Terminal Multifunction Phased Array Radar

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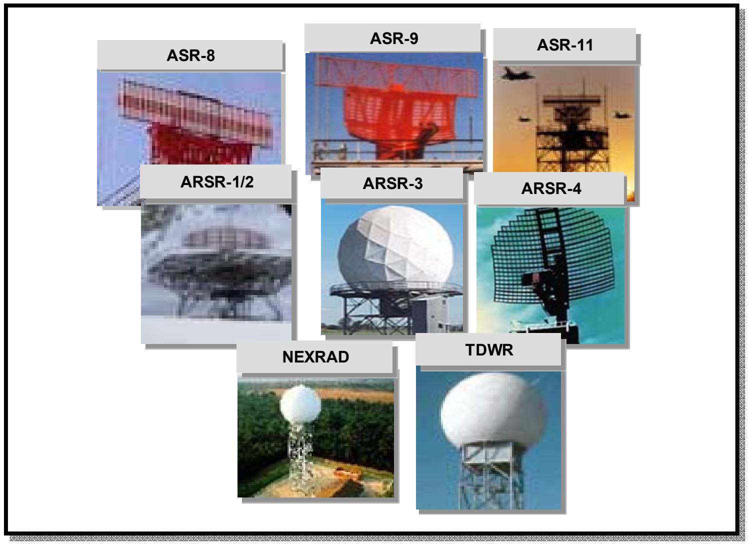
Outline

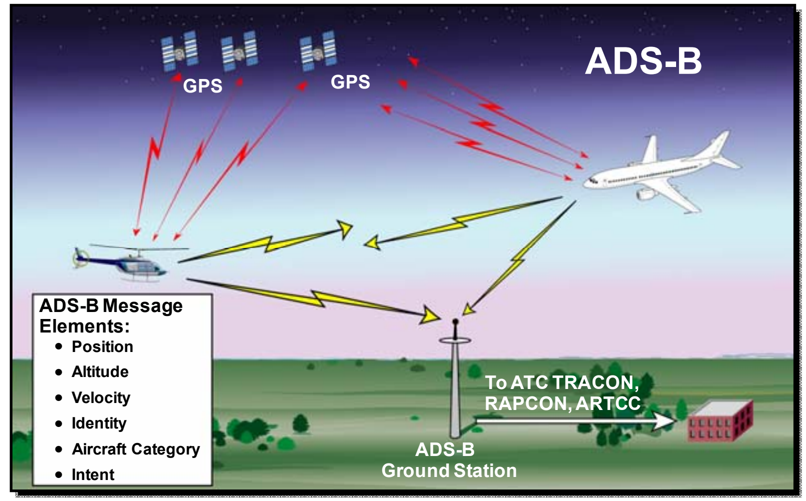
- Motivation
- Terminal MPAR requirements analysis
- Affordability
- Summary

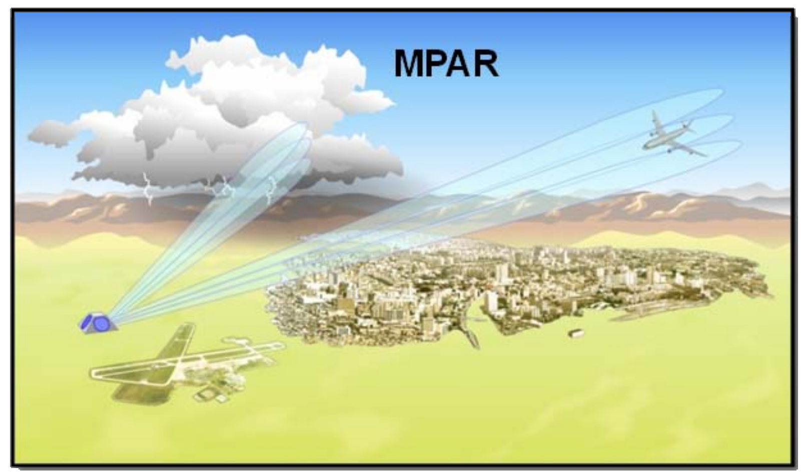
National Air Surveillance Infrastructure

Today



Future





Future Primary-Radar Missions

Weather

Non-cooperative target surveillance

Cooperative surveillance verification and backup

Terminal Area Primary Radar Missions

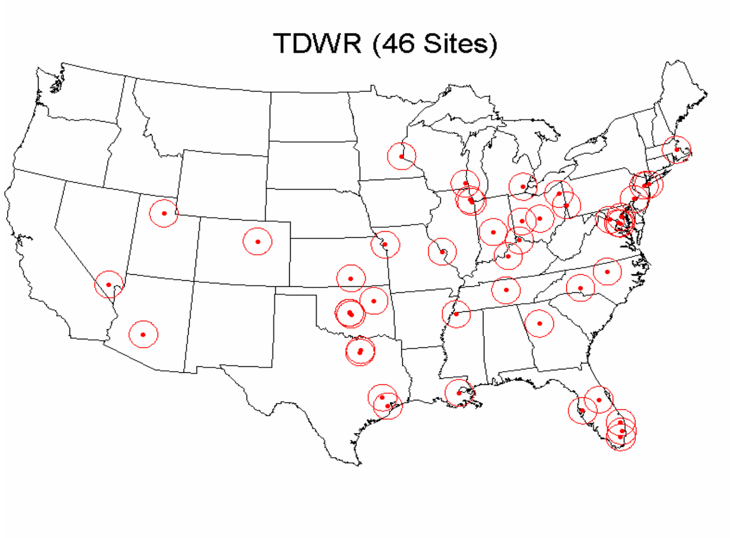
- **ATC terminal radars support unique missions**
  - Low altitude wind shear protection at airports
  - Thunderstorm monitoring (30 sec update)
  - Non-cooperative aircraft surveillance for high-value assets (DoD, DHS)

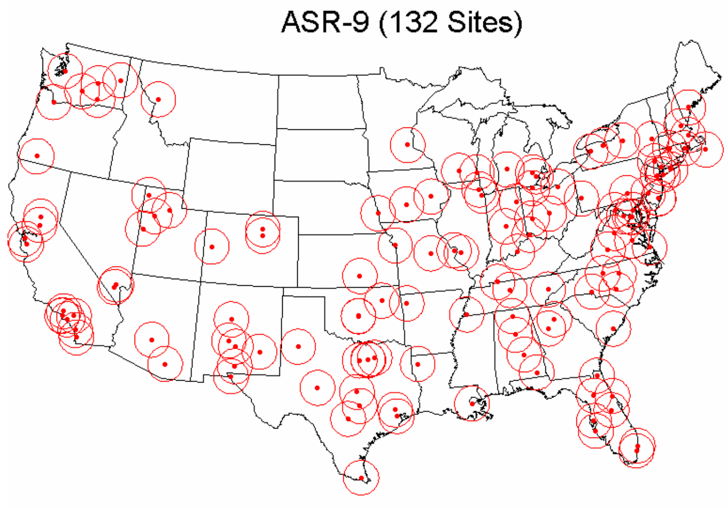
- **FAA Architecture identifies decision points for future terminal area primary radar**

  2011 - Decision to implement NEXTGEN primary radar system which includes weather surveillance requirements

