Colorado State University

Collaborative adaptive weather radar network for major metropolitan regions: The Helsinki implementation

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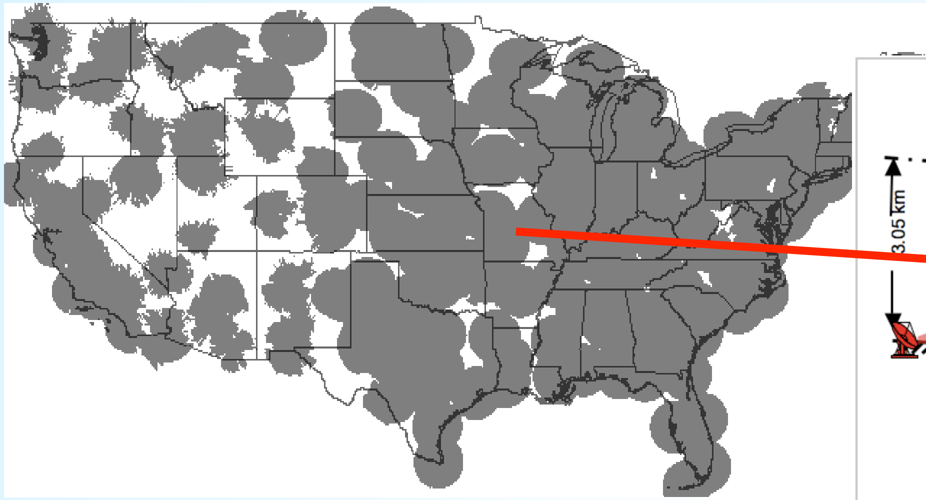
And the full C-CASA team

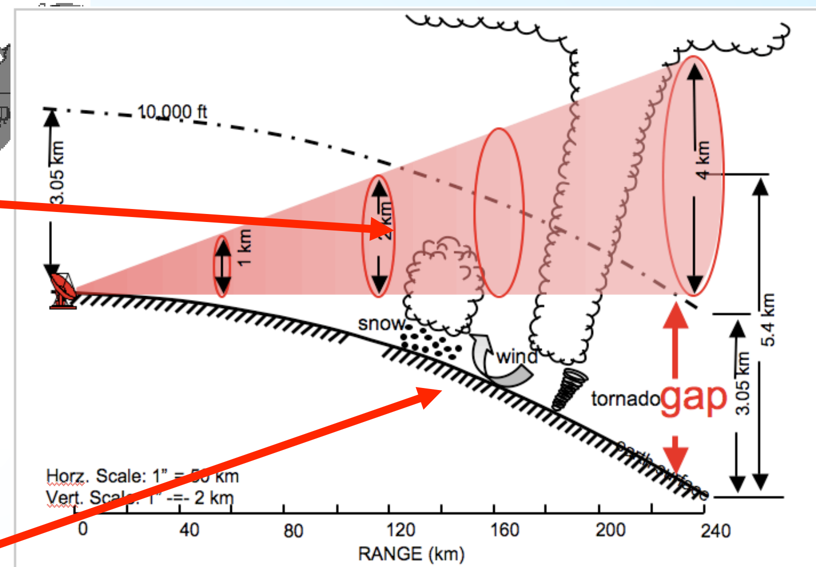
ILMATIETEEN LAITOS
METEOROLOGISKA INSTITUTET
FINNISH METEOROLOGICAL INSTITUTE

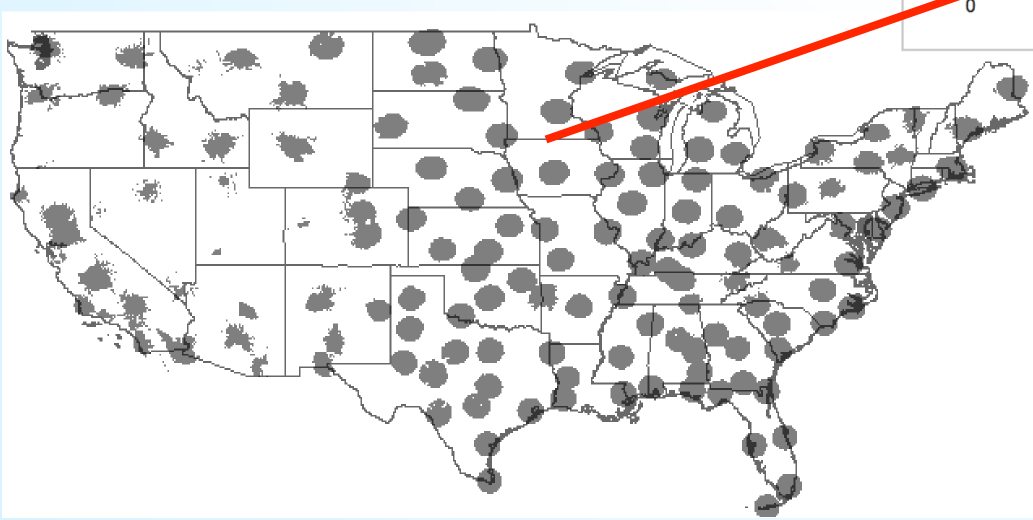
VAISALA

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

Radar Network Solution

- Dense networks of low power, dual pol, multi-Doppler, X-band radars
- High spatial and temporal resolution (250m and 1 minute)
- Smart scans based on weather, user needs and radar capabilities
- Demonstrated successfully in Oklahoma, USA
- Well established now, also being adopted in Asia and Europe.

Tornado Tracking

Anadarko Tornado
May 14, 2009

EF2 Tornado
~9:22 – 9:40PM

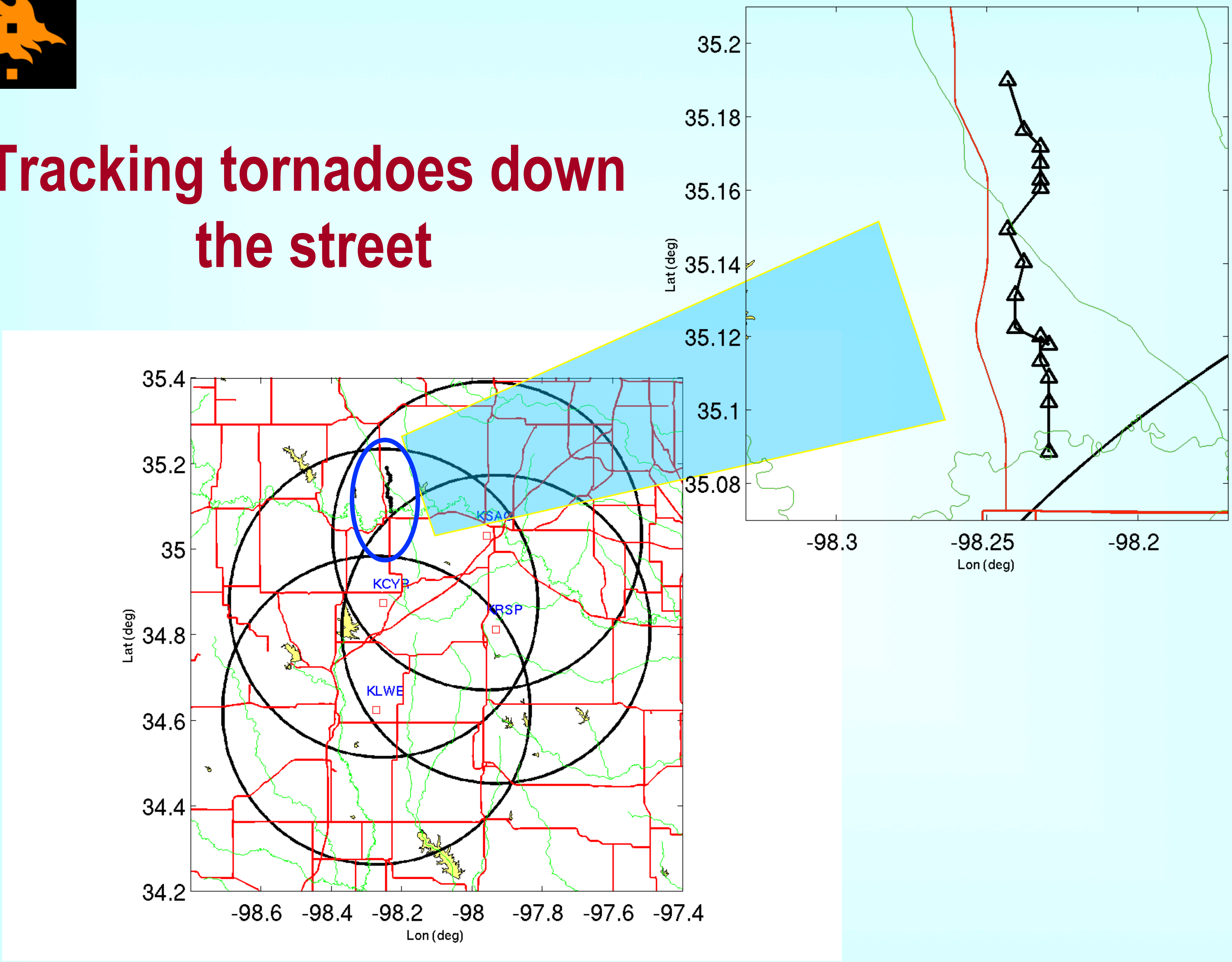
Prolonged Damaging Winds 100mph+

3 injuries
$43 million+ in property damage

CASA Tornado Warning 9:21

NWS Tornado Warning 9:24

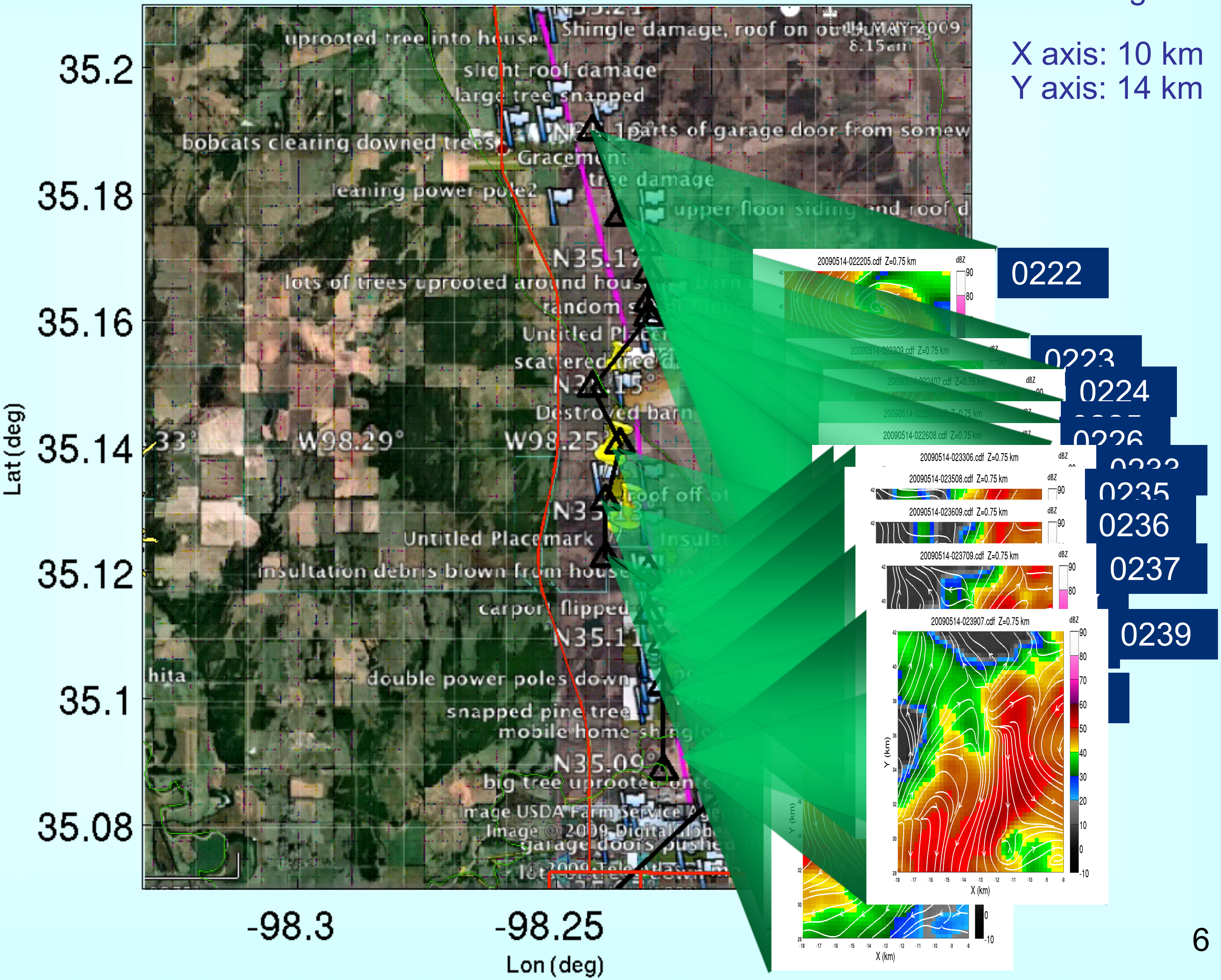
Tracking tornadoes down the street



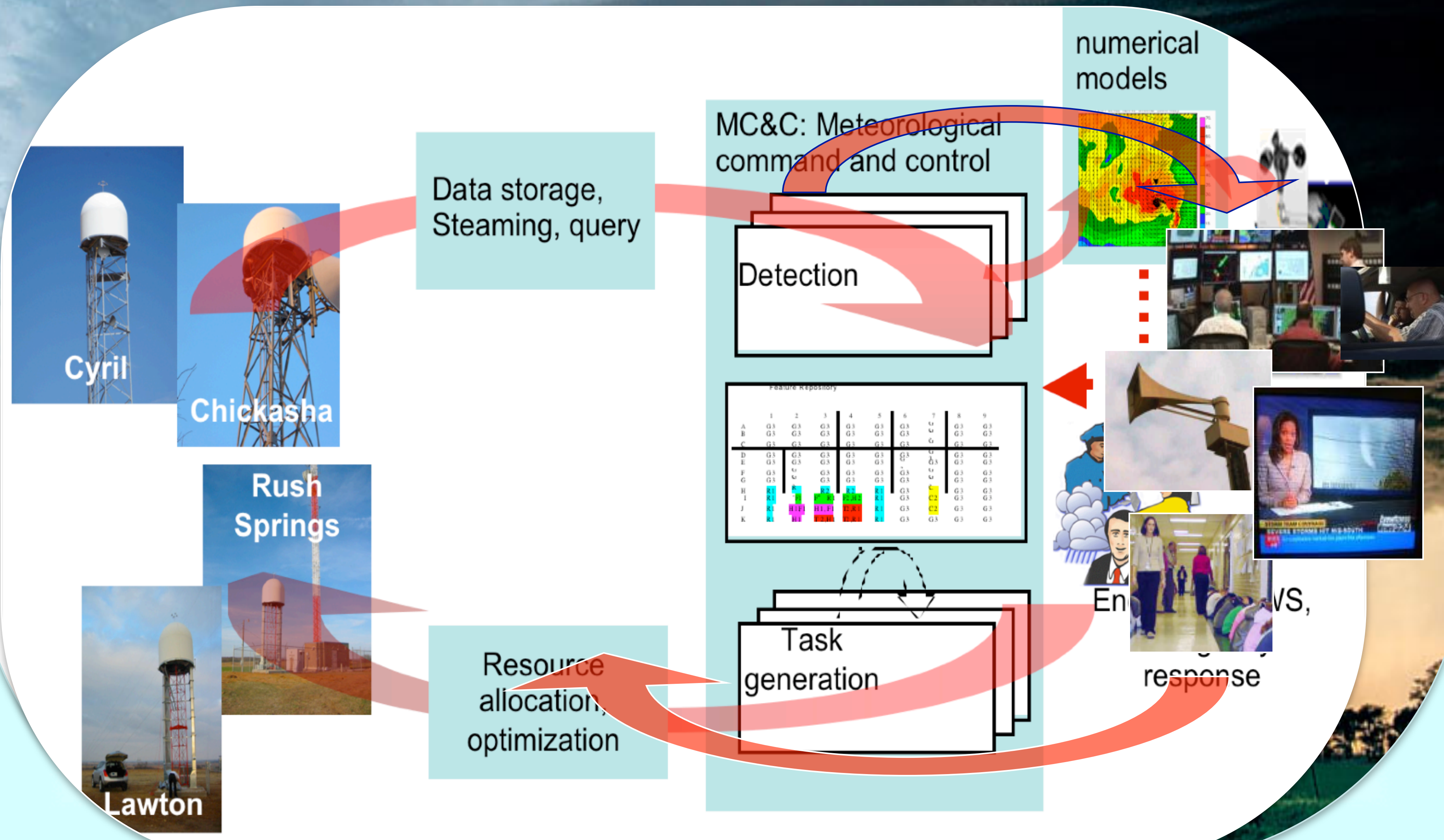
Tornado Path as Observed by IP1 Radars

350 m above ground

X axis: 10 km
Y axis: 14 km



How can we optimize system operation for the best response?



