Orchestrating low-frequency VLBI on LOFAR scales

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Setting the scene

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REVIEW

A decade of sub-arcsecond imaging with the International LOFAR Telescope

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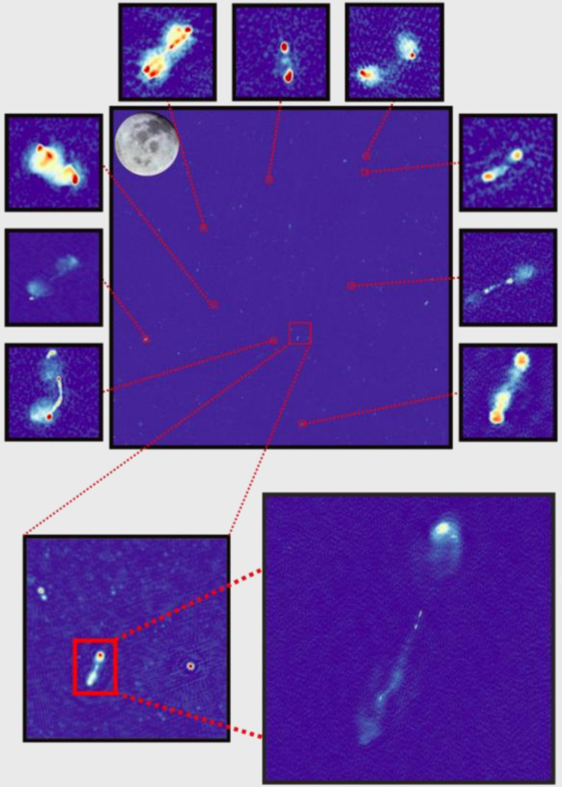
Abstract
The International LOFAR Telescope (ILT) is a pan-European radio interferometer with baselines up to 2000 km. This provides sub-arcsecond resolution at frequencies of <200 MHz. Since starting science operations in 2012, the ILT has carried out observations for the state-of-the-art LOFAR Two-metre Sky Survey, which has 6 arcsec resolution at 144 MHz. Wide-area surveys at low frequencies, while scientifically productive, have to compromise on resolution. Sub-arcsecond imaging with the ILT has become more accessible over the last decade, thanks to efforts to build a publicly available pipeline using LOFAR-specific tools, which has resulted in a dramatic increase in the number of publications. The ILT's combination of resolution, field of view, and low observing frequency make it a unique instrument for a wide range of scientific applications, and it will remain unparalleled even in the era of the Square Kilometre Array Observatory. Here we provide an overview of the technical considerations and calibration methods sub-arcsecond imaging with the ILT. This is followed by a review of the unique capabilities unlocked by sub-arcsecond imaging with the ILT, using examples from the literature for demonstration. Finally we describe ongoing work including: surveying large areas of the sky at high resolution, going deeper in fields with excellent ancillary information, producing images of polarisation, and extending to lower frequencies (<100 MHz).

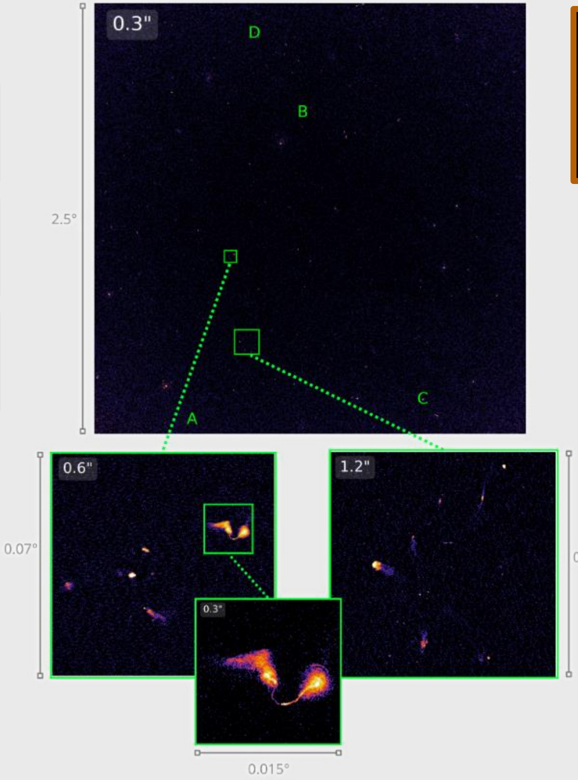
Keywords Radio astronomy · Extragalactic · High-resolution imaging · Radio surveys

