Added value of X-band radar operation and deployment in a cross-border region (NL, D, BE)

Based on study performed with the X-band Aachen radar, Germany

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Written by: **SkyEcho BV:** Yann Dufournet | Albert Oude Nijhuis | Tobias Otto

info@sky-echo.eu

+31 108080235

SkyEcho BV
Mozartstraat 53
7582ET, Losser
The Netherlands

Reviewed by :
Peter Hulst – WL
Sven Robertz - WL
Hidde Leijnse - KNMI
Aart Overeem - KNMI

www.sky-echo.eu

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01draft	13/09/2023	Initial issue.
02	09/10/2023	Full version with feedback integrated from Aart (KNMI)
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05	18/11/2023	Full version with second feedback including report formatting (logos)

Disclaimer

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1 TABLE OF CONTENTS

OVERVIEW PROJECT SUMMARY and DELIVERABLES

Questions		Answer summary	Deliverable
1	Does the addition of an X-band radar to the KNMI's existing international radar composite (IRC) add value?	The addition of X-band radar clearly has an added value as it complements the large-scale rainfall map provided by the C-band radar network operation with higher resolution information at risk prone areas.	2 Study cases with X-band radar integration from the Rijnmond radar to the IRC database
2	Are the data from the X-band rainfall radar in Aachen suitable for adding to the IRC? Determine in consultation with KNMI whether the X-band radar can be added to the existing KNMI product (preferred) or create a derivative product based on the existing IRC product for WL. In all cases, should the end products be made publicly available?	The rainfall radar from Aachen is well suited for IRC data integration. HOWEVER, the process of delivering data will require some adaptation. Due to the commercial nature of the radar, there are some legal restrictions on public data policy (see next question). It is advised to favor the creation of a derivative IRC product rather than adding it to the existing IRC product from KNMI.	2 Study cases of Aachen radar data evaluation based on IRC data comparison.
3	Are there legal restrictions if the Aachen rain radar is added to the public IRC or a derivative public IRC from WL?	The IRC KNMI product follows the public data policy. Because the operator of the Aachen radar is a commercial party, it is not the legislation that imposes restrictions but the terms of delivery as the service is not publicly available	Result based on interview between Waterschap Limburg and Kisters (the Aachen radar operator)

4	What are the costs of mixing the Aachen rain radar into the existing IRC and what are the annual data costs? When mixing the Aachen rain radar into the existing IRC, 2 variants can be considered: mixing in the existing KNMI IRC product or mixing in a derived IRC product using the existing IRC product as a basis.	The yearly cost of mixing the IRC with the X-band radar in a derived product is estimated to reach between k 6800 and € 10200,-	Cost table
5	Does it add value as a water manager to install and manage a rain radar yourself?	There can be an added value in terms of data quality, availability and service flexibility. However, it comes with the need to have in-house radar and data management expertise to keep the radar operational. Such a task could also be outsourced when required. Some alternative ownership models are provided to overcome the above-cited limitations. The client shall select the model that best fit its operation and financial vision.	SWOT table analysis alternatives ownership models
6	What are the installation requirements for a rainfall radar and where should it be located?	We advise to install a minimum of 2 X-band radars to complement the Limburg region with High resolution information. Potential location is provided in the section.	Requirement list + beam blockage analysis in the Limburg area
7	What administrative procedure should be followed to install our rainfall radar?	The administrative procedures can be summarized in 3 main ones: the public tendering procedure to acquire the radar, the radar frequency allocation procedure to allow the radar operation, and some optional procedures to guarantee the service operation.	Frequency allocation analysis + list of other requirements
8	What should be taken into account when installing and managing a rainfall radar?	X-band radar deployment is achieved in 4 steps: 1- Offsite preparation; 2: Radar Site preparation; 3) setup; 4) maintenance.	Activity plan diagram
9	What are the costs for installing and operating your own rainfall radar?	Bulk numbers are provided here based on interviews (incl. material/server and manpower costs) – PRICE CAN DIFFER - For installation (one-time): ~ EUR 1 million. - For operation: ~ EUR 300-400 000 per year The decision whether to invest shall take into account the investment models (questions 5) that fits best the client's vision.	Results of interviews performed

2 INTRODUCTION AND SCOPE

Waterschap Limburg and KNMI are involved in the Interreg project EMfloodResilience which aims at improving preparations for the next extreme flood and thus prevent future loss of life and socio-economic damage. In this context, Waterschap Limburg wants to investigate the impacts and benefits of using higher spatial and temporal resolution rainfall information via the deployment and operation of an X-band radar network. This report summarizes analyses results of the added value of X-band rainfall outputs compared to the KNMI International Radar Composite (IRC) rainfall products currently used in operation. The results of this study may be an input for further investigations regarding the benefit of using higher resolution rainfall to improve water level and flood risk information.
The document is organized to address the specific questions raised by Waterschap Limburg. The first questions are related to a general discussion of the challenges and added value of X-band radar data when used in combination with the KNMI international radar composite (IRC). The subsequent questions address specific topics regarding the potential use of X-band data for the Waterschap Limburg including the X-band weather radar deployed in the city of Aachen and operated by Kisters AG.

3 QUESTION 1 – ADDED VALUE OF AN X-BAND RADAR

Heeft de toevoeging van een X-band radar aan de bestaande internationale radarcomposiet (IRC) van het KNMI een meerwaarde?
Translation: Does the addition of an X-band radar to the KNMI's existing international radar composite (IRC) add value?

In this section datasets from both an x-band radar and the existing IRC KNMI product are compared on case studies.

3.1 INITIAL REVIEW

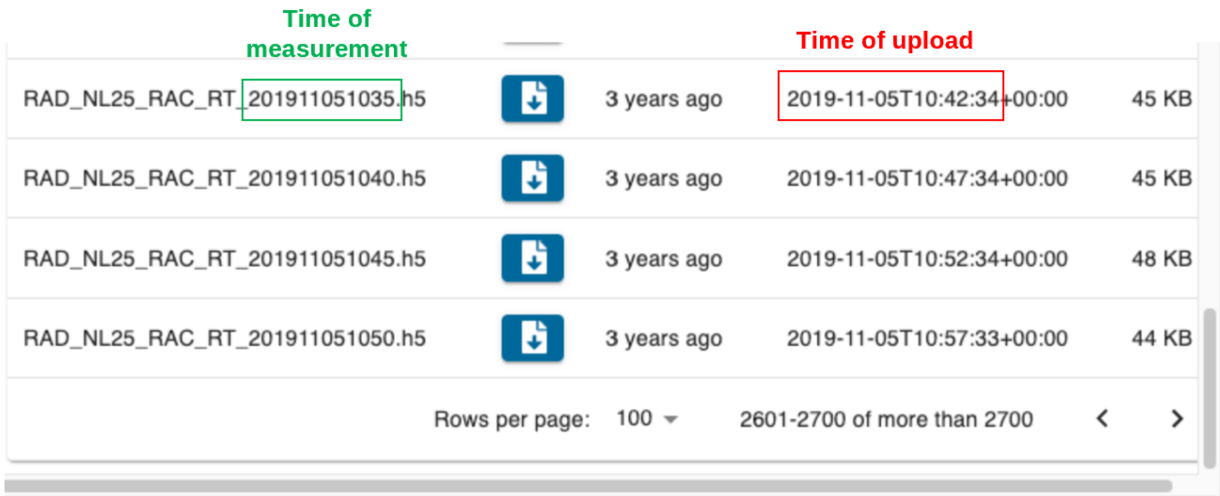
3.1.1 THE IRC DATASET – SHORT DESCRIPTION

Three different IRC datasets are available on the KNMI server:

- Real-time (provided at near real-time): RT
- Early Re-analysis: RE
- Final Re-analysis: RF

IRC data are provided in hierarchical data format h5 format, a standard format for radar data outputs. The IRC data contain rainfall information provided in sets of 5 min rainfall accumulation.

IRC data availability - timeliness
Some checks on the KNMI database have been performed so that an estimation of time required for the data to be available is provided. Such an estimation is done by comparing the time of measurement provided in the filename with the time when the file was uploaded, as presented in the figure below:



Note that for IRC datasets, the time of measurement corresponds to the end time of the measurements, while the time of measurement for the KNMI reflectivity composite (PCP_NA) corresponds to the start of the measurement.

Based on the analysis, the following time lags (i.e. the difference between the time of measurement and time of upload) have been estimated:

Dataset	Time lag	Remark
IRC - Real-time (RT)	7m 33s	
IRC - Early Re-analysis (RE)	+6h30m -- +30h30m next day	packed as daily file
IRC - Final (RF)	20 -35 days variable	packed as daily file
KNMI reflectivity composite	3m 37s	
volume data Den Helder (VOL)	1m 34s	Single radar data
volume data Herwijnen (VOL)	1m 43s	Single radar data
SkyEcho - Rainfall from X-band radar data Rijnmond	< 1m	for comparison purpose only

Table 1 – time of availability of different datasets

Note that rain nowcasting can only rely on datasets available at (near) real-time. For this reason, the next section will only focus on IRC RT integration.

3.1.2 EVALUATION OF X/C BAND RAINFALL COMPOSITE

In this section, we aim to discuss the pro and cons of merging X-band radar information with the existing IRC data composite (which is currently solely based on C-band radar inputs) to create a derived IRC product.

BENEFITS:

Merging multi-frequency radar data allows the end-user to combine the benefits of each frequency bands in a single rainfall composite:

- Thanks to lower frequency attenuation, the C-band radar network can cover a much larger area compared to the X-band radars, allowing monitoring of rain over a long range. For this reason, C-band radars network is usually deployed for far range and volumetric mode to monitoring a large domain at different altitudes. This mode is of great benefit to increase the lead time and quality of rainfall nowcast (i.e. short-term forecast) but is at the expense of the spatiotemporal resolution of the radar.
- X-band radars are much more compact and easier to deploy than C-band radars. Because they monitor on a short-range at higher resolution, X-band radar network can benefit from higher detection of small-scale rain features such as cloudburst features. They are also expected to be more sensitive to very light rain although this doesn't impact very much the rainfall output.
- C-band radars for far range operation have usually range resolution of around 250m at most, while X-band radars can reach resolution up to a few tens of meters close to the radar. The resolution volume of X-band radars being higher, the rainfall within the resolution pixels is less spatially heterogeneous, allowing for higher quality of the rainfall output and better detection of rain intensity spikes.

CHALLENGES:

Combining the data of multi-frequency radar systems come with several challenges which need to be considered and overcome:

Challenges	Possible mitigation
Altitude of reference: Due to their lower maximum range, X-band radars typically monitor the rain close to the radar and thus at lower altitudes compared to the C-band radar network operating for far-range. Due to thermodynamic processes, the property of the rain monitored can be different at different altitude, affecting the data merging process. For this reason, as of February 2023, vertical profiles of reflectivity techniques are applied to C-band radar data (see IRC composite description) to adapt the measurements as if they were taken close to ground based e.g. by extrapolation of the vertical structure of the precipitation measurements close to the radar and apply a correction to far range data.	As end-users are mostly interested by information of the rain at the Earth surface, it is advisable to privilege X-band radar information which is measured closer to the surface, when both radar outputs differs and quality of the X-band output is not affected by large attenuation / interferences.