Urban Challenge -1

- Since 2009 more than half the world lives in urban regions.
- Small area to cover (relatively) , but biggest impact on population covered
- Water economics a big problem for large cities
- Emergency management
- Costal discharge regulations during flood conditions
- Complex terrain and vulnerability

Urban Challenge-2

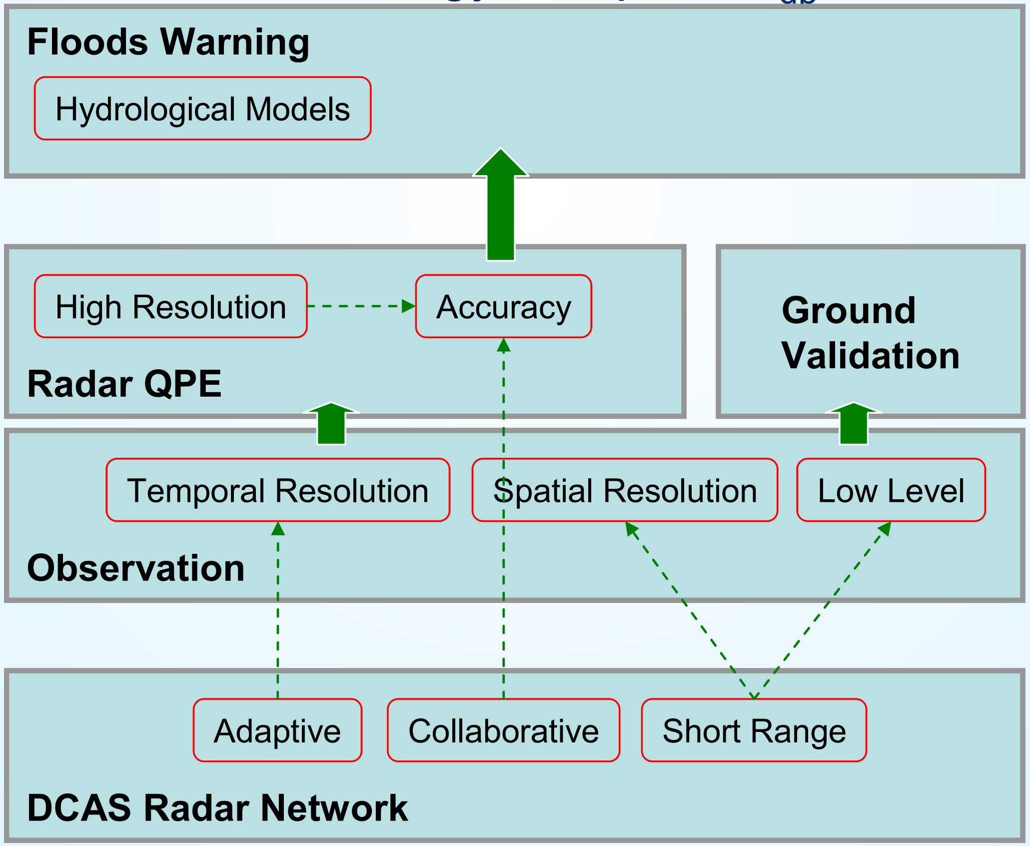
- High spatiotemporal observations are required in order to capture and monitor the highly localized, rapidly evolving rainfall events.

- High resolution hydrologic models have been developed for urban environments, which demand to be driven with high resolution QPE products.

- Urbanization significantly magnifies the scale and impact of floods. Both the spatial resolution and temporal resolution are critically important in monitoring urban floods and flash floods.

QPE Sensing Aspects in a network

- Spatial resolution: mean cross-range resolution ~ 500 m
- Temporal resolution: DCAS closed-loop scan @ 1 min update
- Beam height: < 1 km; advanced clutter suppression filter
- Dual-polarization technology: adaptive K_{dp} estimation

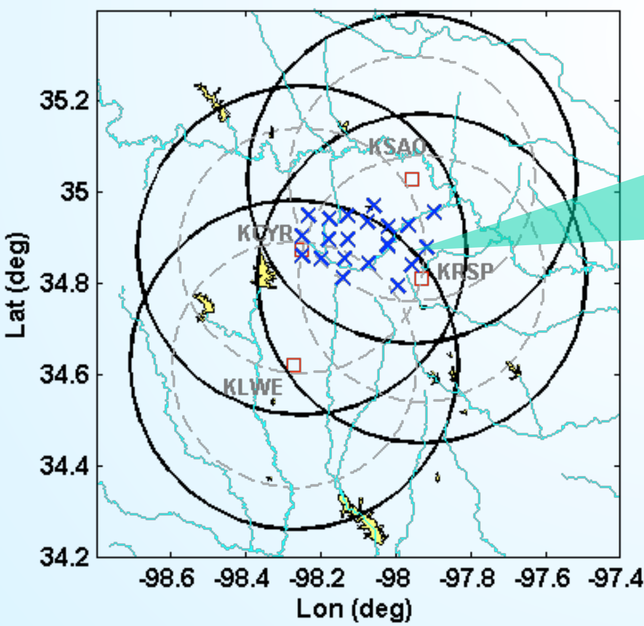


QPE Algorithm: Adaptive K_{dp}

- K_{dp}, as the derivative of Φ_{dp} , can be very noisy.
- Adaptive estimation:
  - Estimate over longer spatial scales in light rain region
  - Estimate over shorter spatial scale in heavy rain region
- Network Advantage: The data volume from radar differs on different propagation path, mainly depending on the cross-beam gradients.
- Network Composition: "Favorable" K_{dp} is chosen according to the quality metric of K_{dp} estimation.

Validation Study

- Gauge comparison was investigated to evaluate the QPE system
- USDA ARS Micronet – A rain gauge network located at the center of the IP1 test bed



Source: http://ars.mesonet.org

Little Washita

Watershed size: 611 km^2
Mean annual precipitation: 760 mm
Gauge network: 20 tip-bucket stations

SAMPLE PRODUCTS AND PERFORMANCE EVALUATION RESULTS

Real-time rainfall products

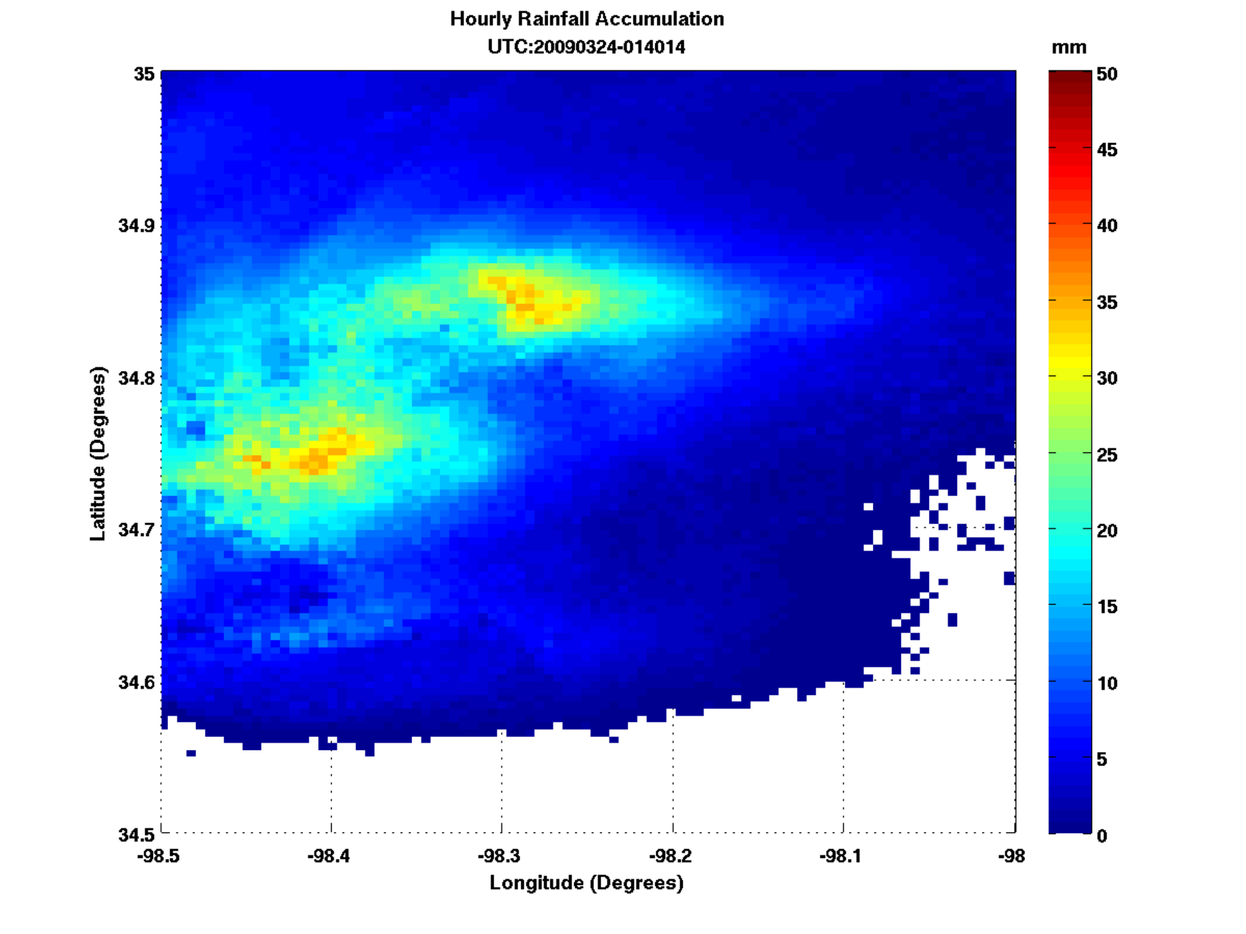
The rainfall products of QPE system include:

- the instantaneous rainfall maps
- hourly rainfall accumulation maps
- Point-wise line traces for diagnostic purposes for comparison against gauges
- Evaluation Scores for 5-, 10-, 15-, 20-, 30-min rainfall estimation

Following are sample products from QPE system.

SAMPLE PRODUCTS AND PERFORMANCE EVALUATION RESULTS (CONT.)

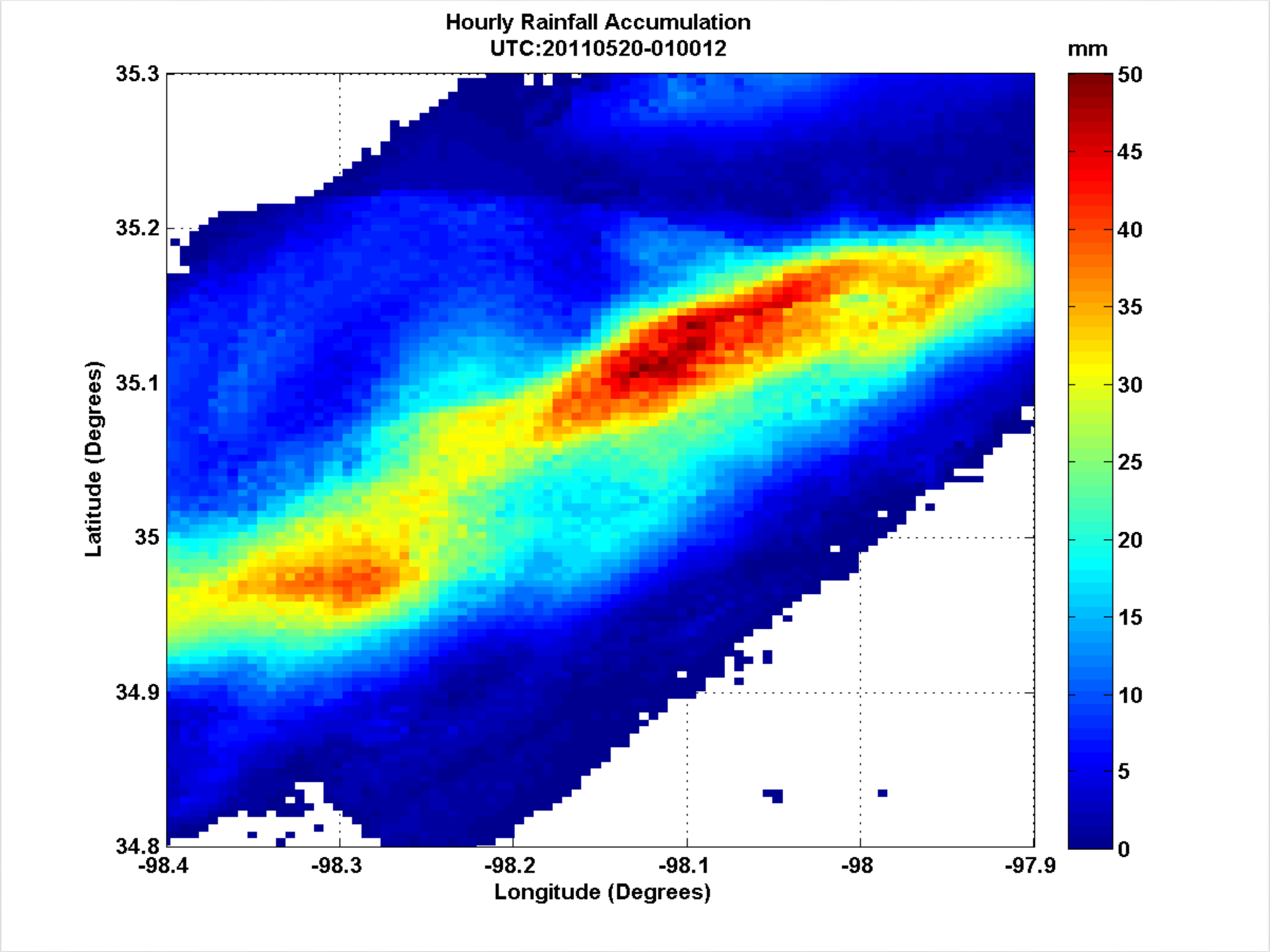
Sample Products: Hourly Rainfall Map



Regional hourly-rainfall map of the storm event on March 24, 2009

SAMPLE PRODUCTS AND PERFORMANCE EVALUATION RESULTS (CONT.)

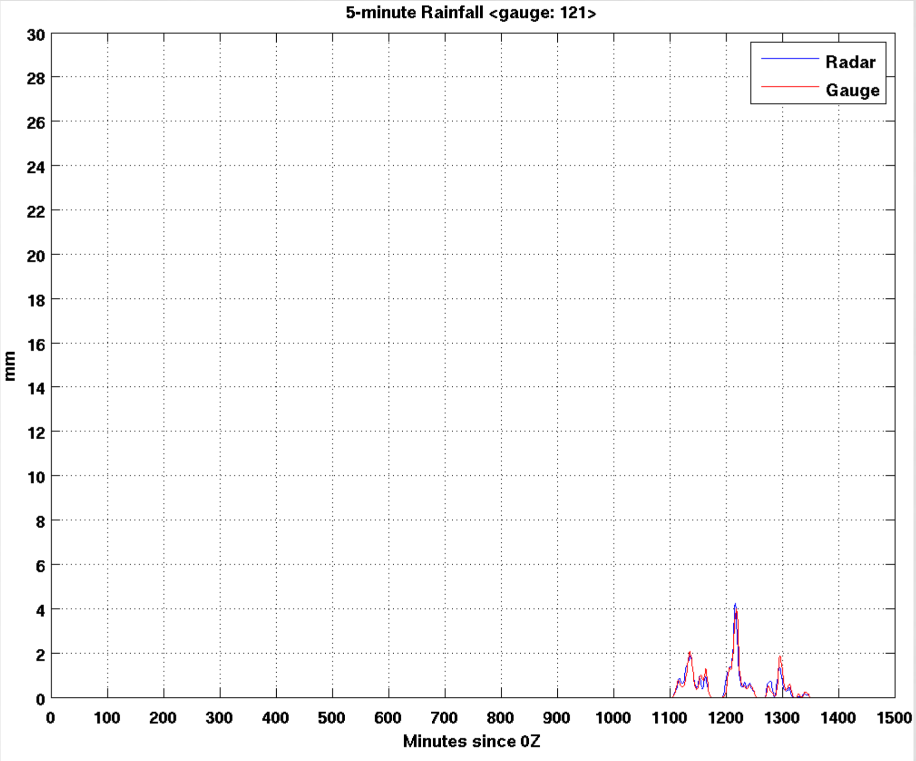
Sample Products: Hourly Rainfall Map---just another case

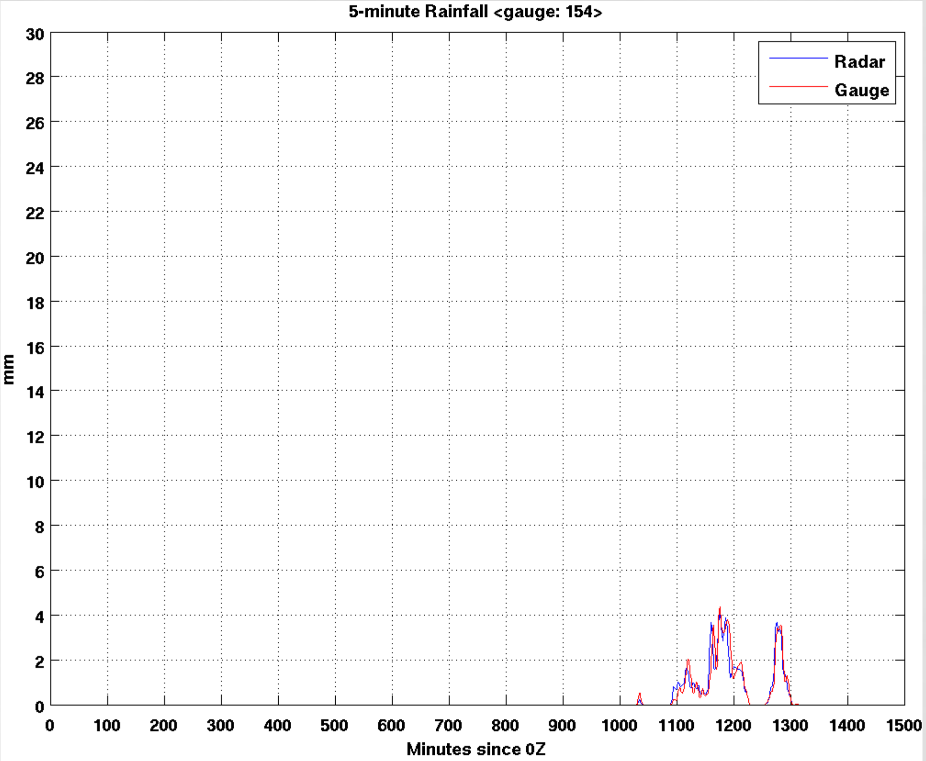


Regional hourly-rainfall map of the storm event on May 20, 2011

SAMPLE PRODUCTS AND PERFORMANCE EVALUATION RESULTS (CONT.)

