Writing and understanding VLBI observation schedules

Matthias Schartner
ETH Zurich

12th IVS Technical Operations Workshop (TOW 2023)

Agenda

- Basics
  - What is a VLBI schedule
  - Optimization problem
- Models and Concepts
  - Sky-coverage
  - Cable wrap
  - Horizon mask
  - Scan length
  - Antenna sensitivity
  - Source brightness
- Examples
  - Intensive
  - 24-hour
- Algorithms
  - Schedule generation
  - Subnetting
  - Tagalong mode
  - Fillin mode
  - Extend observation time
- Schedule evaluation
  - Simulations
- VGOS scheduling

Agenda

self-study ☺

- Basics
  - What is a VLBI schedule
  - Optimization problem
- Models and Concepts
  - Sky-coverage
  - Cable wrap
  - Horizon mask
  - Scan length
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  - Source brightness*
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- Algorithms
  - Schedule generation*
  - Subnetting
  - Tagalong mode
  - Fillin mode*
  - Extend observation time*
- Schedule evaluation*
  - Simulations*
- VGOS scheduling*

* skipping in the interest of time

Limit talk to max 25 minutes

Basics

What is VLBI Scheduling?

- Very Long Baseline Interferometry (VLBI)
  - two telescopes have to observe the same source simultaneously to derive an “observation”
    → coordinate observations
    → provide observing plan
    → “schedule”

- VLBI scheduling
  - generation of such an observing plan
  - can be seen as an advanced **optimization problem**
  - determines observations available during analysis
    → important task

What is a VLBI schedule?

Basically a text file containing all necessary information for the stations and the correlator to observe and correlate a session

- list of all scans in a session
- information about how to observe the scans (observing mode)
- parameters to reproduce schedule
  - scheduling parameters
  - antenna information
  - source information

Different formats exist:

- .skd file https://ivscc.gsfc.nasa.gov/IVS_AC/sked_cat/SkedManual_v2018October12.pdf → stations
- .vex file https://vlbi.org/vlbi-standards/vex/ → correlator
- .vex2 file https://safe.nrao.edu/wiki/bin/view/VLBA/Vex2doc

What do we need to generate a schedule?

- Information regarding the scheduled session (start time, network…) → IVS schedule master
  https://ivscc.gsfc.nasa.gov/sessions/

- Information regarding participating stations
- Information regarding observed sources
- Information regarding observation mode

→ catalogs
https://github.com/nvi-inc/sked_catalogs

- Scheduling software
  - sked https://ivscc.gsfc.nasa.gov/IVS_AC/IVS-AC_data_information.htm
  - sched https://science.nrao.edu/facilities/vlba/docs/manuals/propvlba/sched
  - pysched https://github.com/jive-vlbi/sched
  - VieSched++ https://github.com/TUW-VieVS/VieSchedpp
  - sur_sked http://astrogeo.org/sur_sked/
  - …

Terminology

self-study ☺

- **Session:** VLBI experiment

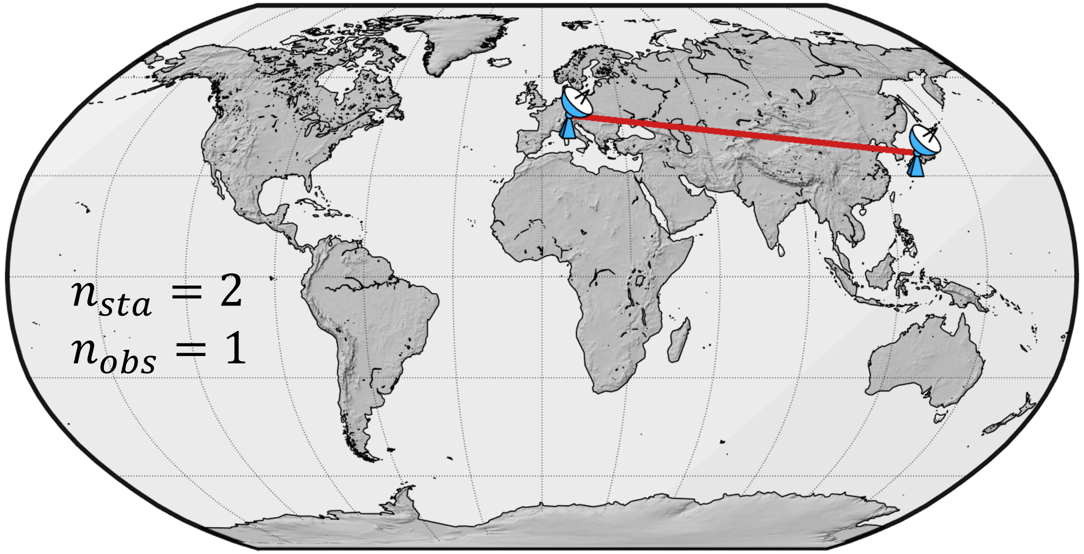
- **Station:** A given VLBI antenna/telescope together with all the electronics and recording equipment
- **Network:** All participating stations within a VLBI session

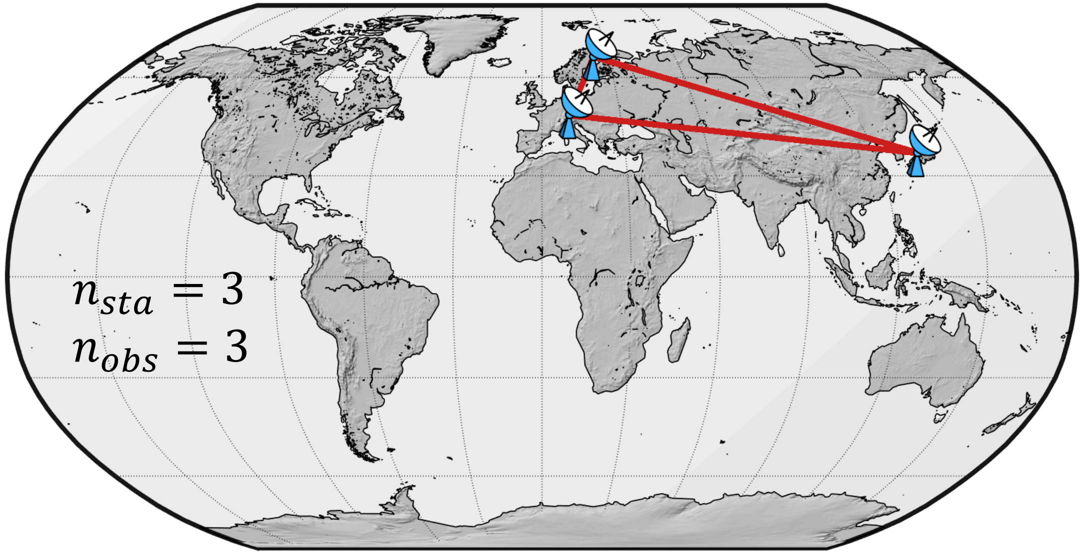
- **Source:** Something that is observed by VLBI
  Usually an AGN (quasar), but could also be satellites or spacecrafts
- **Source list:** All available sources that could potentially be scheduled in this session

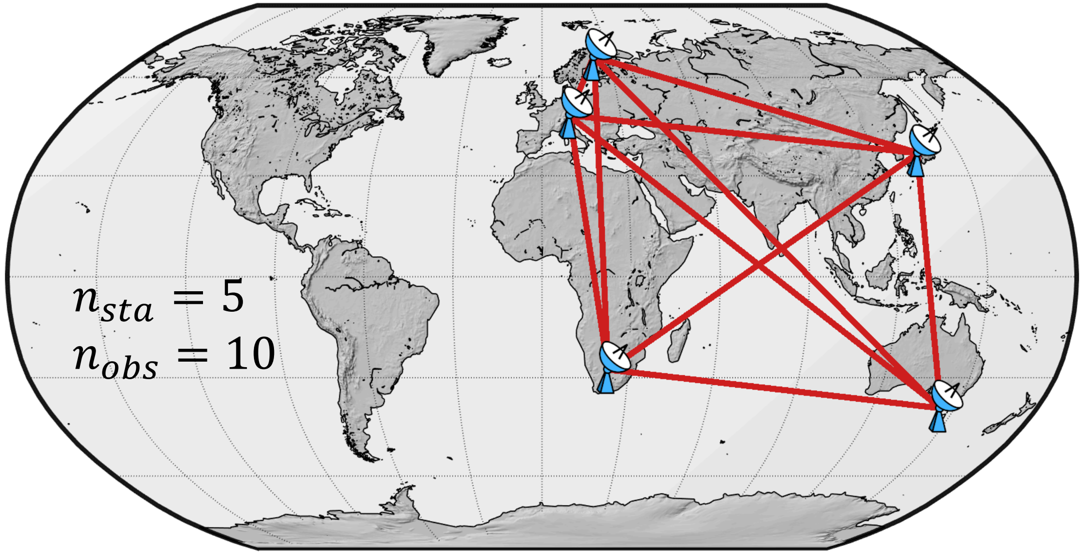
- **Scan:** Two or more VLBI stations simultaneously observe the same source
- **Observation:** The result of cross-correlating the signal from two VLBI stations within a scan

Number of observations per scan

self-study ☺



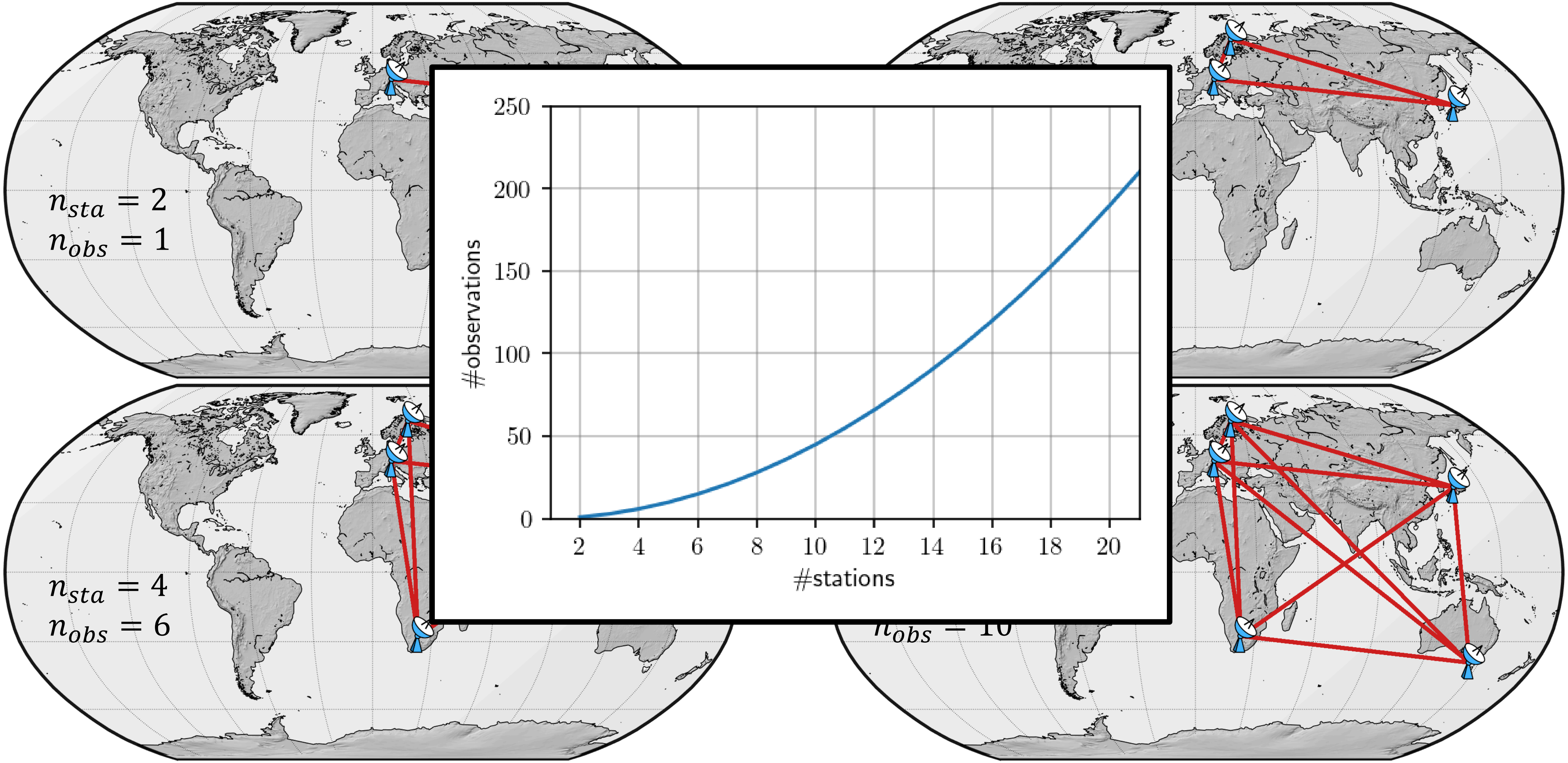




Number of observations per scan

$$n_{obs} = \frac{n_{sta} \cdot (n_{sta} - 1)}{2}$$

self-study ☺



VLBI Sessions

self-study ☺

24-hour sessions

characteristics

- 24-hours long
- (global) network of 8-20+ stations

Objectives

- Earth orientation parameters (EOP)
- Terrestrial reference frame (TRF)
- Celestial reference frame (CRF)
- geophysical models
- source imaging…

Intensive sessions

characteristics

- 1-hour long
- mostly 2-3 stations (up to 5)

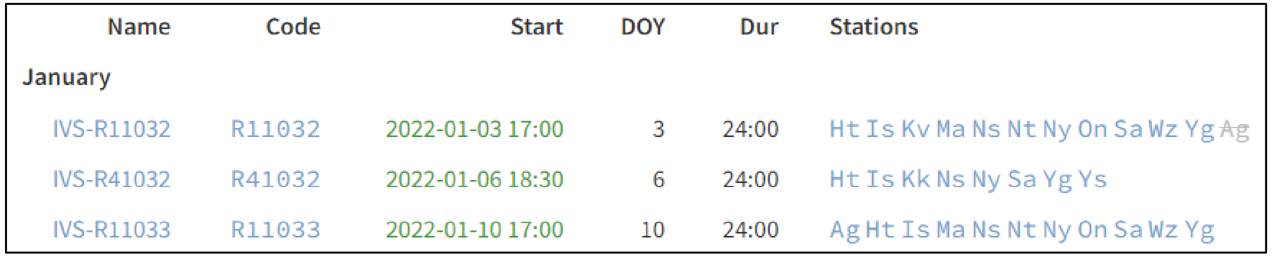
Objectives

- rapid determination of UT1-UTC

Scheduling is an optimization problem

What you have:

- session (time…)



Name	Code	Start	DOY	Dur	Stations
January					
IVS-R11032	R11032	2022-01-03 17:00	3	24:00	Ht Is Kv Ma Ns Nt Ny On Sa Wz Yg ~~Ag~~
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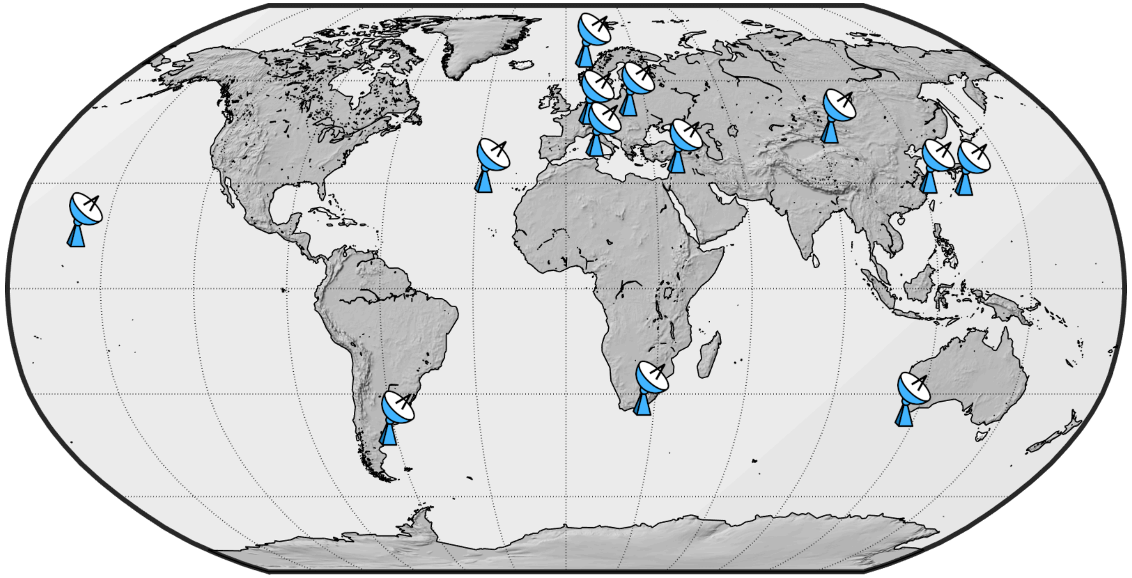

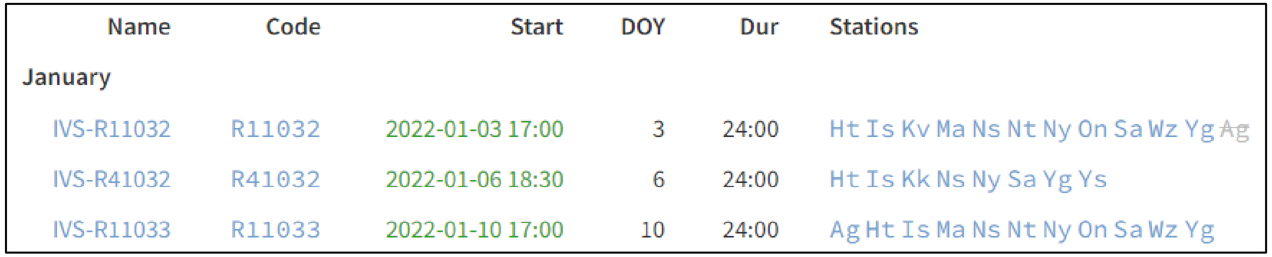

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Scheduling is an optimization problem

What you have:

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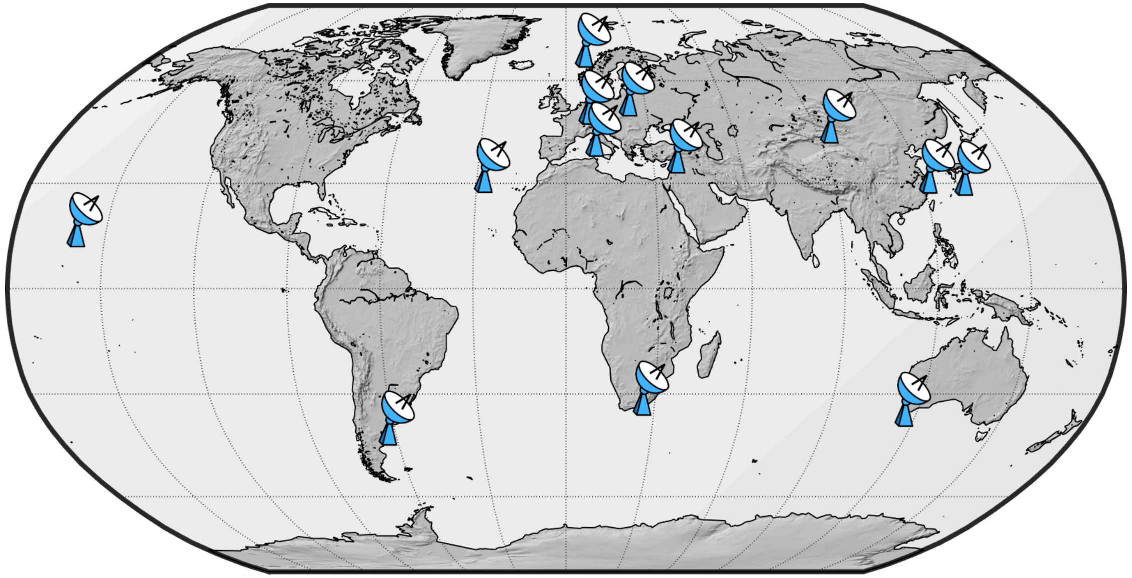
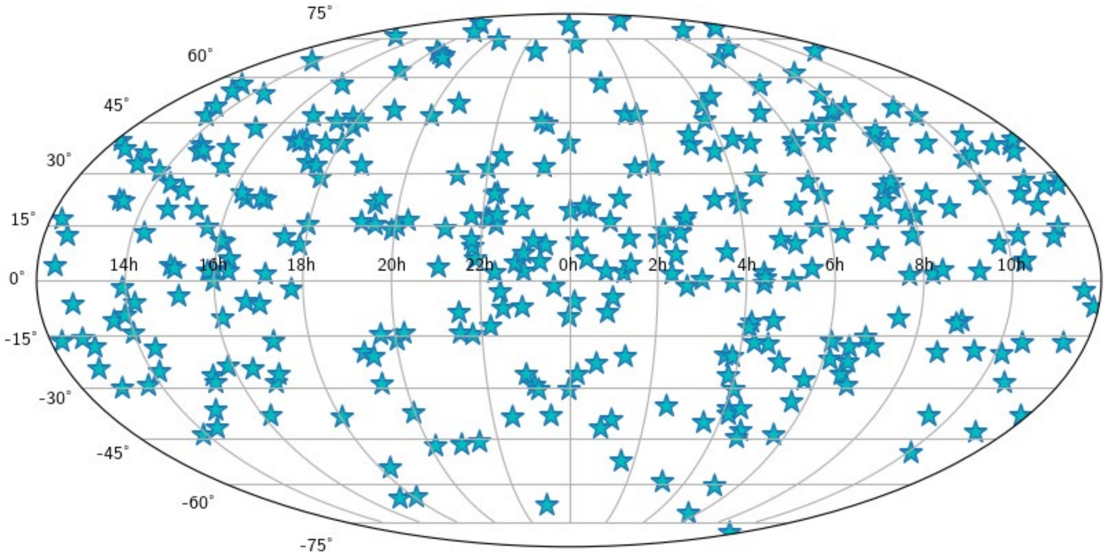
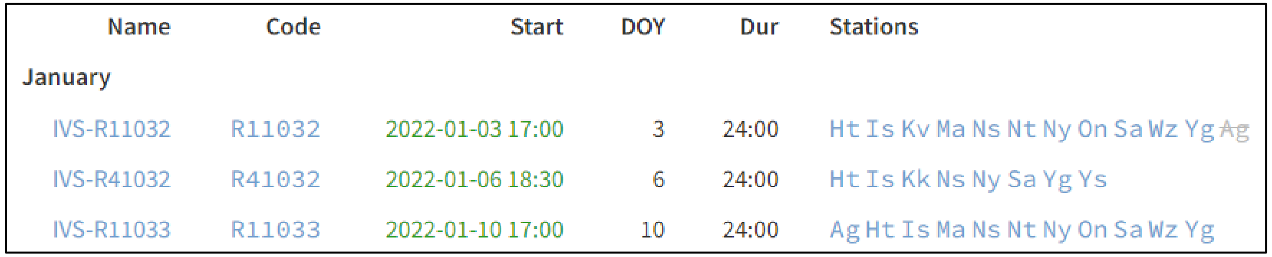
- source list







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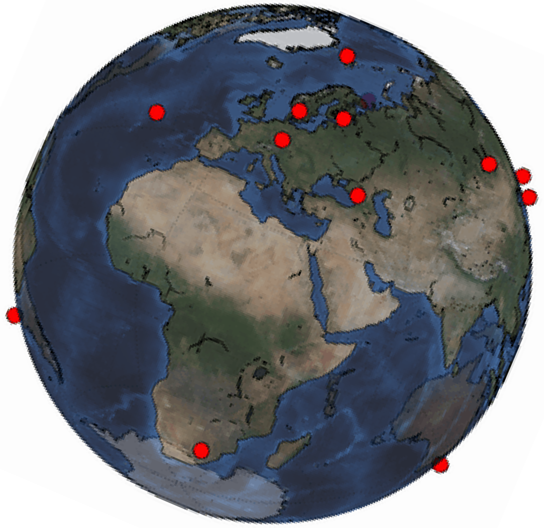
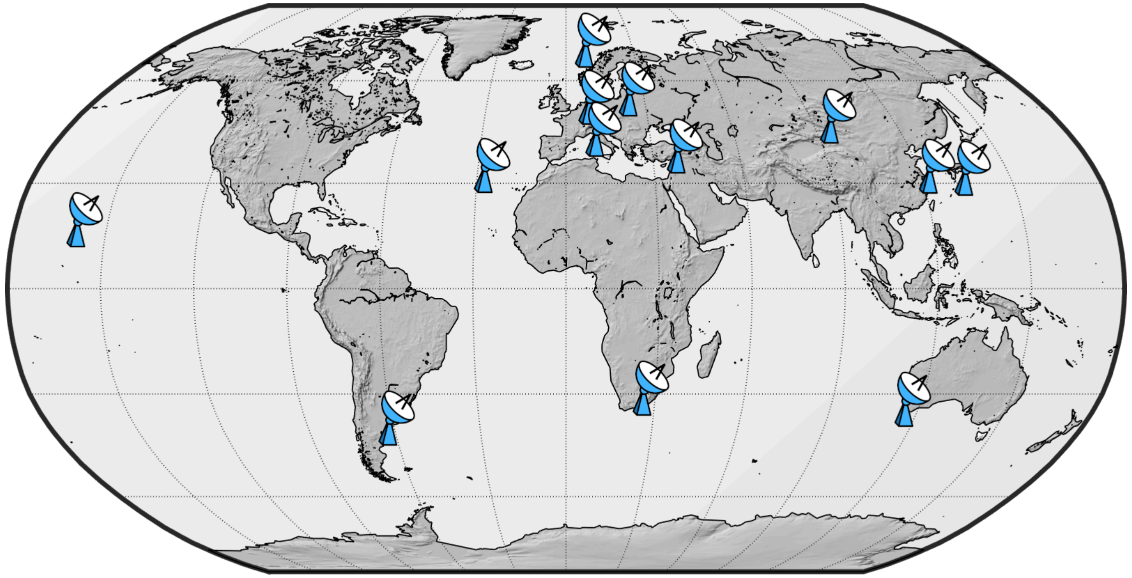
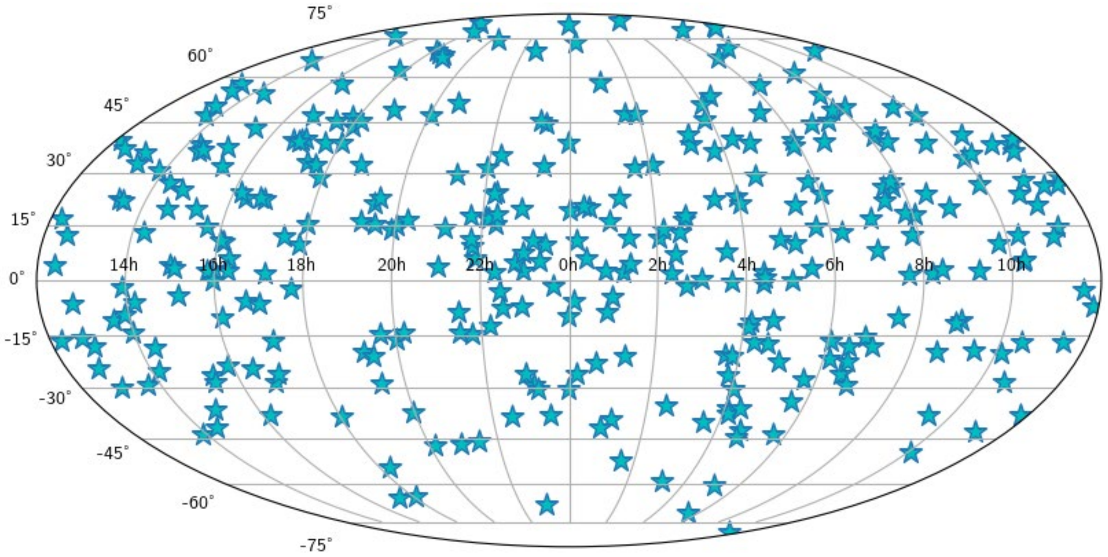
Scheduling is an optimization problem

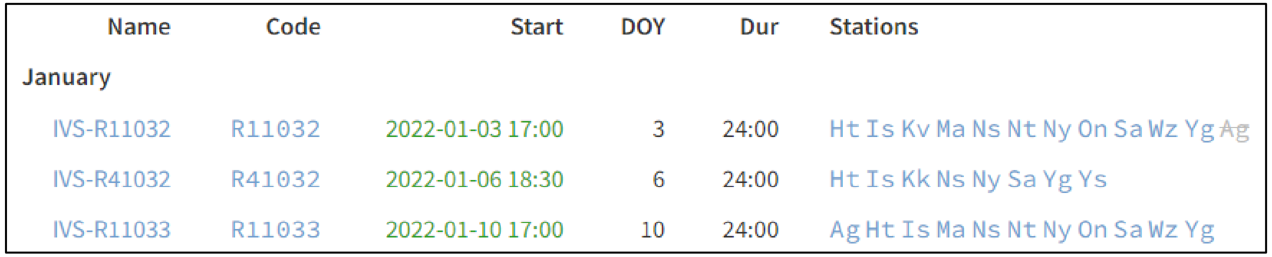
What you have:

- session (time…)
- station network
- source list
- objective (EOP, scale)









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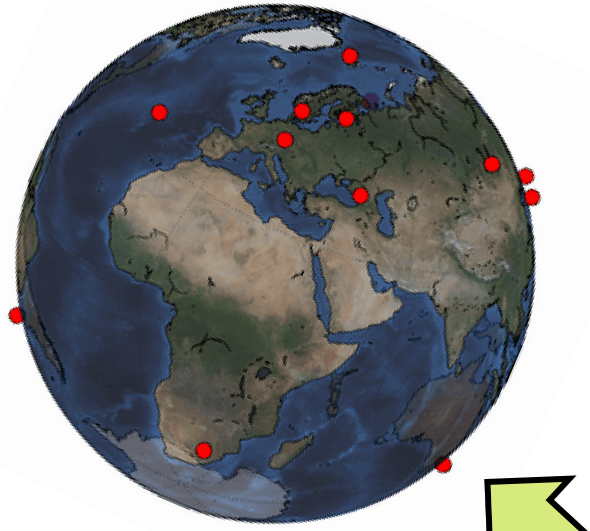

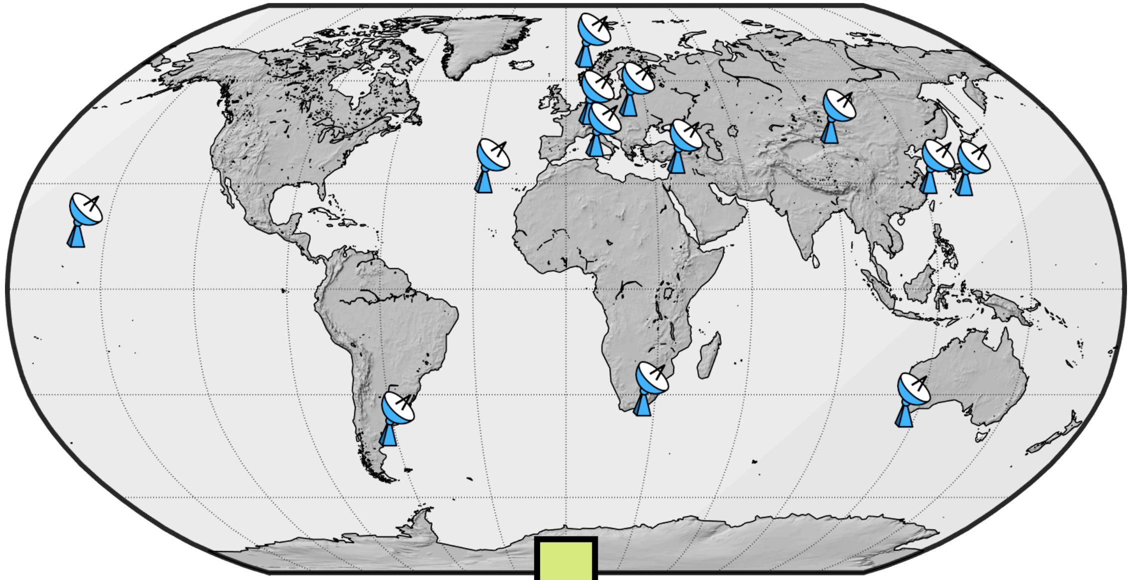

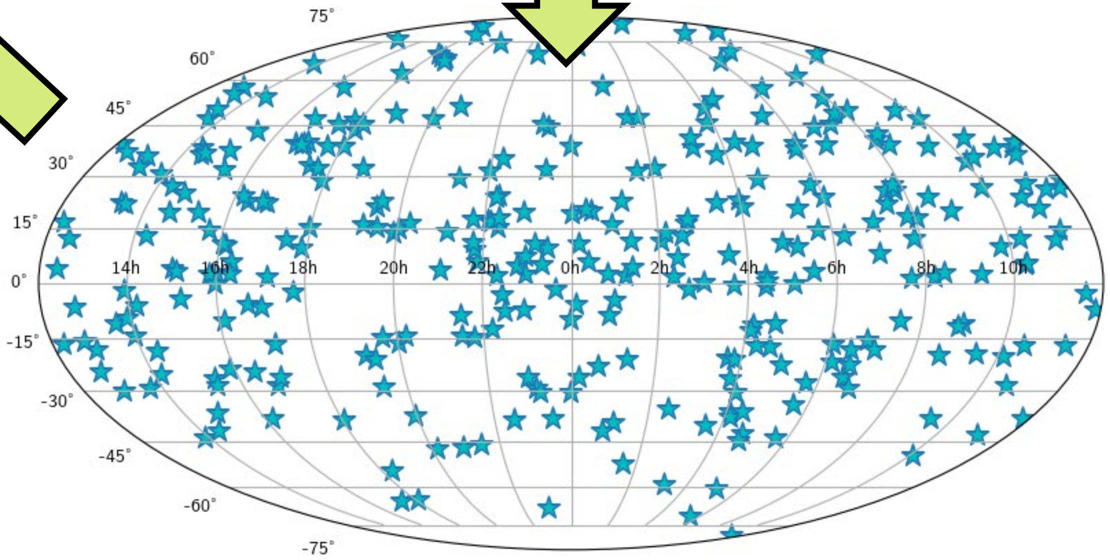

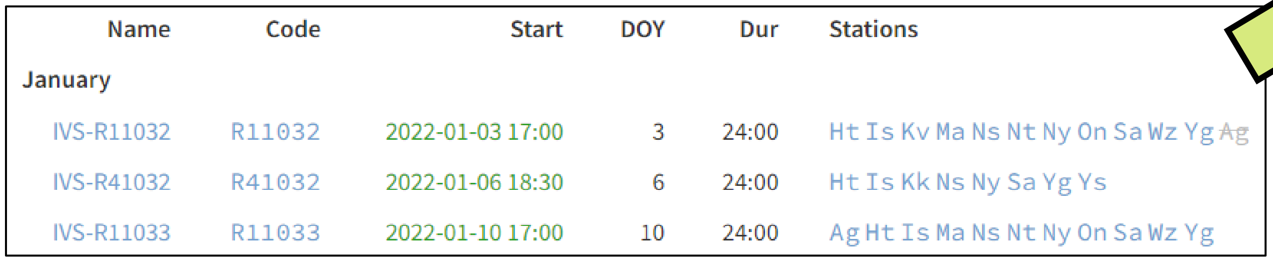

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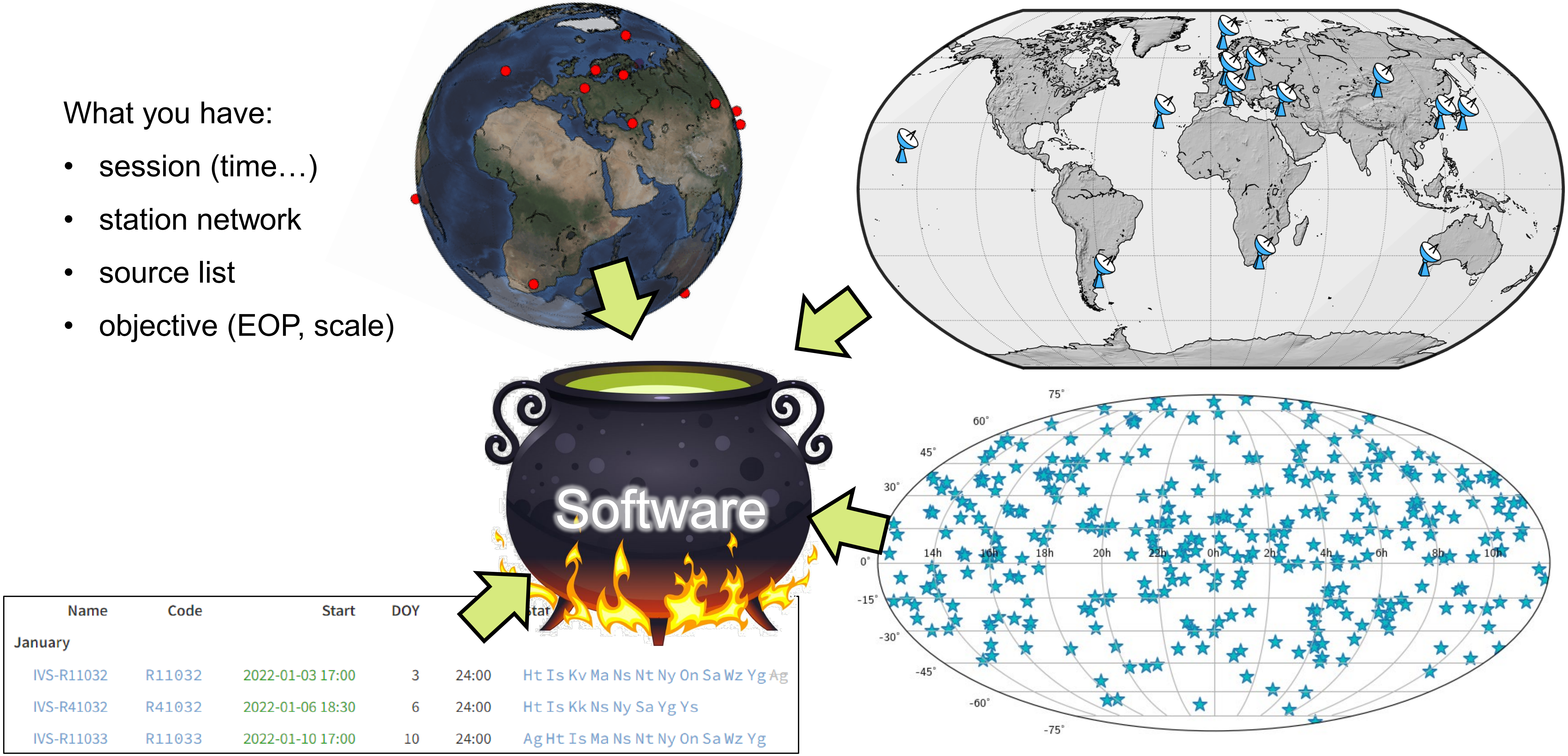

