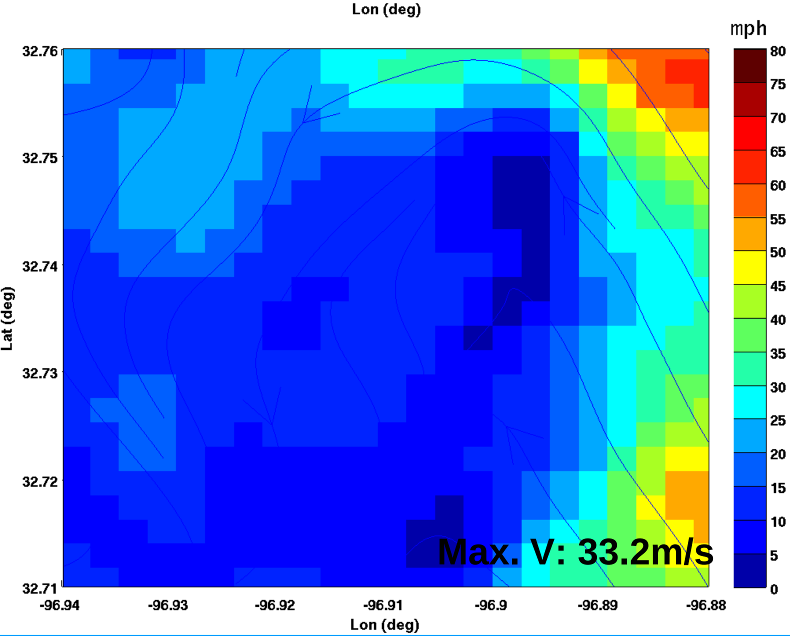


20:14UTC

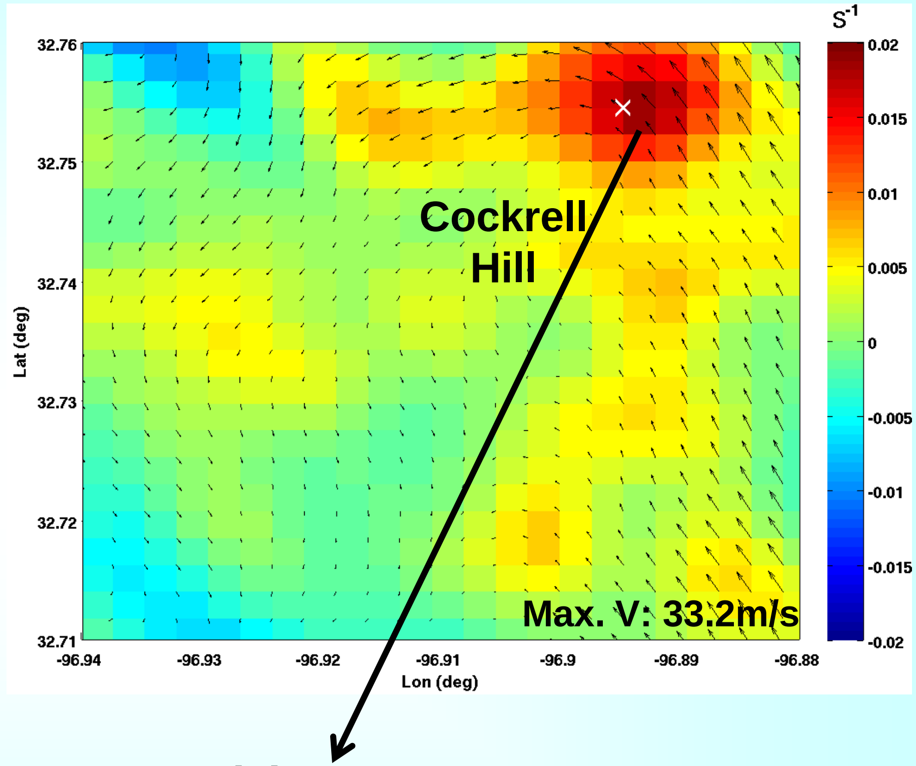
EF0 tornado on May 8, 2014

The CASA DFW Dense Urban Radar Network





Sample Observations of Tornado

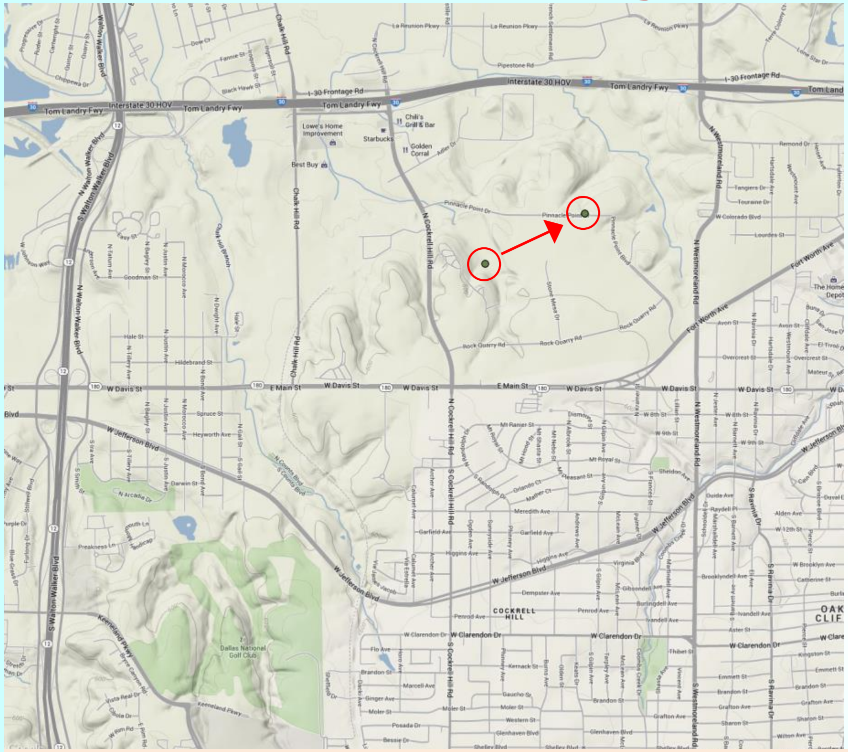


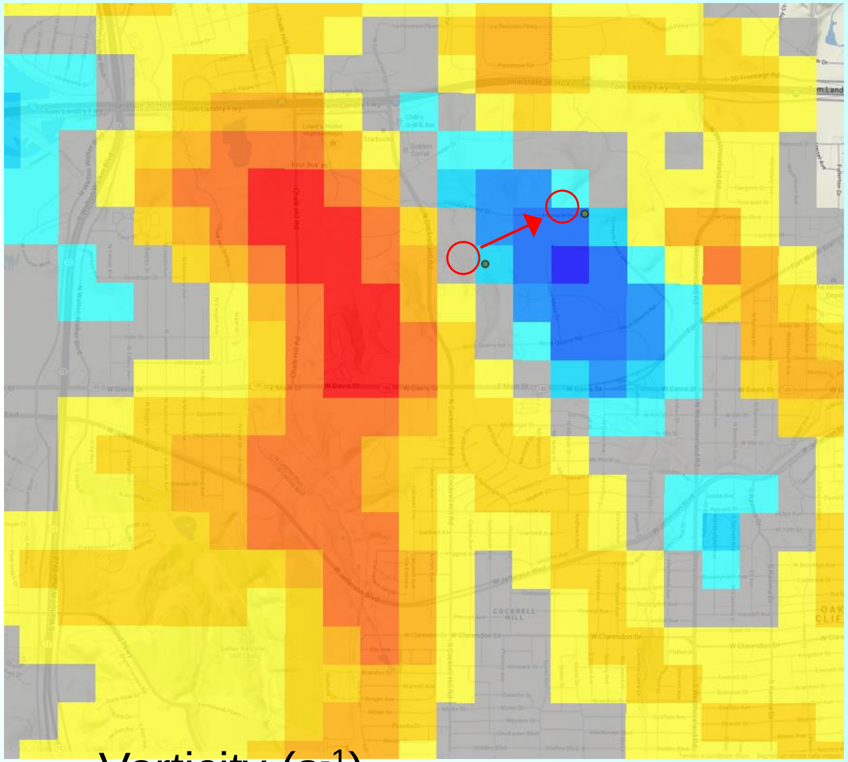
20:15UTC

EF0 tornado on May 8, 2014

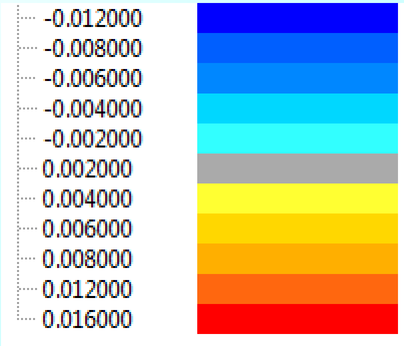
The CASA DFW Dense Urban Radar Network

EF0 tornado on May 8, 2014





Vorticity (s^{-1})



AN ADDITIONAL CREW WENT BACK OUT THIS MORNING AND FOUND DEFINITIVEEVIDENCE OF A TORNADO IN COCKRELL HILL...IN THE AREA SOUTH OF I-30 AND NORTHOF U.S. 180...AND EAST OF NORTH COCKRELL HILL ROAD...AND WEST OF NORTHWESTMORLAND ROAD. .
START LAT/LON: 32.757 / -96.889
END LAT/LON: 32.760 / -96.882

Agree well with ground weather report

The CASA DFW Dense Urban Radar Network

Real-time rainfall products for urban flood applications

Real-time Rainfall Product	Update Rate	Spatial Resolution
Instantaneous Rainfall Rate	60 secs	250mX250m
5-min Rainfall	60 secs	250mX250m
15-min Rainfall	60 secs	250mX250m
30-min Rainfall	60 secs	250mX250m
60-min Rainfall	60 secs	250mX250m
3-hr Rainfall	60 mins	250mX250m
6-hr Rainfall	60 mins	250mX250m
12-hr Rainfall	60 mins	250mX250m
24-hr Rainfall	60 mins	250mX250m

Summary

- X-band radar becomes an emerging tool for rainfall mapping.
- Radar network design and deployment is critical for weather sensing.
- Adaptive scan strategy for high-resolution rainfall observation has been discussed.
- CASA has been operating a dense urban radar network for over five years.
- A number of real-time product systems have been developed. The system performance has been demonstrated through cross validation with *in-situ* observations and ground weather reports.
- These products serve as real-time emergency weather warning tool for urban disaster mitigation.