



Norwegian  
Meteorological  
Institute

# Use of satellite measurements for operational forecasting of volcanic ash in norwegian airspace

SAT-VOLC project, Copernicus meeting, 22-10-2020

# Acknowledgements and project participants

## Budget:

- Met.no: 875 knok,
- NILU: 640 knok,
- NRS-midler: 751 knok

## Project participants Met:

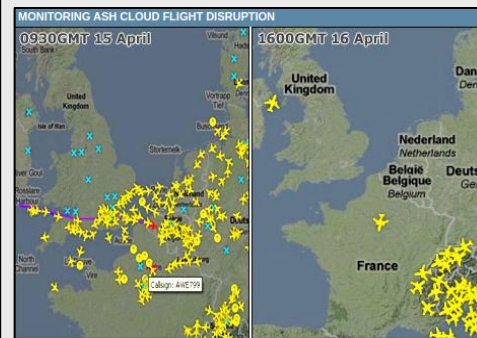
- Hilde Fagerli, Peter Wind, Agnes Nyiri, Heiko Klein, André Brodtkorb, Anna Benetictow

## Project participants NILU:

- Arve Kylling, Espen Sollum

# Problem

- Is it safe to fly?
- Which latitude/longitude?
- Which altitude?
- What time?



Eyjafjallajökull image: Wikipedia user [Árni Friðriksson](#) CC BY-SA 3.0

Satellite image: NASA, public domain

3 Sykefly: Avinor Harstad Narvik Lufthavn

Flight radar: BBC, Volcanic ash: Flight chaos to continue into weekend, Friday, 16 April 2010 21:24 UK

# Estimating ash emissions 1/2

- Uneducated guess
  - “Pick a number based on personal experience”
- Educated guess
  - Look at historic eruptions and try to find a “similar eruption”.
  - Measure deposited ash (on ground - little time information)
  - Measure ash cloud height (planes, radar)
  - Measure air concentrations of ash (air filtering stations)
  - Estimate ash content in atmosphere (satellite images)
  - ...



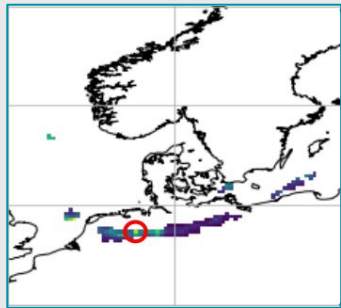
USGS photograph by A. Diefenbach



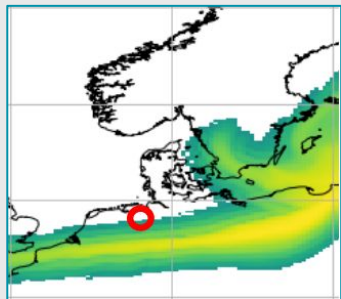
Eyjafjallajökull 2010



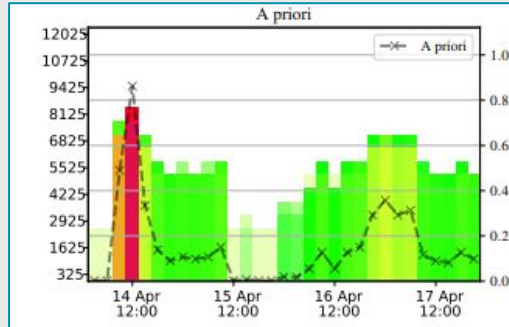
# Source-receptor matrix inversion



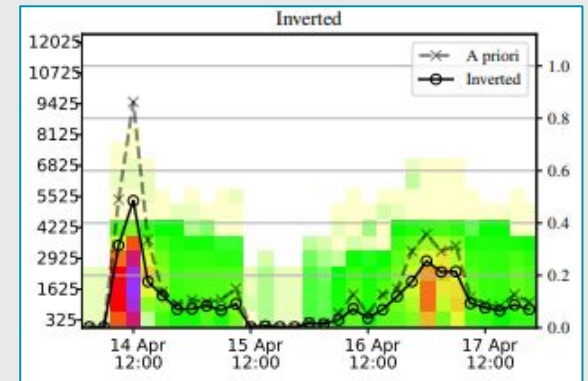
Satellite observations



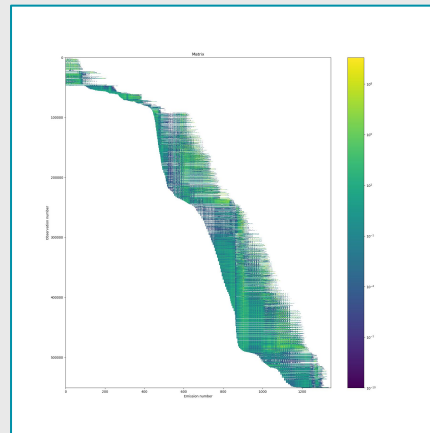
Unit emission simulations



Initial guess (a priori)



