A Low-Cost Mechanically-Steered Weather Radar Concept

18 October 2018

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Fraunhofer FHR

Motivation

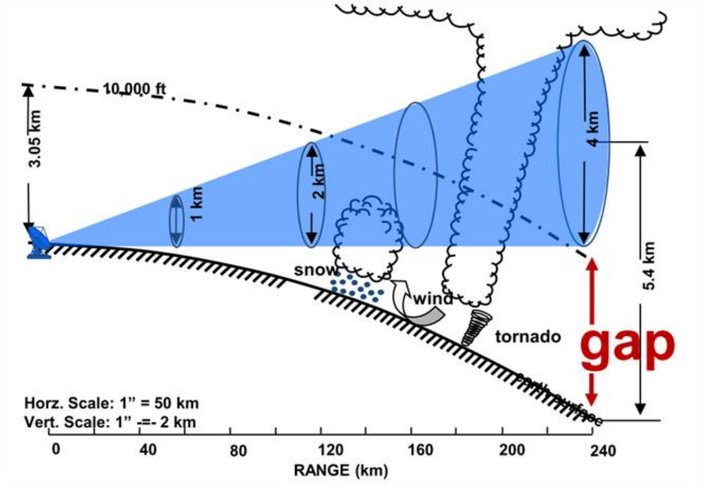
Development of a cost-effective Doppler dual-polarized radar node for a short-range weather radar network

Flash-floods, tornadoes, forest fires

Hailstorms, rainstorms, snow

Motivation

Nowadays, about 70% of the troposphere below 1 km cannot be observed by radar means.

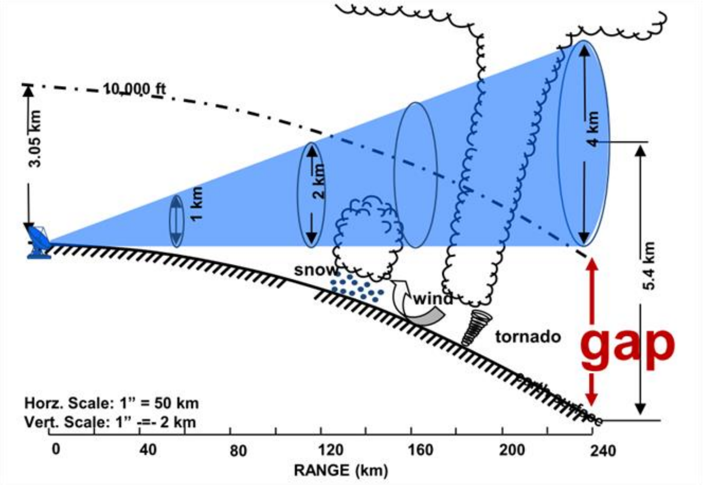


- Being limited by the earth curvature, traditional long range weather radars (up to about 200 Km range) are unable to provide coverage of the lower part of the atmosphere.
- Excerpted from WakeNet-Europe 2013, by Mr. McLaughlin (UMASS) and Mr. Drake (Raytheon)

"There is insufficient knowledge about what is actually happening (or is likely to happen) at the Earth's surface where people live", National Academy of Sciences,1998

Motivation

Nowadays, about 70% of the troposphere below 1 km cannot be observed by radar means.



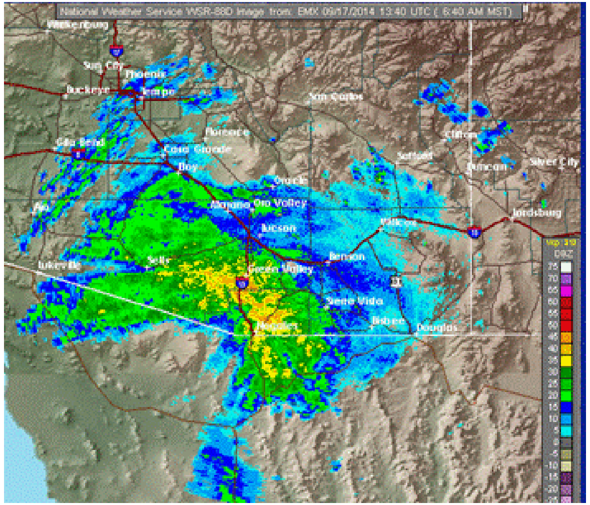
- This yields inherent difficulties in the
  - understanding,
  - prediction
  - and timely reaction

to weather phenomena like intense convective storms and tornadoes which develops up to a height of about 3 Km in the troposphere.

"There is insufficient knowledge about what is actually happening (or is likely to happen) at the Earth's surface where people live", National Academy of Sciences,1998

Motivation

Long-range weather radars suffer from orographic shielding, low space resolution and high revisit time



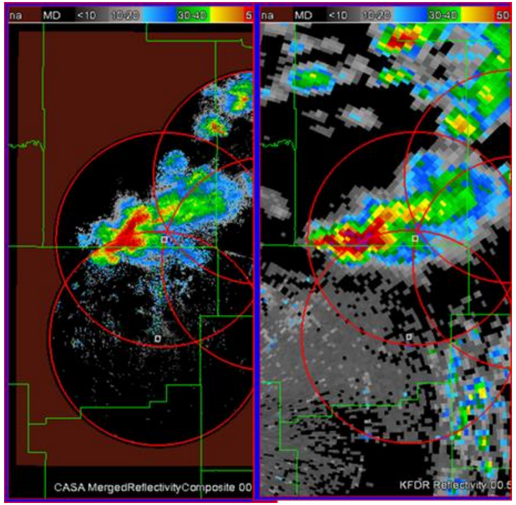
Tropical Storm Odile Flash Flooding in Southeast Arizona, Sept. 2014

- S and C-band radar systems are known to suffer from shielding effects preventing to sound orographically complex areas like Alpine valleys and urban areas.

Excerpted from WakeNet-Europe 2013, by Mr. McLaughlin and Mr. Drake

Motivation

Long-range weather radars suffer from orographic shielding, low space resolution and high revisit time



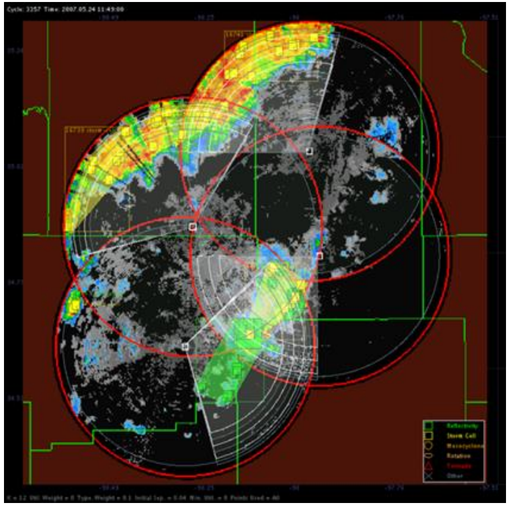
Supercell comparison
(left: X-band CASA, right: S-band NEXRAD)

- Coarse resolution and high revisit time are other known limitations of a sounding approach based on a limited number of long range units, overall leading to operational maps of about 1 Km³ radar bins with a typical update time of 5 minutes.

Excerpted from WakeNet-Europe 2013, by Mr. McLaughlin and Mr. Drake

Motivation

To overcome these limitations, the development of a network of short-range X-band dual-polarized Doppler weather radars is proposed



CASA X-band AESA experimental network

- A <u>networked approach</u> generates high resolution composite maps of short-range units with a typical refresh rate of one minute

<u>Excerpted from WakeNet-Europe 2013, by Mr. McLaughlin and Mr. Drake</u>

Motivation

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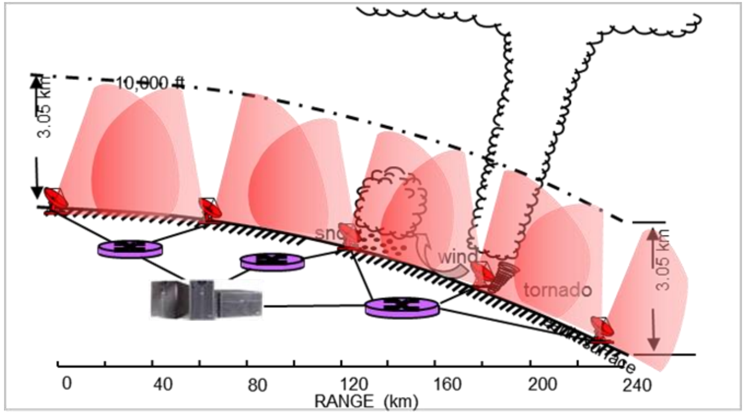


CASA X-band AESA experimental network

- A networked approach generates high resolution composite maps of short-range units with a typical refresh rate of one minute and improve monitoring of the lower troposphere.

Excerpted from WakeNet-Europe 2013, by Mr. McLaughlin and Mr. Drake

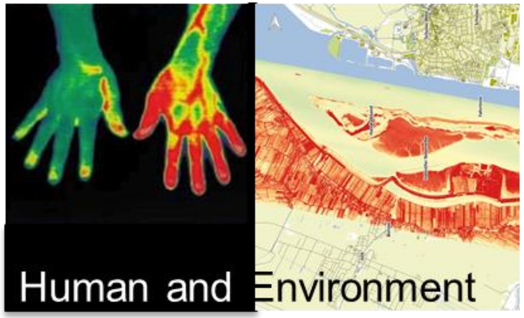
Fraunhofer FHR

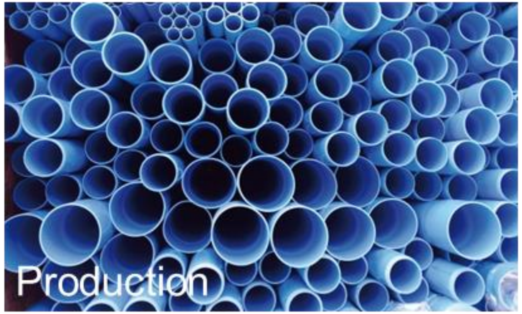
Excellence in radar research since 1957

About 300 employees, 24M€ budget

Part of Fraunhofer Gesellschaft since 2009

Fraunhofer FHR business units



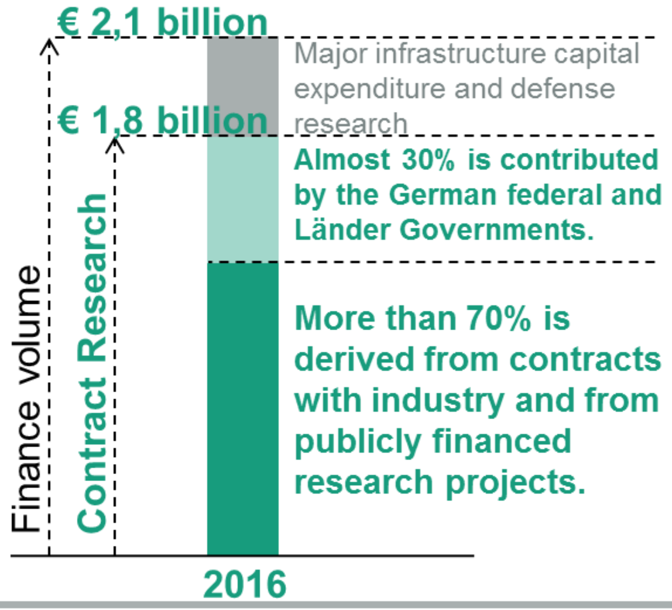


The Fraunhofer-Gesellschaft at a Glance

The Fraunhofer-Gesellschaft undertakes applied research of direct utility to private and public enterprise and of wide benefit to society.