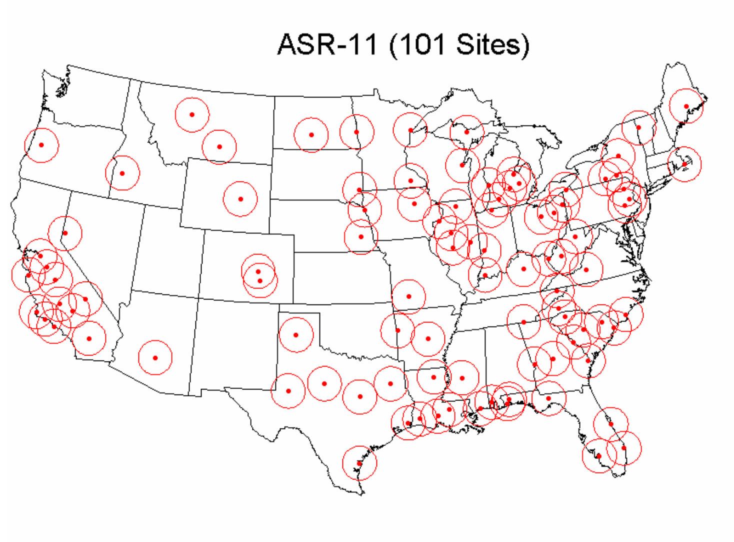
  2014 - Decision for replacement of legacy primary radars (ASR-8, ASR-9), based on air traffic safety, security and weather surveillance requirements

U.S. Airport “Weather” Radars

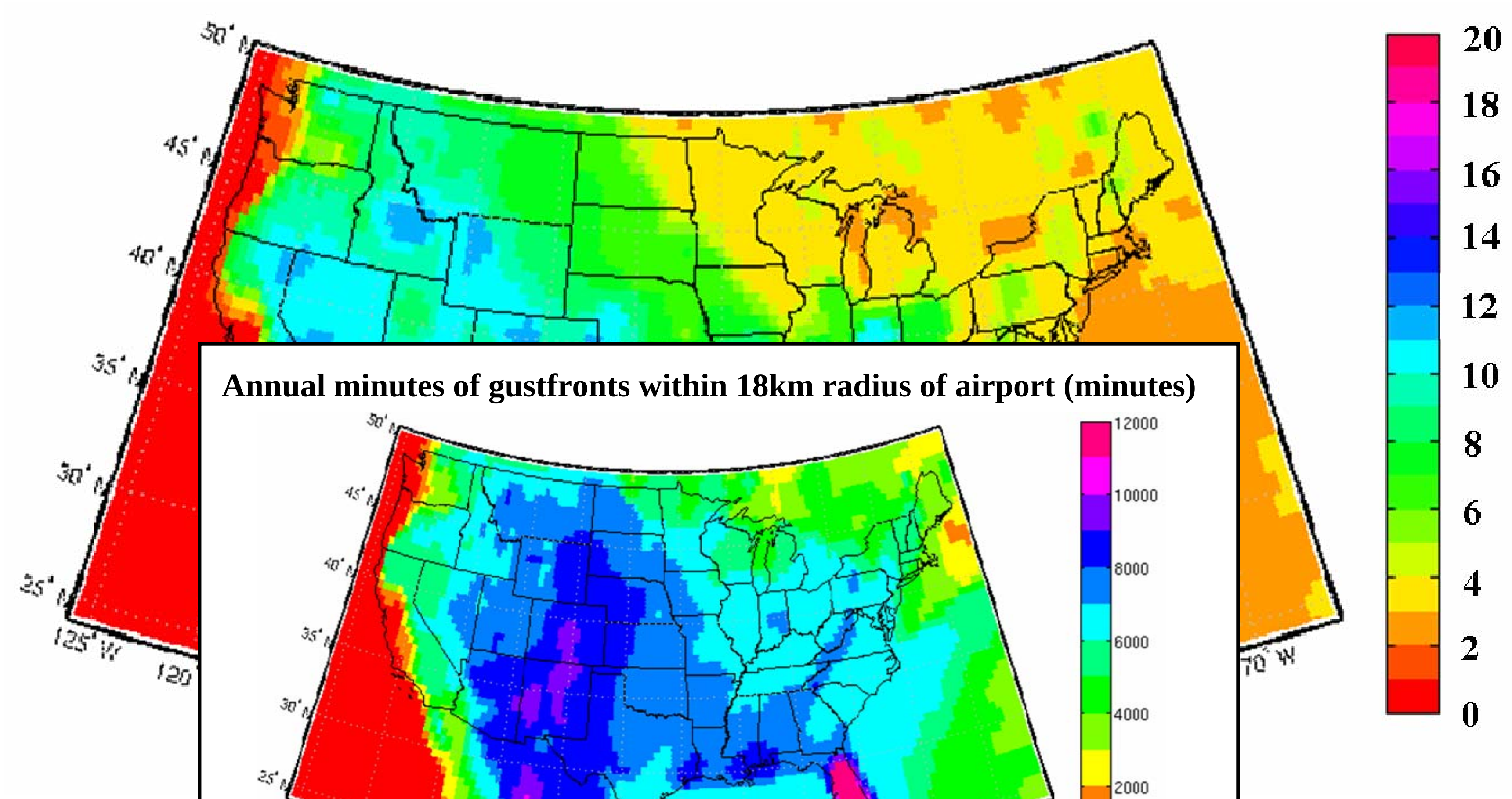




Current NWS weather radar (WSR-88D) network does not provide the near-airport low altitude coverage or update rate (30 – 60 sec) needed by terminal ATC