Volume resolution:	
The effective radar resolution volume size increases with range to the radar due to the angular widening of the radar beam as function of range. The range resolution depends on the RF bandwidth used by the radar. Due to their lower maximum range and larger RF bandwidth used compared to C-band, post-processed X-band weather radar can achieve a higher spatial resolution (goal: 100m x 100m grid) compared to C-band weather radar (typically processed to 1km x1km grid).	If the user requirements benefit from higher spatial resolution of the radar data, a mixed C- and X-band composite should try to maintain the higher spatial resolution of X-band weather radar data implementing an adaptive merging process. This allows to maintain the spatial features of small but potentially strong precipitation cores but leads to a higher data volume of the multi-frequency composite which needs to be considered in the down-stream processing chain.
Asynchronous scanning time:	
Measurements of multiple independently operated radar will naturally differ and will not be synchronized also by potentially employing different scanning sequences.	Alignment of the composite time resolution to the input data with the lowest time resolution. Alternatively, a more complex processing may be employed to extrapolate measurements at a higher time resolution also for input data with a low time resolution.
Difference in hardware calibration and rain retrieval calculation:	
Rain retrieval methods and radar calibration may differ between different radars leading to inconsistencies in the composite.	Proper evaluation of the rainfall retrieval and calibration methods employed for the different radars is suggested, e.g. ensuring that the rainfall is derived for the same reference height (typically ground level). Performing validation of the radar composite ideally with independently measured data.

3.1.3 OUR PROPOSITION FOR DATA INPUT MERGING

The merging process can be done step-wise as indicated below:

- The 5-min rainfall sums of near-real time measurements are used as input.
- The data are adapted to the IRC high-resolution regional grid.
- A mask for “X-band data available” is created by gap filling and speckle removal (rr > 0).
- “X-band only” mask is created, by 5 km erosion (removal) from the “X-band data
- available” mask. By doing so, a smooth transition is created
- Current option: In case both sources are used, the maximum value is taken.

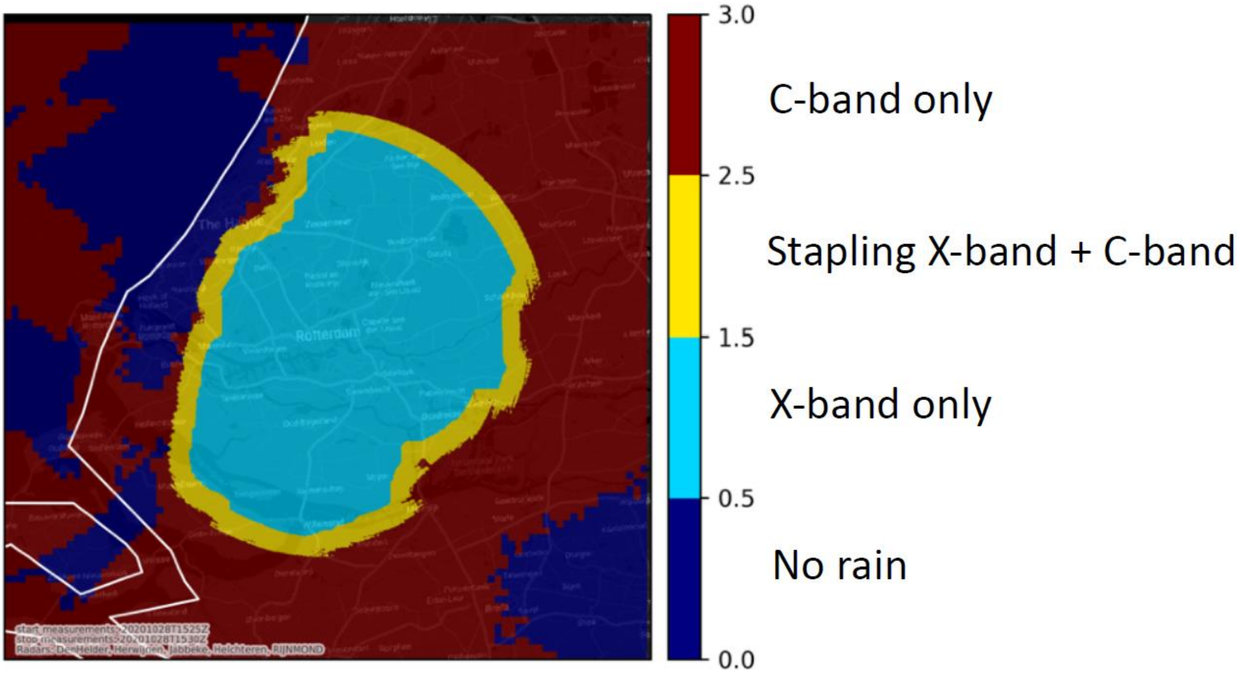


Figure 1 - Data merging methodology

3.2 DEMONSTRATION OF X-BAND RADAR / IRC COMPOSITE

SkyEcho evaluated the X-band radar / IRC composite, using the X-band radar system located in Rotterdam. This radar is a frequency-modulated continuous-wave (FMCW) quad-polarisation system which allows high quality Doppler polarimetric filtering and higher rain data quality in real-time. The radar is manufactured by MetaSensing and owned by the Rotterdam municipality. SkyEcho is operating this radar system allowing for complete access of the radar data for this project.

Figure 2- X-band rain radar (Rijnmond) located in Rotterdam

A case study from 28 October 2020 is taken as an example for the testing of the composite merging algorithm with the IRC RT product of KNMI.

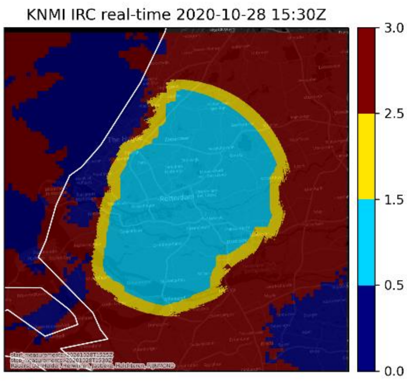
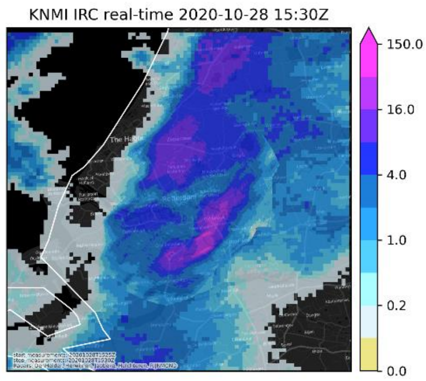
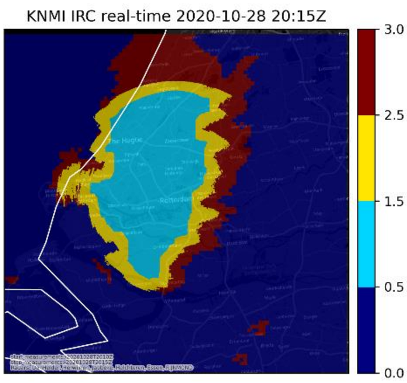
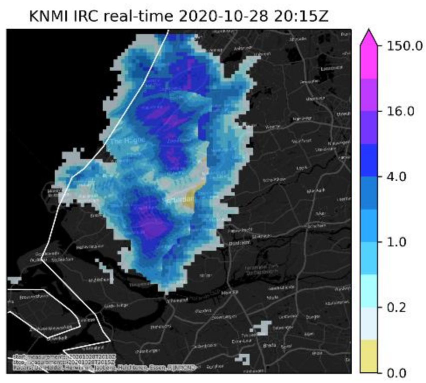
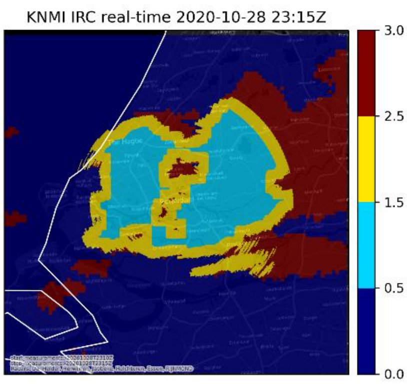
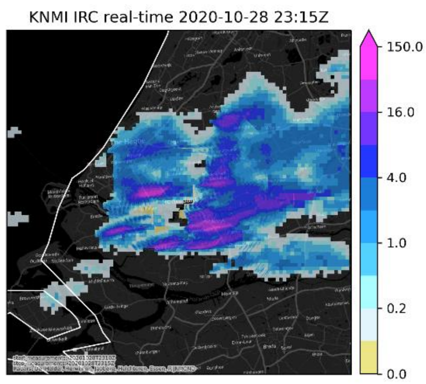
Merging categorization	Merging result
	
	
	

Table 2 - study cases of radar composites presented for the region of Rotterdam

The time to handle the merging is quite efficient with a time lag of a less than a minute. It is therefore possible to create a derived IRC product in less than 9 min according to availability time provided in Table 1.

3.3 EVALUATION

The methodology proposed demonstrates that the development of derived IRC / X-band composite is feasible on an operational basis, with promising results:

- The two data sets are well merged with smooth transitions and good rain cell fit.
- The area covered by the X-band gives critical high-resolution information to the end-user

Due to time constrains, the methodology is pretty simple and would require further improvement before being used in an operational manner.

- The 5 min summation of the 1 min X-band dataset would need to be interpolated to avoid the banded artifact as seen in Figure 3 .
- To decrease the required radar processing time by 1 min, merging of the X-band radar data into the existing IRC product could be investigating.
- The merging area shall be further elaborated to reach a quality-based composite by taking other parameter than maximum rain intensity into account, i.e. distance to the radar, Attenuation coefficient, data quality etc... The combination of the radar data before producing the IRC composite with gauge adjustment could also be considered. It has however not been investigated here as it would require a change of the current KNMI's radar processing chain.
- The transition area (stapling) would require more thorough analysis and validation to optimize the data fusion.

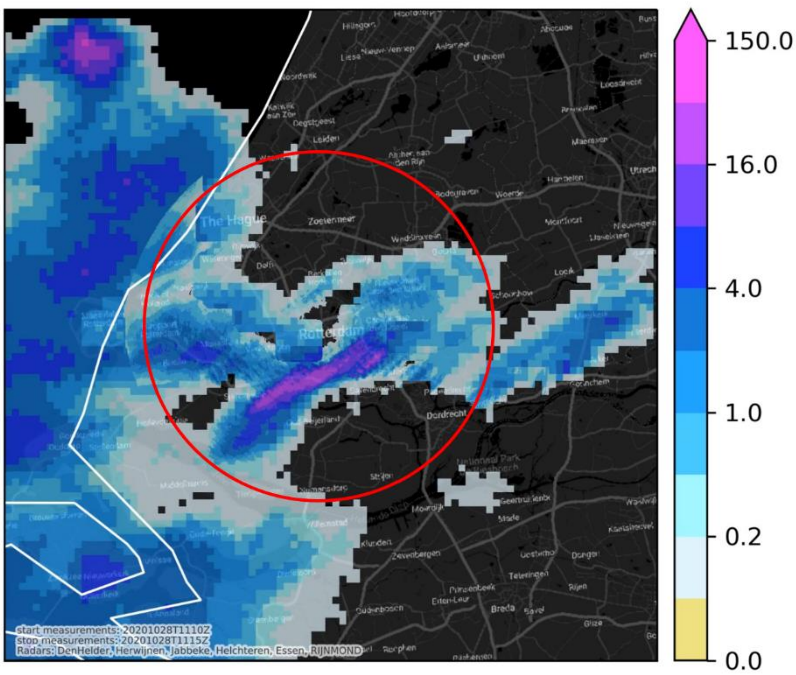


Figure 3: Ripples effect can be seen in the high resolution area of the merging due to the intrinsic averaging applied in this example.