24 500 staff

69 institutes and research units



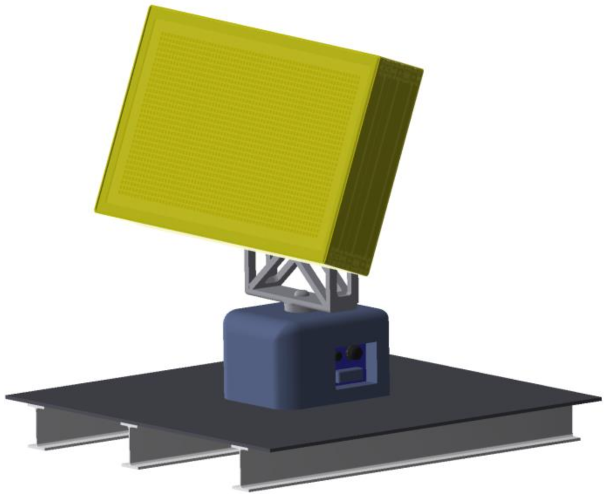
Fraunhofer FHR

Overview

- Concept design
- Enabling technologies
- Manufacturing
- System design
- Feasibility
- Summary

Concept design

Mechanical assembly



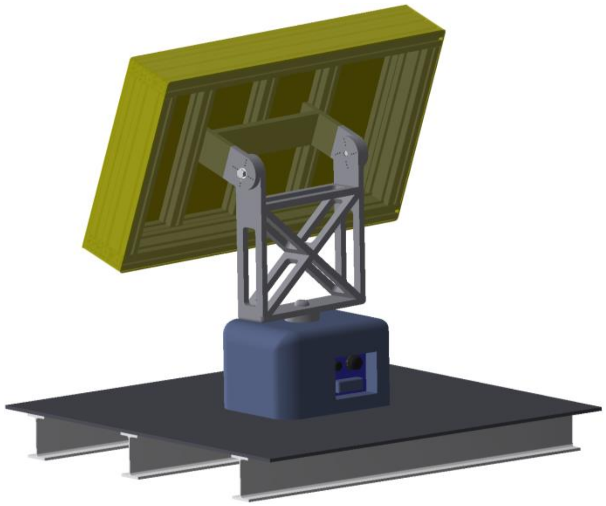
Concept rendering mock-up, front

- Flat aperture
  - 0.5 m^2 array panel area
  - Four panels framed as a flat aperture
  - Antenna aperture connected to a rotor by an arm, mechanically adjustable elevation tilts (up to 11° in 1° step)
  - Receiver over-elevation
  - Distributed power generation

Flat aperture

Concept design

Mechanical assembly



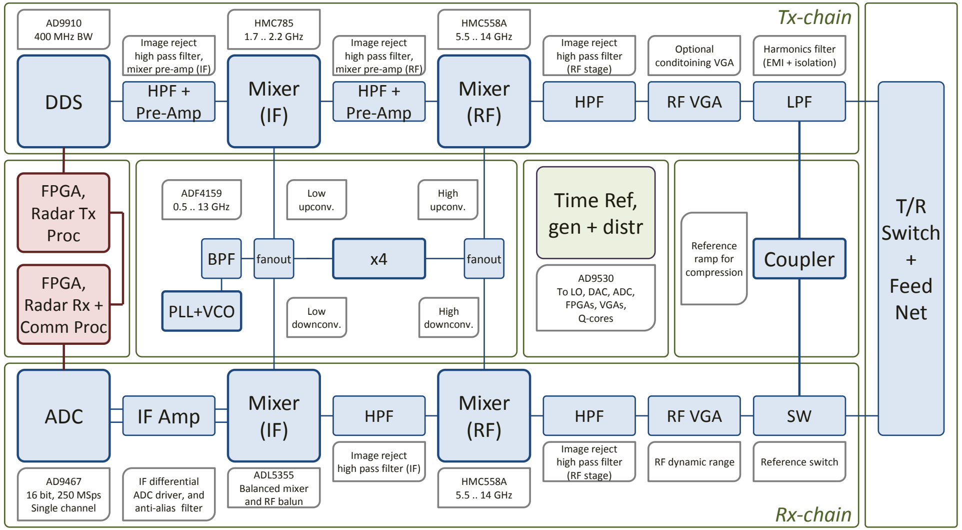
Concept rendering mock-up, back

- Flat aperture
  - 0.5 m^2 array panel area
  - Four panels framed as a flat aperture
  - Antenna aperture connected to a rotor by an arm, mechanically adjustable elevation tilts (up to 11° in 1° step)
  - Receiver over-elevation
  - Distributed power generation

Flat aperture

Concept design

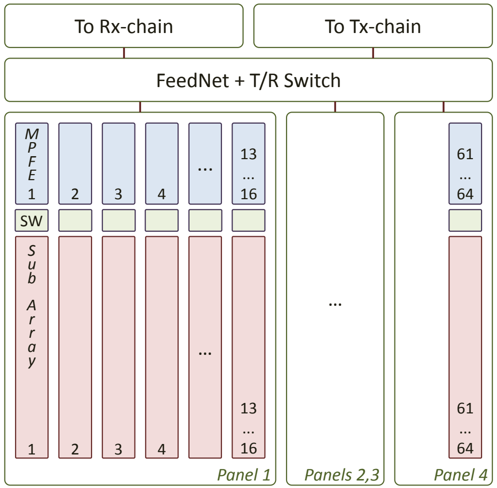
Back-end



Back-end transmitter and receiver chains including on-board digital processing

Concept design

Front-end



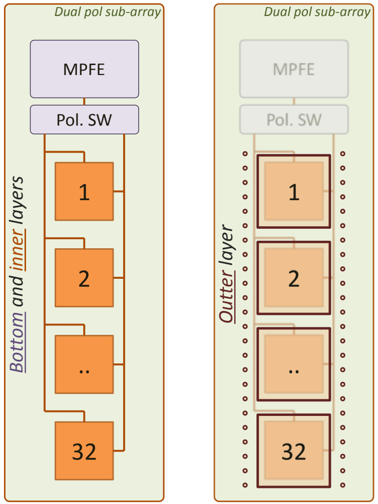
Front-end overview

- **Array**
  - Based on an integrated T/R front-end MMIC plus polarization switch and sub-array radiating column.
  - Each Medium Power Front End (MPFE) feeds a linear sub-array of 32 patches arranged as a column.
  - 64 radiating columns for a total radiating surface of about 960 x 480 mm.
  - Modular design based on 4 panels.
  - Connected to the Tx and Rx chains via a common feeding network plus T/R switch.

Panel-based modular design

Concept design

Front-end

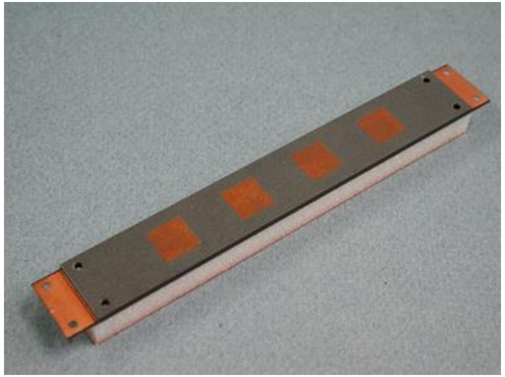


Patch sub-array column
with polarization switch

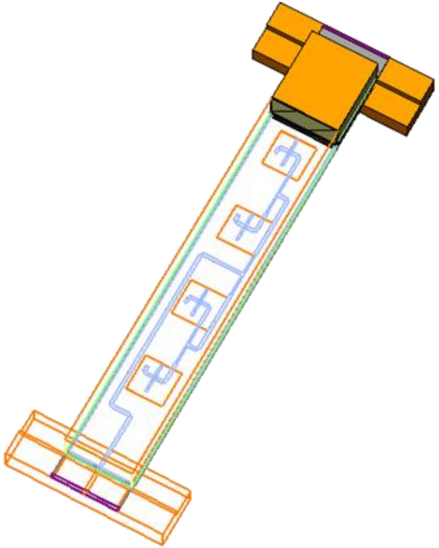
- Sub-array column with polarization switch
  - horizontal and vertical ports of each patch sub-array fed by a common MPFE plus polarization switch on the PCB back-side.
  - Allows for alternate polarization modes in transmission and reception ("Alternate Transmit Alternate Receive" mode).
  - Stacked patch design for improved bandwidth exceeding 300 MHz.
  - Low insertion loss switch (e.g. Analog Devices HMC1118).

Crucial components

Front-end, column sub-array



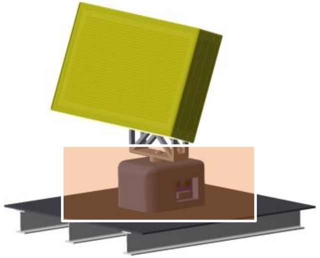
Column sub-array



Aperture feeding detail

Crucial components

Mechanical assembly



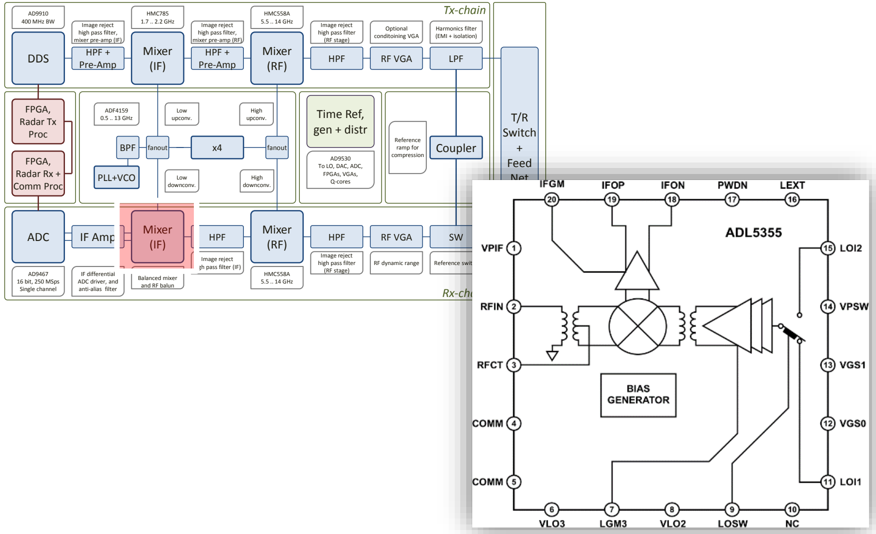
- Rotor
  - Horizontal working position
  - 250 kgm^2 moment of inertia (max)
  - 5.5 rpm (max)
  - Ø 410 mm, tabletop
  - Absolute encoder
  - Integrated slip-ring
  - Up to 200 kg load
  - Remotely controllable
  - Abound 15 K$ unitary cost

FIBROTOR EM.NC.15, FIBRO GmbH

Rotor

Enabling technologies

Back-end, receiver



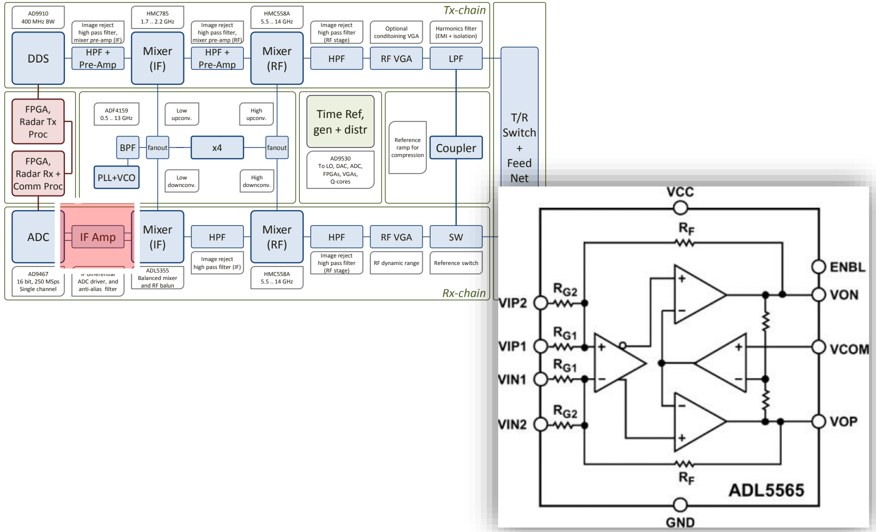
Analog Devices ADL5355

- Balanced Mixer
  - Integrated RF balun
  - Integrated differential IF amplifier
  - 1200..2500 MHz RF
  - 30..450 MHz IF
  - Suitable for early implementation of differential signaling.