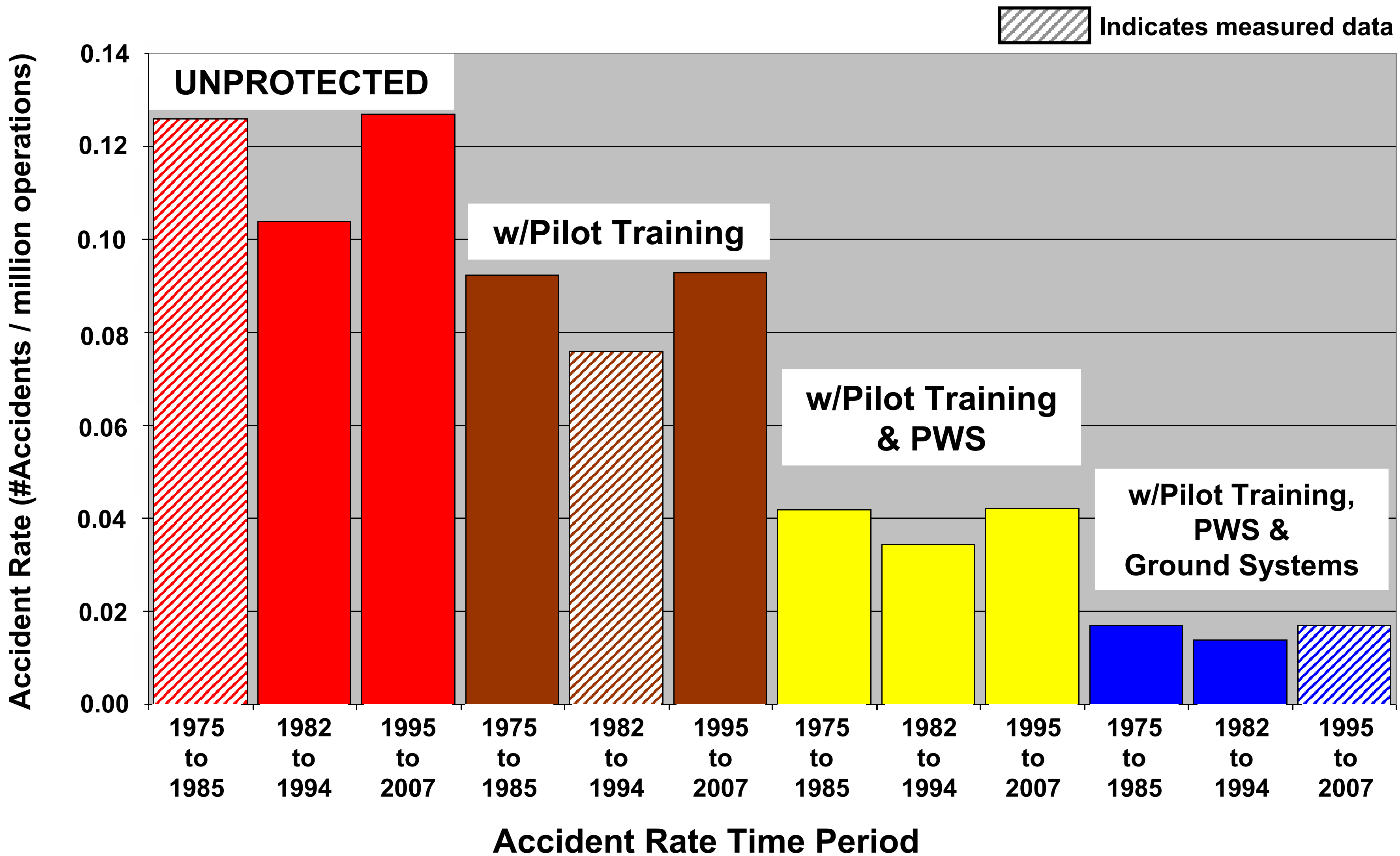
U.S. Airport Microburst Exposure



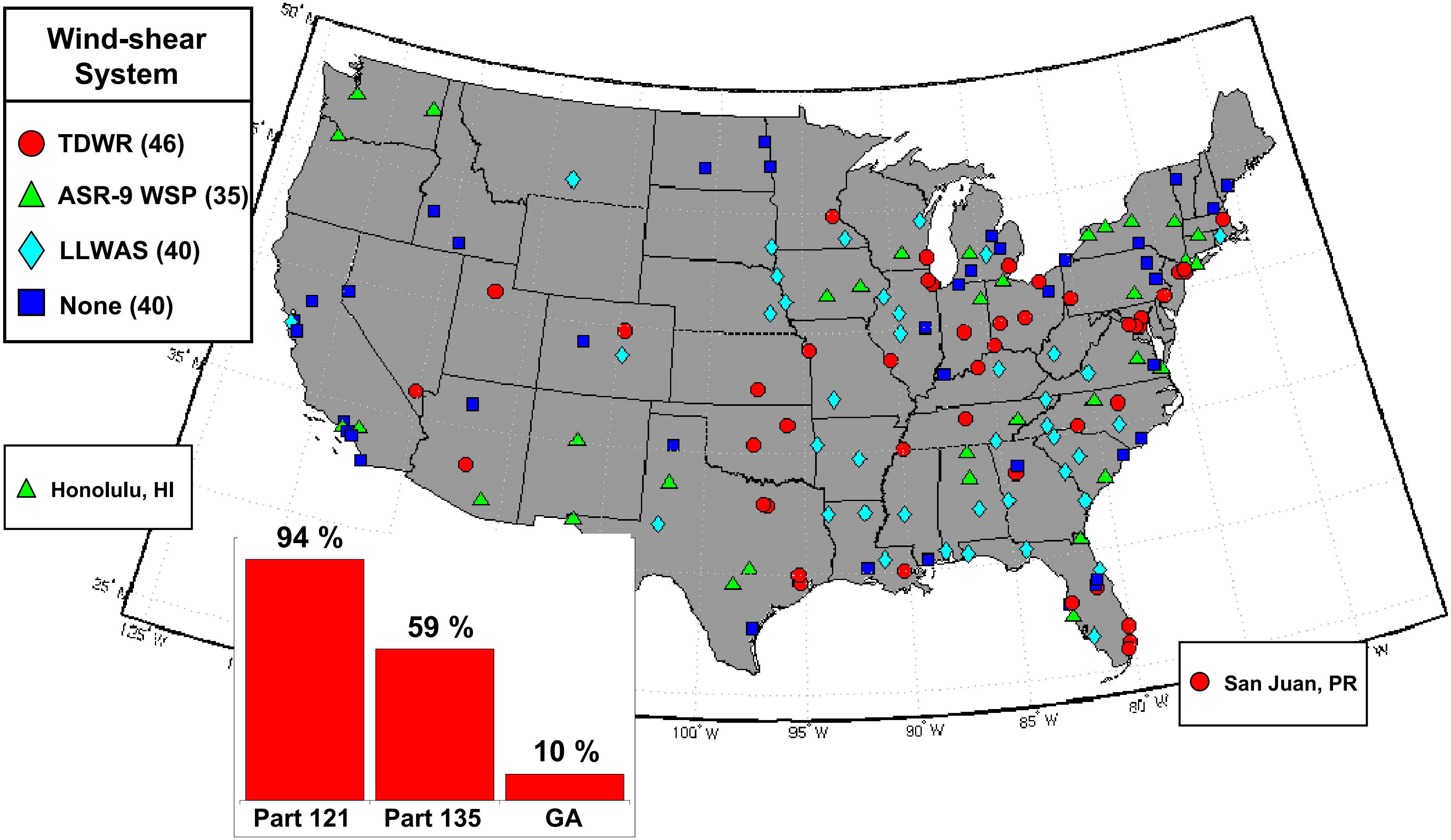
Annual minutes of gustfronts within 18km radius of airport (minutes)

Annual m ... t (thousands)

U.S. Wind Shear Accident Rate (Part 121/129)