Setting the scene

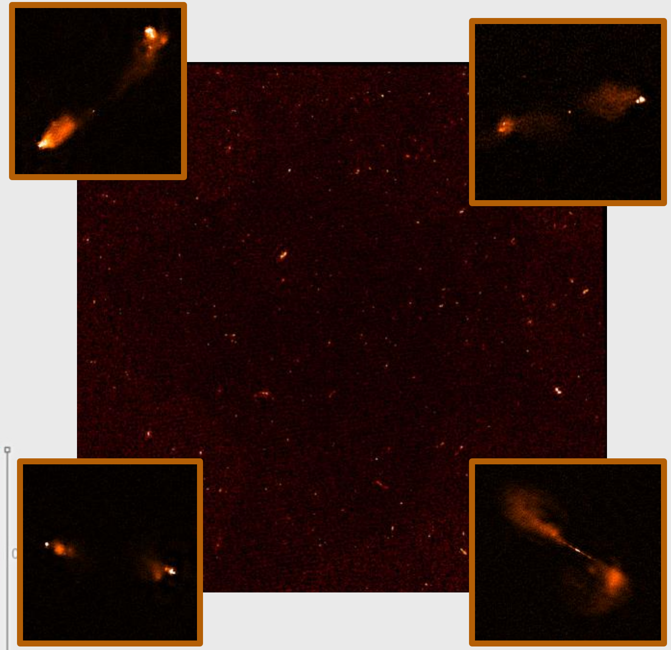
Sweijen et al. 2022



de Jong et al. 2024



Escott et al. subm.



Outline

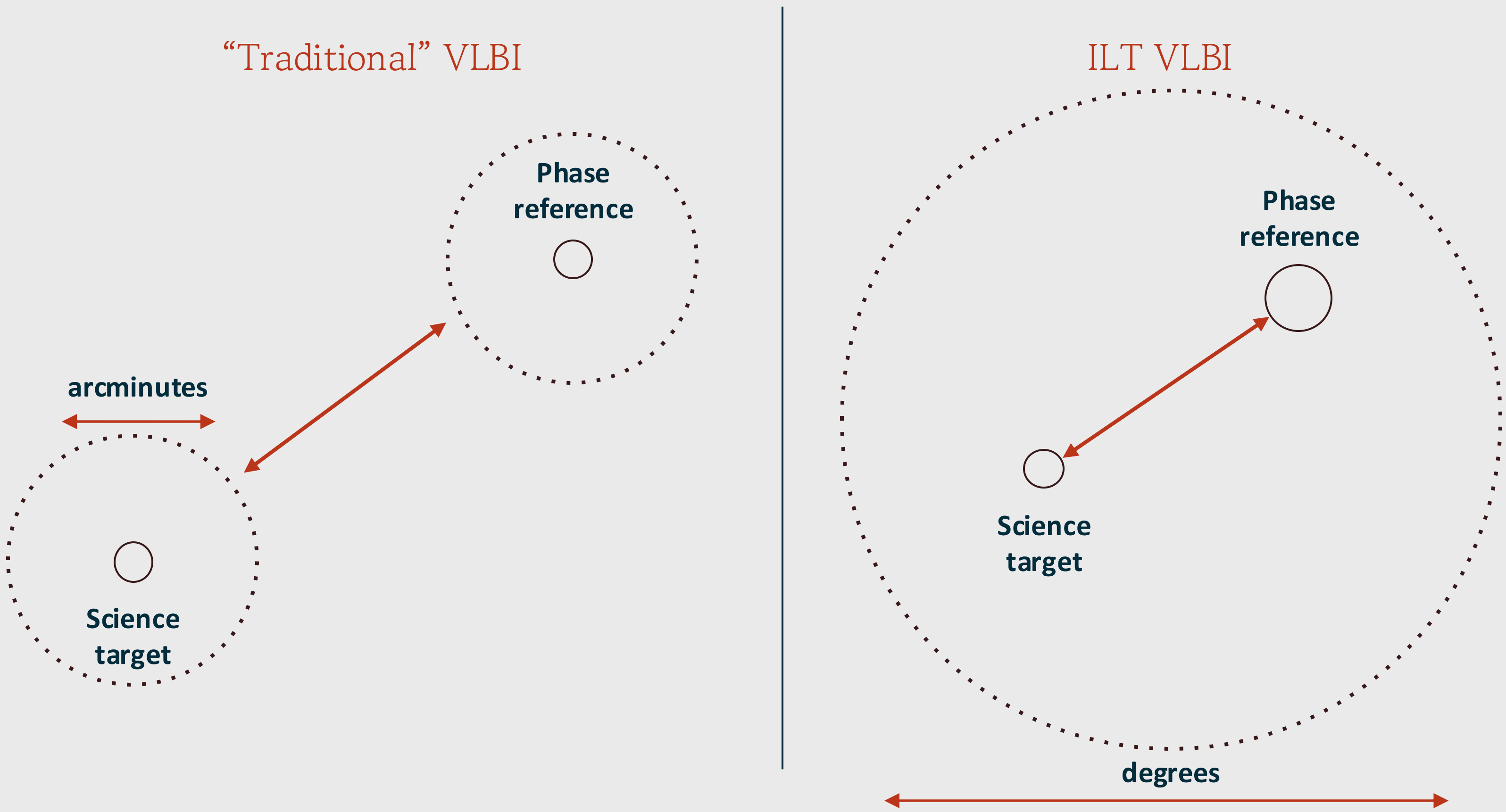
VLBI with the International LOFAR Telescope

