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Enabling Ultra-low Power Machine Learning at the Edge

"The Turbinator: A Contact-less Turbidity Sensor utilizing Laser, Camera and Low Power Neural Network Processing"

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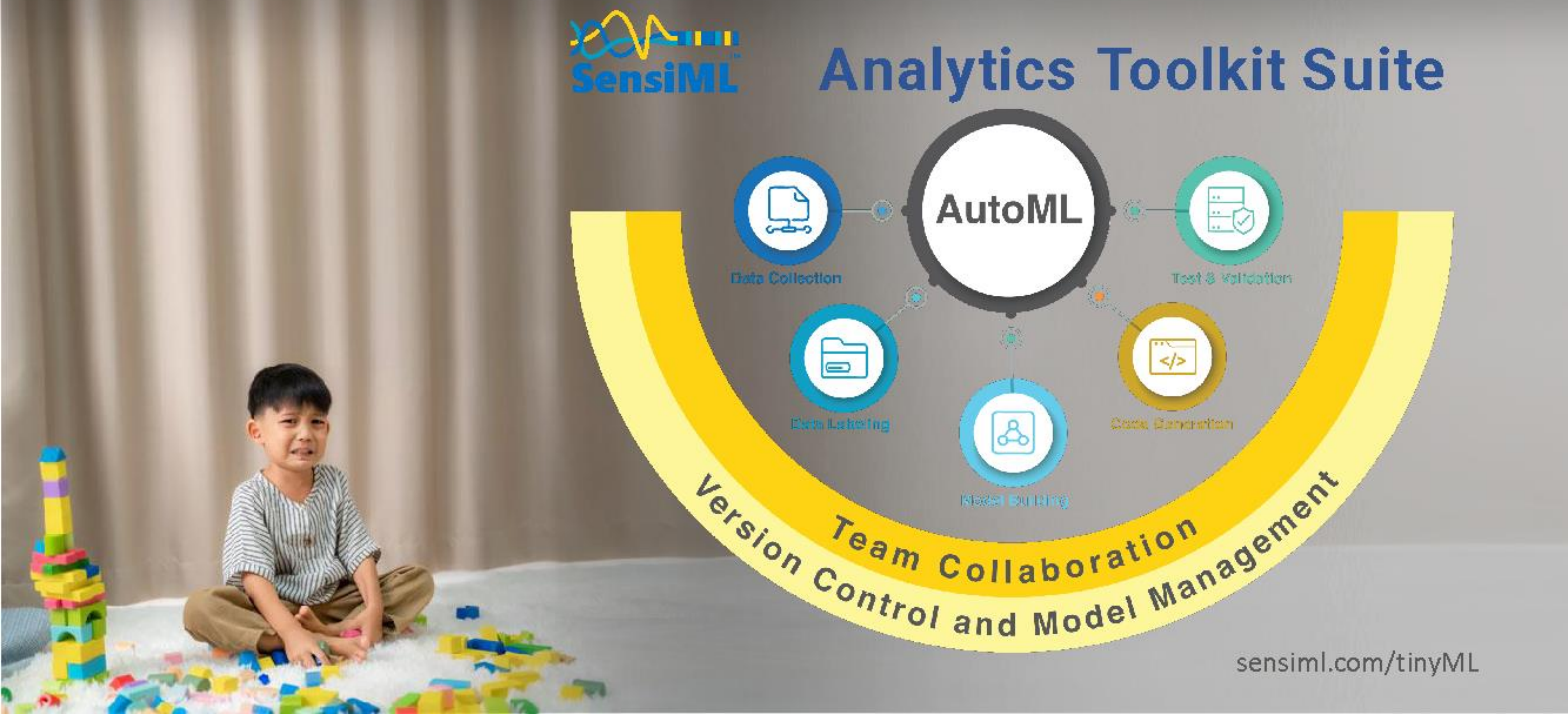

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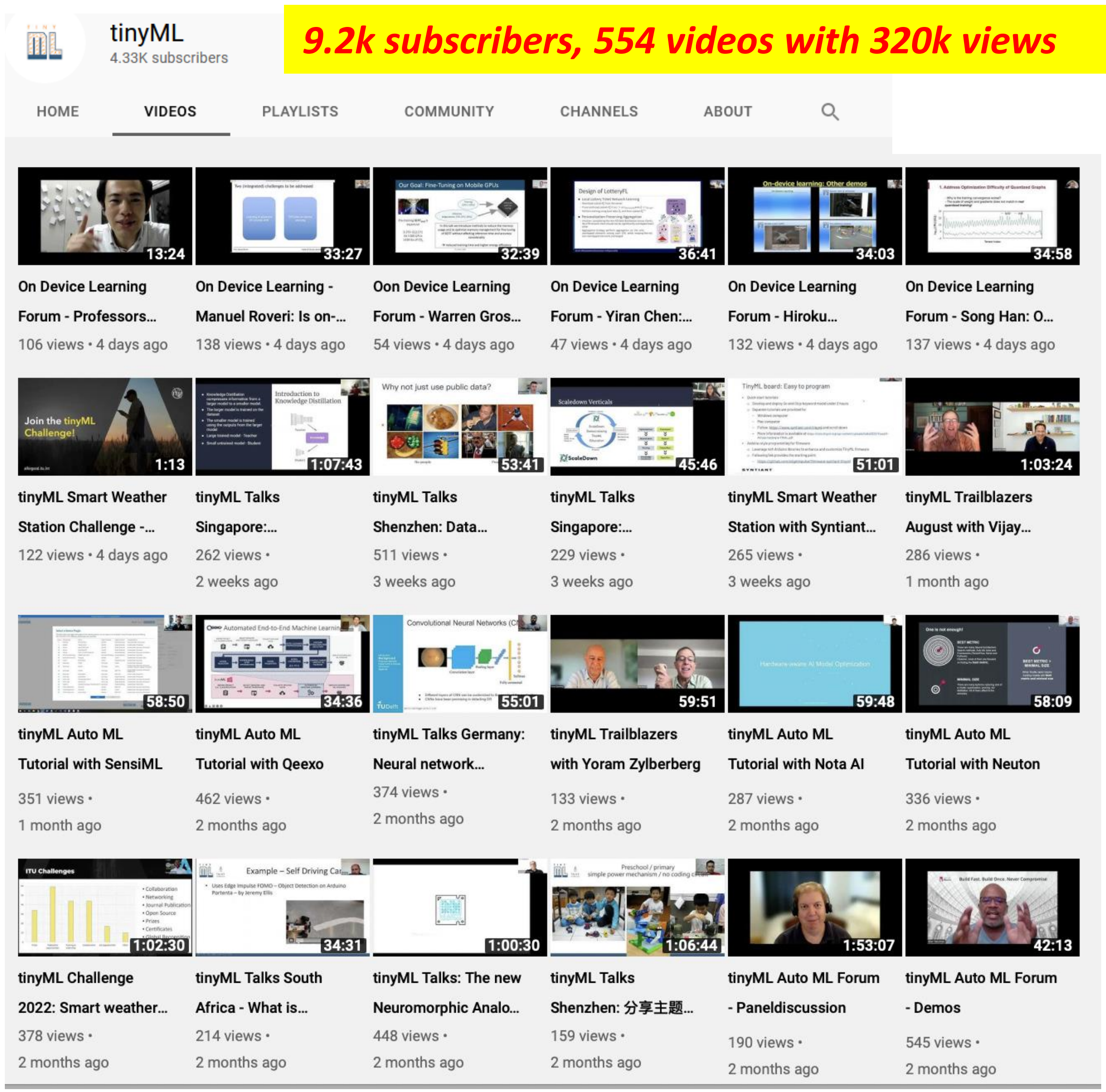

