Multichannel Sense-and-Avoid Radar for Small UAVs

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NASA Aeronautics Research Mission Directorate (ARMD)

LEARN Technical Seminar

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Outline

- The innovation
  - Problem statement / Solution requirements / Implementation
- Technical approach
  - System overview – Radar / Vision / Flight Director & Autopilot
  - Radar – Technical approach / Status
  - Vision – Technical approach / Status
  - Flight Director & Autopilot – Technical approach / Status
  - Flight Testing – Platforms / Status
- Status of the LEARN effort to date
  - Accomplishments / Schedule status
- Next steps

The innovation

- Problem statement

Small unmanned aerial vehicles (sUAVs) may have a bright future in the commercial and industrial service sector.

- Pipeline surveillance, agricultural surveys, road traffic monitoring

Unacceptable risks result from the UAV's of lack situation awareness.

- Hazard to both ground-based and airborne assets.
- August 17, 2011 collision between U.S. Air Force C-130 cargo plane and an RQ-7 Shadow UAV over Afghanistan.

Integration into the NAS requires compatibility with existing systems (e.g., transponder-based collision avoidance) as well as avoidance of non-cooperative objects (e.g., towers, balloons).

The innovation

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- Solution requirements

  Using programmable radar-ready integrated circuits, provide small UAVs with situation awareness by remotely sensing nearby objects and reporting their positions and closing rates to on-board guidance system.

Platform – 40%-scale Yak-54 RC aircraft

Key specifications

wingspan 3.1 m; length 3.1 m; payload 4 kg; empty weight 18.1 kg ; cruise speed 36 m/s

Sensor requirements (from AE analysis*)

Key requirements

detection range 300 to 800 m;
range accuracy 10 m; range-rate resolution 1 m/s;
Doppler accuracy 10 Hz; update rate 10 Hz;
field of view 360° in azimuth, ±15° in elevation; angular accuracy 3°

* Stastny TJ; Garcia G; Keshmiri S; "Collision and Obstacle Avoidance in Unmanned Aerial Systems Using Morphing Potential Field Navigation and Nonlinear Model Predictive Control," *ASME Journal of Dynamic Systems, Measurement and Control*, Under Review, July 2013.

The innovation

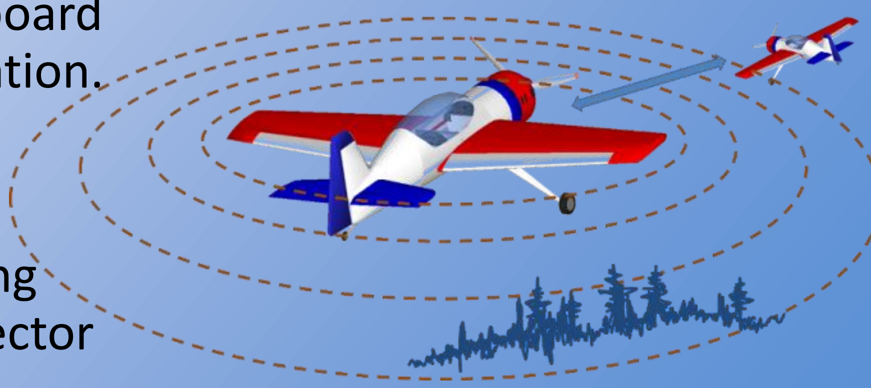
- Implementation
  - Microwave radar provides all-weather, day/night detection and ranging capability of non-cooperative objects.
  - Frequency-modulated continuous-wave (FMCW) operation reduces transmit power requirements for measurement of range and radial velocities (via Doppler processing).
  - Multichannel system enables relative position knowledge in 3-D.

Phase I scope

Proof-of-concept demonstration aboard Cessna-172 for performance evaluation.

Phase II scope

Miniaturized version for flight testing integrated with autopilot/flight director and vision system.



The innovation

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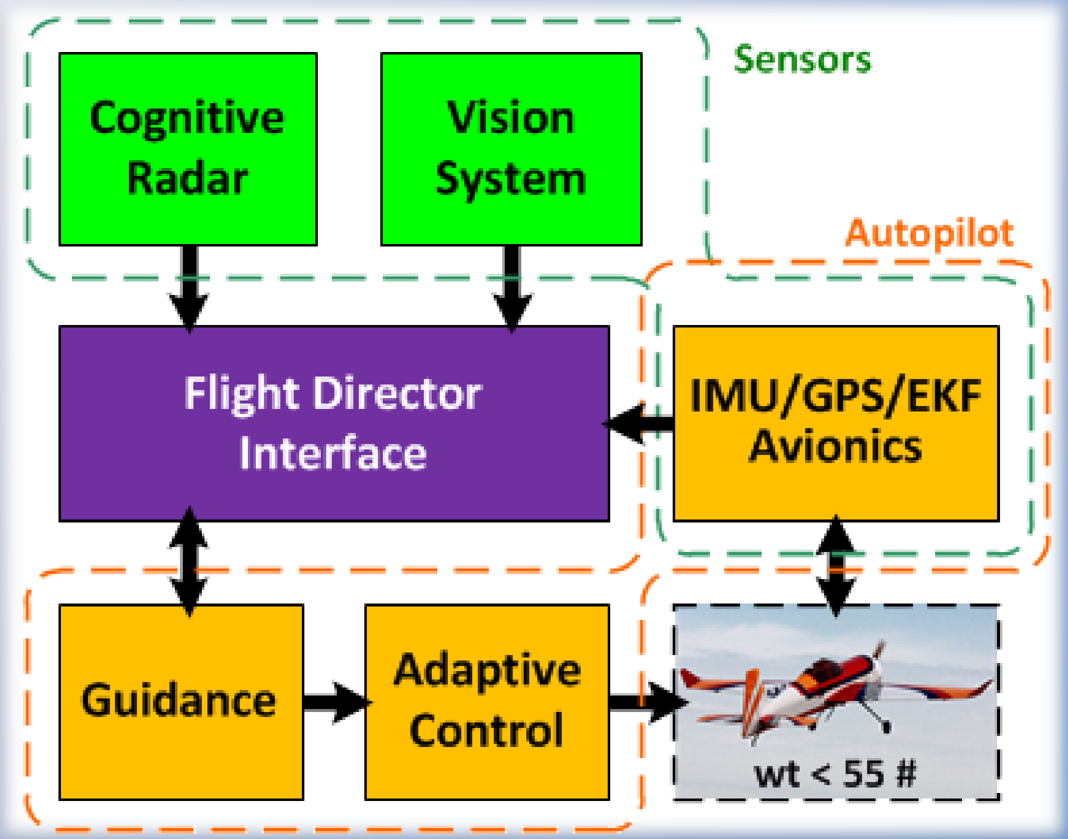
- Implementation – system level

Integrated system

- Flight director
  Inputs: Cognitve radar
  Inputs: Vision system
  Inputs: IMU, GPS, avionics
  Outputs: Guidance commands

- Autopilot
  Inputs: Guidance commands
  Outputs: Servo controls

- TK1 multicore processor
  Inputs: IMU, GPS, EKF data
  Inputs: radar data
  Inputs: vision image data
  Outputs: guidance commands



The innovation

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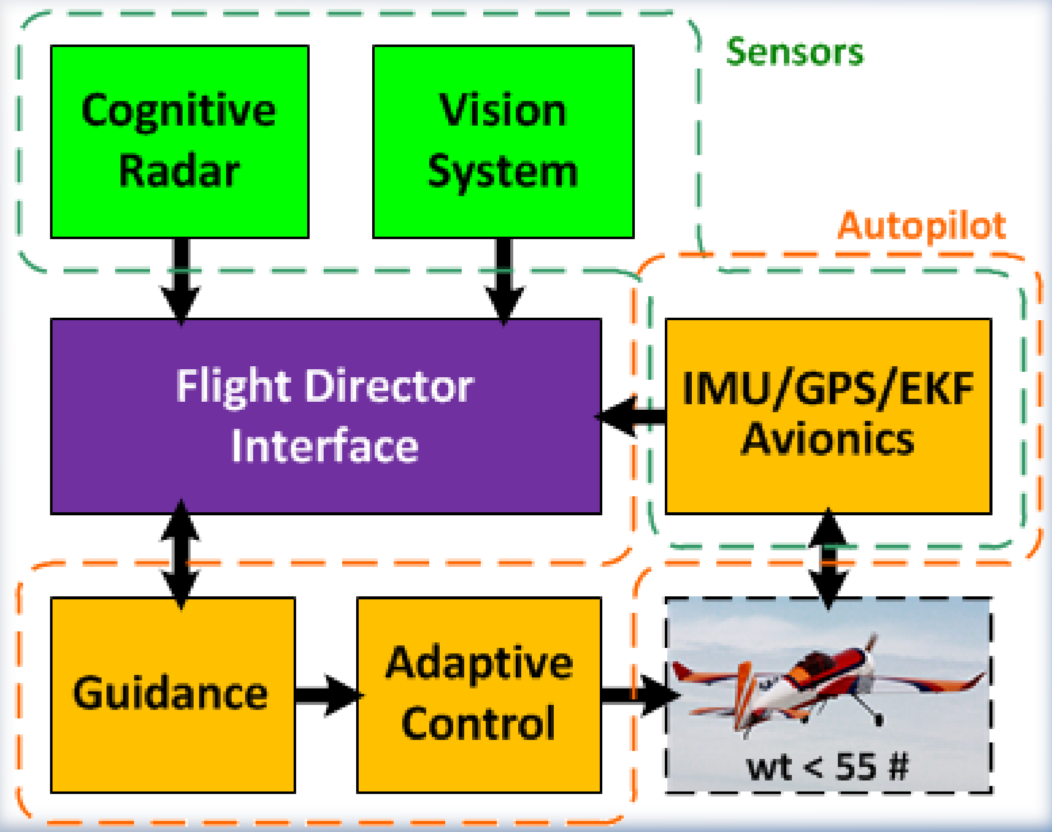
- Implementation – system level

Subsystems

- Cognitive radar
  remotely senses nearby objects
  reports their positions, closing rates
- Vision system
  images region of radar-detected object
  reports size of object
- Flight director & autopilot
  outputs safe trajectory using
  UAV knowledge, radar and vision data
- TK1 multicore processor
  on-board, real-time execution of
  flight director, autopilot, vision
  image proc., radar data processing



The innovation

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- Implementation – system level

  Subsystems

  – Cognitive radar
  remotely senses nearby objects
  reports their positions, closing rates