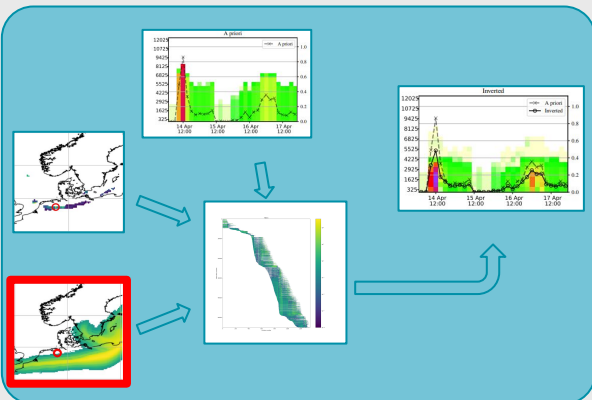
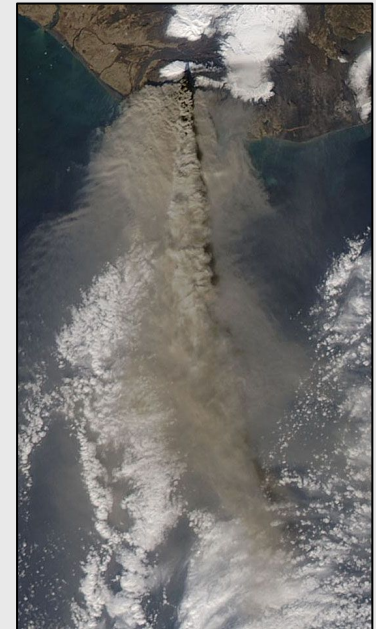
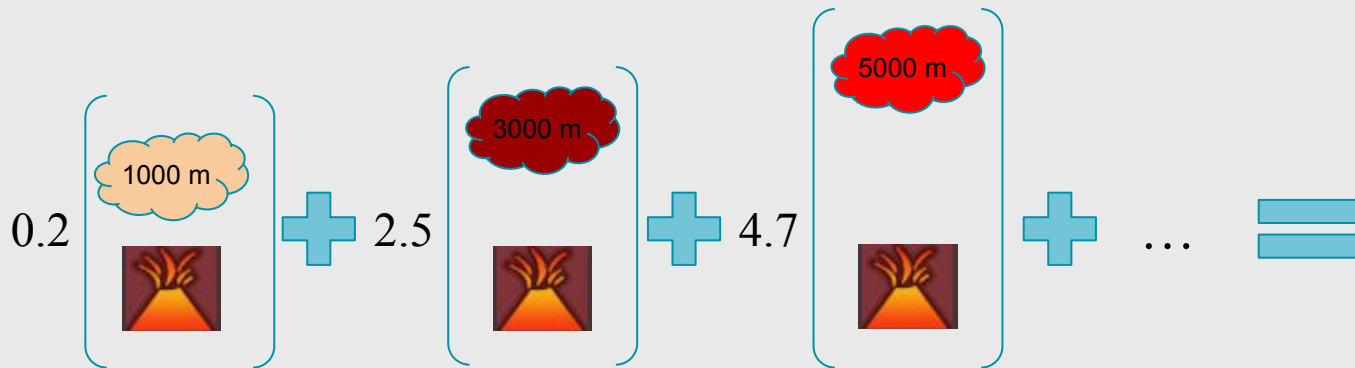
Educated estimate (a posteriori)