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TINY ML TALKS *webcast*

Reminders

Slides & Videos will be posted tomorrow

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Please use the Q&A window for your questions

Jens Wilhelmsson

Jens Wilhelmsson M.Sc. in Complex Adaptive Systems from Chalmers University of Technology in Gothenburg, Sweden. Since 2019, he is working at IVL Swedish Environmental Research Institute with applying machine learning within different environmental research projects. His main interests are computer vision, image processing and related sensor development.

The Turbinator: A Contact-less Turbidity Sensor utilizing Laser, Camera and Low Power Neural Network Processing

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2023-04-27

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Agenda

- About me and the company I work for
- What is turbidity and why measure it?
- Existing turbidity sensors and its challenges
- Brief history of the Turbinator
- How the Turbinator works
  - Physical measurements
  - The data
  - The ML part
  - The tiny part
  - The communication
- Challenges, limitations and some future ideas

IVL Swedish Environmental Research Institute and I

- Independent, non-profit research institute, owned jointly by the Swedish government and the business community through a foundation.
- 50/50 applied research/consulting within fields related to the environment.
- 400 employees.

- B.Sc. Engineering physics + M.Sc. Complex adaptive systems.
- Likes to apply AI to new fields where the impact is large.
- Sensor development (mostly proof-of-concept)

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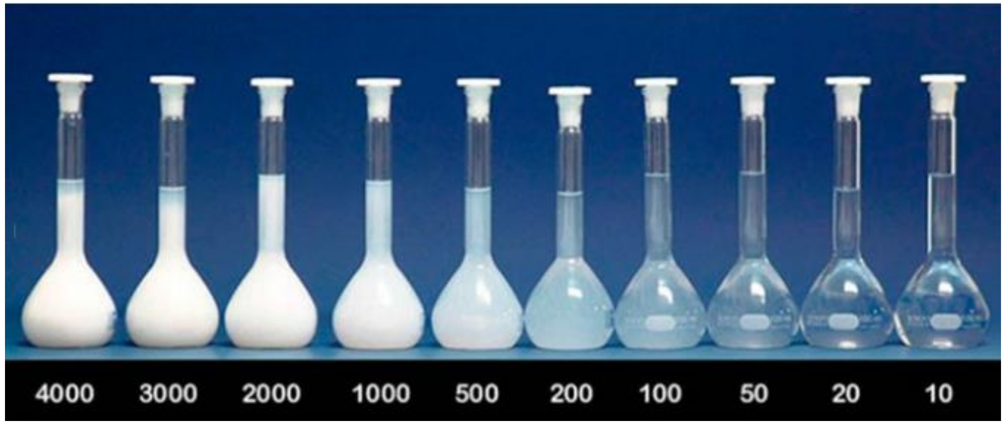
What is turbidity and why measure it?

- Turbidity is a measure of the clarity of water due to the presence of suspended particles such as sediment, microorganisms, algae or other pollutants.

- Drinking water quality
- Environmental monitoring
- Wastewater treatment
- Industrial processes

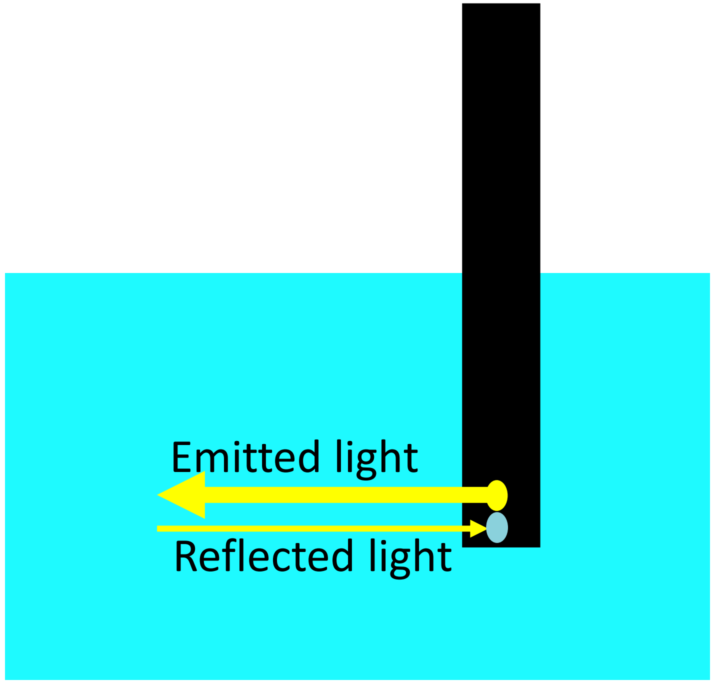


https://www.ultra-filter.com/process-filtration/turbidity--ambiguity-of-a-liquid/