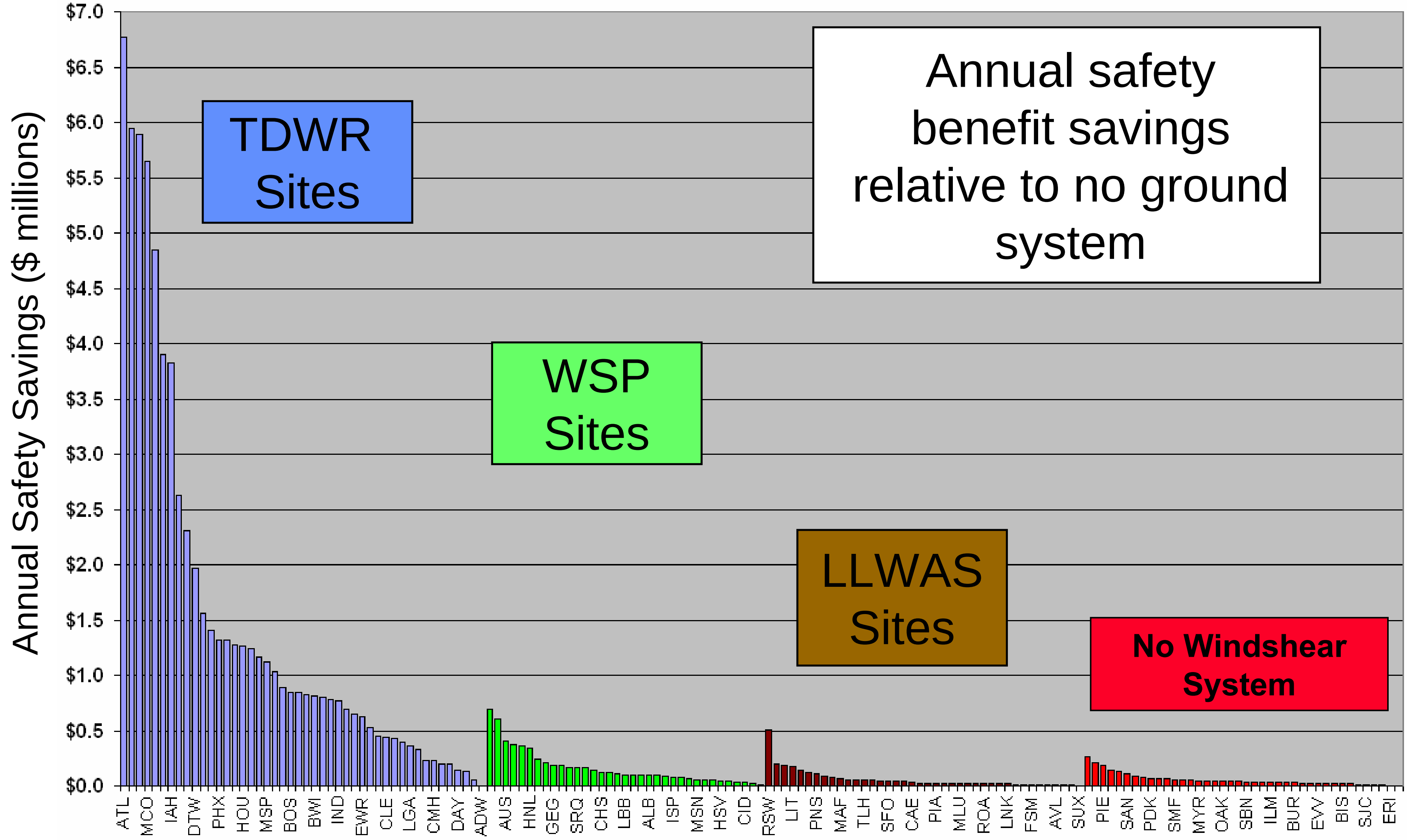


Wind Shear Systems Benefit Analysis



Flight Category Coverage

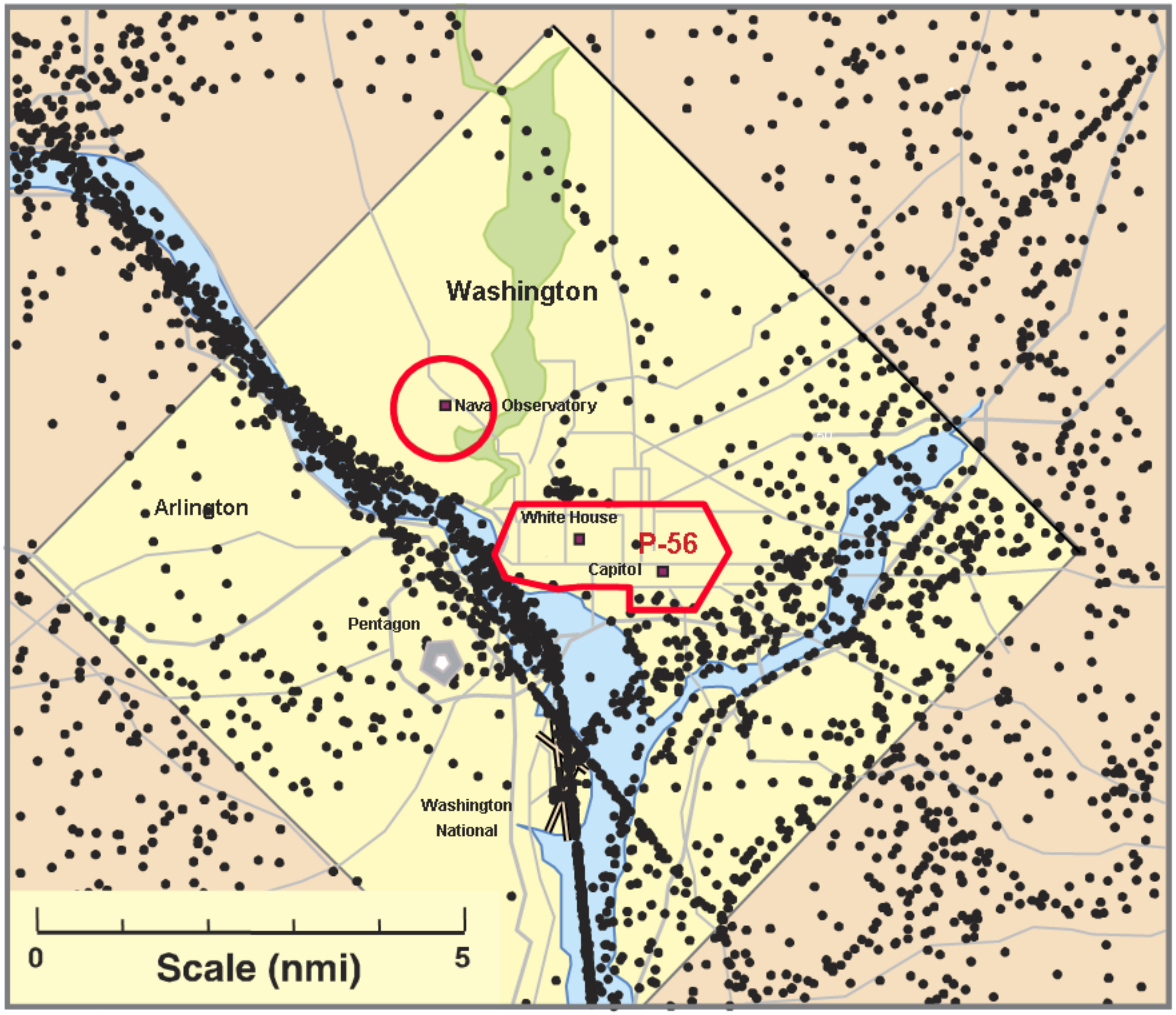
Wind Shear Cost Savings by Airport (Per annum average: 2010-2025)



Non-Cooperative Aircraft Surveillance

- Current FAA primary/secondary radars provide an essential backbone to DoD/DHS homeland air picture and decision support systems
- Considerable interest on the part of DoD in “sense and avoid” capability for UAS operations in civil airspace
  - Ground radar most viable near/mid term solution
- Our perspectives on enhancement priorities
  - Network compatible radar interface
  - External access to unfiltered target detections (amplitude, Doppler velocity, …)
  - Target height information
- DoD/DHS will deploy ancillary sensors as necessary to meet specific operational needs

Homeland Defense Environment in National Capital Region (NCR)



- High density of non-hostile traffic
- Lack of accurate 3-D surveillance
- Anomalous behavior difficult to detect

•••• 4 hour FAA radar data collection, 33% of detections shown

Enhanced Regional Situation Awareness System

SENSORS

Wide Area | *3-D* | *Visual*

FAA Radars And Data Bases | Mode-S RCVR | NORAD TADIL-J | Elevated Sentinel Radars | Ground Based Sentinel Radars | Hi-Res EO Sites | Hi-Perf EO/IR and Warning Systems

Redundant Networks

FUSION

Evidence Accrual and Decision Support

Primary Facility Fusion and Aggregation

Redundant Networks

- Lincoln developed Integrated Air Picture, Decision Support, ID, and Visual Warning deployed for operational use in NCR

USERS

Fan-out to Multiple Users

Air Situation Decision Support Display and Camera Control

Portable Air Situation Display

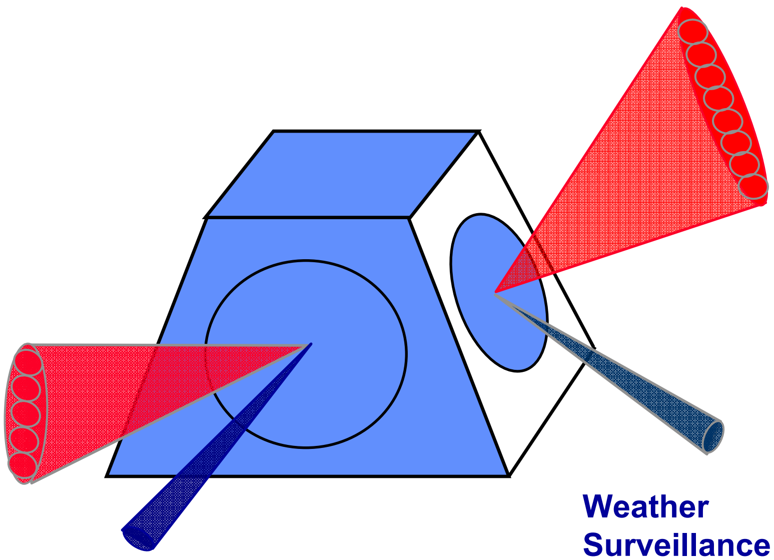
ATC Cooperative Surveillance (ADS-B) Backup and Integrity Monitoring