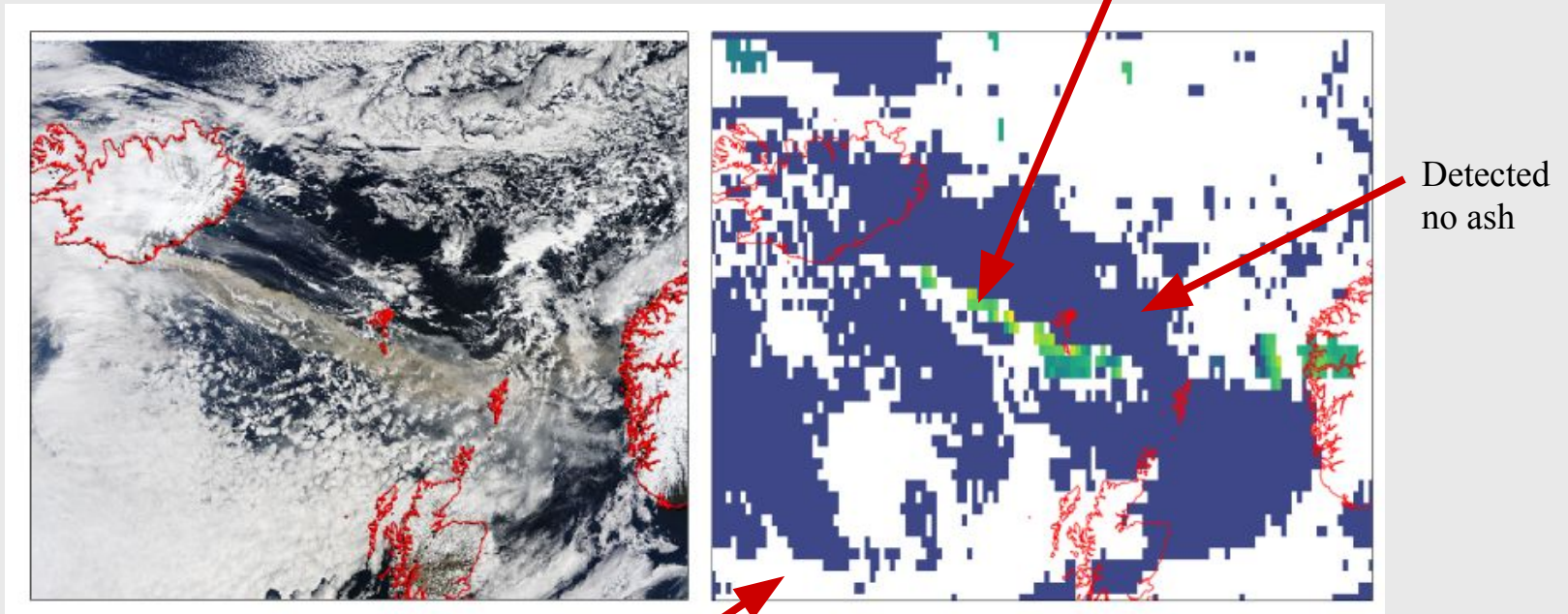
Source-receptor matrix

# Unit emission simulations

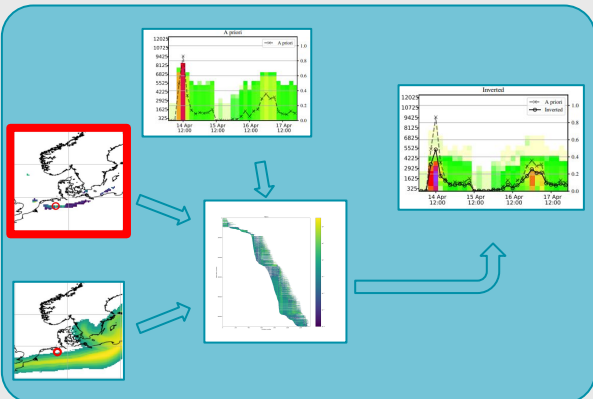
- For each time point: simulate 1 unit of ash emitted at different altitudes
- Find the combination of these emissions that match “best” with the satellite images



# Satellite images 1/2

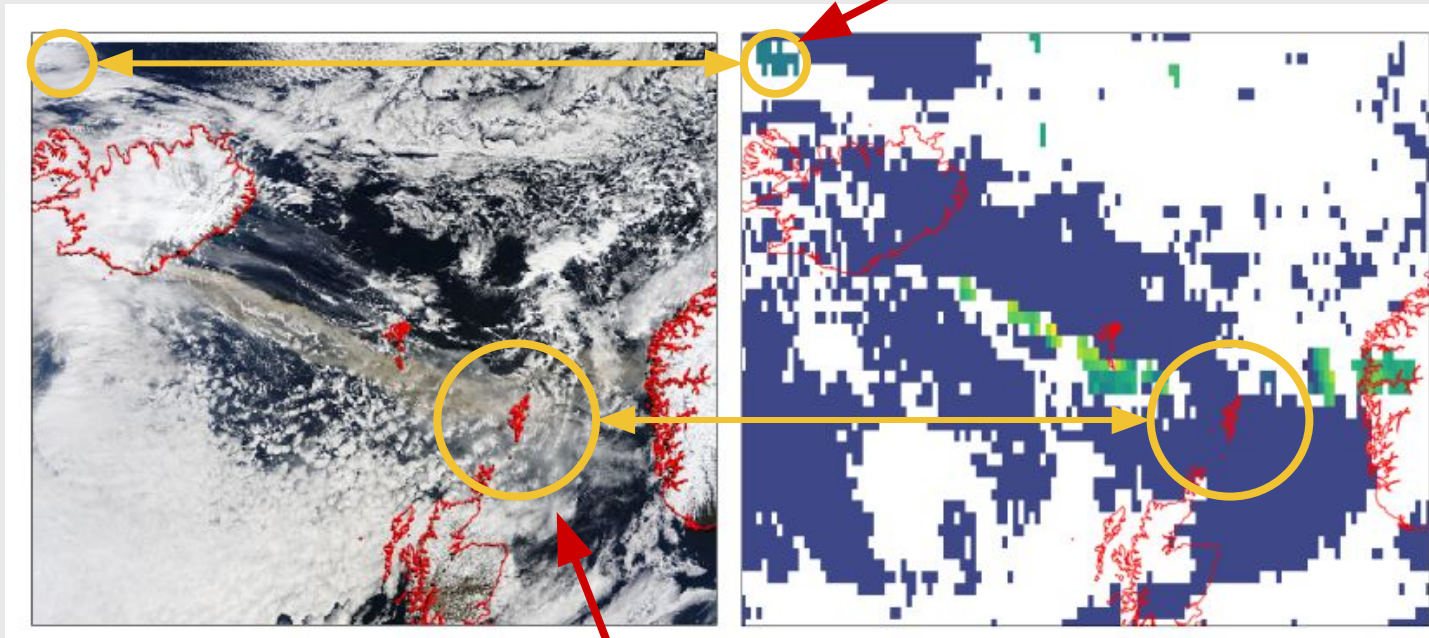


Not sure  
(e.g., clouds)

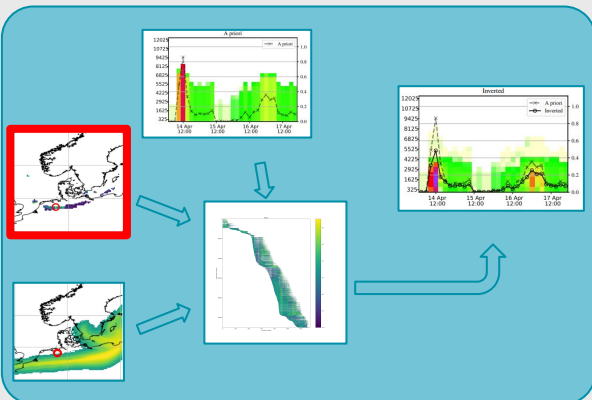


# Satellite images 2/2

False positives?