Advices and Conclusion
The mixing of an X-band radar dataset with a derived IRC product using the existing IRC product as a basis has been tested. The X-band radar information can be well integrated into the current IRC

composite in an operational manner. The higher resolution provided by the X-band radar can very well complement the large-scale rainfall map provided by the far range mode of the C-band radar network.

Further evaluation on the end-user side would however need to be performed to evaluate the benefit of the new IRC/X-band integration into the water management system. This would require the following steps:

- Evaluation of the data merging technique over a long dataset (e.g. 1 year)
- Incorporation of the new data layer into the FEWS system of Deltares (used by most of the Waterboards)
- Result analysis by comparing it with using the standard IRC layer only

4 QUESTION 2 – SUITABILITY OF AACHEN RADAR INTEGRATION INTO IRC

Zijn de gegevens van de X-band buienradar in Aken geschikt om toe te voegen aan de IRC? In overleg met KNMI bepalen of de X-band radar toegevoegd kan worden aan het bestaande product van het KNMI (voorkeur) of een afgeleid product maken op basis van het bestaande IRC product voor WL. In alle gevallen moeten de eindproducten openbaar beschikbaar kunnen worden gesteld?

Translation: Are the data from the X-band rainfall radar in Aachen suitable for adding to the IRC? Determine in consultation with KNMI whether the X-band radar can be added to the existing KNMI product (preferred) or create a derivative product based on the existing IRC product for WL. In all cases, should the end products be made publicly available?

This chapter aims at evaluating the quality and availability of the Aachen radar outputs to evaluate whether this radar is suitable to be integrated in the IRC composite. First, an overview of the Aachen radar and the online platform HydroMaster used to disseminate its data. Next, a qualitative comparison of the Aachen radar data with the KNMI International Radar Composite (IRC) and rain gauges operated by Waterschap Limburg is reported for selected study cases. Finally, an analysis of the Aachen radar coverage is performed.

4.1 AACHEN X-BAND WEATHER RADAR AND DATA DISSEMINATION

4.1.1 AACHEN RADAR

Kisters AG and GAMIC GmbH installed in 2021 a solid-state X-band weather radar close to the city of Aachen on top of a building of Kisters AG at the coordinates

Aachen Radar Location: 50.711741N 6.138026E.

The radar is operated by Kisters with the support of Gamic.
Radar data are disseminated via the the online platform HydroMaster (https://www.HydroMaster.com). For this analysis, access of the Hydromaster portal was granted for

few months' times. The data are provided with a 125m spatial / 5 min resolution and available within 5 min.

4.1.2 KISTER'S HYDROMASTER PLATFORM DESCRIPTION

HydroMaster is a precipitation radar visualisation and analysis tools which allows to derive rain gauge-calibrated cumulative precipitation amounts. The platform provides past, near real-time and future precipitation data. Users can define areas of interest (e.g. water catchments) and hotspots, define thresholds and setup the generation of automated warnings.

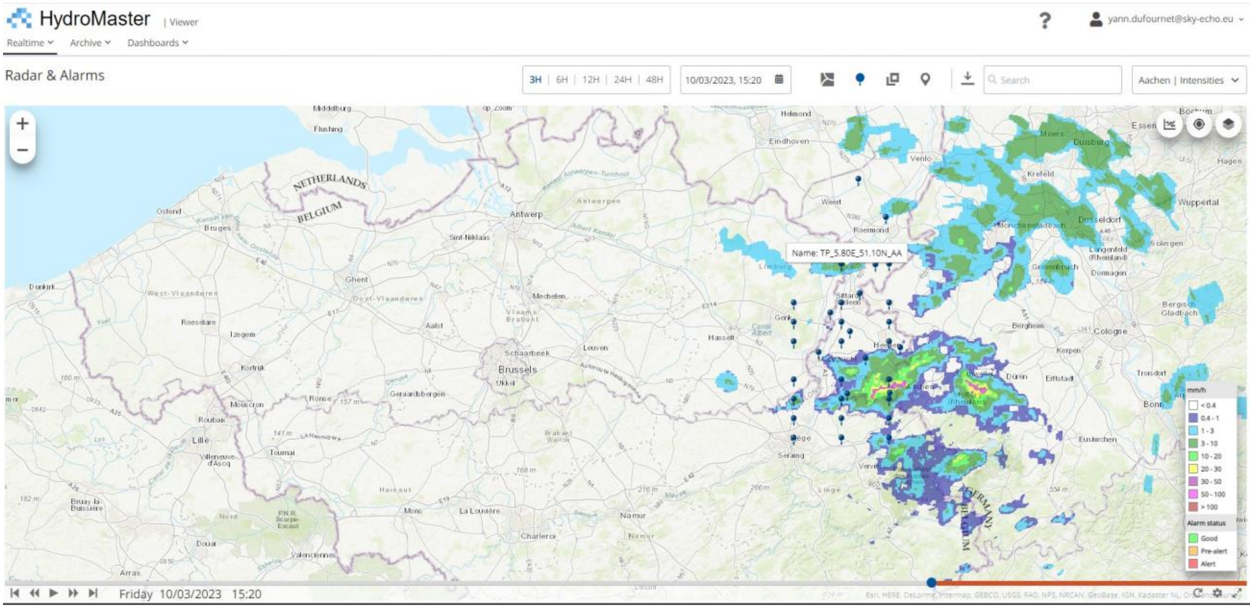


Figure 4: Kister's HydroMaster platform main screen showing Aachen radar data and a grid of hotspots defined by SkyEcho.s

Impact assessments of precipitation events are supported by comparison with return periods as well as providing the possibility to past-event assessments. Figure 4 shows the HydroMaster main screen with activated Aachen radar data layer.

Pros	Cons
Easy radar-based rainfall visualization incl. archive and nowcasting. Possibility to define user objects, e.g. catchments, to get rainfall accumulation	No direct access to radar-based rainfall data at native spatial and temporal resolution, instead API data access limited to radar-based, rain gauge adjusted rainfall data for user defined objects.

Table 3 - HydroMaster Pros and Cons.

The HydroMaster platform also provides an application programming interface (API) to query the data via software. Via the API, the metadata and time series data for customer objects of the HydroMaster can be accessed. This covers the list of users created objects (Types: Catchment, Zone of Interest, Hotspot) with attached archived, measured and forecasted time series data. The HydroMaster API also provides Web Map Services (WMS) with time-dependent data e.g. to provide concrete layer images typically in Portable Network Graphics (PNG) format.

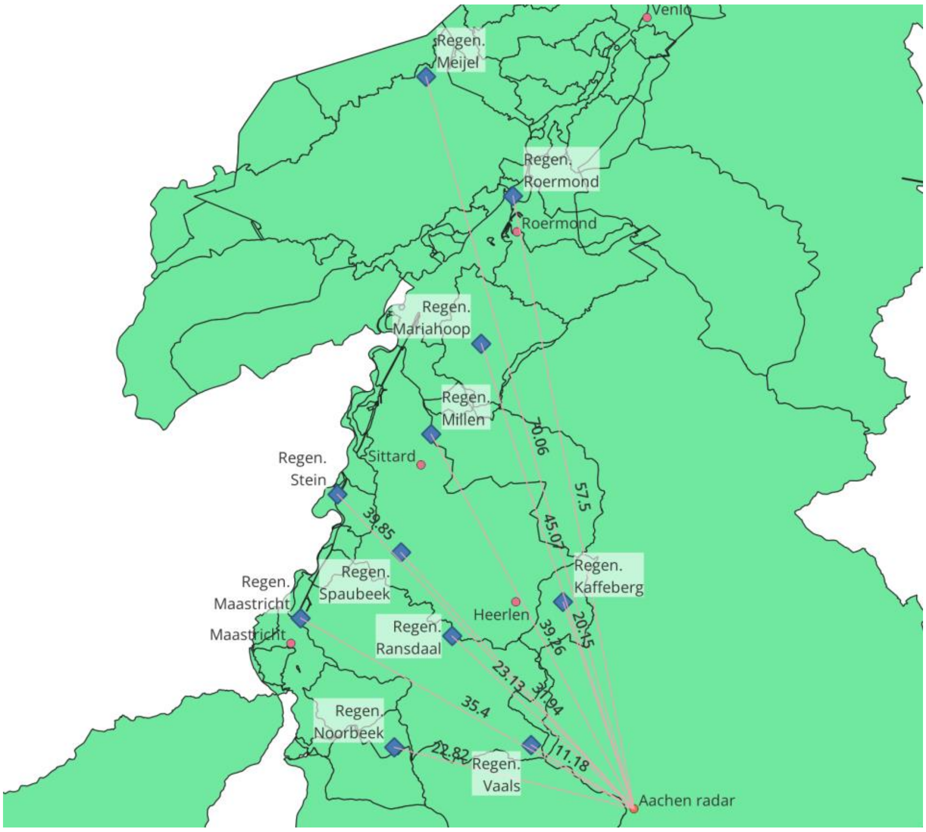


Figure 5 - Mapping and distance (in km) of the Waterschap Limburg raingauges from the X-band Aachen Radar

4.2 COMPARATIVE EVALUATION

The goal of this section is to get a qualitative evaluation of the rainfall information collected by different sensors in the Limburg region, based on different study cases. Such an evaluation will be performed as follows:

- Three different rain sensors are compared:
    - Raingauge: Raingauges measure the rainfall accumulation at a single point (typical catchment area of 200 cm²) directly at the surface (no rain change issues) with a typical measurement resolution of 0.1 mm. The raingauge network managed by Waterschap Limburg is used in this analysis. It is quite well distributed over the entire area of interest.
    - Aachen X-band radar: *X-band radar measure the rain close to the ground over an area up to 50 km around the radar location. X-band radars typically provide measurements at higher spatial resolution compared to C-band radars.*
    - IRC radar composite (from C-band radars): *See description in section 1.1.*
- Three different data analysis
    - Rainfall accumulation (maps and timeline) - used to evaluate rainfall amount falling on the ground - Comparing rainfall accumulation over a specific period allows us to avoid time scale effects of the observation when comparing different types of sensors.
    - Rainfall intensity (maps and timeline) - used to evaluate maximum intensity detected which can have a large impact on water runoff: Rainfall events can be quite

heterogeneous and the analysis of spatial and temporal rainfall heterogeneity, as well as information on the maximum rainfall intensity, allows us to evaluate the impact of resolution on the data collected.

- Radar artifact detection - used to evaluate minimum rain intensity detected and potential non-meteorological echoes or interferences.

Raingauge network vs the Aachen radar (See also Figure 5):

Raingauge name	Distance from Aachen radar (in km)	Catchment area at Raingauge location (Name | area in km^2)	Remarks
Vaals	11.18	Geul | 217.79	
Kaffeberg	20.15	Roer | 108.32	
Spaubeek	31.94	Geleenbeek | 270.36	
Noorbeek	22.82	Voer | 16.36	
Ransdaal	23.13	Geul | 217.79	
Maastricht	35.40	Geul | 217.79	
Millen	39.26	Geleenbeek | 270.36	Located at the edge of the catchment
Stein	39.85	Ur | 13.46	
Mariahoop	45.07	Vlootbeek | 79.73	
Roermond	57.50	Maas | 166.21	
Meijel	70.06	Neerbeek | 283.57	

Table 4 - List of raingauges and specific characteristics

Two study cases are being used for this evaluation and are reported in the presentations annexed to this document. Note that for these two study cases, an updated IRC data set is used compared to the one of 2020 of Question 1.
A summary of both study cases is first provided in the section below.