  – Vision system
  images region of radar-detected object
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  on-board, real-time execution of
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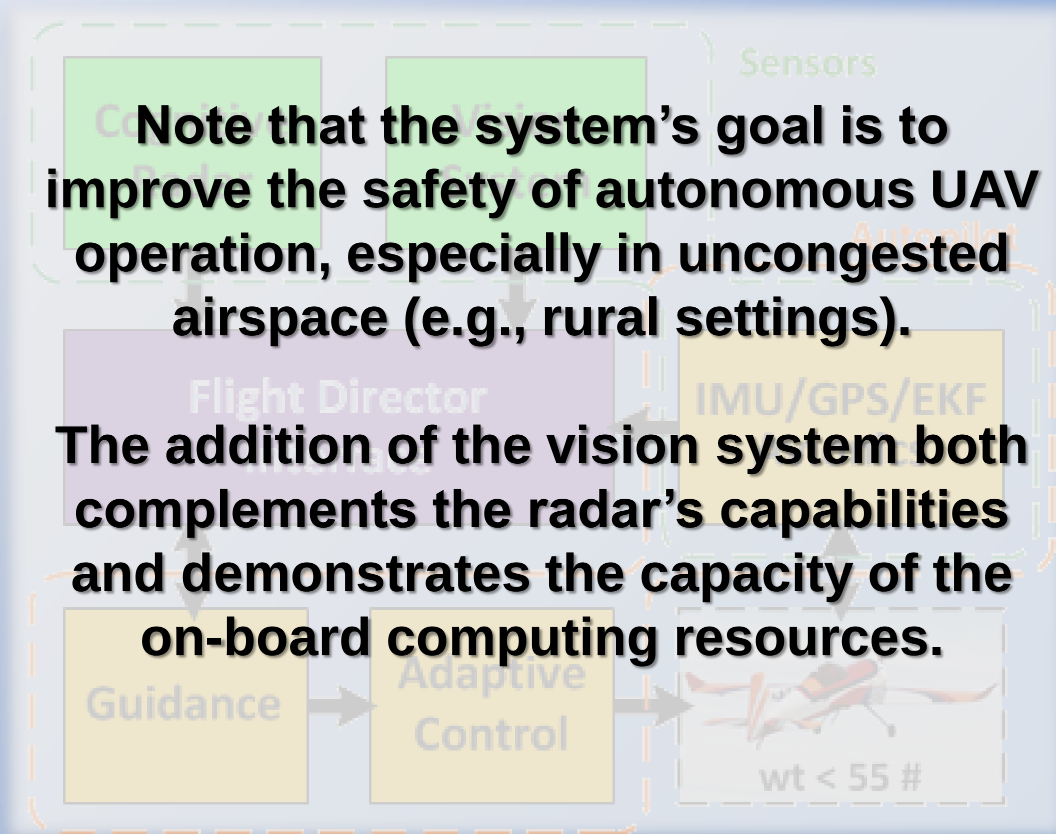

Note that the system's goal is to improve the safety of autonomous UAV operation, especially in uncongested airspace (e.g., rural settings).

The addition of the vision system both complements the radar's capabilities and demonstrates the capacity of the on-board computing resources.

Radar System

Radar – technical approach

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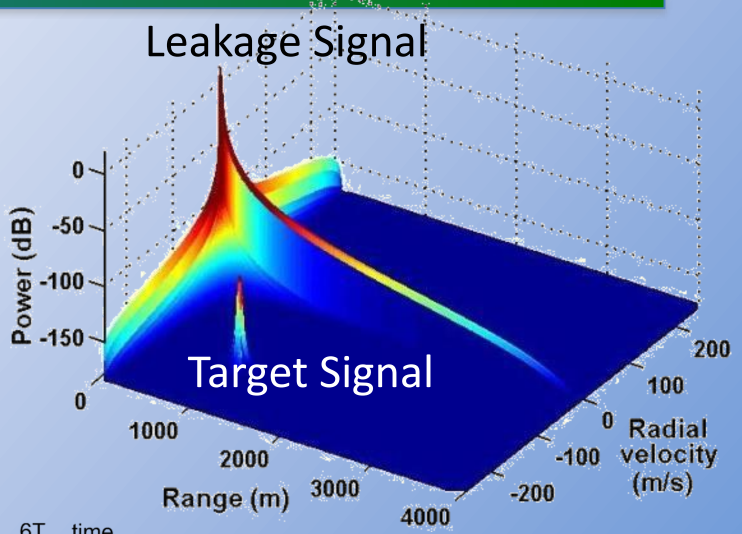
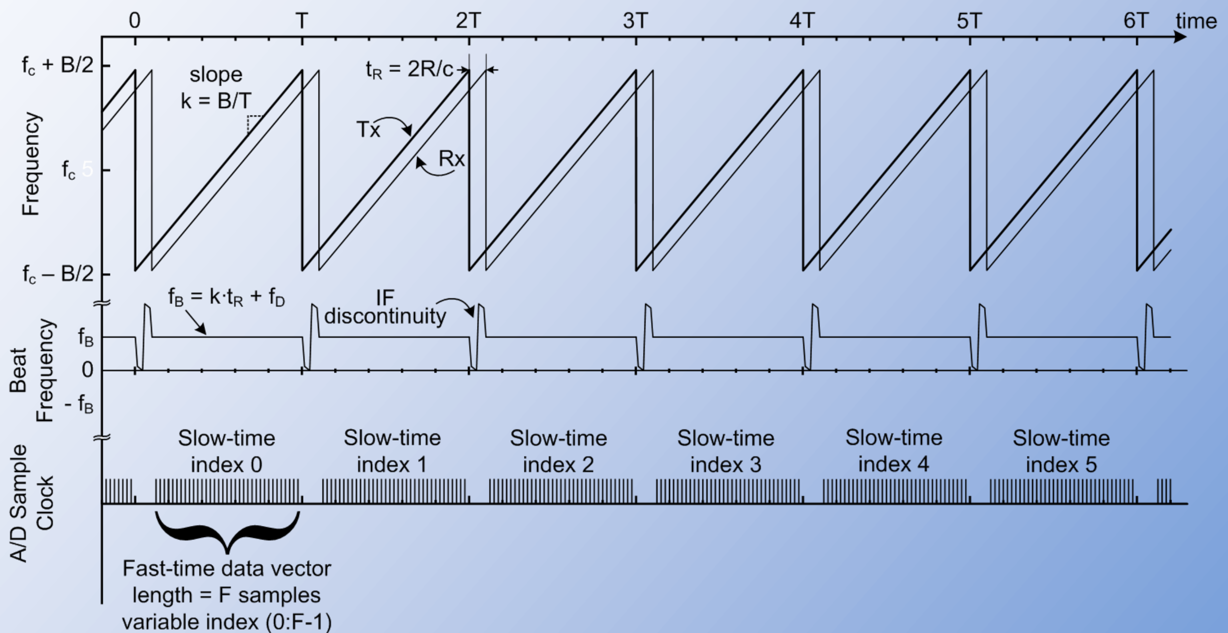
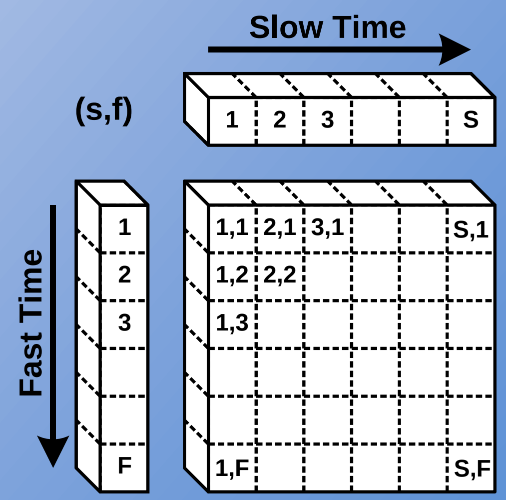
- Theory

  To overcome the challenge of strong Tx-Rx coupling, signals from targets near zero in both range and Doppler are ignored to permit reliable target detection. Signal processing involves 2-D fast Fourier transform (2-D FFT).







Radar – technical approach

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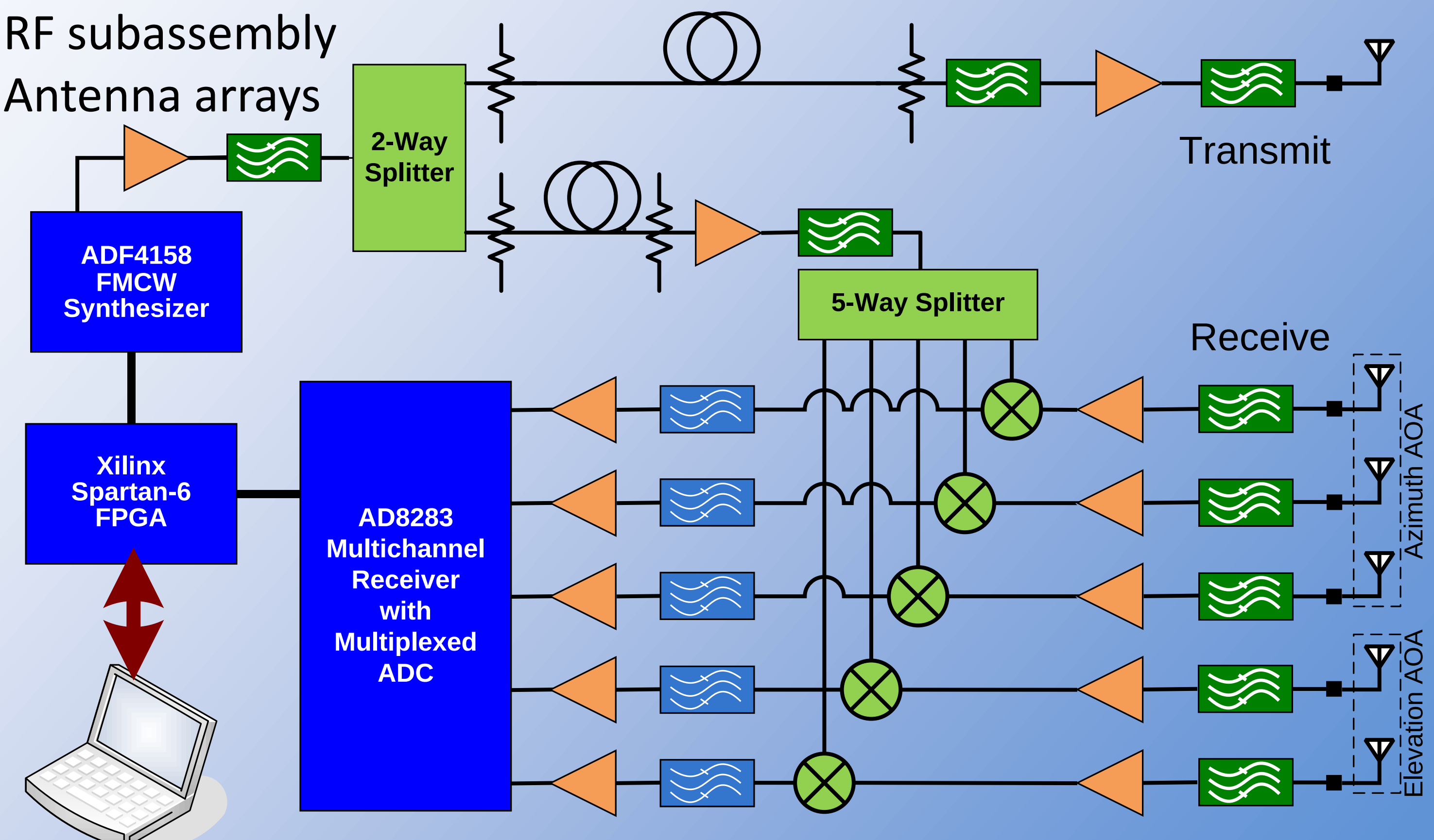
- Implementation – 1st-generation radar block diagram
  - Radar-ready ICs: FMCW synthesizer & multichannel ADC
  - FPGA
  - RF subassembly
  - Antenna arrays



