The SERENA project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 779305.

SERENA

Joint SERENA/Car2Tera/GRACE Winter School 2020:

Technology and integration platforms for mm-wave communication and radar applications

Short-range mm-wave radar sensors for airborne applications

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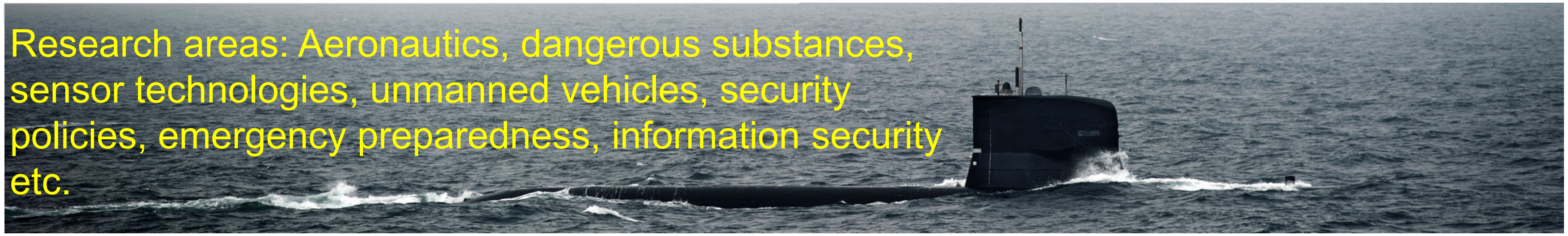
15th January 2020

gan-on-**S**ilicon **E**fficient mm-wave eu**R**opean syst**E**m i**N**tegration pl**A**tform

Swedish Defence Research Agency (FOI)



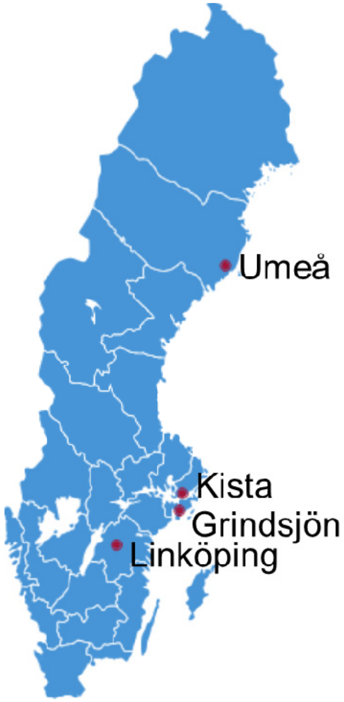
Research areas: Aeronautics, dangerous substances, sensor technologies, unmanned vehicles, security policies, emergency preparedness, information security etc.

FOI personell and locations

960
employees

750
Researchers
and analysts

40%
Ph.D.'s



Outline

- Brief introduction to Radar fundamentals and applications (historical perspective)
- Short-range mm-wave radar sensors for airborne applications (aircraft, helicopter, drones)
- Microwave/mm-wave short-range radar activities at FOI (examples)
- Summary

Radar: Basic principles (system examples)

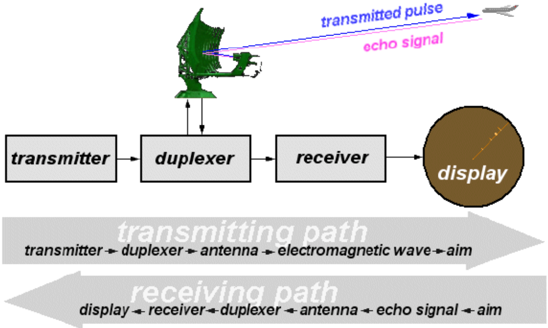


Figure 4: Block diagram of a primary radar with the signal flow

Figure 10: Parabolic antenna of the Weather radar *Meteor* manufactured by Gematronik

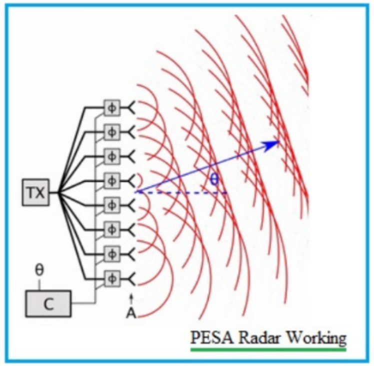
$$R = \frac{t_{delay} \cdot c_0}{2}$$

R is the slant range
t_{delay} is the time taken for the signal to travel to the target *and* return
$c0$ is the speed of light (approximately $3 \cdot 10^8$ m/s)

“Radartutorial” (http://www.radartutorial.eu)

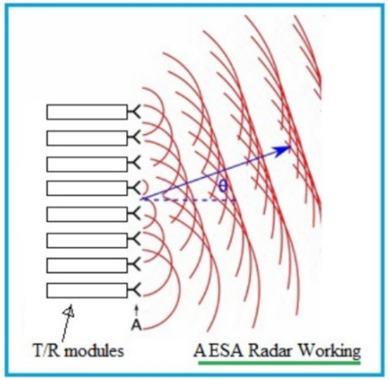
- RADAR = **RA**dio **D**etection and **R**anging (since the speed of EM waves is known, the distance to a target can be determined by measuring the time required for a transmit pulse which is reflected and received)
- Modern radars are used to measure the range as well as the direction (angle) and speed of the target
- Long-range radars traditionally realised using parabolic dish antennas (surveillance, weather radar)

Radar: phased arrays (PESA vs AESA)



PESA Radar Working

http://www.rfwireless-world.com/Terminology/AESA-radar-vs-PESA-radar.html



AESA Radar Working

- Phased arrays have been realised as a passive electronically steerable antenna (PESA) array using a central source (Tx) and a receiver unit (Rx). Low-loss phase shifters needed to maintain a high output power level and a high SNR.

- Active electronically steerable antenna (AESA) arrays are increasingly being used in modern radar and wireless communication systems. A Tx/Rx (T/R) module is required at each antenna element which increases the overall cost (e.g. they can correspond to 30-50% of the cost of an AESA radar). The main advantages are better performances (e.g. faster scan rate and a graceful degradation (not depending on a single Tx/Rx unit).

Radar: active and passive phased arrays

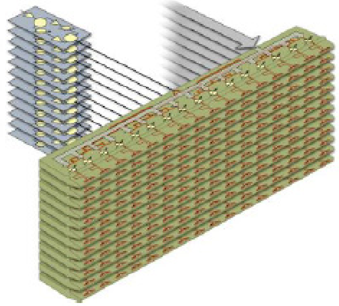
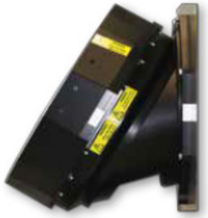


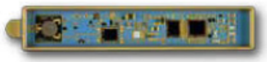
Figure 23: Planar array of a phased-array antenna, each radiating element needs an own phase shifter

http://www.radartutorial.eu

CAESAR integrated in Typhoon



AESA Antenna and Re-Positioner



Transmit/Receive Module

Example of an X-band (8-12 GHz) AESA radar

Eurofighter E-Captor AESA Radar Spec sheet
https://www.hensoldt.net/solutions/air/radar/eurofighter-e-captor-aesa-radar/

- In many of today’s defence radar systems, beam-steering is achieved using mechanical and/or electronic scanning (a passive electronically scanned array requires a phase shifter behind every antenna element)
- An active electronically scanned array (AESA) requires a transmit and receive module (TRM) behind each antenna element which increases the cost but gives better performance (e.g. faster scan and more reliable)
- GaAs MMIC based AESA radars were introduced 10-30 years ago in ground, maritime and airborne sensors. Some of the more recent AESA radars include GaN MMICs (e.g. SmartL, Giraffe 4/8A and Patriot NG radar)

Attenuation at different frequencies

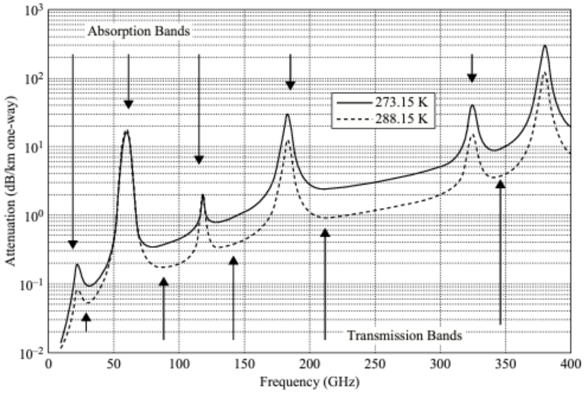


FIGURE 3-2 ■ Radar Transmission and Absorption Bands.