4.2.1 STUDY CASE #1

Date	**8th March 2023**		
Interest	Snow event with disruptions reported - NOS news	Available information	
Local information			
	Overview Webcam - Roermond Snow transforming into rain during the day *Source: Toren 7*		

<table>
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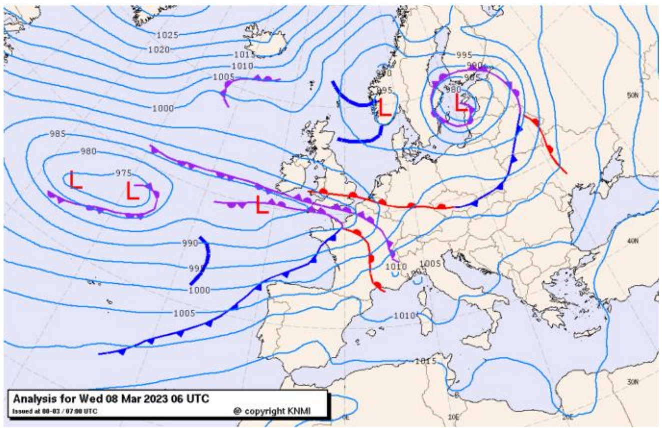
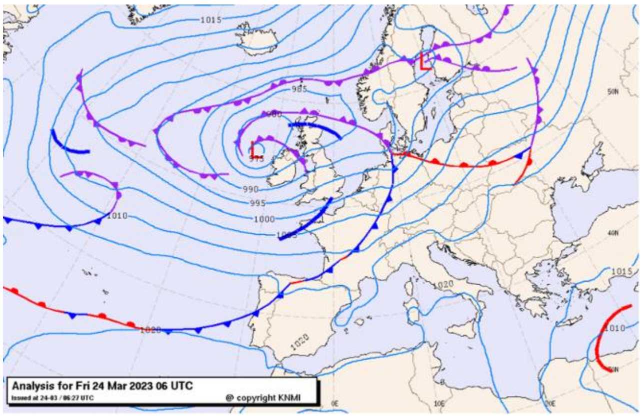
<tr><td>
</td><td>Frontal activity observed with warm and occluded front moving northward and crossing the Limburg region.

source: KNMI</td></tr>
</table>

4.2.2 STUDY CASE #2

Results and analysis are also shown for the second case study. It is worth mentioning that the conclusion presented in this report are however similar for both study cases analyzed, hence only one study case is shown in this report.

<table>
<tr><td>Date</td><td>24th&25th March 2023</td></tr>
<tr><td>Interest</td><td>Rain Only event with heavy local rain cells crossing the Limburg region from West to East.</td></tr>
<tr><td colspan="2">Synoptic situation</td></tr>
<tr><td colspan="2"><table><tr><td>
</td><td>– Cold front overpass on 24th March followed by many occlusions front
– Only rain (no hail / snow)
– Convective case with very local heavy rain events

source: KNMI</td></tr></table></td></tr>
</table>

Accumulated rainfall analysis on 24th March

The daily accumulation is overall consistent between the Aachen radar and the IRC composite. Some differences can be noted for different area however (Figure 6:

- The norther Domain: The Aachen radar shows clear lack of sensitivity in the northern domain compared to the IRC.

- The southern domain: the IRC composite is lacking detectability in this region compared to the Aachen radar. Note the Metadata in the IRC dataset showed that some radars (Essen, Jabbeke) were partially unavailable for this analysis, probably explaining this strong lack of detectability.

  This example shows the importance of combining several data sources. Also note that the monthly accumulation calculation is performed differently between the IRC and Aachen data set. It is probable that some smoothing or interpolation might be added in the accumulation calculation of the IRC products while a straightforward summation of the 1min dataset is performed for the Aachen radar (information not confirmed).

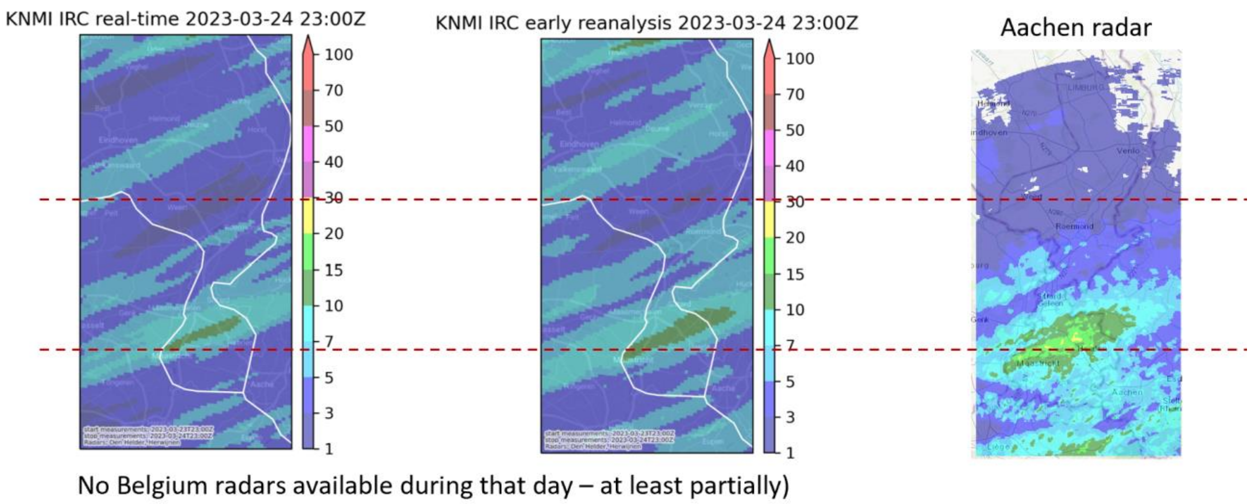


Figure 6 - Accumulated rainfall as compared between IRC and the Aachen X-band radar

Rainfall intensity comparison analysis

Roermond rainguage site

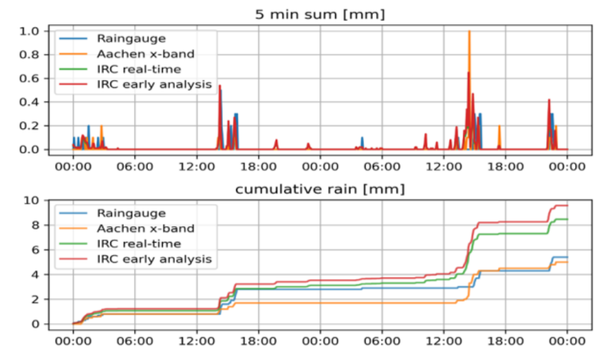


Figure 7 - comparison rainfall intensity accumulation at the Roermond site from Different sensors

Meijel

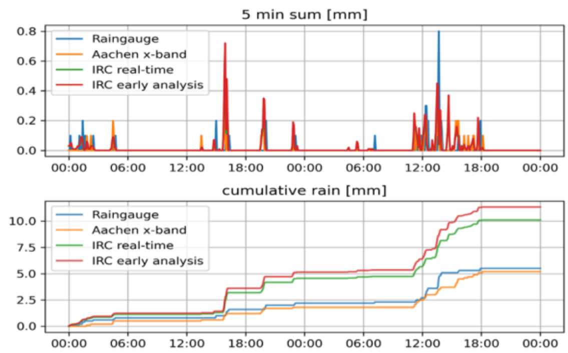


Figure 8 - comparison rainfall intensity accumulation at the Meijel site from Different sensors

Maastricht raingauge site

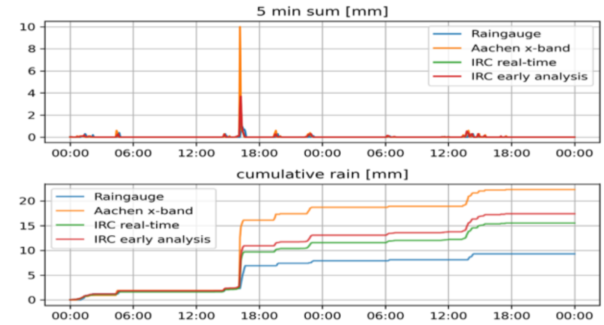


Figure 9 - comparison rainfall intensity accumulation at the Maastricht site from Different sensors

Noorbeek raingauge site

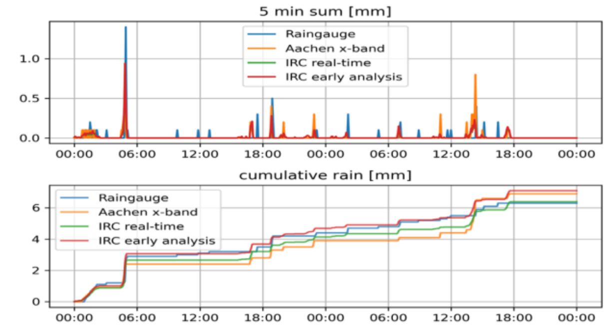


Figure 10 - comparison rainfall intensity accumulation at the Noorbeek site from Different sensors

Evaluation summary:

- Rain measurement is well synchronized in time but less in rainfall intensity amplitude
- Rain intensity is hard to compare in general: unknown rain estimation calculation from Aachen radar, different elevation (altitude), different time integration, radar inherent issue
- Spikes are affecting the analysis in the rain accumulation. They are observed both for rain gauges and Aachen radar. These spikes seem however consistent qualitatively with radar rainfall animation maps showing local strong precipitation cores moving eastward which might reflect some scaling effects.
- Quantisation at 0.1 mm is troublesome for the Aachen radar data and the raingauge data. For tipping-bucket raingauges, as used here, this is typical, without the consequence of missing rain. For radar, such a quantisation is unnecessary, and has the consequence that some (very) light rain is missed.
- Secondary issue: The X-band radar data from Hydromasters is sometimes missing timestamps (12:30 for example, for Maastricht). In the analysis they are gap-filled.

AACHEN RADAR - ARTIFACTS DETECTION

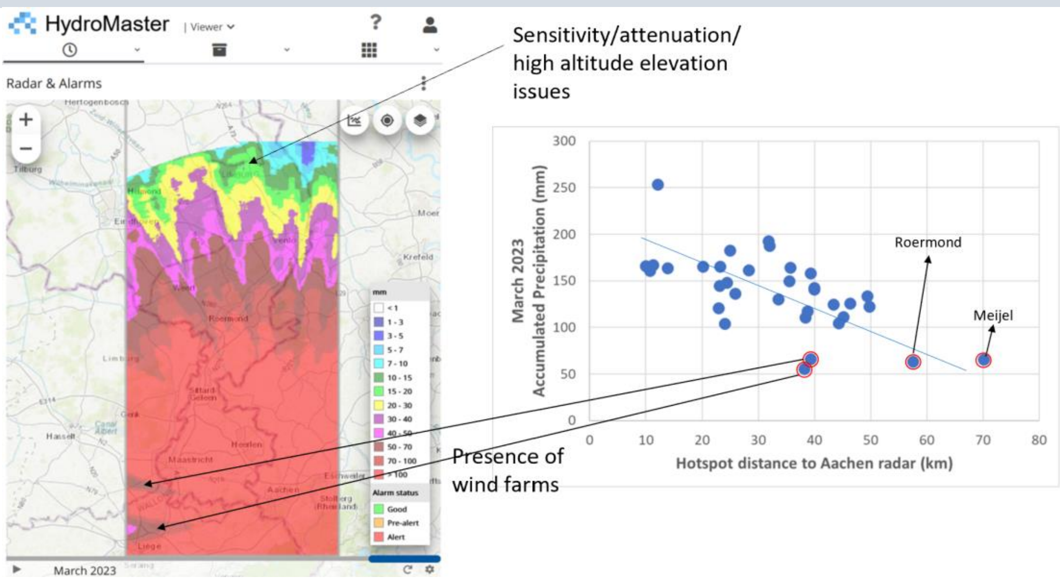


Figure 11 - Monthly plot accumulation of the Aachen Radar from March 2023

The monthly accumulation plot (Figure 11) computed from the Kisters platform is used to possibly detect any Artifacts that may be hiding in the data. No significant artifacts have been identified besides some small issues due to the presence of wind farms.