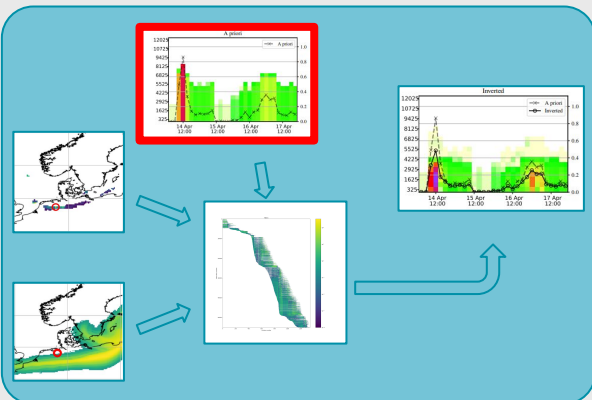
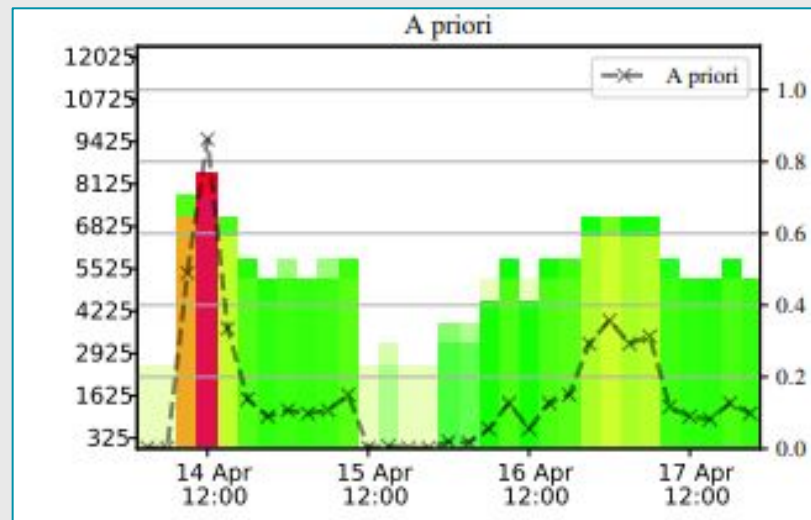


False negatives?



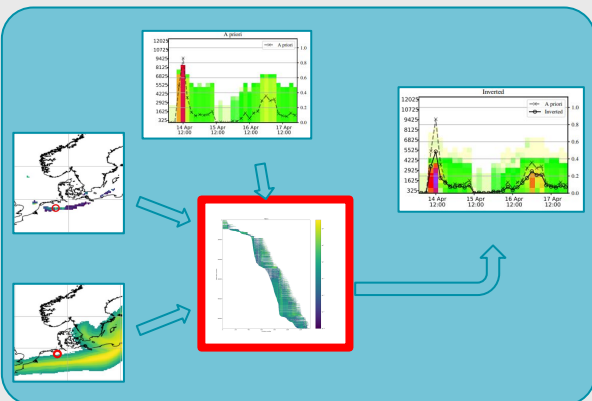
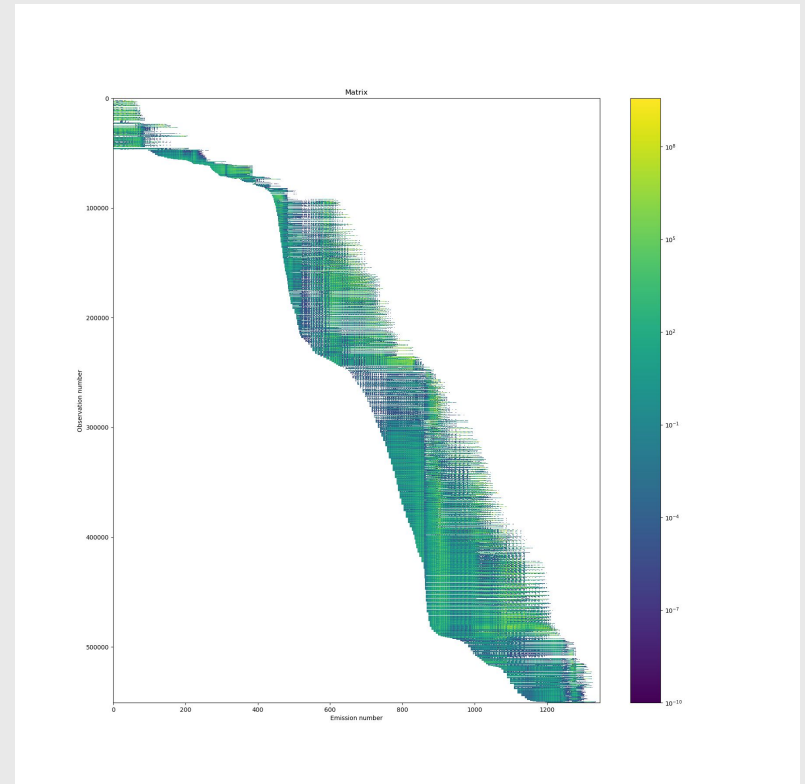
# Initial eruption estimate

- Based on ash cloud top observations and e.g., formula of Mastin et al.