Orchestration with the Common Workflow Language

PILoT: an end-to-end ILT VLBI pipeline

Future outlook & developments

VLBI with the International LOFAR Telescope



VLBI with the International LOFAR Telescope

"Traditional" GHz VLBI

Phase errors dominated by **tropospheric and instrumental** effects

Calibration is interpolated between science target and phase reference

Time and bandwidth **smearing is limited** due to always pointing on-source

Baseline coverage tends to be sparse -> very **restricted spatial scales** covered

ILT VLBI

Phase errors dominated by **dispersive ionospheric** effects

Calibration matches 1:1 between science target and phase reference

Time and bandwidth **smearing set by data averaging** (i.e. your storage capacity)

Spatial **scales from ~1 deg to 0.3 arcsec** sampled with a single observation

VLBI with the International LOFAR Telescope

8 hour synthesis

1 s integration time

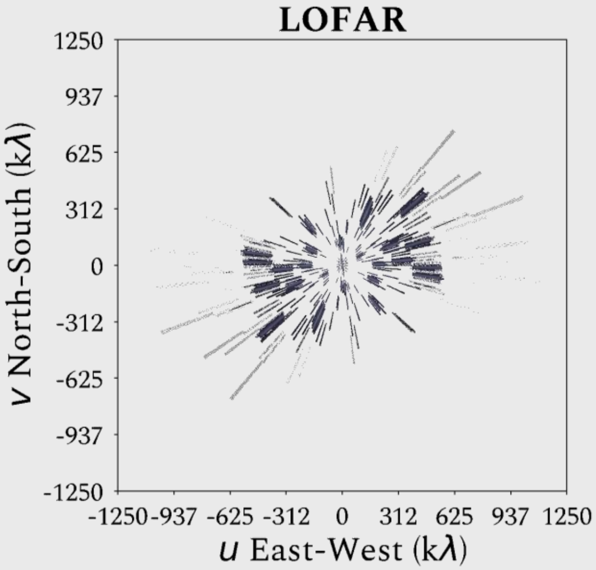
120-168 MHz

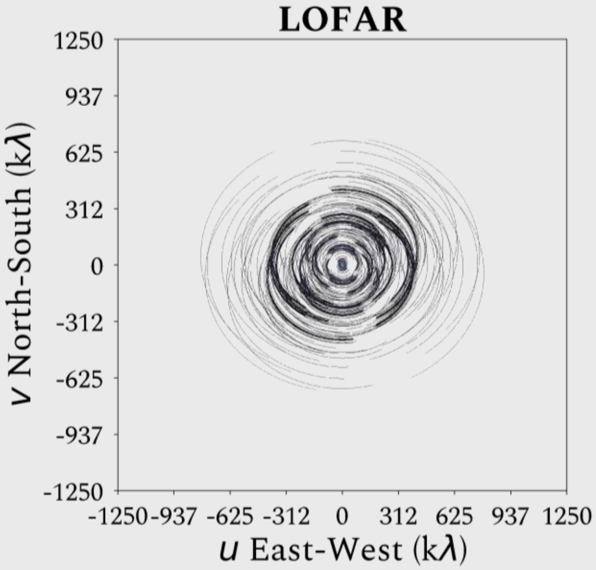
12.205 kHz channel resolution

~240 subbands of 195kHz

5 TB per observation

~6,000 observations needed (northern hemisphere)





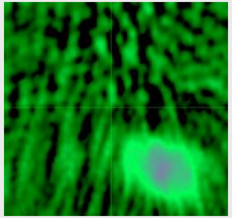
Dear Frits,

You are using 229.76% of your quota.

VLBI with the International LOFAR Telescope

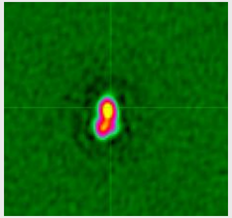
Systematics and Dutch calibration 5 TB

- Polarisation alignment, clock offsets and bandpasses for **all stations**
- Direction-dependent calibration of full NL-station FoV for NL stations
- High quality, deep 6” resolution sky image



Primary “delay” calibration 5 TB

- Bright (>0.1 Jy) compact source to correct **bulk ionosphere**, **primary beam variations** and **astrometry + polarisation** (where possible)
- Self-calibration, no fringe fitting*



Direction dependent calibration 20-50

- Faint (>0.025 Jy) secondary sources to correct **differential ionosphere and primary beam variations**
- Calibrators form Voronoi tesselation for facet imaging

Imaging ~400 GB per facet

- ~1-2” intermediate resolution image (~1.5 GB)
- ~0.6” intermediate-high resolution image (~10 GB)
- ~0.3” high-resolution image (~40 GB)

Large-scale orchestration

Managed clusters for distributed processing (e.g. Slurm)

- Parallelise over frequency chunks
- DD calibrators can be treated independently
- Facets can be imaged independently

Open standards for defining pipelines

- Decouple software from pipelining
- Easier integration with schedulers like Slurm
- Industry support

Common Workflow Language

A **declarative language** to describe inputs and outputs of "steps"

Per-step resource requirements

Supports containerised execution (Docker or Apptainer)

Used across many science areas

Open standard

```
class: CommandLineTool
cwlVersion: v1.2
id: aoflagging
label: AOflagger
doc: Runs the AO-flagging module of DP3.

baseCommand: aoflagger

inputs:
  - id: msin
    type: Directory
    inputBinding:
      position: 0
    doc: Data to be processed in MeasurementSet format.
outputs:
  - id: msout
    doc: Output MeasurementSet.
    type: Directory
    outputBinding:
      glob: $(inputs.msin.basename)
requirements:
  - class: InitialWorkDirRequirement
    listing:
      - entry: $(inputs.msin)
        writable: true
  - class: ShellCommandRequirement
  - class: InlineJavascriptRequirement
  - class: ResourceRequirement
    coresMin: 6
    ramMin: $(inputs.memory)

hints:
  - class: DockerRequirement
    dockerPull: vlbi-cwl

stdout: aoflag.log
stderr: aoflag_err.log
```