Sample Products: Point-wise line traces for 5-min rainfall



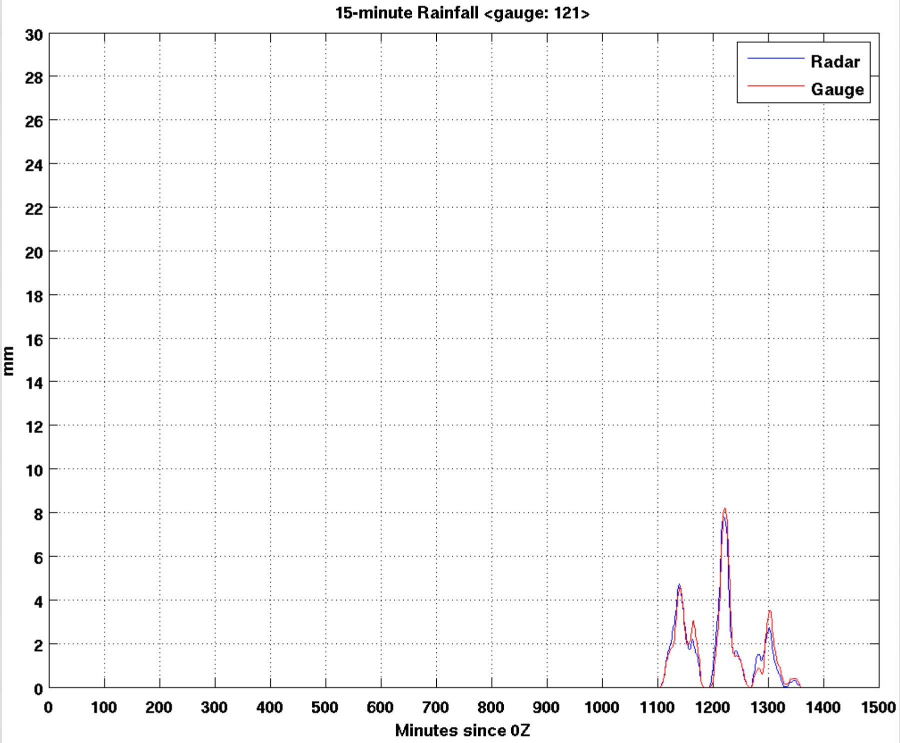


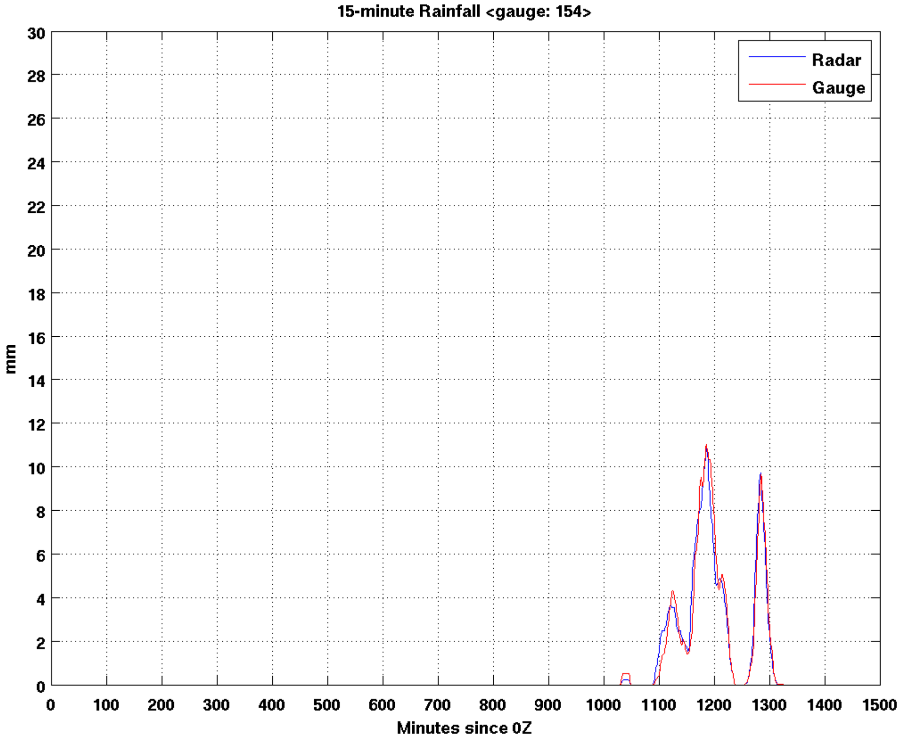
(a) *(b)*

5-minute *rainfall point wise trace against gauges of June 14, 2010 event*
(a) at the location of gauge 121 (Latitude: 34.9586, Longitude: -97.8986)
(b) at the location of gauge 154 (Latitude: 34.8553, Longitude: -98.1369)

SAMPLE PRODUCTS AND PERFORMANCE EVALUATION RESULTS (CONT.)

Sample Products: Point-wise line traces for 15-min rainfall



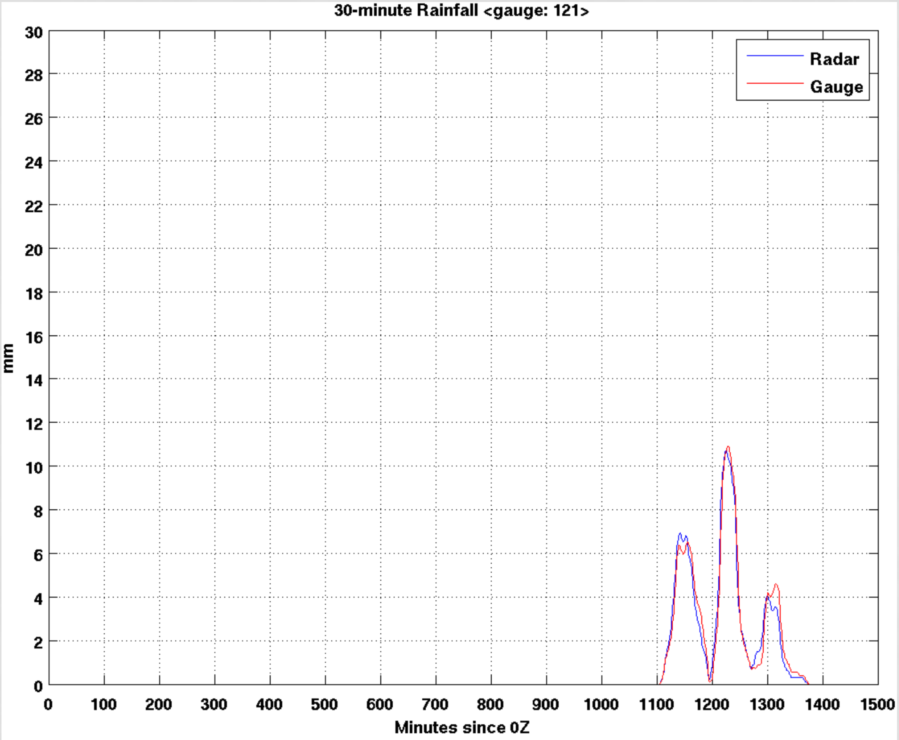


(a) *(b)*

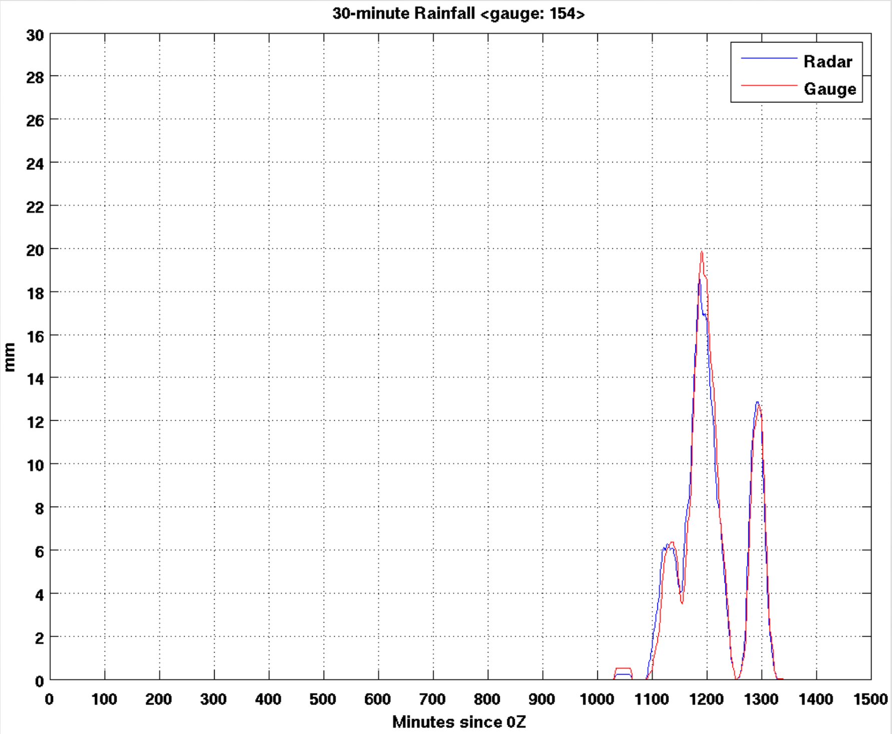
15-minute *rainfall point wise trace against gauges of June 14, 2010 event*
(a) at the location of gauge 121 (Latitude: 34.9586, Longitude: -97.8986)
(b) at the location of gauge 154 (Latitude: 34.8553, Longitude: -98.1369)

SAMPLE PRODUCTS AND PERFORMANCE EVALUATION RESULTS (CONT.)

Sample Products: Point-wise line traces for 30-min rainfall



(a)



(b)

***30-minute** rainfall point wise trace against gauges of June 14, 2010 event*
(a) at the location of gauge 121 (Latitude: 34.9586, Longitude: -97.8986)
(b) at the location of gauge 154 (Latitude: 34.8553, Longitude: -98.1369)

SAMPLE PRODUCTS AND PERFORMANCE EVALUATION RESULTS (CONT.)

Evaluation Results

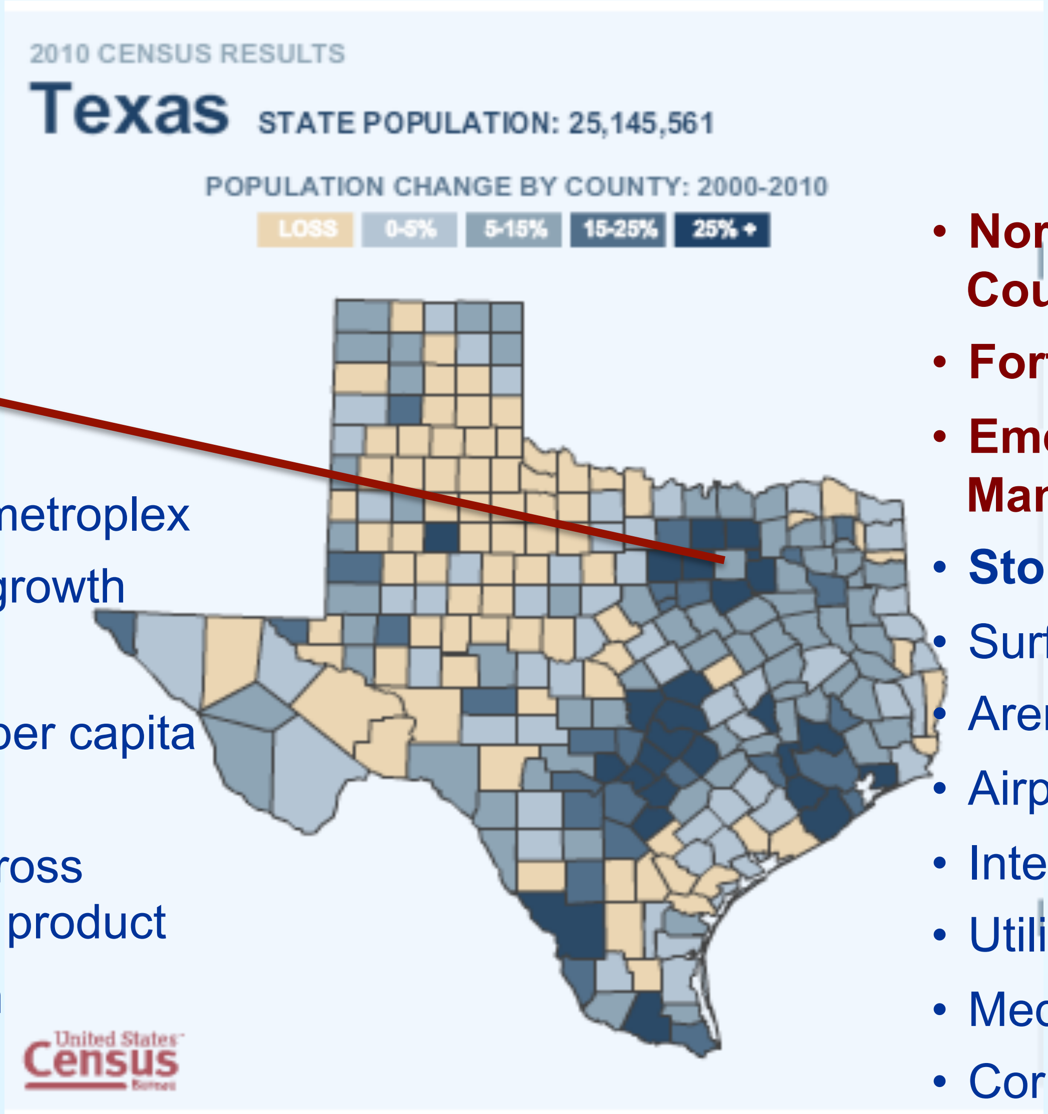
20 precipitation events passing over the Little Washita gauge network during past 3 years (2009-2011) are analyzed and evaluation metrics are computed as follows,

Rainfall Product	NSE
Instantaneous Rainfall Rate	47%
5-minute Rainfall Estimates	39%
10-minute Rainfall Estimates	34%
15-minute Rainfall Estimates	31%
20-minute Rainfall Estimates	30%
30-minute Rainfall Estimates	27%
60-minute Rainfall Estimates	23 %

DFW: A Vibrant, Growing Metroplex

6.3 million people

- 4th largest metroplex
- Population growth 25%+
- 2nd highest per capita lane miles
- 6th largest gross metropolitan product
- 33,000 sqkm

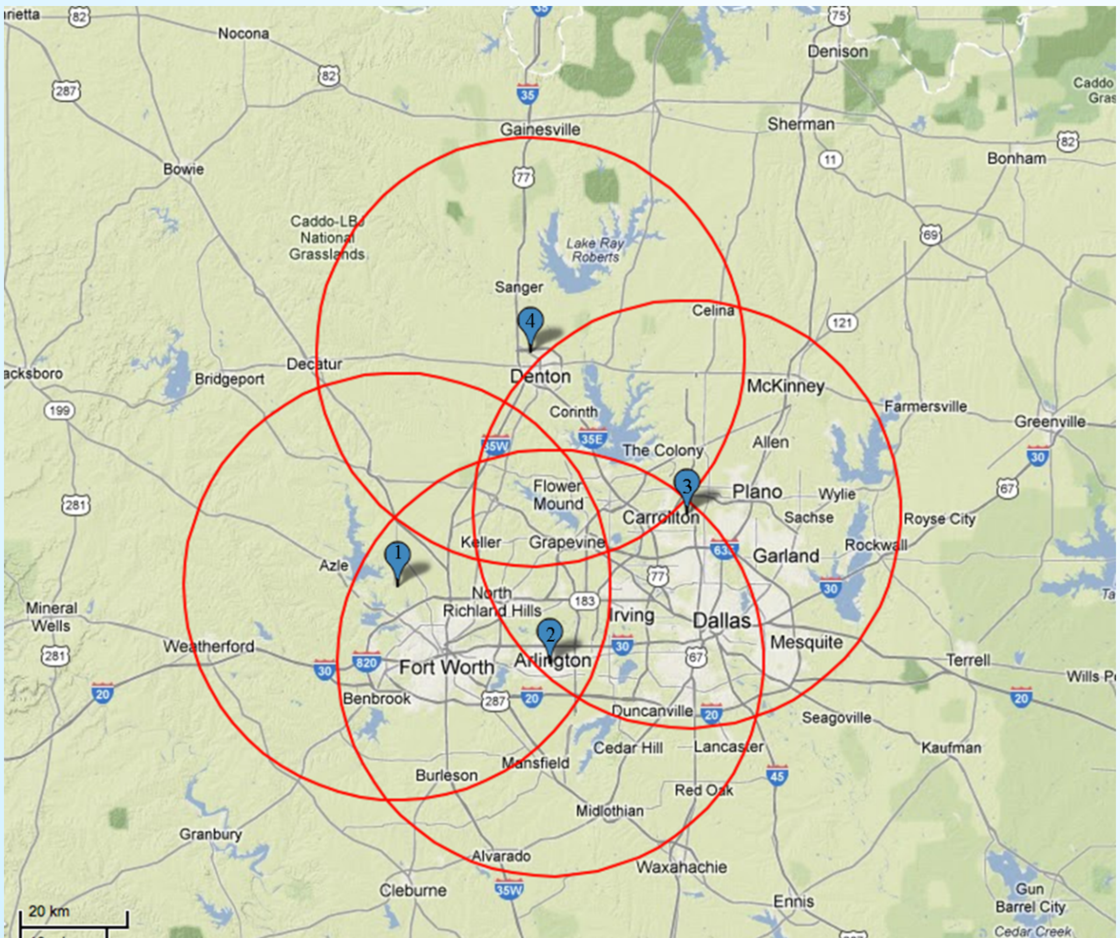


- **North Central Texas Council of Governments**
- **Fort Worth WFO**
- **Emergency Management**
- **Storm water managers**
- Surface transportation
- Arena Events
- Airports
- Interior Port (Ft. Worth
- Utilities
- Media
- Corporate HQ's

Urban Test Beds

- CASA end-to-end benefits in a densely populated urban environment
- Hazards: urban flash floods, hail, ice, high winds, tornadoes.
- Networks-of-Networks: CASA radars in heterogeneous sensor networks: architecture, products, forecaster decision making
- Model for local, private, federal participation and ownership of urban radar networks.
- Platform for collaboration among CASA researchers and industry partners.