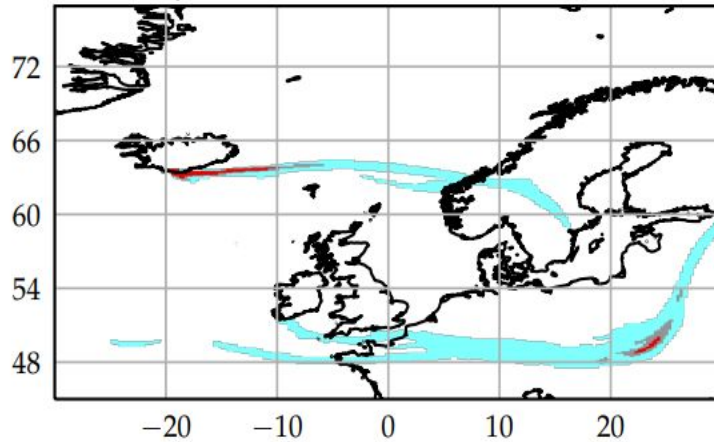
# Source-receptor matrix

- Each row corresponds to one observation
- Each column corresponds to one emission timepoint and altitude
- Millions of observations (around 1000 satellite images)
- Thousands of a priori estimates (around 6000)

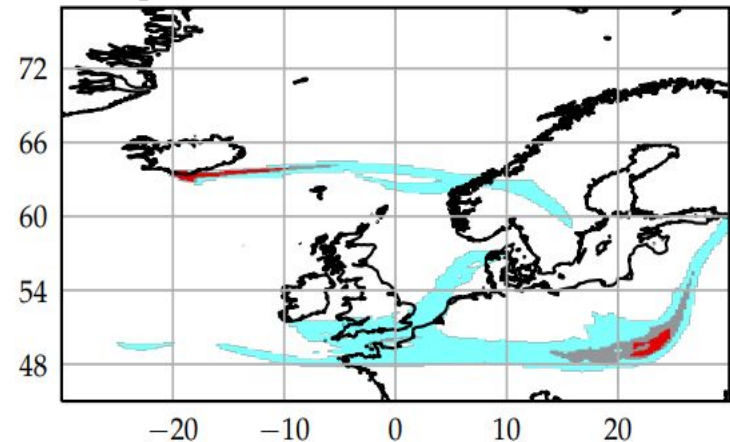


# A posteriori estimate

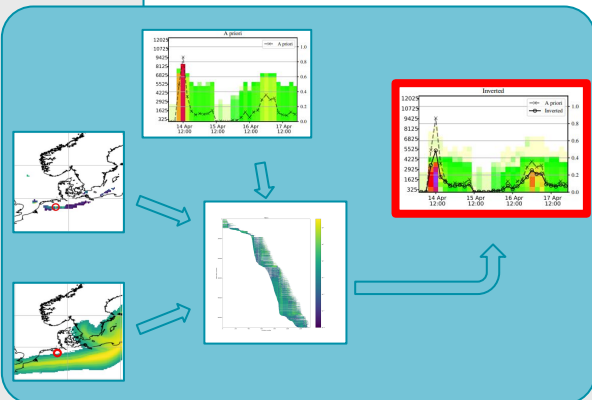
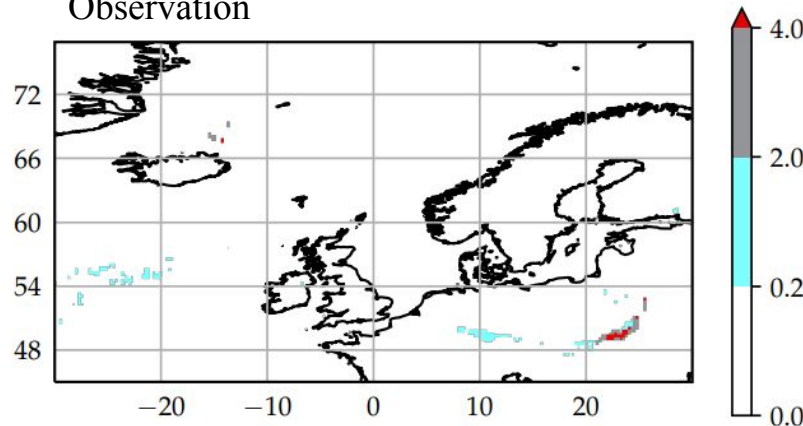
Initial guess