Balanced mixer

Enabling technologies

Back-end, receiver



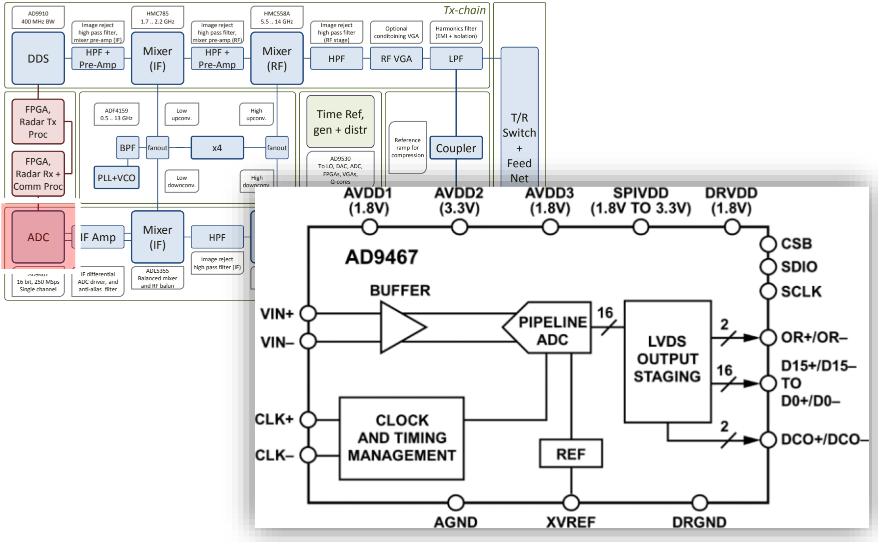
Analog Devices ADL5565

- Differential amplifier
  - High dynamic range
  - Differential input to differential output
  - 3 dB bandwidth of 6 GHz
  - 2 ns settling time
  - 11 V/ns slew rate
  - Differential ADC driver

Differential amplifier

Enabling technologies

Back-end, receiver



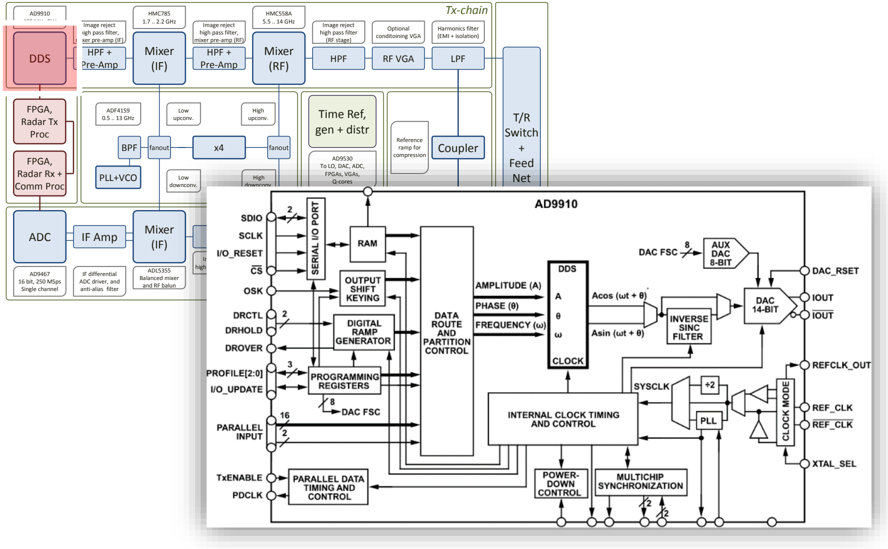
Analog Devices AD9467

- Analog-to-Digital converter
  - Single channel differential input
  - 16-bit, 250 MSps
  - 90 dBFS SFDR to 300 MHz
  - 60 fs rms jitter
  - High dynamic range differential IF sampler

Analog-to-Digital converter

Enabling technologies

Back-end, transmitter



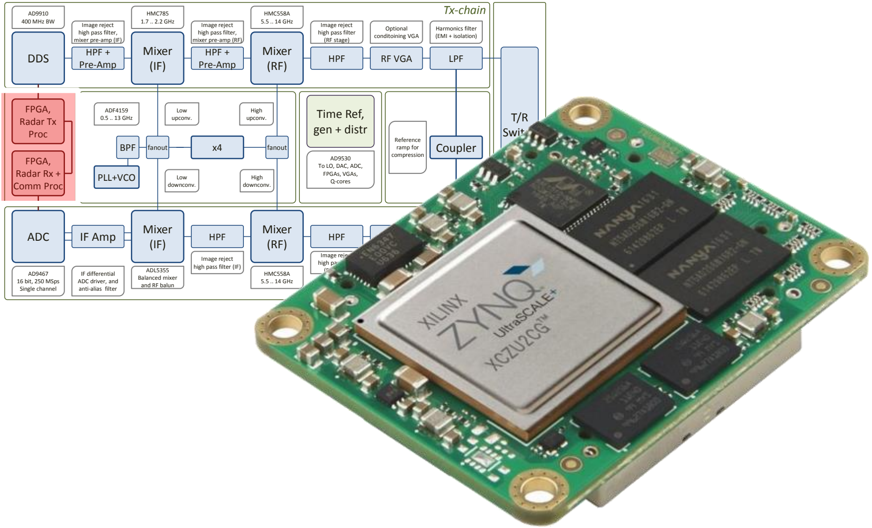
Analog Devices AD9910

- Direct digital synthesizer
  - Integrated 14-bit DAC
  - 1 Gbps sample rate
  - 400 MHz analog bandwidth
  - Digitally defined frequency sweeps
  - Frequency agile
  - Digital waveform generation

Direct digital synthesizer

Enabling technologies

Back-end, signal and data processing



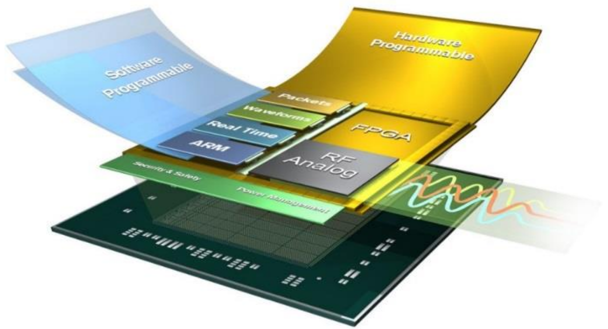
Xilinx Zynq UltraScale+
multiprocessor system-on-chip (MPSoC)

- Hardware back-end definition
  - Availability of FPGA logic blocks and processing cores into the same chipset yields fundamental advantages:
    - Hardware Defined Radio (HDR)
    - Over-the-Air (OTA) algorithms updates and parameters fine tuning
    - Accurate balancing of signal processing and computational tasks
    - Sufficient on-board processing power for raw processing and data reduction.

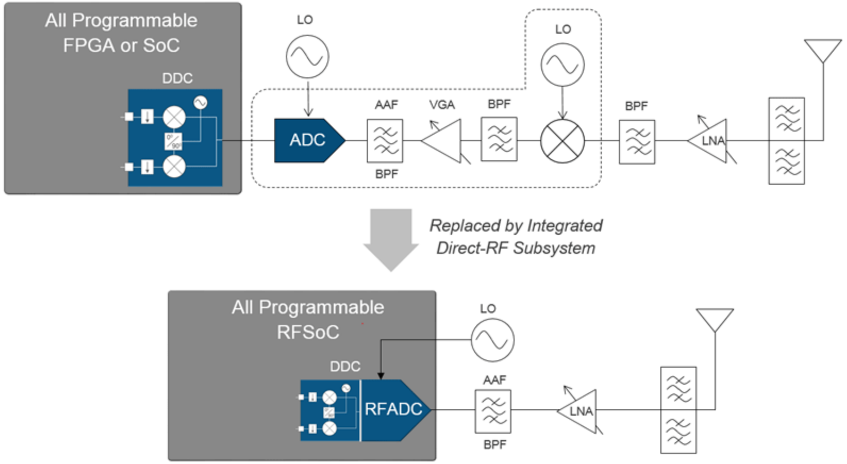
User programmable platform

Enabling technologies

Back-end, signal and data processing



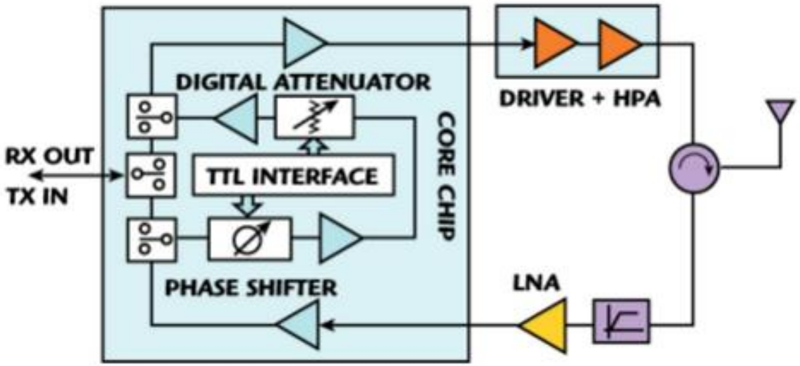
Xilinx Zynq UltraScale+ RFSoC Family integrating the RF signal chain for 5G wireless and Radar. Sixteen 2GSPS 12-bit ADCs and sixteen 6.4GSPS 14-bit DACs on-chip.



All Programmable RFSoCs monolithically integrate RF data converters for up to 50-75 percent system power and footprint reduction.