"Principles of modern radar radar applications", W. L. Melvin, J. A. Scheer (Editors) (Scitech Publishing)

- Atmospheric attenuation increases rapidly with frequency (RF power more costly to generate @ mmW)
- Depending on the required angular resolution (≈λ/size of antenna aperture) and sensor requirements (size, weight, DC power constraints) max range also constrained by the transmit power, losses and noise.
- mm-wave radars (> 30 GHz) can achieve high resolution with compact size but also more limited in range

Front-end architectures (homodyne, heterodyne)

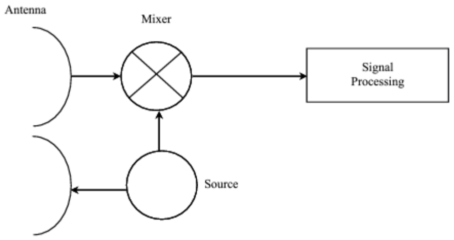


FIGURE 2.2-4 ■ Homodyne CW Radar Block Diagram with Separate Antennas for Transmit and Receive.

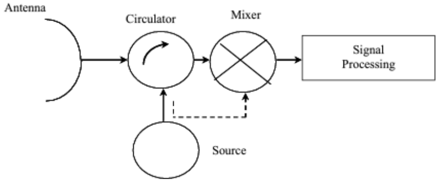


FIGURE 2.2-5 ■ Single Antenna Homodyne CW Radar Block Diagram.

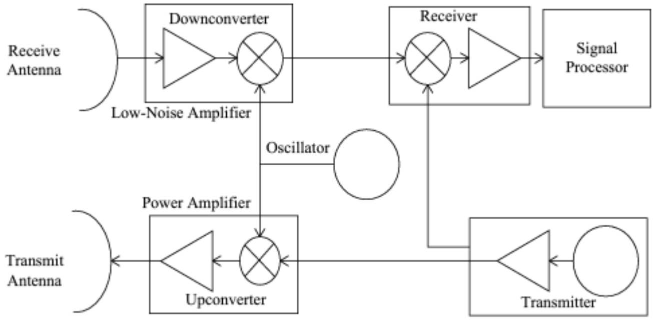


FIGURE 2.2-6 ■ Heterodyne CW Radar Block Diagram.

“Principles of modern radar radar applications”, W. L. Melvin, J. A. Scheer (Editors) (Scitech Publishing)

- Unlike pulsed radar, CW radars do not require high peak power levels and they can be quite simple to realise.
- A circulator will be required unless the transmitter and the receiver use separate antennas.
- A single mixer is used in a homodyne transceiver architecture whereas separate up/down-converters are utilised in a heterodyne transceiver front-end (IF is up-converted with the LO and RF down-converted to IF).

Frequency Modulated Continuous Wave (FMCW)

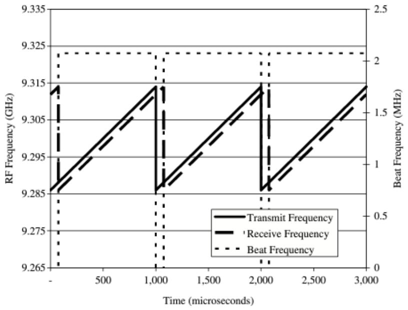


FIGURE 2.3-1 ■ Transmit-and-Receive Frequency as a Function of Time with Beat Frequency Shown.

$$\frac{f_b}{t_d} = \frac{\Delta F}{T_m}$$

$$f_b = \frac{\Delta F}{T_m}\frac{2R}{c}$$

"Principles of modern radar radar applications", W. L. Melvin, J. A. Scheer (Editors)
(Scitech Publishing)

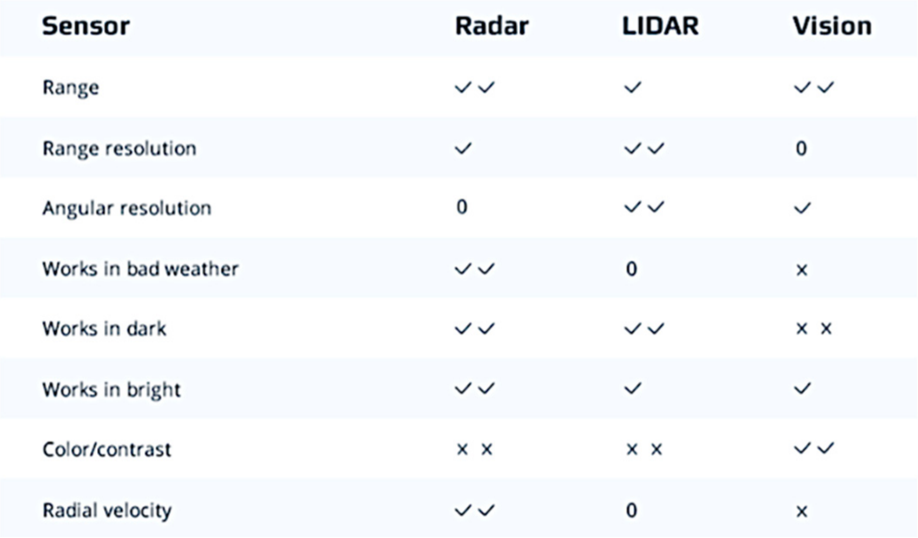
- FMCW radars can use linear or nonlinear waveforms (e.g. sawtooth, triangle, sinusoidal or noise etc).
  The receive signal comes from an echo of a target located a distance **R** from the transmitter.

- By measuring the resulting beat frequency $\mathbf{f_b}$ (= $f_{Tx} - f_{Rx}$) we can determine **R** (related to the target delay $\mathbf{t_d}$)

- The duration of the linear modulation $\mathbf{T_m}$ is set so that it lasts longer than the round-trip transmit time for the most distant target to be observed, thus avoiding ambiguities.

- The beat frequency is equal to frequency sweep slope (bandwidth/modulation period) times the transit time.

Radar vs other sensors



Sensor	Radar	LIDAR	Vision
Range	✓✓	✓	✓✓
Range resolution	✓	✓✓	0
Angular resolution	0	✓✓	✓
Works in bad weather	✓✓	0	×
Works in dark	✓✓	✓✓	× ×
Works in bright	✓✓	✓	✓
Color/contrast	× ×	× ×	✓✓
Radial velocity	✓✓	0	×

https://www.intellias.com/the-ultimate-sensor-battle-lidar-vs-radar

- Radar can provide all-weather/all-day sensor capabilities with adequate resolution

Short-range mm-wave radar sensors for airborne applications (examples)

Short-range mm-wave radar for helicopters/UAV

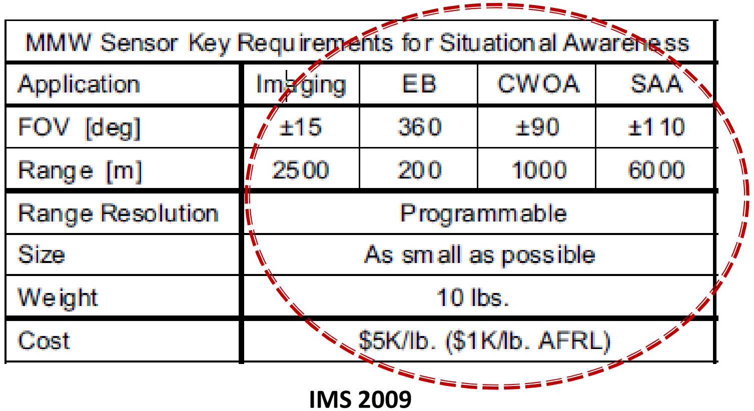
- Rotating wing aircrafts such as helicopters can experience a condition called brown-out or white-out when landing in environments with sand, dust and snow.
- Estimates made by the US government show that $100M per year in damage are caused by these conditions and many accidents due to reduced visibility conditions when landing in such harsh environments[1].
- Short-range (collision-avoidance) radar sensors in airborne vehicles (e.g. drones and helicopters) for enhanced safety in harsh and non-visible weather conditions.