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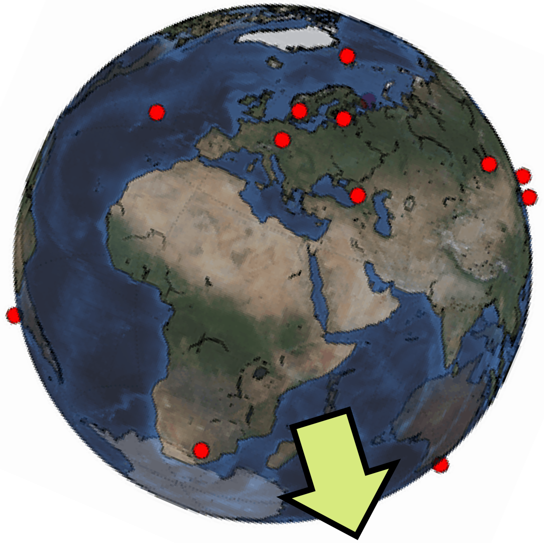

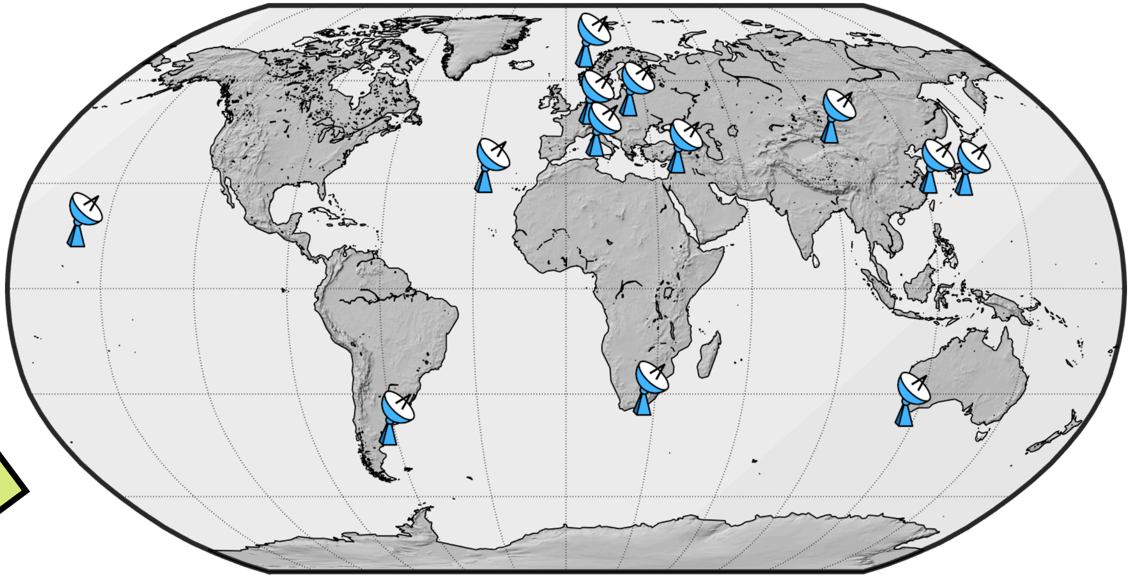

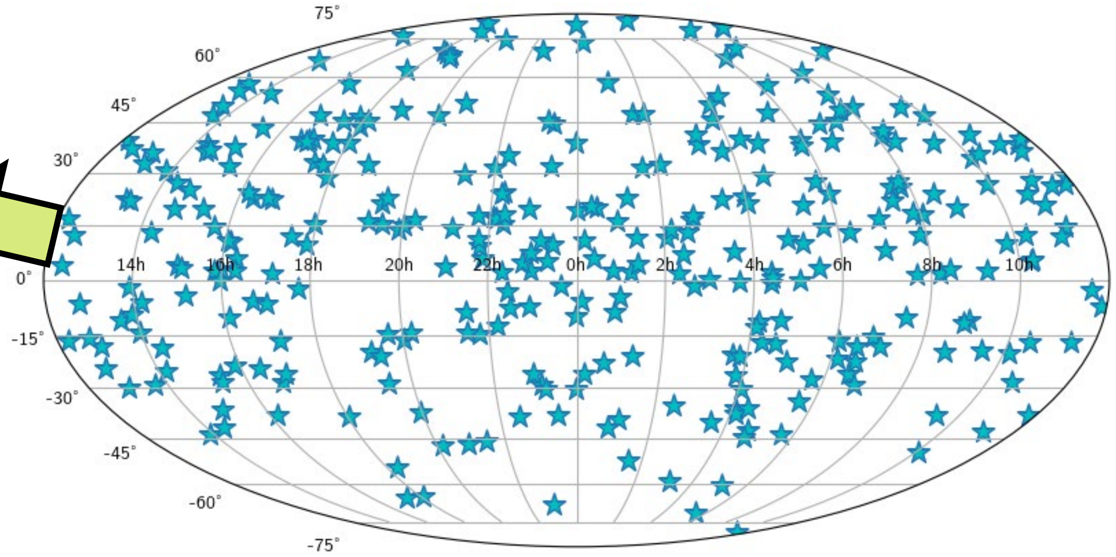

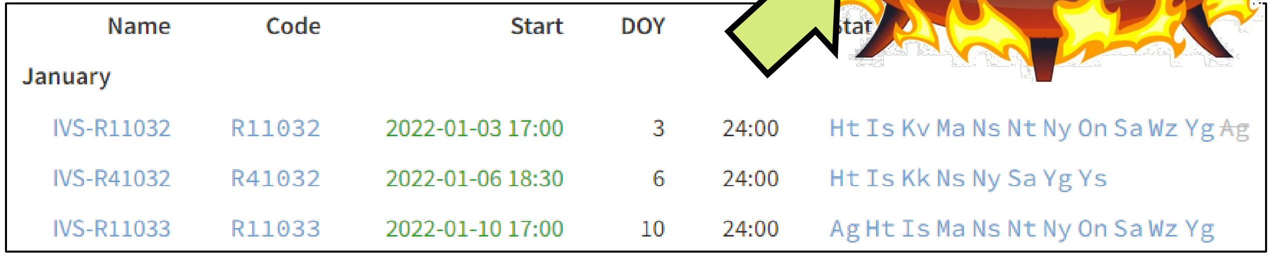

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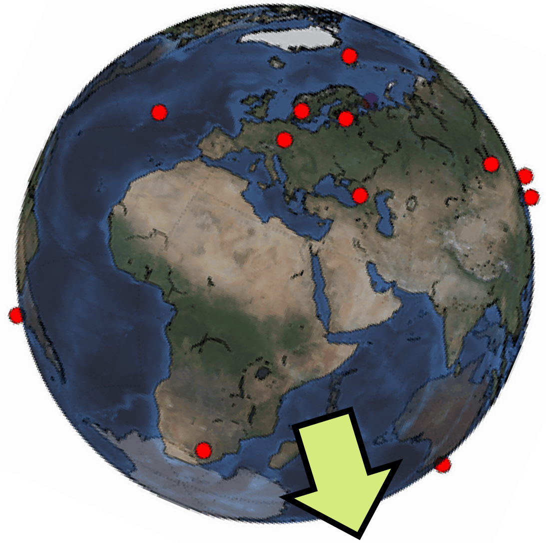

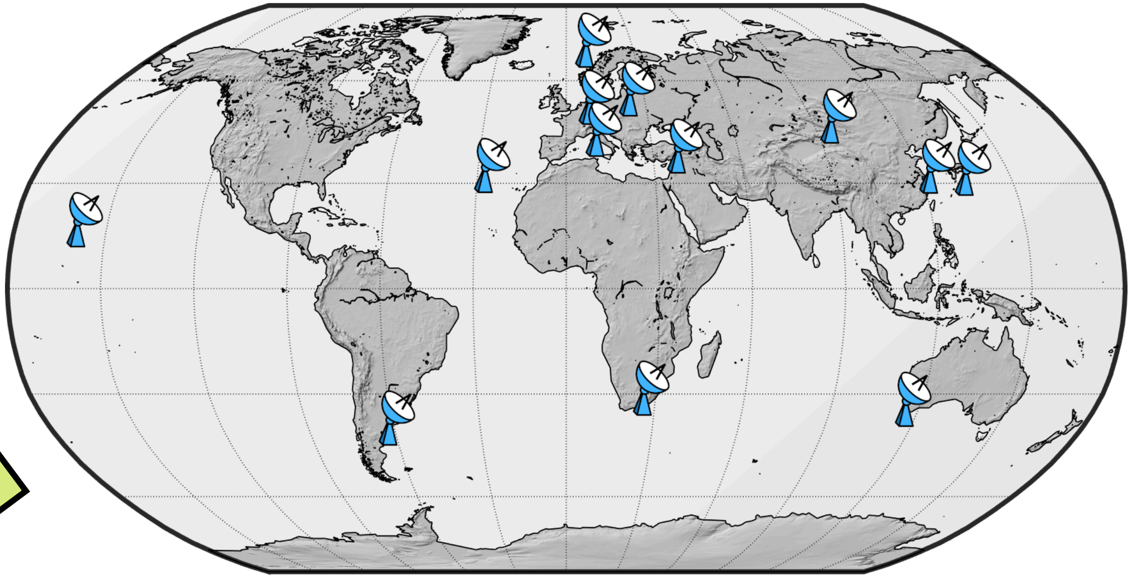

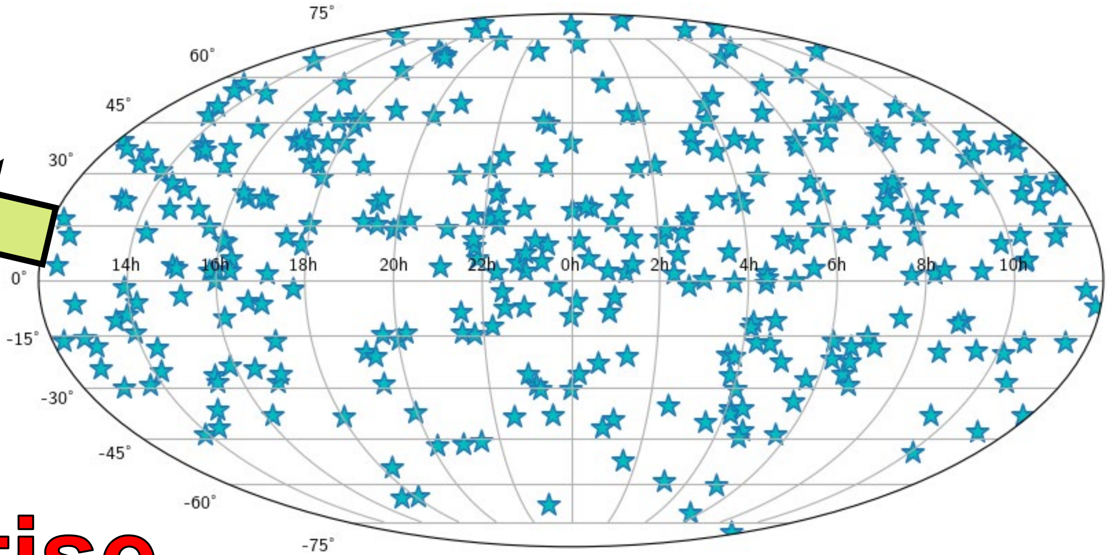

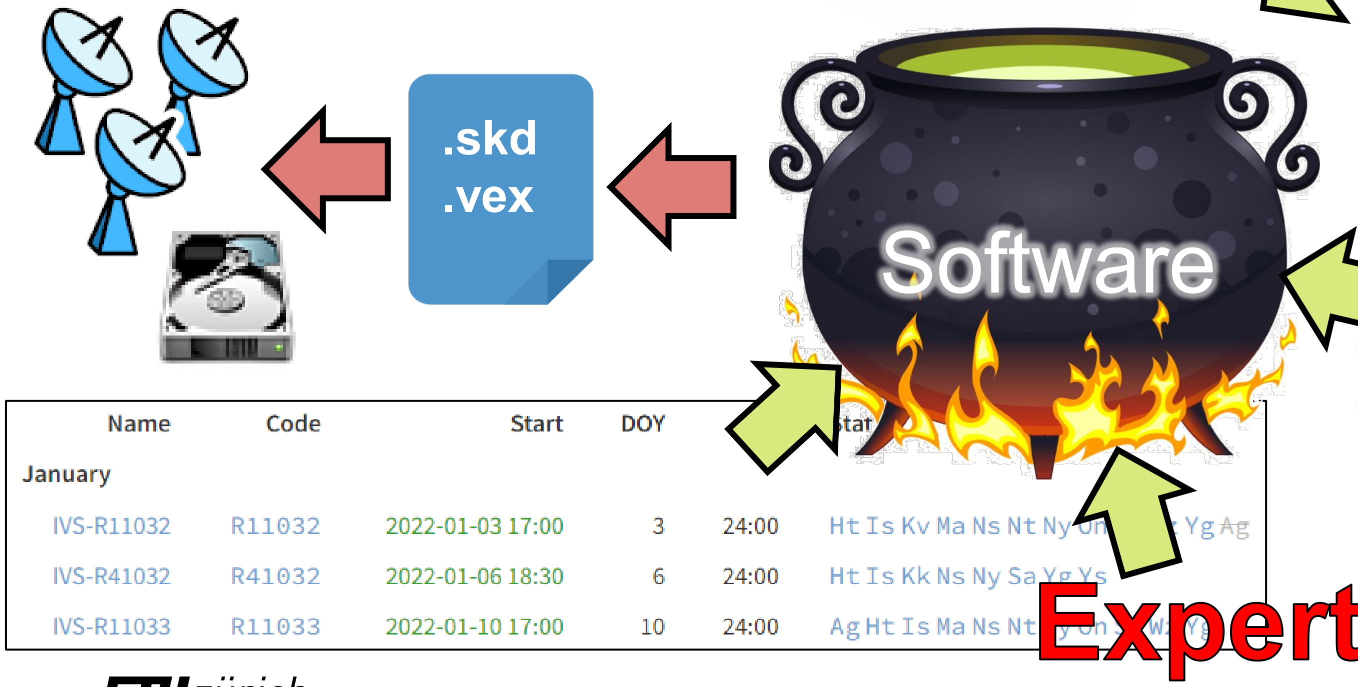

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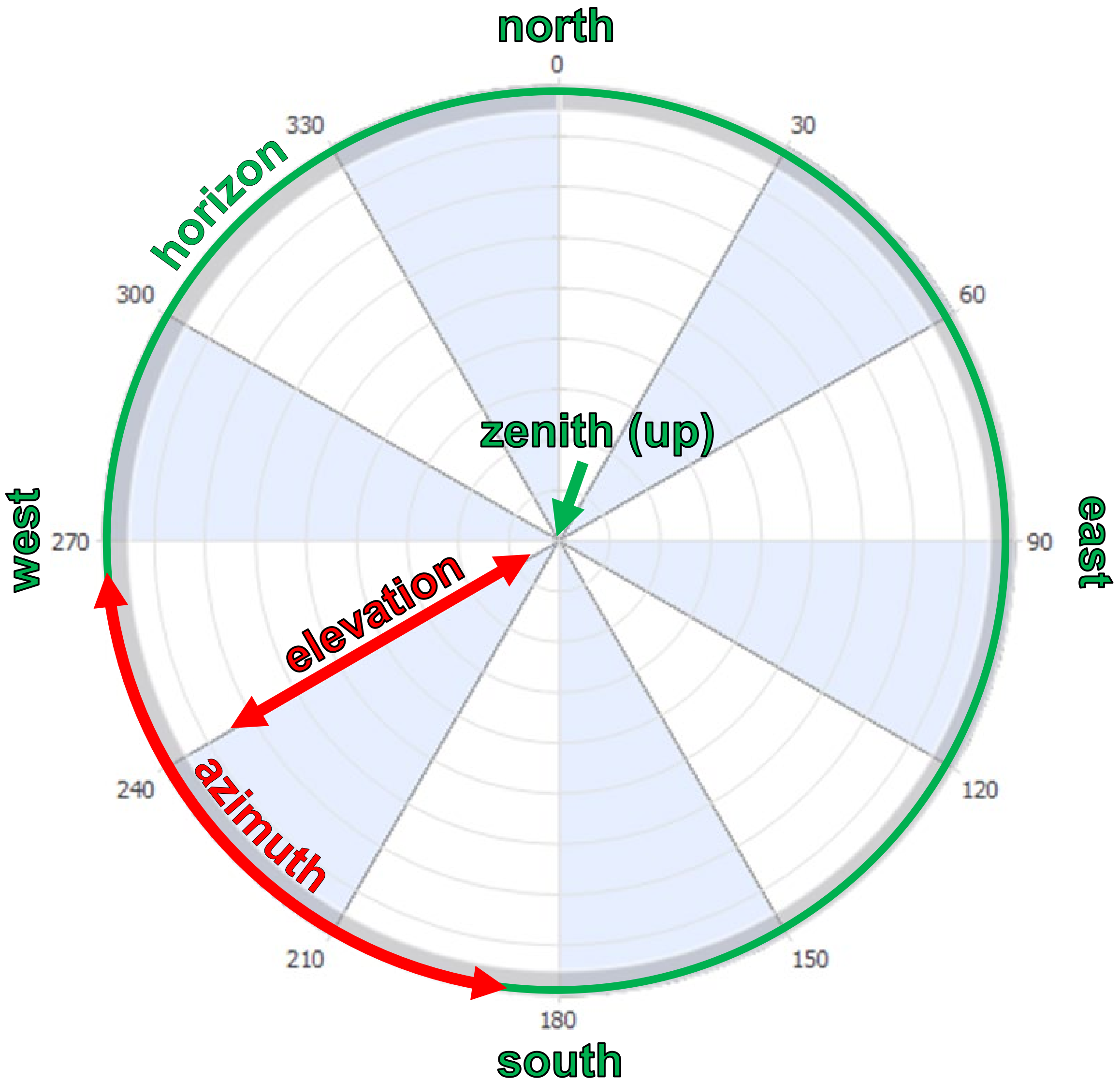
Models and Concepts

Sky-coverage

- tropospheric delays need to be estimated
- highly correlated with clock and height

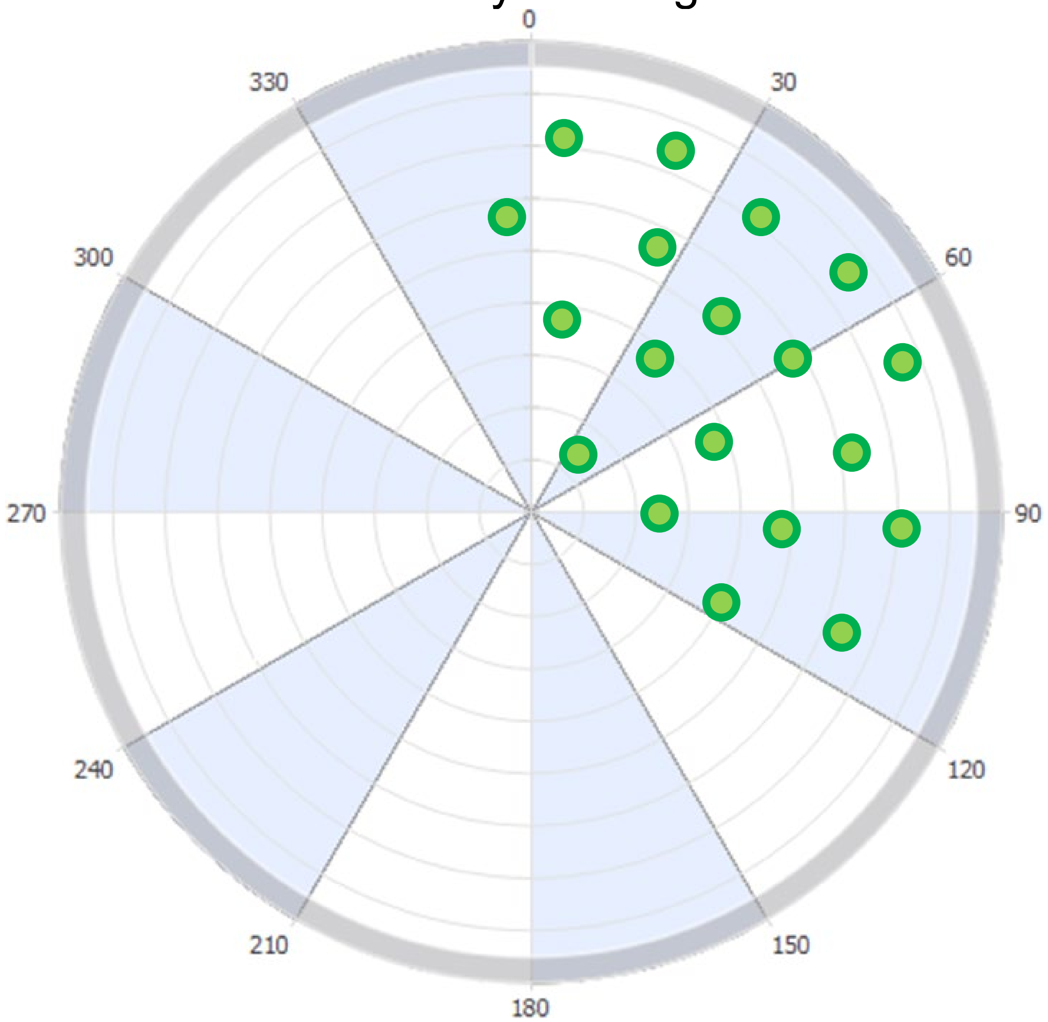
Solution:

- observations to different azimuth and elevation angles to disentangle effects
- over short period of time

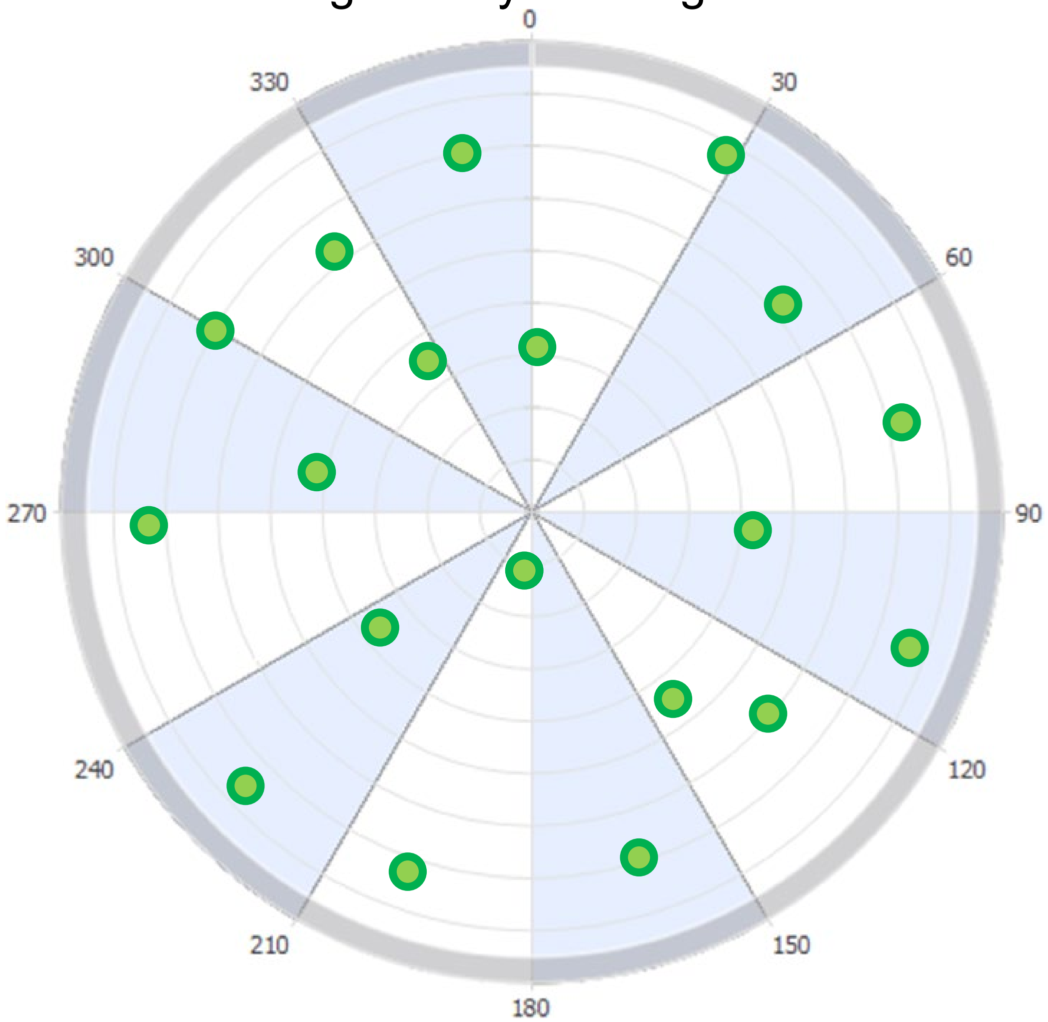


Sky-coverage

bad sky-coverage

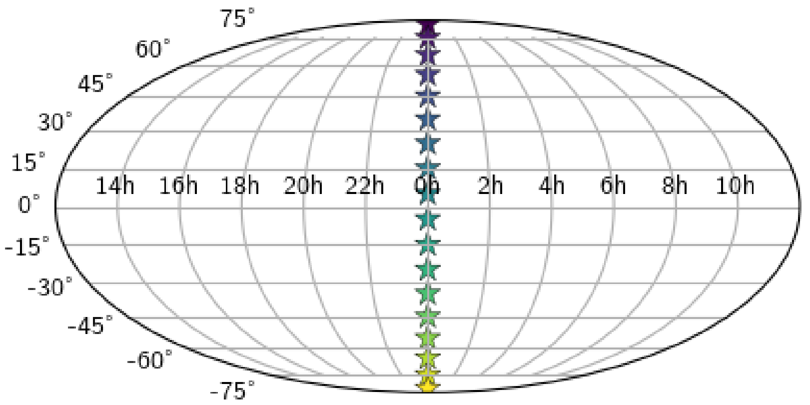


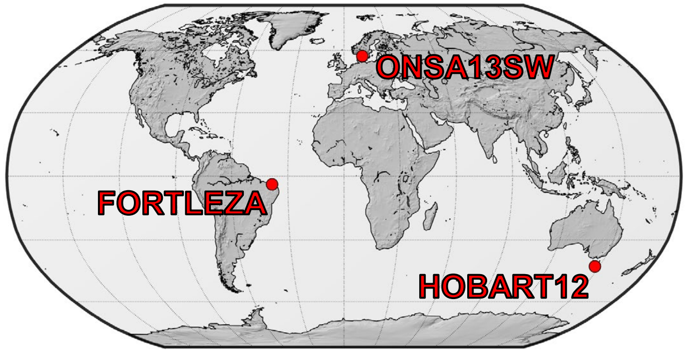
good sky-coverage

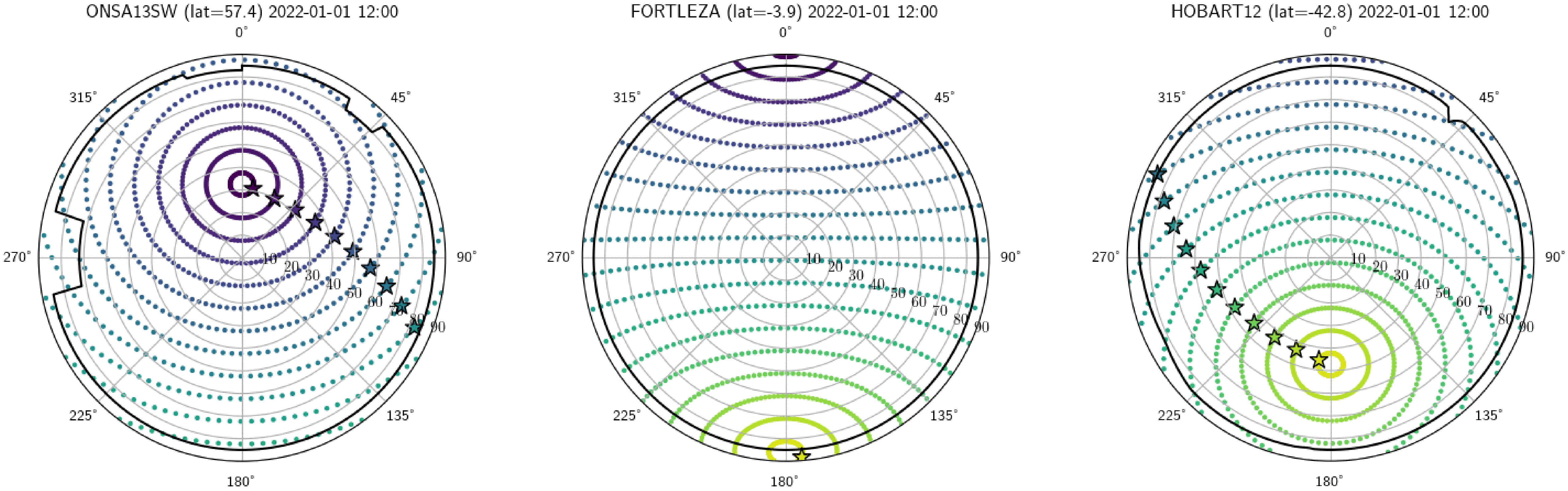


Intermezzo: Sky-coverage

self-study ☺







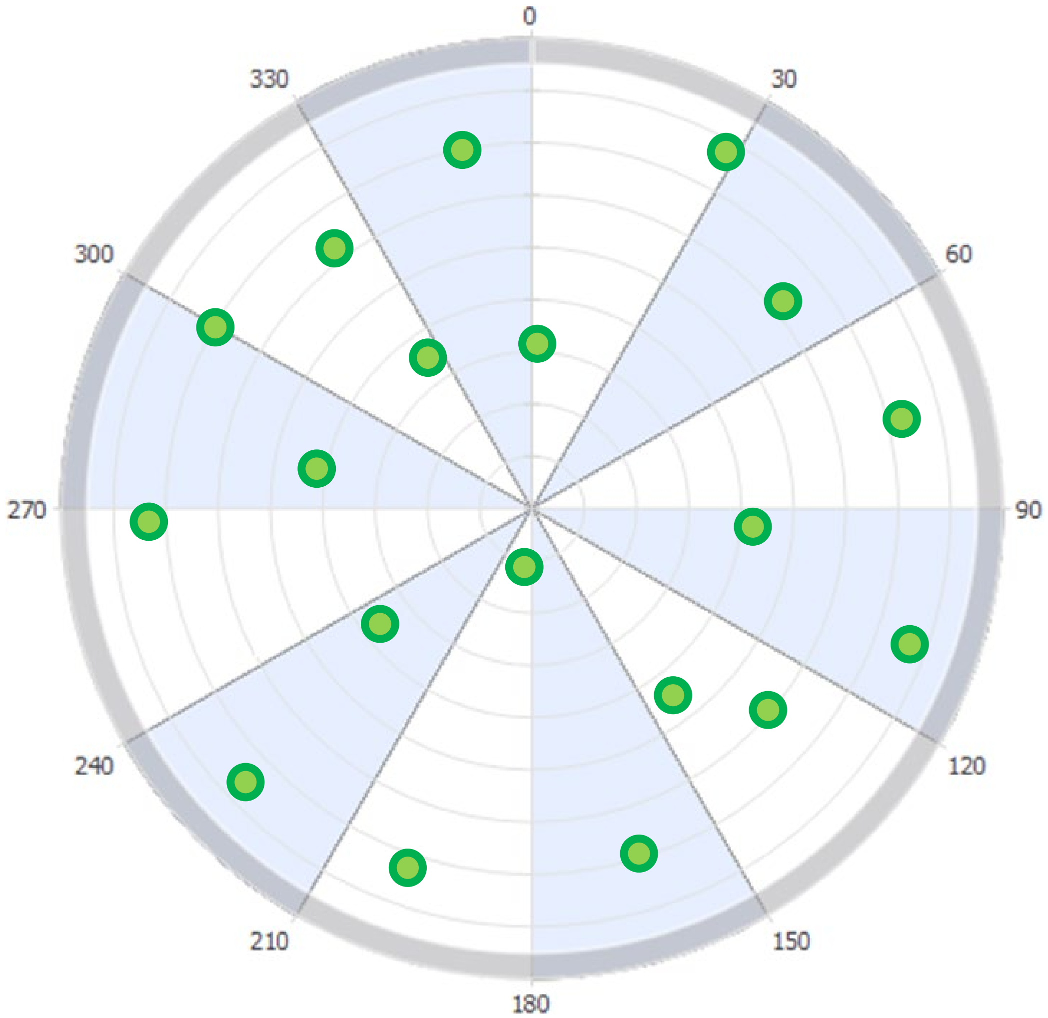
Sky-coverage

For estimating **ZWD**:

- Observations at **different elevation angles** (in particular high and low elevations)

For estimating tropospheric **gradients**:

- Observations at **different azimuth angles** (north-south, east-west)



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The challenge of VLBI scheduling

You want to have good sky-coverage
→ **long slew distances**

You want to have high number of scans
→ **short slew times**

It is not possible to fulfill both at the same time
→ **scheduling is all about finding trade-offs**

VGOS motivation for building small but fast slewing telescopes

Gipson (2016)
Schartner and Böhm (2019)

The challenge of VLBI scheduling

self-study ☺

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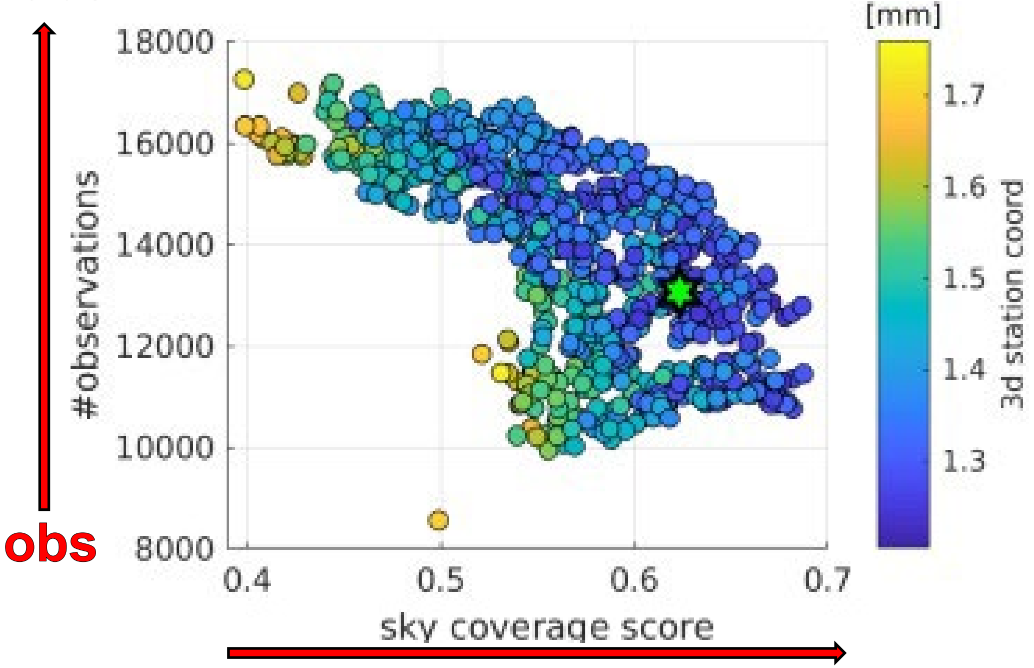
high # obs

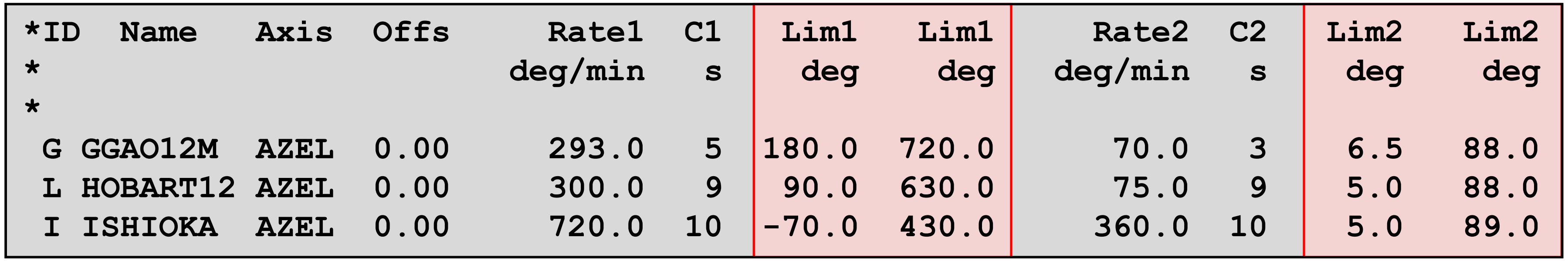


low # obs

bad sky-cov **good sky-cov**

Schartner and Böhm (2020)

Cable wrap



```
*ID  Name     Axis  Offs        Rate1  C1   Lim1    Lim1       Rate2  C2   Lim2    Lim2
*                             deg/min   s    deg     deg     deg/min   s    deg     deg
*
 G GGAO12M  AZEL  0.00        293.0   5  180.0   720.0        70.0   3    6.5    88.0
 L HOBART12 AZEL  0.00        300.0   9   90.0   630.0        75.0   9    5.0    88.0
 I ISHIOKA  AZEL  0.00        720.0  10  -70.0   430.0       360.0  10    5.0    89.0
```

antenna.cat

three sections:

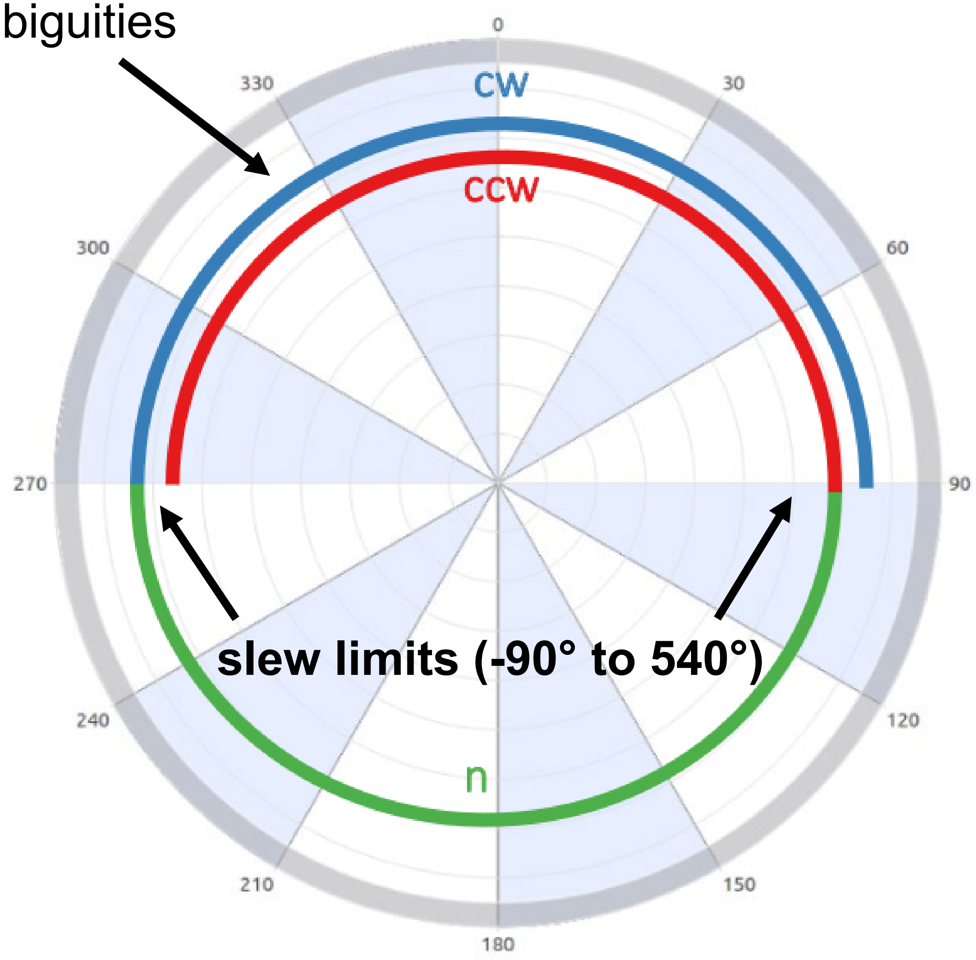
ccw: counter cw

n: neutral

cw: clock-wise

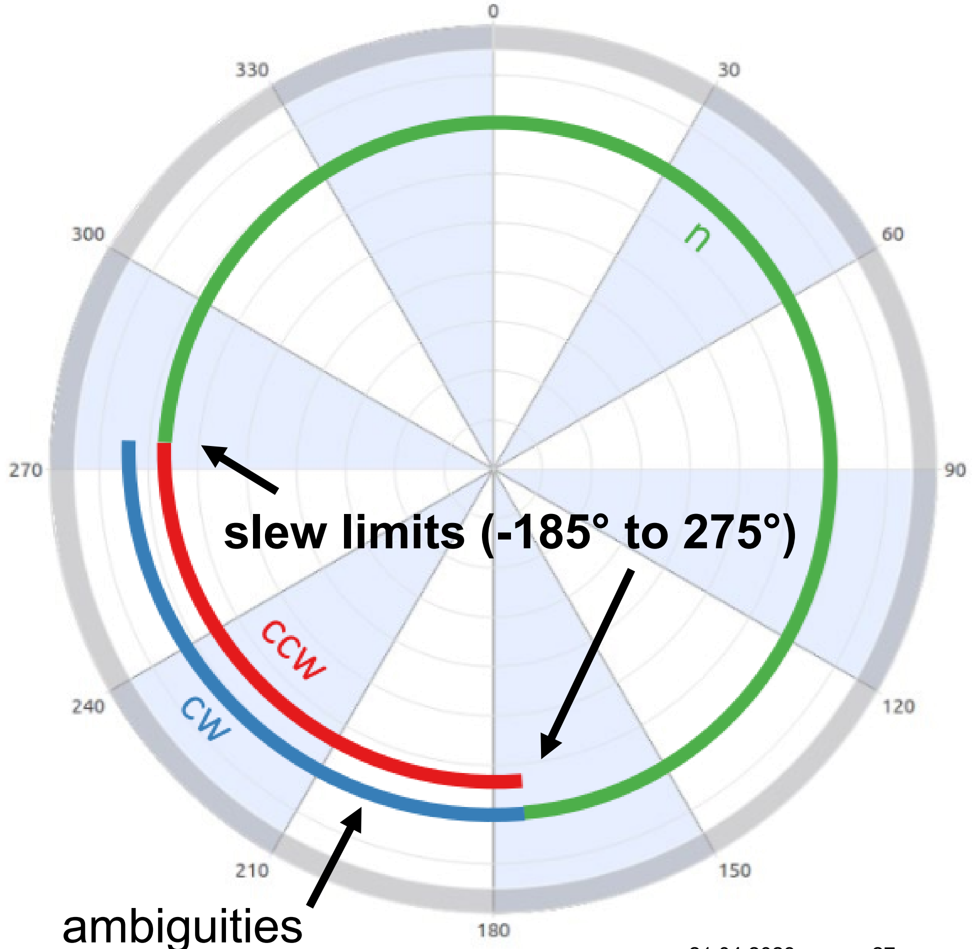
WETTZ13N

ambiguities



slew limits (-90° to 540°)

HART15M



slew limits (-185° to 275°)

ambiguities

Cable wrap
Slewing from A to B

```
*ID  Name     Axis  Offs        Rate1  C1   Lim1    Lim1      Rate2  C2   Lim2    Lim2
*                             deg/min   s    deg     deg    deg/min   s    deg     deg
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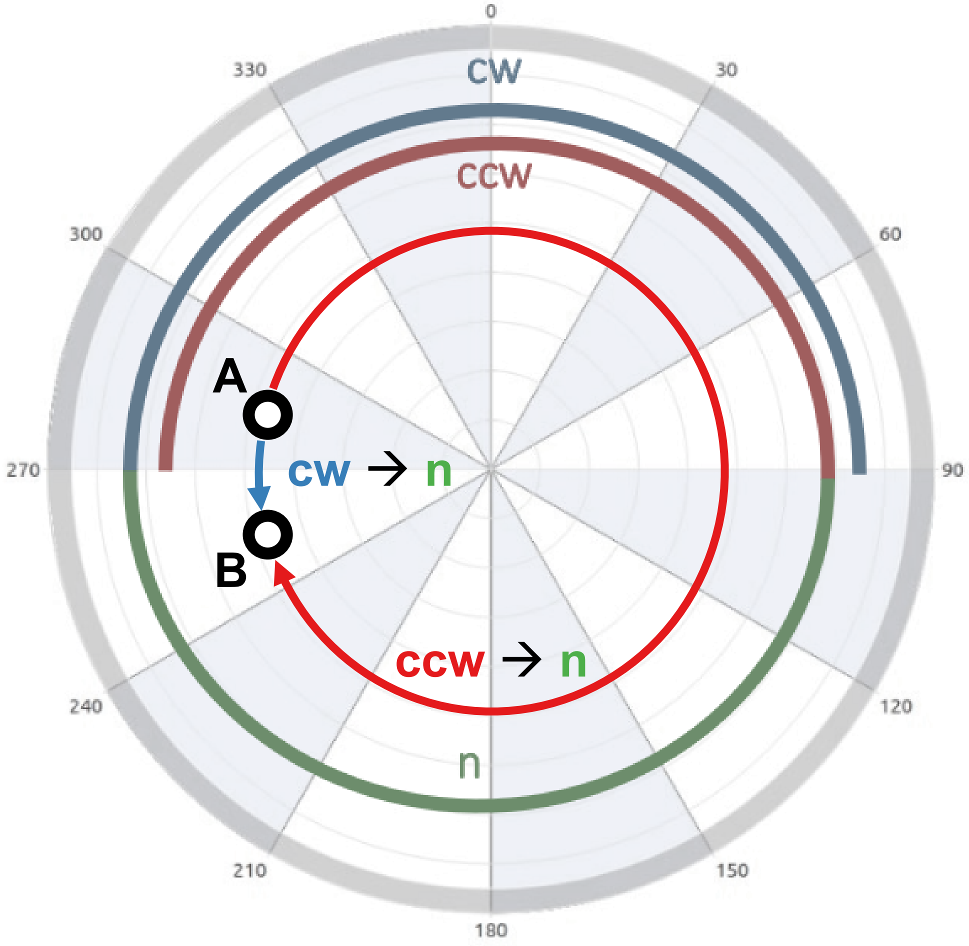
WETTZ13N



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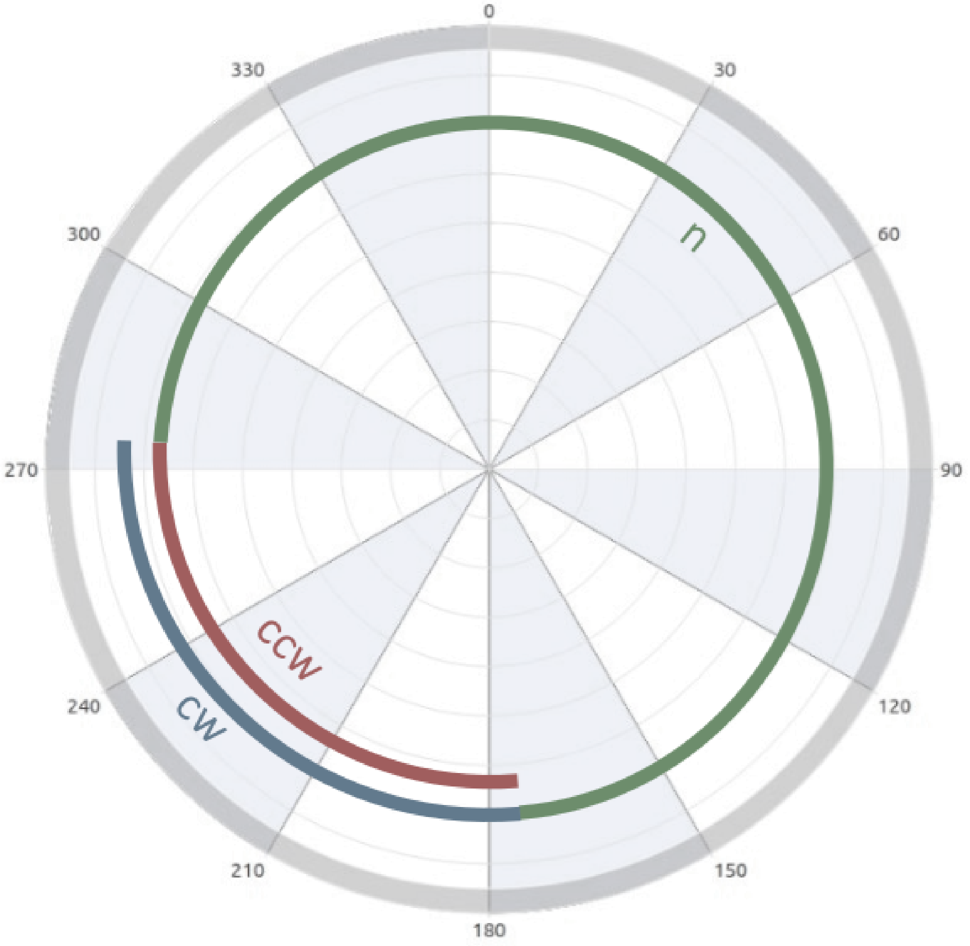
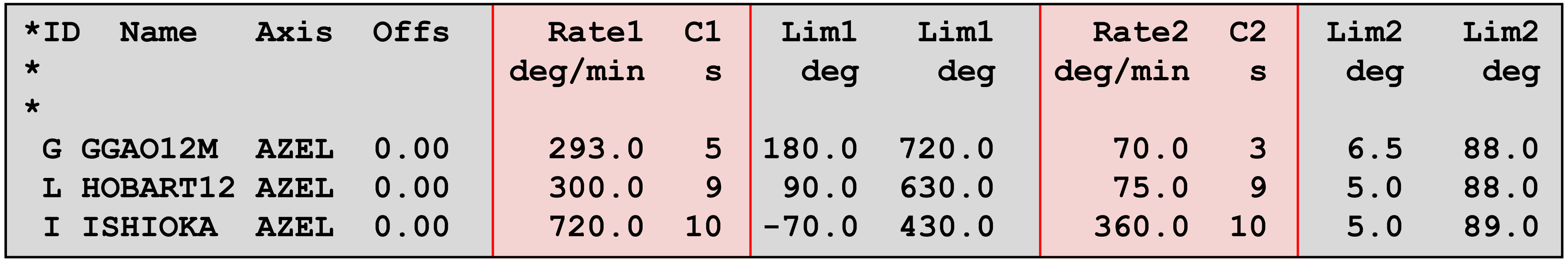


Slew time



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*                             deg/min   s     deg     deg    deg/min   s     deg     deg
*
 G GGAO12M   AZEL   0.00      293.0   5   180.0   720.0       70.0   3     6.5    88.0
 L HOBART12  AZEL   0.00      300.0   9    90.0   630.0       75.0   9     5.0    88.0
 I ISHIOKA   AZEL   0.00      720.0  10   -70.0   430.0      360.0  10     5.0    89.0
```
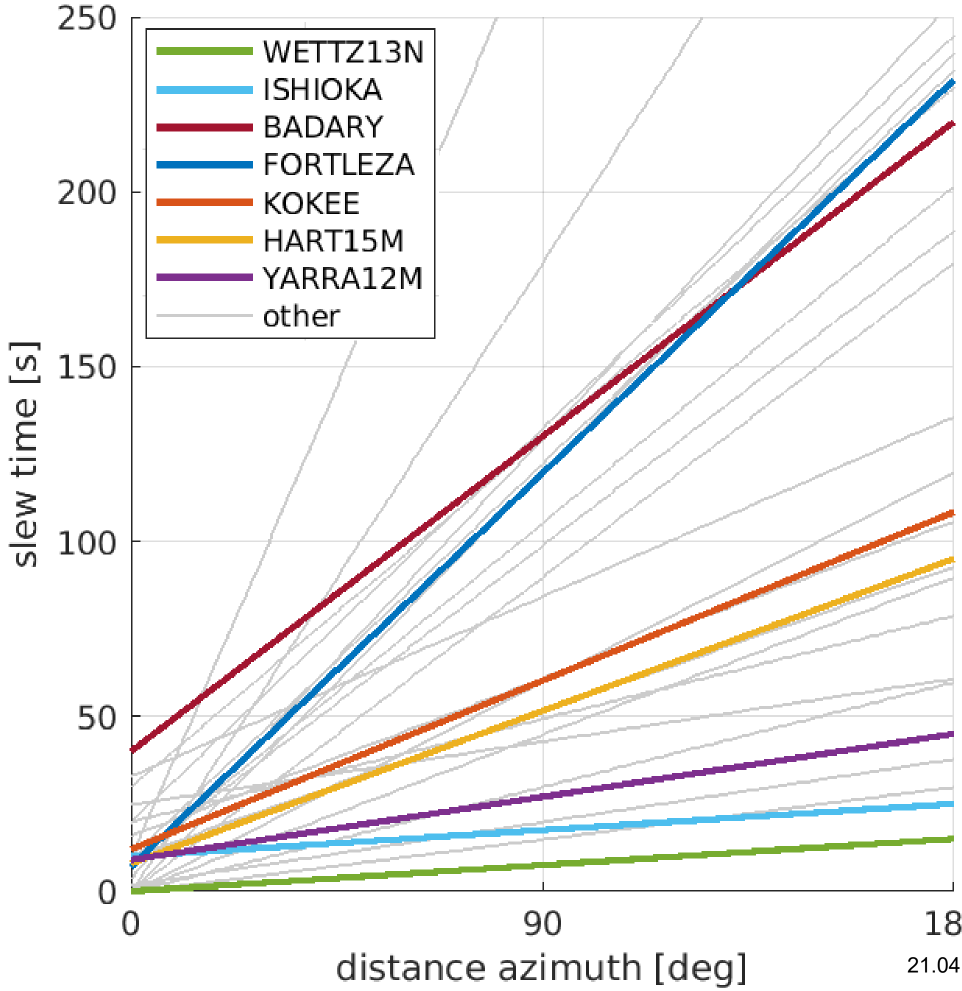

antenna.cat

- Different antenna mounts
  - **azimuth/elevation**
  - hour angle/declination
  - X / Yew
  - X / Yns
- slew time calculated per slew axis
  - $slew = max\{slew(el),\ slew(az)\}$
- different models
  - **slew rate + constant offset**
  - + acceleration
  - + deceleration
  - special models

opportunity



Horizon mask

```
*ID Name    TLC  az  el  az  el ... az  el (az)
*               deg deg deg deg ...
 H KOKEE12M K2    0  10 238  14 244 10 260  5 280 10 295 25 300 35
 -              305  40 310  45 325 40 330 35 335 30 340 10 350  5 360
 H  GGAO12M Gs    0   6  15   5  58  3  90  4 130  3 149  3 150 11
 -              152  18 157  27 167 37 177 41 187 43 197 43 360  6
```

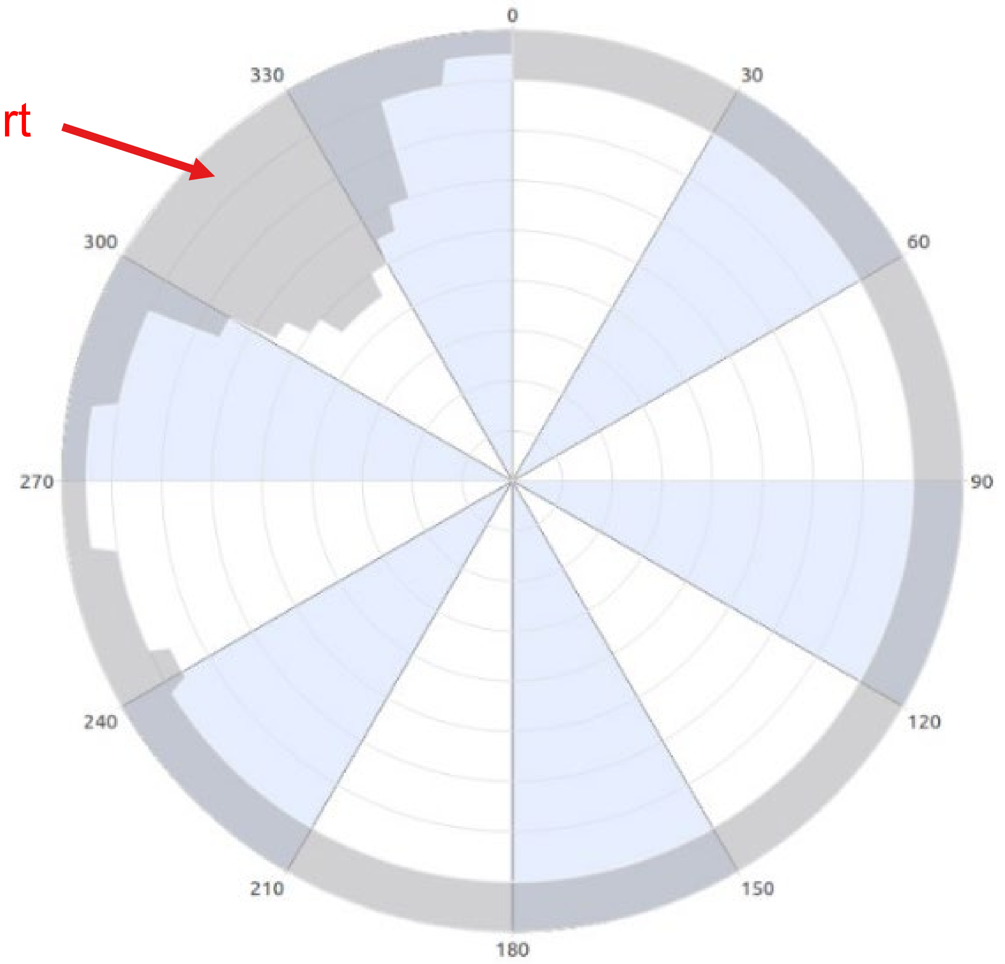
`mask.cat`

- Obstacles prevent direct view of sky
  - buildings
  - mountains
- RFI prevents clear observations
  - cities
  - radar
- Horizon mask defines lowest observable elevation per azimuth
- (additionally, we typically use a 5 degree cut-off elevation angle)

opportunity

Not possible to observe this part of the sky

KOKEE12M



Required observation duration

self-study ☺

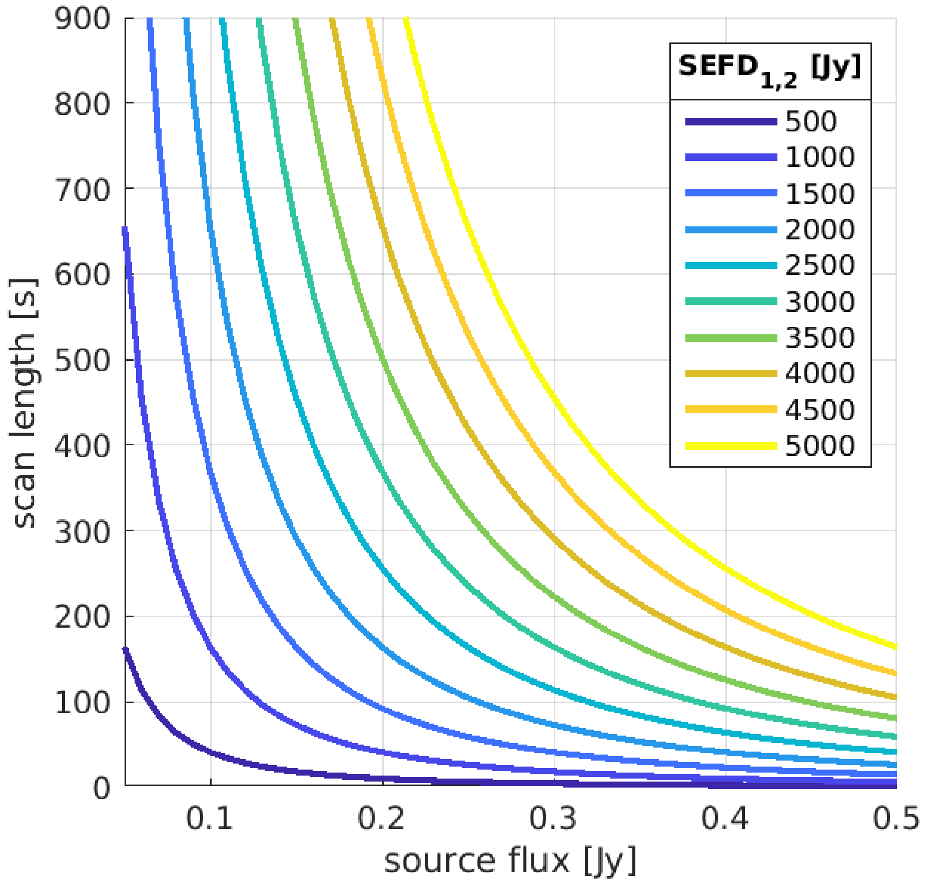
$$\mathrm{T}_{band,1,2} = \left(\frac{SNR_{band}}{\eta F_{band}}\right)^2 \cdot \left(\frac{SEFD_{band,1} \cdot SEFD_{band,2}}{rec_{band}}\right)$$