Enabling technologies

Front-end



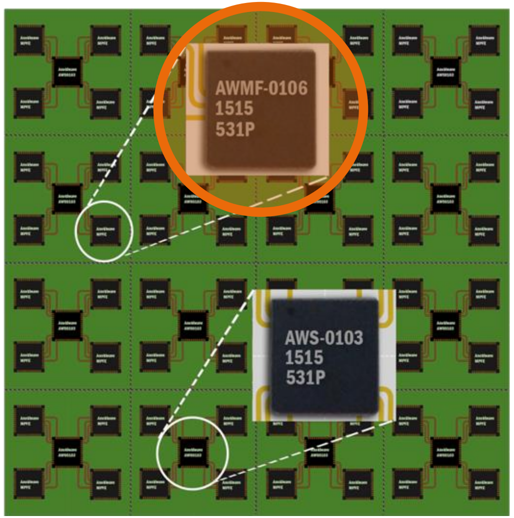
United Monolithic Semiconductors
CHC3014 TRM and external circuitry

- Legacy COTS X-band TRMs relying on external components
  - The development of X-band weather radars has been carried on by research centers and some commercial entities for more than 20 years.
  - However, the lack of a sufficient scale of integration at a core chip level prevented so far the development of effective solutions.

Legacy TRMs

Enabling technologies

Front-end



Bi-dimensional AESA concept design
(courtesy of Anokiwave)

- New generation of highly-integrated low-cost TRMs
  - Newly available low-cost TRMs integrating complete AESA functionalities on-chip offer for the first time sufficient hardware infrastructure for the development of low-cost dual-pol Doppler X-band weather radars based on AESA technology

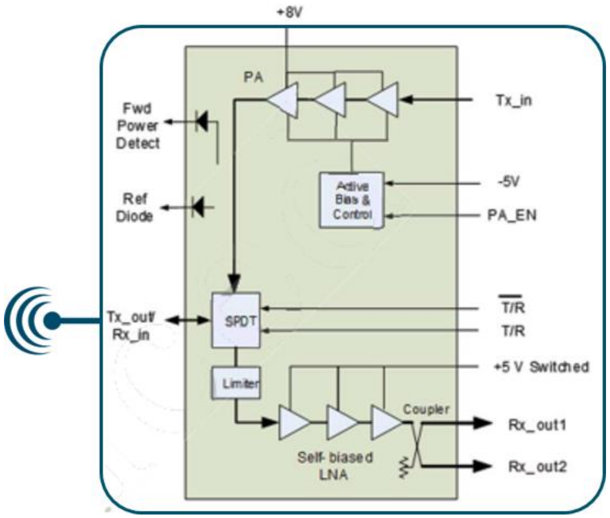
New highly-integrated TRMs

Anokiwave

Fraunhofer FHR

Enabling technologies

Front-end



Anokiwave AWMF-0106
"Medium Power Front-End"

- Anokiwave AWMF-0106 "Medium Power Front End"
- X-band TRM offering integrated on-chip
  - power amplifier
  - low noise amplifier
  - Rx passive limiter
  - and T/R SPDT switch.
- The unit is EAR99 / ITAR free and packaged as a compact 7x7 mm² PQFN.

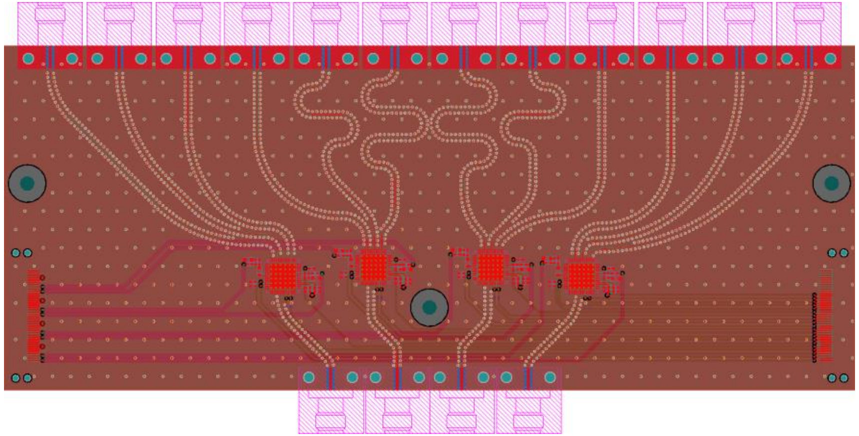
New highly-integrated TRMs

Anokiwave

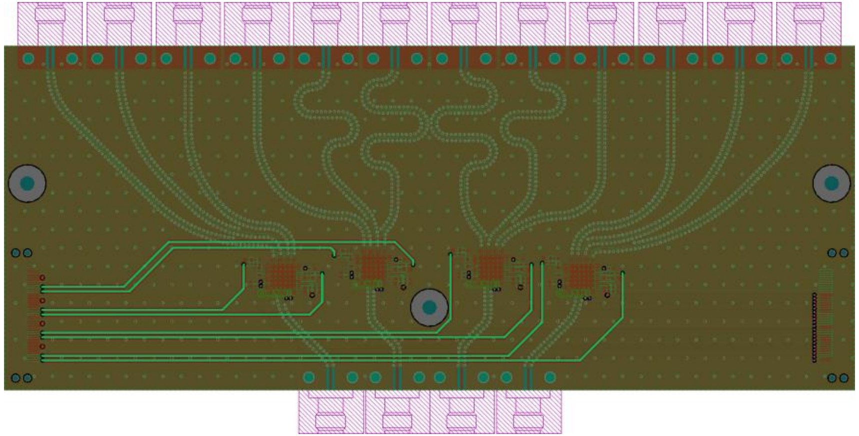
Fraunhofer FHR

Crucial components

Front-end, MPFE



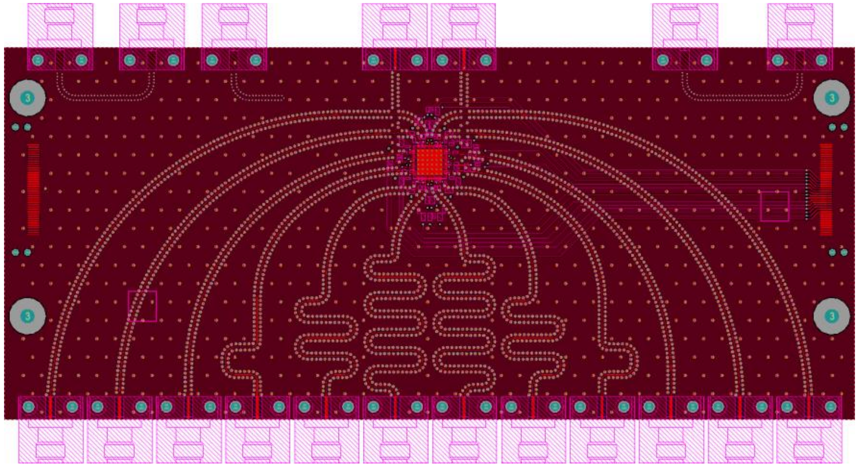
MPFE PCB layout
Top layer



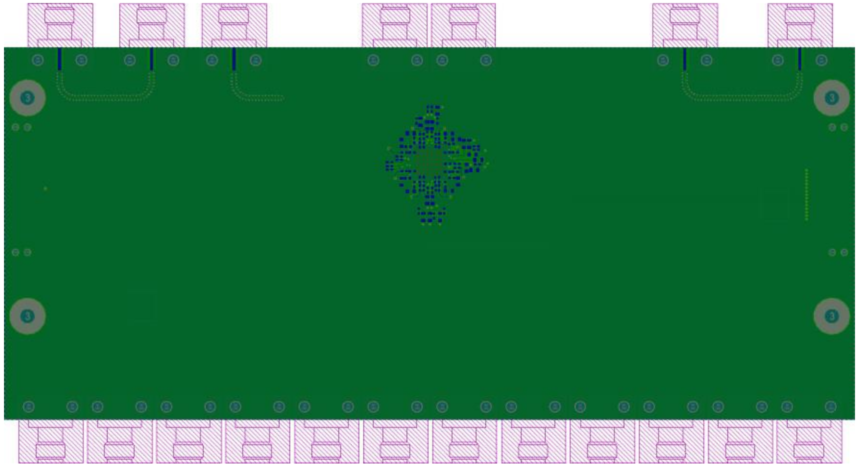
MPFE PCB layout
DC supply tracks

Crucial components

Front-end, Quad-Core



Quad-Core PCB layout
Top layer

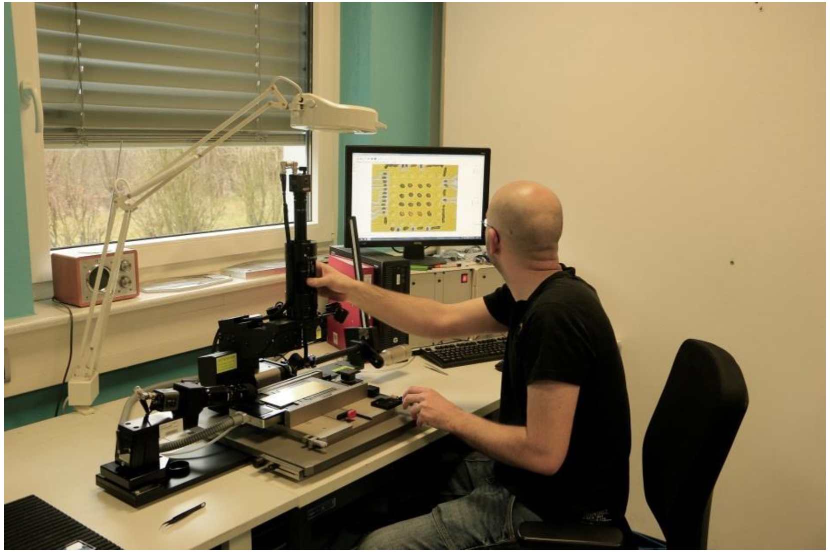


Quad-Core PCB layout
Bottom layer

Manufacturing

Assembly by Fraunhofer Integrated Circuits and Sensor Systems ISS
(contact: Dirk Nüßler, dirk.nuessler@fhr.fraunhofer.de)

Manufacturing



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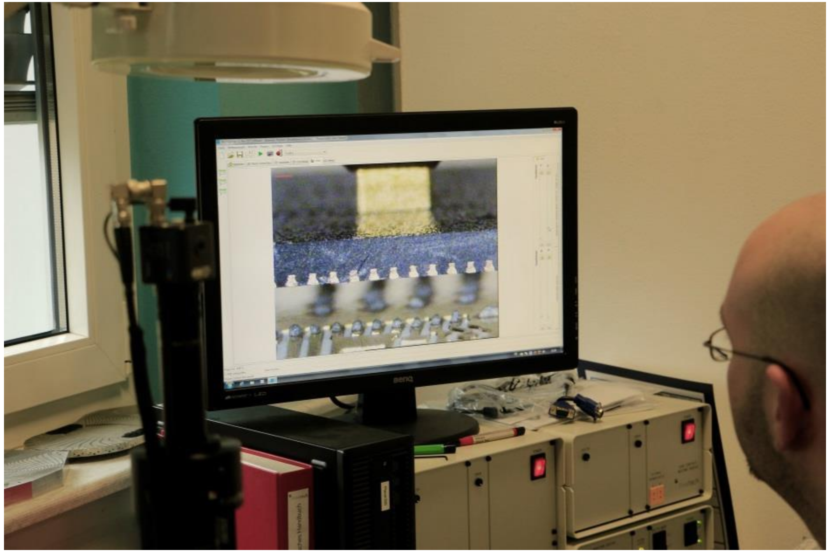