Helicopter pilots need to see the outside world (or a reasonable representation of it) to hover accurately — making brownouts a problem. Graham Lavery Photo

https://www.verticalmag.com/features/battling-brownouts/

[1] E. W. Ray ”W-band high power amplifier for brown-out radar,” NAVAIR Public Release 11-147

Short-range 94 GHz radar sensor (landing-aid)

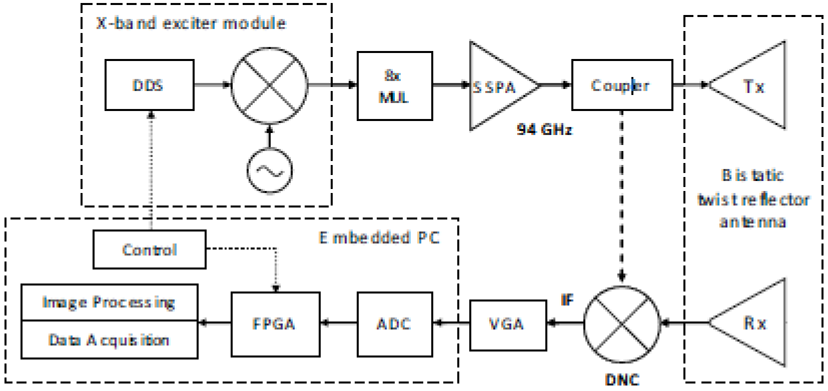


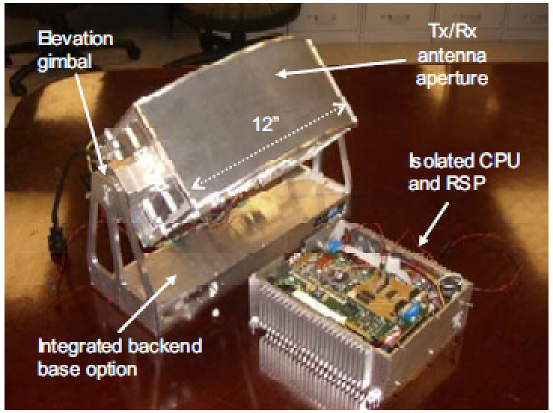
MMW Sensor Key Requirements for Situational Awareness				
Application	Imaging	EB	CWOA	SAA
FOV [deg]	±15	360	±90	±110
Range [m]	2500	200	1000	6000
Range Resolution	Programmable			
Size	As small as possible			
Weight	10 lbs.			
Cost	$5K/lb. ($1K/lb. AFRL)			

IMS 2009

- Honeywell (US) performed field tests with a 20 lbs mechanically scanned 94 GHz imaging radar unit incl. a 2W power amplifier. Angular resolution of ≈1° can be obtained at 94 GHz (30 cm aperture size).
- A main challenge is to demonstrate **compact, light-weight and affordable** mm-wave radar sensors for airborne platforms such as fixed wing airplanes and rotorcrafts (incl. drones) which impose stringent requirements in terms of being able to minimize size, weight, power and cost (SWaP-C).

Short-range 94 GHz radar sensor (landing-aid)

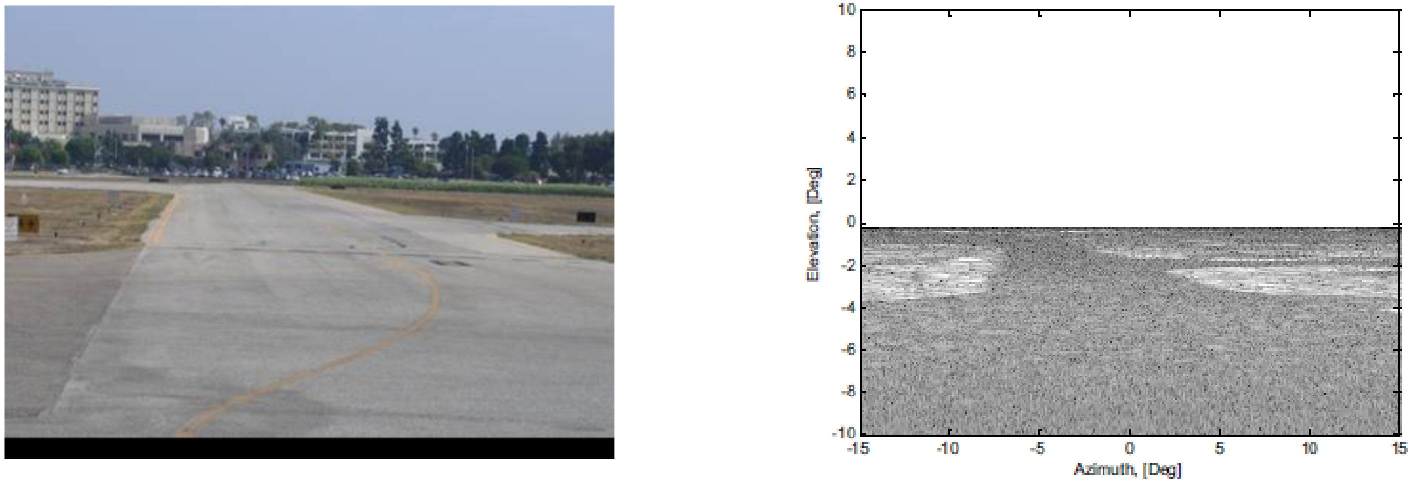




D.S. Goshi et al., ”Recent Advances in 94 GHz FMCW Imaging Radar Development”, *Proc. of the 2009 IEEE Int. Microwave Symposium*, pp. 77-80, 2009.

- Frequency Modulated Continuous Wave (FMCW) radar systems are often deployed in various short-range applications and some of the main advantages over pulsed radars are relaxed output power requirements (which more easily can be realised using solid-state electronics) and a simple architecture.

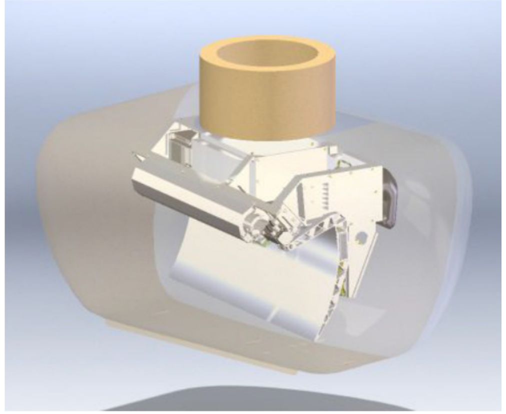
Short-range 94 GHz radar sensor (landing-aid)



D.S. Goshi et al., ”Recent Advances in 94 GHz FMCW Imaging Radar Development”, *Proc. of the 2009 IEEE Int. Microwave Symposium*, pp. 77-80, 2009.

- Field tests done with the 94 GHz mechanically scanned radar sensor (mounted on the roof of a truck), looking at an airport taxiway to simulate a runway landing strip, demonstrated imaging radar capabilities.

Short-range 94 GHz radar sensor (landing-aid)



J. Cross et al., ”MMW Radar Enhanced Vision Systems: The Helicopter Autonomous Landing System (HALS) and Radar Enhanced Vision System (REVS) are rotary and fixed wing enhanced flight vision systems that enable safe flight operations in degraded visual environments”, *Proc. of SPIE Vol. 8373, 2013.*

- SNC (US) has developed 94 GHz reflector based radar sensors for both helicopter and aircraft landing and also looked into planar apertures as the non-planar one is larger than desired for aircraft installation.

94 GHz synthetic aperture radar (SAR)

W. Johannes et al., ”Miniaturized High Resolution Synthetic Aperture Radar at 94 GHz for Microlite Aircraft or UAV ”, *Proc. of IEEE, 2011.*

- Fraunhofer (GER) has demonstrated a successful use of a 94 GHz SAR sensor on a microlite aircraft.
- Waveguide based slotted array antennas + FMCW radar front-end module (100 mW of output power)
- Flight tests generated high resolution SAR images and may also be operated on board a small UAV.