Computed estimate

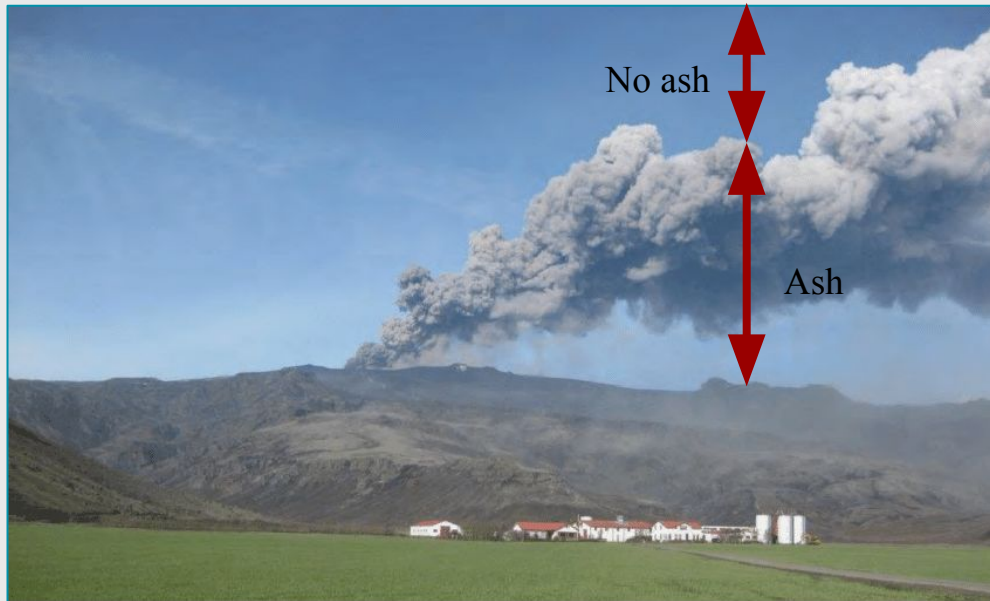


Observation



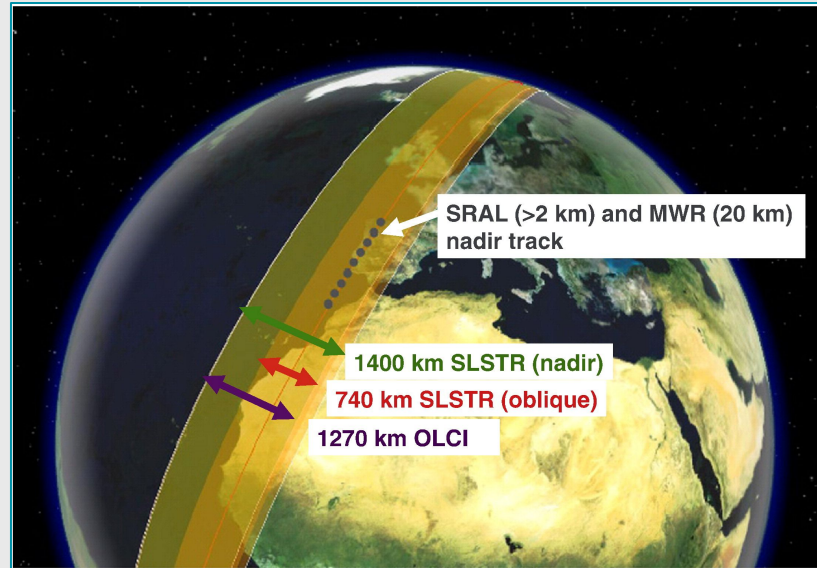
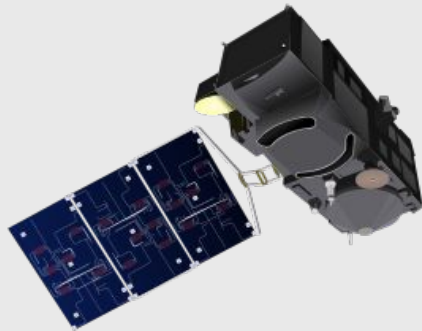
# SAT-VOLC: Altitude information

- Aim of project is to include altitude information from satellite images!
  - Sentinel-3 has the SLSTR instrument which can estimate top of ash cloud
- Elegant approach: Split every observation into two observations
  - Ash up to ash cloud top
  - No ash above ash cloud top