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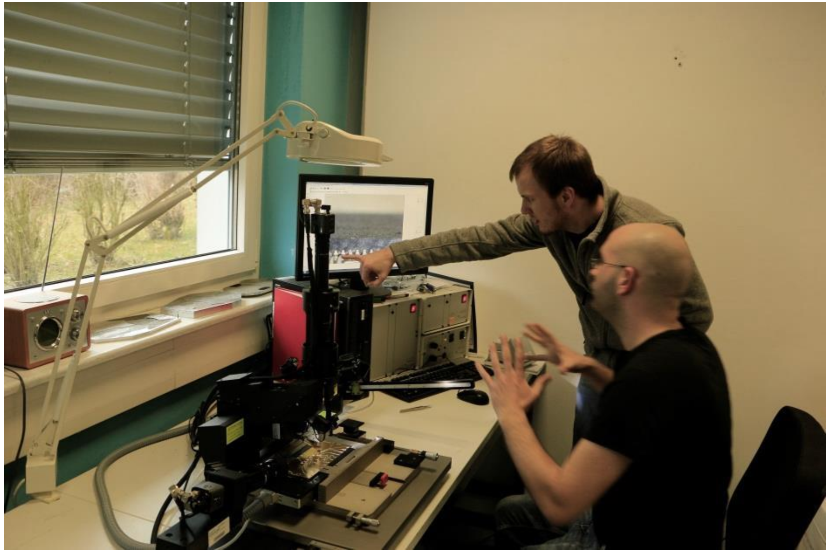

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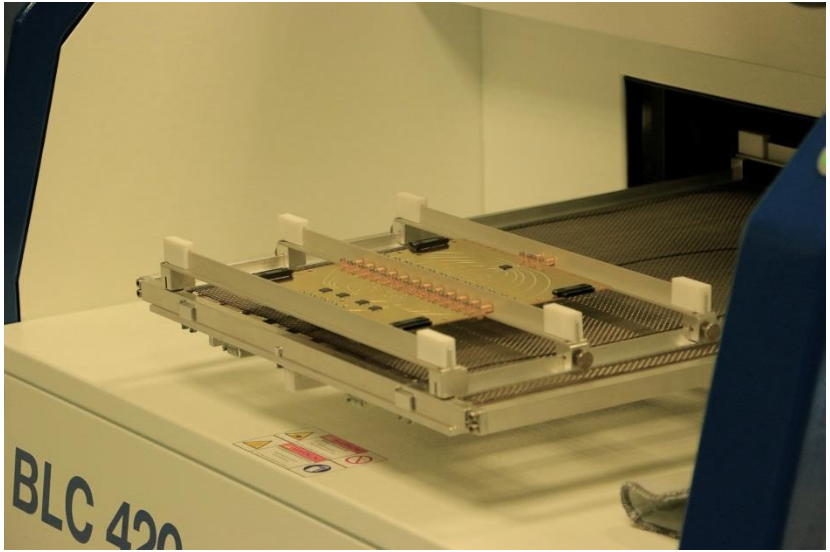

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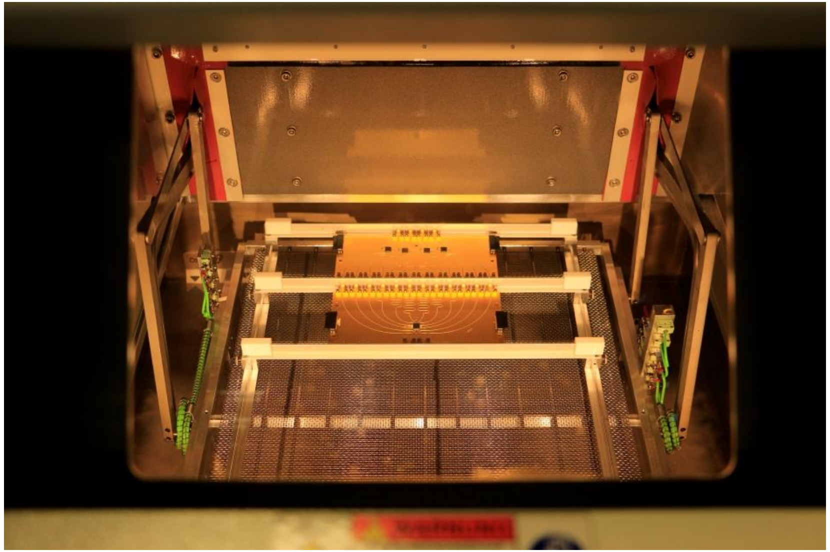

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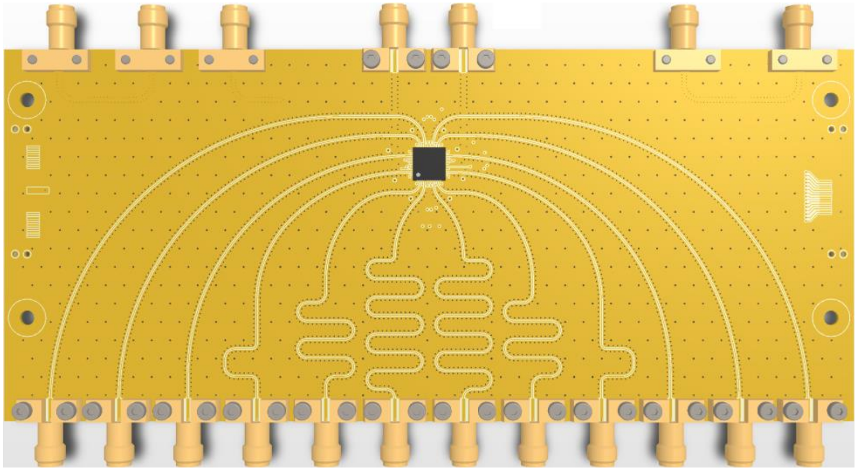
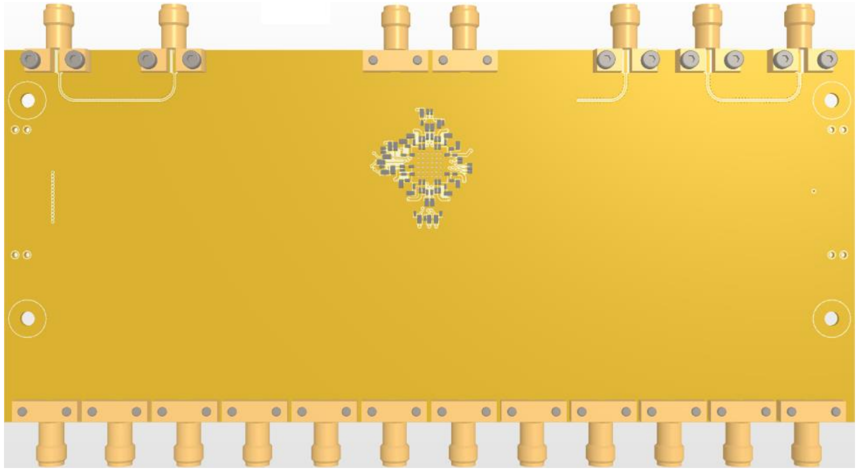
Crucial components

