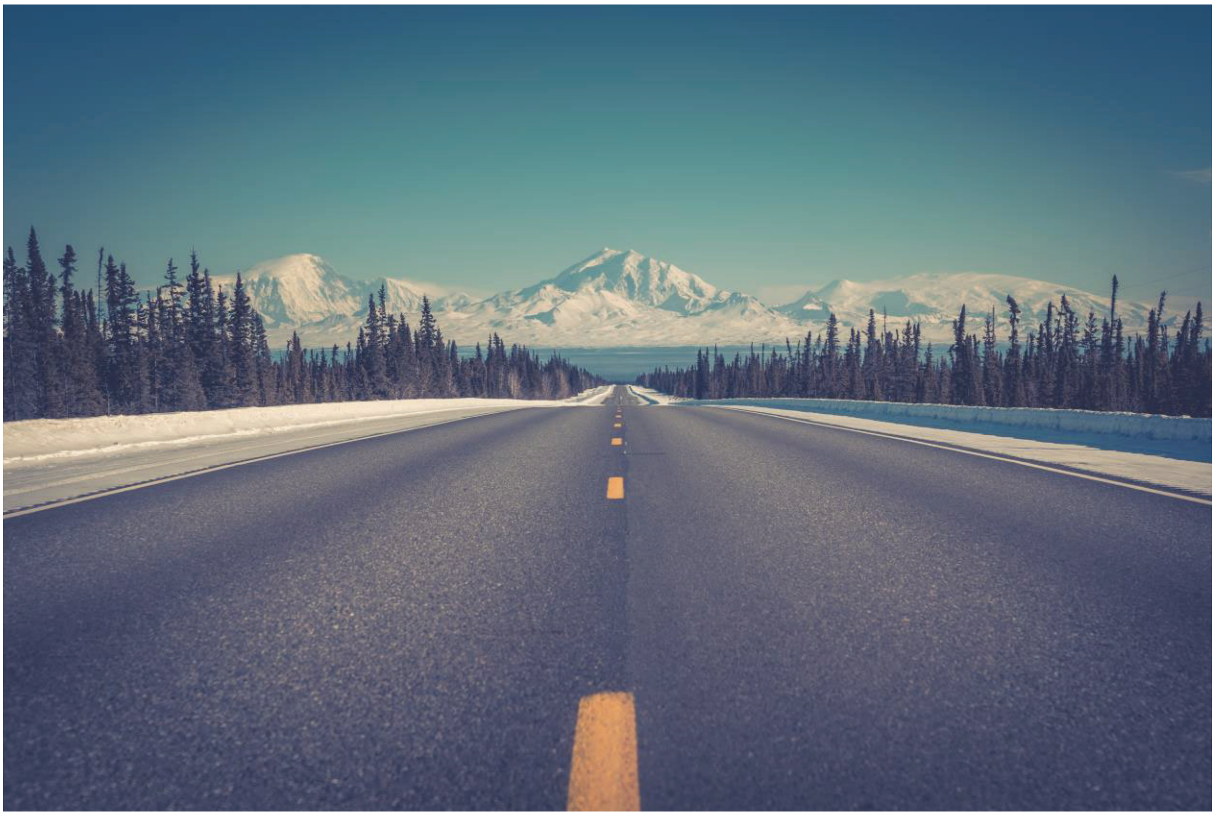
Black ice warning system for improved traffic safety



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Datum: Maj 2023

Projekt inom Elektronik, mjukvara och kommunikation - FFI

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1 Sammanfattning

Detta projekt nådde framgångsrikt sina mål. Projektet syftade till att bygga en sensor som kan identifiera tillståndet på vägyta framför ett fordon i rörelse, innan hjulen når det intressanta området. En radarsensor med polarimetrisk förmåga krävs för att kunna urskilja vägytans tillstånd när sensorn är i rörelse.
Inom projektet utvecklade, testade och utvärderade vi två olika koncept för att bygga en polarimetrisk radar. Radarsensorprototyperna tillverkades och testades framgångsrikt. Mätningar i verklig trafik utfördes för att verifiera sensorernas förmåga att särskilja ytor i olika tillstånd. Nyligen kunde vi verifiera att båda sensorerna kunde detektera ett vått område på vägbanan i realtid när fordonet var i rörelse. På grund av de rådande väderförhållandena är sensorerna ännu inte testade på isiga eller snötäckta vägytor. Mer information om resultaten och bilder finns i det bifogade dokumentet.