- **Backup needed in the event of a wide-area GPS outage (e.g. jamming, solar storms) or single-aircraft avionics failure**
- **Integrity monitoring needed to guard against “spoofing”**
- **FAA ADS-B backup strategy calls for retention of many legacy radars**
  - All primary radars
  - Secondary radars in high density terminal airspace
- **Backup strategy will be re-evaluated as experience with ADS-B is gained**
  - Alternatives under investigation include wide-area multilateration, DME, e-Loran and other non-radar alternatives (but these are all “cooperative”)

Outline

- Motivation
- Terminal MPAR requirements analysis
  - Weather services
  - ADS-B backup
- Affordability
- Summary

Terminal MPAR



334 MPARS required to duplicate today's airspace coverage. Half of these are scaled "Terminal MPARS"

- **Active Array (planar, 4 faces)**
  - Diameter: 4 m
  - TR elements/face: 5,000
  - Dual polarization
  - Beamwidth: 1.2° (broadside)
    2.0° (@ 45°)
  - Gain: > 40 dB
- **Transmit/Receive Elements**
  - Wavelength: 10 cm (2.7–2.9 GHz)
  - Bandwidth/channel: 1 MHz
  - Frequency channels: 2
  - Pulse length: 80 μs
  - Peak power/element: 5 W
- **Architecture**
  - Overlapped subarray
  - Number of subarrays: 16
  - Maximum concurrent beams: 12

Terminal Area Weather Radar Services

- Specific requirements in place for wind shear detection
  - $P_d > 0.9$; $P_{fa} < 0.1$
  - Minimum radar cross section, update period, latency, etc.
- "Requirements" for more general weather radar services derived based on assumption that current capabilities must at least be maintained
  - Thunderstorm mapping/position tracking with 30 sec updates
  - Measurement of precipitation at airport affecting visibility and/or runway braking action
  - Wind measurements supporting operations at high-density airports
    - Airport wind shifts
    - Rapidly varying winds affecting sequencing merging operations

Weather Radar Equation

$$dBZ_{min} = -75.4 + 10\log\left(\frac{\lambda^2 L_n L_c L_o B_s T_s 10^{\kappa R/10}}{\eta_i P_e t_{pw} N_e^2 F_a^2}\right) + 20\log(R)$$

Wavelength:	$\lambda = 0.1\ m$
Tx aperture factor:	$L_n = 1.28$ *(uniform illumination)*
Pulse compression loss:	$L_c = 1.58$ *(with pulse compression)*
	$= 1$ *(w/o pulse compression)*
Other losses:	$L_o = 2$ *(estimate)*
Bandwidth:	$B_s = 10^6\ Hz$
System temperature:	$T_s = 730\,°K$
Atmos. attenuation & lensing:	$k = 0.0175$ *dB/km (usually ignored, set to 0)*
Rx illumination factor:	$\eta_i = 0.71$ *(circular Taylor 40 dB)*
Power per element:	P_e *(W)*
Pulse length:	t_{pw}*(s)*
Number of elements:	N_e *(for 100% fill factor)*
Fill factor	F_a
Range	R *(km)*

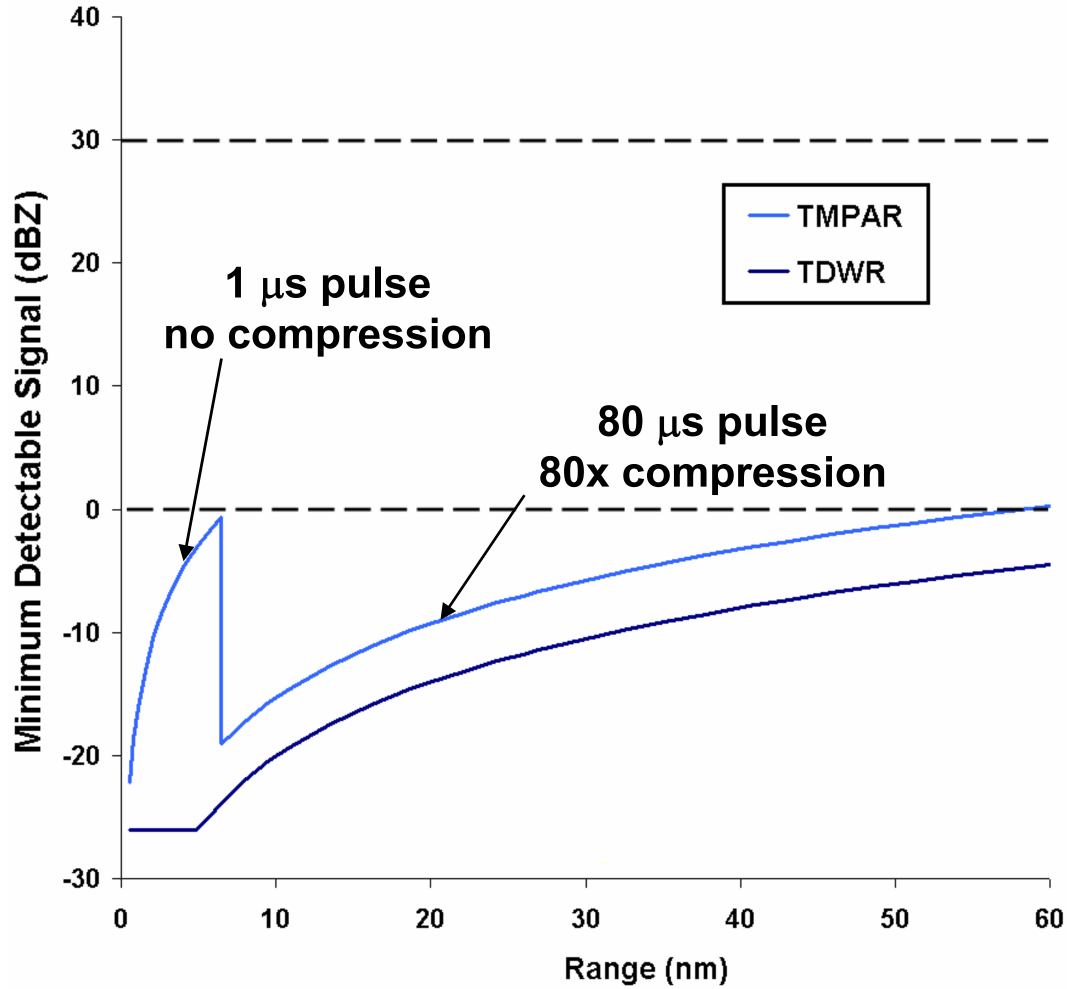
$$dBZ_{min} = -59.5 + 10\log\left(\frac{\lambda^2 B_s T_s L_e 10^{\kappa r/10}}{P_t \tau G_t G_r \theta_{BW}\phi_{BW}}\right) + 20\log(R)$$