Dallas-Fort Worth Urban Demonstration Network



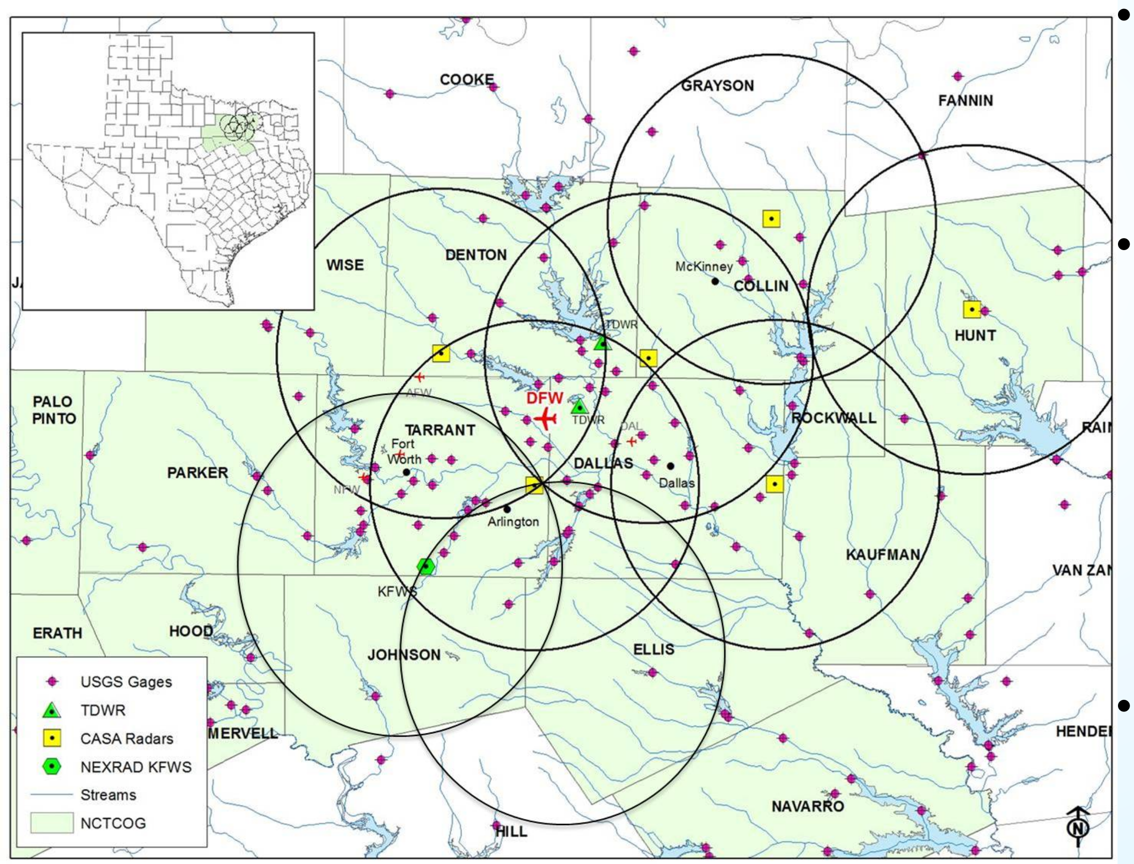
layout of initial 4 radars (they were CASA IP1 radars)

Research activities:

- Urban flash flood and hydrology sensing
- Hydrometeor identification
- Low level wind sensing
- Network of Networks demonstration
- Forecast, decision making and impacts

etc…

Dallas-Fort Worth Urban Demonstration Network

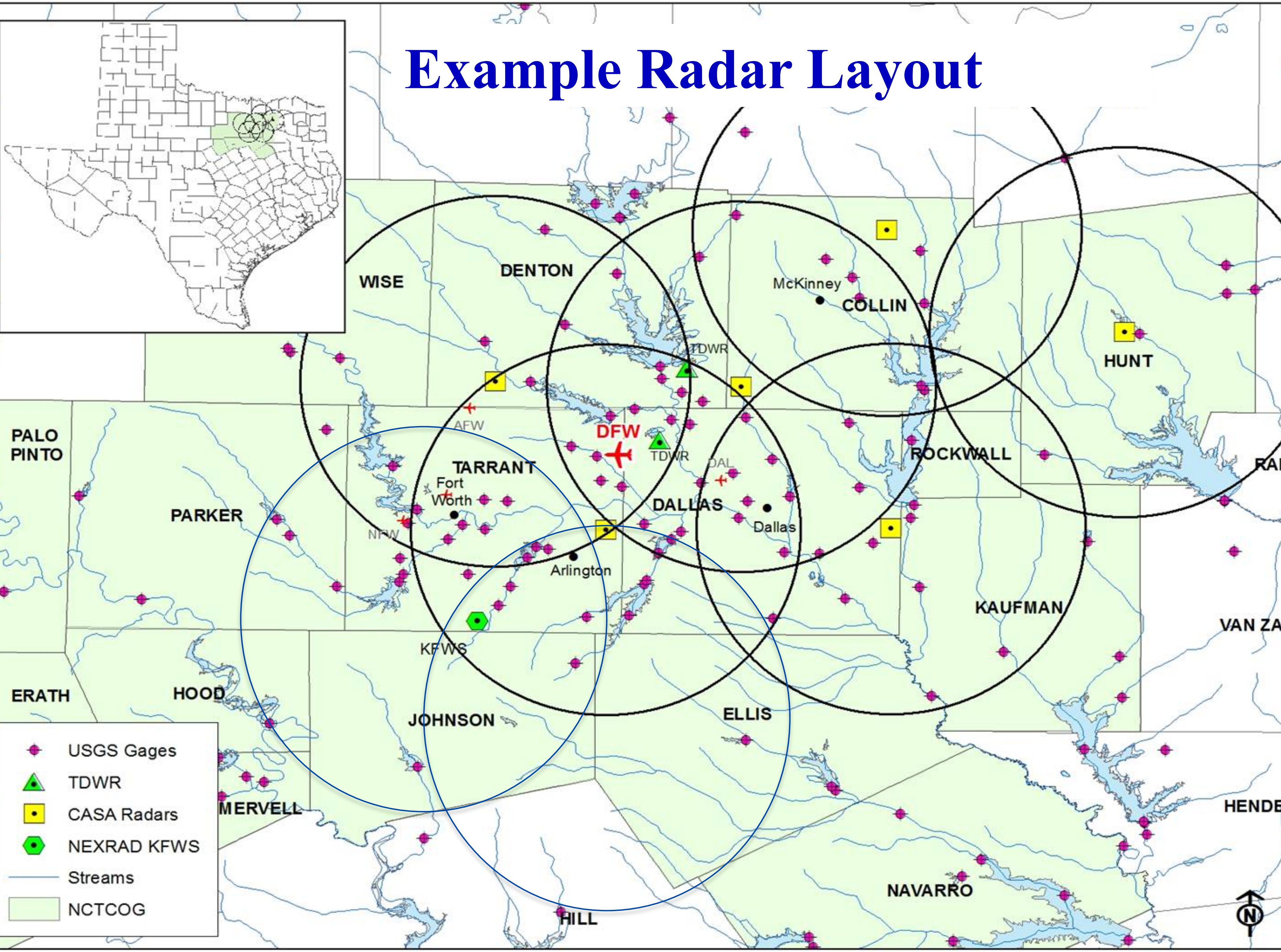


Tentative layout of 8 X-band radars in DFW area

Goals:

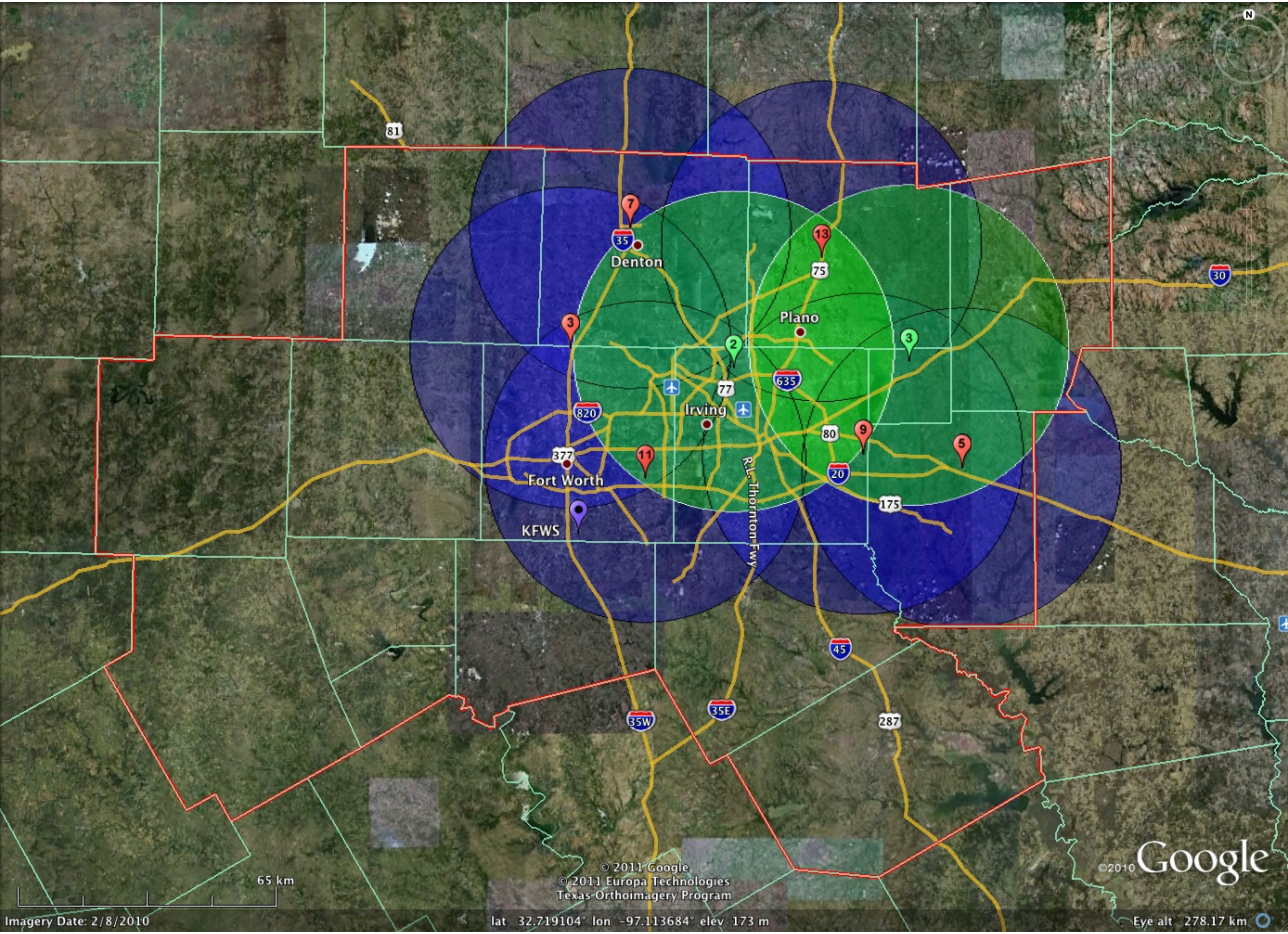
- To demonstrate the value of DCAS X-band radar networks in Urban environment.
- To provide warnings and forecasts for a range of public and private decision-makers that result in measureable benefit for public safety and the economy. Urban flash flood and hydrology sensing
- Hydrometeor identification
  Low level wind sensing

Example Radar Layout

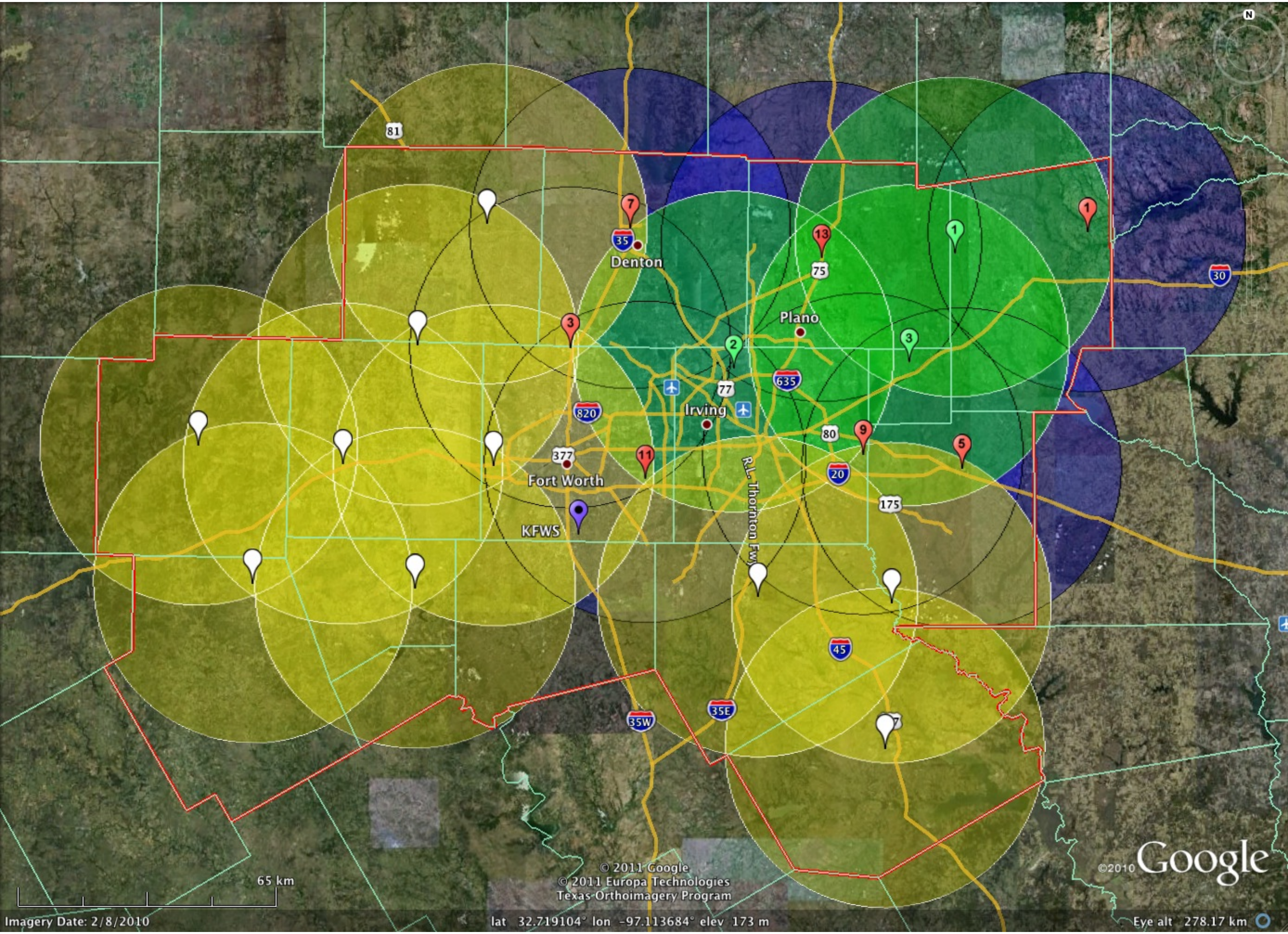


Benefits of CASA for Urban Severe Weather Warning

- Users of data Emergency Managers, Forecasters are integral to the development of the system.
- Neighborhood-scale data…How decisions are made in Emergency Management
  - Fined scale data
  - Low to the ground
- Can we decrease warning sizes and reduce false alarms?



Denton
Plano
Irving
Fort Worth
KFWS
R.L. Thornton Fwy
81
35
75
635
77
820
377
80
20
175
30
45
35W
35E
287
7
13
3
2
3
11
9
5
65 km
© 2011 Google
© 2011 Europa Technologies
Texas Orthoimagery Program
©2010 Google
Imagery Date: 2/8/2010
lat 32.719104° lon -97.113684° elev 173 m
Eye alt 278.17 km



Denton
Plano
Irving
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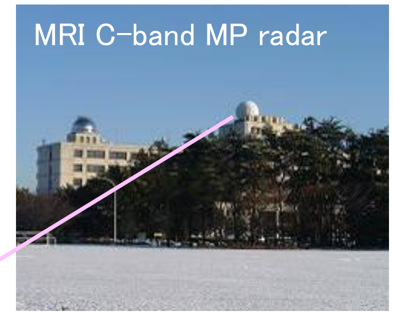
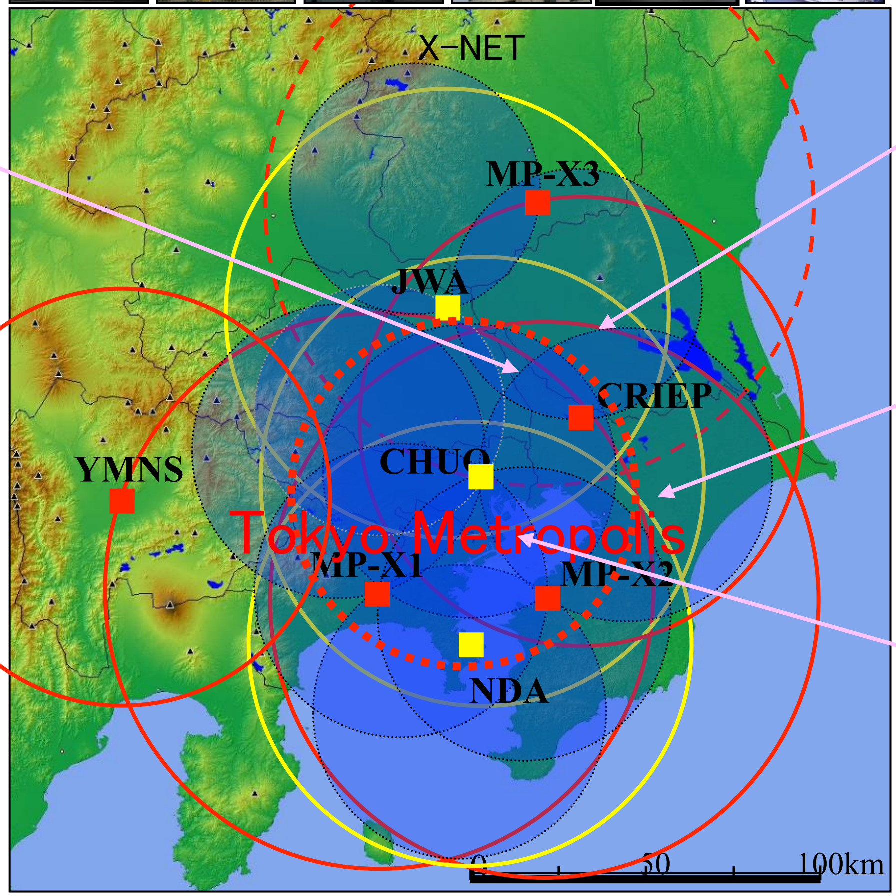
R.L. Thornton Fwy
© 2011 Google
© 2011 Europa Technologies
Texas Orthoimagery Program
65 km
Imagery Date: 2/8/2010
lat 32.719104° lon -97.113684° elev 173 m
Eye alt 278.17 km
©2010 Google

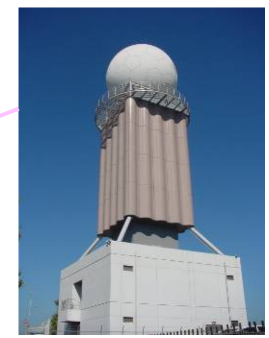
14 Doppler Radars

Research/operation weather radars concentrate in the Tokyo Metropolitan Area: X-NET(5 X-band MP radars and 3 Doppler radars), two X-band MP radars of River Bureau, MRI C-band MP radar and 3 JMA C-band operational Doppler radars.