2 Executive summary in English

The purpose of the project was to bring our earlier research results to a level closer for commercialization. We wanted to build a sensor that can identify the condition of the road surface in front of a vehicle in motion before the wheels reach the sensed area. This is a challenging task since the road surface is random and the radar response varies significantly as the sensor measures different areas. A radar sensor with polarimetric capabilities is required to be able to distinguish the state of the road surface when the sensor is in motion.
We developed and tested two different types of compact polarimetric radar sensors, we tested both sensors in traffic and we were able to detect a wet patch on the surface of the road in real time. More tests are planned on icy and snow-covered surfaces.

3 Bakgrund

Ice formations on top of the road surface cause reduced contact friction between the vehicle and the road. Knowledge of the road surface conditions is important for road traffic safety and is essential for reducing the number of injuries and deaths linked to weather related traffic accidents. For example, in the US, 1 235 145 car accidents, 5 376 deaths and 418 000 injuries, are reported on average per year as a result of weather-related accidents (accidents that occur in the presence of adverse weather and/or slick pavement conditions). According to “Icy Road Safety”, the fatality rate due to icy road conditions is 3.6 times the total deaths from all other weather hazards combined. While snowy and wet road conditions are recognizable by the driver, a thin transparent ice layer, so-called “Black Ice”, is impossible to visually detect and distinguish from wet surfaces. The black ice usually forms when moisture from rain or fog freezes and forms a thin ice layer on top of the road surfaces. Black ice is transparent and the road may look wet or even dry to the driver, giving no indication that the road ahead is extremely slippery. This makes black ice a particularly dangerous road condition. An automotive sensor looking ahead of the vehicle and able to predict the traction properties of the road surface would reduce the consequences of weather related traffic accidents.
The existing technologies for ice detection can be summarized in the following groups:

- Sensors embedded in the road surface ,
- Infrared cameras that are mounted on elevated supports to assess their surrounding areas- such as the Infrared Road Ice Detection System
- systems sensing the road conditions under the vehicle, these sensors measure the surface temperature remotely or use IR or radar type of sensors to detect ice , under the vehicle.

The first two groups of sensors provide information only at selected and limited areas of the road. The third group provides information of the road surface conditions under the vehicle and after the wheels have come into contact with the ice. There is also a method to detect low friction sections of the road based on data received by already existing sensors in the car. The method compares the rotational speed of the driveshaft and the axles of the vehicle and delivers an estimate of the level of friction.

Clearly, there is a need for a sensor that can distinguish ice or wet surface from dry.

4 Syfte, forskningsfrågor och metod

The project aimed at building a sensor that can identify the condition of the road surface in front of a vehicle in motion, before the wheels reach the area of interest. A radar sensor with polarimetric capabilities is required to be able to distinguish the state of the road surface when the sensor is in motion. This is a challenging task since the road surface is random and the radar response varies significantly as the sensor measures different areas. In our earlier work at the microwave laboratory at Chalmers we tested a method that can handle the randomness of the surface, however it required measurements of full polarimetric scattering matrix **[S]**. The **S** matrix is used to calculate a set of polarimetric parameters such as “Entropy” - a measure of the randomness of the object, and “Depolarization. Our earlier research results[1] showed that both parameters increase when the surface is ice-covered compared to dry surface, while if the surface is wet – they change in the opposite direction.
Within the project we developed, tested, and evaluated two different concepts for building a polarimetric radar. The radar sensor prototypes were successfully manufactured and tested. Measurements in real traffic were carried out to verify the sensors capability to differentiate surfaces in different states. Recently we could verify that both sensors were able to detect a wet patch on the road surface in real time when the vehicle was in motion. Due to the current weather conditions the sensors are not yet tested on icy or snow-covered road surfaces. More details on the results and pictures are provided in the attached document.