FOI activities on microwave/mm-wave short-range radar for airborne applications

FOI activities on μ/mm-wave radar technologies

Phased array based
Radar systems (FM)

Small UAV with
C-band Radar
(FOI)

SERENA (EU)

MEMS Terahertz
systems (SSF)

Smart
Micromachined
Antennas (Vinnova)

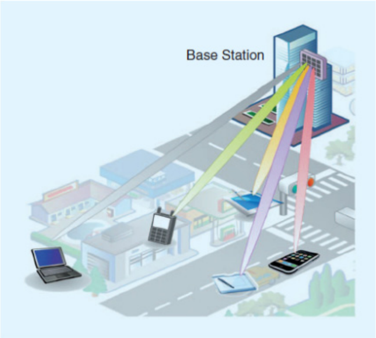
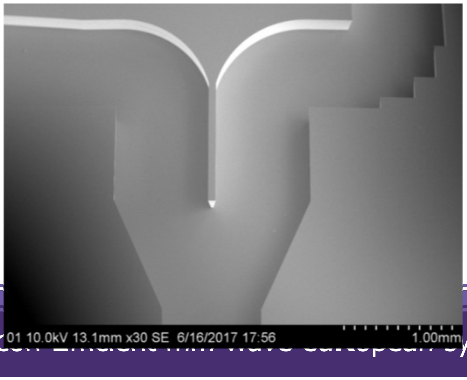
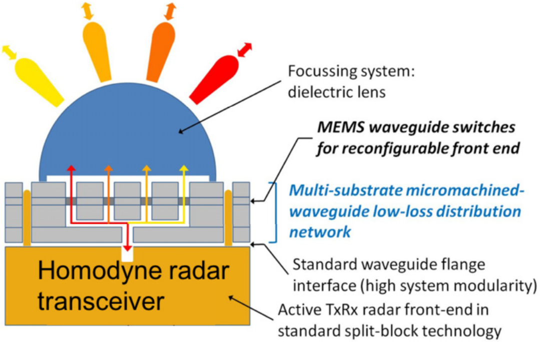


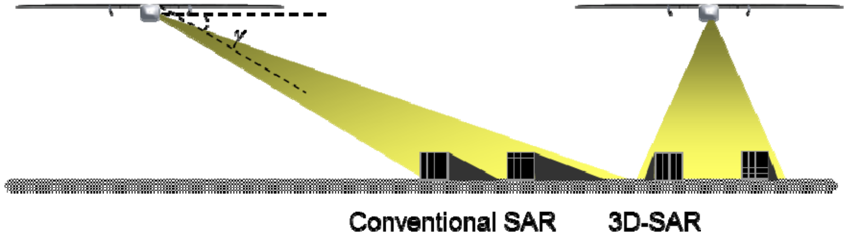
Figure 1. *An envisioned use case of massive MIMO in 5G.*





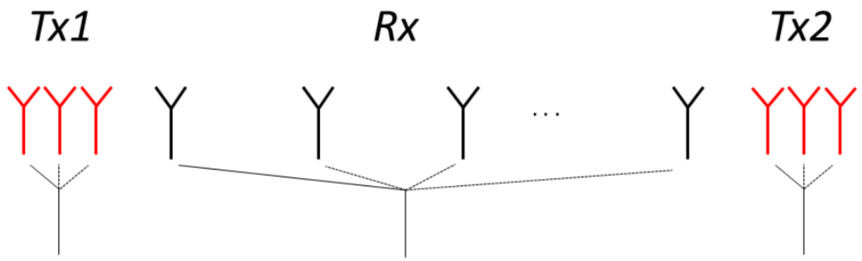
K-band 3D-SAR (Synthetic Aperture Radar)

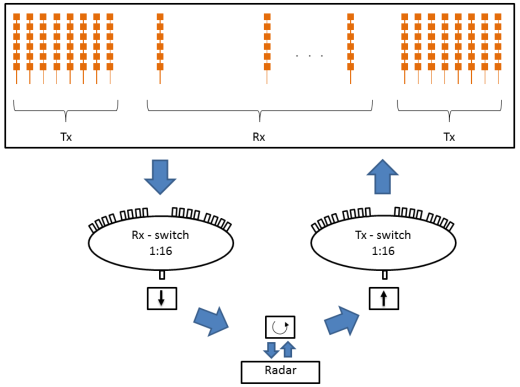
K-band 3D-SAR (application example – scenario)



- Side-looking conventional (2D) SAR struggles with shadowing effects
- Especially problematic in urban environments with steep height variations
- 3D-SAR reduces the shadowing effects by its nadir geometry
- A large array antenna is required to achieve a sufficient cross-track resolution
- Concepts for sparse array antenna architectures are studied
- Initial 3D-SAR tests at FOI using an exp. K-band antenna prototype and a mechanical scanner

K-band 3D-SAR (antenna front-end architecture)

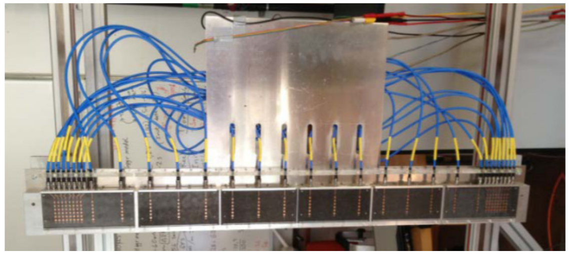


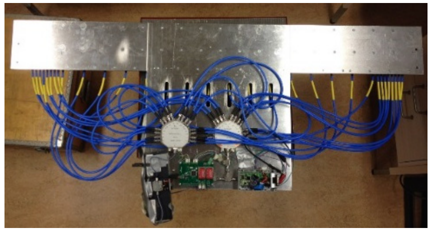


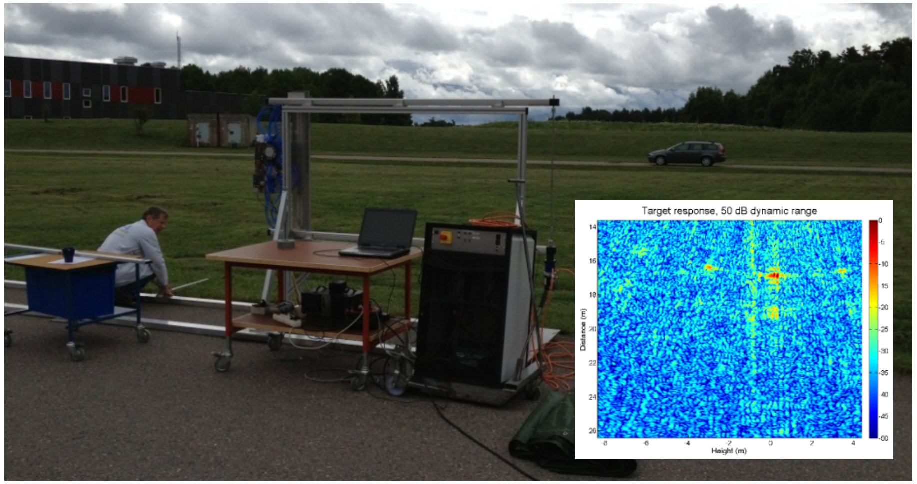
- A switched multi-static (sparse and compact) antenna architecture is used (since a large and fully populated phased array antenna is considered too complex & costly)

- The exp. array antenna architecture (8 Tx + 16 Rx + 8 Tx) is used to demonstrate a system with reduced size complexity and cost (the increased measurement time with this method limits its use to fixed or slowly varying scenarios)

K-band 3D-SAR (exp. prototype – meas. setup)

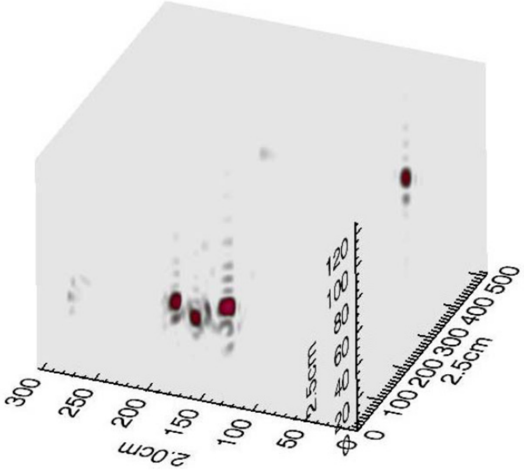






- Targets: cars and corner reflectors (@ 20- 40 m distance)
- 8 m “flight” distance (in 2 m sections) in SAR-direction
- @ 25-26.5 GHz, BW=750 MHz and 1500 MHz (20 and 10 cm of range res.)