Current techniques for measuring turbidity

Typical turbidity sensor
https://www.campbellsci.ca/obs500

Photosensor and LED



Light is reflected by particles in the liquid
-> More reflected light = higher turbidity

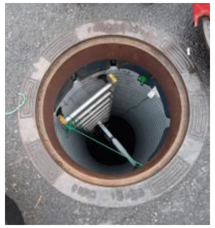
The challenges for current measurement techniques

https://nerrdsonthewater.com/2017/03/10/our-sonde-grew-a-beard/

- Fouling -> high maintenance
- Expensive

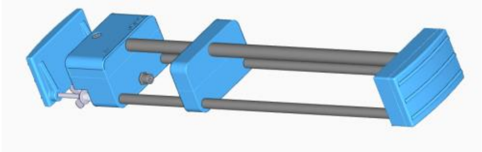
The brief history of the Turbinator

My colleague Fredrik gets an idea of how to measure turbidity without touching the water



What should we use it for? Let's start with stormwater systems

Try to collect training data for the neural network in the stormwater system, realize that its not going to work



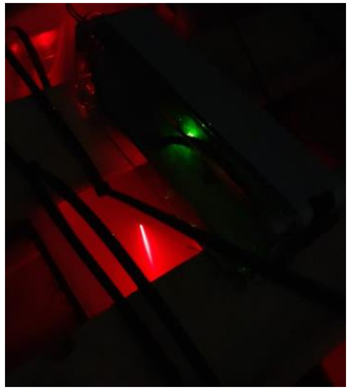
Initiate cooperation with EEWare and Greenwave to build next generation prototypes

Learn from Greenwave how quantization works ☺

3 prototypes deployed in Gothenburg

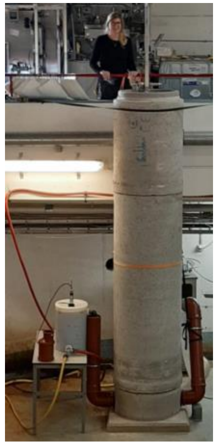
2018 — 2023

Verify that the theory works in a minimal lab setup



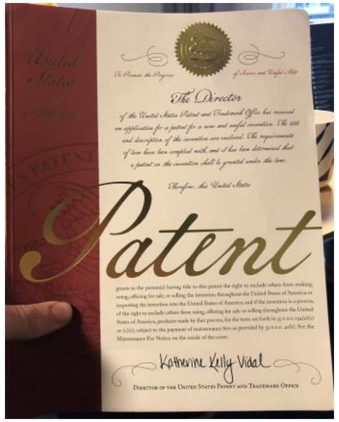
Develop first prototype based on off-the-shelf hardware

Start building facility for collecting training data



Train first neural network based on training data from the data collection facility

10 first prototypes received from EEWare and patent approved



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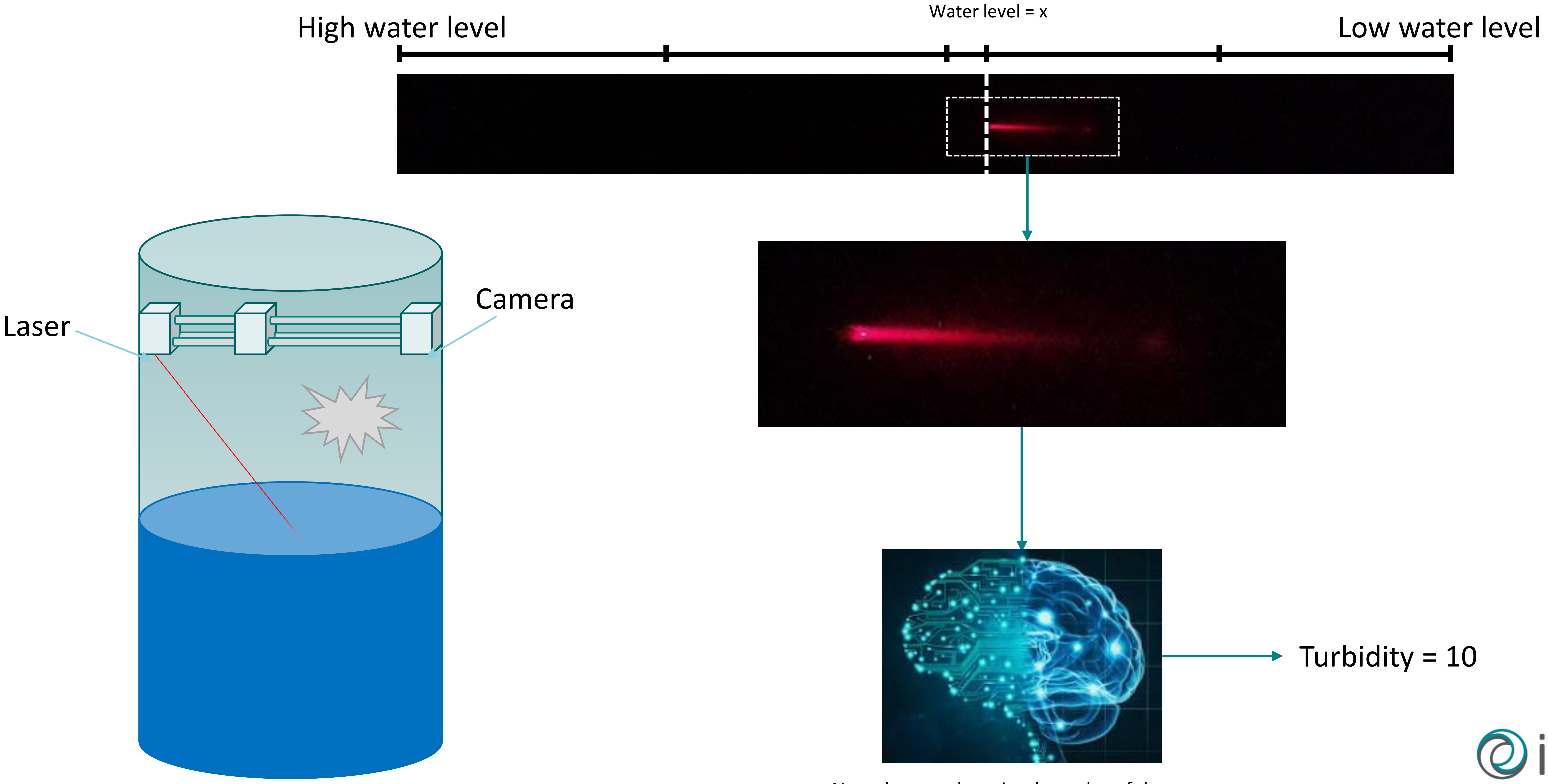
How it works