5 Mål

The purpose of the project was to bring our earlier research results to a level closer for commercialization. We wanted to build a sensor that can identify the condition of the road surface in front of a vehicle in motion, before the wheels reach the sensed area. To test the method, we used a laboratory instrument configured as polarimetric radar. The method showed to be very promising and could discriminate icy from dry and wet surfaces in laboratory conditions. However, to test the method in real traffic we needed a compact sensor, based on a commercial chipset.
Thus, since there are no commercial products that can be adapted for this application, the main purpose of this project was to develop a compact radar sensor that can be integrated on a vehicle and tested in traffic. Within the project we developed and tested two different approaches to build a polarimetric radar sensors. We used commercial chips provided by Texas Instruments for the 77-81 frequency band. Both prototypes were manufactured and proved to be working as expected. At the final stage of the project, the sensors were tested in traffic and were able to detect a wet patch on the road surface.

[1] V. Vassilev, ” Road surface recognition at mm-wavelengths using a polarimetric radar”, *IEEE Transactions on Intelligent Transportation Systems, 23(7): 6985 -6990.*

6 Resultat och måluppfyllelse

Even though delayed, this project fully achieved its goals. We successfully developed and demonstrated two types of radar sensors, capable of identifying road surface condition. A short description of the sensors and a summary of measurements are presented below.

Design and manufacturing

Within the project we developed and tested two different approaches to build a polarimetric radar sensors. We used commercial chip-set provided by Texas Instruments for the 77-81 GHz frequency band that are interfaced to waveguide structures. To achieve a cost-effective solution, which contains the transitions to waveguides we developed a custom dielectric stack that allows the integration of the waveguide transitions on to the radar printed circuit board (PCB). The waveguide structures are screwed to the radar PCB, this way avoiding the use of additional boards and/or bond-wires.

A single horn sensor

To build a polarimetric radar at least 2 transmitters (Tr) and two receivers (Rec) are required, each of them transmitting/receiving either horizontal (H) or vertical (V) polarization.

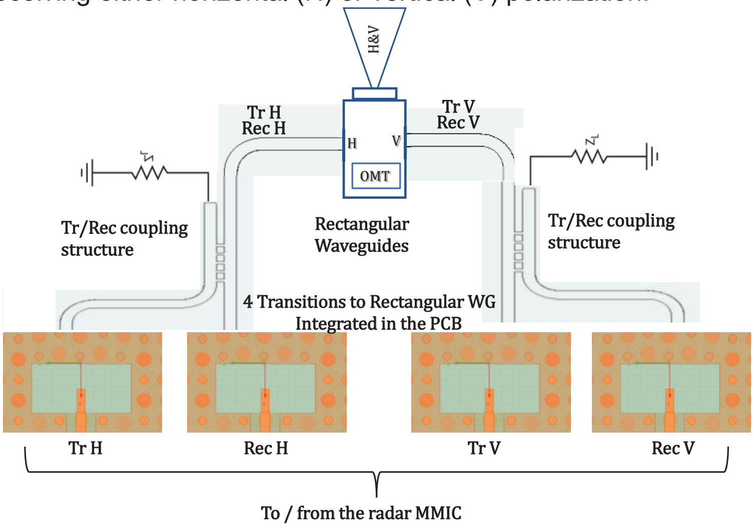


Figure 1 A block diagram of the single horn radar. A rectangular waveguide block containing the waveguide transitions is attached to the radar board. Each Tr/Rec is interfaced to a rectangular waveguide. A pair of waveguide couplers bring together one Tr and one Rec for each of the polarizations. Both polarizations are connected to a polarization filter (OMT) and are fed to a horn antenna. This way all Tr/Rec are sensing the same spot on the surface.