COMMON WORKFLOW LANGUAGE

An end-to-end pipeline

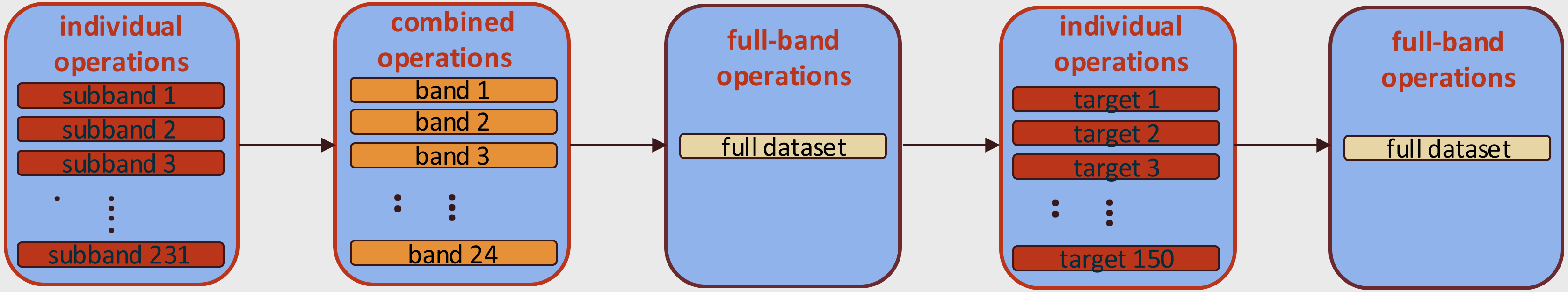
PILOT - Pipeline for the **I**nternational **LO**FAR **T**elescope
https://github.com/LOFAR-VLBI/VLBI-cwl
van der Wild in prep.

Common Workflow Language as “definition glue”

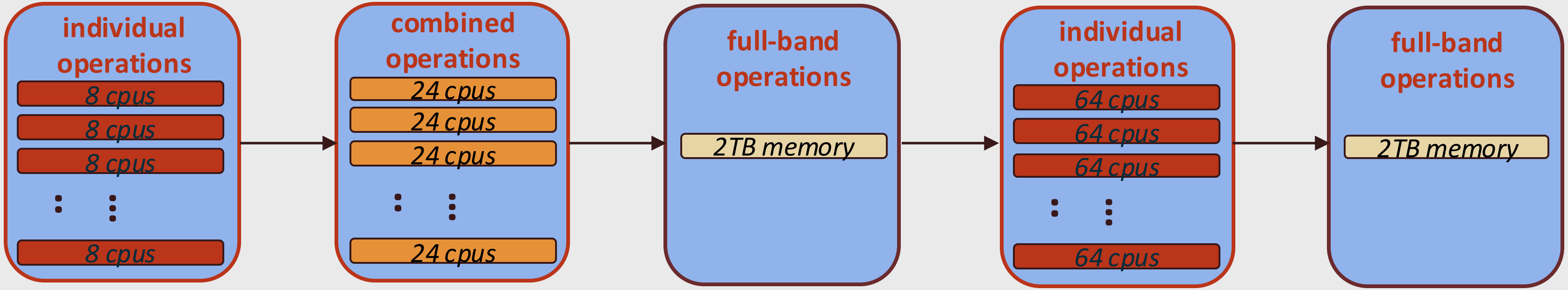
Toil CWL runner for easy exploitation of Slurm clusters