Neural network, trained on a lot of data

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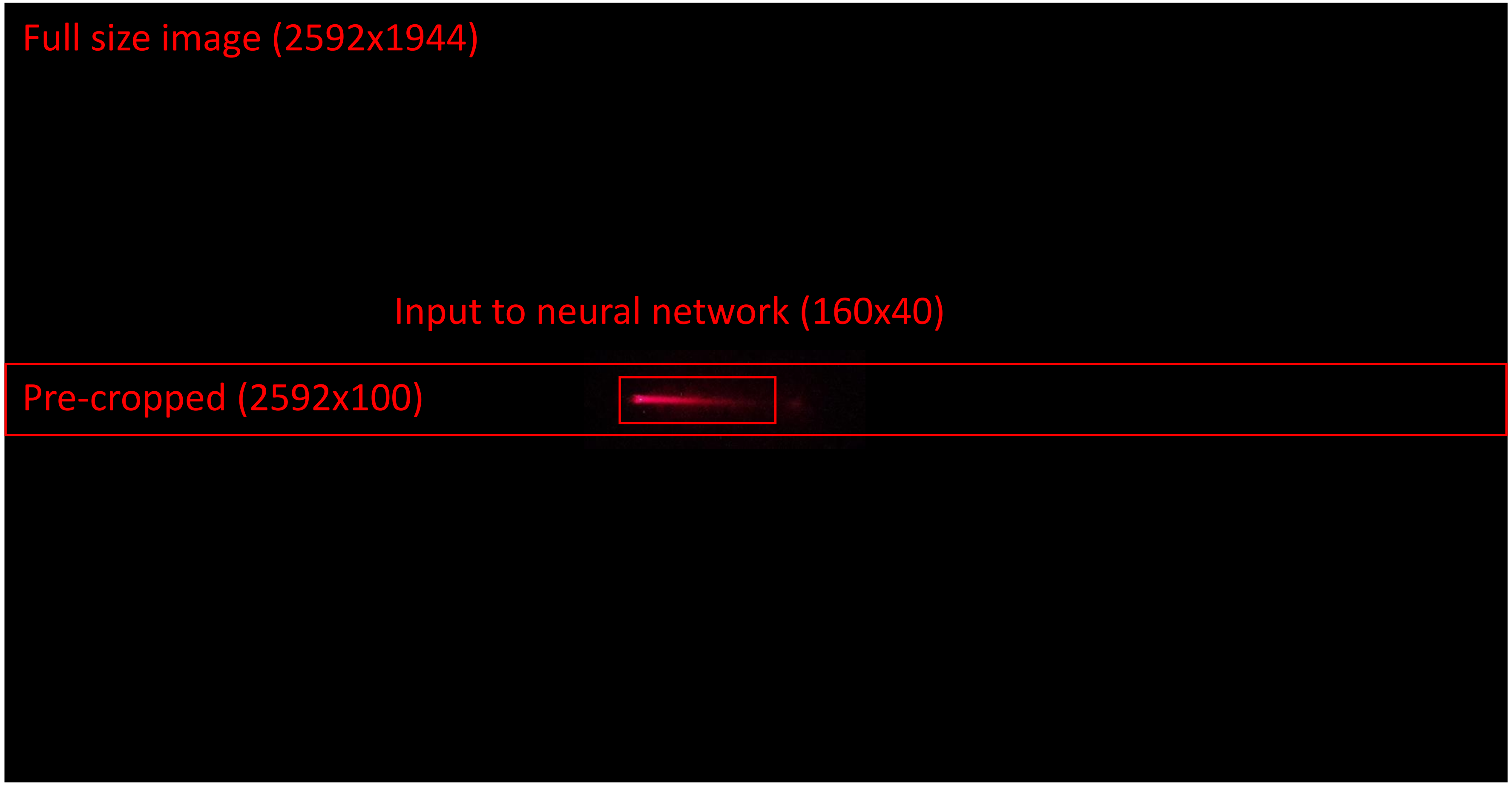
Finding the laser dot in the image



- We can’t maintain the whole image in memory. Not even 2592x100.
- Argmax is the current (not so good) solution
- Maybe possible to compress image since its mostly black and run neural network on compressed information?
- First take another photo with low resolution and find laser?
- Just implement a better version of argmax?