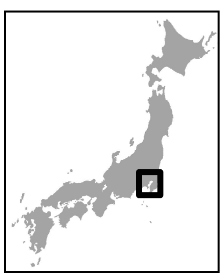


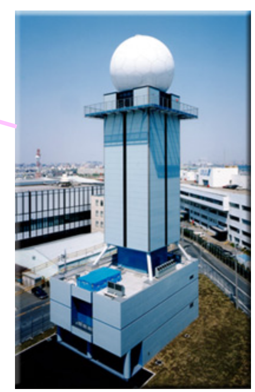
JMA Kashiwa C-band Doppler radar





JMA Narita Airport C-band Doppler radar



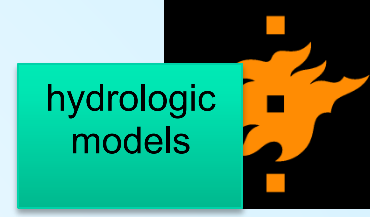


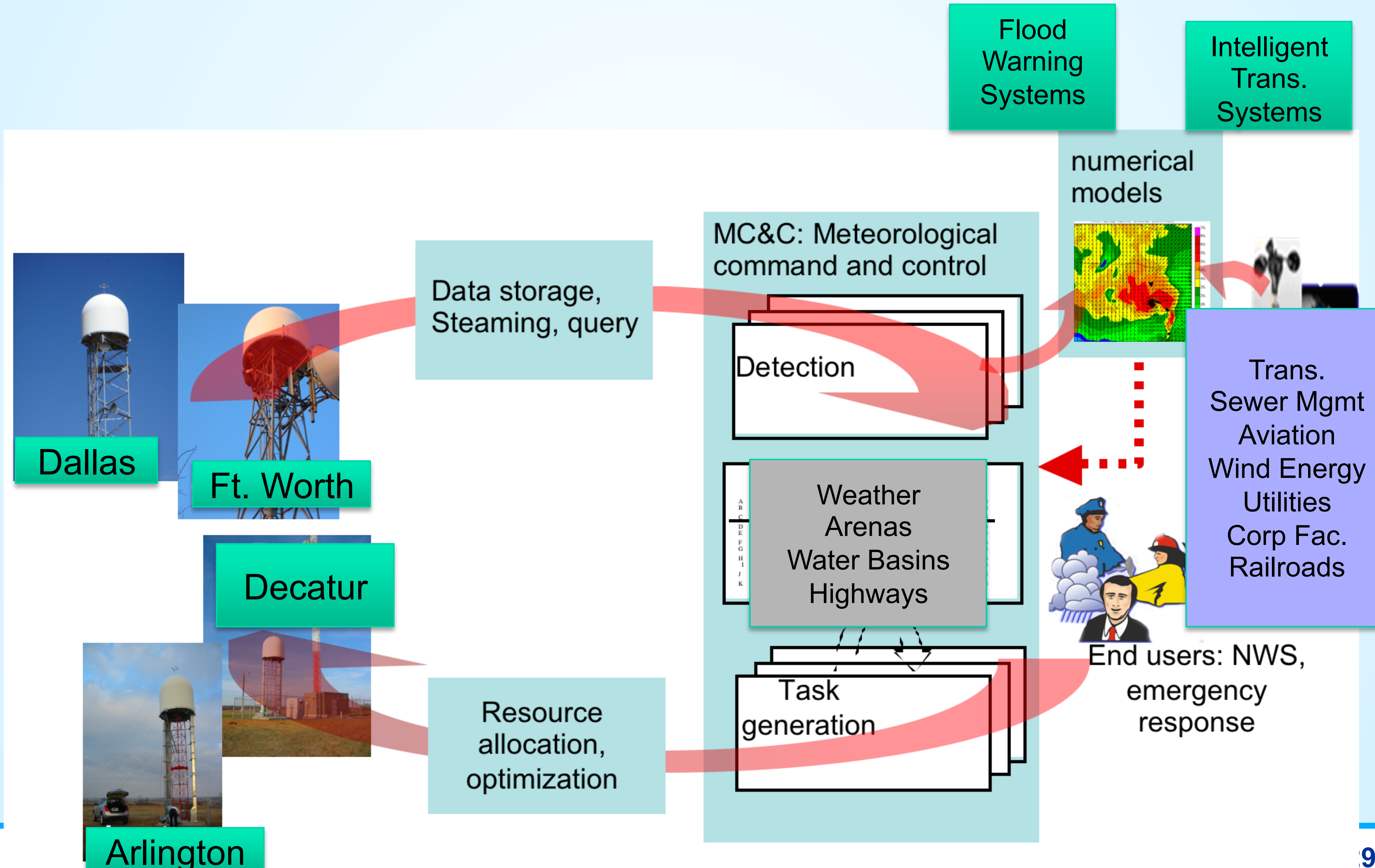
JMA Haneda Airport C-band Doppler radar

M. Maki of NIED and X-NET Group

Courtesy Dr Maki and Dr Shimizu

Urban Network
End-to-End Systems View





The urban networks are complex systems

- The urban network are a complex system of technology, environment, built infrastructure and the society.
- Smart urban systems should take the, “end to end system”, into consideration
- Now that the advantages of X band networks have been demonstrated we are starting to explore other frequency systems.

C band alternative

- There is a large C band network around the world that is already paid for.
- Can we build new networks for urban regions anchored around existing systems?
- C band is an excellent compromise between S and X.
- C band industry is mature and well developed.
- Can we reduce the number of radars by moving to C band and still be effective.

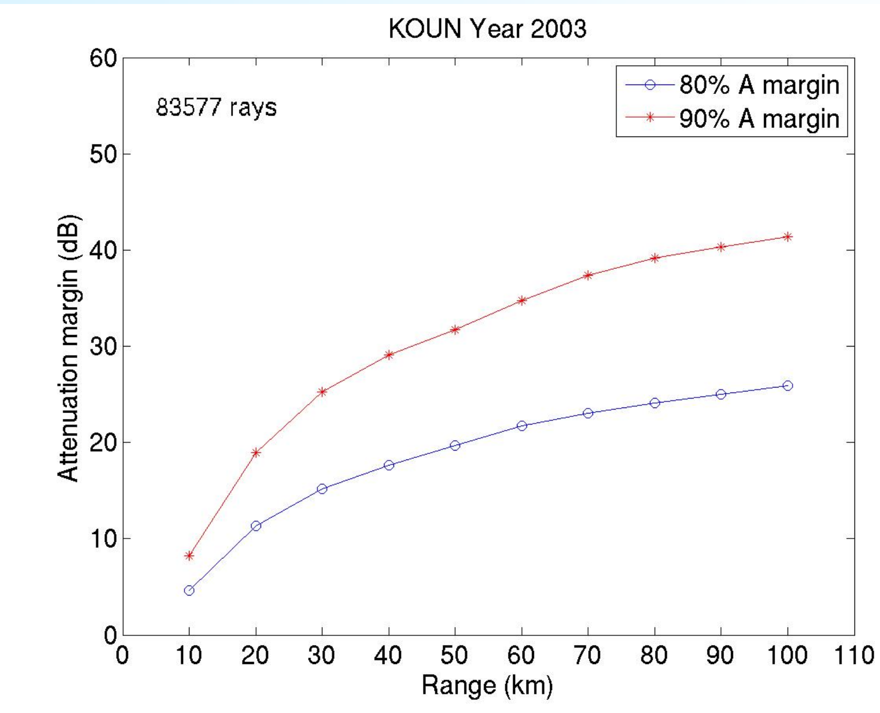
C-band collaborative radar networks Advantages and compromises

- Technology and installation issues…
- Attenuation – Directly scales with frequency
- Range velocity ambiguity
- Social foot print (C band fairly high, X band low –S band extremely high).
- Coverage to large Metro Regions – Megacities- Example Shanghai , Mumbai, Rio?
- Develop a C band collaborative adaptive demonstration network leveraging exiting assets.

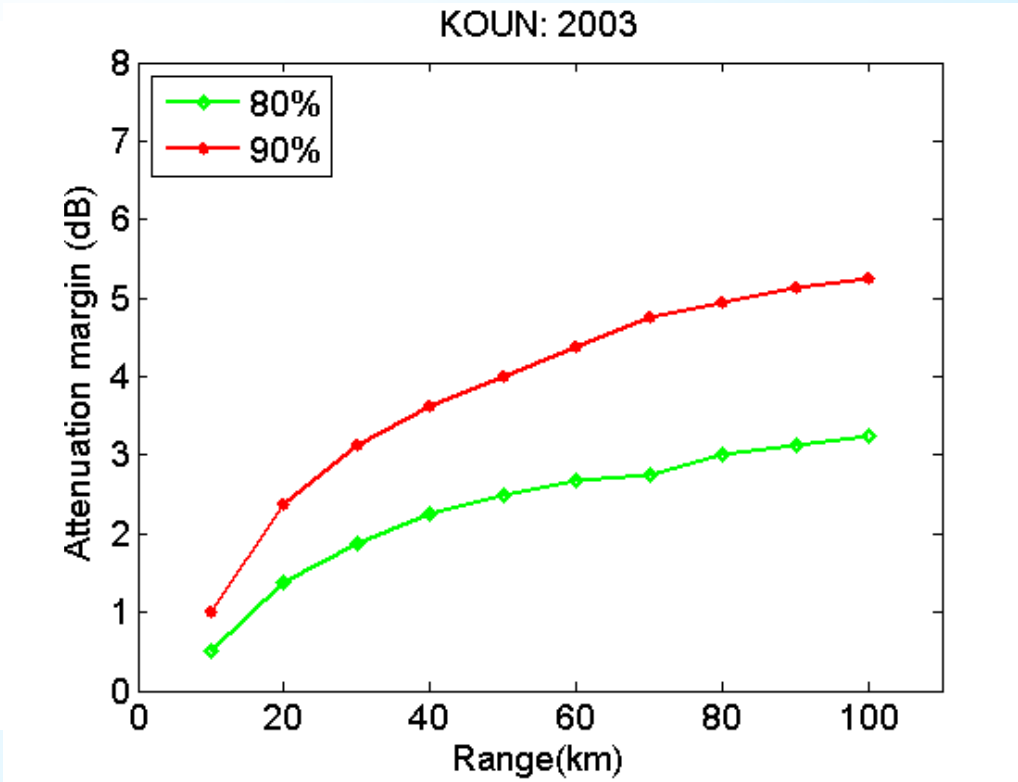
Impact of Attenuation

Statistics evaluated from CO/ Kansas and Oklahoma at X and C band for Spring Climatology

X band



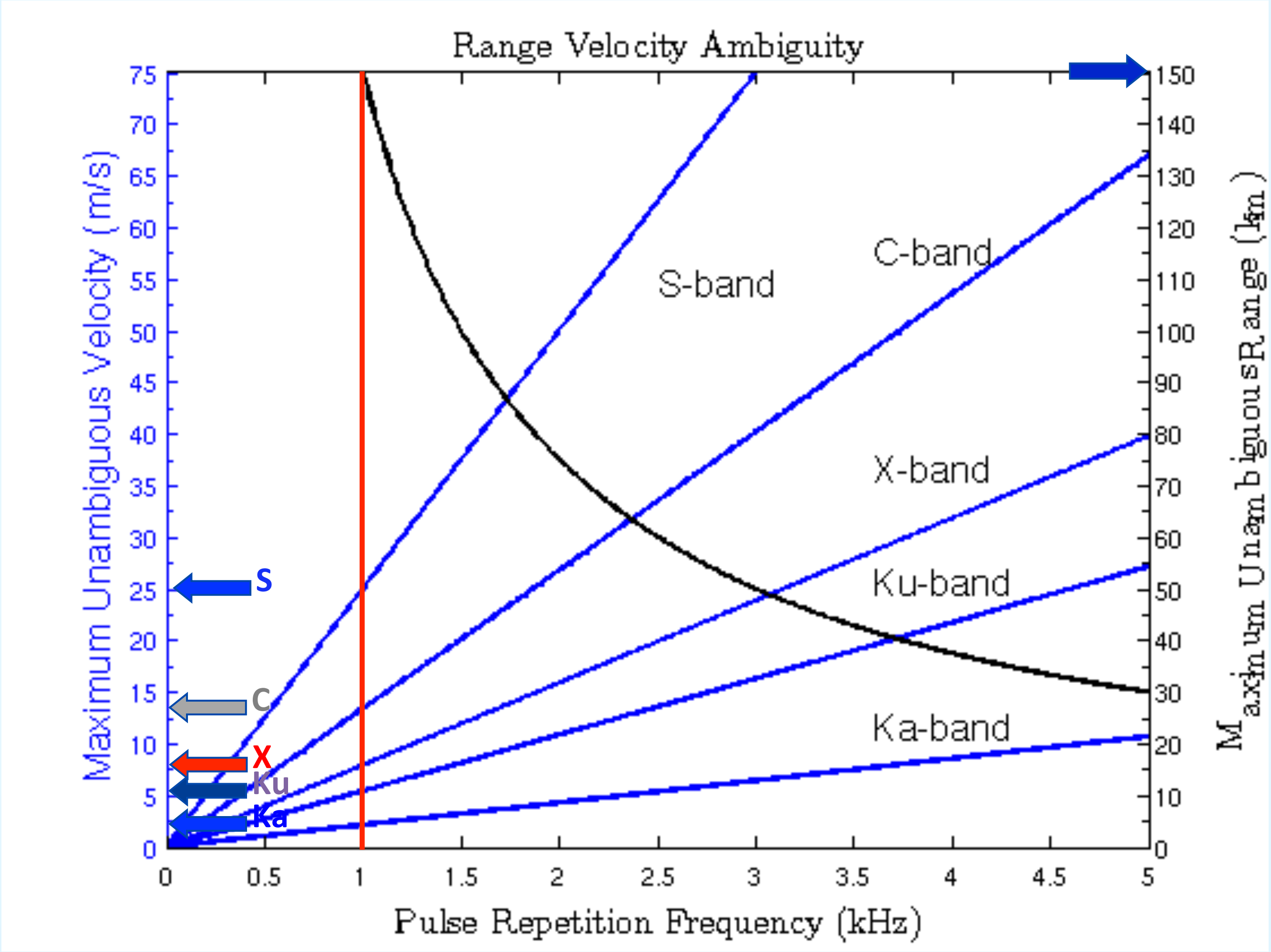
C band



Range/ Doppler Ambiguity

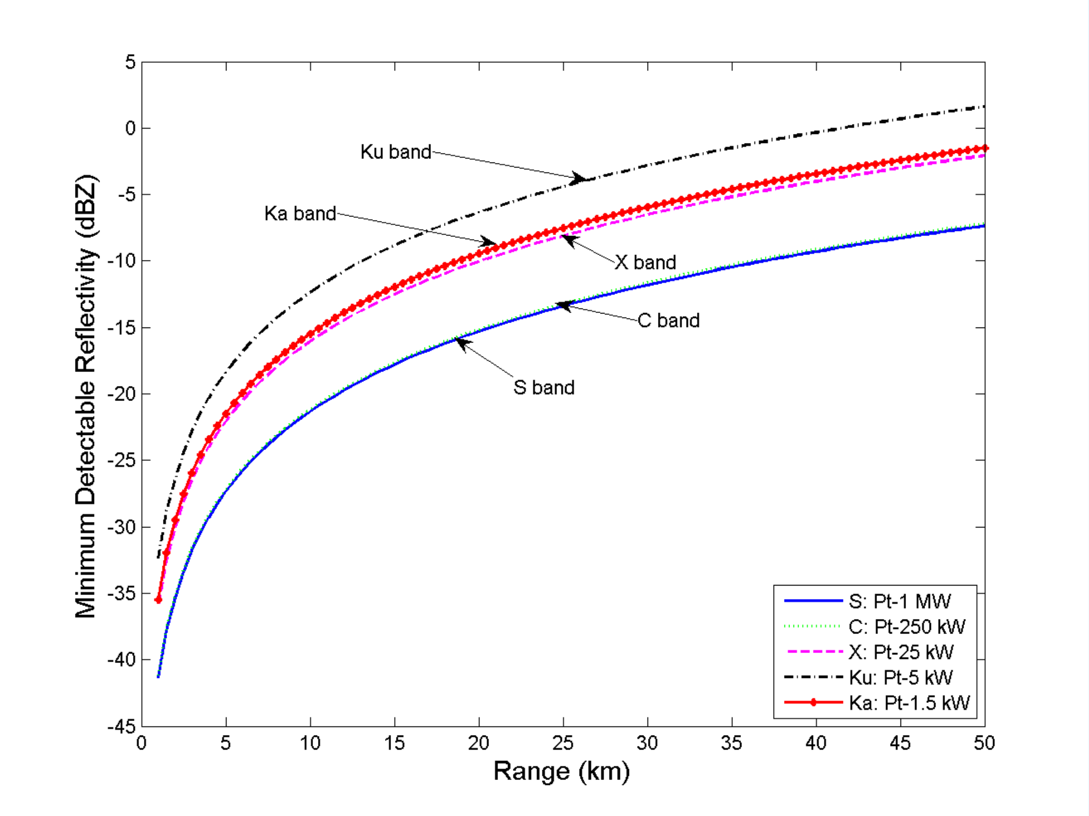
- Special Mitigation efforts are needed.
- Need similar technical solutions.
- Implications on signal processing