Radar – technical approach

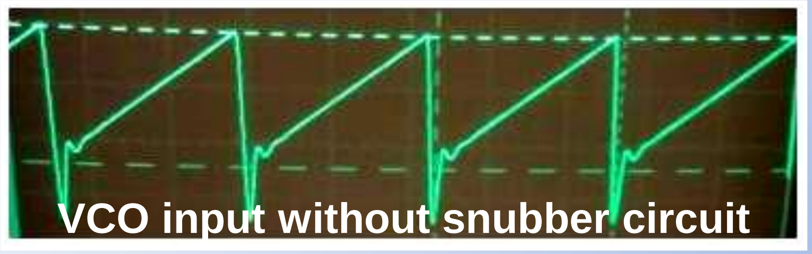
NASA Aeronautics Research Institute

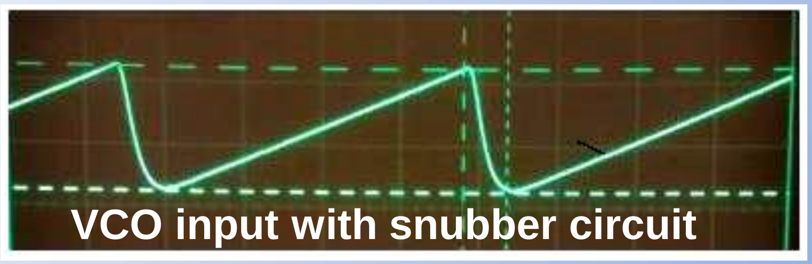
- Implementation – radar-ready subsystems

FMCW synthesizer

Analog Devices ADF4158

- FMCW signal generation
- Center frequency: 1.445 GHz
- Bandwidth: 15 MHz
- Modified evaluation board


VCO input without snubber circuit


VCO input with snubber circuit

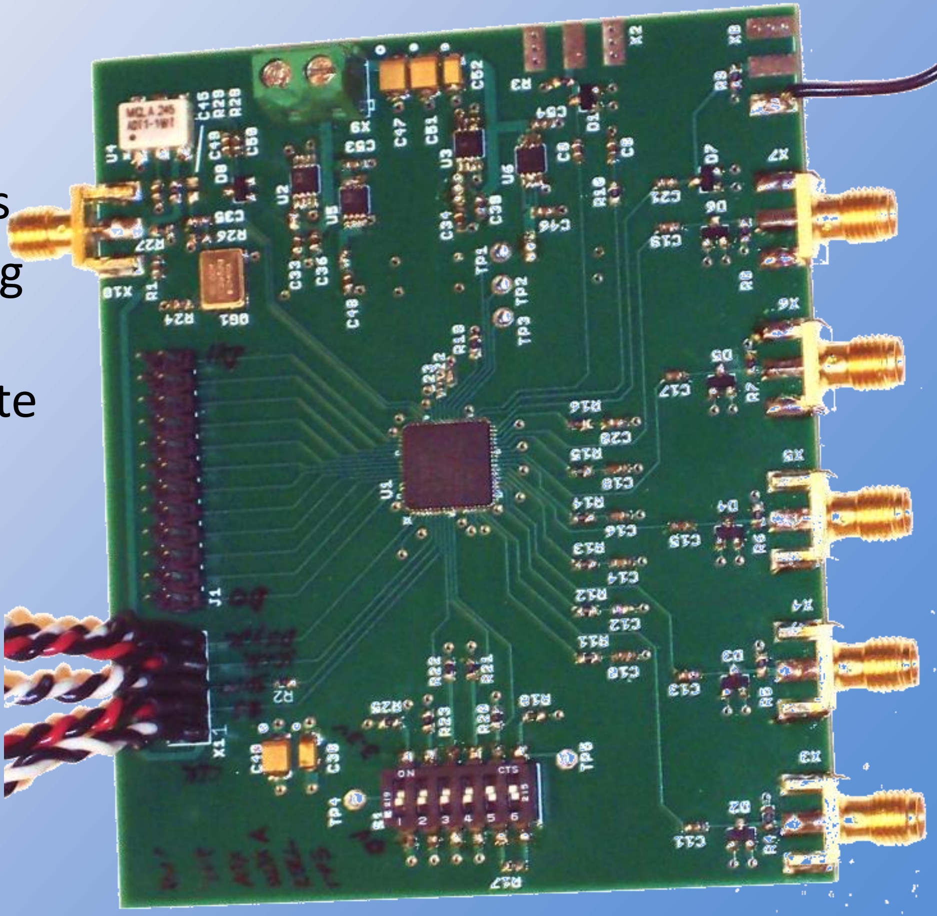
Radar – technical approach

- Implementation – radar-ready subsystems

multichannel ADC with analog preprocessing

Analog Devices AD8283

- Custom PC board developed
- Up to 6 multiplexed analog channels
- Integrated analog signal conditioning via programmable LNA, PGA, AAF
- Operated at 4 MSa/s per channel rate



Radar – technical approach

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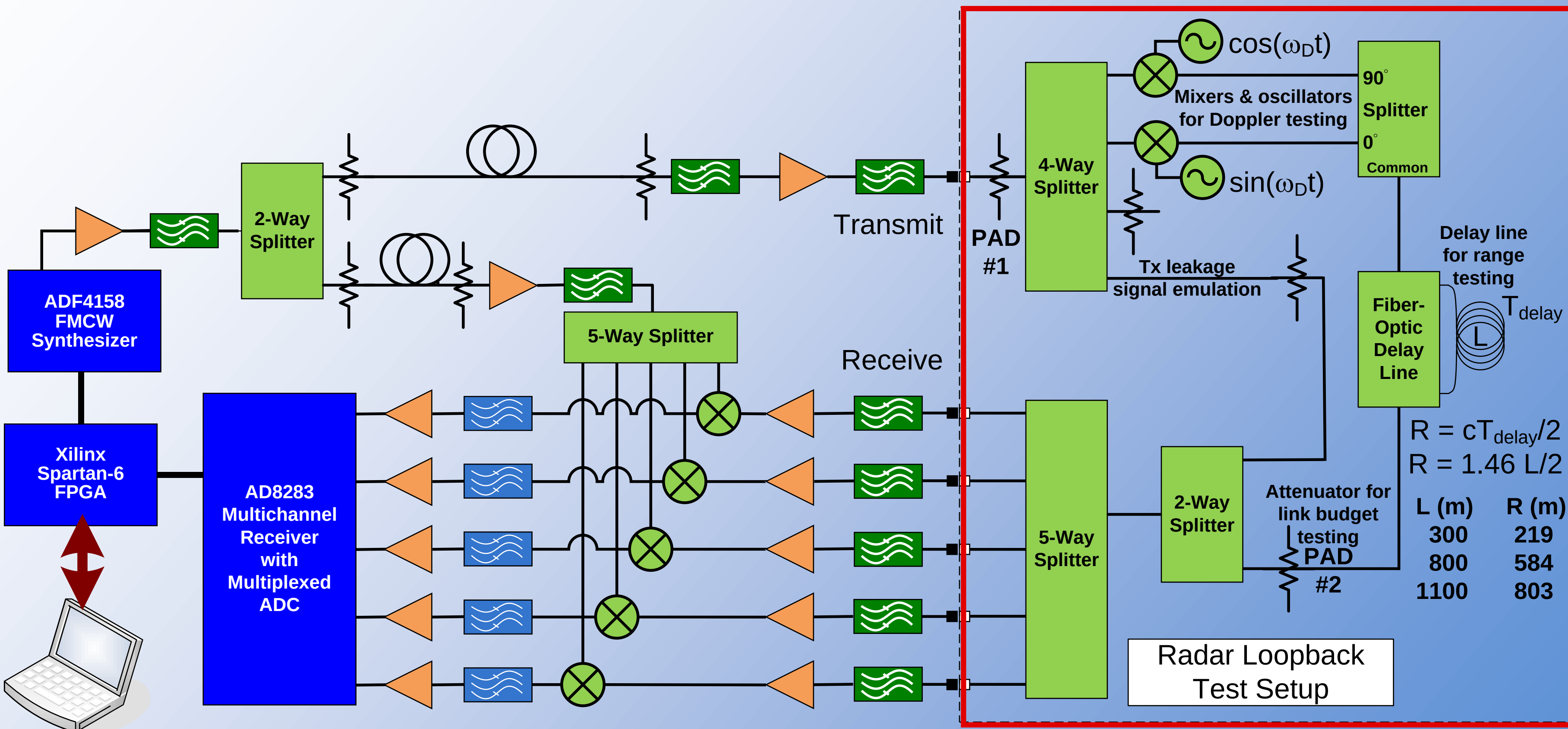
- Performance – lab testing setup (loopback)