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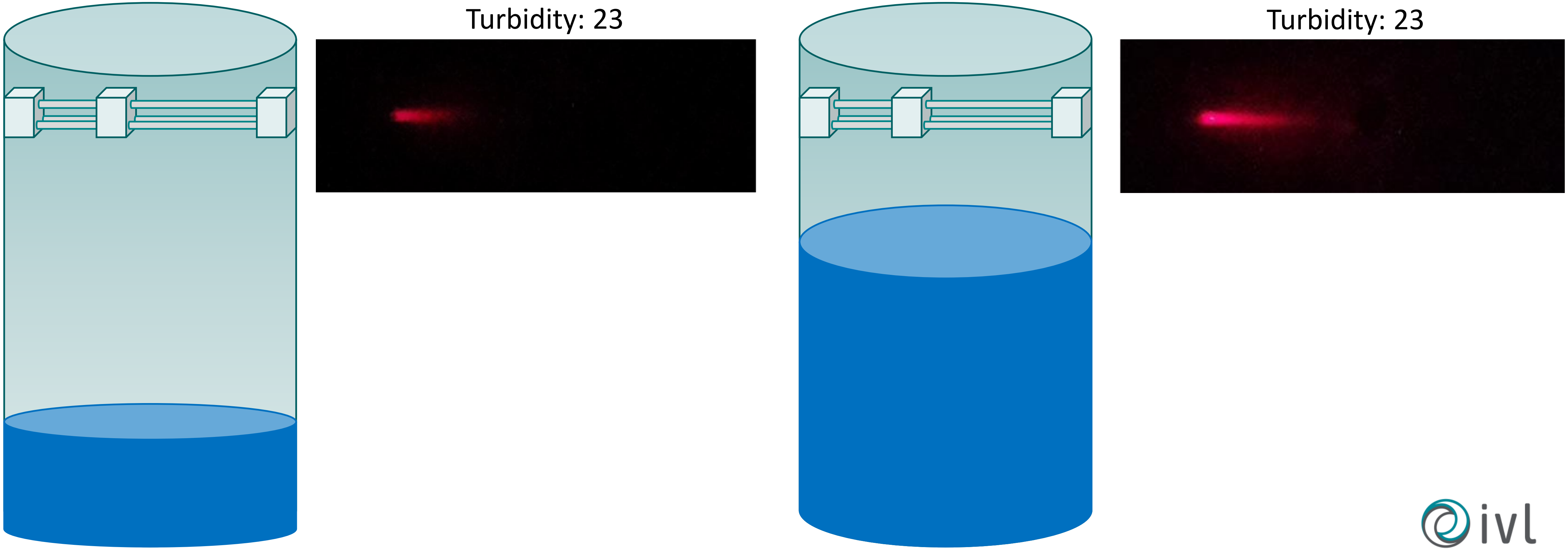
The distance to the surface varies and complicates everything



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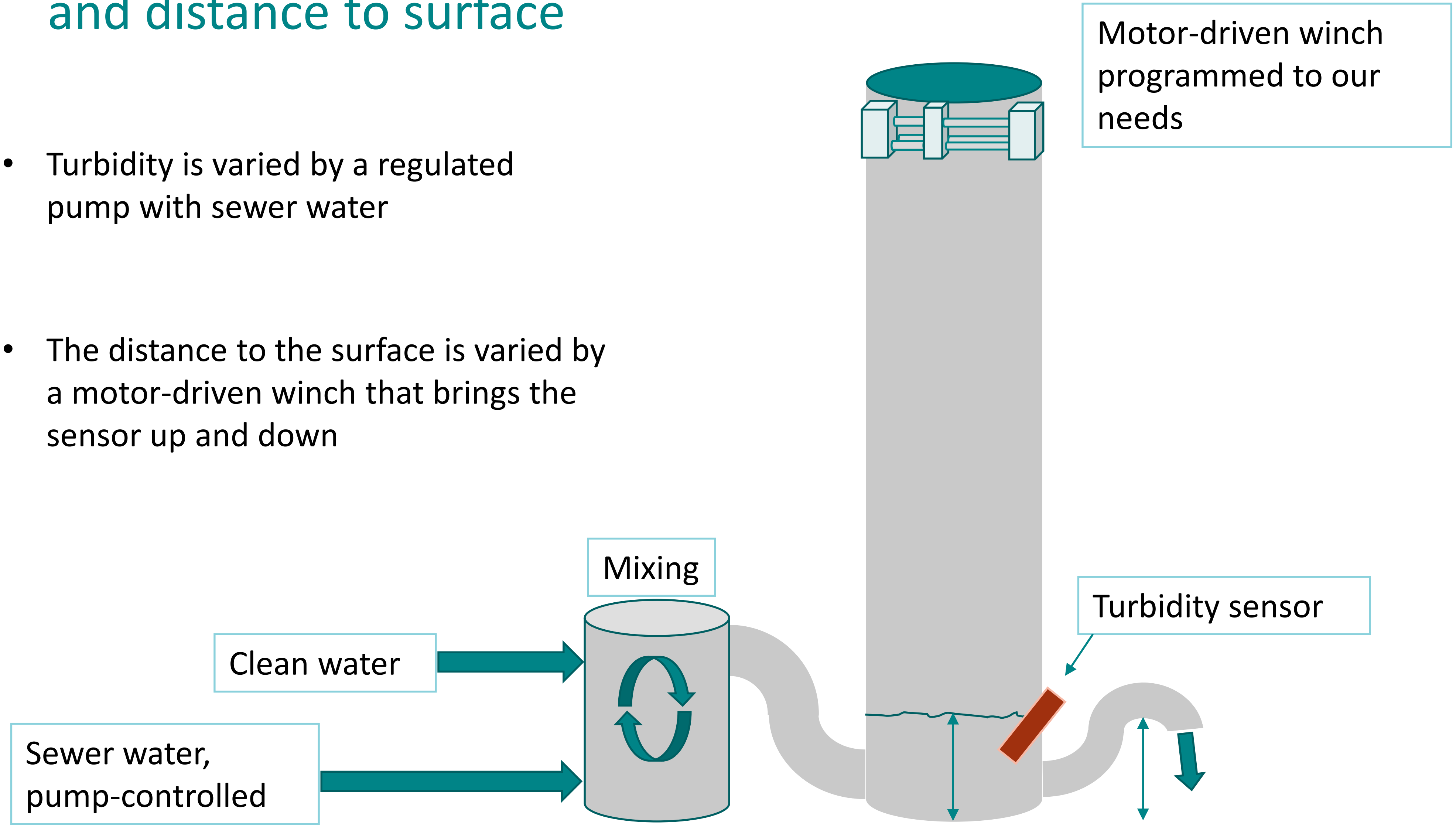
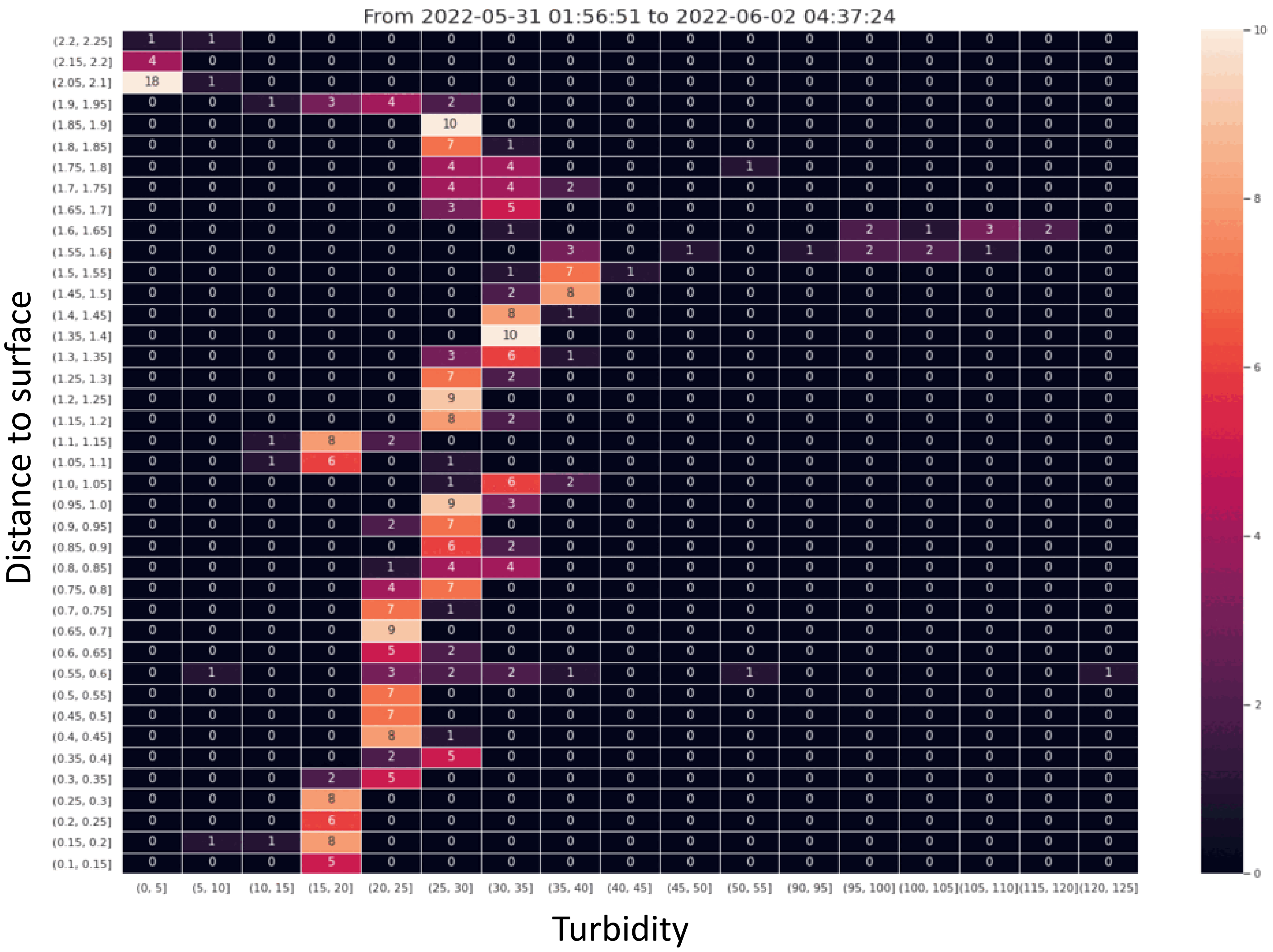
Gather data while varying both turbidity and distance to surface