4.3 COVERAGE AND CATCHMENT ANALYSIS

A beam blockage analysis of the Aachen radar has been generated based on the surface topography. The analysis for two elevation angles is shown below:

BEAM BLOCKAGE AT 1 DEGREE ELEVATION

At 1 degree elevation (Figure 12), beam blockage is the highest in the south part of the X-band area due to the presence of low-level mountains. Partial beam blockage is also observed in the North West direction, where the Limburg region is located. The Aachen radar implements acquisitions at also at higher elevation angles to ensure the monitoring of rain towards directions with beam blockage effects at lower elevation.

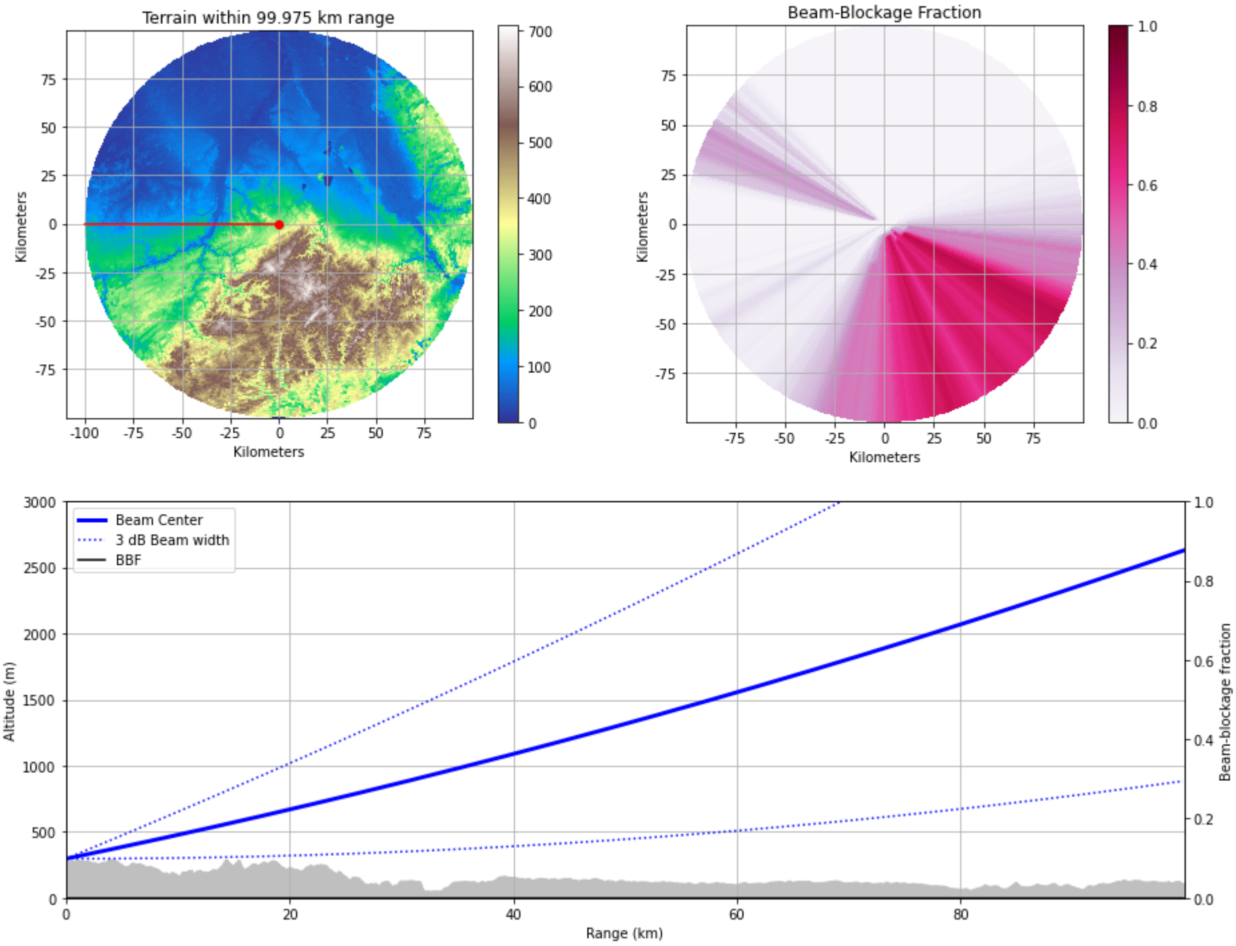


Figure 12 - beam blockage - 1 degree elevation

BEAM BLOCKAGE AT 2.9 DEGREE ELEVATION

At 2.9 degrees elevation (Figure 13), the beam blockage due to the orography is negligible. It is however worth mentioning that the center of the radar is beam quickly reach high altitude (1400 m at 20km) reducing the capacity of the radar to monitor low level clouds and associated rain events. If rain is present at higher altitudes, the rainfall rate at ground level needs to be estimated based on assumptions of the rainfall event vertical structure (vertical profile of reflectivity) similar to what is implemented for the IRC. Whether such processing steps are implemented for the Aachen radar is not known to the authors of this document.

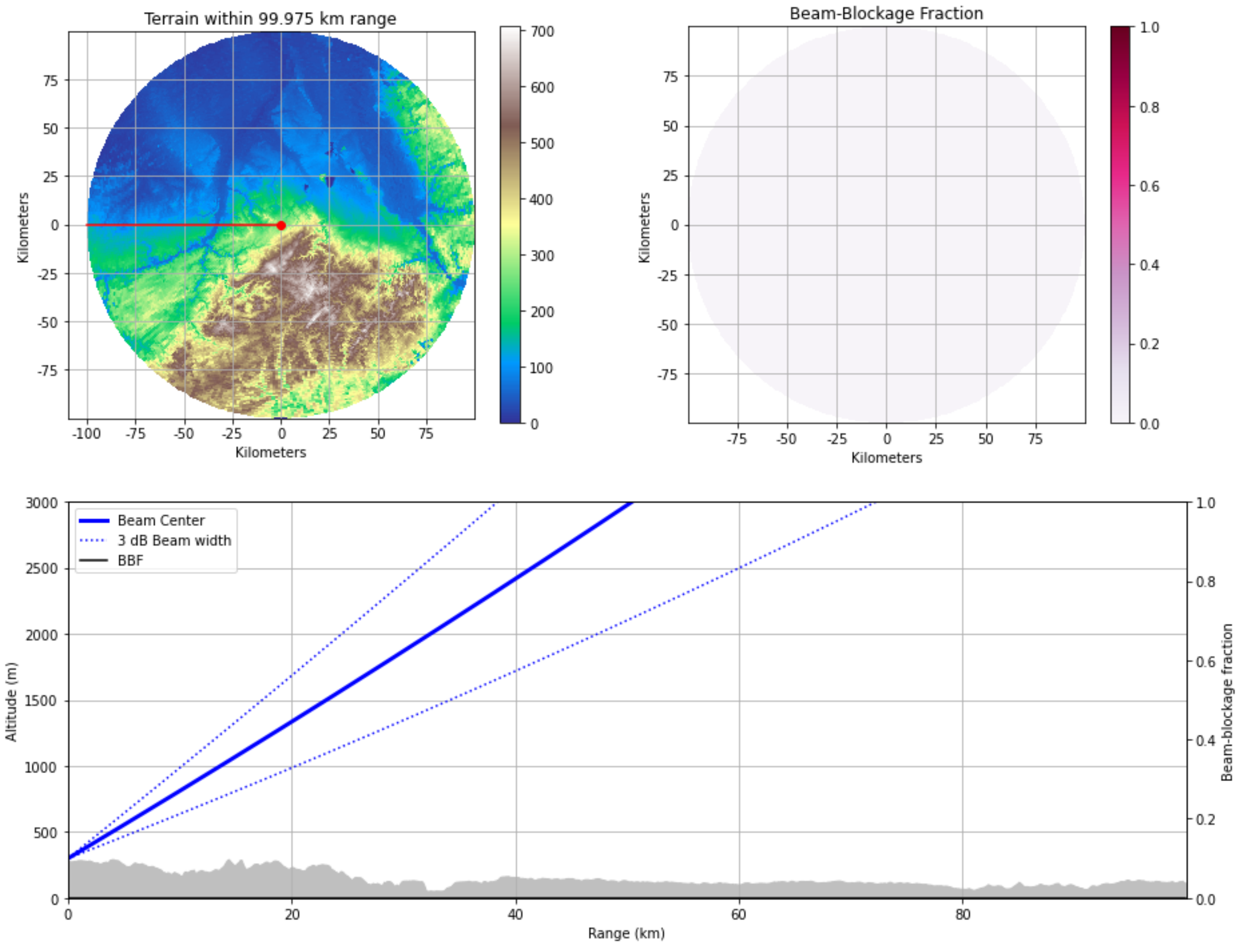


Figure 13 - beam blockage at 2,9 degrees elevation

Advices and Conclusion
General advice regarding the Aachen radar and its usage for WL • The Kisters' platform Hydromaster currently provides rainfall time series (historic and forecast) for user-defined locations and catchments which may be integrated into the Deltares FEWS software to support the water management. However, the X-band weather radar data is currently only disseminated via the commercial platform HydroMaster. These highly processed data do currently not allow to generate a derived composite product which integrates the Aachen radar data into IRC to provide high-resolution spatio-temporal rainfall

data. Radar data are also not public. The integration of the data in the existing IRC product is therefore not allowed without concertation with Kisters.

At this stage, it is not recommended to modify the existing IRC product but to create a 2nd derived product next to the existing IRC product, so that:

- Experience can be gained with the product of an x-band radar
- To avoid any restriction on the public status of the KNMI products due to the commercial nature of the Aachen radar data. Discussion with the commercial party would anyhow be required.

5 QUESTION 3 – LEGAL RESTRICTIONS FOR X-BAND INTEGRATION

Zijn er wettelijke beperkingen als de Aachen rain radar wordt toegevoegd aan het openbare IRC of een afgeleid openbaar IRC van WL?
Translation: Are there legal restrictions if the Aachen rainradar is added to the public IRC or a derivative public IRC from WL

[Note: This question is answered by Watershap Limburg]
There is a restriction in the use in the KNMI IRC if it affects the public character of the KNMI IRC. This is one of the reasons that a derivative product to the public KNMI IRC is now also assumed.
Because the operator of the Aachen radar is a commercial party, it is not the legislation that imposes restrictions but the terms of delivery. For example, the data now shared via Hydromaster are not suitable for creating a composite image. Also, the owner of the Aachen radar can determine whether a composite image with the Aachen radar images may be shared publicly or not. With any operational use of the Aachen radar, these conditions should be set forth in an agreement.
Potential legal restrictions regarding the Aachen radar data need to be discussed between Waterschap Limburg and Kisters AG which disseminates the Aachen radar data.