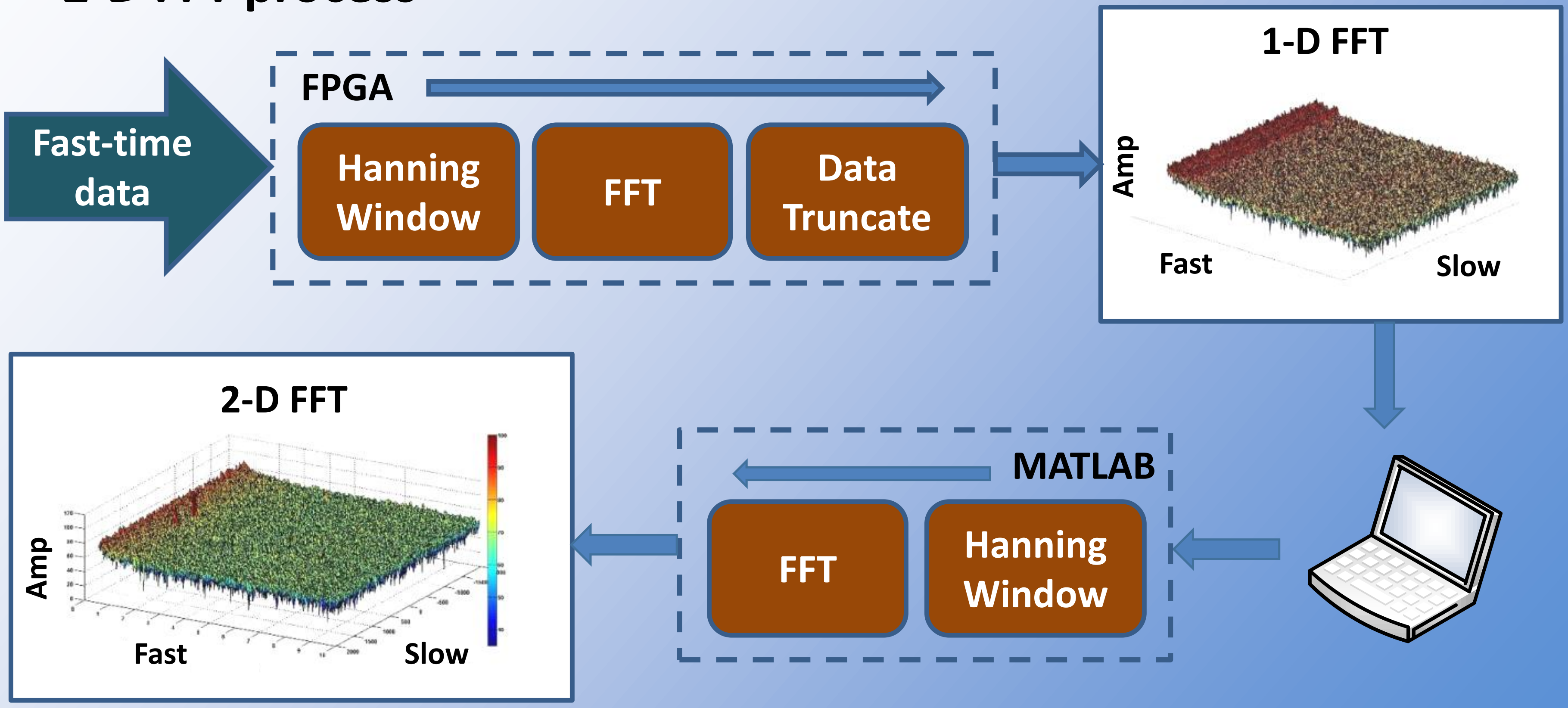


Radar – technical approach

NASA Aeronautics Research Institute

- Performance – FPGA processing description

2-D FFT process



Radar – technical approach

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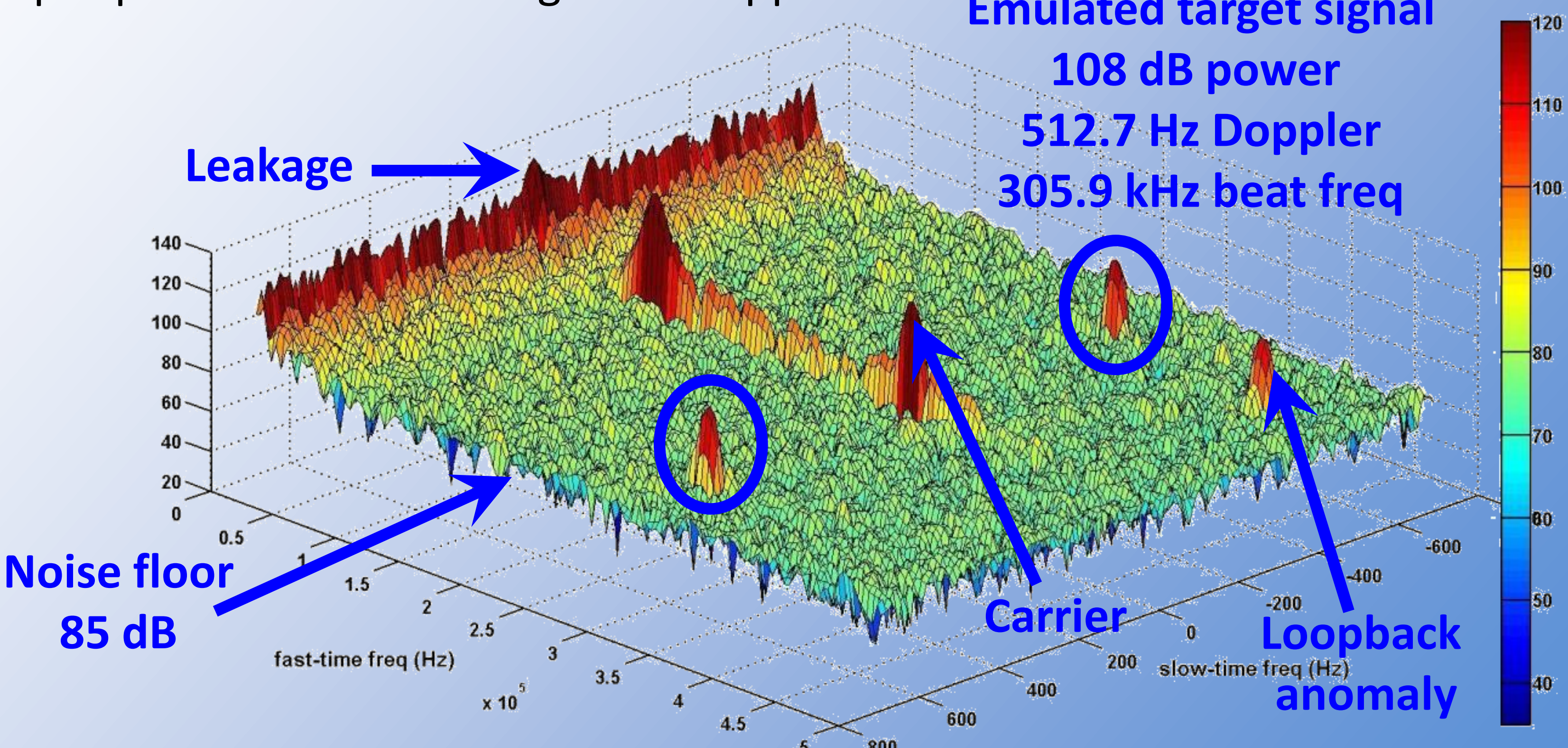
- Performance – FPGA processing example results

3-D graphic output

Loopback setup with leakage using 800-m fiber delay line (584 m range)
Input signal power -112 dBm, 500-Hz double-sideband modulation, output plot truncated in range and Doppler.



Flight test results (22 Feb. 2014)

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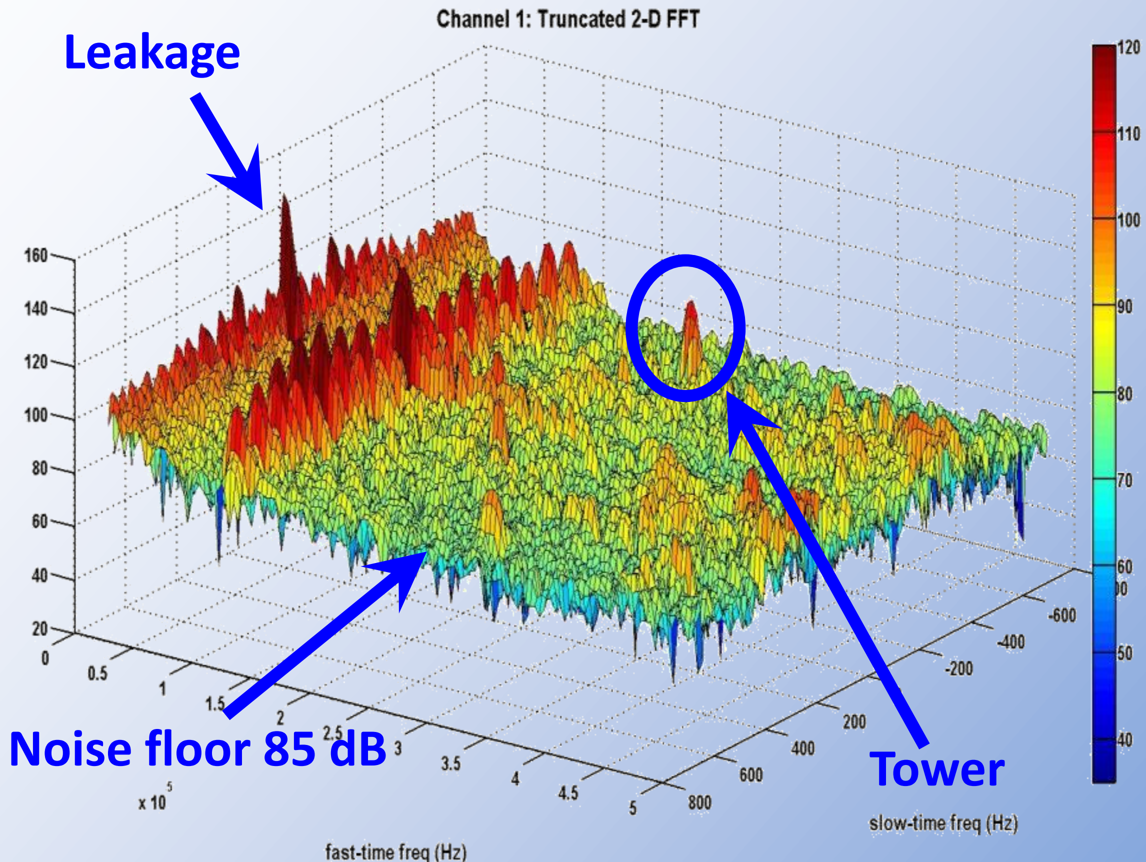
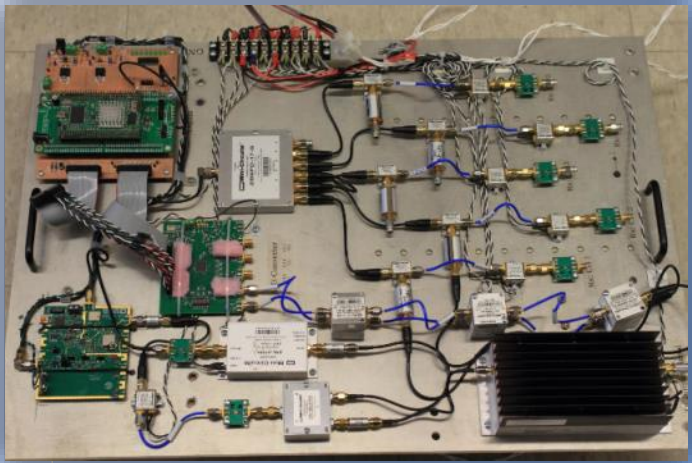
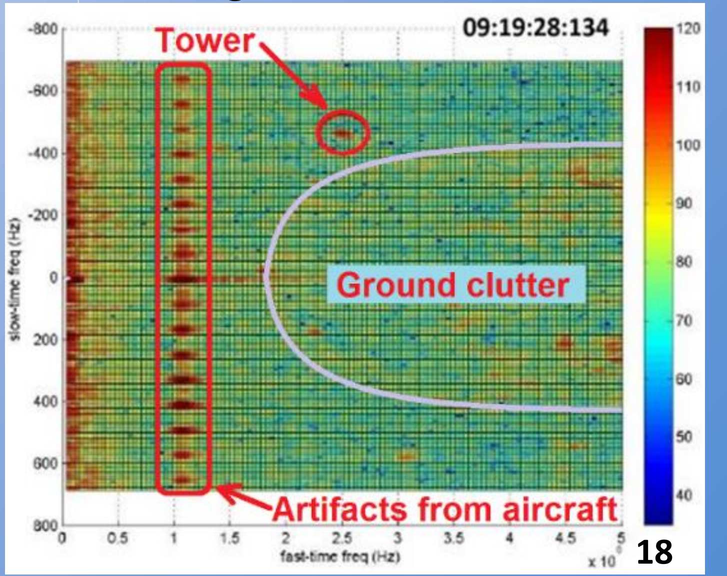
- Flight on KU Cessna 172 experimental aircraft past a 300’-tall radio tower