Front-end, Quad-Core



Quad-Core PCB layout
Top layer rendering

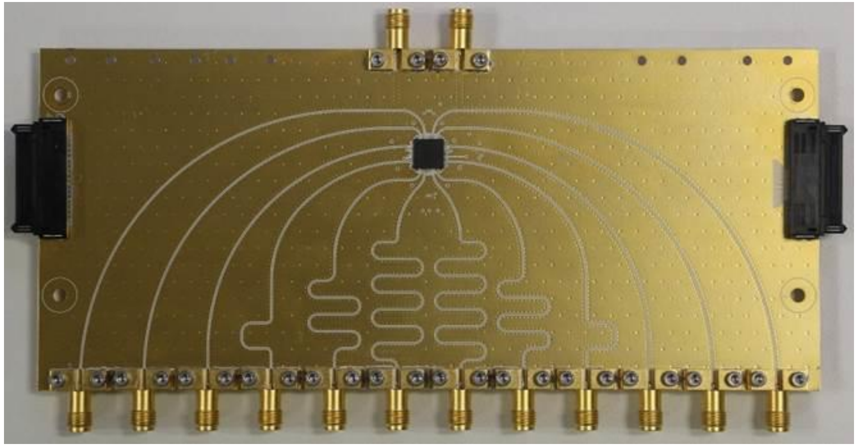


Quad-Core PCB layout
Bottom layer rendering

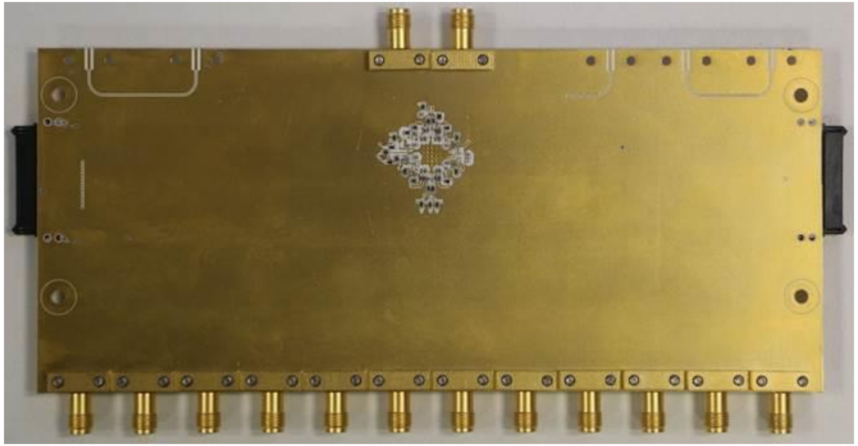
Fraunhofer FHR

Crucial components

Front-end, Quad-Core



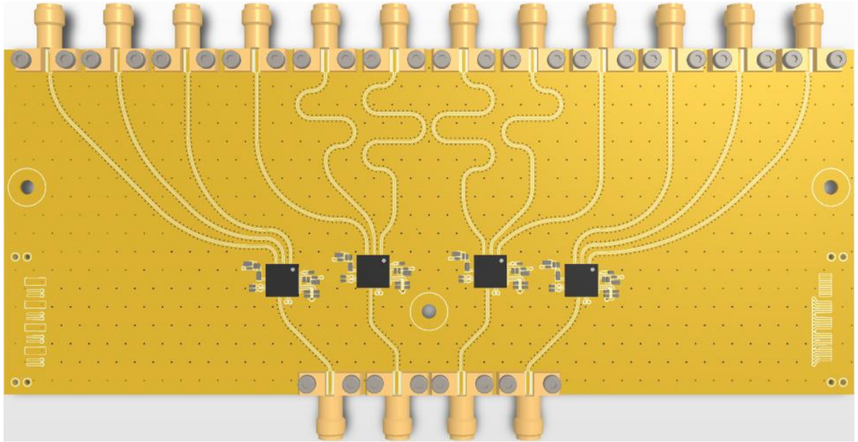
Quad-Core PCB
Top layer



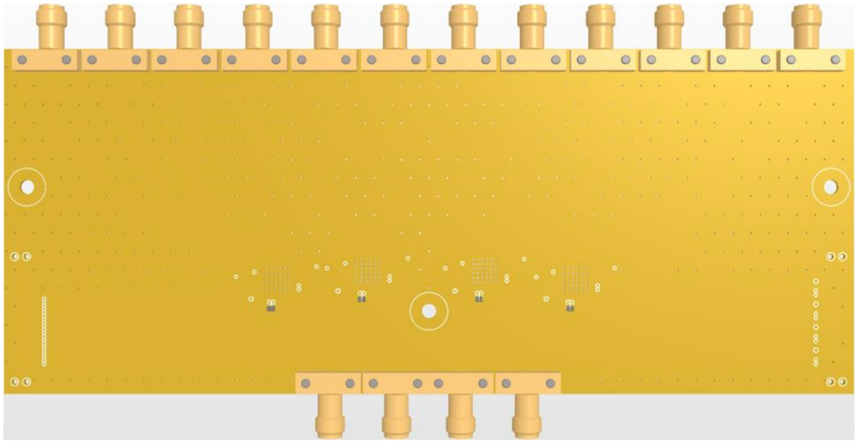
Quad-Core PCB
Bottom layer

Crucial components

Front-end, MPFE



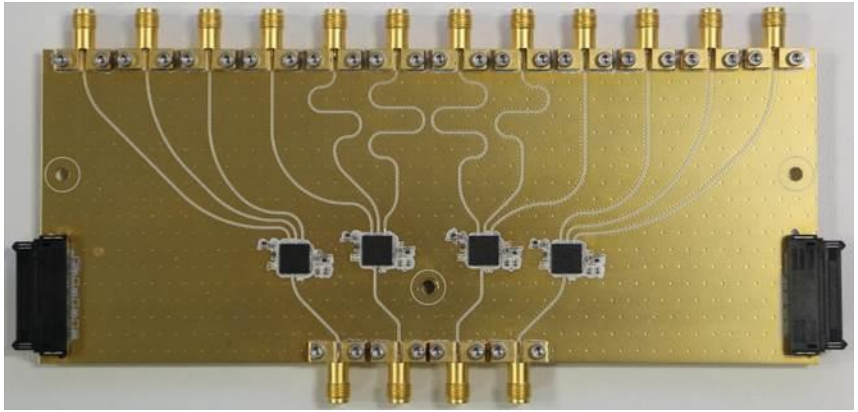
MPFE PCB layout
Top layer rendering



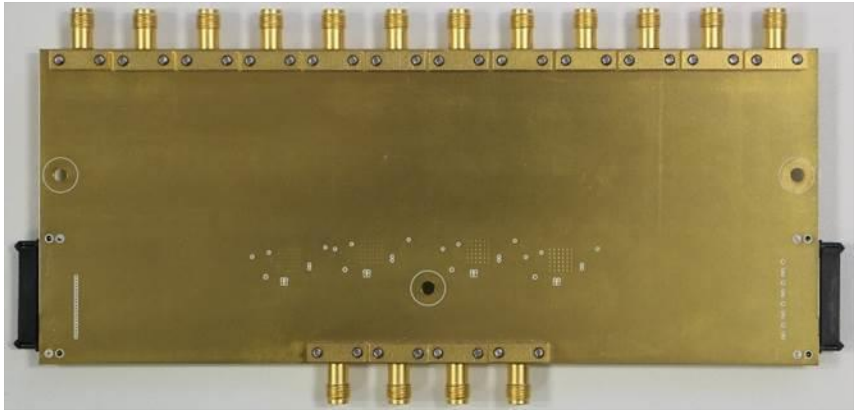
MPFE PCB layout
Bottom layer rendering

Crucial components

Front-end, MPFE



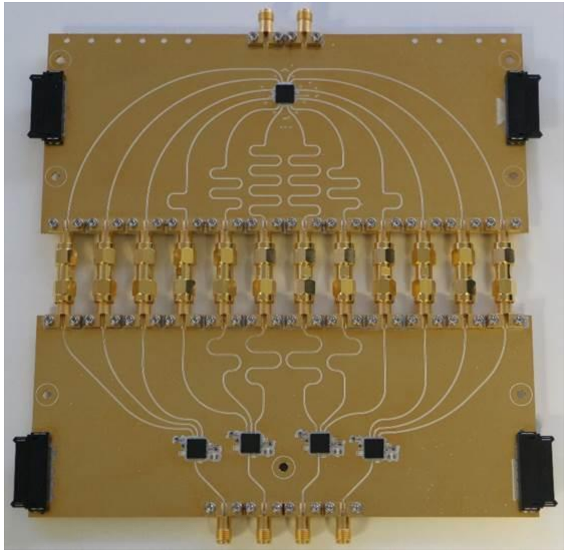
MPFE PCB
Top layer



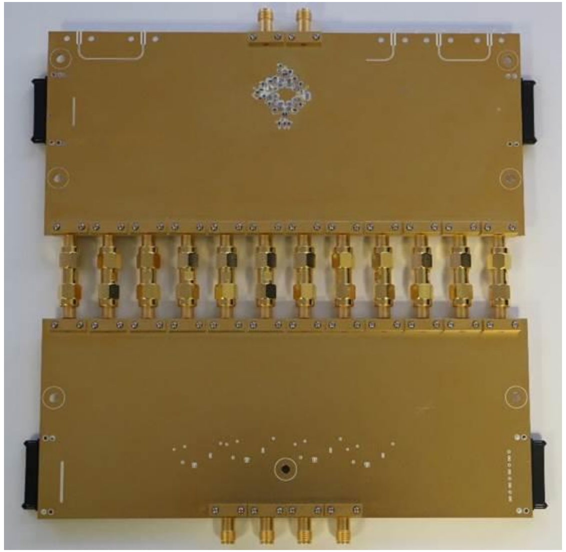
MPFE PCB
Bottom layer

Crucial components

Front-end, full assembly



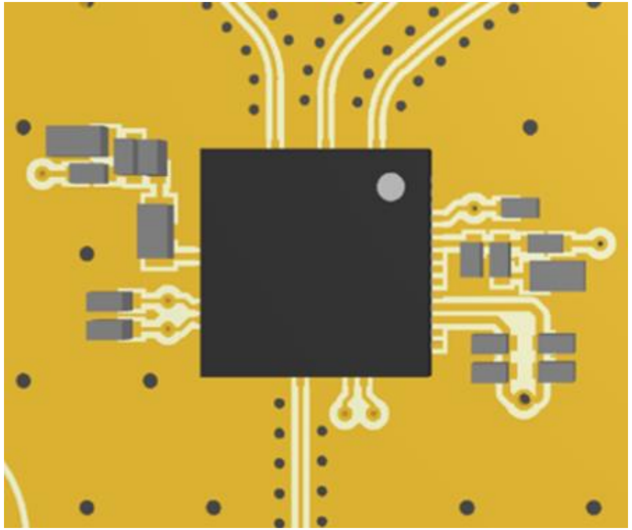
Full assembly
Top layer



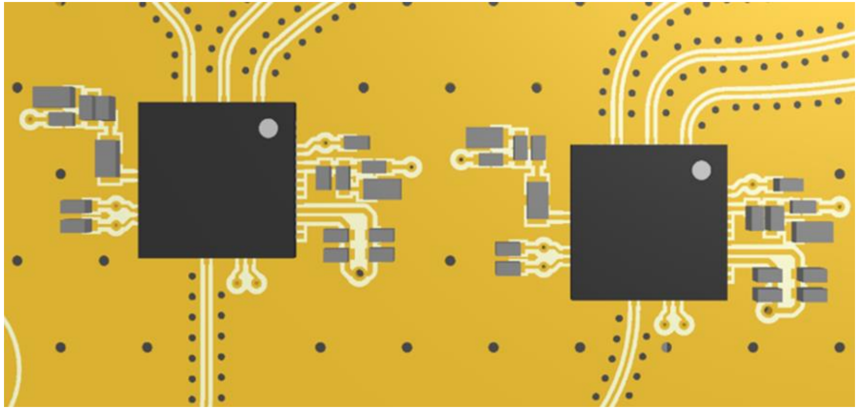
Full assembly
Bottom layer

Crucial components

Front-end, MPFE



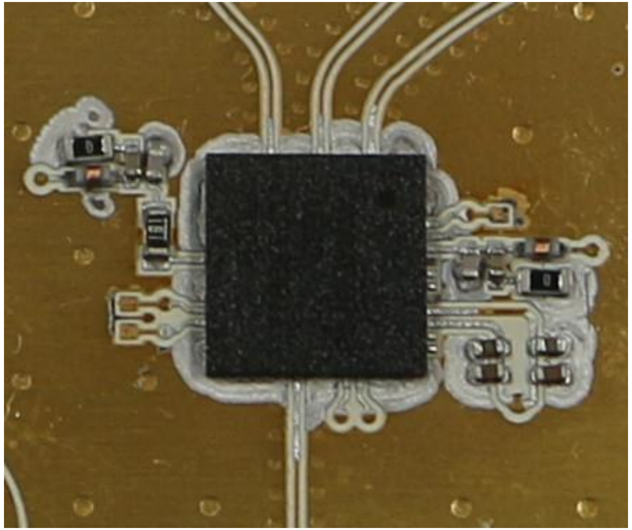
MPFE and external components
Top layer rendering



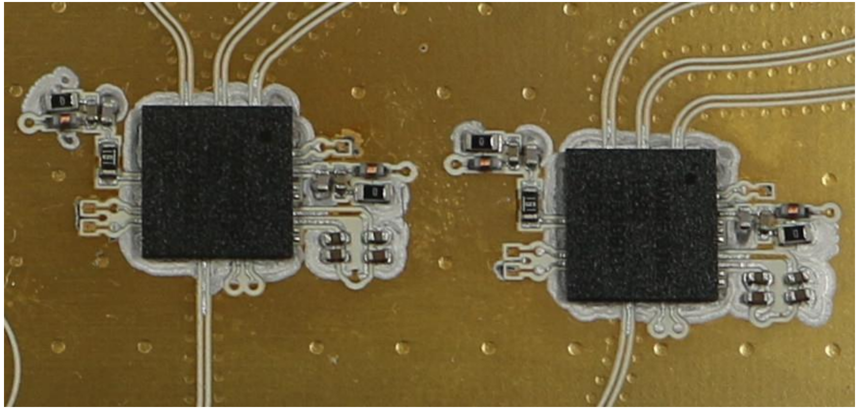
Required board surface
Top layer rendering