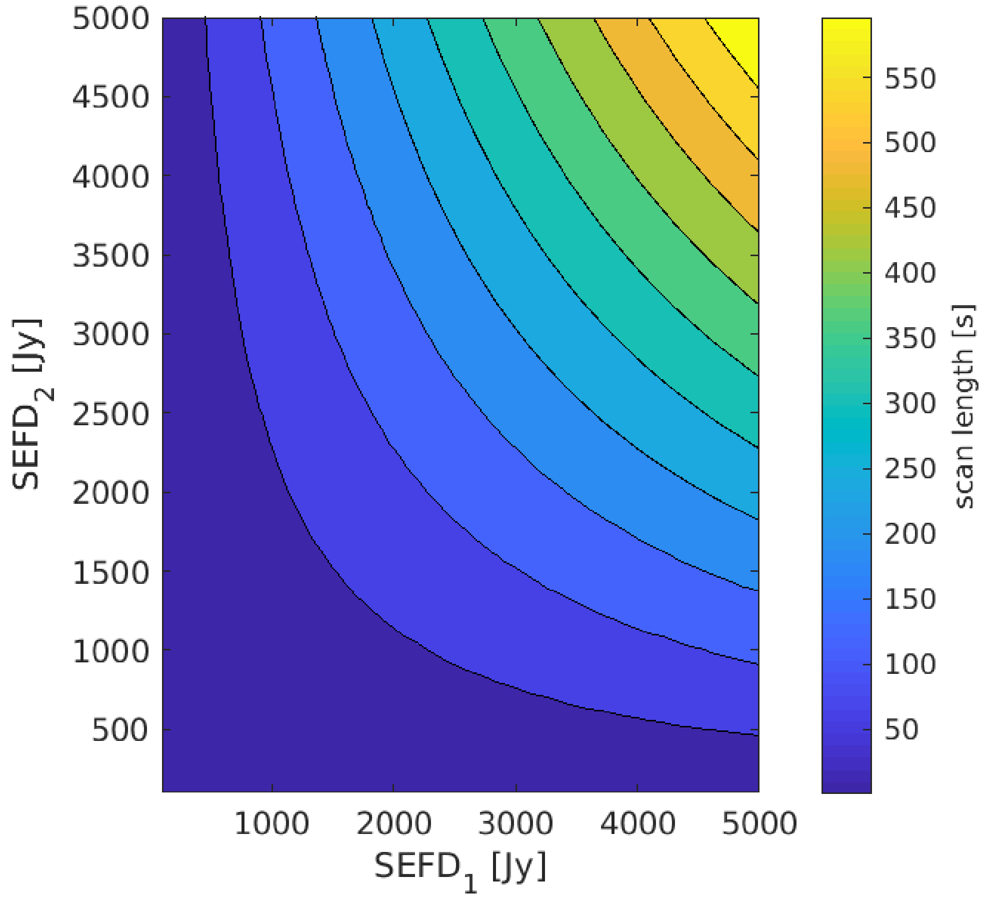
$T_{band,1,2}$ = *observation duration between station 1 and 2 on this band*
SNR_{band} = *target signal to noise ratio for this band*
η = *efficiency factor*
F_{band} = *source flux density in this band*
$SEFD_{band}$ = *station sensitivity (for station 1 and 2)*
rec_{band} = *recording rate in this band*

Required observation duration

self-study ☺

$$T_{band,1,2} = \left(\frac{SNR_{band}}{\eta F_{band}}\right)^2 \cdot \left(\frac{SEFD_{band,1} \cdot SEFD_{band,2}}{rec_{band}}\right)$$





Antenna sensitivity

```
*Antenna    ID DAT_Name    … X SEFD  S  SEFD   el- dependent SEFD param                        Equip
*                               Jy       Jy
*
 WESTFORD   07 WESTFORD    … X 3000  S  4000   S 1.0 0.962 0.0384 X 1.0 0.939 0.0608   RDBE      MARK6
 WETTZELL   33 WETTZELL    … X  750  S  1115   S 1.0 0.934 0.0660 X 1.0 0.948 0.0516   DBBC_DDC Flexbuff
 YEBES40M  105 YEBES       … X  250  S  1500                                           DBBC_DDC FlexBuff
```

`equip.cat`

- SEFD (System Equivalent Flux Density)

$$SEFD = \frac{2kT_{Sys}}{A_e} \cdot 10^{26} = \frac{2kT_{Sys}}{\eta_A A_g} \cdot 10^{26} = \frac{8kT_{Sys}}{\eta_A \pi D^2} \cdot 10^{26}$$

k = Boltzmann constant

$A_e = \eta_A A_g =$ effective aperture

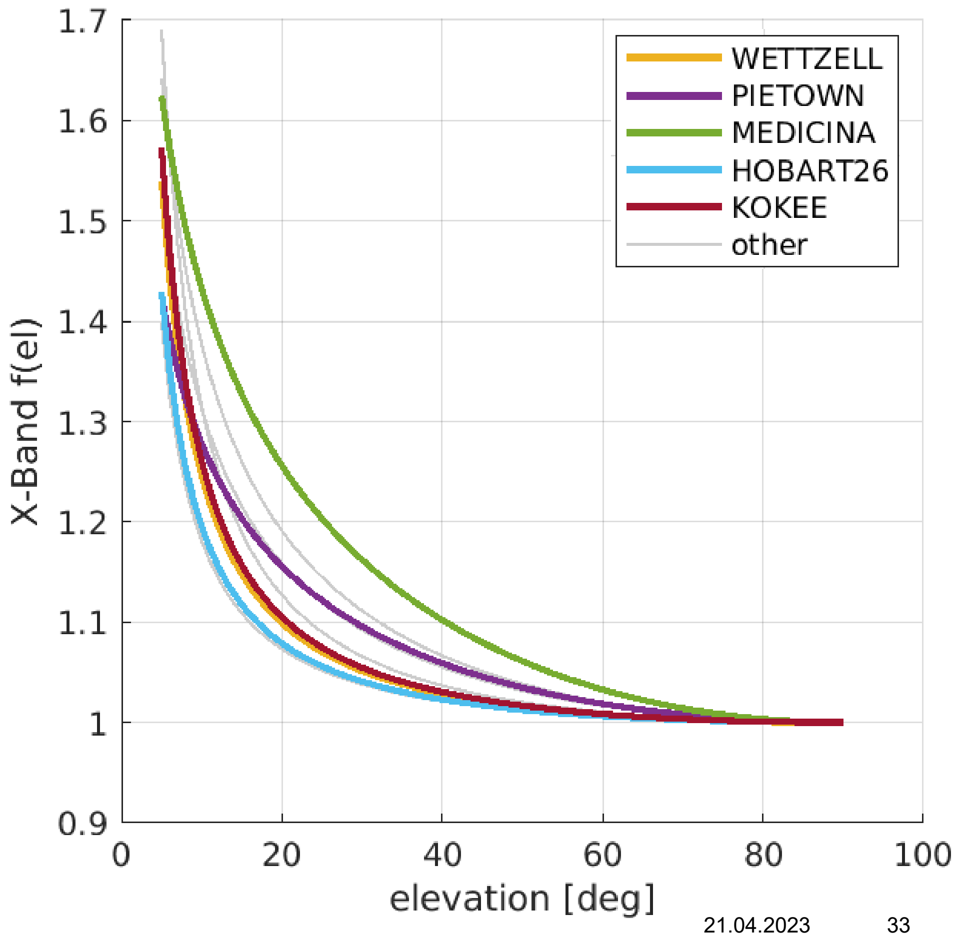
η_A = aperture efficency factor

$A_g = \frac{\pi D^2}{4}$ (for circular aperture antennas)

D = antenna diameter

- SEFD is function of frequency, elevation, time, …
  - regular SEFD measurements
  - elevation dependent correction

opportunity



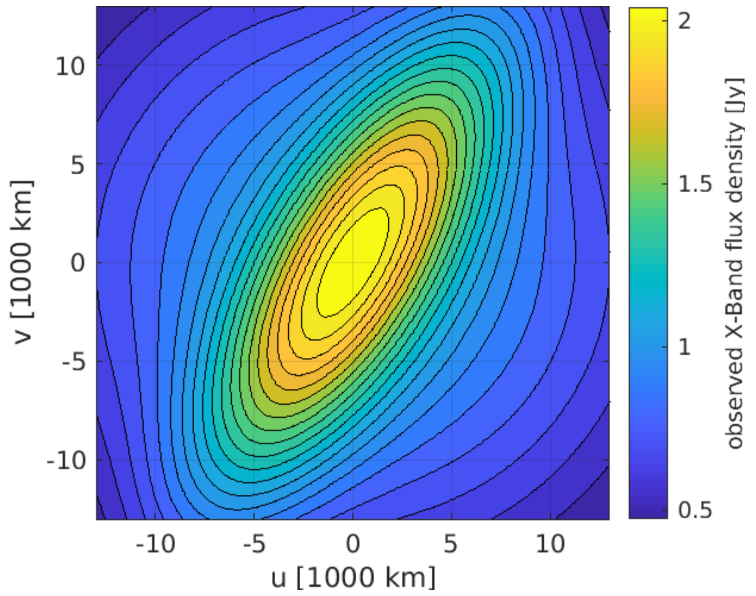
Source brightness

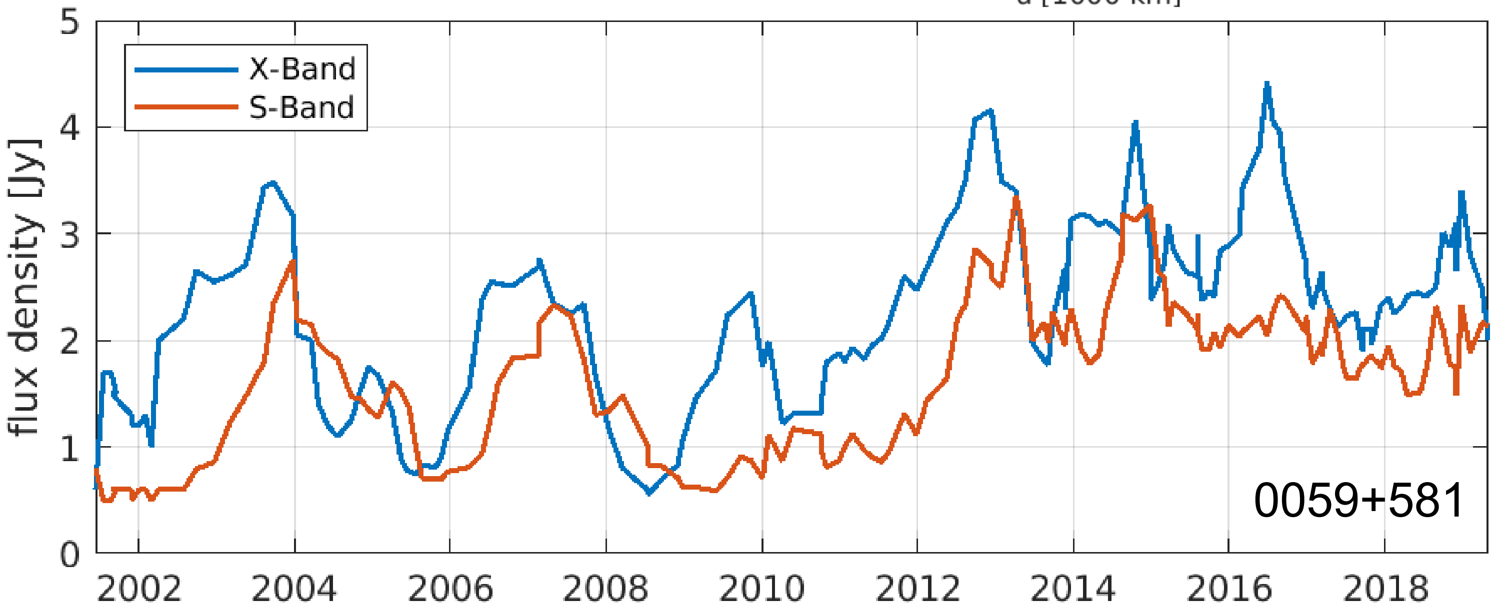
self-study ☺

Source flux density

- function of frequency, time, projected baseline length, and orientation (UV-plot)
- Various models/sources available
  - constant
  - baseline-length dependent
  - Gaussian components
  - clean components
  - images

opportunity





Source brightness

self-study ☺

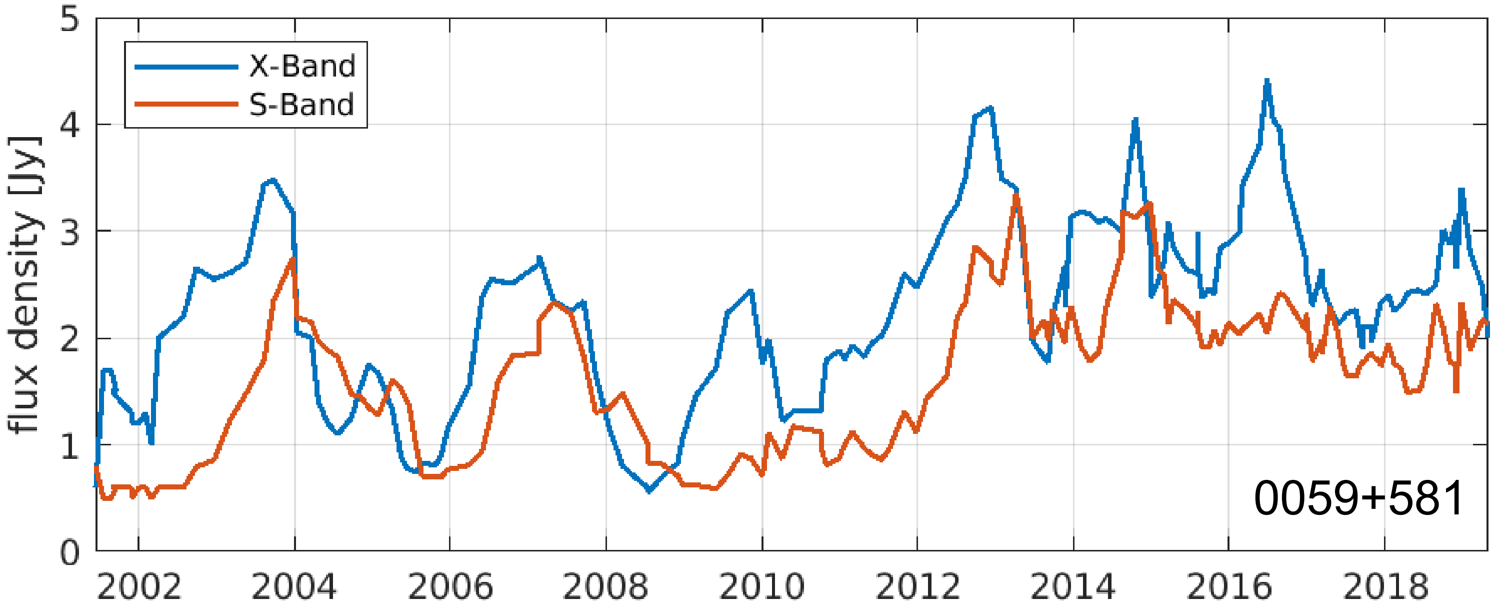
Source flux density

- function of frequency, time, projected baseline length, and orientation (UV-plot)
- Various models/sources available
  - constant
  - baseline-length dependent
  - Gaussian components
  - clean components
  - images

opportunity

```
* Name   band typ lenght flux length flux length ...
*                    km    Jy     km   Jy      km ...
*
 2325-150  X    B      0  0.42  13000
 2325-150  S    B      0  0.69  13000
 2000-330  S    B      0  0.17   1000 0.14 13000
 2000-330  X    B      0  0.34   1000 0.22 13000
* Name   band typ  gaussian components
 0059+581  X    M  3.90  0.30  1.00    0.   0.0   0.0
 0059+581  S    M  5.49  1.50  1.00    0.   0.0   0.0
```