Measured results





Proof-of-concept system using custom PCBs



Radar – technical approach

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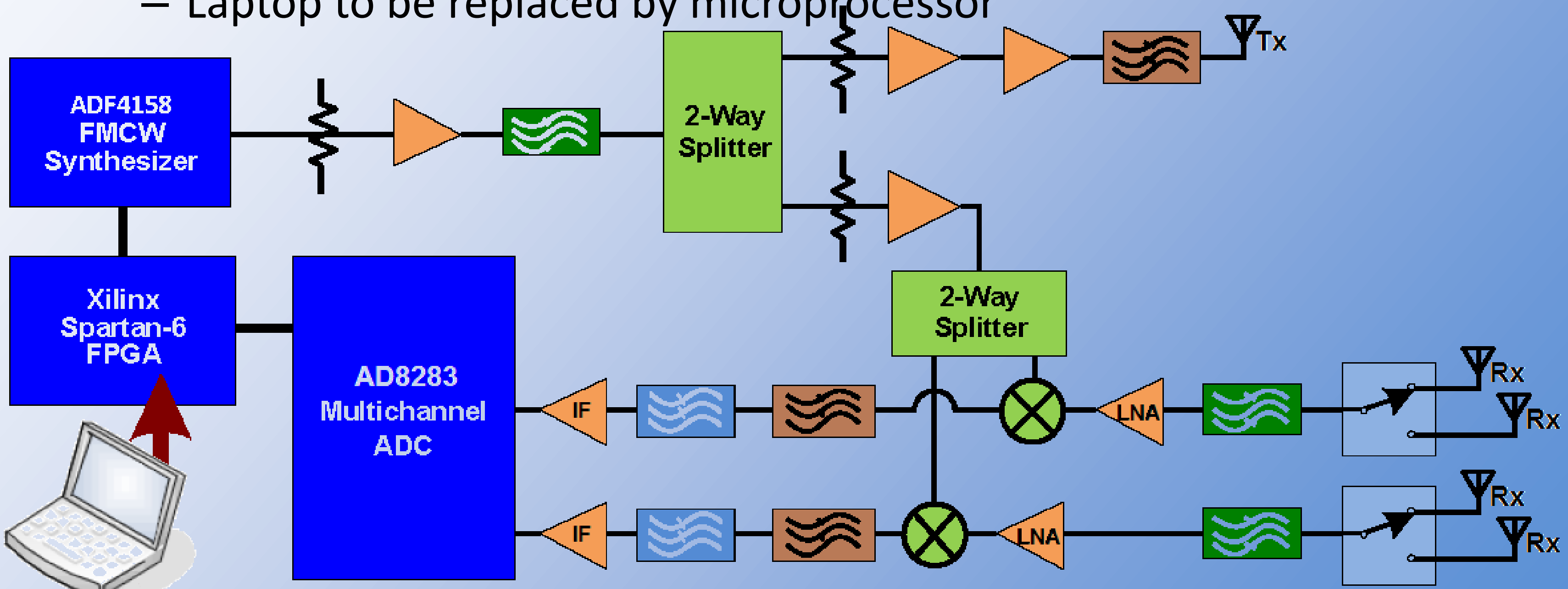
- Implementation – 1st-generation (miniaturized) radar block diagram (2.36 GHz operation)
  - Radar-ready ICs: FMCW synthesizer & multichannel ADC
  - FPGA
  - RF subassembly
  - Antenna arrays
  - Laptop to be replaced by microprocessor



Radar – status

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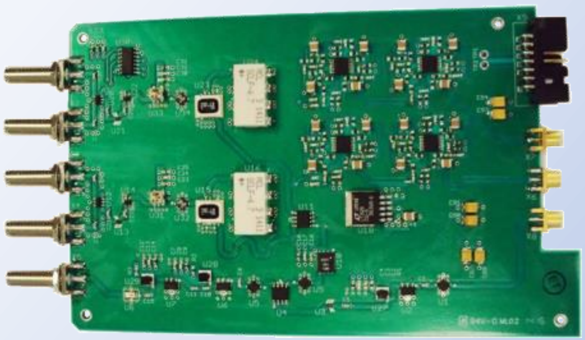
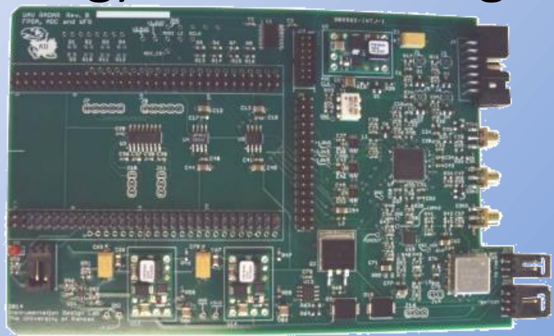
- Miniaturized system implementation (1st generation)

  Custom (in-house) designed RF (analog) board and digital board



Miniaturized RF front end assembly (Tx and Rx) (6.5” x 4”, 3 oz.)



Miniaturized digital subsystem (6.5” x 4”, 2.8 oz.) without the FPGA daughterboard

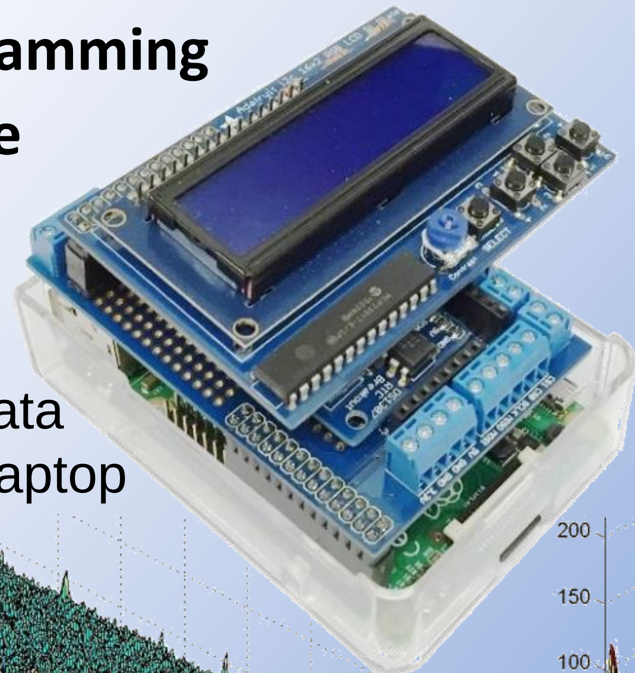
	Proof-of-Concept System	Miniaturized System
Size	18.5” x 26” x 6”	6” x 4” x 0.5”
Weight	>50 lbs	0.36 lbs*
Power consumption	30 W	<10W
Center Freq.	1.445 GHz	2.36 GHz
Bandwidth	15 MHz	15 MHz
Transmit power	23 dBm	21 dBm
Observation time	100 ms	100 ms
Max detection range	430 m	860 m

* Weight does not include antennas and battery

Six antenna array composed of two COTS antenna assemblies (7.5” tall x 3.4” diameter, 12.2 oz.)

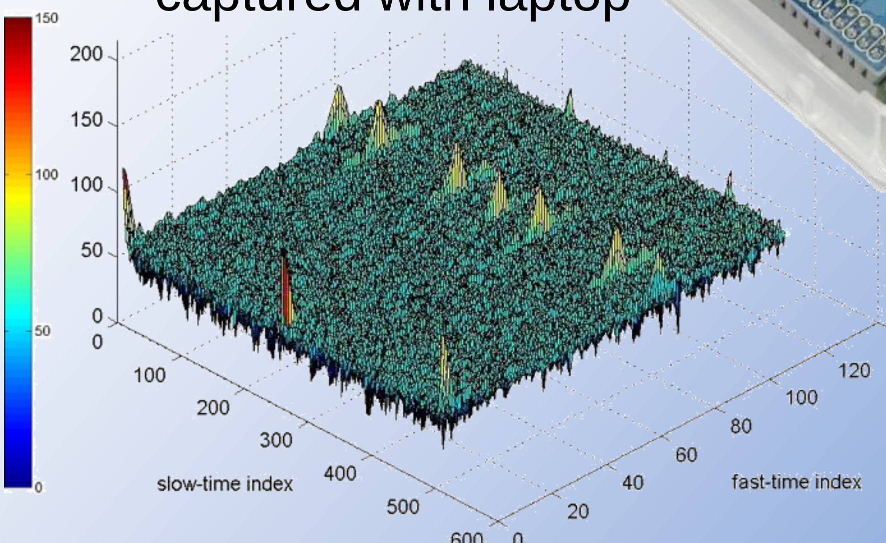
Radar – status

- Laptop replaced by Raspberry PI for UAV flight testing
  - **Radar programming**
  - **Data capture**

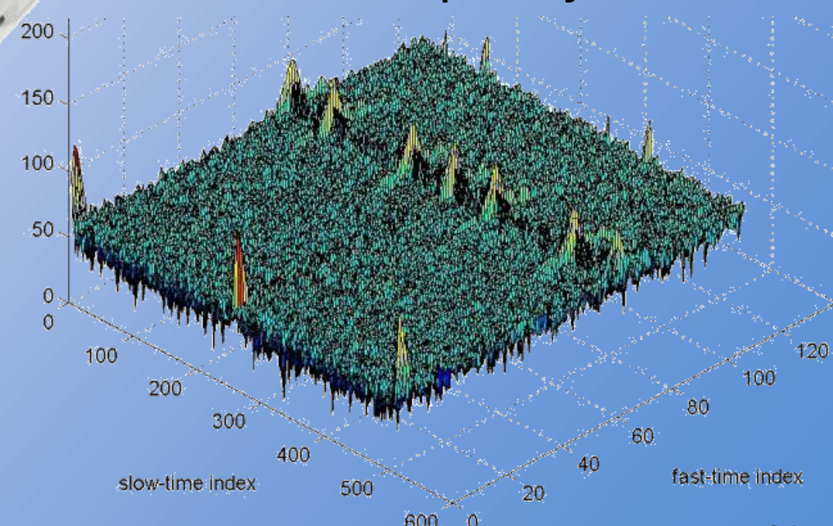


This effort was accomplished under POC and NASA SBIR

Loopback data captured with laptop



Loopback data captured with Raspberry PI



Radar – status

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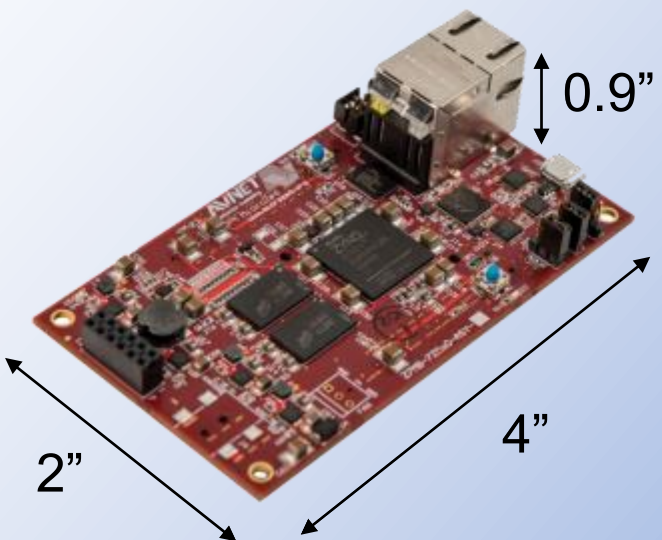
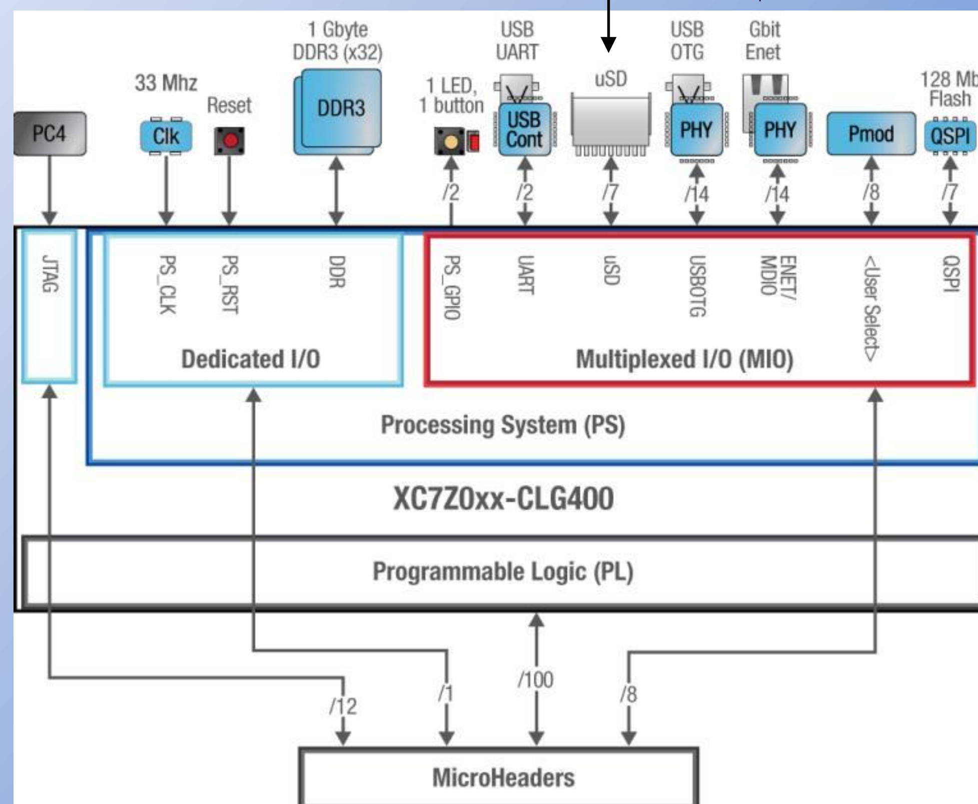
Board: MicroZed (industrial version)
FPGA: Xilinx Zynq 7Z020
Memory: 1 GB, DDR3
Previous FPGA: Ztec Spartan 6 (obsolete)