Range Velocity Ambiguity



- There is always a trade off between maximum unambiguous velocity and maximum unambiguous range

Statement on Minimum detectable signal



Beam Width: 1deg

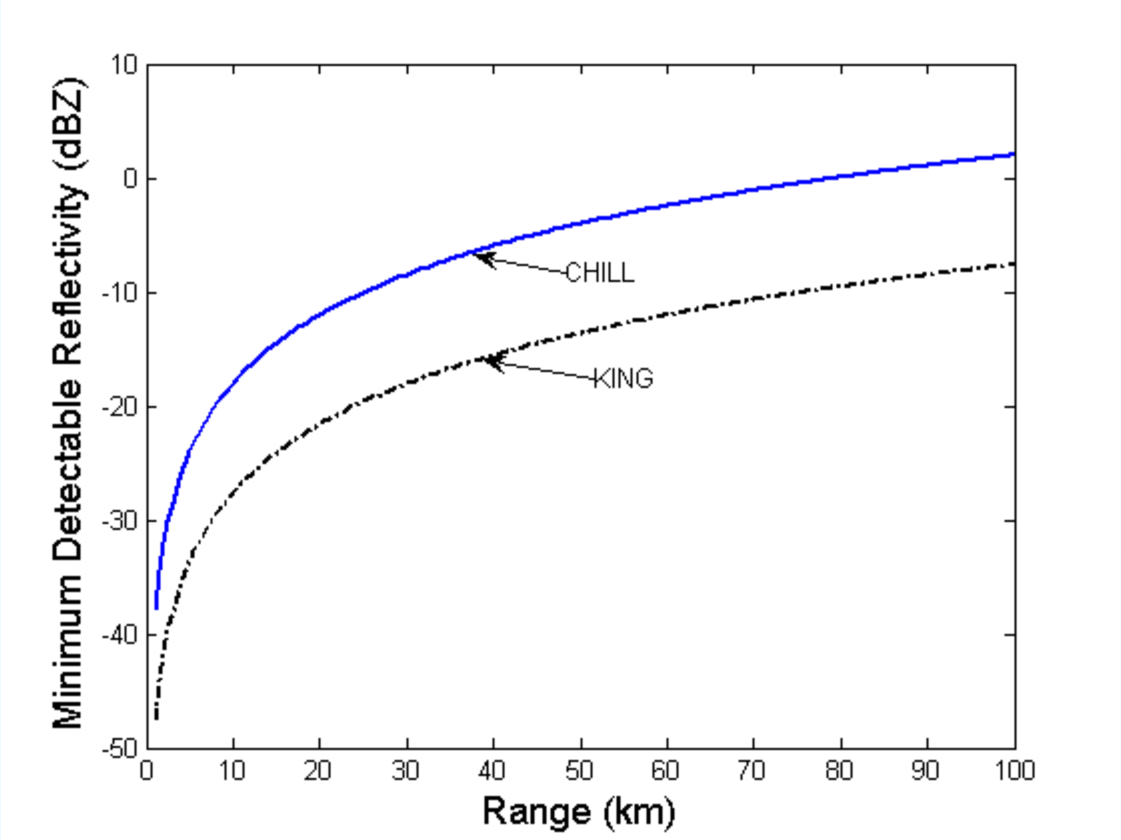
Range resolution: 100 m

Noise Floor: -110 dBm

$$\min(Z_e) = \frac{1}{\pi^5 |K_w|^2}\left(\frac{2}{cT_0}\right)\left[\frac{(4\pi)^3 l_{wg}^2}{P_t G_0^2}\right]\left(\frac{8\ln 2}{\pi\theta_1\phi_1}\right)\lambda^2 r_0^2 (kTB); \qquad \lambda = \frac{c}{f}$$

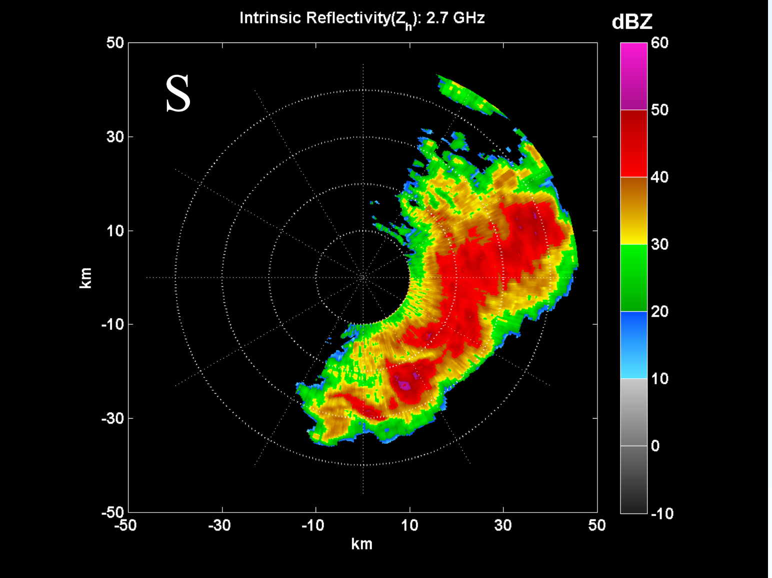
Minimum detectable reflectivity $\propto$ 1/(Transmit power, Frequency and antenna gain)

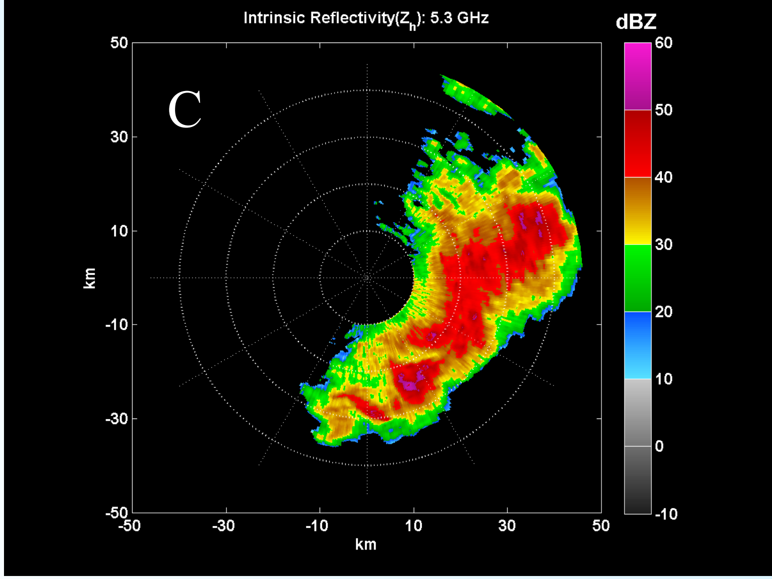
Design/Cost Impacts

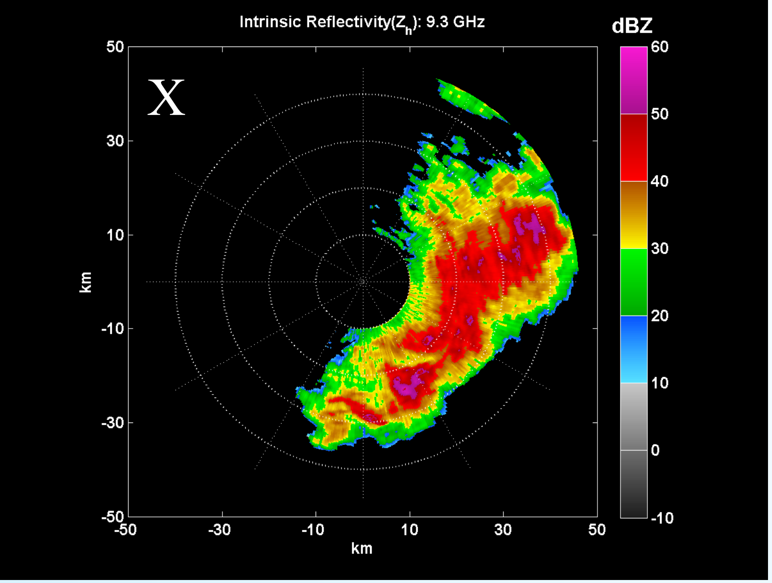


KING City – C band
Peak power: 250 kW,
Range resolution: 125m,
Antenna diameter: 6.1 m,
Gain: 49.2 dB,
Beam width: 0.62 deg,
Noise floor:-110 dBm
(assumed)
D/λ: 113.9

CHILL – S band
Peak power: 1 MW,
Range resolution: 150m,
Antenna diameter: 8.5 m,
Gain: 43 dB,
Beam width: 1.1 deg,
Noise floor:-113 dBm
D/λ: 77.3



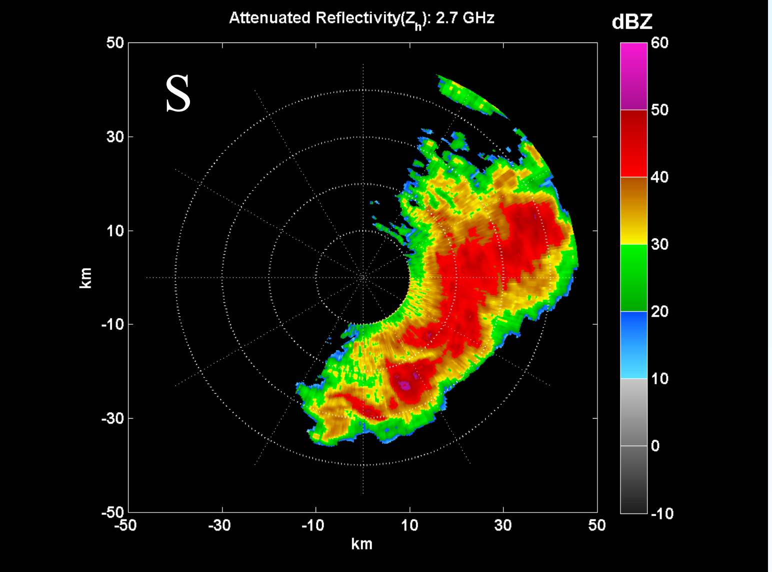


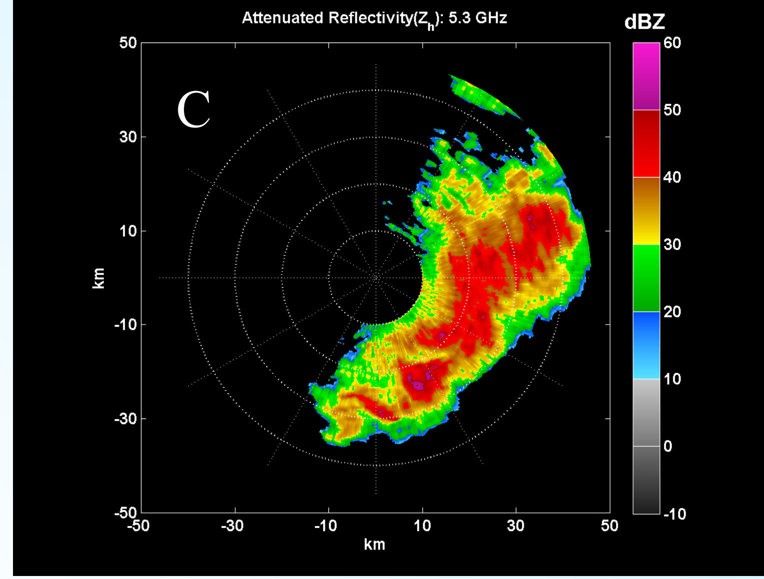


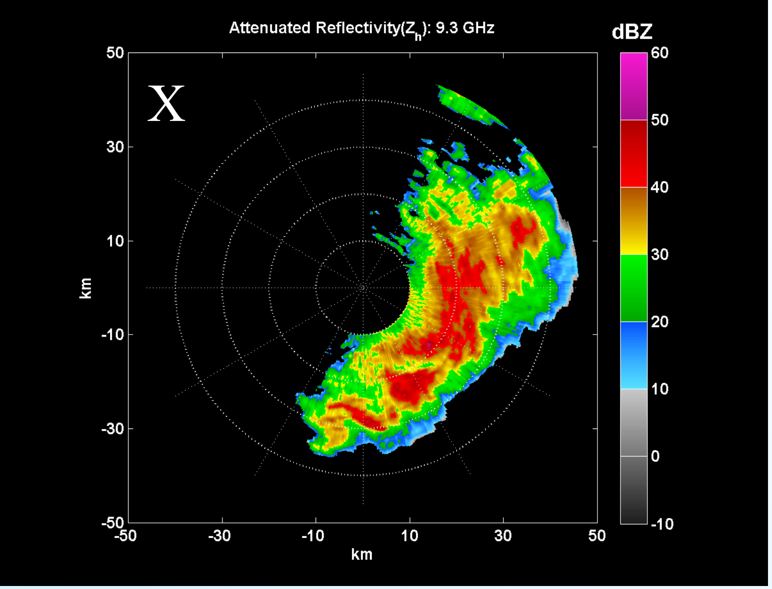
Ku

Ka

Intrinsic reflectivity: horizontal (Z_h: dBZ)



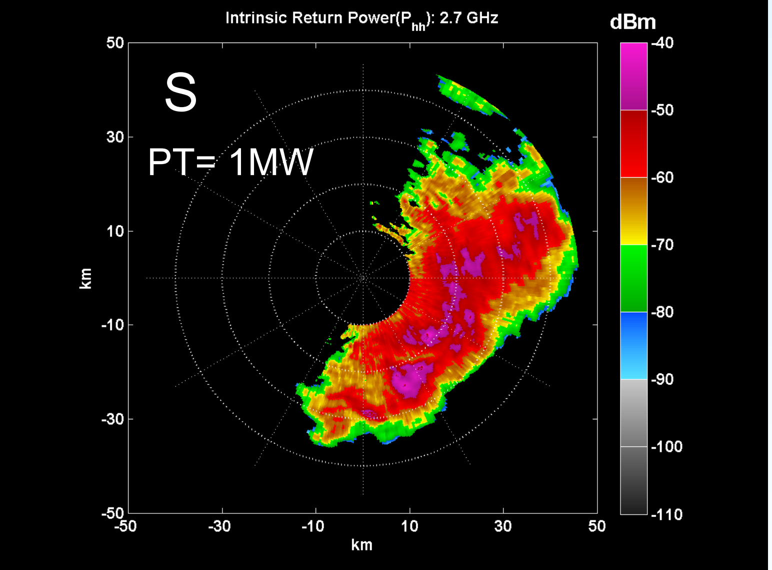


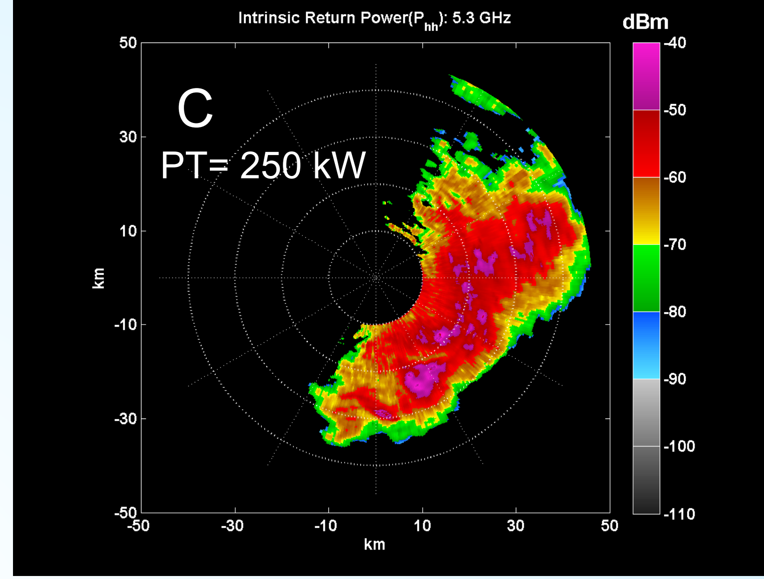


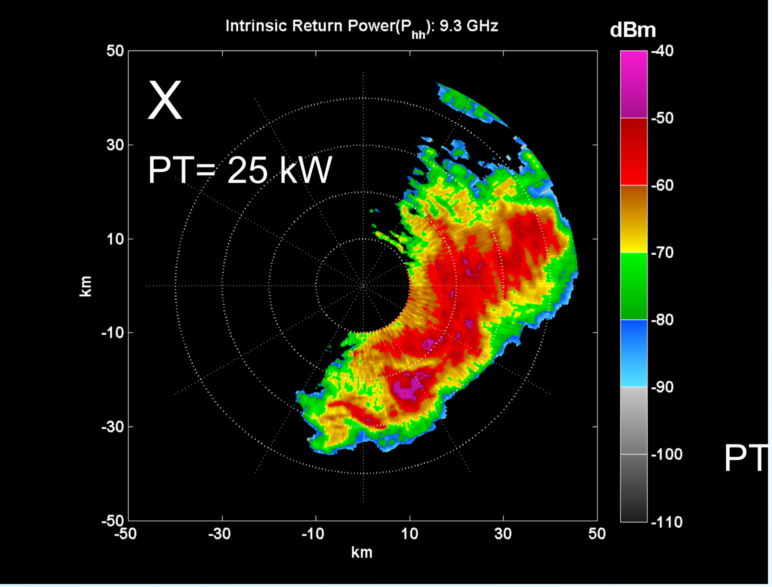
Ku

Ka

Attenuated reflectivity: horizontal (Z_h: dBZ)