6 QUESTION 4- COST ESTIMATION FOR X-BAND DATA INTEGRATION

Wat zijn de kosten van het mengen van de Aachen rain radar in de bestaande IRC en wat zijn de jaarlijkse datakosten? Bij het mengen van de Aachen rainradar in de bestaande IRC kunnen 2 varianten worden overwogen: mengen in het bestaande IRC-product van het KNMI of mengen in een afgeleid IRC-product waarbij het bestaande IRC product als basis wordt gebruikt.
Translation: What are the costs of mixing the Aachen rain radar into the existing IRC and what are the annual data costs? When mixing the Aachen rain radar into the existing IRC, 2 variants can be considered: mixing in the existing KNMI IRC product or mixing in a derived IRC product using the existing IRC product as a basis.

For this question, only the mixing in the existing KNMI IRC product is considered. As mentioned earlier, Aachen radar data are commercial data that do not follow public data requirement policy at the moment. It is therefore not possible to integrate them into a derived IRC product.

6.1 ASSUMPTIONS TAKEN WITHIN THE COST ESTIMATION

The following assumption are taken in the estimation:

- It is assumed that the IRC data are managed, processed and made available via an API by KNMI. Therefore, no additional manpower cost is added for development and maintenance of the solution. Any use of outsourcing parties would increase the cost estimation.
- The cost estimation is based on SkyEcho's own experience. Cost might differ based on the IT computing service provider used for specific activities. Economic conditions of 2023 have been assumed.
- The cost for distributing the data via API is constraint to Waterschap Limburg. The server capacity assumed does not consider a large number of users (i.e. in case the data would be made available to the public).
- *Non-recurring expenses (e.g. development and setup) costs are not considered here.*
- *The cost for the provision of the Aachen radar data needs to be directly discussed between Waterschap Limburg and Kisters AG and could not be considered here.*

6.2 COST ESTIMATION

Cost item	# months	Estimated unit cost	Estimation total	Remarks
Data collection and temporary storage	12	50,-EUR	600,- EUR	SSD volume 256 GB
Data processing	12	420,-EUR	5040,-EUR	Cloud computing instance 8 cores, 32GiB memory, SSD interface, ethernet with 15 Gbit/s
Data distribution	12	40,-EUR	480,-EUR	API
Maintenance	12	200,-EUR	2400,-EUR	approx. 2 hours/month
		TOTAL COST Estimation (excl. VAT):	8520,-EUR	

Taking into account a 20% margin on the estimation, the yearly cost can be estimated between EUR 6.800,- and EUR 10.200,-.

7 QUESTION 5 -ADDED VALUE – OPERATION OWNERSHIP

Heeft het als waterbeheerder toegevoegde waarde om zelf een regenradar te installeren en te beheren?
Translation: Does it add value as a water manager to install and manage a rain radar yourself?

7.1 ADDED VALUE ANALYSIS

A SWOT analysis is provided below to evaluate the self-deployment and operation of one or more X-band radar(s) in the Limburg region.

7.1.1 SWOT ANALYSIS - SELF DEPLOYMENT

STRENGTHS	WEAKNESSES
- Full control of radar positions - optimal distribution of the radars to cover the region for water management purpose	- Deployment cost is pretty high for a single entity - Deployment requires the participation of several stakeholders such as transport company, radar manufacturer, building manager, energy provider. The setup management tasks are therefore considered very high.
OPPORTUNITIES	**THREATS**
- By owning the radar, the waterboard have the possibility to request service at lower price compared to a full as-a-service fee.	- In case of failure to properly setup the system, the waterboard is the only one to bare the entire investment risk.

7.1.2 SWOT ANALYSIS – SELF OPERATION

STRENGTHS	WEAKNESSES
- the radar antenna scanning can be adapted to the needs of the client without having to follow any standard operation. This could for example be used to better monitoring risk-prone area in the Limburg region.	- in-house processing require dedicated IT tools and manpower which makes the service more costly for the waterboard. - The experience gained from self-operation is limited to the radar(s) purchased by the waterboard. Additional improvement and development might require the support of an external operator.
OPPORTUNITIES	**THREATS**
- New radar monitoring features can be specifically adapted to the waterboard needs	- No X-band radar expertise available at the waterboard - Third party service will be required

– Potential return on investment possible, Processed data can be sold or distributed to collaborators – Radar data can be released publicly without third-party approval	

A ‘client outsourcing operation’ model is advised if the client wishes to purchase and operate the radar system, so that no additional hiring is required.

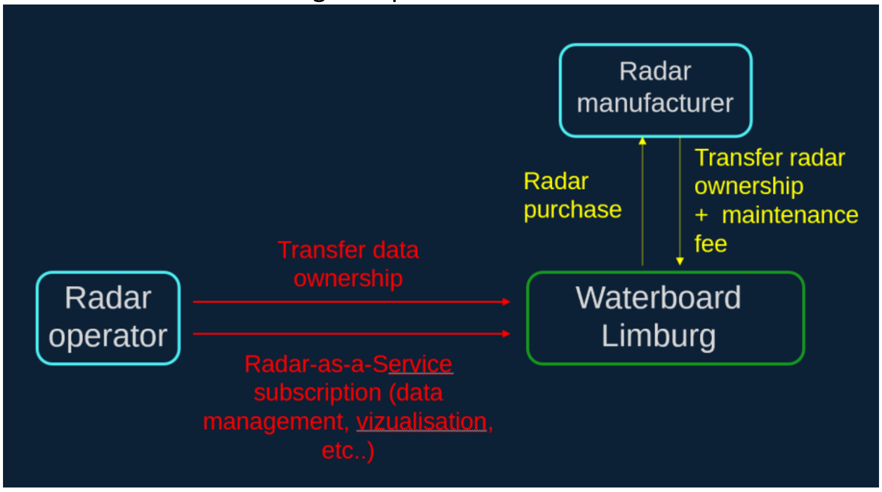


Figure 14 - Client outsourcing operation model

7.2 ALTERNATIVE SOLUTION BASED ON COST MUTUALISATION

Several alternatives are proposed in this section, which might benefit more the waterboard on a longer term.

7.2.1 FULLY PRIVATE OPERATION MODEL

The radar and data/services provided are fully owned by a private operator:

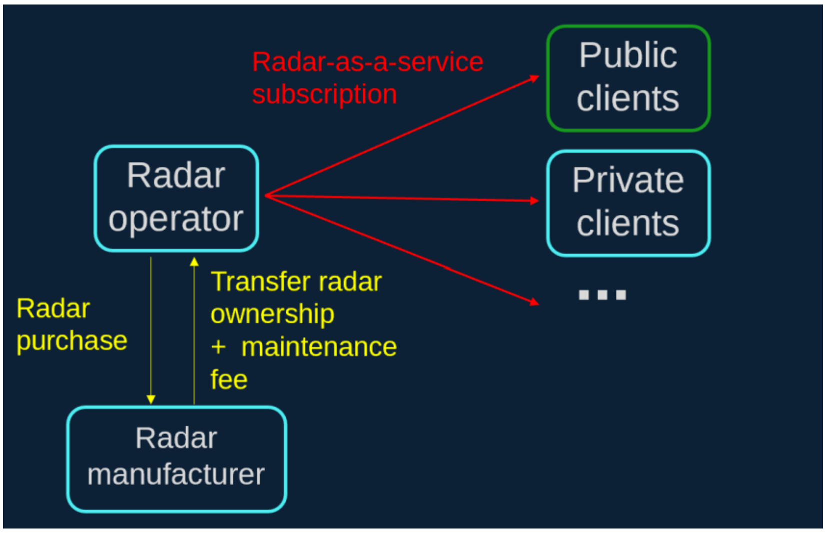


Figure 15 - fully private operation model

PRO: limited risk | limited responsibility | lower price | improved services (as it is developed for multiple radar systems)
CON: Commercial data – no public data policy | dependent on external operator | potential risk of discontinuity | require a validated market interest in the area of deployment to make sure that the radar is commercially viable.

PUBLIC OPERATION MODEL

The radar is owned by a public body (here we assume KNMI as owner of the radar). The radar can be either operated and setup by KNMI or outsourced to an external party.
PRO: the cost of deployment / operation is mutualized over different public body | KNMI has the expertise to process and maintain the radar data processing | the waterboard is already working with KNMI for the rainfall data information.
CON: The entire high cost for deployment / operation is on the shoulders of the public bodies. There is a need of political will to do so (like in Japan) | This model requires an high involvement of the public body to setup and maintained the system. Part of the activity would probably need to be outsourced.

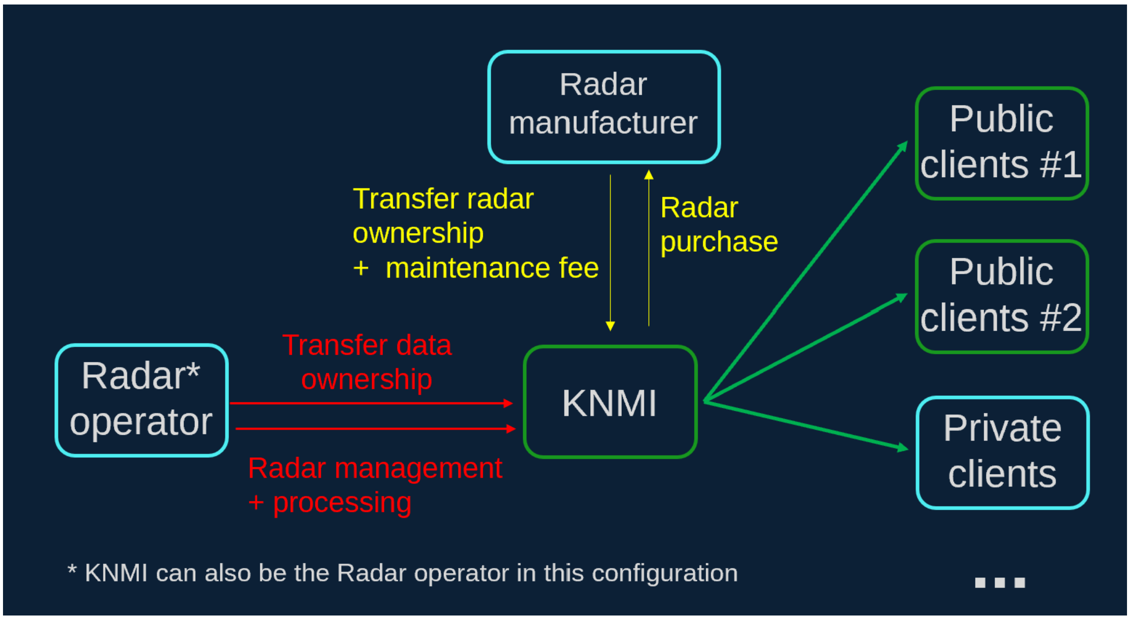


Figure 16 - Public operation model

PUBLIC - PRIVATE PARTNERSHIP MODEL

The last option is to take benefit of both public and private bodies.