- Turbidity is varied by a regulated pump with sewer water
- The distance to the surface is varied by a motor-driven winch that brings the sensor up and down



Data coverage matrix



But we also get a lot of junk data

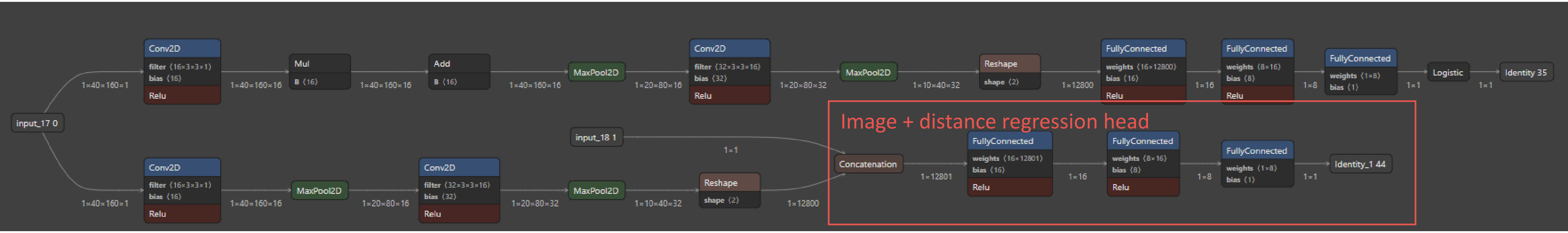
- Can’t find laser in the image
- No water
- Too high water level to catch laser with the camera
- Something on the surface
- …

→ We train a separate neural network to learn to identify if the image is similar to the good training data

Design neural network based on our requirements

- Turbidity depends on the both image and the distance to surface
- We need to be able to tell if the incoming image is worthy creating a turbidity prediction

- Multi-input model (image and distance to surface)
- Multi-output model (turbidity and indication of image quality)



(image by netron.app)