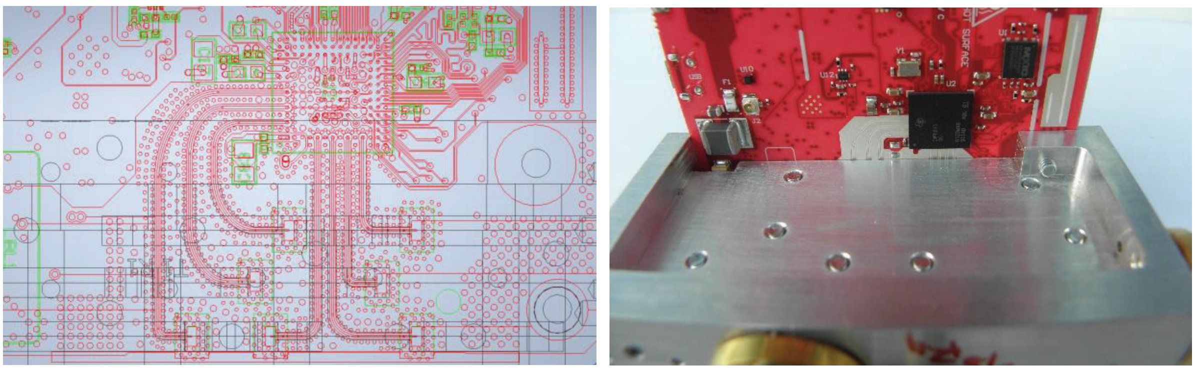


Figure 2 ***To the left*** *a part of the board layout showing the radar chip and transitions to the rectangular waveguide. Three transmitters and 4 receivers are interfaced to waveguide using transition structures embedded in the dielectric stack.*

To the right*: A picture of the radar board attached to the waveguide block.*

Pros

- \+ Only 1 Horn Antenna is needed
- \+ All Tr/Rec are focused onto the same spot of the surface
- \+ No risk for generating cross-pol components in the hardware
- \+ Can work at any range

Cons

- Limited isolation between Tr and Rec: about -20 to -25 dB of the transmitted power leaks towards the receiver in the hardware. As result the receivers are operated with reduced gain (increased noise) in order to avoid saturation.
- Loss of performance: >2 times increase in noise in addition to < ½ of the available power is transmitted due to the coupling structures in the waveguide block.

Double horn sensor

The double horn sensor uses two horns connected through circular waveguides to the radar board. One horn accommodates two transmitters (Tr), the other horn 2 receivers (Rec), this way we achieve high isolation between the Tr/Rec.

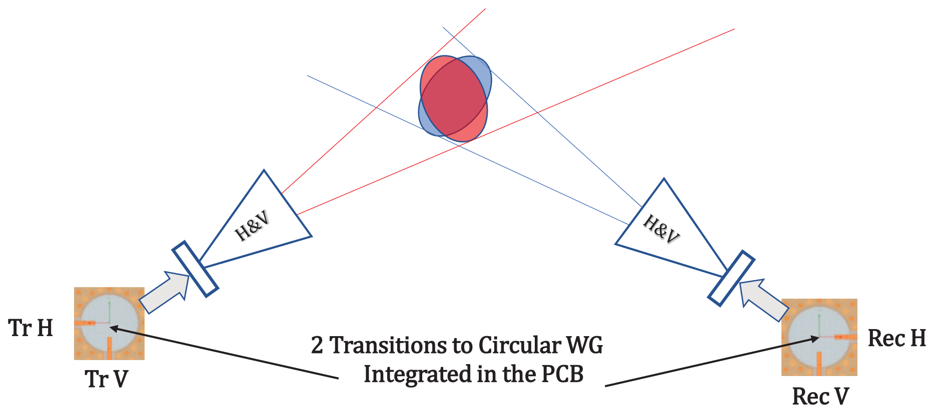
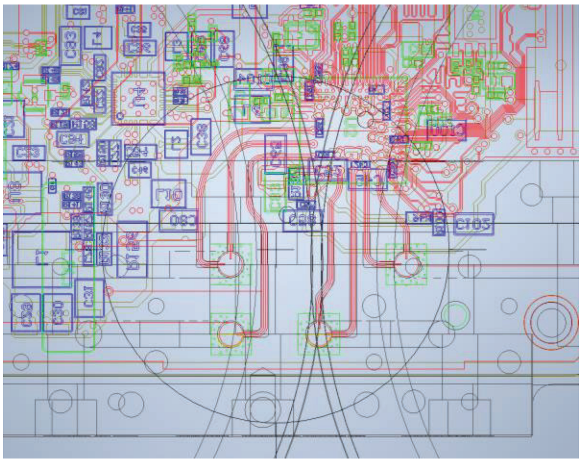