$P_t = P_e N_e F_a$

$G_t = 4\pi/(\theta_{BW}\phi_{BW}L_n)$

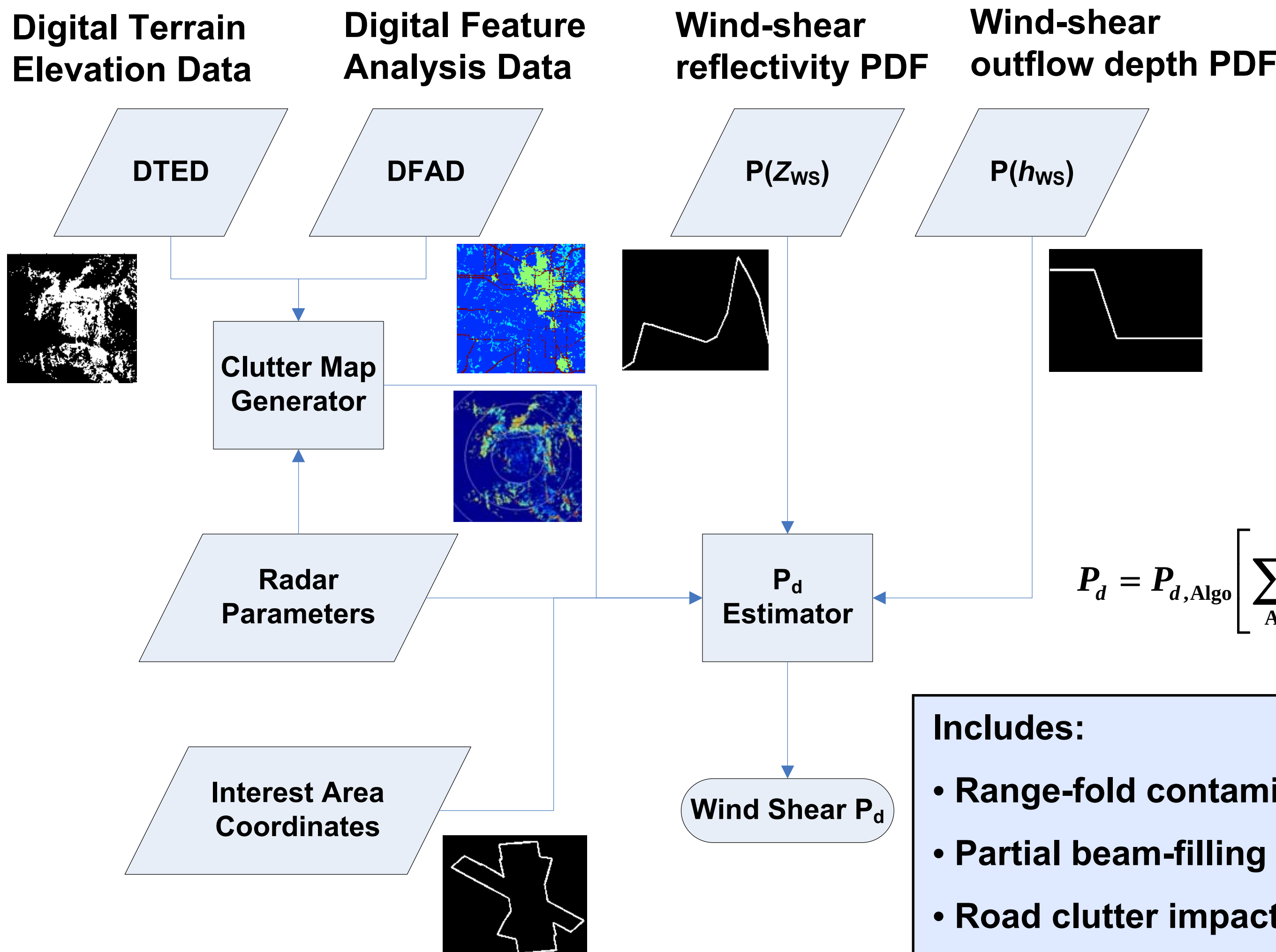
$G_r = \eta_i \pi N_e F_a$

Terminal MPAR Weather Sensitivity
5,000 TR-elements, 5 W peak power per element



0 dBZ sensitivity sufficient with exception of a few western U.S. airports (DEN, SLC, LAS,…)

Airport-Specific Radar Wind-Shear Detection Performance Model



$$P_d = P_{d,\mathrm{Algo}} \left[\sum_{\mathrm{A}} \sum_{Z_{\mathrm{lo}}(\vec{r})}^{Z_{\mathrm{hi}}(\vec{r})} p(Z_{\mathrm{WS}}) \Delta A \right] / \sum_{\mathrm{A}} \Delta A$$

Includes:

- Range-fold contamination effects
- Partial beam-filling signal loss & “noise” gain
- Road clutter impact
- Various signal processing effects

Mean Wind Shear Detection Probability at Evaluated Airports

Wind Shear Detection Probability	Microburst	Gust Front
ASR-9 WSP	0.89	0.68
TDWR	0.97	0.92
Terminal MPAR	0.93	0.81
Terminal MPAR & Lidar	0.97	0.93

Defined requirements for TDWR airports:

Microburst $P_d > 0.9$

Gust Front $P_d > 0.7$

$P_{fa} < 0.1$

Future Required Surveillance Performance

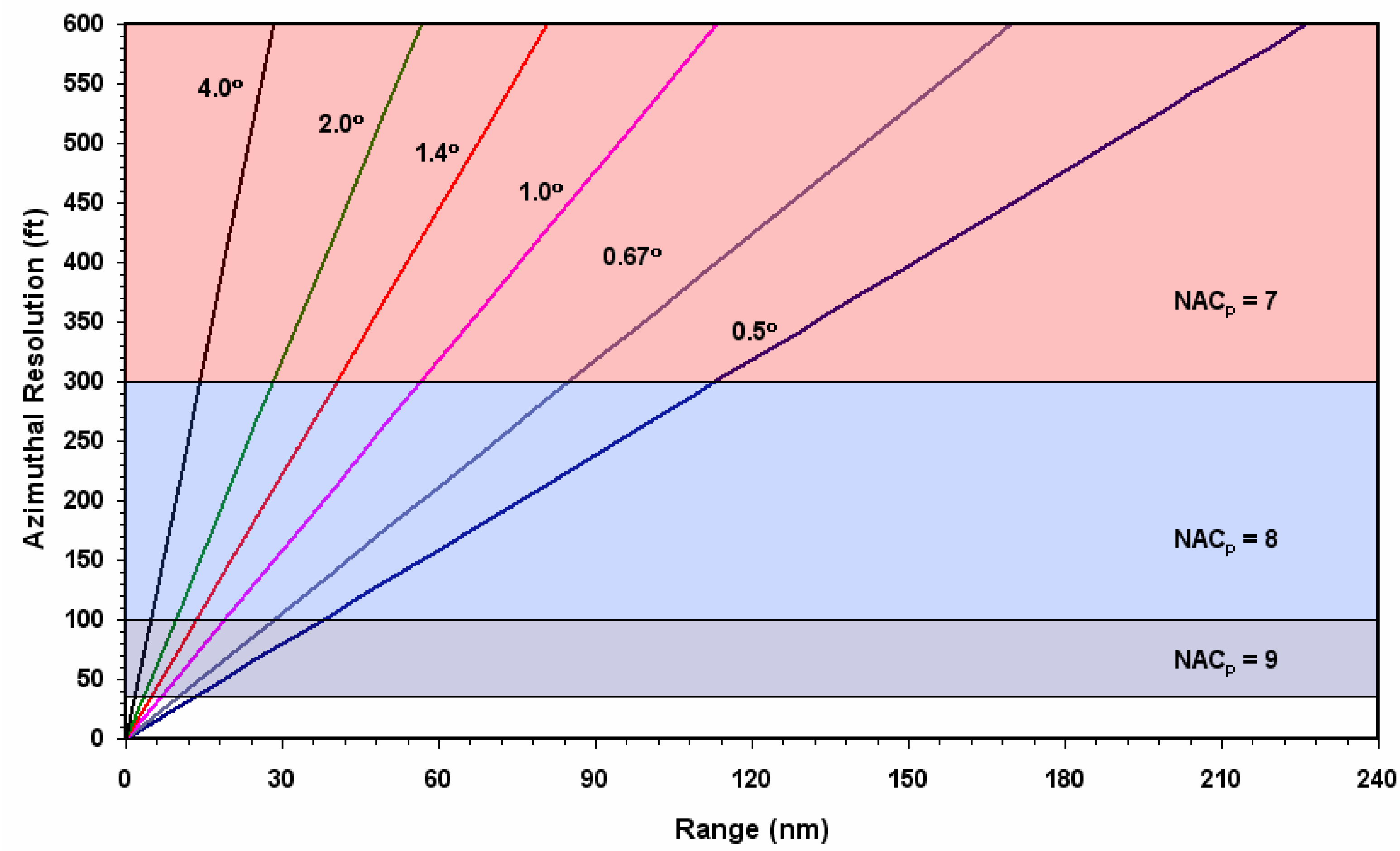
Parameter	Airspace	Value
Position Accuracy	All	35-100’ (95%) NAC_p = 9* 100-300’ (95%) NAC_p = 8 300-600’ (95%) NAC_p = 7
Update Interval	Terminal High Rate En Route	3 sec (95%)
	En Route	6 sec (95%)

*NAC_p = Navigation Accuracy Category (position)

Note: altitude assumed available via barometric altimeter.