K-band 3D-SAR (measurement results)

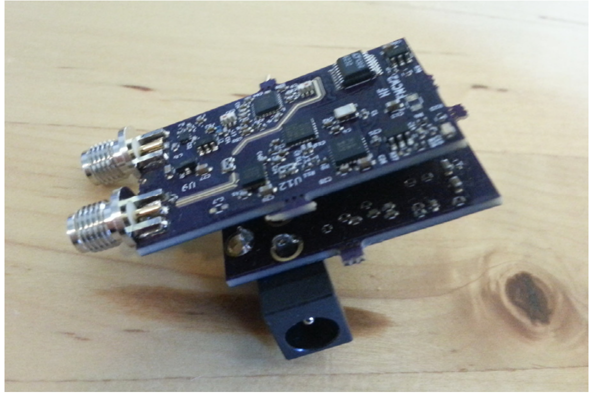


- 3D view of a car and a corner reflector (obtained from 3D-SAR measurements)
- Corner reflector is clearly seen to the right (additional returns probably due to car head lights and front)
- Radar measurements validate the sparse array antenna concept for the experimental 3D-SAR system

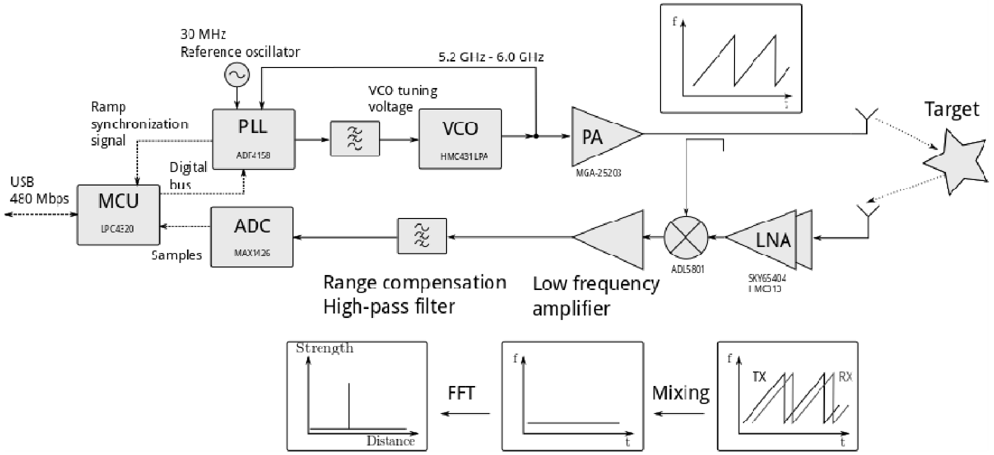
5.4-6.0 GHz SAR sensor on a small UAV

5.4-6.0 GHz radar sensor (used on a UAV)

- Open-source-based HW and SW*
  - Further development (system integration) done at FOI based on MIT:s coffee can low-cost radar design
  - The price of 3 FMCW radar modules is about 2 kUSD (incl. PCB manufacturing and component assembly)

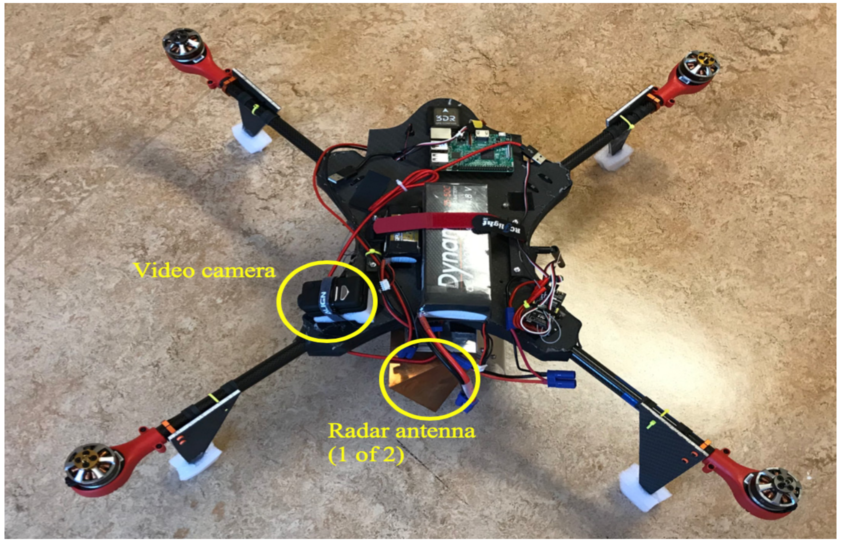


*https://github.com/Ttl/fmcw2

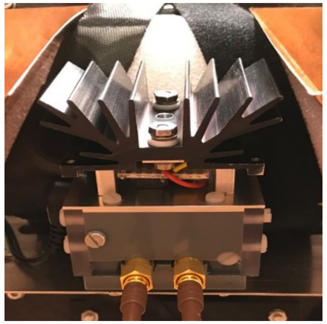


5.4-6.0 GHz radar sensor (mounted on a UAV)

- Radar on a small drone (quadracopter)
  - UAV outer dimensions: 85 cm x 85 cm
  - Max payload weight: 0.5 kg
  - Remote control of UAV and radar unit
  - Low-weight horn antennas (15 dBi, 92 g)

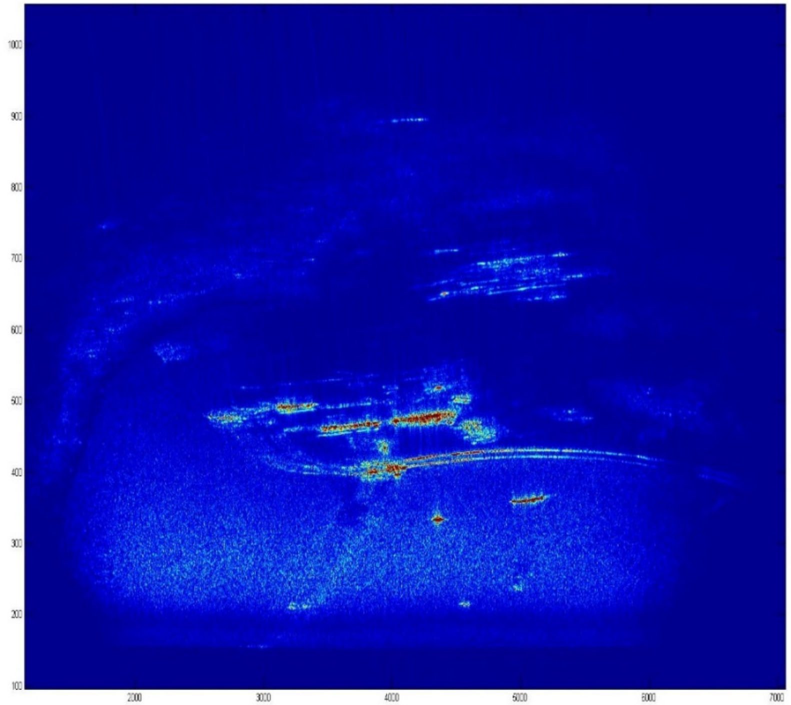


Small drone with a C-band radar sensor unit developed at FOI and used for SAR measurements



Radar unit incl. two PCBs (2 cm x 3 cm), cooling flange and fan

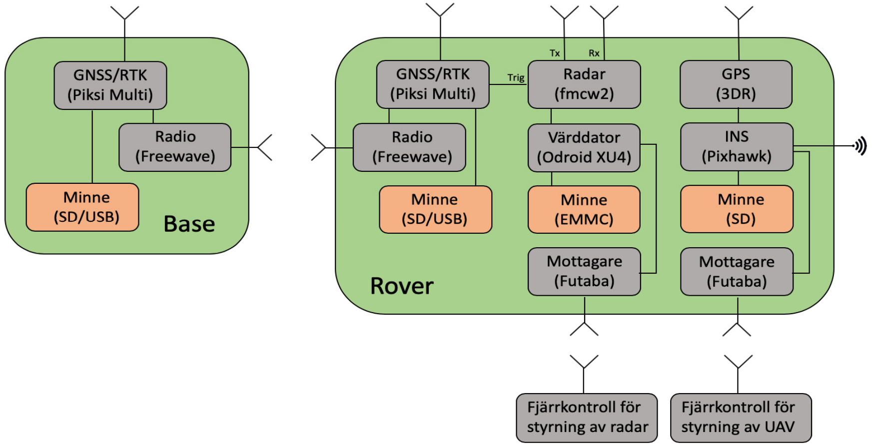
Initial C-band SAR measurements from a UAV (1)



Initial C-band SAR measurements from a UAV (2)

- Flying SAR measurements using a small drone (quadracopter)
- Theoretical range and angular resolutions are equal to 25 cm and 7 cm, respectively
- Flying altitudes equal to 8-24 m were used during tests and incl. distances up to 80 m
- During the measurements the UAV was controlled by autopilot
- Reasonably good quality of obtained SAR images (considering no positioning data was used)
- An autofocus technique resulted in an improved quality (better focus) of SAR images
- Subsequent developments made at FOI include position sensor integration (1 cm accuracy)
- This enables SAR images from arbitrary (curved) flight trajectories (e.g. due to wind gusts or to realise other SAR modes such as interferometric SAR or 3D-SAR)
- Move to higher frequencies (mm-wave) to enable phased array to fit a smaller platform