Figure 3 A block diagram of the double horn sensor with circular waveguides. One horn antenna accommodates the 2 transmitters, the other – the receivers. This arrangement provides high isolation between the Tr/Rec. The horns are tilted at some angle and the beams are crossing at a certain range.



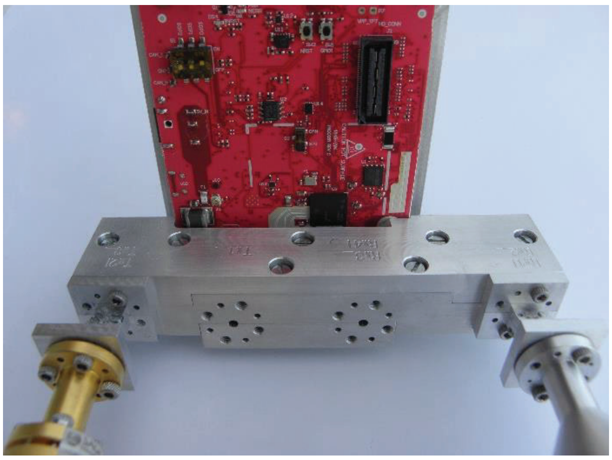


Figure 4 ***To the left*** *a part of the board layout showing the radar chip and transitions to the circular waveguide. Three transmitters and 4 receivers are interfaced to circular waveguides using transition structures embedded in the dielectric stack.*

To the right*: A picture of the radar board attached to the waveguide block. The waveguide to the left contains the H/V Tr, the right waveguide the H/V Rec.*

This solution has the following features:

+ High isolation between Tr and Rec

+ No need for polarization filter

- Need for 2 horn antennas
- Risk for exciting cross-pol products in the circular waveguide at discontinuities
- Antennas need to be pointed at the same distance (optimum performance only at specific distance)

Field Measurements

After testing and verification of the radar-sensors functionality, they were attached to a vehicle and tested in traffic. The tests were carried in April 2023 and we did not have access to icy or snow-covered road surfaces, therefore we performed test where we drove along a dry road surface, which at one area is wet.

*Figure 5 **To the left**: a picture of the two-horn sensor attached to a vehicle. **To the right**: a picture of the wet patch on the road surface. The surface is slightly wet and does not contain visible water droplets.*

Measurements with the single horn sensor

To characterize the road surface we calculate two polarimetric parameters: Entropy – a measure of the surface randomness and the target depolarization. Our previous work[2] showed that these 2 parameters are sensitive to the properties of the surface with icy or wet surfaces clearly distinguishable from dry surfaces.