Crucial components

Front-end, MPFE



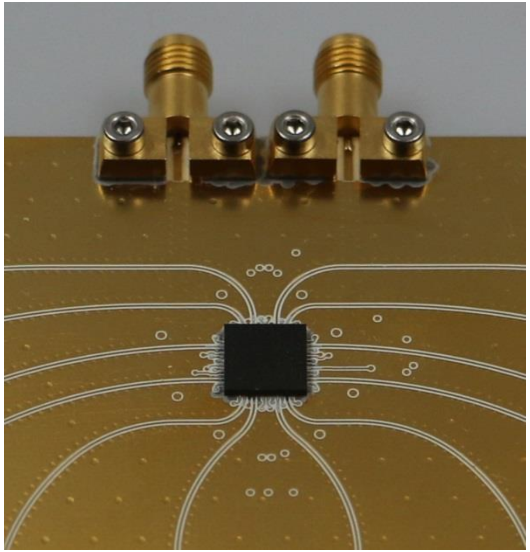
MPFE and external components
Top layer



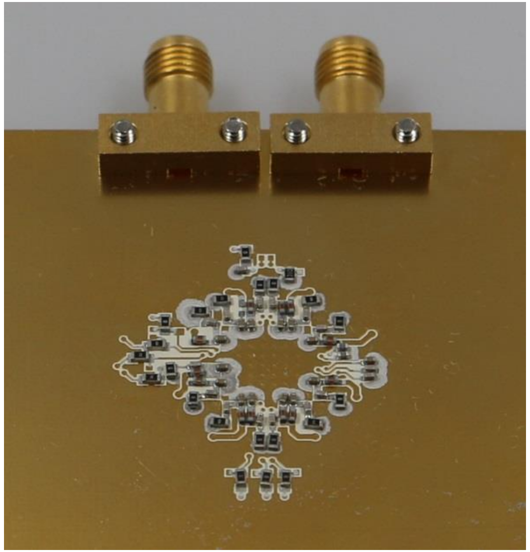
Required board surface
Top layer

Crucial components

Front-end, Quad-core controller



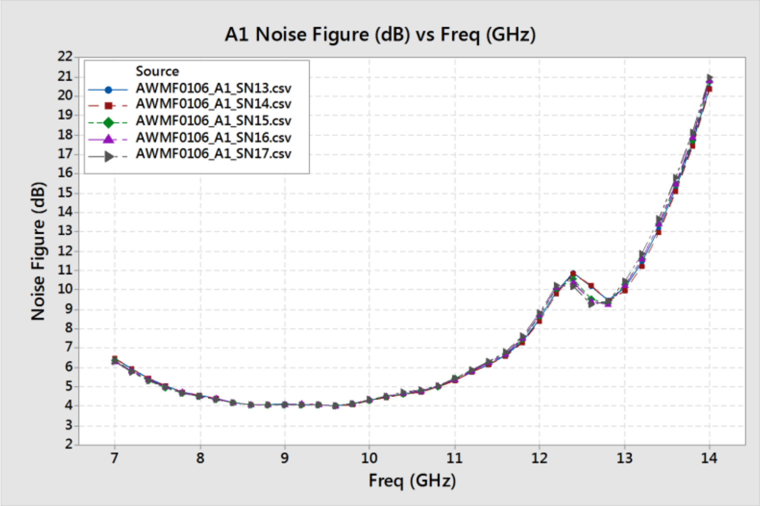
Quad-core and external components
Top layer



Required board surface
Bottom layer

Crucial components

Front-end, MPFE



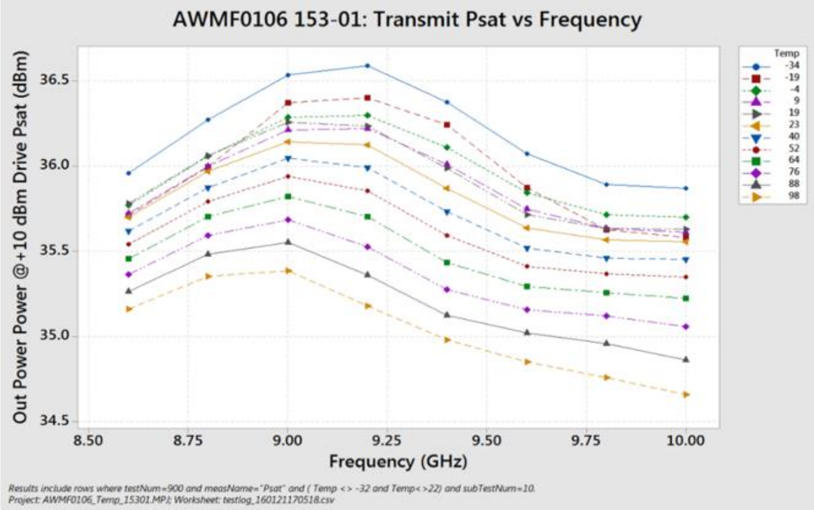
Receive mode noise figure vs. frequency
(3.3 dB @ 9.0 GHz)

- Anokiwave AWMF-0106 "Medium Power Front End"
- In receive mode, the unit features
  - a noise figure as low as 3.3 dB
  - 23 dB linear gain
  - self-biased LNA
  - integrated passive limiter.

New highly-integrated TRMs

Crucial components

Front-end, MPFE



- Anokiwave AWMF-0106 “Medium Power Front End”
- In transmit mode, the unit features
  - up to 5 W HPA
  - 29 dB linear gain
  - active PA bias & control
  - integrated Tx power detector.

Saturated Tx power vs. frequency over temperature

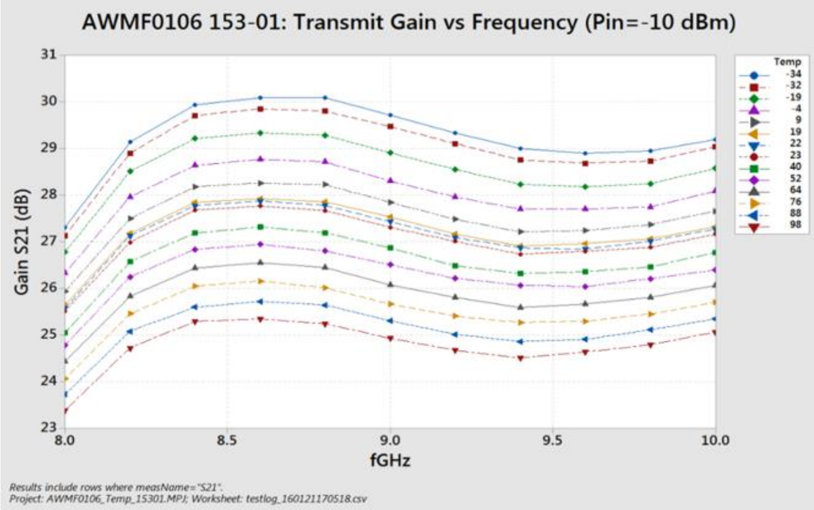
New highly-integrated TRMs

Anokiwave

Fraunhofer FHR

Crucial components

Front-end, MPFE



Small signal Tx gain vs. frequency over temperature

- Anokiwave AWMF-0106 "Medium Power Front End"
- In transmit mode, the unit features
  - up to 5 W HPA
  - 29 dB linear gain
  - active PA bias & control
  - integrated Tx power detector.

New highly-integrated TRMs

System design

Main figures @ 50 Km range (255x255 mm aperture)		
Array, el, elements	:	32
Array, az, elements	:	64
Array, el, length	:	509.7 mm
Array, az, length	:	1019.5 mm
Array, el, aperture3	:	3.2 deg
Array, az, aperture3	:	1.6 deg
Array, gain	:	33.1 dB
Waveform, Tm length	:	5.0 us
Waveform, BW	:	6.0 MHz
Waveform, slant res	:	25.0 m

System parameters

- A 0.5 m² array of 64x32 elements radiating about 250 W will be sufficient to detect a rainfall rate of 1 mm/h at 40 km range.
  - ¼ KW radiated power
  - 5 us chirp, 6 MHz bandwidth
  - 128 scans per each elevation
  - Staggered PRF of 500 us and 333 us leading to a maximum Doppler speed of 75 m/s
  - 25 dBZ sensitivity floor (~1 mm/h, Continental Europe)

Fraunhofer FHR

System design

```
Main figures @ 50 Km range (255x255 mm aperture)

RadarEq, Pt                    :   256.0 W
RadarEq, Rmax, ground          :    46.1 km
RadarEq, blind distance        :   749.5 m

RadarEq, noise figure          :     7.0 dB
RadarEq, signal pwr            :  -118.9 dBm
RadarEq, noise pwr             :  -106.2 dBm

RadarEq, SNR, in               :   -12.7 dB
RadarEq, SNR, out              :    16.1 dB
RadarEq, proc gain, compr.     :    14.8 dB
RadarEq, proc gain, tot        :    35.8 dB

RadarEq, Zmin                  :    25.0 dBZ
RadarEq, Rmin                  :     1.0 mm/h
```

System parameters

- A 0.5 m² array of 64x32 elements radiating about 250 W will be sufficient to detect a rainfall rate of 1 mm/h at 40 km range.
  - ¼ KW radiated power
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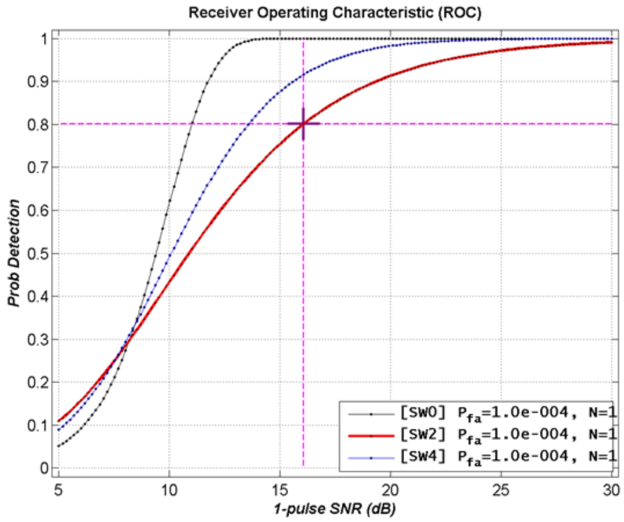
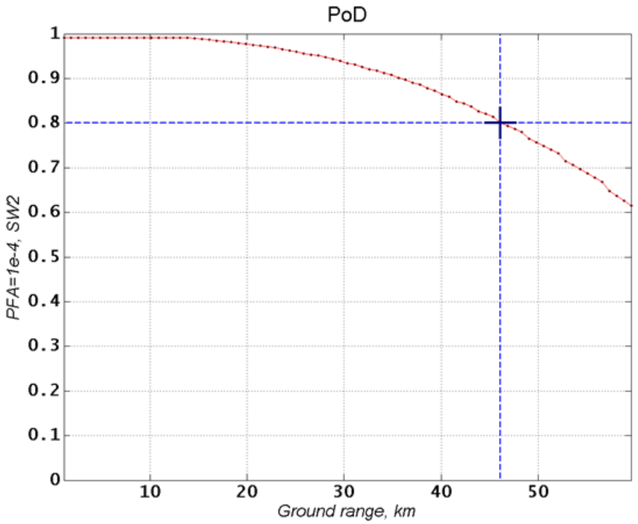
System design

Power budget



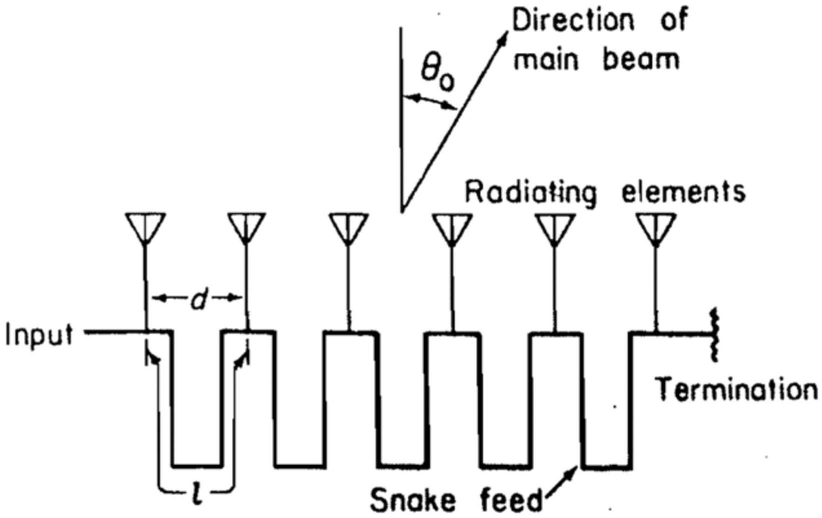
Receiver Operating Characteristic
(Swerling2 model in red)



PoD @ PFA=1e-4, Swerling2 model

System design

Elevation steering



From Skolnik, 1981
"Introduction to Radar Systems"