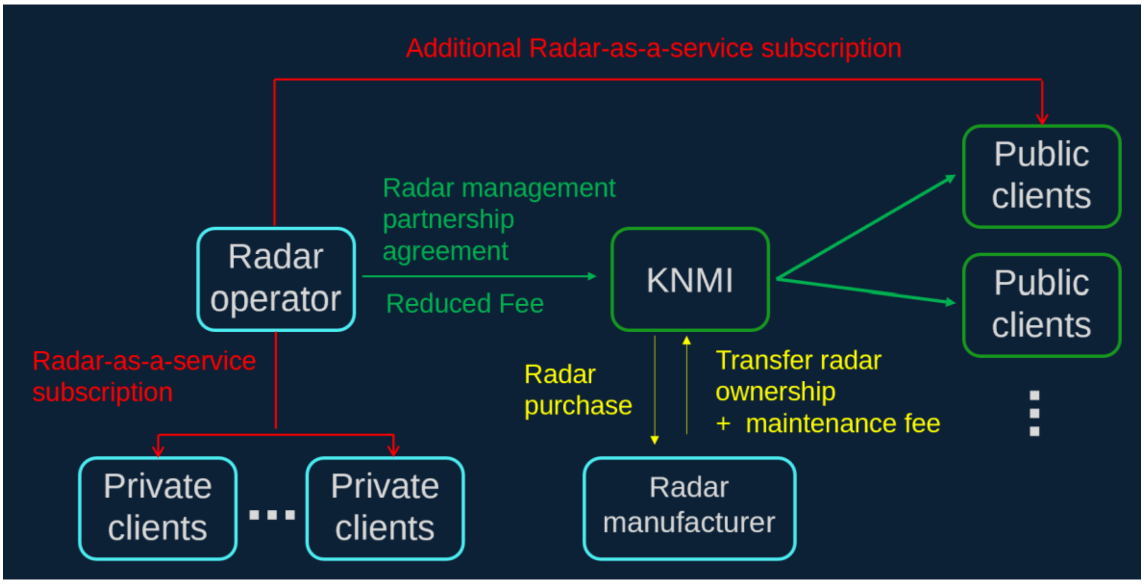


Figure 17 - Public Private partnership

By creating a partnership,
PRO: Public investment can be pushed down further due to the investment from a private partner | responsibilities can be shared | the use of the new data can be optimized for different market segments and for different application thanks to the participation of the private sector
CON: Risk on public data policy – open discussion is required between public and private parties to determine which data can be put in the public domain | Public/private partnership have legal constraints that need to be well evaluated before going to this path | Political will is required | Trust between the private and public parties must be managed.

Advices and Conclusion
Deploying and managing your own radar presents both pros and cons: The main benefit comes in terms of the full access to data for public purposes and the control on data quality, service flexibility (tuned for the client's purpose). There are, however, both technical and financial limitations. Owning a radar: • requires specific management and engineering expertise to keep the radar operational. • Owning a radar is more expensive as all the cost are on the client's side. In this section, some alternative ownership models are provided to overcome the above-cited limitations. The client shall select the model that best fit its operation and financial vision.

8 QUESTION 6 – RADAR OPERATION REQUIREMENTS

Wat zijn de installatievereisten voor een buienradar en waar moet deze zich bevinden?
Translation: What are the installation requirements for a rainfall radar and where should it be located?

8.1 RADAR DEPLOYMENT REQUIREMENT AND CONSTRAINTS

When deploying a new radar, the following requirements need to be considered:

- Reduction of beam blockage - the field of view of the radar system needs to be as wide as possible to fully profit from the measurement - It is therefore advised to have the radar deployed on the highest building or mountain in the area. The radar may also be deployed on top of a mast.
- Access to internet and electricity - for continuous operation, the radar needs to be plugged to the electricity grid. Internet access is needed so that the radar can be controlled remotely and data can be transferred to the client/users in near real-time.
- Security - the radar needs to be out of reach from unauthorized person in order to avoid damage and any potential health threat. The deployment on the roof top of a high building with secured access is recommended.
- Minimum radar range: The radar typically suffers from a blind area which can be up to 1 km around the radar. It is recommended to deploy the radar in an overlapping network to cover the blind spots, or to install the radar in an area with limited interest of the near range around the radar.
- Potential client requirements: the client should clearly evaluate and list all risk area (due to high traffic, population density, etc...) and flood prone area that require the most accurate monitoring. Overlapping of multiple X-band radar should be considered in the highest risk area to avoid any disruption.

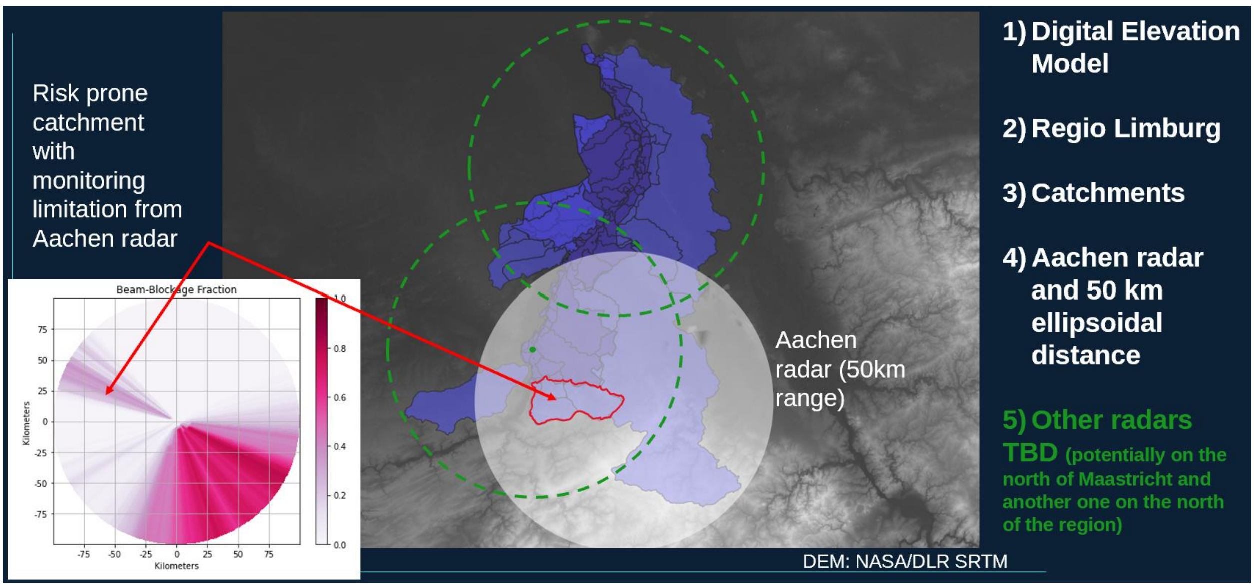


Figure 18 - Radar deployment analysis

8.2 POTENTIAL LOCATION OF DEPLOYMENT

8.2.1 AREA MAPPING

The Limburg region is currently covered by one X-band radar (the Aachen radar) on the South West of the domain and one catchment (in red in Figure 18) is considered a Risk Prone catchment which require more careful monitoring.

8.2.2 ADVICE ON NUMBER OF RADAR TO BE DEPLOYED

SkyEcho advices to install **two** new X-band radars to complement the existing Aachen radar and the C-band radar network and cover the entire Limburg region (see Figure 18). This advice is based on the following arguments:

- Limitation of the maximum range of the radar to 50km to guarantee acceptable rain quality and spatial resolutions within the whole region.
- Overlap of the high-risk prone catchments with two radar to improve the robustness of the monitoring.
- This number represent the minimum acceptable number to cover the entire Limburg region while keeping good rain quality standards.

Advices and Conclusion
We advise to install a minimum of 2 X-band radars to complement the Limburg region with High resolution information. If budget limitation, we suggest to deploy only one X-band radar in the south of the region near Maastricht as the south can be considered as more flood prone area.

9 QUESTION 7 – ADMINISTRATION PROCEDURE

Welke administratief procedure moet worden gevolgd om onze buienradar te installeren?
Translation: What administrative procedure should be followed to install our rainfall radar?

9.1 ADMINISTRATIVE REQUIREMENTS

9.1.1 FREQUENCY ALLOCATION REQUEST

The operation of a weather radar as active RF instrument requires a frequency license. Figure 19 shows how radio-frequency regulation is organized at different level (worldwide, European and at national level). On national level, frequency licenses are managed by the *Rijksinspectie Digitale Infrastructuur*.

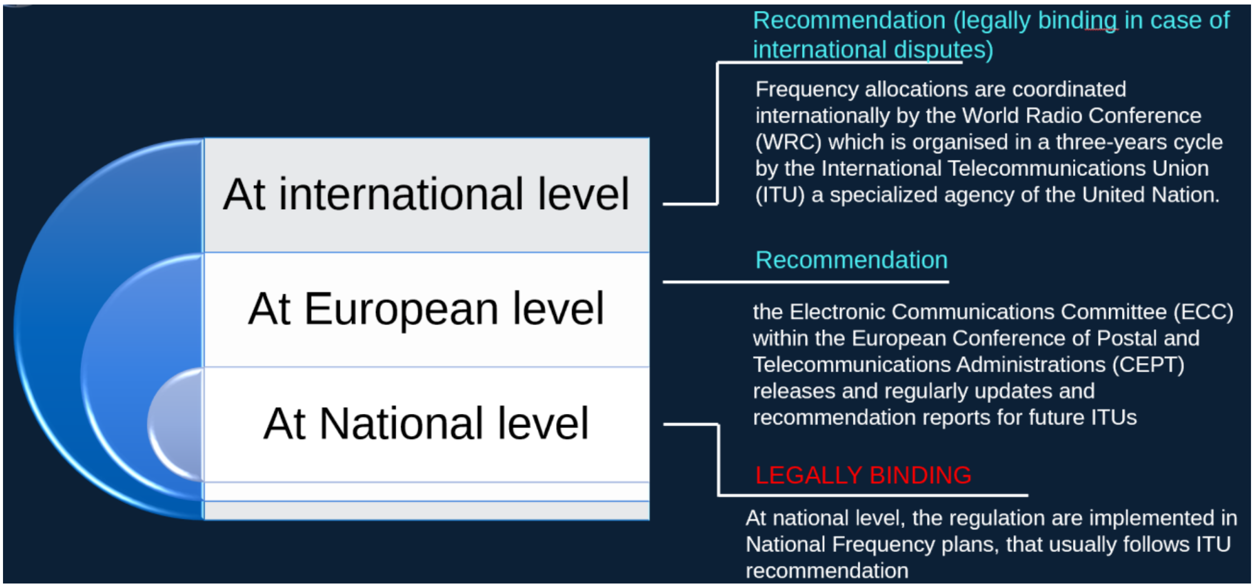


Figure 19 - Multi-level radio frequency regulation.

Potential consequences of frequency plan update:

- Any new X-band weather radar in the Netherlands will probably need to operate in the frequency band 9200 – 9300 MHz
- For radars operating close to the border, some issue could arise if the frequency band 9200 – 9300 MHz is not allowed for weather radar operation abroad (Belgium) – see Figure 20.

The Aachen radar center frequency is not known. Though, it can be safely assumed that the Aachen radar operates with a frequency which is in line with the ITU agreements.

Status frequency 9.300 MHz – 9.500 MHz

International	WMO-ITU handbook	2020	"According to provision 5.475B, ground-based radars used for meteorological purposes in the band 9300 MHz and 9500 MHz have priority over other radiolocation uses"
International	ITU Radio Regulations	2020	
European	ECA table		9300 MHz - 9500 MHz for Weather Radar (ETSI Standard EN 303 347-3).
Netherlands*	Frequentieplan	2014*	No explicit allocation to X-band weather radars, but the ITU footnote for the frequency band of 9300 – 9500 MHz has been adopted unchanged (frequency allocated for military and civil)
Belgium	X-band radar frequency allocation not implemented on national level		
Germany	Frequenzplan	2022	X-band weather radar allocation within 9200 – 9300 MHz and 9300 MHz - 9500 MHz (for civil purpose only)

* New Frequentieplan 2023 currently under revision

NOTE for Netherlands: due to Defense request, this frequency band will certainly be removed for civil purposes in the new frequency plan, deviating from the international recommendation. A lower frequency band is already requested for new X-band weather radar operations (RIJNMOND Radar)

Figure 20 - Regulations and recommendations for X-band meteorological radar operation frequency.