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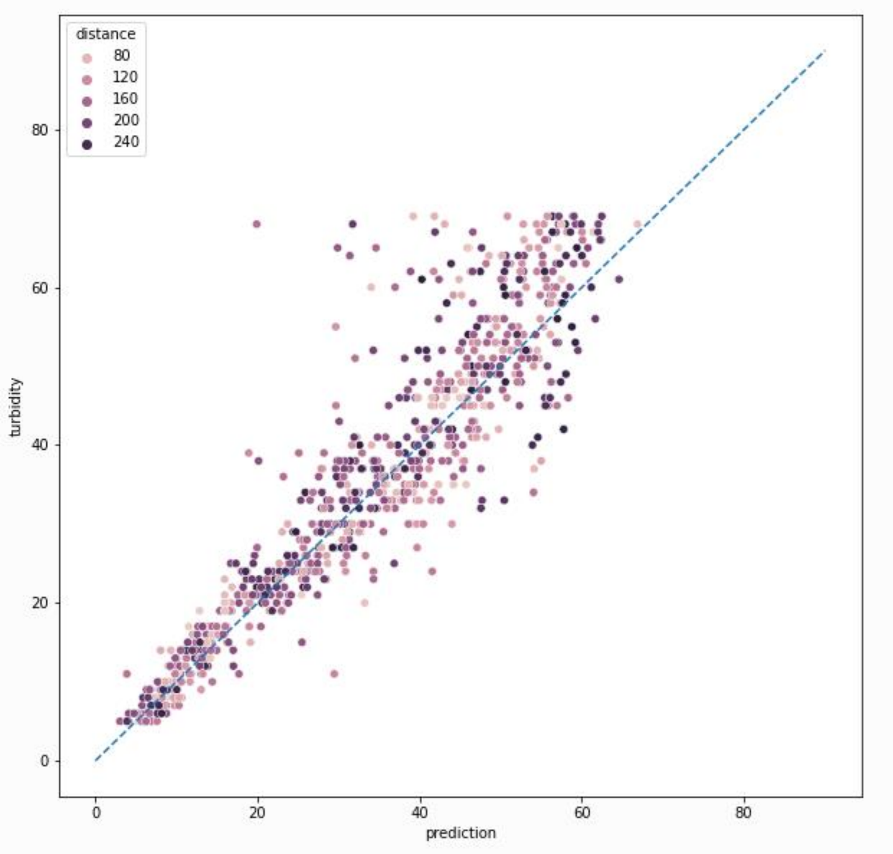
Luckily, the theory seems to hold

- Mean error of around 10-15% on validation data.
- This accuracy would never be enough in a lab but considering we are not touching the water, we're very satisfied with the results.



Time to move on from the ML part to the tiny part

- The main requirement: the sensor must be able to be left in a stormwater well for more than a year (of course the longer the better) without maintenance or battery charging.

- The neural network has to be able to run on the sensor with very low power consumption

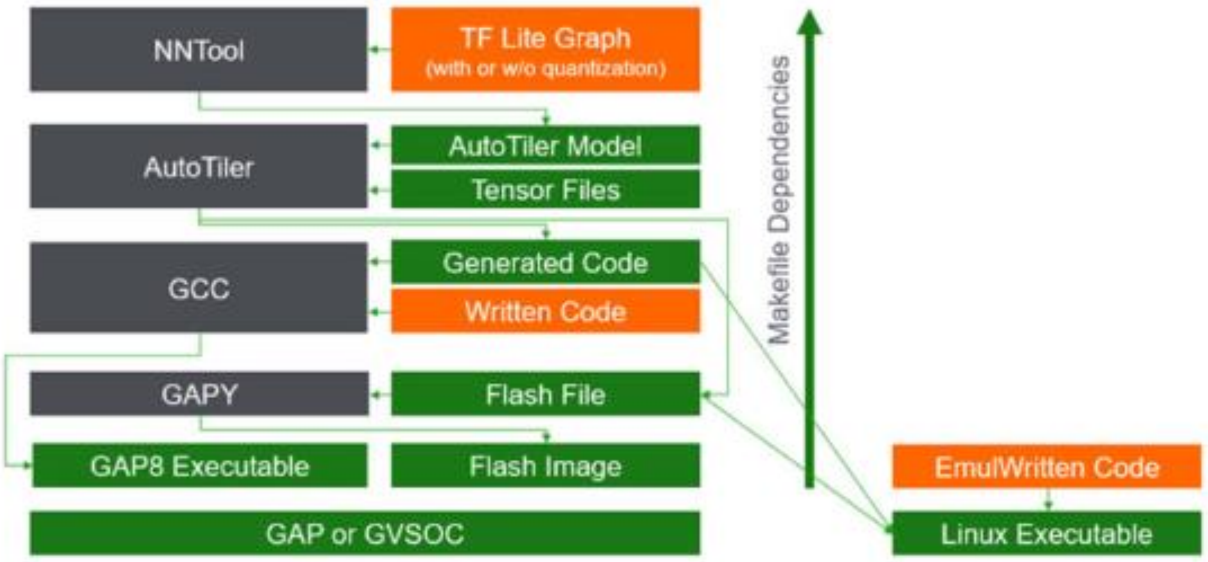
- Greenwave GAP8 – ultra low power AI processor

Making Tensorflow Lite models able to run on Greenwave GAP8 processor

- We convert our Tensorflow model to Tensorflow Lite. Then use the GAP toolchain – GAPflow. It contains:

- NNTool: python package with tensorflow lite model as input. It implements model optimization and quantization, and creates AutoTiler models.

- AutoTiler: optimizer of data memory management between memory within and outside GAP processors. Generates C-code to be executed on the GAP8.