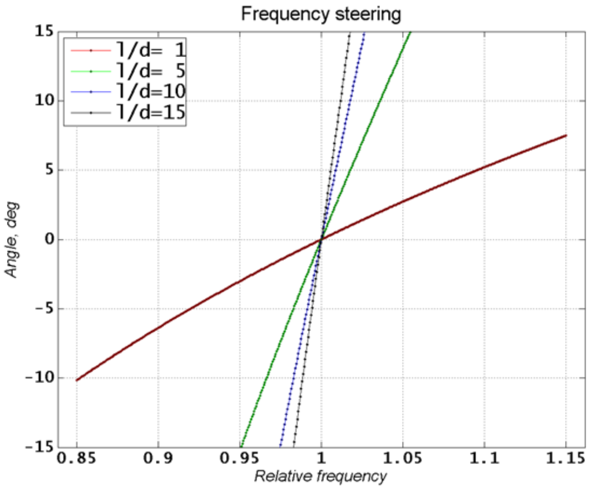
- Concept implementation of frequency beam steering via serial feeding and meandering.

$$sin(\theta_0) = \frac{l}{d}\left(1 - \frac{f_0}{f}\right)$$

Fraunhofer FHR

System design

Elevation steering



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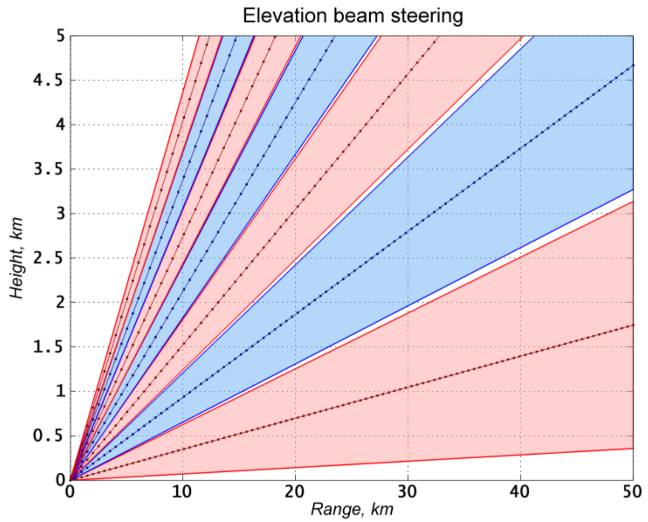
System design

Elevation steering

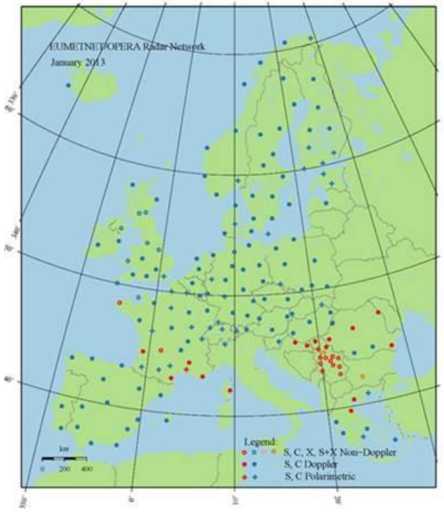


Volume coverage pattern

- Total frequency sweep
  - 9.096 to 9.746 GHz
  - Excursion of 650 MHz
- Beam axis and 3 dB aperture
  - 7 elevations (-10 to 10 deg)
  - with fixed tilt of 12 deg

Feasibility

Market potential

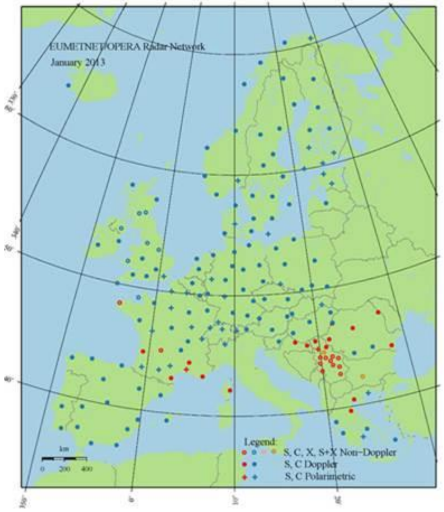


OPERA radar network

- Huge market potential for effective, sustainable and reliable solutions.
- OPERA radar network
  - 248 km average range
  - 202 operational radars
  - 184 Doppler
  - 48 Dual-pol
  - 8 X-band
  - 3 X-band Doppler dual-pol

Feasibility

Market potential



OPERA radar network

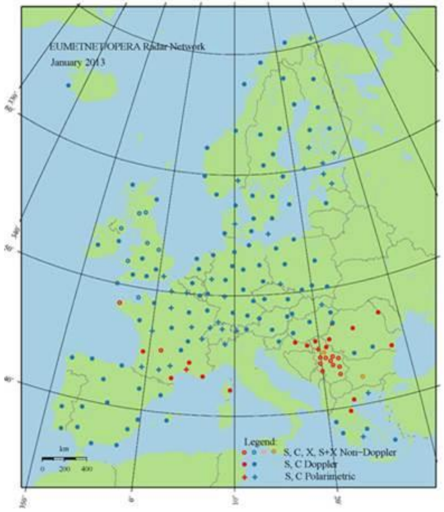
- Equivalent number of long-range and short-range radars for „blanket“ coverage (assumed 150 km and 30 km range)

	S/C-band radars	X-band radars
Europe	**144**	**3600**
France	9	227
Germany	5	126
UK	3	86
Belgium	1	11

Fraunhofer FHR

Feasibility

Market potential



OPERA radar network

- Key success condition, when output products match long-range radars (Doppler, dual-pol, 3D scanning) data quality:

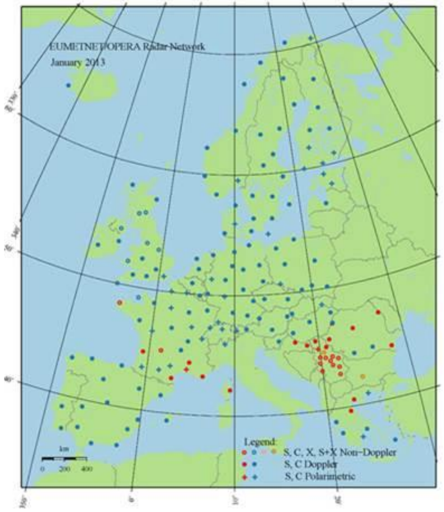
low-cost

(assumed 5M€ cost per S-band radar, about 80K€ is the unitary X-band limit cost)

Fraunhofer FHR

Feasibility

Market potential



OPERA radar network

- Applications
  - Gap filling for long range radars
  - Low troposphere sensing
  - High resolution atmospheric hazard detection (urban security, flash floods, hail storms)
  - Airport security, including landing path monitoring, avian hazard surveillance
  - Precision approach radar

Feasibility

Power consumption

AESA chipsets DC power requirements

Per chipset

```
MPFE , tx      : 16.0 W (8V x 2A @ 4W)
MPFE , rx      :  0.5 W
MPFE , avg     :  0.6 W (1% d.c.)

QCore, tx      :  1.8 W
QCore, rx      :  1.8 W
QCore, avg     :  1.8 W
```

AESA chipsets power consumption
(1% duty cycle)

Chipset DC power consumption

Per panel

```
MPFE , avg     :   38.4 W ( 0.6 W x 64)
MPFE , peak    : 1024.0 W (16.0 W x 64)
```

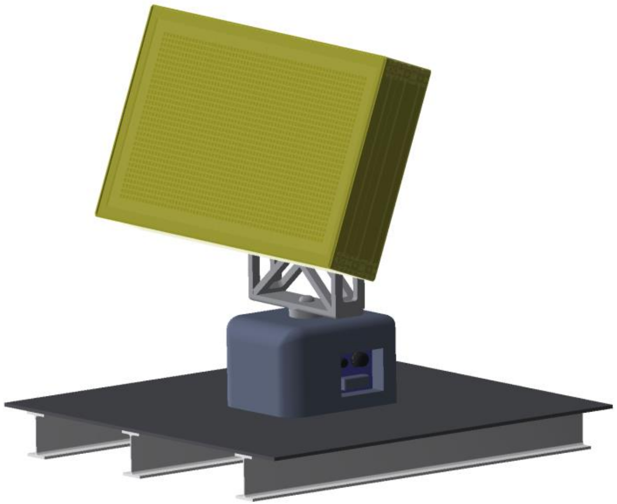
Four panels

```
Tot   , avg    :  153.6 W
Tot   , peak   : 4096.0 W
```

Per panel and total
MPFE power consumption

Feasibility

Cost estimate based on current listing



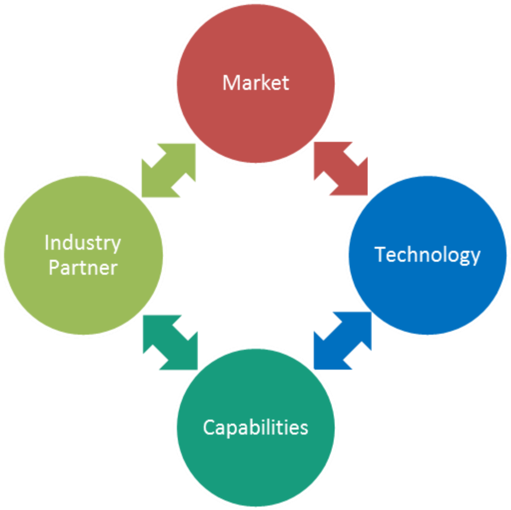
Overall cost estimate	
Back-end , signal processing	: 6K USD
Back end , cabling and boxing	: 2K USD
Back-end , RF PCB and components	: 9K USD
Front-end, chipsets and components	: 16K USD
Front-end, RF PCB	: 27K USD
Antenna , framing and supports	: 7K USD
Antenna , rotor incl. splip-ring	: 16K USD
Total cost estimate	: 83K USD

Array of 64 MPFEs on RO4350B laminate

COTS back-end electronics

Summary

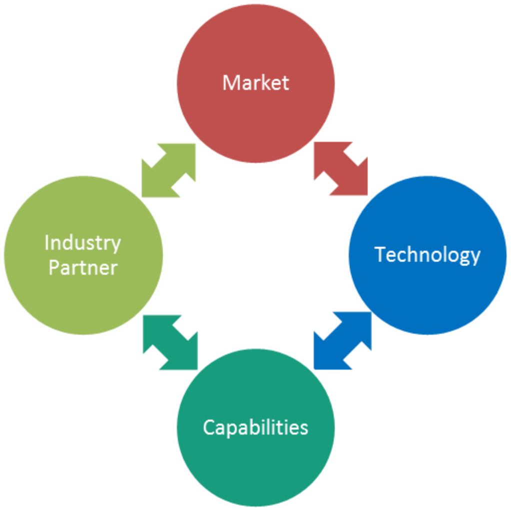
A concept for low-cost weather monitoring



- A new generation of low-cost integrated front-ends offering complete T/R functionalities on chip is available on the market, carrying a <u>potential</u> to trigger a <u>sustainable</u> development of <u>dense</u> X-band weather radar networks.

Summary

A concept for low-cost weather monitoring



- Judicious redesign of mechanically rotated solutions complemented by novel enabling technologies might provide a cost-effective subset of capabilities comparable to AESA apertures within surveillance-oriented hydrology applications.

Thank you very much for your attention !!