flux.cat

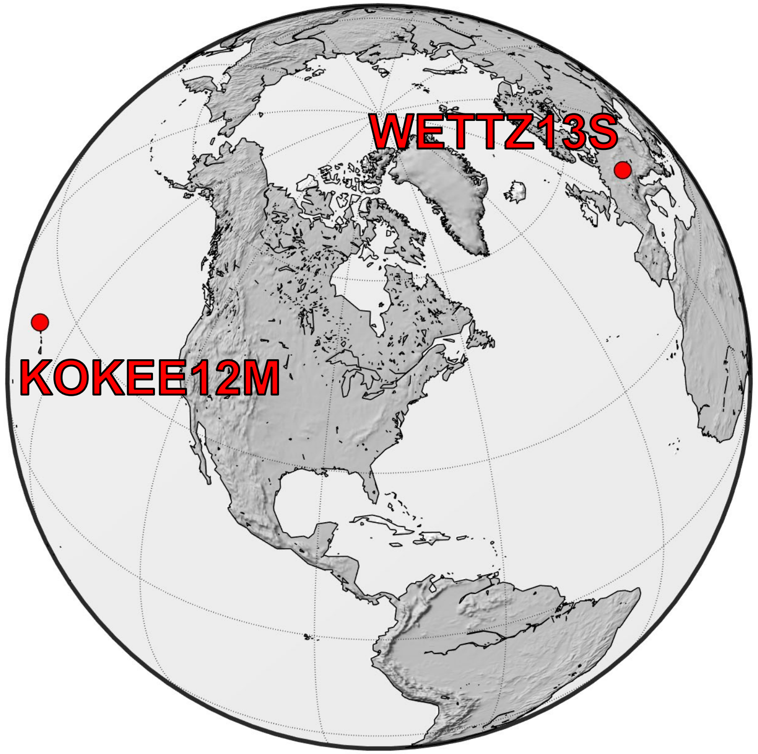


Example: Intensive session

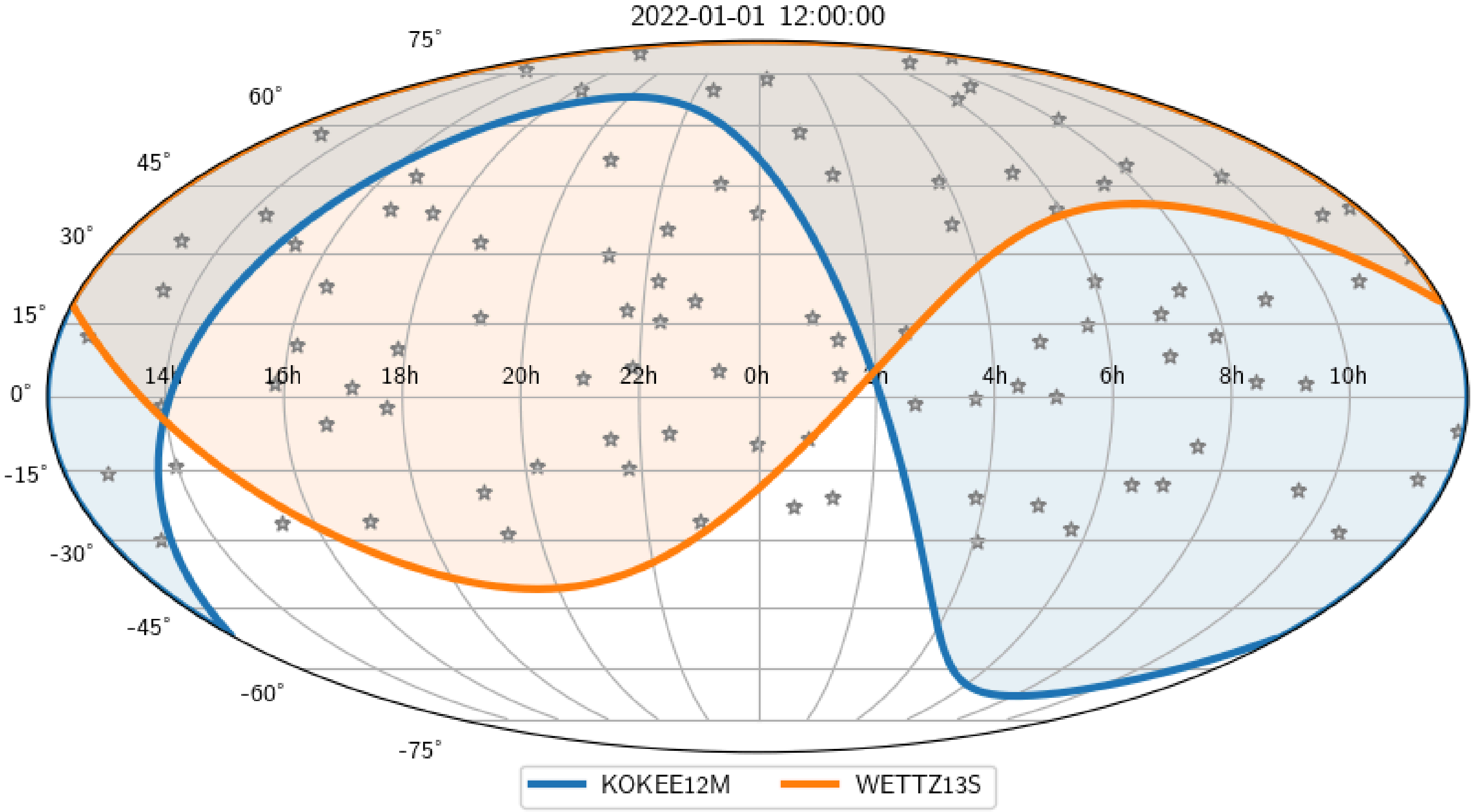
Example VGOS Intensive baseline

suitable baseline

- WETTZ13S
- KOKEE12M



theoretically possible observable sky

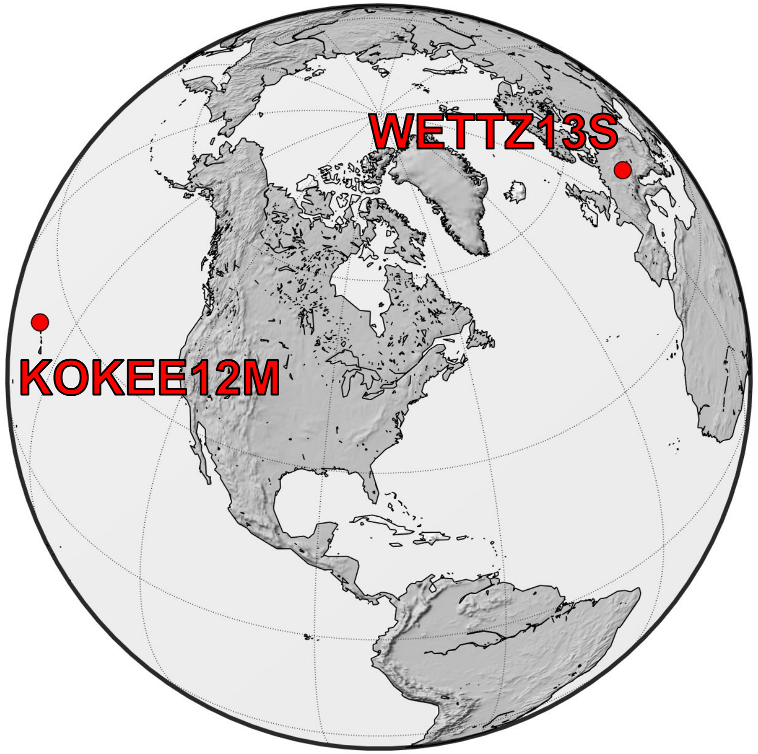


Matthias Schartner – mschartner@ethz.ch

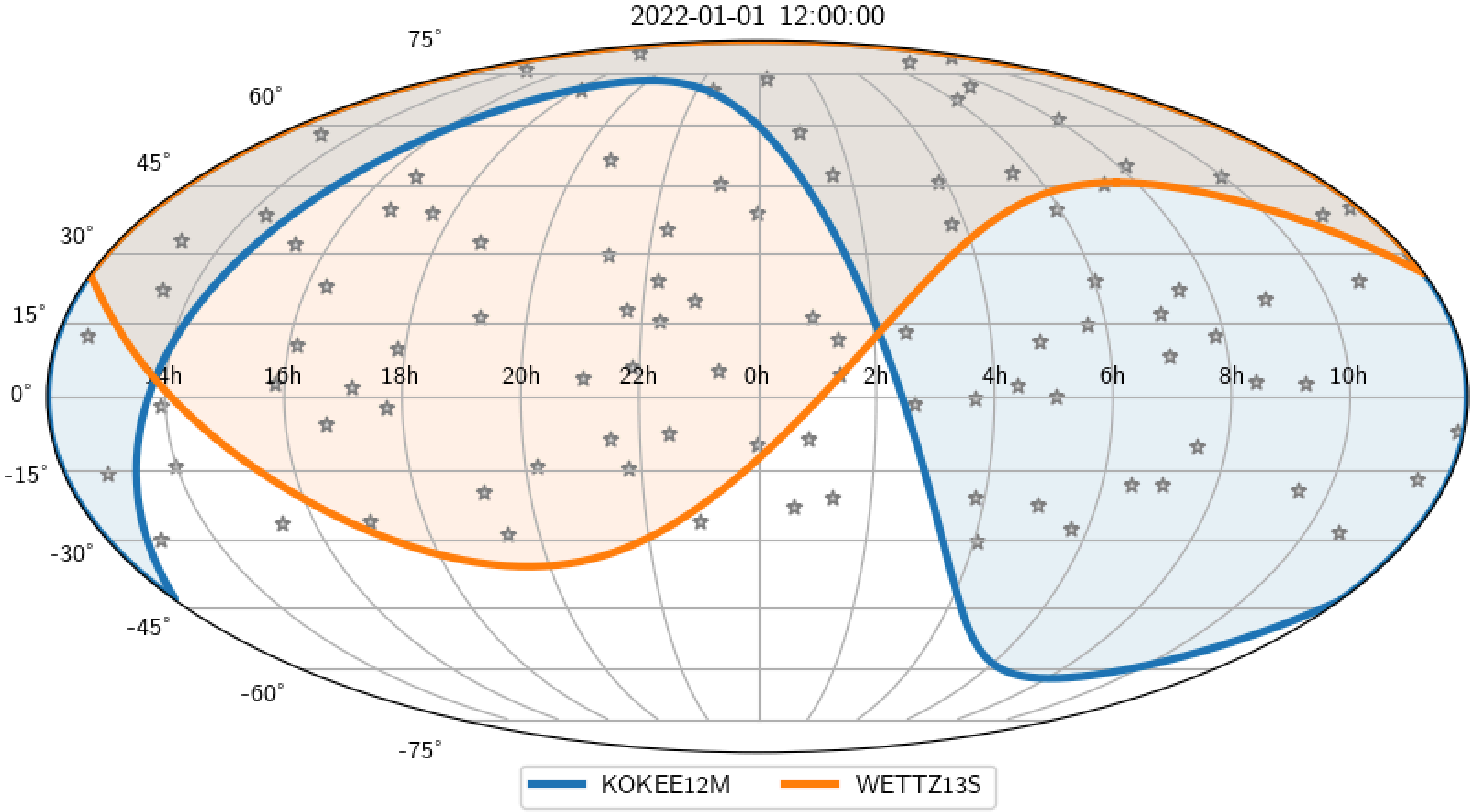
Example VGOS Intensive baseline

suitable baseline

- WETTZ13S
- KOKEE12M



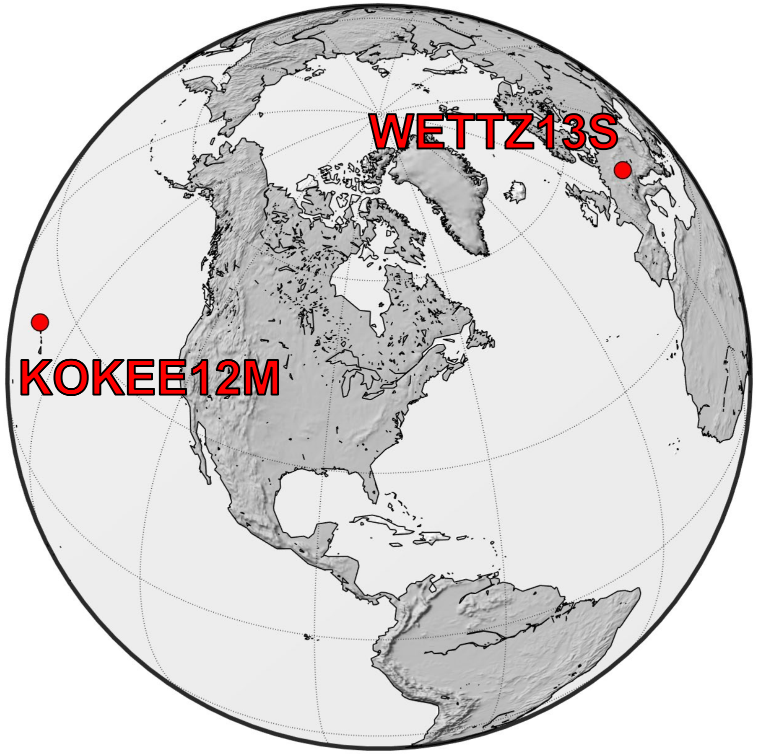
theoretically possible observable sky + 5° cutoff elevation



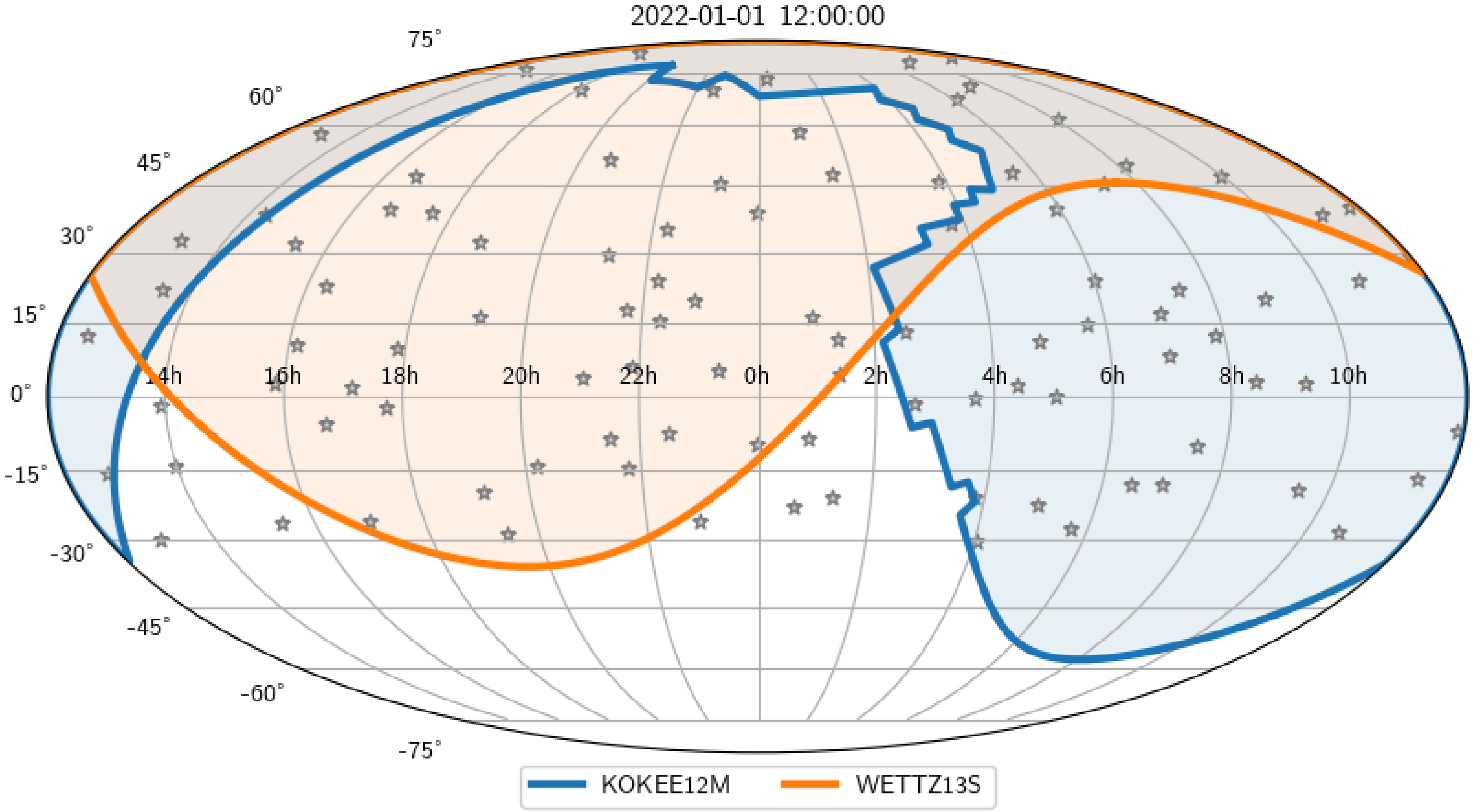
Example VGOS Intensive baseline

suitable baseline

- WETTZ13S
- KOKEE12M



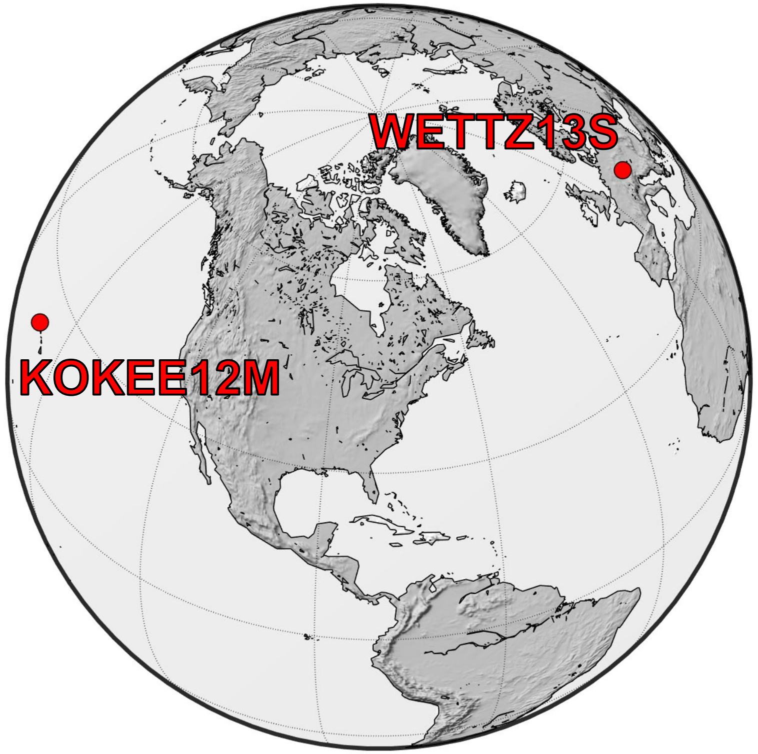
theoretically possible observable sky + 5° cutoff elevation + horizon mask