# Sentinel-3 SLSTR instrument

- Launched 2016-02-16
- Lifetime 7 years
- Launch weight: 1250 kg

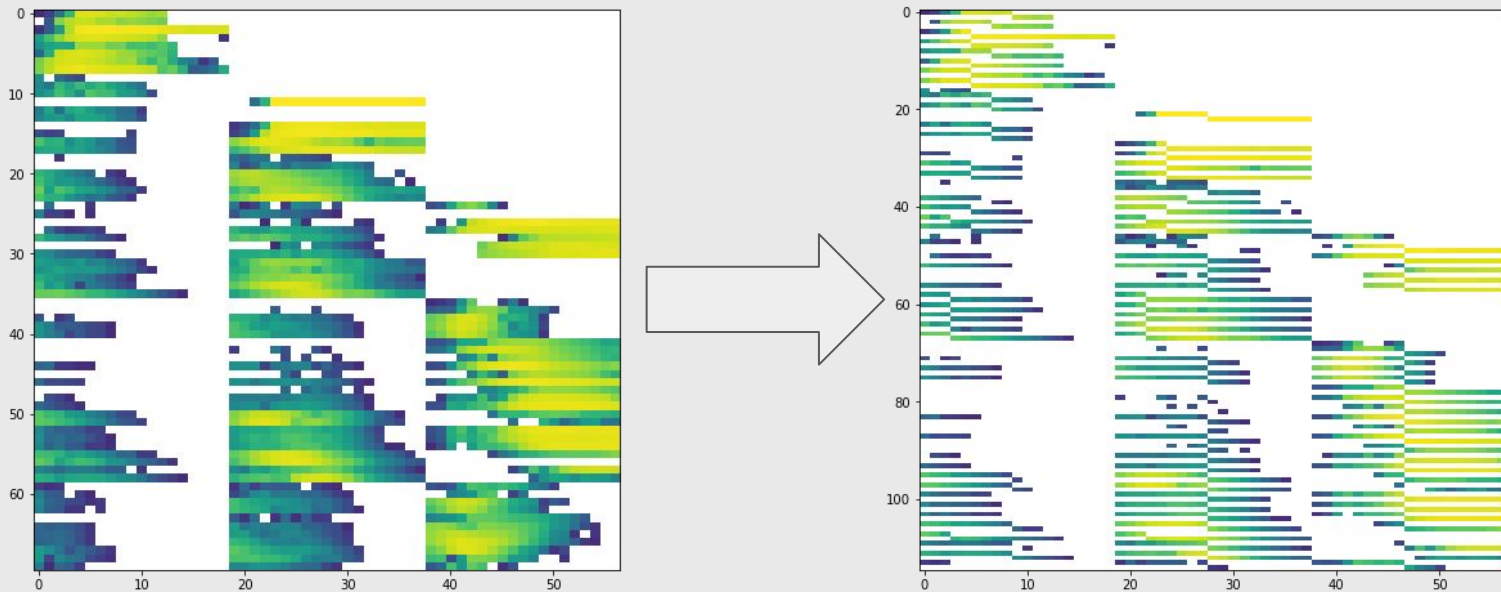


- SLSTR (Sea and Land Surface Temperature Radiometer) will determine global sea-surface temperatures to an accuracy of better than 0.3 K
- SLSTR has dual-view capabilities which can be used to estimate altitude of ash cloud top

Satellite image: User [SkywalkerPL](#) on Wikimedia, CC BY 4.0  
Sentinel-3 swath width image: ESA

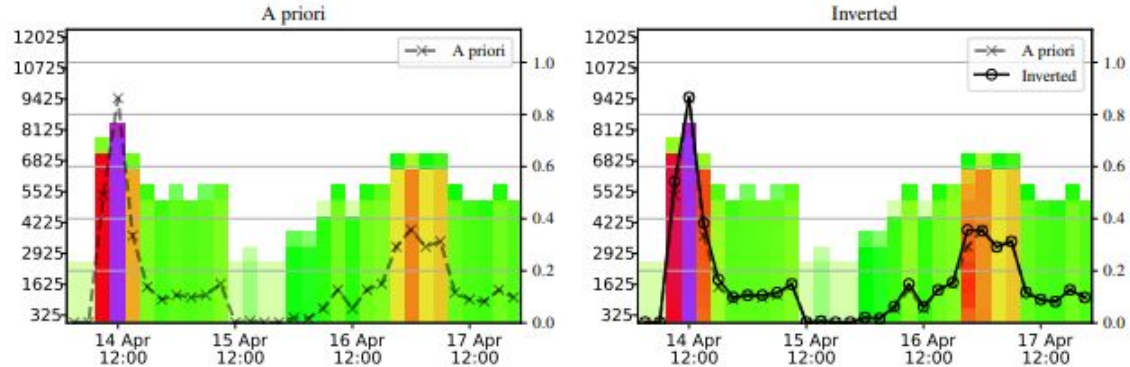
# Add more equations to matrix

- By splitting each observation into ash / no ash, we get two equations per observation

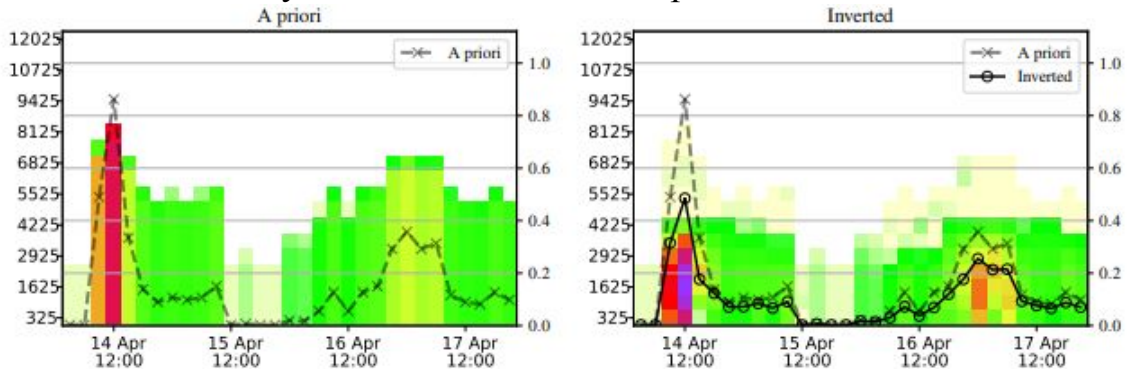


# Results - adding altitude

Altitude = synthetic truth ash cloud top



Altitude = half synthetic truth ash cloud top



# Operational use at Met

- Currently the operational inversion procedure at Met
  - Testing with June 2019 Raikoke eruption ongoing
- Inversion procedure for over 1 month of Eyjafjalla takes around 24-48 hours
  - 5-10 hours to simulate forward runs (on Nebula supercomputer)
  - 56.5 million observations matched with 6061 emissions
  - Corresponds to a matrix of around 72 gigabytes of non-zeroes
  - Clever reformulation stores matrix as a small 6061x6061 matrix
  - Inversion can run on your laptop!
- Smaller cases runs in a few hours.
  - Most time spent on forward simulations