Common Workflow Language

Varying levels of parallelism throughout processing



Individual resource requirement can be scheduled efficiently with Toil



Large-scale orchestration

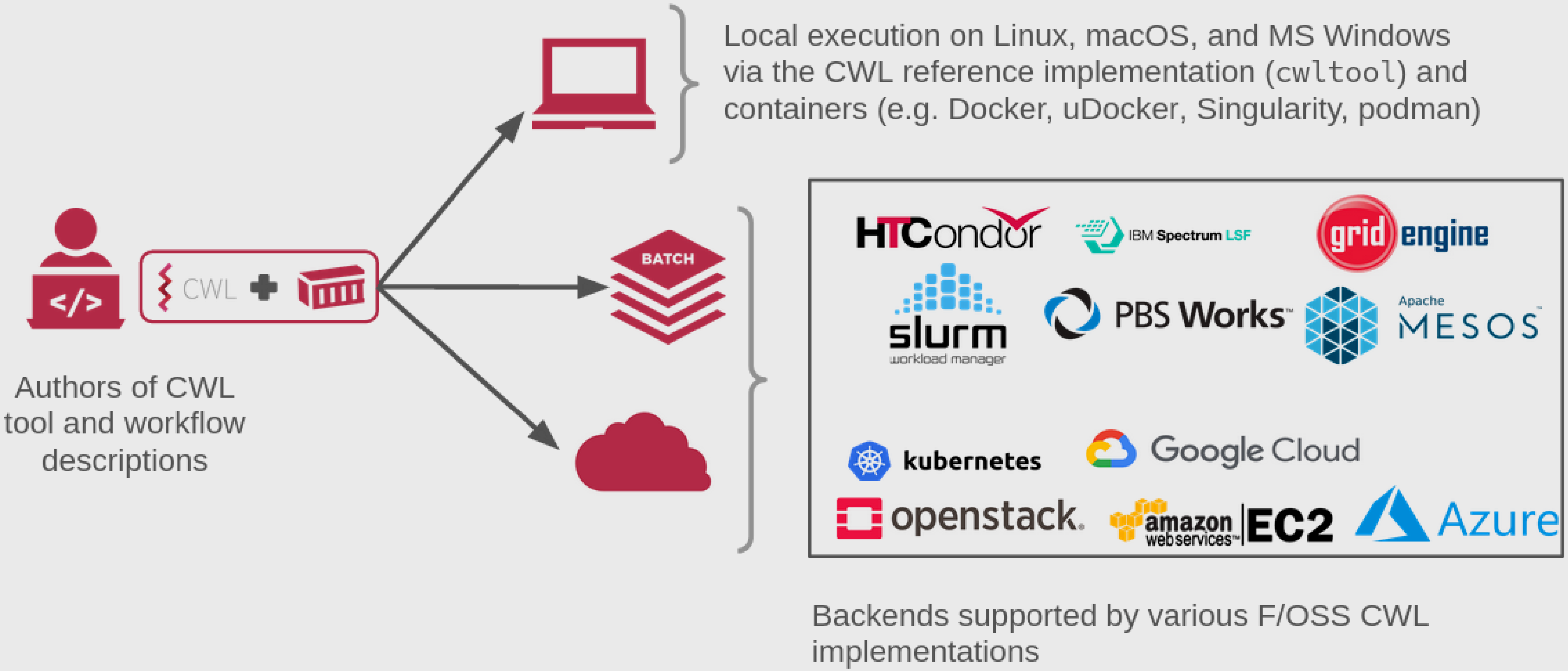
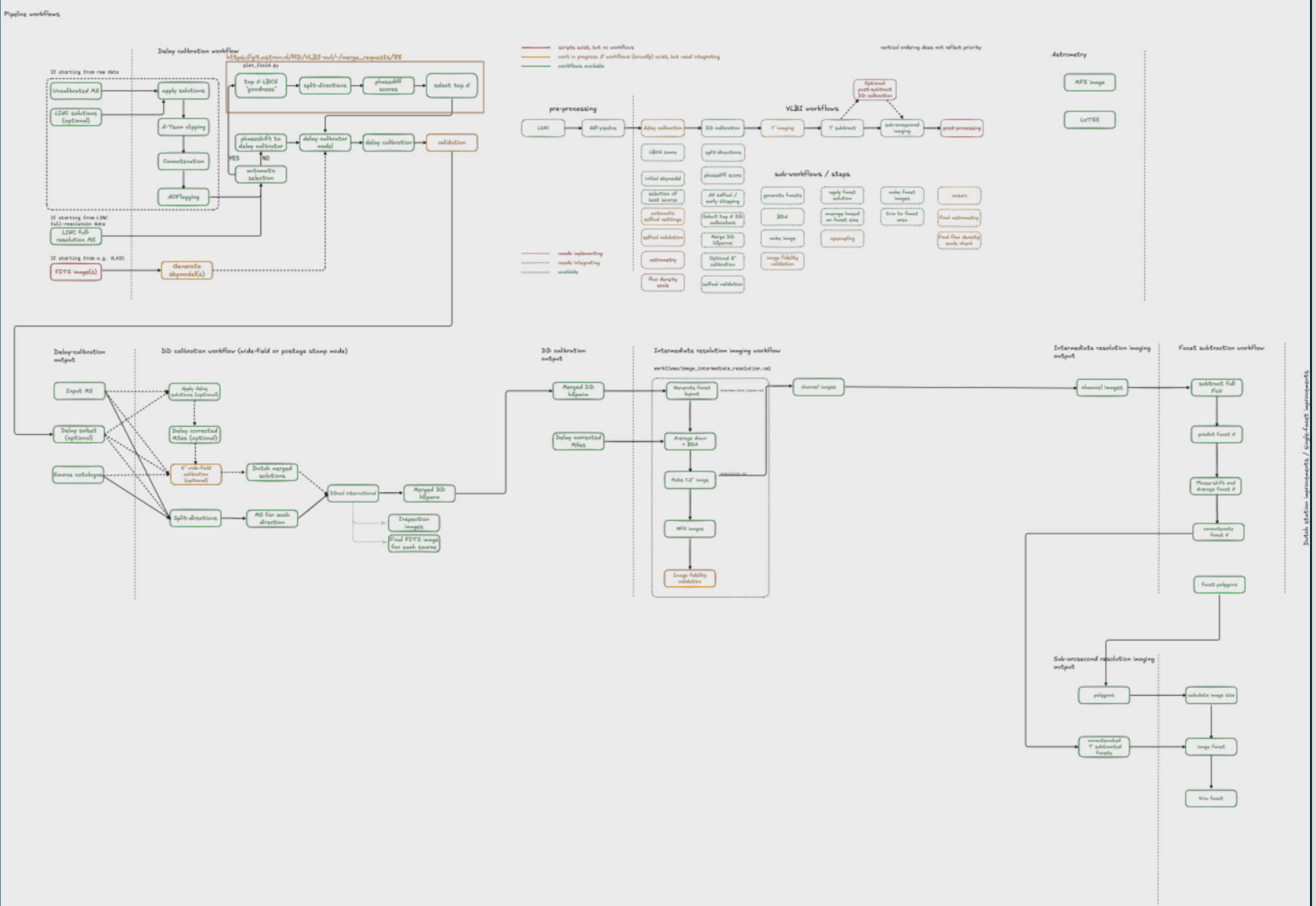