Cont'd C-band SAR measurements from a UAV(1)



GNSS/RTK
(Piksi Multi)

Radio
(Freewave)

Minne
(SD/USB)

Base

GNSS/RTK
(Piksi Multi)

Trig

Tx

Rx

Radar
(fmcw2)

GPS
(3DR)

Radio
(Freewave)

Värddator
(Odroid XU4)

INS
(Pixhawk)

Minne
(SD/USB)

Minne
(EMMC)

Minne
(SD)

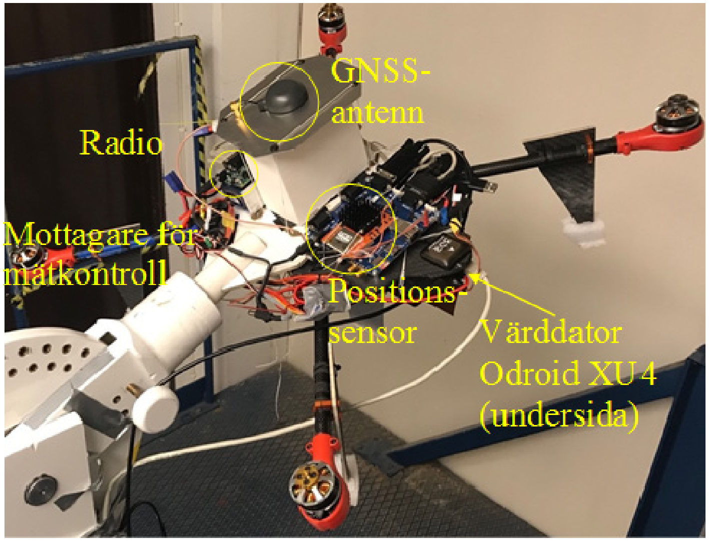
Mottagare
(Futaba)

Mottagare
(Futaba)

Rover

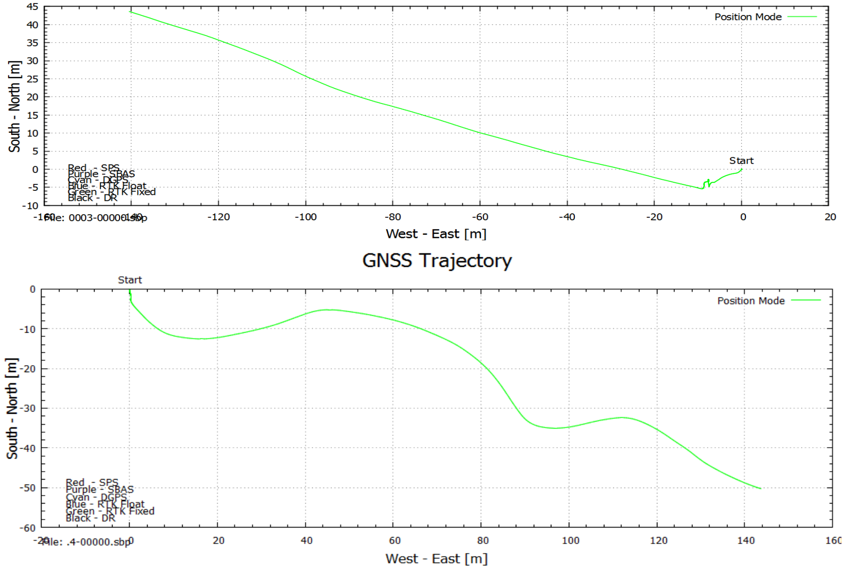
Fjärrkontroll för
styrning av radar

Fjärrkontroll för
styrning av UAV

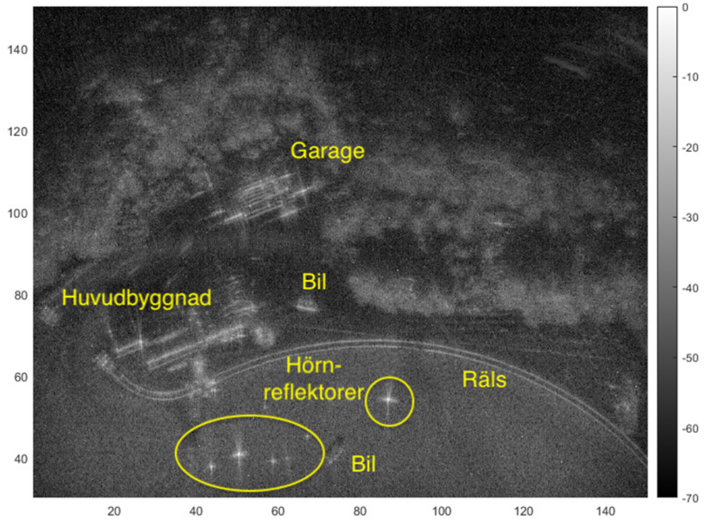


UAV equipped with radar, positioning sensor and radio to receive correction data from the ground (Base)

Cont’d C-band SAR measurements from a UAV(2)



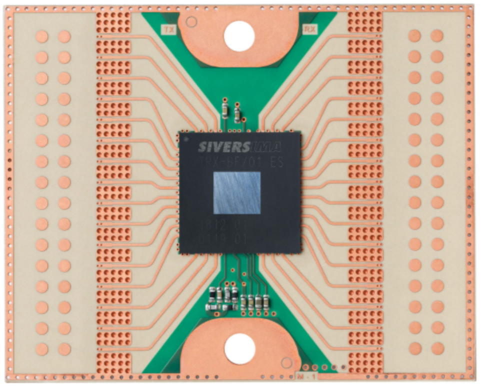
GNSS Trajectory



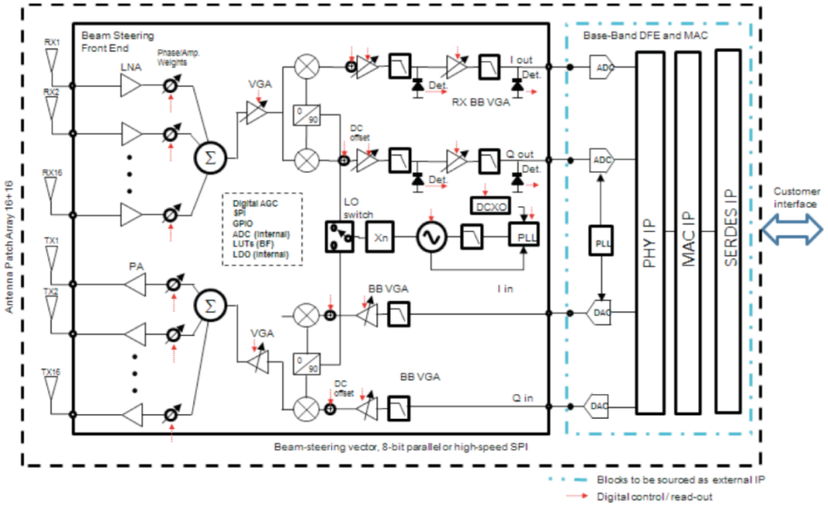
Good quality of generated SAR images based on the low-cost 5.4-6.0 GHz radar with positioning sensor (incl. both almost straight and curved trajectories and/or non-constant speed)

mm-wave front-ends and phased arrys

mm-wave active phased array (COTS example)

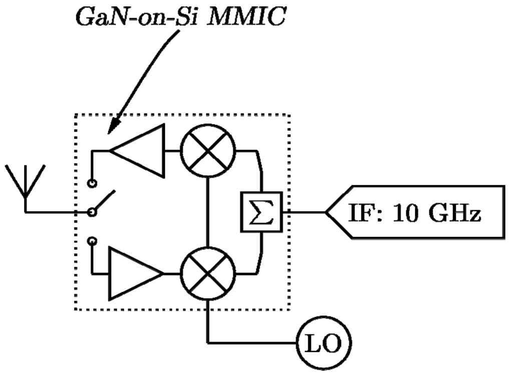


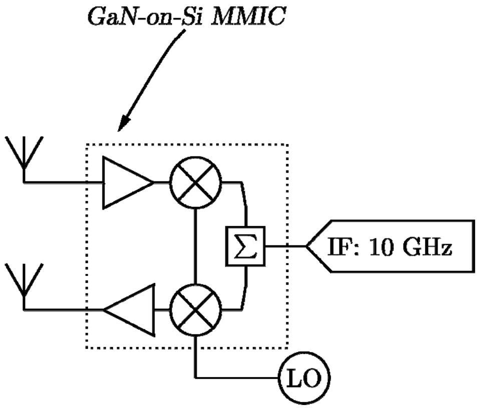
https://www.siversima.com



- mm-wave el. steerable antennas (phased arrays) can more easily fit to platforms such as smaller UAV (e.g. see above ex. of a COTS 57-66 GHz 16 Rx/16 Tx beamforming module with +40 dBm output power)