# Results and future work

- Paper on arXiv
  - <https://arxiv.org/abs/2005.09942>
- Sourcecode archived on Zenodo
  - <https://zenodo.org/record/3859884>
- Data archived on Zenodo
  - <https://zenodo.org/record/3855526>
  - <https://zenodo.org/record/3818196>
- RCN proposal submitted!  
Inverse Methods for Accurate Source Term Estimation
  - NILU and Met UK involved
  - Researcher project

**IMASTE**  
Inverse methods for accurate source term estimation

André R. Brodtkorb<sup>a</sup>, Arve Kylling<sup>a</sup>, Erik Berge<sup>a</sup>, Sabine Eckhardt<sup>a</sup>, Nikolaos Evangelou<sup>a</sup>, Heiko Klein<sup>a</sup>, Magnus Ulmøen<sup>a</sup>





Figure 1: Volcanic eruptions and nuclear accidents can severely impact society. The Eyjafjallajökull eruption in 2010 shut down the European airline traffic immediately, and the Fukushima nuclear accident will continue to affect the surrounding area in years to come. Knowing what and where emissions come from is essential to protect people and infrastructure.

**Problem:** Atmospheric dispersion is challenging, but today's operational dispersion models are capable of creating high quality predictions given high quality input. It is important to track and make predictions for ash from volcanic eruptions and (accidental) release of radionuclides into the atmosphere. Unfortunately the models are only as good as the input data, and determining the true emission from real-world observations remains an unsolved problem.

**State of the art:** It is possible to estimate emissions from a volcano based on high quality satellite images of the ash plume and a sufficiently accurate description of the atmospheric winds. Unfortunately, we know that satellite images contain significant amounts of noise and that weather forecasts are inaccurate. This means that the inversion procedures being used operationally only provide reliable estimates of the emissions under certain favourable conditions. For radionuclide emissions current state-of-the-art approaches focus on estimating source location, whilst source activity and uncertainty remains an open question. Inversion routines that work well with academic test cases exist, but these are currently not able to handle real-world data with uncertainties.

**Project approach:** We will develop new formulations of the inversion problem that are less sensitive to errors in meteorological input data combined with exploitation of so-called local fraction simulations. Local fractions can enable simulation of thousands of emissions in the same time a single run takes today, which will enable us to simulate with ensemble meteorology to accurately describe the uncertainties of our predictions as well as significantly improve forecast skill. As any inversion formulation is only as good as the data you feed it, we will use state-of-the-art machine learning techniques to filter and remove false positives and negatives in satellite images of volcanic ash. We will further develop this methodology to address the more challenging radioactive emission scenarios with fewer observations and possibly moving emission sources. The project is an interdisciplinary effort that requires expertise from applied mathematics, meteorology, physics, statistics, and high-performance computing.

**Estimating volcanic ash columns and inversions**

André R. Brodtkorb<sup>1</sup>, Anna Benedicte Valdebenito<sup>2</sup>

<sup>1</sup>The Norwegian Meteorological Institute  
<sup>2</sup>NILU - Norwegian Institute for Air Research

This paper describes the inversion procedure for estimating ash emission rates from retrieval observations. The procedure consists of five stages: (1) general observations; (2) collocation/match observations to solve overdetermined system. We go through it for synthetic cases, and performance for real-world system of equations used in the inversion and used in this work is freely available under an open license.

**1 Introduction**

Determining ash emissions during a volcanic eruption and volcanic ash transport in the atmosphere. There are ground sightings, plane/helicopter sightings, and satellite images may give spatial extent of the volcano. The plume height observations can help however, this approach may not provide a realistic procedure attempts to remedy this by using satellite better ash emission estimate.

The main idea of the ash emission estimation is to use a set of forward simulations with unit emission that best matches the observed ash locations and heights for sulphur dioxide emission, see e.g., [2, 3] and [4] for determination for the Eyjafjallajökull 2011 eruption. This work extends the approach to also incorporate ash cloud height as an observation in the inversion. The manuscript is organized as follows: In Section 2 the theory behind the inversion procedure is outlined. The atmospheric dispersion model is described in section 3. The synthetic benchmark cases and real-world cases are described in sections 4 and 5, respectively. The paper is summarized in section 6.

**2 Mathematical formulation**

We base our inversion procedure on the approach taken by [2], and adopted to ash emission by several authors (see e.g., [5] and the references therein). The inversion procedure is based upon creating a so-called source-receptor matrix,



Norwegian  
Meteorological  
Institute