Based on ADS-B NPRM dated October 2, 2007

MPAR Azimuthal Resolution vs. Range (20:1 Monopulse)

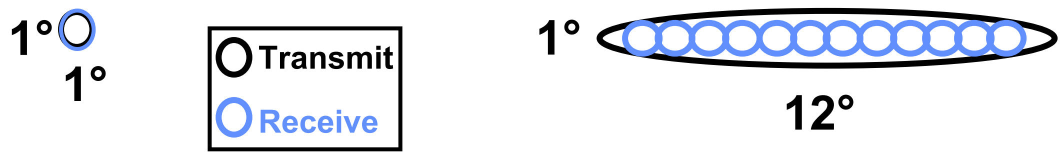


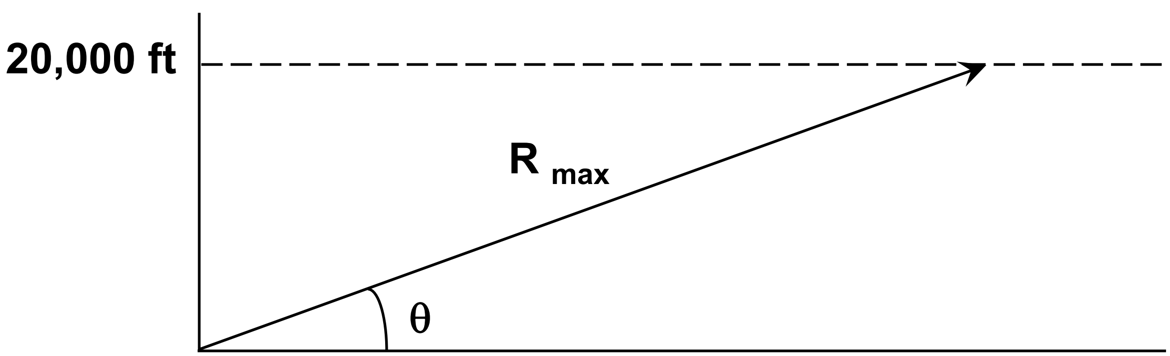
- ***Range-azimuth position location sufficient for NAC_p = 7***
- ***Need multi-lateration (range-range) positioning for NAC_p = 9***

Energy Management to Achieve Necessary Scan Update Rates

Low Elevation

High Elevation





$$R_{max} = Max\_Alt / \sin(\Theta)$$

Example TMPAR Weather Scan

(20,000' max altitude, 60 nm range,60° max elevation)

Elevation Angle	Elevation Beam Width	Azimuthal Extent	Dwells	CPI	PRI (s)	Slant Range to 20kft	Beam Spoil	12 Concurrent Beams			
								Channels	Azimuths	Total	Time (s)
0.0	1.6	90	70	50	0.001	60	1.0	2	1	2	1.75
1.6	1.6	90	70	50	0.001	60	1.0	2	1	2	1.75
3.1	1.5	90	70	50	0.001	60	1.0	2	1	2	1.75
4.7	1.5	90	70	50	0.001	40	2.2	2	2	4	0.87
6.2	1.5	89	70	50	0.001	30	3.9	2	4	8	0.43
7.7	1.5	89	69	50	0.001	24	6.0	2	6	12	0.29
9.2	1.5	89	69	50	0.001	20	8.6	2	8	16	0.22
10.7	1.5	88	69	50	0.001	18	11.6	2	11	22	0.16
12.2	1.5	88	68	50	0.001	16	14.9	2	12	24	0.14
13.7	1.5	87	68	50	0.001	14	18.8	2	12	24	0.14
15.2	1.5	87	68	50	0.001	13	23.0	2	12	24	0.14
16.7	1.5	86	67	50	0.001	11	27.5	2	12	24	0.14
18.2	1.5	85	66	50	0.001	11	32.5	2	12	24	0.14
19.7	1.5	85	66	50	0.001	10	37.8	2	12	24	0.14
21.2	1.5	84	65	50	0.001	9	43.6	2	12	24	0.14
22.7	1.5	83	65	50	0.001	9	49.6	2	12	24	0.13
24.2	1.5	82	64	50	0.001	8	56.0	2	12	24	0.13
25.8	1.5	81	63	50	0.001	8	62.8	2	12	24	0.13
27.3	1.5	80	62	50	0.001	7	69.9	2	12	24	0.13
28.9	1.6	79	61	50	0.001	7	77.4	2	12	24	0.13
30.4	1.6	78	60	50	0.001	7	85.2	2	12	24	0.13
32.0	1.6	76	59	50	0.001	6	93.3	2	12	24	0.12
33.6	1.6	75	58	50	0.001	6	101.7	2	12	24	0.12
35.2	1.6	74	57	50	0.001	6	110.5	2	12	24	0.12
36.9	1.7	72	56	50	0.001	5	119.5	2	12	24	0.12
38.5	1.7	70	55	50	0.001	5	128.9	2	12	24	0.11
40.2	1.7	69	53	50	0.001	5	138.6	2	12	24	0.11
42.0	1.8	67	52	50	0.001	5	148.6	2	12	24	0.11
43.7	1.8	65	51	50	0.001	5	158.8	2	12	24	0.11
45.6	1.9	63	49	50	0.001	5	169.4	2	12	24	0.10
47.4	1.9	61	47	50	0.001	4	180.2	2	12	24	0.10
49.4	2.0	59	46	50	0.001	4	191.3	2	12	24	0.09
51.4	2.1	56	44	50	0.001	4	202.7	2	12	24	0.09
53.4	2.2	54	42	50	0.001	4	214.3	2	12	24	0.09
55.6	2.3	51	40	50	0.001	4	226.1	2	12	24	0.08
57.8	2.4	48	37	50	0.001	4	238.1	2	12	24	0.08
60.2	2.5	45	35	50	0.001	4	250.3	2	12	24	0.07

10.60

Weather and Aircraft Scan Timing Summary

Function	Scan Update Period (sec)
Aircraft "Track While Scan"	4.0
Rapid Update Weather Volume Scan	4.0
Wind Shear Scans	60
3-D Weather Volume Scan	120

Adaptive scanning could increase update rate for "high value" aircraft or weather targets