2-D FFT Memory Space

External Storage

Communication To Tegra K1



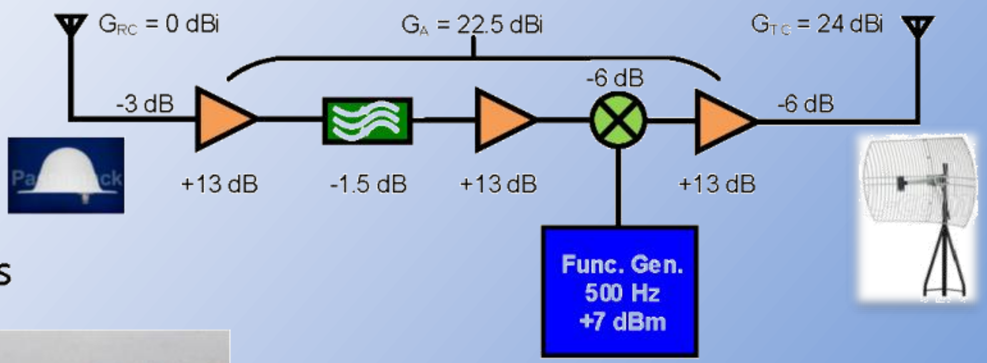
Radar – status

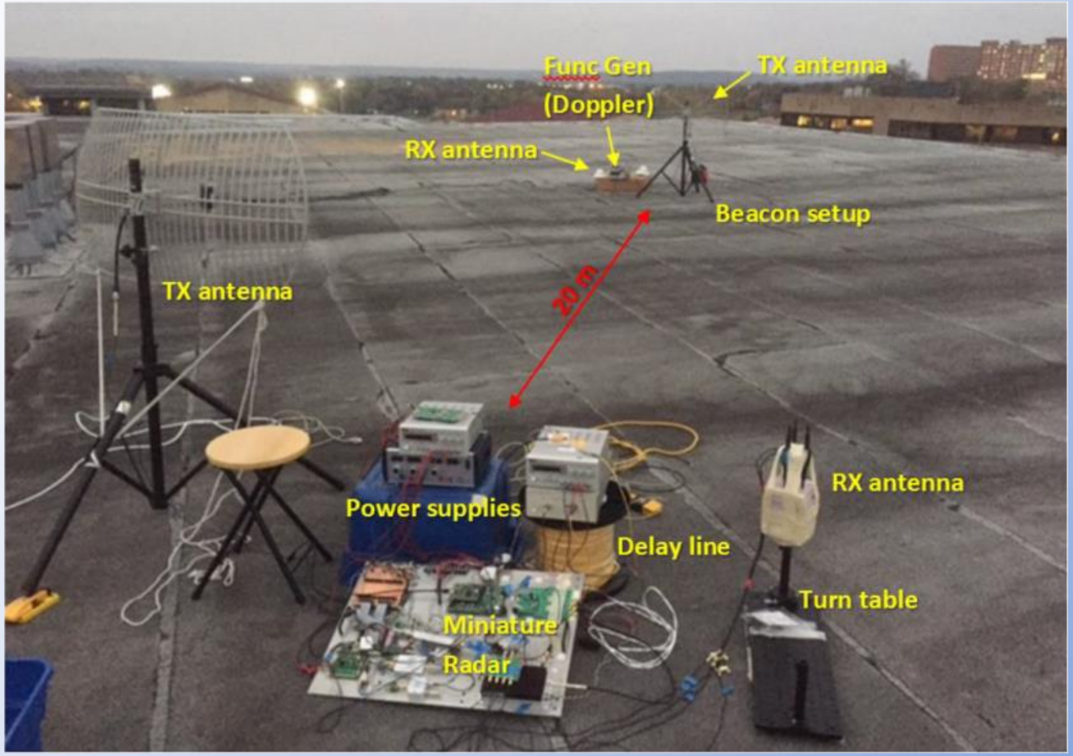
Angle of Arrival Calibration Target

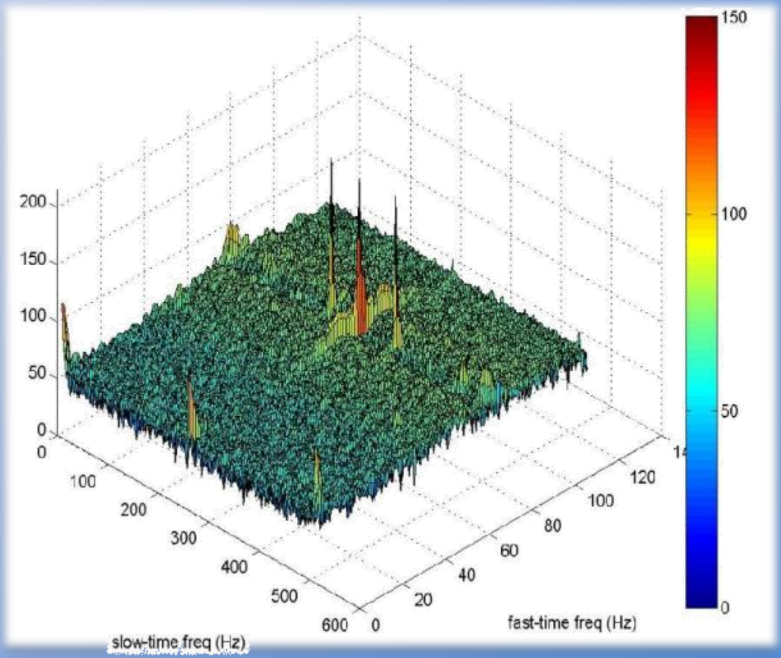
Target size: 17.5 dBsm

Data gathered:

- 360° azimuth in 10° increments
- ±60° elevation in 10° to 5° increments







Radar – status

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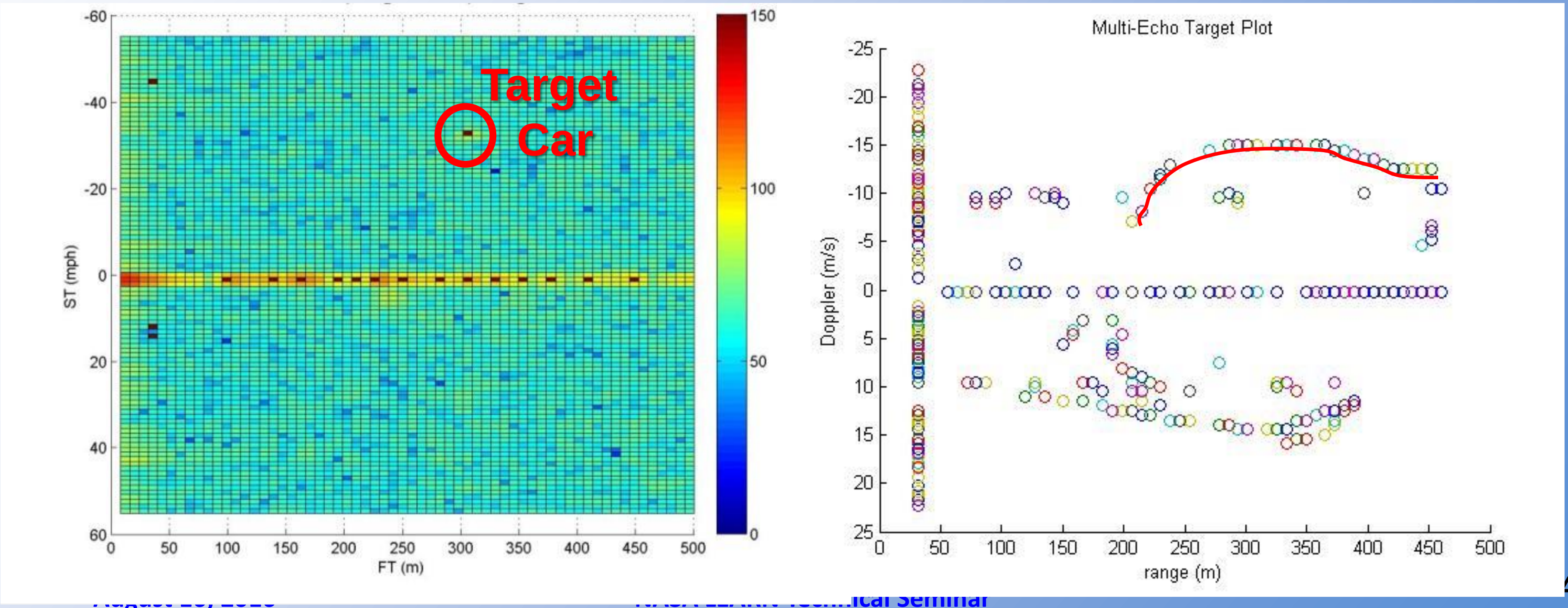
- Ground-based testing

  Rooftop data collection to validate
  range, Doppler, Az/El angle measurements

1. Photo of approaching car
2. Radar image showing target detection of the car in range and Doppler
3. detected targets from consecutive radar updates showing approaching car outlined in **red**.