Image credit: CWL documentation

but.... it's complicated and expensive!



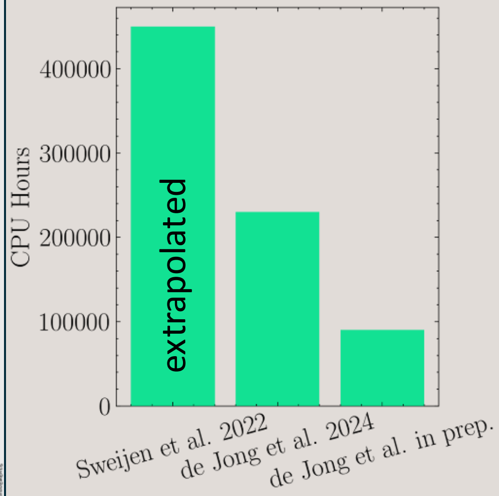


Image credit: Jurjen de Jong

120,000 core hours per observation is still **156 days on 32 cores!**

Furter optimisation still needed

Summarising & what's next?

This talk

- ILT VLBI pipeline is rapidly stabilising as an end-to-end pipeline
- Efficient resource usage with CWL and Toil

What's next?

- Profiling and optimisation: processing is **stable and manageable**, but still **computationally expensive** (see also next talk by Jurjen)
- Italy and Bulgaria stations will join with LOFAR2.0, creating baselines up to **2700 km**
- LoTSS-HR: postage-stamp imaging of >10 mJy LoTSS sources
- iLoTSS: full FoV imaging high-resolution counterpart to LOTSS
- LOFAR2.0 Ultra-Deep Observation: ~3000 hours ILT imaging on EDF-N region

Thank you. Questions?

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