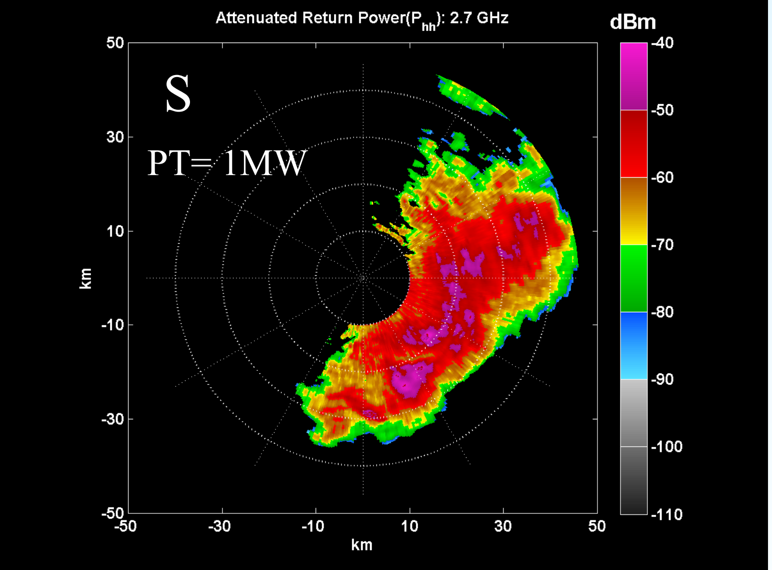
Ka

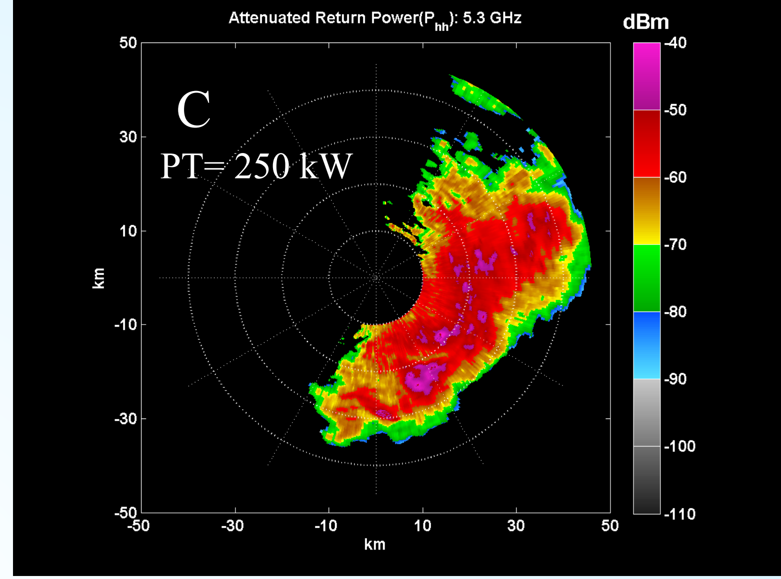
PT= 1.5 kW

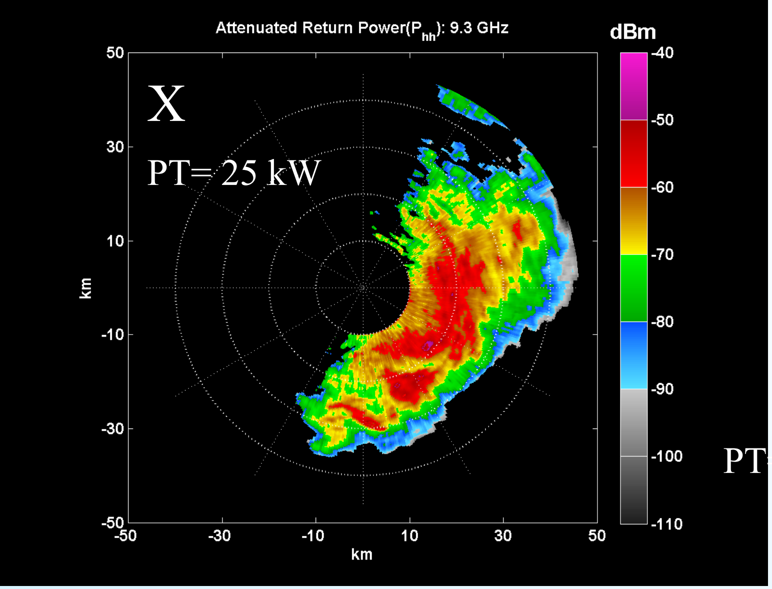
Intrinsic return power: horizontal (P_{hh}: dBm)

-Beam width: 1deg,

- Range resolution: 150m







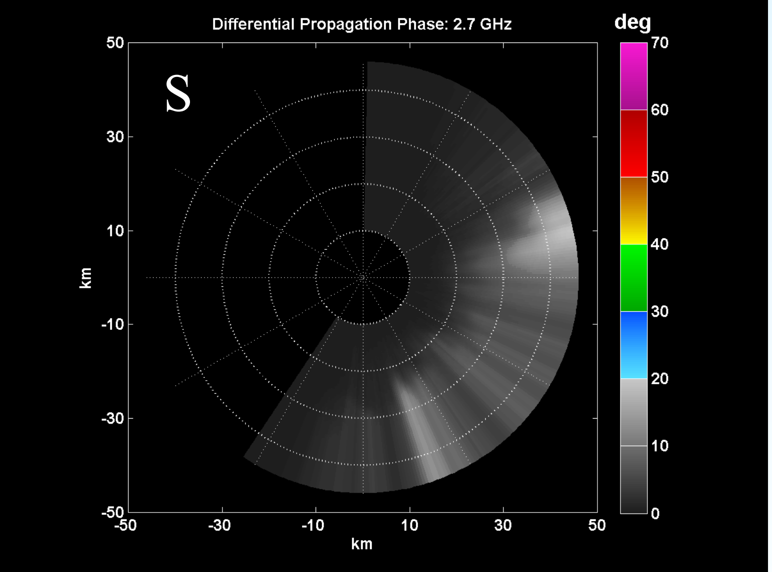
Ku

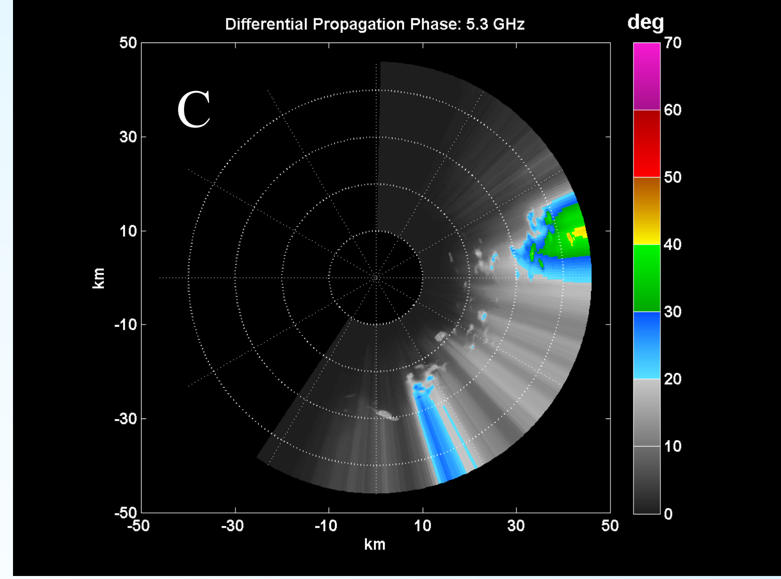
PT= 5 kW

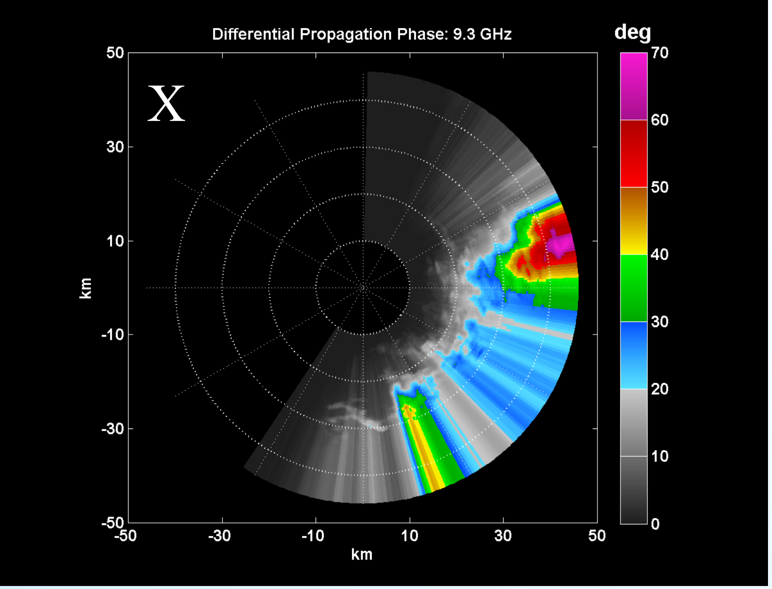
Ka

PT= 1.5 kW

Attenuated return power: horizontal (P_{hh}: dBm)



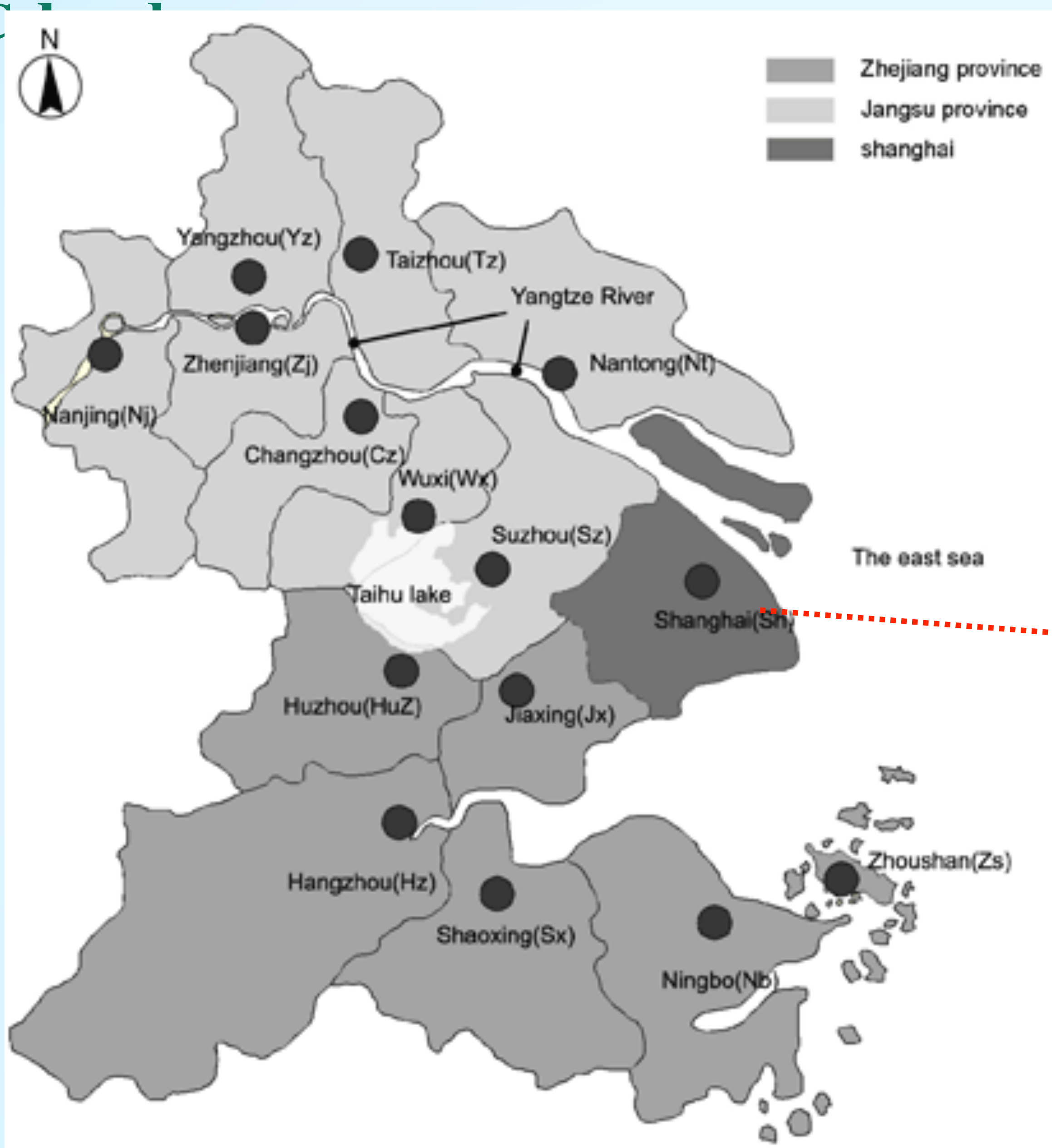




Differential Propagation Phase (degree). Higher numbers good for rainfall measurement.

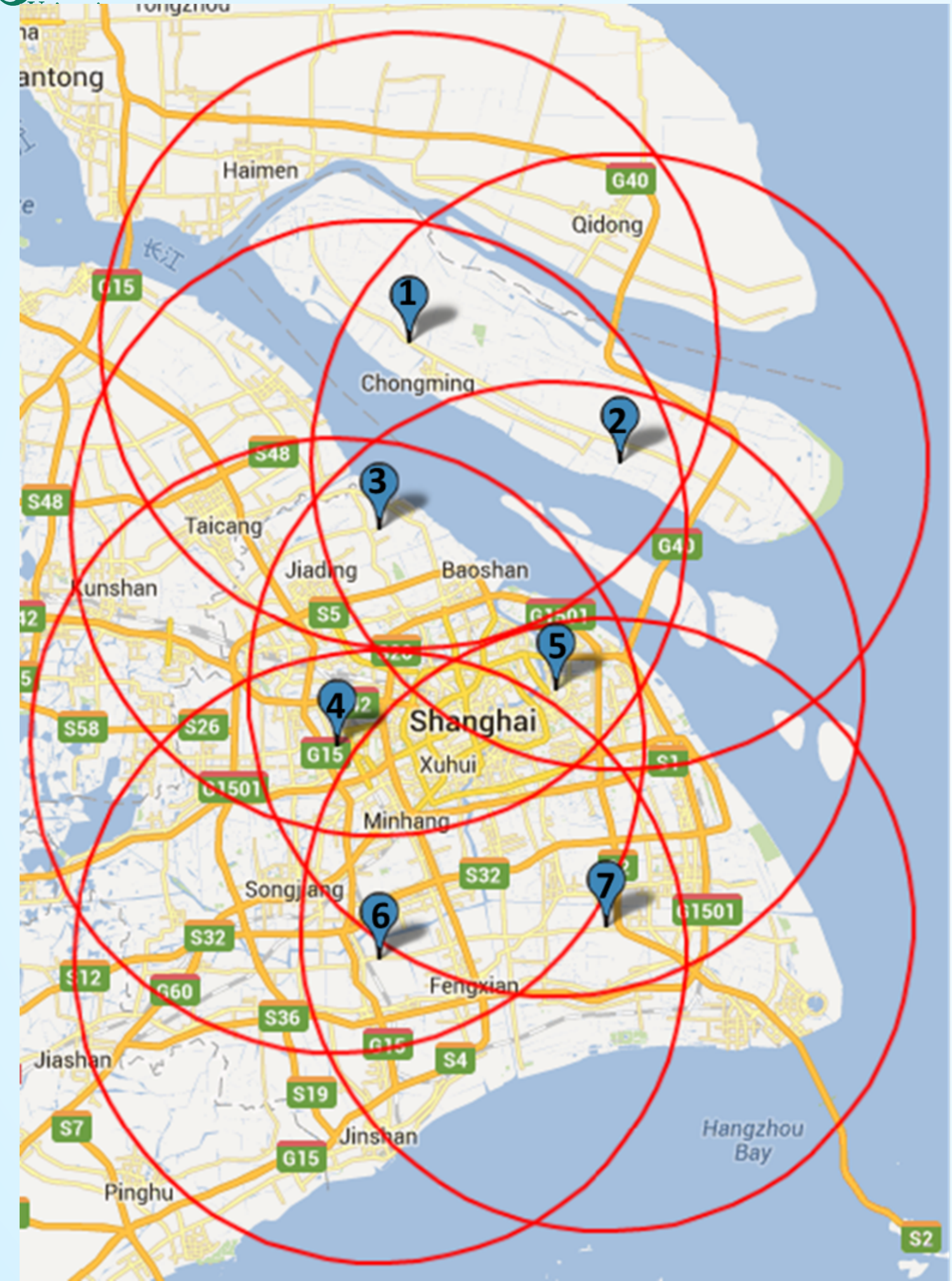
The greater Yangtze River Delta metropolitan region

- The urban build-up in the Yangtze River Delta has given rise what may be the largest concentration of adjacent metropolitan areas in the world.
- It covers an area of ***99.6 thousand square kilometers*** and is home to ***over 105 million people*** as of 2010.
- http://en.wikipedia.org/wiki/Yangtze_River_Delta