Radar – status

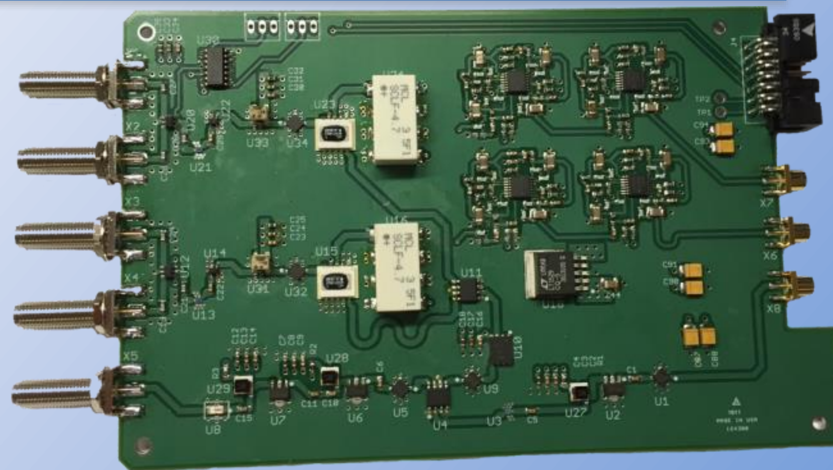
- 2nd-generation hardware

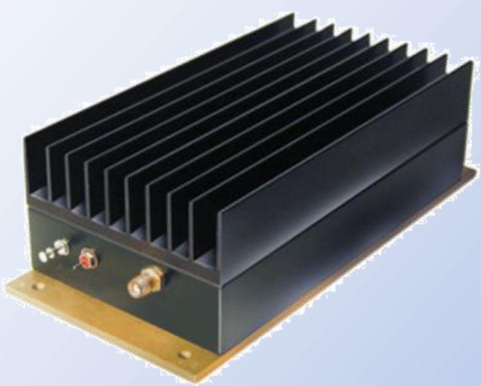
  Operating frequency changed to 2.45-GHz ISM band

  Miniaturized RF board developed

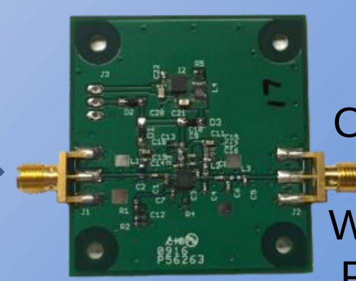
  Digital board (FPGA, DDS, ADC) is next

  Miniature transmit power amplifier developed





Gain:	30 dB
Output:	28 dBm
Size:	7” x 3.3” x 2”
Weight:	28.4 oz.
Power:	13 W



Gain:	33 dB
Output:	28.1 dBm
Size:	1.8” x 2” x 0.3”
Weight:	0.5 oz.
Power:	3 W

Radar – status

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- Cognitive frequency selection
  - 2.45-GHz ISM band operation (relaxed FCC licensing)
  - Anticipated EMI due to Wi-Fi and other users
  - Radar will sense ambient EMI and adapt center frequency operation to maximize SNR

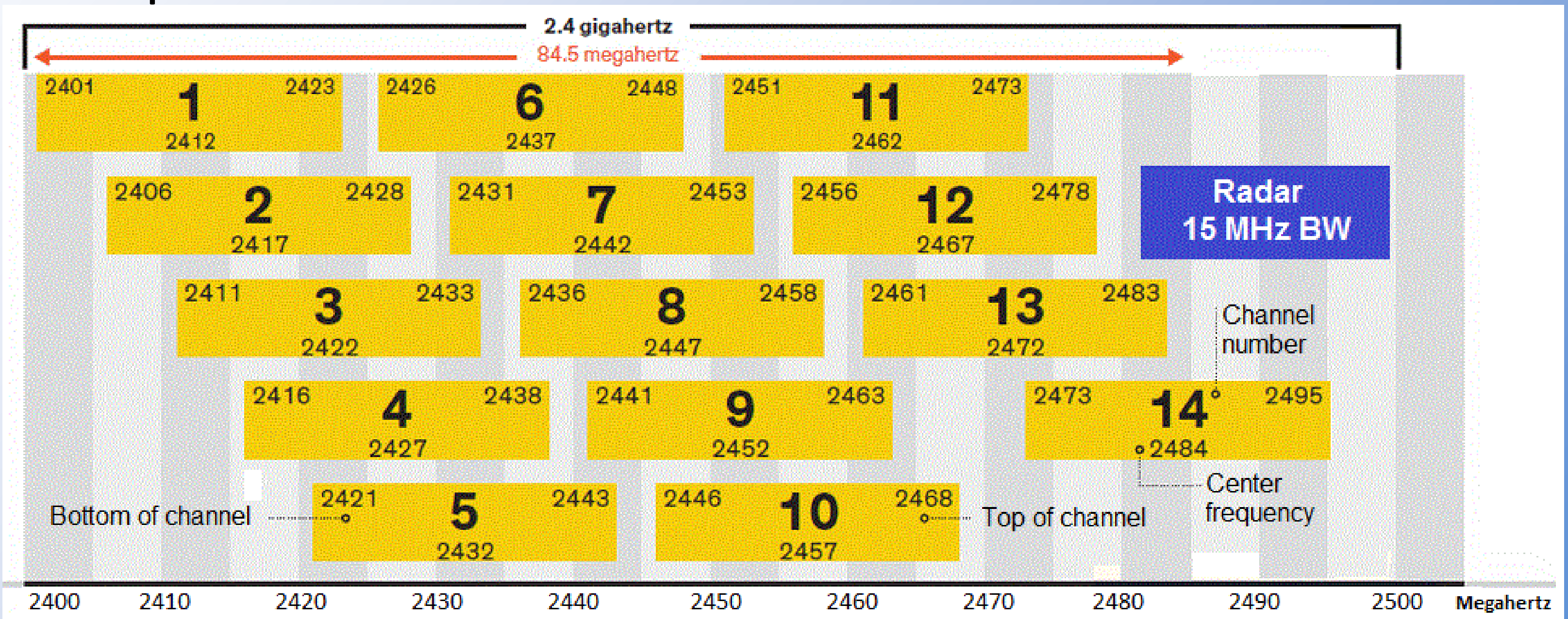
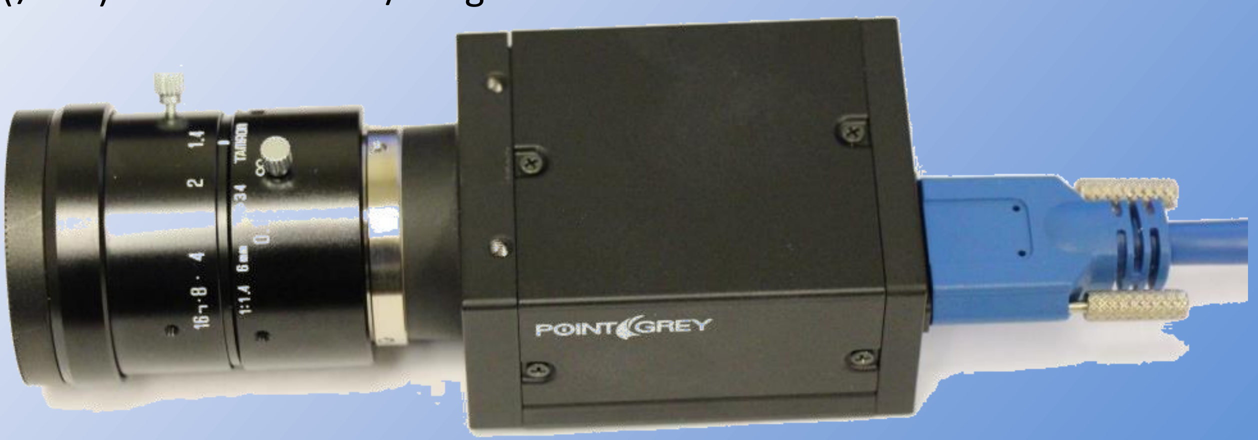


Chart showing radar within 2.4-GHz Wi-Fi spectrum adapted from IEEE Spectrum, July 2016

Vision System

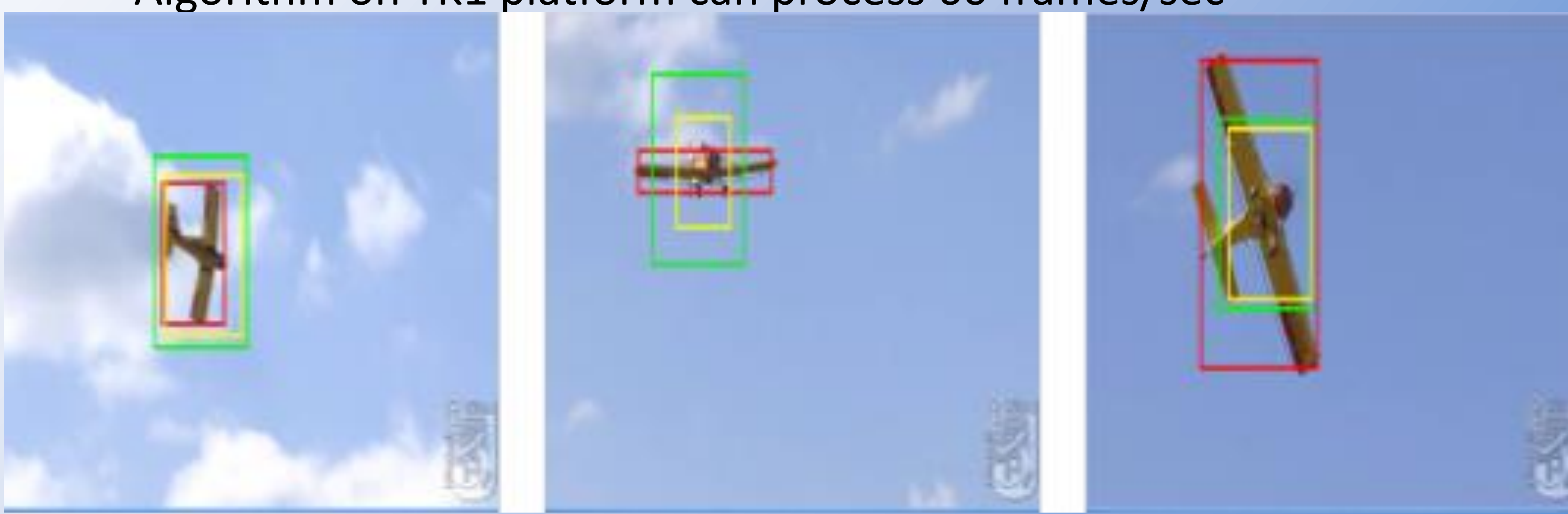
Vision – technical approach

- Implementation
  - **Hardware**
    - Grasshopper USB3 vision camera from Point Grey
      - Grasshopper3 GS3-U3-32S4M
      - 44 mm x 29 mm x 58 mm / 90 g
    - Tamron lens
      - M118FM06 Tamron C-mount
      - 6-mm compact fixed-focal-length
      - system field of view is about 50° by 40°
      - (Ø x L) 29 x 44.48 mm / 90 g



Vision – status

- Accomplishments
  - **Vision system**
    - Algorithm for target tracking in dev / testing using recorded images
  - **Nvidia Tegra TK1 multicore processor**
    - Real-time processing of vision algorithms demonstrated in lab
    - Algorithm on TK1 platform can process 60 frames/sec



Red box shows our algorithm results; yellow and green represent published techniques – our approach runs faster and requires no training