Outline

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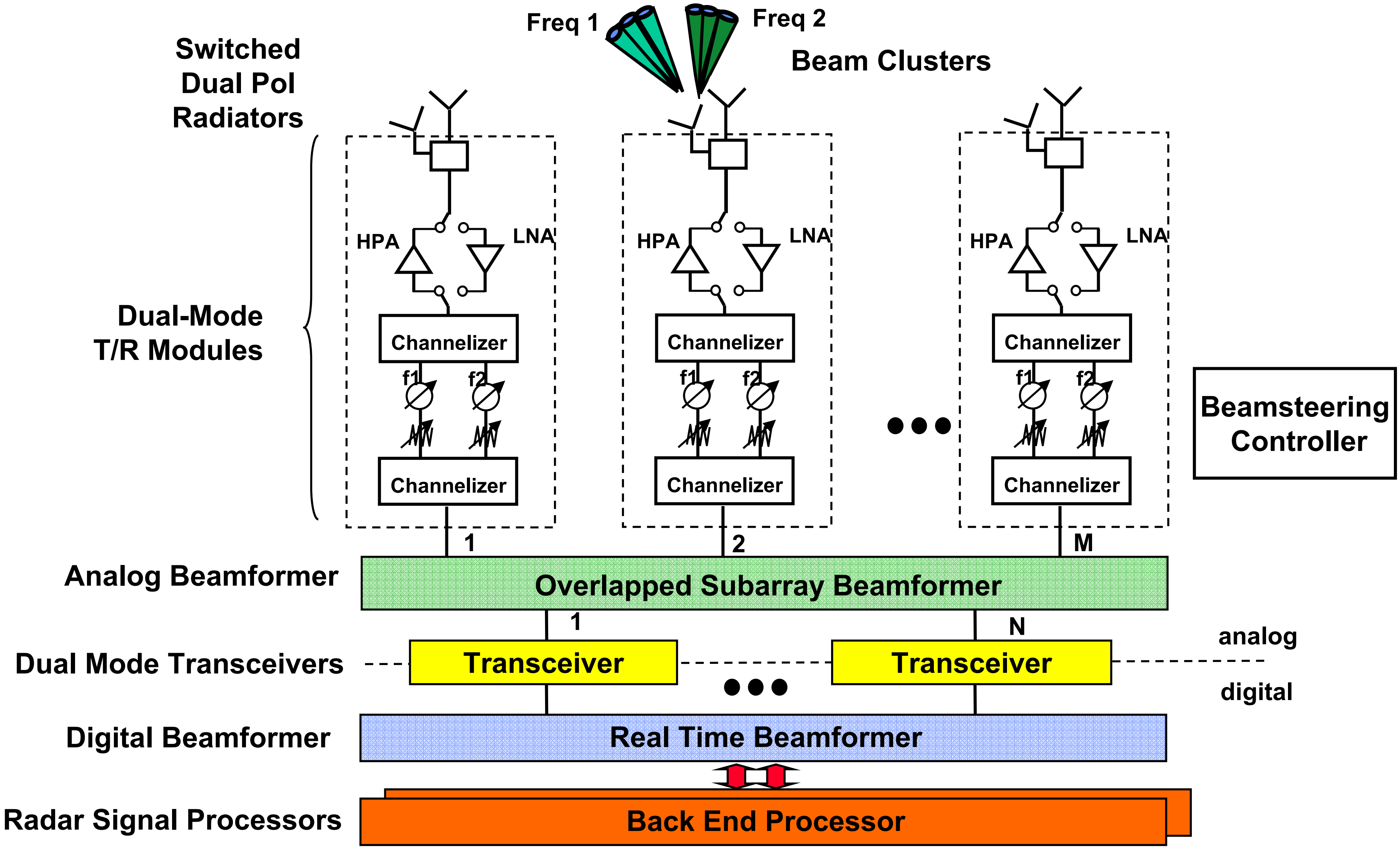
  - **Weather services**
  - **ADS-B backup**
- **Affordability**
- **Summary**

Terminal MPAR Architecture



Critical Challenges and Enablers

Challenges:

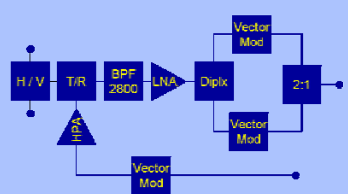
- Ultra-low cost array (~ $50k / m^2$)
- Multiple independent beams or beam clusters
- Scalable aperture sizes
- Open architecture
- Low operations and maintenance costs

Enablers:

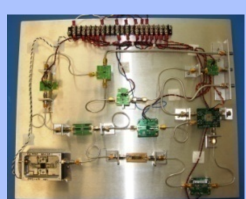
- Low peak power, duty cycle and bandwidth
- Highly integrated T/R chips
- Scalable array sub-panels
- Design for manufacturability
- Chip-based beamformers
- Integrated digital receivers

MPAR Array Panel Development

Dual Mode T/R Module*

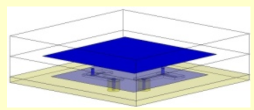


T/R Module Spec

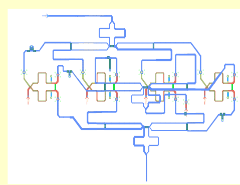


Discrete Component Prototype

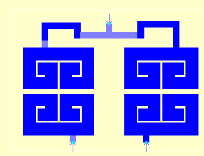
Multilayer Antenna Array*



Dual Pol Stacked Patch Antenna

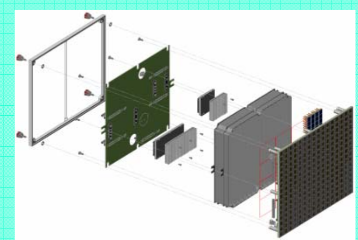


Overlapped Subarray Beamformer



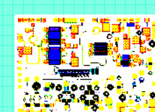
Diplexing Filters

Panel Subassembly

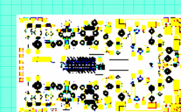


Line Replaceable Unit (LRU)

Custom T/R Chipset**



Tx chip

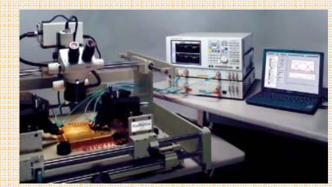


RX chip

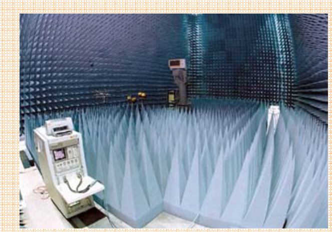
LNA/Limiter chip

** *Funded under Tyco IR&D*

Measurements



Bench top Network Analyzer Tests



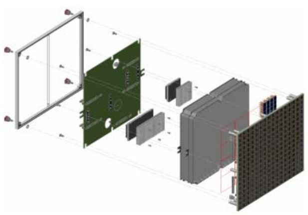
Antenna Test Facility

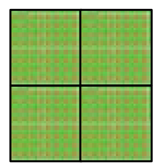
Terminal MPAR Prototype Development Schedule

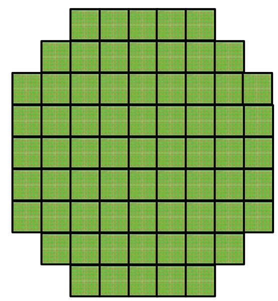
2008	2009	2010	2011
PDR	CDR	Testing CDR	

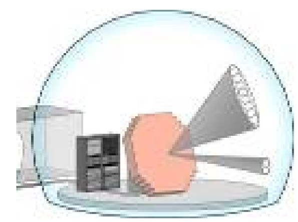
Concept Development, Design, and Subsystem Prototyping	System Fabrication and Assembly	Experimental Testing and Evaluation

Panel	Subarray	Array	Data Collection









Analog and Digital Hardware:

- 8 x 8 Element Panel
- Transceiver
- 256 Element Subarray
- Digital Beamformer (DBF)
- 5000 Element Array
- 24 Channel DBF
- Collect Multimode Data

Systems Analysis & Signal Processing:

- Waveform Design
- Systems Analysis
- Algorithm Dev
- System Simulation
- System Simulation
- Test Planning
- Process Data
- Report Results

Summary

- Specific concept for a Terminal Multifunction Phased Array Radar developed
  - Provides primary radar services in lieu of ASR-8/9/11 and TDWR
  - Can support backup or integrity verification for ADS-B
- Affordability being addressed through exploitation of wireless industry technology
  - Critical subsystems development and test underway
- Multiagency coordination of MPAR concept is underway
  - Senior level working group (FAA, NOAA, DHS, DoD)
  - National Academy of Sciences independent assessment