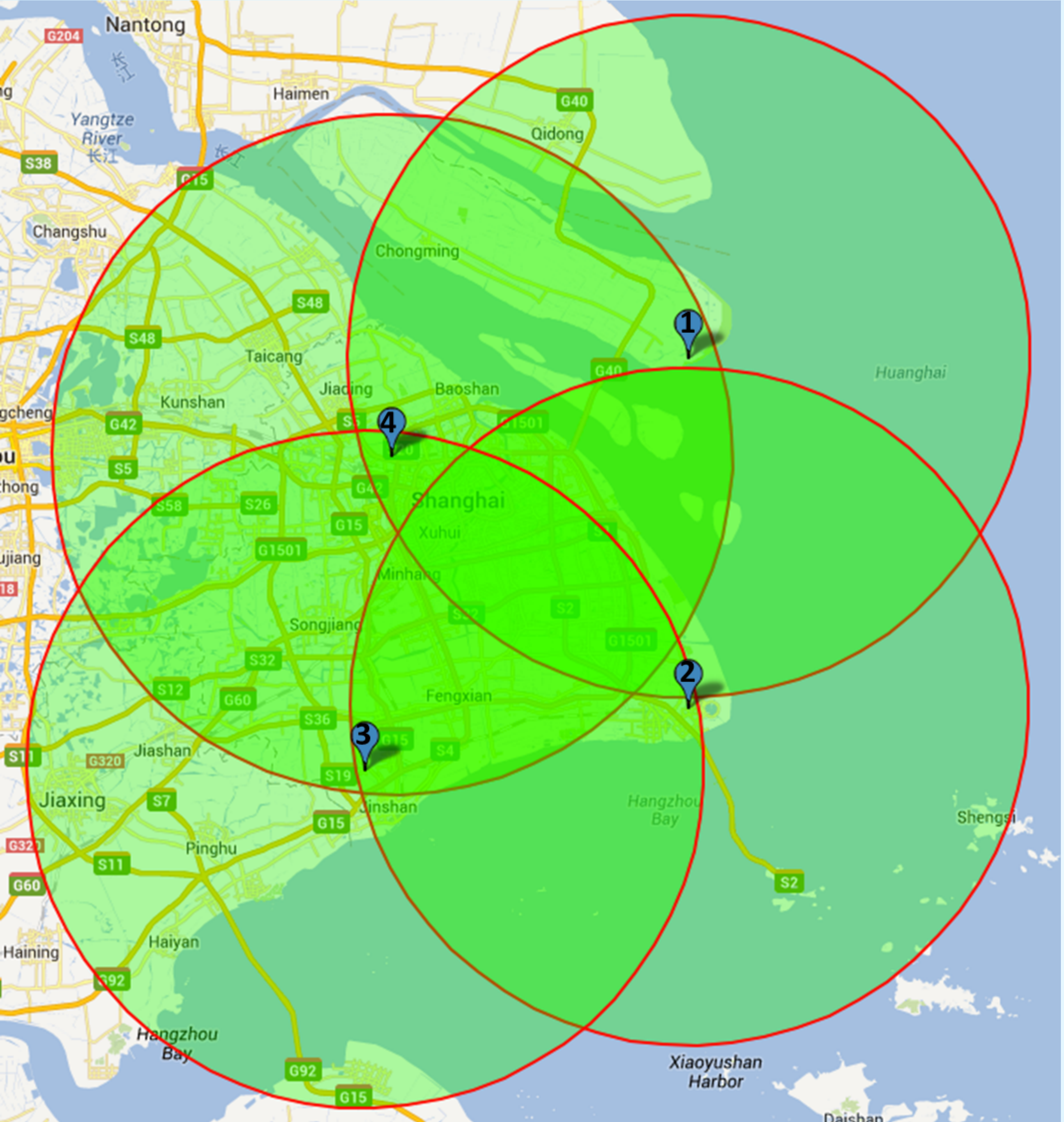


Shanghai

Yangtze River Delta



- Maximum range of each radar is 40 km
- Radar Locations:
  - Radar 1: 31.672N, 121.385E
  - Radar 2: 31.531N, 121.673E
  - Radar 3: 31.454N, 121.343E
  - Radar 4: 31.200N, 121.286E
  - Radar 5: 31.266N, 121.585E
  - Radar 6: 30.952N, 121.345E
  - Radar 7: 30.989N, 121.655E



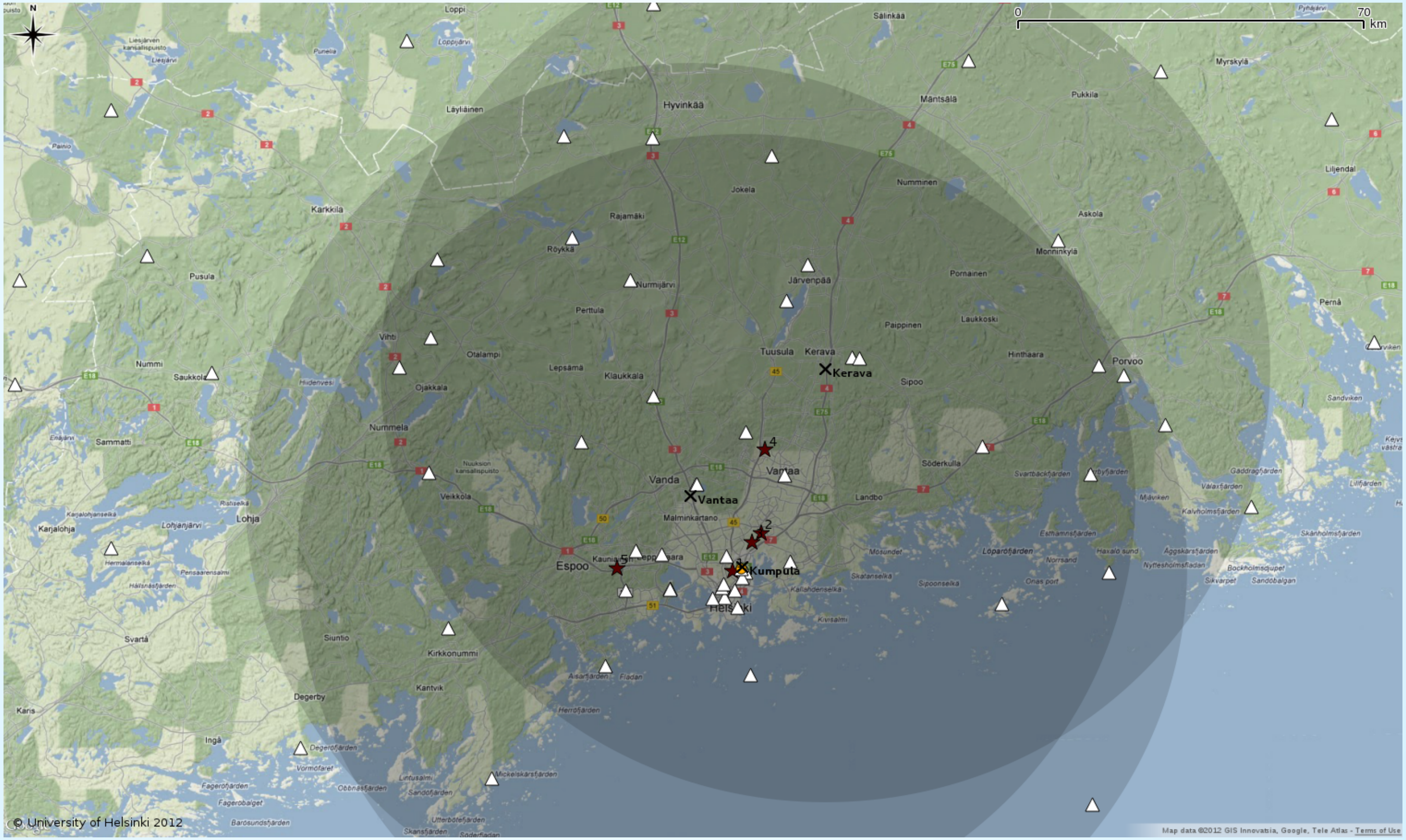
- 4 C-band radar overlay in Shanghai
- Maximum range of each radar is 60 km.

Radar Locations:
Radar 1: 31.455N, 121.9E
Radar 2: 30.9N, 121.9E
Radar 3: 30.8N, 121.3E
Radar 4: 31.3N, 121.35E

The Helsinki Demonstration testbed

- Leverage existing assets
- Pathfinder demonstration for megacity implementation; example
- Mumbai, Sao Paolo, Rio, Shanghai, Beijing, Ho Chi Minh City, Ankara
- Multi-sector usage, Aviation, emergency management, water management (big story), transportation
- Central role in smart and sustainable cities

Helsinki C band radar network testbed (details to follow)



Summary

- Urban radar networks as a multi-user platform is already taking hold in many cities (European program, Japan, DFW)
- Networked Dual-polarization radar observations, especially the specific differential propagation phase, has been used successfully for flood monitoring/ mitigation
- Radar network very useful to track severe weather at high spatial and temporal scale.
- Requires large number of X band radars
- C-band alternative is proposed based on coverage, cost benefit and attenuation considerations.
- Helsinki will have the first such network

Networked QPE Methodology

Dual-polarization Rainfall Algorithm

QPE system is *Kdp*-based.

The instantaneous rainfall rate can be related to drop size distribution (DSD) as,

$$R = 0.6\pi \times 10^{-3} \int v(D) D^3 N(D) dD$$

where *D* is the equivalent drop size in diameter (mm)
N(D) is DSD
v(D) is the terminal fall speed of raindrop (m/s)

The specific differential propagation phase (*Kdp*) can be related to DSD as,

$$Kdp = \frac{\pi^2}{6\lambda} C \int (1-r) D^3 N(D) dD$$

$$R = aKdp^b$$

where *C* is a constant
r is the axis ratio of raindrops
λ is the wavelength

Rainfall relation in CASA's IP1 test bed: $R = 18.15 Kdp \uparrow 0.791$

CASA QPE Methodology (cont.)

Evaluation Metrics

The performance evaluation include score computations of the mean bias, the normalized mean bias, and the normalized standard error (NSE), which are defined as,

Mean bias: $\langle e \rangle = \langle R_R - R_G \rangle$

Normalized Mean Bias: $\langle e \rangle_N = \langle R_R - R_G \rangle / \langle R_G \rangle$

NSE: $NSE = \langle | R_R - R_G | \rangle / \langle R_G \rangle$

Colorado State University

CASA QPE Methodology (cont.)

More…

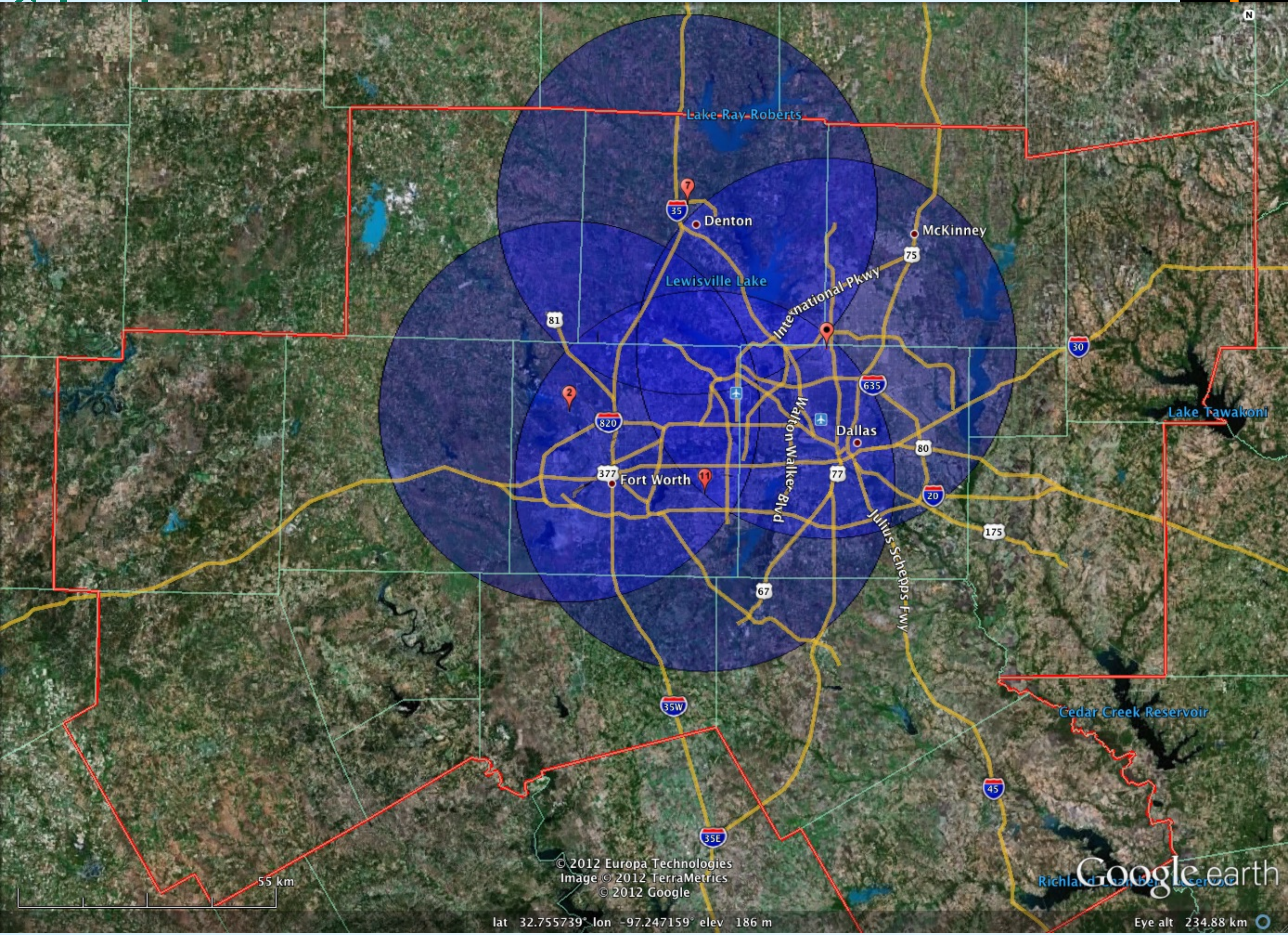
- Only *Kdp*'s from the 2.0 degree elevation scan are used when computing the rainfall rate

  - the beamwidth of CASA radars is about 1.8 degree
  - at 2 degree elevation angle, the clutter would come from sidelobes and its impact would be minimal after clutter filtering
  - all of the measurements from the network can be regarded as being taken simultaneously because the 2 degree scan can be completed within 20s

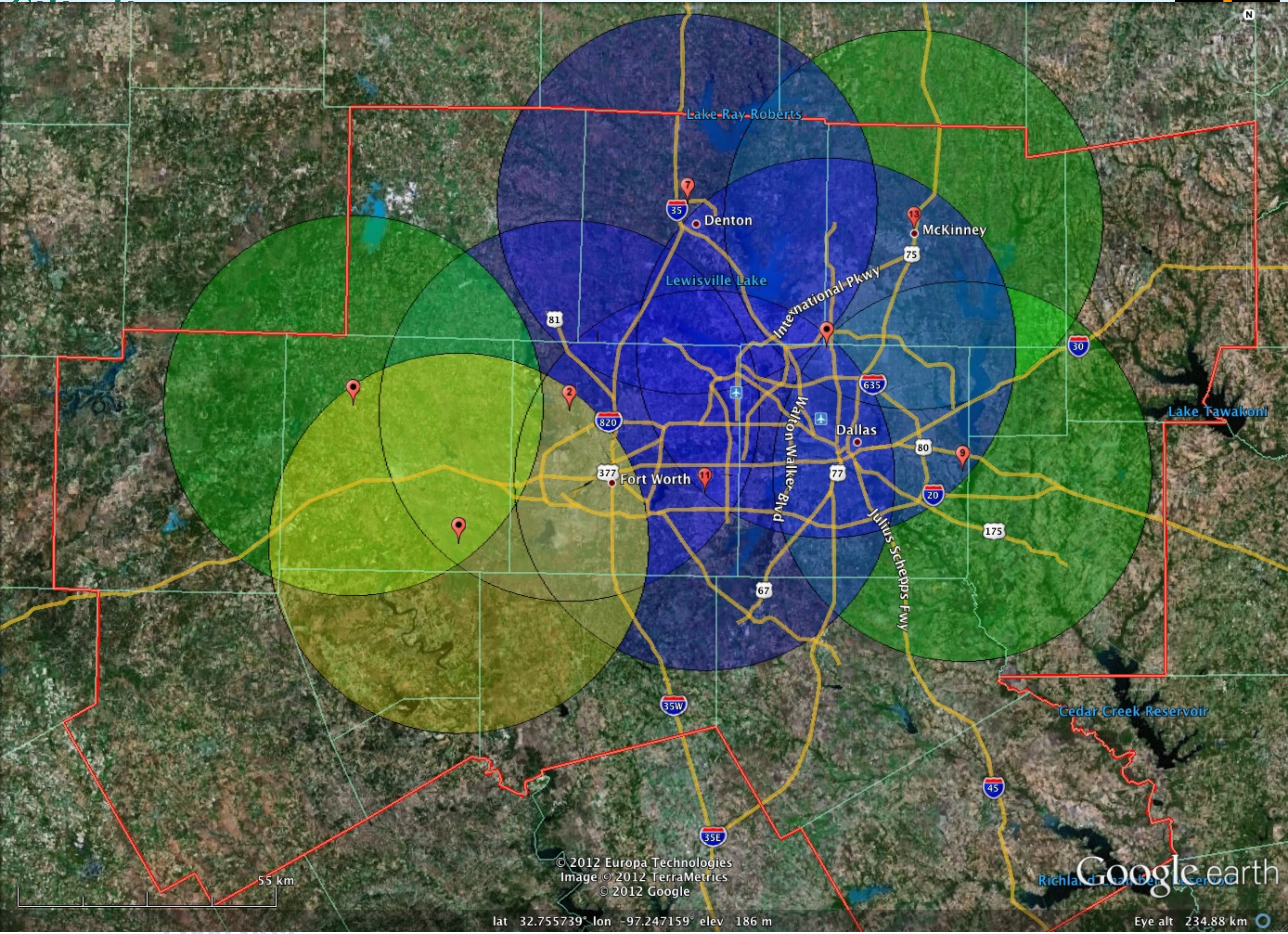
- An adaptive algorithm was developed to estimate *Kdp* (Wang and Chandrasekar 2009), which is implemented in CASA QPE system.

- The *Kdp* field from all the four radar nodes will be fused before the rainfall conversion algorithm is applied.

  - The *Kdp* field is merged rather than the rainfall field
  - The composite *Kdp* estimates are constructed based on the quality of the individual *Kdp* to produce the network's QPE products in this project.



Lake Ray Roberts
Denton
McKinney
Lewisville Lake
International Pkwy
Walton Walker Blvd
Dallas
Fort Worth
Julius Schepps Fwy
Lake Tawakoni
Cedar Creek Reservoir
55 km
© 2012 Europa Technologies
Image © 2012 TerraMetrics
© 2012 Google
Google earth
lat 32.755739° lon -97.247159° elev 186 m
Eye alt 234.88 km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35
75
81
820
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175
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35W
45
35E
55 km
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