9.1.2 OTHER ADMINISTRATIVE REQUIREMENTS

Other administrative procedure may be relevant for the procurement and deployment of a new radar system:

- Public tendering over EUR 1 million – compulsory for public organizations
- Insurance: the transportation, deployment and operation of an X-band radar include some risks that may require to be insured due to the high initial and maintenance cost of the system.
- Appointment of a project manager: Several stakeholders will be involved for the installation of a new system including property owner (where the radar will be deployed), the radar manufacturer, the radar operator, a transporter as well as internet and electricity provider, etc... It is strongly advised to employ a project manager to organize the deployment.

Advices and Conclusion
The administrative procedures can be summarized in 3 main ones: the public tendering procedure to acquire the radar, the radar frequency allocation procedure to allow the radar operation, and some optional procedures to guarantee the service operation. When installing a radar, it is strongly advised to appoint a project manager to handle such administrative tasks.

10 QUESTION 8

Waar moet rekening mee worden gehouden bij het installeren en beheren van een buienradar?
Translation: What should be taken into account when installing and managing a rainfall radar?

10.1 ACTIVITY PROCESS DESCRIPTION

Installing and managing a radar is not an easy task. It requires:

- Time: typical time from decision to operation can be between 6 months to more than a year.
- A large set of expertise: from civil engineering to legal matters - a project manager and several companies are usually outsourced to do the job

We can sort the type of activities into 3 different categories based on the project timing - see Figure 21 (Note: the commercial contracting phase is not included in this section):

1. A preparation phase (before deployment - steps 1 and 2)
2. A deployment phase (step 3) - where the radar system is being installed and set up for operation - this phase also includes a post deployment step where the radar is system goes to a preliminary evaluation
3. An operation phase (step 4) - where most of the work is to maintain the operation (including end-user service distribution) and quality of the radar system

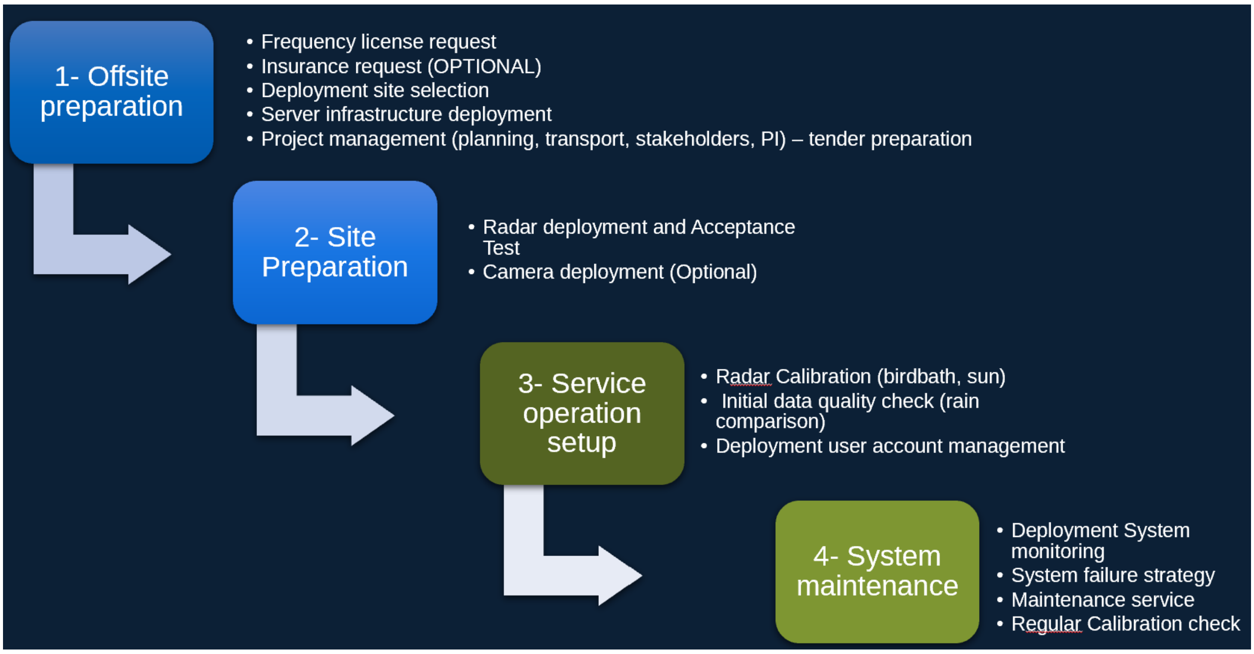


Figure 21 - A possible Activity planning overview

10.2 POTENTIAL ASSOCIATED RISKS

Due to the involvement numerous stakeholders and the complexity of the planning, we have drawn up a list of general potential associated risks below:

- Potential delivery delays: delays in the deployment of X-band weather radar system are the main risk that can be encountered. The delay can be due to:
  - A problem with one or multiple stakeholders (delay, unavailability, etc.)
  - The weather situation (especially during on-site installation and calibration)
  - Communication between stakeholders were not good enough
- The radar doesn't perform according to plans: some potential causes: the site has been wrongly chosen (multiple beam blockage or interreference), one of the hardware components is badly calibrated, one of the hardware components is lacking
- The project plan is lagging: 1) some activities are not well covered, 2) there is no project manager and complex communication.

Advices and Conclusion
X-band radar deployment is achieved in 4 steps: 1- Offsite preparation; 2: Radar Site preparation; 3) Service setup; 4) Service maintenance Potential risks associated to the deployment and operation activities have been provided. To support the radar activities, we strongly advise the client to hire a dedicated project manager, that shall handle activity management and communication (either in-house or outsourced). The manager could also handle the administrative tasks as mentioned in the previous section.

11 QUESTION 9 – COST ESTIMATION FOR RADAR OPERATION

Wat zijn de kosten voor plaatsen en exploiteren van een eigen buienradar?
Translation: What are the costs for installing and operating your own rainfall radar?

Due to potential conflict of interest, this question is handled by Waterschap Limburg itself. Two interviews have been conducted by Waterschap Limburg. A summary of each interview is presented here. Sensitive information (price dropdown) is removed and are kept at the sole discretion of Waterschap Limburg.

INTERVIEW WITH THE MUNICIPALITY ROTTERDAM - THE RIJNMOND RADAR

Questions X-band radar for consultation with municipality of Rotterdam on Aug. 2, 2023
Interview with Bob de Jong of the municipality of Rotterdam

Question 1 - What prompted you to install your own radar?
More insight into precipitation distribution over the city of Rotterdam. Occasions that a station on the ground did not register anything because there was no rainfall there and a little further on there were problems with too much precipitation. Eventually Rotterdam also wants to be able to effectively control pumping stations with the rain radar.

Question 2 - How long did the preparation process take?
The project started in 2018 and the radar was installed in 2019. However, the radar only functioned for 3 months because the wrong license for the frequency to be used was delivered. Adjusting the new radar to the new transmission frequency took 8 months. The radar has yet to be put back in place.

Question 3 - Was an outside consultant used for preparation?
Yes

Question 4 - How was the implementation tendered?
The implementation was put out to European tender.
The supplier became MetaSensing from Italy.
https://metasensing.com/wp-content/uploads/2022/09/MetaSensing-QX-120.pdf

Question 5 - Setup
The radar is on a 150-meter-high building and then an additional scaffold to rise above the parapet.

Question 6 - How is the management of the radar organized?
Rotterdam has considered having the radar managed or taken over by others such as KNMI because Rotterdam is not a meteorological institute.
For now, KNMI does not seem to be interested in doing so. The effort of the Municipality of Rotterdam is mainly procurement, contract management and coordinating activities. For this alone, 0.5 to 1 FTE should be taken into account.
Maintenance and repair are performed on a directional basis by the supplier.
Data processing is performed by SkyEcho BV.

Question 7 - How are the data processed?
The raw data (reflections) are owned by the Municipality of Rotterdam. These raw data are processed by Sky-Echo into precipitation maps. The precipitation maps remain the property of Sky-Echo. Software developed remains from Sky-Echo.

What have been the investment costs?
The cost of the radar in 2019 was € 520,000.00. Added to this are the costs for installing and setting up the system. The conversion of the radar cost € 150,000.

Investment cost estimated by Waterschap Limburg:

Preparation, permit application location research tender	€ 100,000
Radar	€ 600,000
Installation	€ 100,000
Commissioning, purchase and license costs software	€ 100,000
Other and unexpected	€ 100,000
Total excl. VAT	€ 1,000,000
Total incl. VAT	€ 1,200,000

What are the management costs?
Annual inspection of the radar costs about €2,000.00 This is without any replacement of parts.
For data processing, Rotterdam now pays a license fee. In this construction, the processed data remain the property of Sky Echo.
In the worst case, a new frequency is assigned and the radar must be adjusted accordingly. In the case of Rotterdam this cost € 150,000 excluding on-site costs and 8 months' time. Here €100,000 was contributed by third party, since the need for the conversion was caused by them.

Estimated management costs per year by Waterschap Limburg:

Inspection, minor repairs and general maintenance	€20,000
Building up provision for major repairs and unexpected conversion	€ 50,000
Data cost	€ 60,000
Rent, electricity, data communication	€ 50,000
Development and contingency	€ 50,000
Hiring external expertise	€ 50,000
Personnel costs management	€ 100,000
Total excl. VAT	€ 380,000
Total incl. VAT	€ 460,000

Is there a partnership with other parties?
Yes, with 3 water boards

Will the data be made publicly available?
The intention is that the data will also be accessible to residents of Rotterdam. Government and businesses will have to purchase an additional license.

Other
The X-band radar has a range of at least 40 km.
[*Note SkyECHO: The range is now extended to 50 km*]

INTERVIEW WITH KNMI

Questions X-band radar for consultation with KNMI on Sep. 14th, 2023
Interview with Mando de Jong at KNMI.
KNMI-radars standing in Den Helder and Herwijnen. These were renewed in 2016.

Question 1: How is radar management organized?

- Maintenance and repair is made from the supplier Leonardo. A 10-year maintenance contract has been drawn up for this purpose. This maintenance contract includes:
  - 2 times a year preventive maintenance (including calibration)
  - 24/7 breakdown service
  - Software (Rainbow) for processing the radar data.
- The radar must be in operation 98.5% of the time. Outage maximum 6 to 7 days per year including maintenance
- All radar data are the property of KNMI. KNMI performs all other processing on data itself.

Question 2: How will the data be processed?
The radar data and data from the Belgian and German radars are read into Rainbow.
Rainbow makes radar composite. Rainbow runs on Amazon webservices.

Question 3: What have been the investment costs for the C-band radar?
Radar € 1.000.000
Excusive costs for tower, installation etc.

Question 4: X-band radar management costs estimated by WL per year after discussion with KNMI:

Maintenance, inspection and minor repairs	€ 30,000
Building up provisions for major repairs and unexpected conversion	€ 50,000
Data cost	€ 20,000
Rent, electricity, data communication	€ 50,000
Development and contingency	€ 50.000
Hiring external expertise	€ 50,000
Personnel costs management	€ 100,000
Total excl. VAT	**€ 350,000**
Total incl. VAT	**€ 430,000**

Advices and Conclusion

Bulk numbers are provided here based on interviews (incl. material/server and manpower costs) – PRICE CAN DIFFER

- For installation (one-time): ~ EUR 1 million.
- For operation: ~ EUR 300-400 000 per year

The decision whether to invest shall take into account the investment models (questions 5) that fits best the client’s vision.

If the client wishes to invest in the radar, it will need to follow the public procedure, e.g.:

- problem description based on this study and selection on investment model
- (European as > 1 Mio Euro) Tendering procedure
- Budget assignment
- Assignment

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