94 GHz radar transceiver architectures (SERENA)





- Monolithically integrated (potentially single-chip) mm-wave radar transceivers could enable a higher level of integration (miniaturisation) if performance and cost targets may be fulfilled (e.g. @ W-band)

- GaN-on-Si technology has the potential to scale wafer size from 4” to 8” and beyond thereby reducing the chip fabrication cost (i.e. below GaAs and close to that of SiGe but with higher performance)

95 GHz radar sensor characteristics (examples)

Parameter	**Values**	**Applications (examples)**
Frequency range	92-95 GHz (92-100 GHz)	• Landing-aid/anti-collision Radar [1-3] • Climate monitoring/Doppler Radar [4-5] • Radars for bird detection at airports and airfields [6]
Output power	0.5-1 W (2 W)	
Detection range	1-5 km	
Range resolution	2-5 cm	
Angular resolution	0.5-2° (1-3 mrad)	
Noise Figure	5-8 dB	

[1] D.S. Goshi et al., "Recent Advances in 94 GHz FMCW Imaging Radar Development", *Proc. of the 2009 IEEE Int. Microwave Symposium*, pp. 77-80, 2009.
[2] http://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/topics/jti-cs2-2017-cfp07-sys-01-10.html
[3] D.S. Goshi et al., "Cable Imaging with an Active W-Band Millimter-Wave Sensor" *Proc. of the 2010 IEEE Int. Microwave Symposium*, pp. 1620-1623, 2010.
[4] J. Delanoe et al., "BASTA: A 95-GHz FMCW Doppler Radar for Cloud and Fog studies", *Journal of Atmospheric and Oceanic Technology*, vol. 33, pp. 1023-1038, May 2016.
[5] A. Fung *et al.*, "Advanced W-Band Gallium Nitride (GaN) Monolithic Microwave Integrated Circuits (MMICs) For Cloud Doppler Radar", https://data.nasa.gov/Earth-Science/Advanced-W-Band-Gallium-Nitride.../mv4f.../data.
[6] L .A. Klein et al., "MMW Radar for Dedicated Bird Detection at Airports and Airfields", Proc. of the Int. Bird Strike Committee, pp. 205-220, 2003.

Ka/W-band GaN-on-Si based frontends (SERENA)

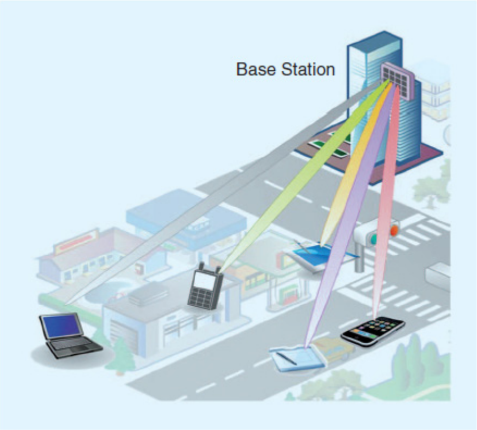


Figure 1. *An envisioned use case of massive MIMO in 5G.*

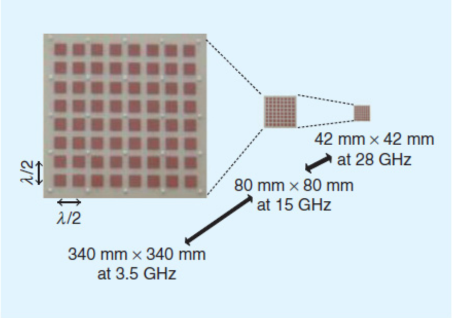
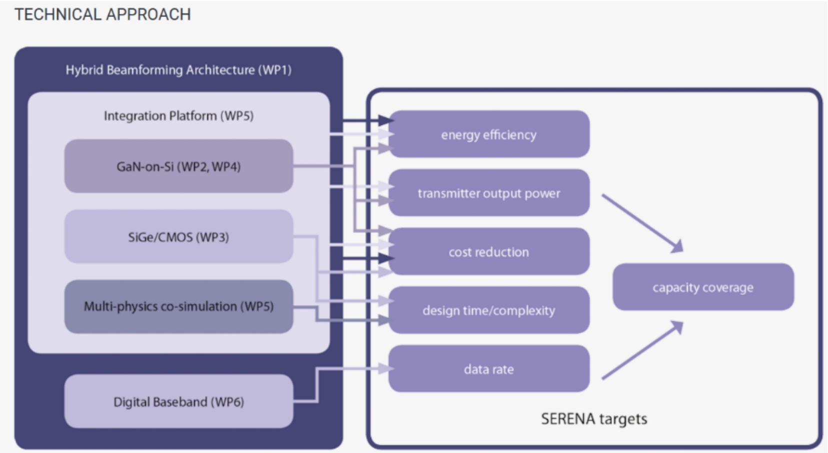


Figure 2. *An image showing the size of an RF front-end panel with 8 × 8 arrays for 3.5, 15, and 28 GHz.*

S. Shinjo et al., “Integrating the front-end,” IEEE Microwave Magazine, July/August 2017.



TECHNICAL APPROACH

Hybrid Beamforming Architecture (WP1)

Integration Platform (WP5)

GaN-on-Si (WP2, WP4)

SiGe/CMOS (WP3)

Multi-physics co-simulation (WP5)

Digital Baseband (WP6)

energy efficiency

transmitter output power

cost reduction

design time/complexity

data rate

capacity coverage

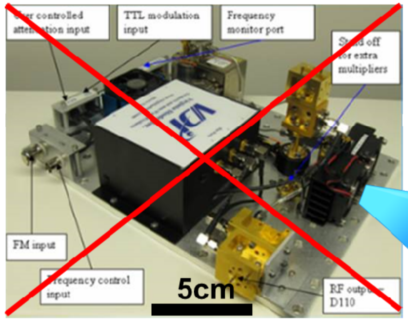
SERENA targets

https://serena-h2020.eu/

- An initial version of an E/W-band GaN-on-Si front-end MMIC (incl. PA, LNA and up/down-converter) co-designed by FOI and Ericsson, fabricated by OMMIC, is presently being characterised (exp. results to be reported later on)

μ-machined mmW/THz system integration

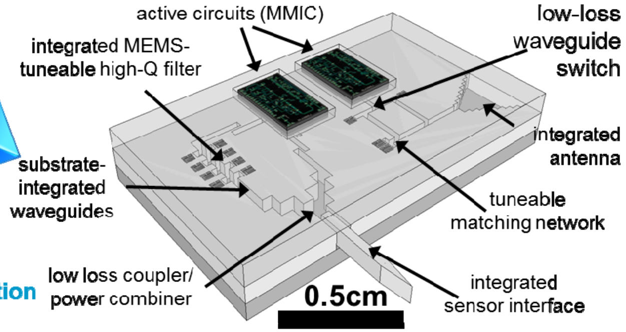
µ-machined system integration (mmW/THz)



Conventional, commercial THz system (VD, USA)

1000x smaller
1000x lighter
100x lower cost
10x less power consumption
higher performance

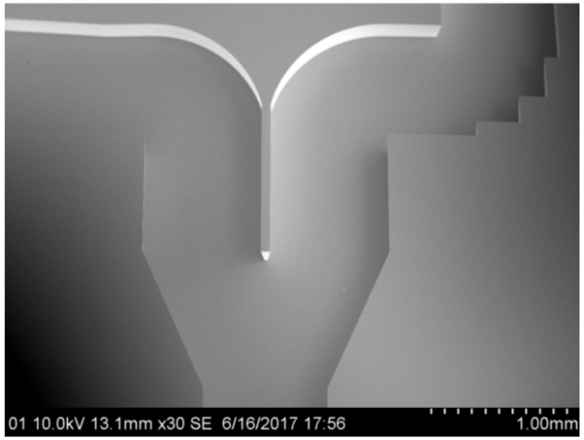
Proposed THz microsystems - enabled by micromachined heterogenous mm-wave/THz integration platform:



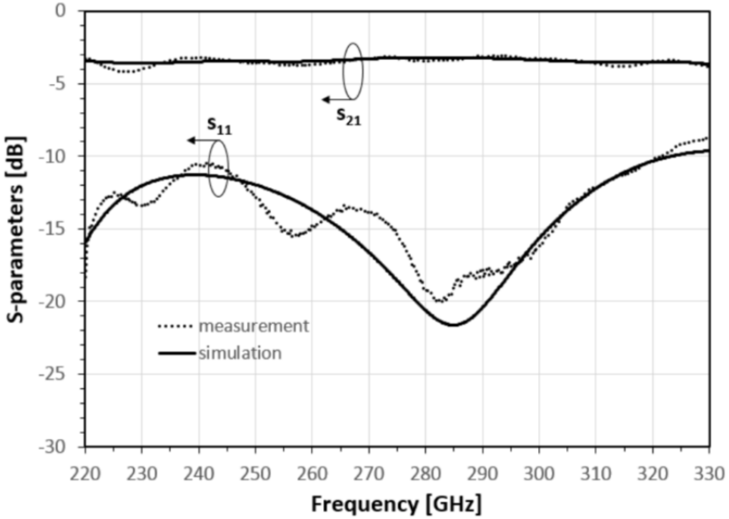
- A silicon based micromachined system integration platform developed at KTH (prof. J. Oberhammer) is being used in a national research project funded by SSF (MEMS Terahertz Systems)

- FOI has designed some power splitters/couplers and non-galvanic transitions (MMIC-to-waveguide)

µ-machined system integration (mmW/THz)

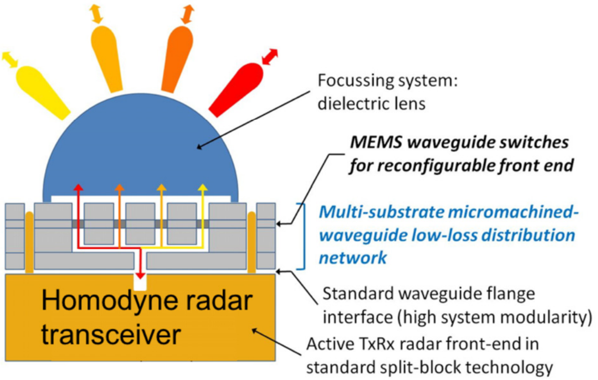


[IEEE APMC 2017]



- Some Si µ-machined power splitters and hybrid couplers (designed by FOI and fabricated at KTH) show relatively low losses (<0.5-1 dB) within the 200-300 GHz frequency range

µ-machined steerable antenna (340 GHz radar)



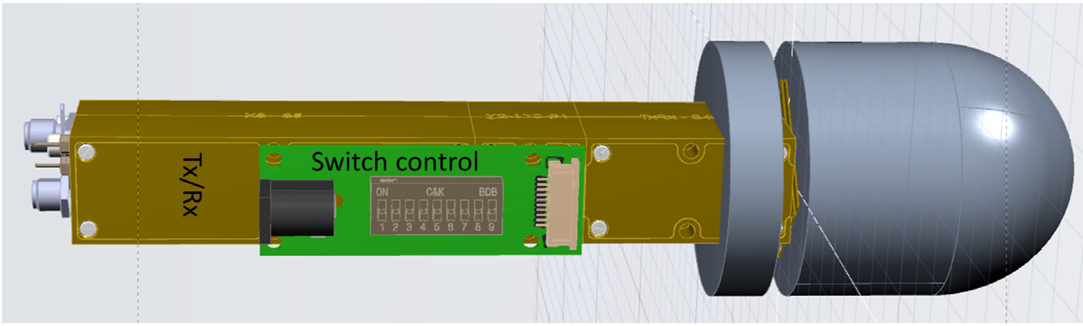
Focussing system: dielectric lens

MEMS waveguide switches for reconfigurable front end

Multi-substrate micromachined-waveguide low-loss distribution network

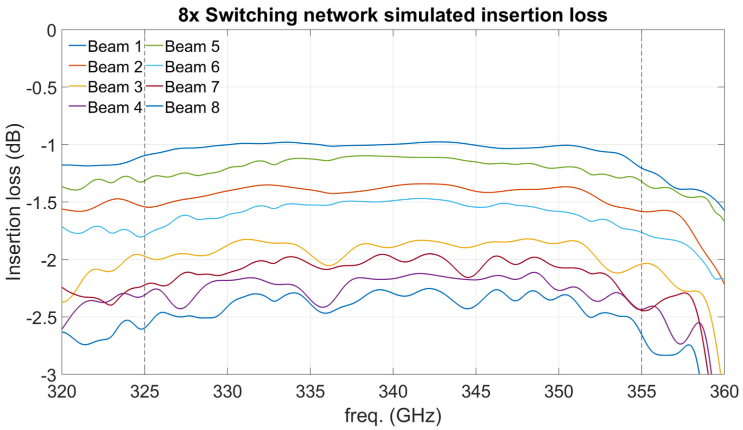
Standard waveguide flange interface (high system modularity)

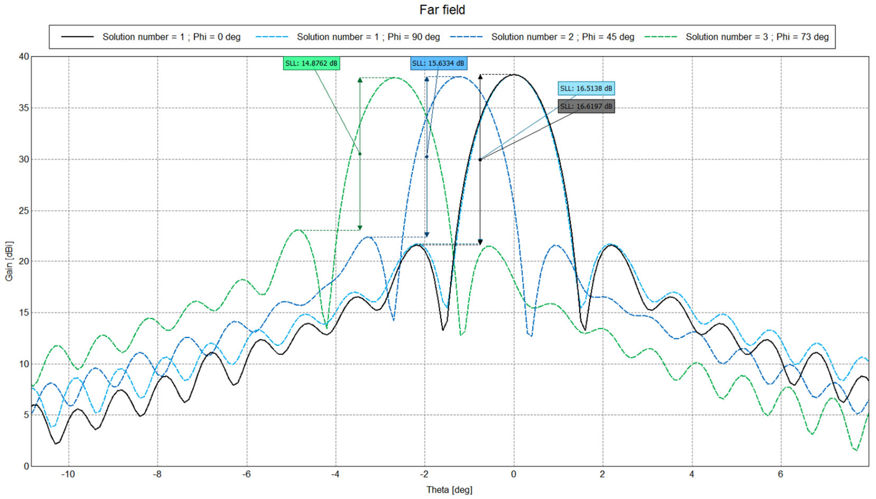
Active TxRx radar front-end in standard split-block technology



- 340 GHz FMCW radar with an electrically steered focal plane array antenna and RF MEMS-based waveguide switches (on-going Vinnova project)
- Targeting miniaturised mm-wave/THz sensing and communication systems

µ-machined steerable antenna (340 GHz radar)





Total Gain (Frequency = 340 GHz)

- Low permeability dielectric lens antenna (CNC milled Rexolite 1422 lens): 37 dB gain, SLL < -14 dB in the FoV
- 320-350 GHz SP8T switch network: RL > 15 dB, IL < 2.5 dB

- 340 GHz radar module (COTS): 0-2 dBm Tx power, 15 – 20 dB Rx conversion loss (30 GHz bandwidth)

Summary

- mm-wave short-range radar sensors have been developed for airborne vehicles (e.g. aircrafts and helicopters) for SAR and to enhance safety in harsh and non-visible weather conditions (landing-aid).

- Such systems have typically been realised using fixed or mechanically scanned antennas (bulky).

- A main challenge is to demonstrate compact, light-weight and affordable mm-wave radar sensors for airborne platforms such as fixed wing airplanes and rotorcrafts (incl. drones) which impose stringent requirements in terms of being able to minimize size, weight, power and cost (SWaP-C).

- More recent advances in GaN and Silicon based IC technologies together with a use of novel mm-wave system integration methods using e.g. multi-layer PCBs or silicon micromachining are expected to pave the way for more highly integrated low-cost phased arrays for short-range radar applications.

Acknowledgements

- Present and past colleagues at FOI and other places involved in activities on μ/mm-wave short-range radar sensors for airborne applications and related technology development. The initial work on such sensors at FOI was led by Andreas Gustafsson and is presently led by Dr. Jan Svedin.

- The Swedish Armed Forces (FM), the European Union (EU), The Swedish Foundation of Strategic Research (SSF) and The Swedish Innovation Agency (VINNOVA) are also acknowledged for their respective funding of parts of the work included in this presentation

SERENA Grant Agreement No. 779305

“The SERENA project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 779305.”

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