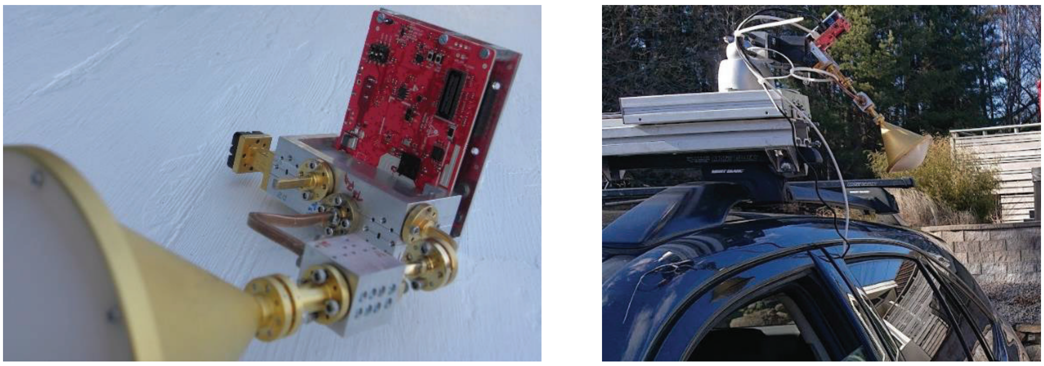


Figure 6 A closer look at the single horn radar sensor. To the right the sensor attached on to the car.

[2] *vvwaves.se*

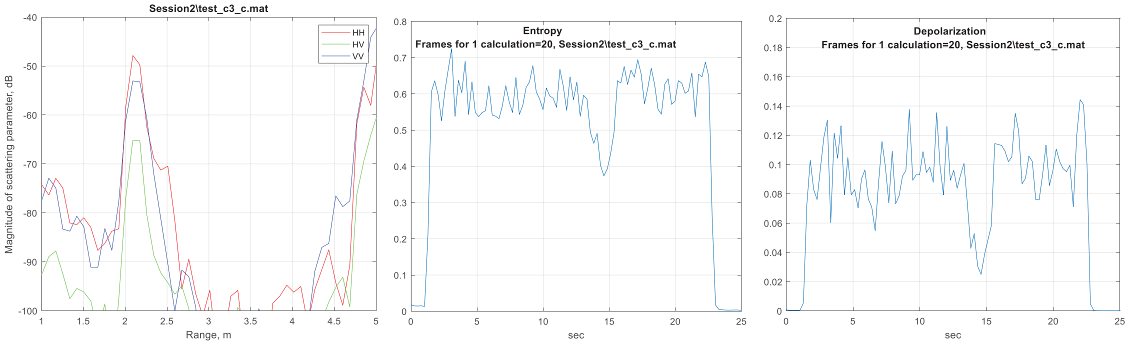


Figure 7 ***To the left****: magnitude of the surface response from the surface. Three of the 4 polarimetric scattering parameters are shown the co-pol components in red and blue and a cross-pol component in green. This plot indicates the high SNR of about 40 dB.* ***In the middle****: the Entropy as the car passes from dry to wet and back to dry surface. The entropy drops by 33% from 0.6 to 0.4 at around 15s after the start when passing over the wet patch. The entropy at the beginning and the end of the sequence is 0 as the car stands still.* ***To the right****: the depolarization for the same sequence showing a clear reduction at 15s after the start.*

An example of measurements with the single horn radar are summarized in Figure 7, the show the entropy and depolarization as the car passes from dry to wet to dry surface. Both Entropy and Depolarization clearly detect the presence of wet surface.

Measurements with the dual horn sensor

Similar measurements, summarized in *Figure 1*, were carried out with the 2 horn radar.