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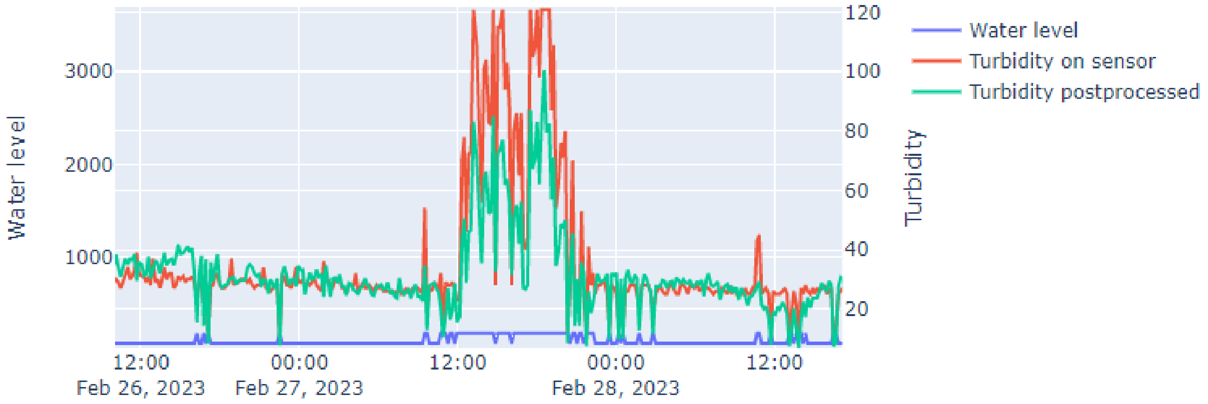
Moving from floating point to integer precision by quantization

- The GAP8 processor uses integer precision when doing its neural network calculations. This means that our floating point tensorflow model has to be quantized, which causes some loss in accuracy.
- In other words, each of the floating point weights in the network and each floating point bias (100k+ parameters) has to be rounded in an efficient way to not lose accuracy.
- With that said, we do experience some accuracy drop (sometimes to the order of 10-20%). But we have not made an effort to minimize it!

But! All data (images) are stored on the sensors, so when we bring the sensors back from the wells, we can postprocess all data with floating point precision



Send data from stormwater wells using NB-IoT

NB-IoT

- We decided to go for NB-IoT, it sends data using the cellular network, in contrast to the option LoRa which uses local gateways.
- Some problems with connectivity due to the thick iron lids covering the sensor.

Pros of NB-IoT:
- Better penetration of structures than LoRa.
- Plug and play as long as we have SIM-cards for the country we're in (and that there are cellular reception).

Cons of NB-IoT:
- Only small amounts of data can be sent.
- Higher power consumption than LoRa.

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What are the current challenges, improvement ideas and limitations?

- The reception in certain stormwater wells is bad.
- It is energy consuming to send data, it stands for the majority of the energy consumption.
- The environment in the stormwater wells is harsh.
- The OK/NOK classification of images need to be improved, a lot of data is marked bad.
- Finding the laser dot in the images is hard with our current limitations in computing power.
- We can’t send images, costs too much energy
- Training data does not cover all possible variations in turbidity and distance to surface.

- New antenna? External maybe? Workshops ongoing.
- Especially if we move to GAP9 which reduces energy consumption a lot, sending data will be what drains our battery.
- Can’t change this, but the sensor need to be able to withstand the harsh environment.
- Train classifier with more data. Current network has discrete output, maybe move to continuous?
- Input image very big for neural network. Limited standard functions on the processor. Maybe train another localization neural network
- In the future maybe add expansion pack with cable going above surface with antenna and solar cell/power supply?
- Building new data collection facility. Also, investigate the possibility of augmenting data.
  How can we know if the augmented data is realistic?

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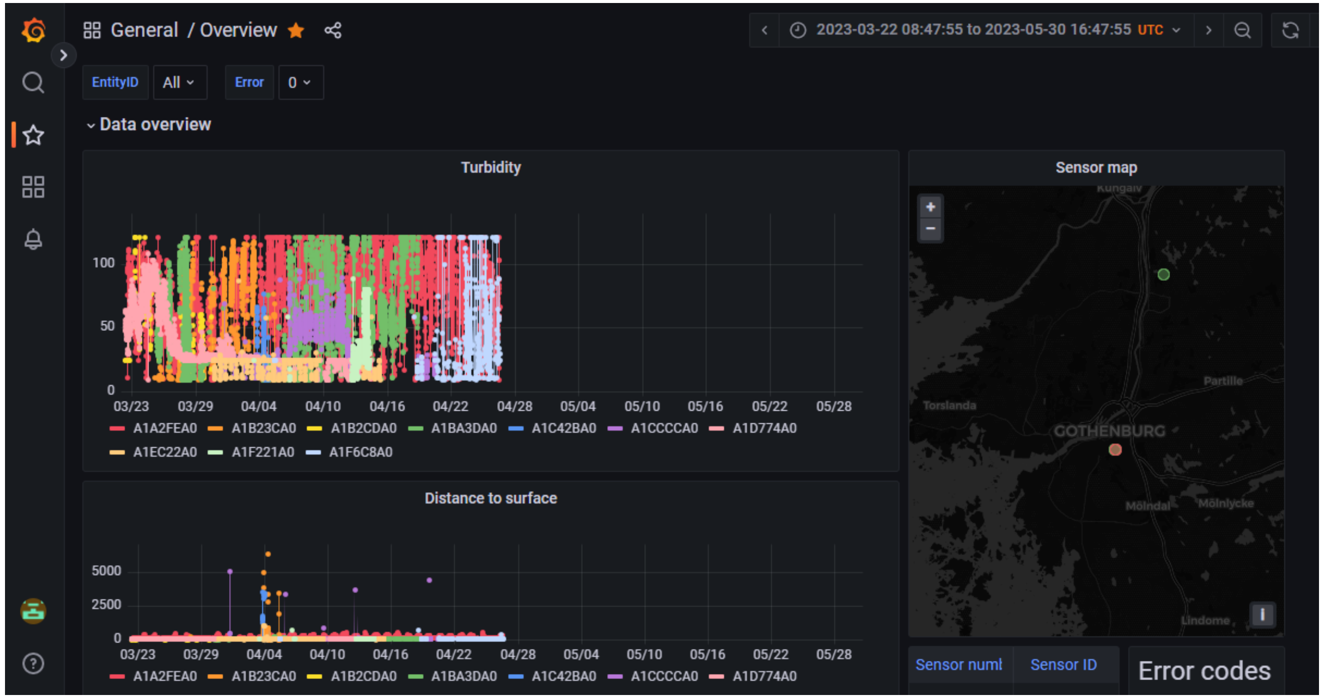
Some remaining topics

- What happens on the receiving end of the NB-IoT communication? The data platform!
- What can we achieve using 1000 Turbinators that all measure turbidity and water level in the stormwater system in a city? A lot!



Thank you!

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