Flight Director & Autopilot System Hardware and Algorithms

TK1 – technical approach

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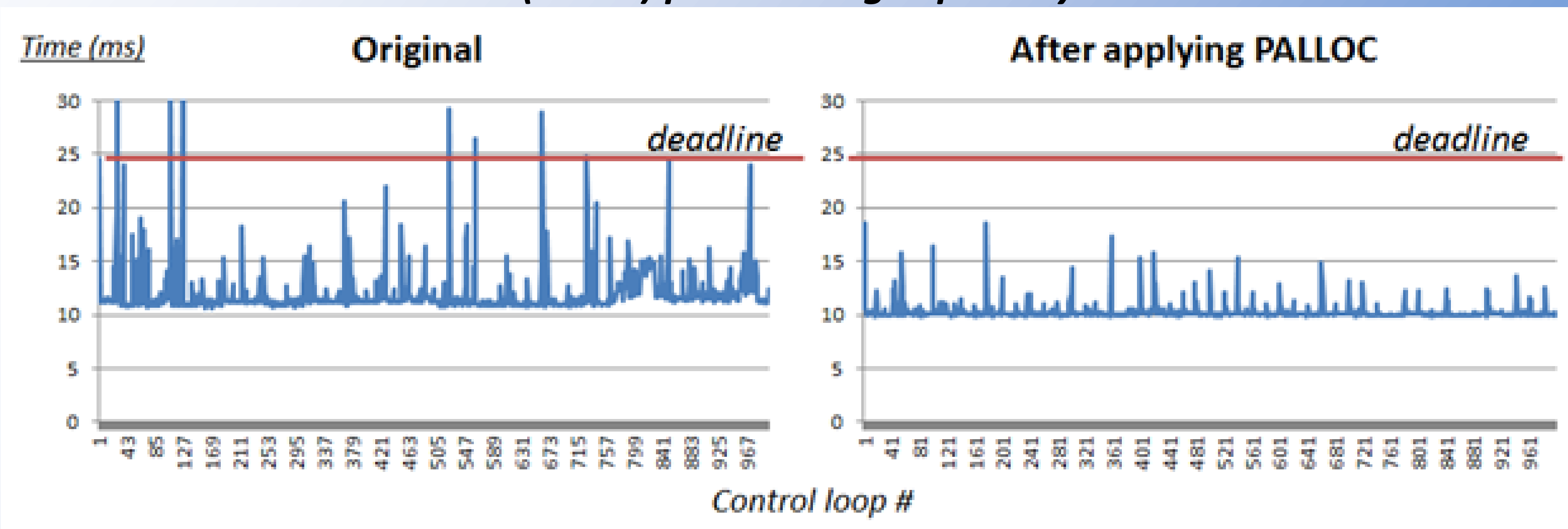
- Nvidia Tegra TK1 multicore processor
  - Real-time processing of vision algorithms demo’d in lab
  - Real-time processing of radar signals demo’d in lab
  - Memory allocator (partitioning) PALLOC shown to improve execution times. ***Our previously developed kernel level memory allocator PALLOC supports advanced resource (cache) partitioning capability.***



Execution time variations of the flight controller before and after applying PALLOC.

TK1 – technical approach

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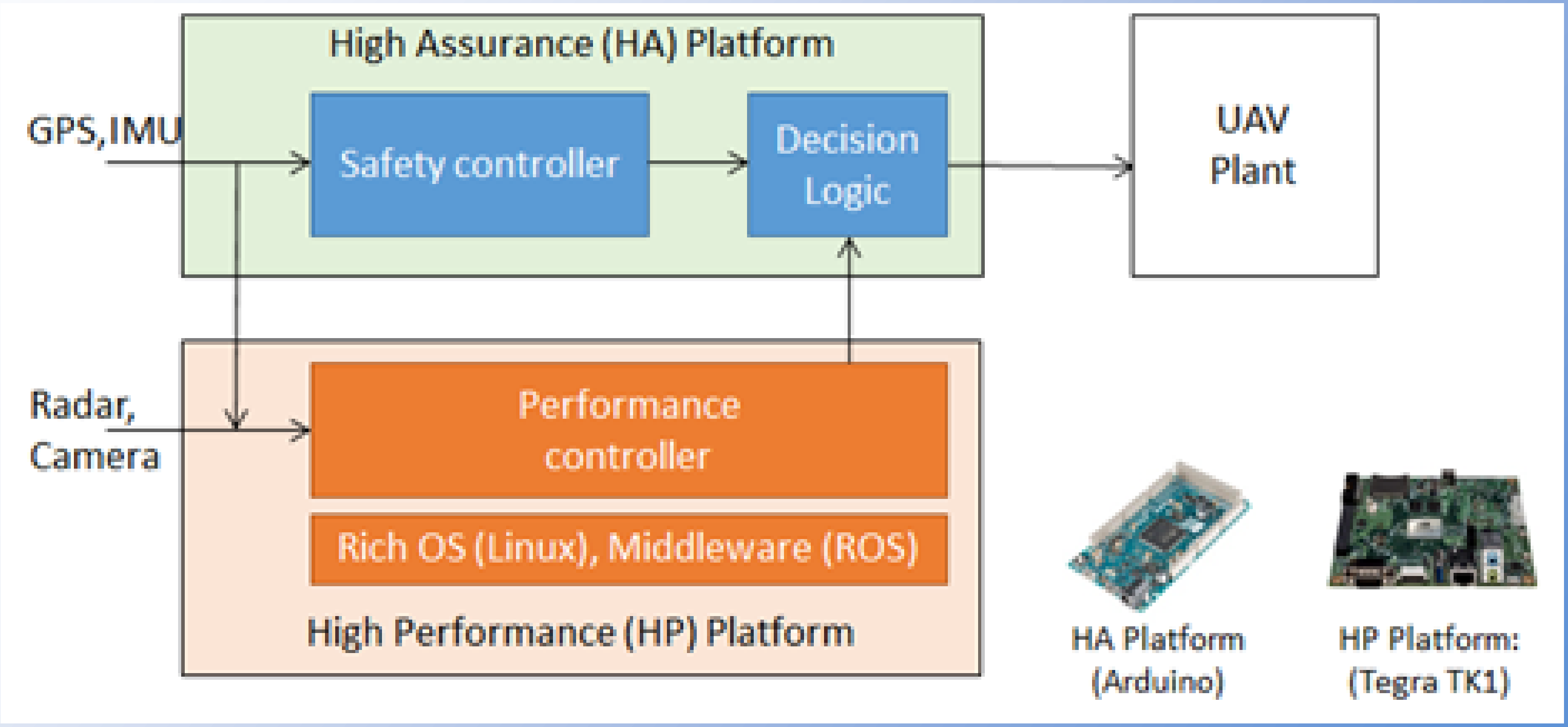
- Nvidia Tegra TK1 multicore processor
  - Radar and Vision algorithms integrated using the TK1's GPU cores
  - Simplex, fault-tolerant architecture to improve dependability



Flt dir – technical approach

- Accomplishments – integration of autopilot and flight director with multicore processor
  - A 5”x 5” PC board developed that provides aircraft interfaces with the Tegra K1 multicore processor.
  - Autopilot and flight dir. running on Tegra cores with partitioned memory.
  - Assembly has been lab tested and installed on two UAVs.

←33% Yak-54 fixed-wing aircraft

DG-808 fixed-wing glider →

Flight Systems

Flt testing – technical approach

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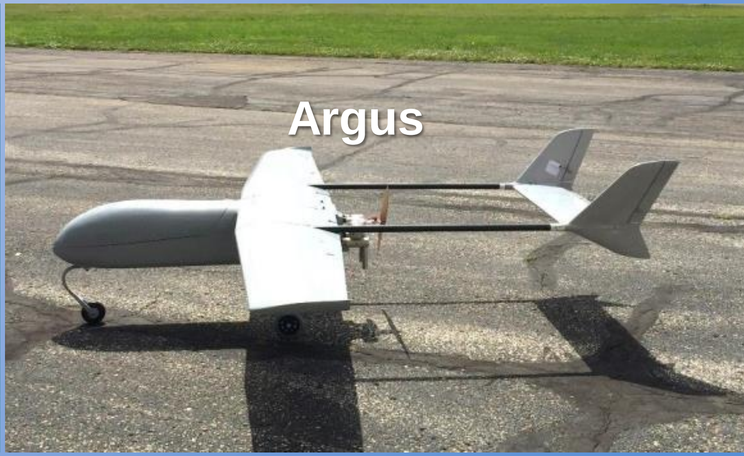
- Platforms/Flight Director/Autopilot
  - > 50 sUAV flight tests conducted for validation and verification, including 7 autonomous using in-house algorithms and hardware
  - FAA issued blanket COA for small UAS (< 55#)
  - Three UAS platforms have been designed, manufactured, instrumented; thus far two have been flight tested
  - Our AE team has, for the first time, captured in real-time the system I.D. (e.g., aircraft flight coefficients) of a UAS platform (DG808) for another NASA team



Status of the LEARN effort to date

Publications

- Garcia G; Keshmiri S; “Adaptive and Resilient Flight Control System for a Small Unmanned Aerial System,” International Journal of Aerospace Engineering, Volume 2013, Article ID 289357, 25 pages, 2013.
- Shi L; Allen C; Ewing M; Keshmiri S; Zakharov M; Florencio F; Niakan N; Knight R; “Multichannel sense-and-avoid radar for small UAVs,” 32nd Digital Avionics Systems Conference (DASC), Syracuse, NY, Oct 6-10, 2013.
- Valsan PK; Yun H; Farshchi F; “Taming Non-blocking Caches to Improve Isolation in Multicore Real-Time Systems,” *IEEE Intl. Conference on Real-Time and Embedded Technology and Applications Symposium (RTAS)*, 2016 (selected as one of the Outstanding Papers)

Status of the LEARN effort to date

Publications

- Pellizzoni R; Yun H; "Memory Servers for Multicore Systems," *IEEE Intl. Conference on Real-Time and Embedded Technology and Applications Symposium (RTAS)*, 2016
- Vivekanandan P; Garcia G; Yun H; Keshmiri S; "A Simplex Architecture for Intelligent and Safe Unmanned Aerial Vehicles," *IEEE International Conference on Embedded and Real-Time Computing Systems and Applications (RTCSA)*, August 2016
- Wang G; Wu Y; "Real-Time Visual Tracking: Promoting the Robustness of Correlation Filter Learning" *European Conference on Computer Vision (ECCV)*, October 2016

Status of the LEARN effort to date

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Schedule status (Q2/Q3 milestones) **[12-mo no-cost extension granted]**

- fabrication and characterization of revised miniaturized RF assembly
  RF board being characterized, digital board in layout
- fabrication and testing of vision system utilizing portion of multicore processor
  Complete: Algorithm refinement continues
- laboratory validation of radar system with flight director
  Delayed: Interfaces tested, integration awaiting new radar HW
- laboratory validation of vision system with flight director
  On track: Vision algo refinement to improve performance on low-contrast targets
- integration of system hardware on manned aircraft incl. interfacing aircraft data system
  Delayed: pending lab testing/integ of new radar HW

Next steps

- ***Radar system***
  Complete assembly of new miniaturized radar
  Airborne validation on surrogate manned aircraft
- ***Flight director / multicore processor***
  Continue refining autopilot/flt director algorithms with customized dynamic model
  Integration testing with radar and vision sys
- ***Vision system***
  Continue collection of in-flight video from UAV tests flights
  Refine algorithm development using flight data
- ***Validation / verification***
  Continue UAS flight tests and optimize control algorithms

Next steps

- ***Radar system***
  Radar freq migration to 2.4-2.5 GHz ISM band
  Cognitive freq selection within ISM band
  Board redesign of miniaturized RF subsystem
- ***Flight director / multicore processor***
  Flight test of integrated autopilot/flight director *
  Miniaturization of custom PC board
- ***Vision system***
  Collection of in-flight video from UAV tests flights
  Algorithm development using flight data
- ***Validation / verification***
  Prep for system integration on manned aircraft

***** Will be first ever flight test of NMPC algorithm***

Backup slides

Radar – status

NASA Aeronautics Research Institute

A variety of programs have supported development of the Multichannel Sense-and-Avoid Radar for Small UAVs, each with their own objectives. While objectives may overlap, these are not duplicative as the differing technical approaches are pursued.

Technical Objectives	LEARN II	POC	KBOR	NASA SBIR
shift to 2.45-GHz ISM band	●			●
cognititve frequency selection	●			●
range-dep sensitivity vs latency	●			
integrate with flight director	●	●		
detach from laptop		●		
new FPGA		●		
onboard data storage		●		
increased Tx power		●		
upgraded test capabilities		●		
integrate with microprocessor		●		
hardware consolidation			●	●
increased data throughput			●	
real-time radar processing			●	
radar flight testing	●		●	
random phase encoding				●