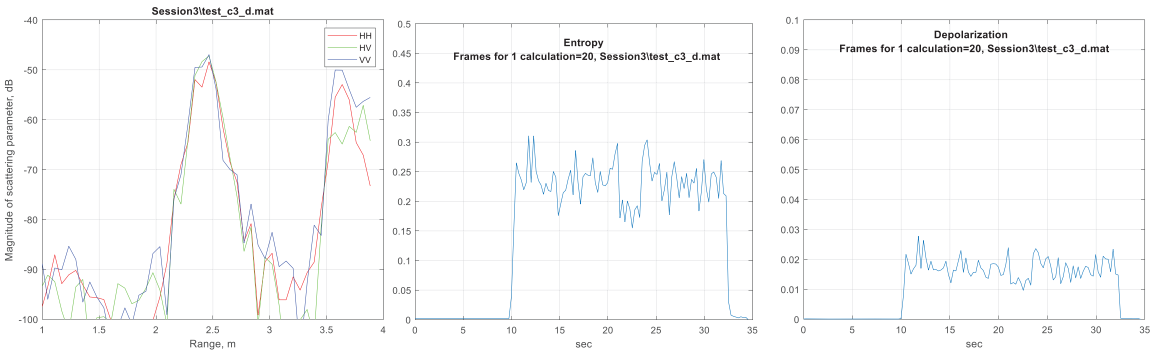


Figure 8 ***To the left****: magnitude of the surface response from the surface. Three of the 4 polarimetric scattering parameters are shown the co-pol components in red and blue and a cross-pol component in green.* ***In the middle****: the Entropy as the car passes from dry to wet and back to dry surface. The entropy drops from 0.25 to 0.19 at around 21s after the start when passing over the wet patch. The entropy at the beginning and the end of the sequence is 0 as the car stands still.* ***To the right****: the depolarization for the same sequence showing a clear reduction at 21s after the start.*

Software

A software to process data in real time was implemented. It consists of 2 parts:

- The first part, the firmware, is uploaded to the radar board and its primary function is to reduce the volume of data to be transmitted to the computer. The data reduction is implemented by averaging several chirps (minimum 16) producing one frame. In its current implementation the firmware does not produce range/Doppler map and therefore can not handle doppler offset in the data (Only the 0 Doppler bin is transmitted).
- The second part is implemented in “Python” and is running on the host computer. This program receives the frames from the radar board through UART interface and calculates the polarimetric parameters in real time. It displays the results and saves a copy of the received frames for a reference.

7 Spridning och publicering

7.1 Kunskaps- och resultatspridning

Hur har/planeras projektresultatet att användas och spridas?	Markera med X	Kommentar
Öka kunskapen inom området	X	This is really a cutting edge work, there are no analogues of a sensor with such a capability commercially available.
Föras vidare till andra avancerade tekniska utvecklingsprojekt	X	Yes, we have already contact with 2 companies interested in our technology. Our expectations are that in near future we will be able to carry on tests as part of a pre-study specific for their applicatio.
Föras vidare till produktutvecklingsprojekt		Not yet.
Introduceras på marknaden		Not yet, but we will be working on in the near future.
Användas i utredningar/regelverk/ tillståndsärenden/ politiska beslut		

7.2 Publikationer

This work is not published yet, but some parts of it will be presented on a workshop at the microwave week later this year.

8 Slutsatser och fortsatt forskning

Two alternatives of a radar sensor for road surface identification are developed. Tests were carried out outdoors. Due to the current weather conditions the sensors are not yet tested on icy or snow-covered road surfaces. Both sensors are able to detect a wet patch on the road surface in real traffic and in real time. However, we are confident that if we can detect wet surface, we can also detect ice-covered surfaces. Measurements of icy, snow-covered surfaces are planned for winter 23-24. A printed circuit board (PCB) consisting of 7 metal layers was developed and manufactured with the help of Aspocomp in Finland. The layer stack is design such that it can accommodate inbuilt transitions from microstrip line to waveguide. This feature makes it possible to cost-effectively interface the PCB to the waveguide structures by simply screwing them together.
Software was developed in collaboration with *Safe Radar* to process radar raw-data data and calculates the properties of the surface in real time.

9 Deltagande parter och kontaktpersoner

The project was carried away by VVWaves AB only, but we collaborated with other companies, such as Safe Radar Research AB and Aspocomp.