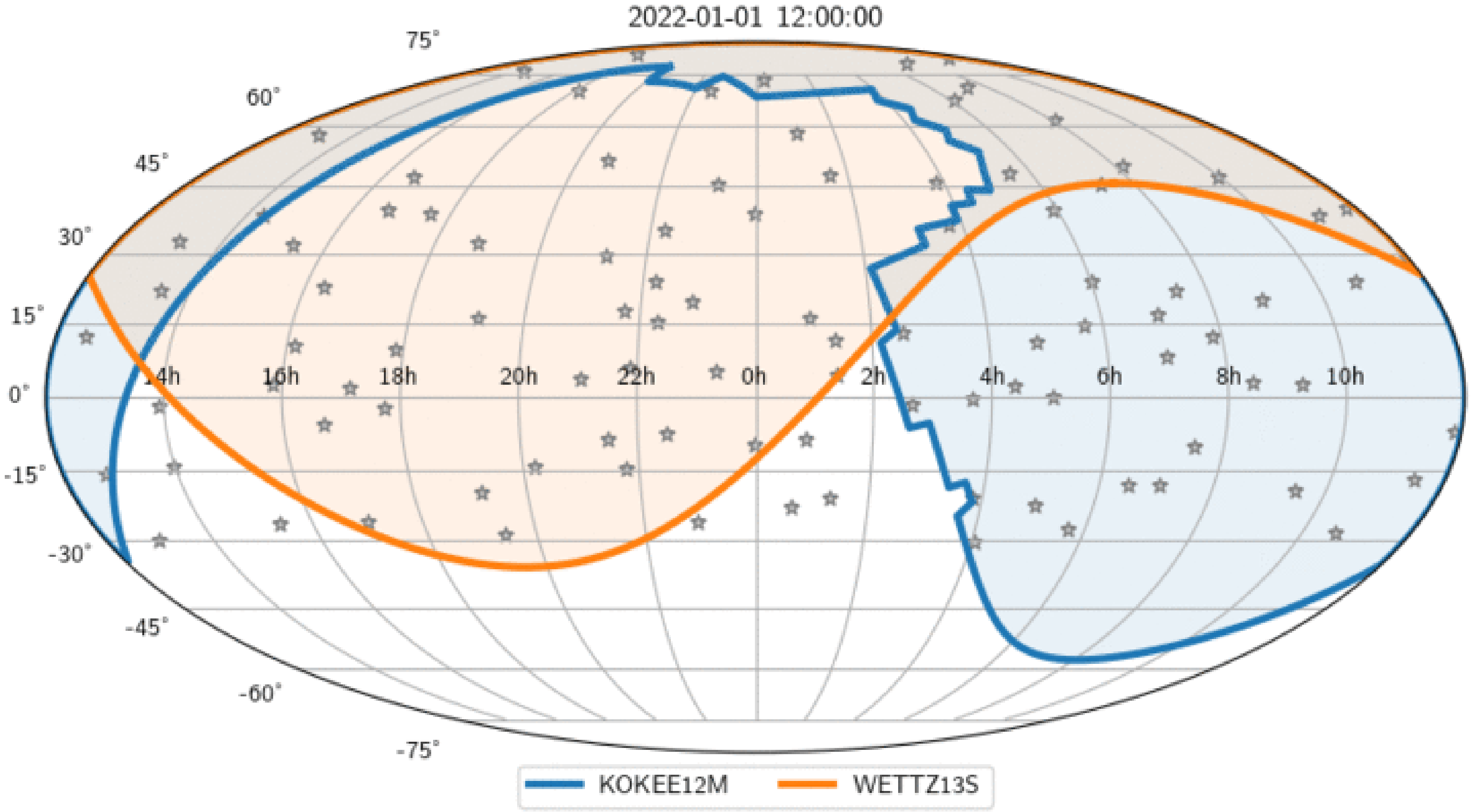
Example VGOS Intensive baseline

suitable baseline

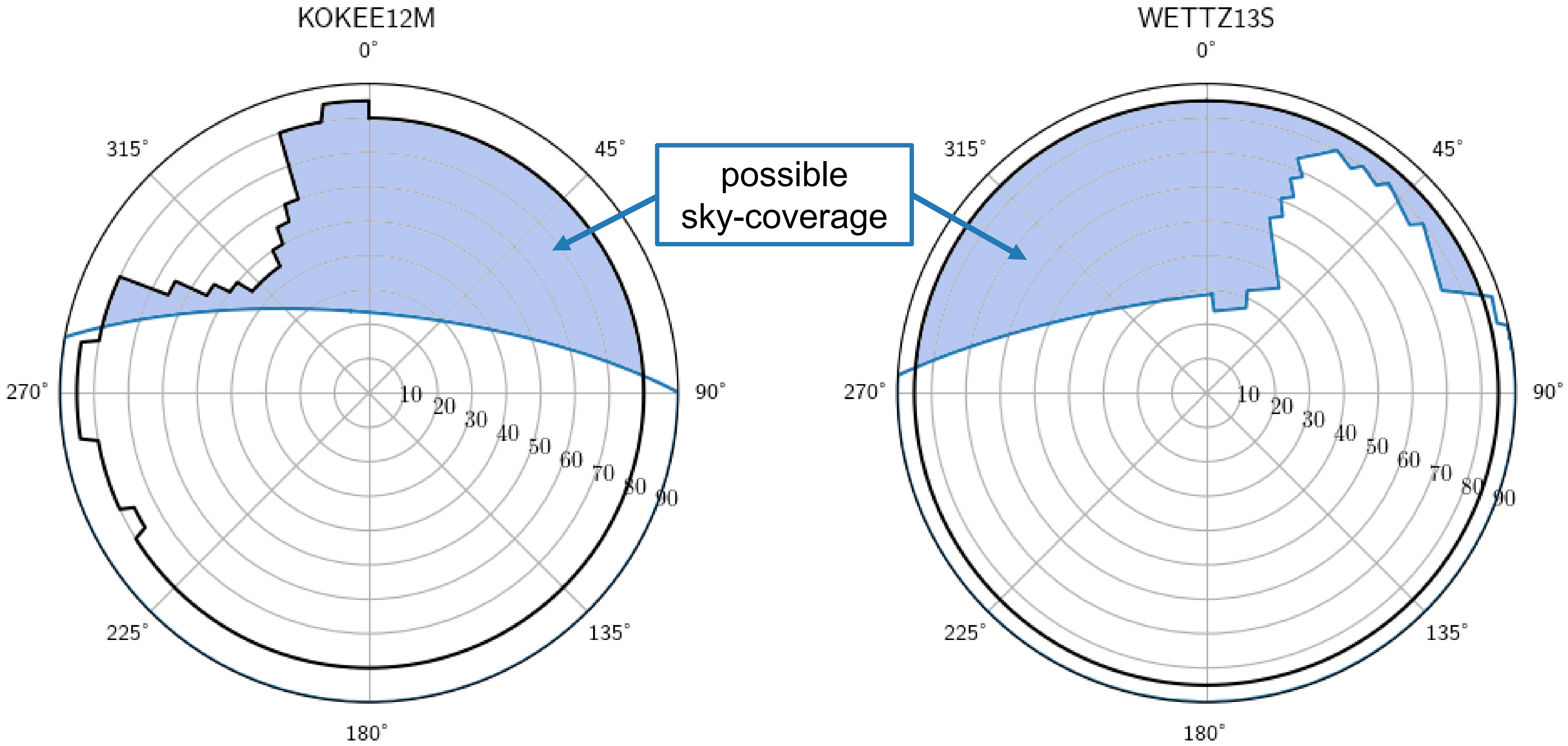
- WETTZ13S
- KOKEE12M



theoretically possible observable sky + 5° cutoff elevation + horizon mask

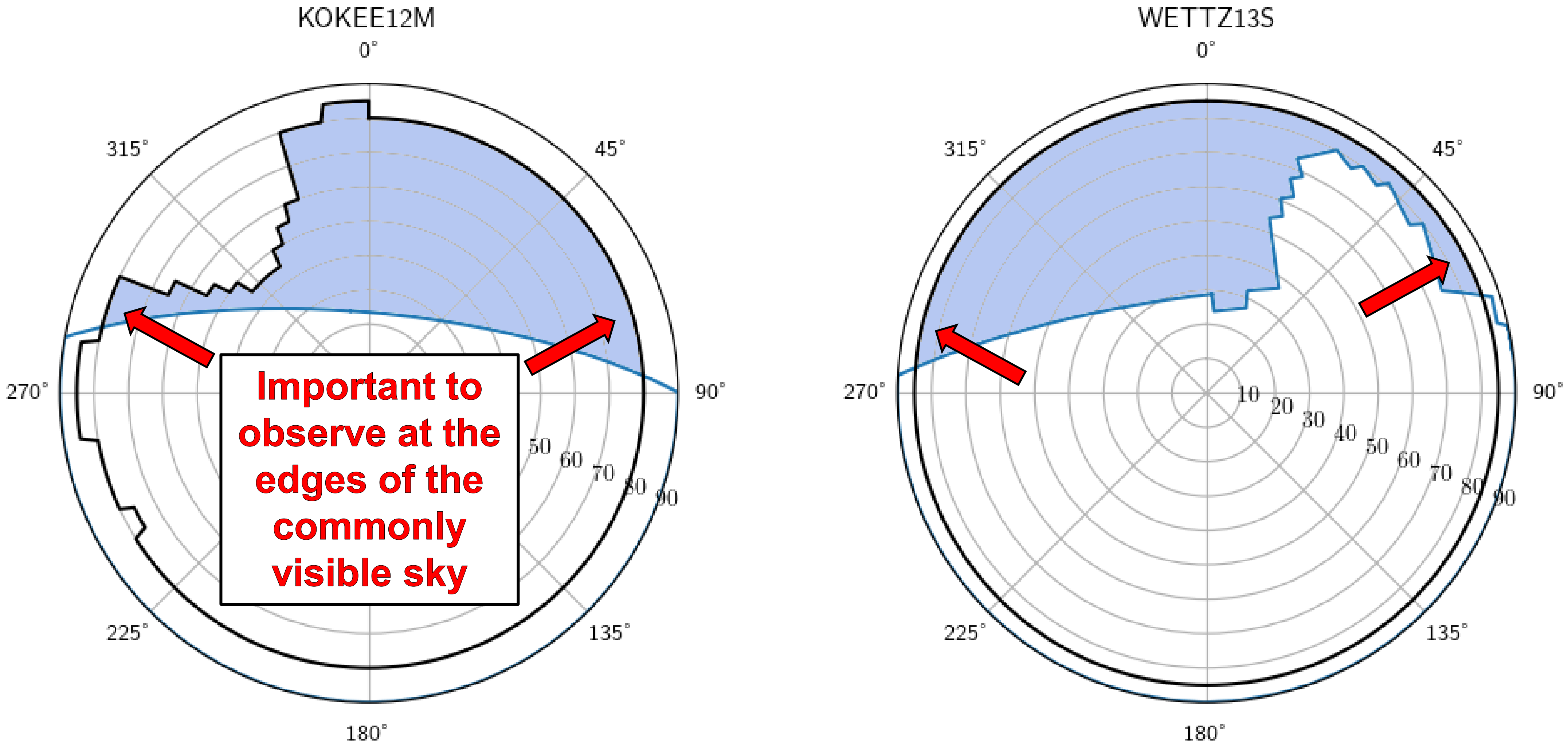


Example VGOS Intensive baseline



possible sky-coverage

Example VGOS Intensive baseline – Why expertise is important

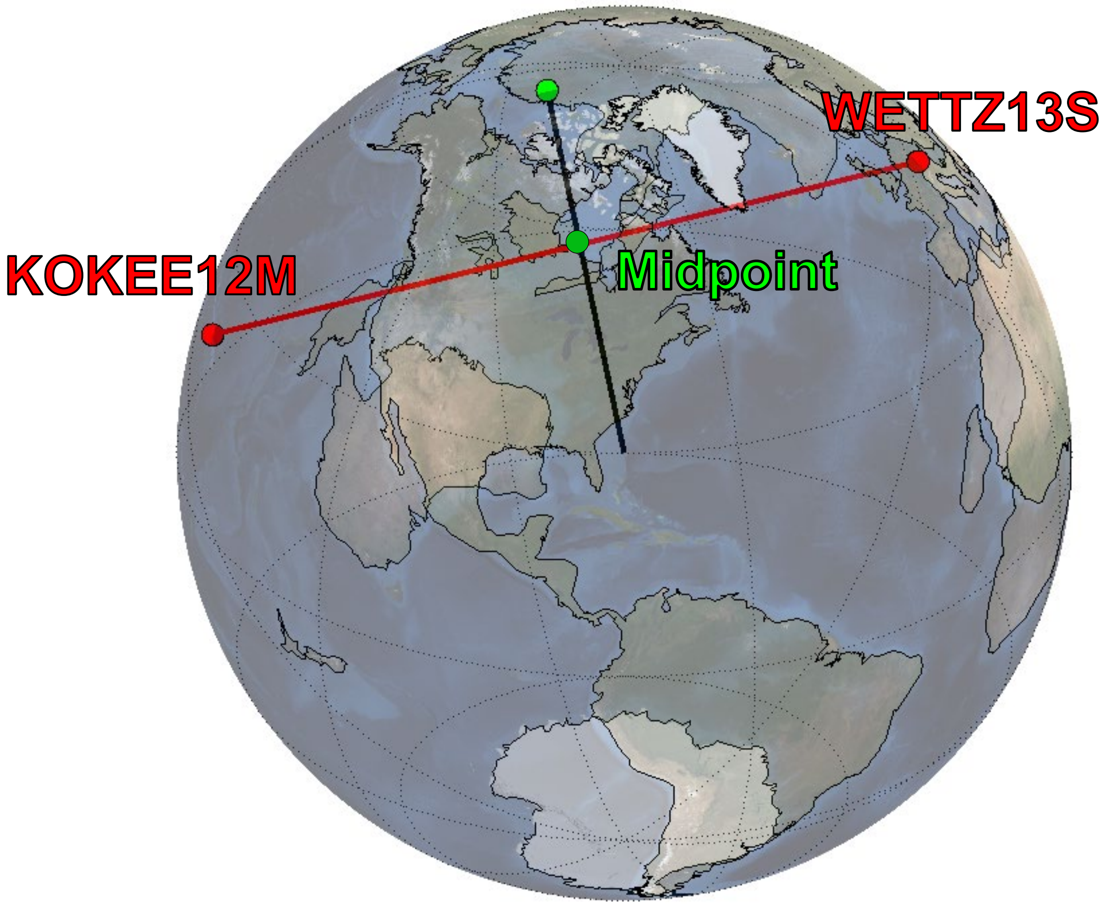


Important to observe at the edges of the commonly visible sky

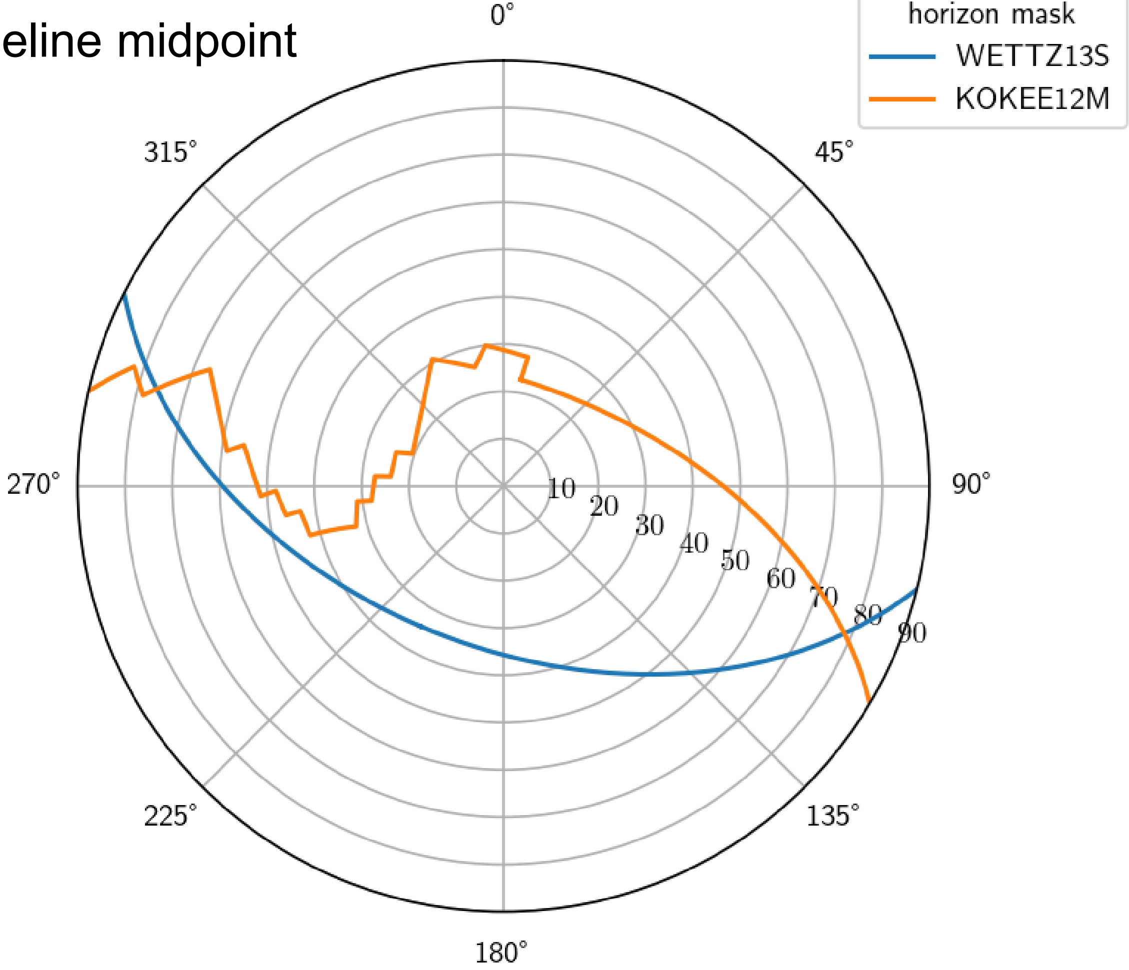
Matthias Schartner – mschartner@ethz.ch

Example VGOS Intensive baseline

self-study ☺



horizon masks from baseline midpoint



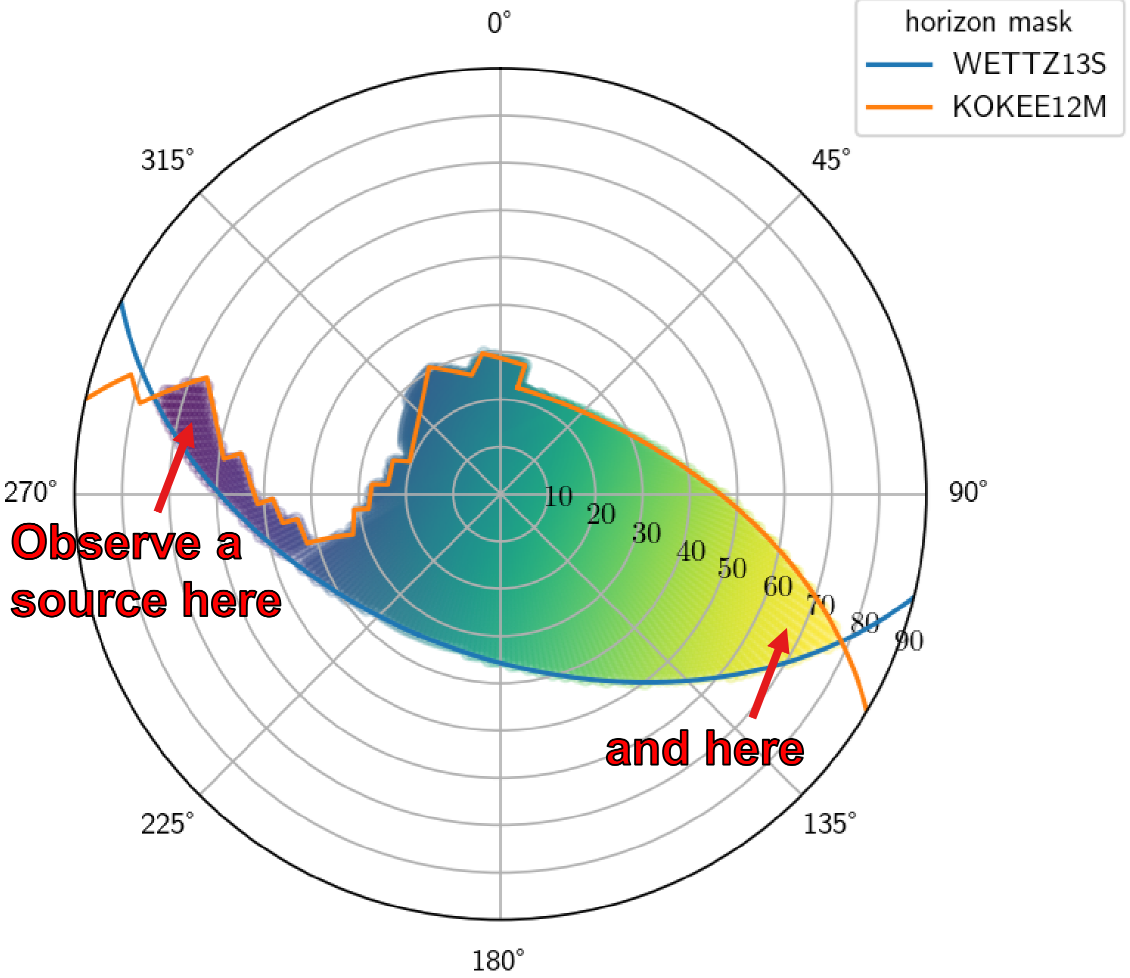
Example VGOS Intensive baseline

self-study ☺

- color-coded partial derivatives of dUT1
  - beneficial to put observations at **corners of mutually visible sky**
- but dUT1 is not only parameter that is estimated
  - ZWD: observations at **different elevation angles**

Conclusion:

Place observations around the edges of mutually visible sky (especially at the corners)



Observe a source here

and here

Know your objective

self-study ☺

Intensive session

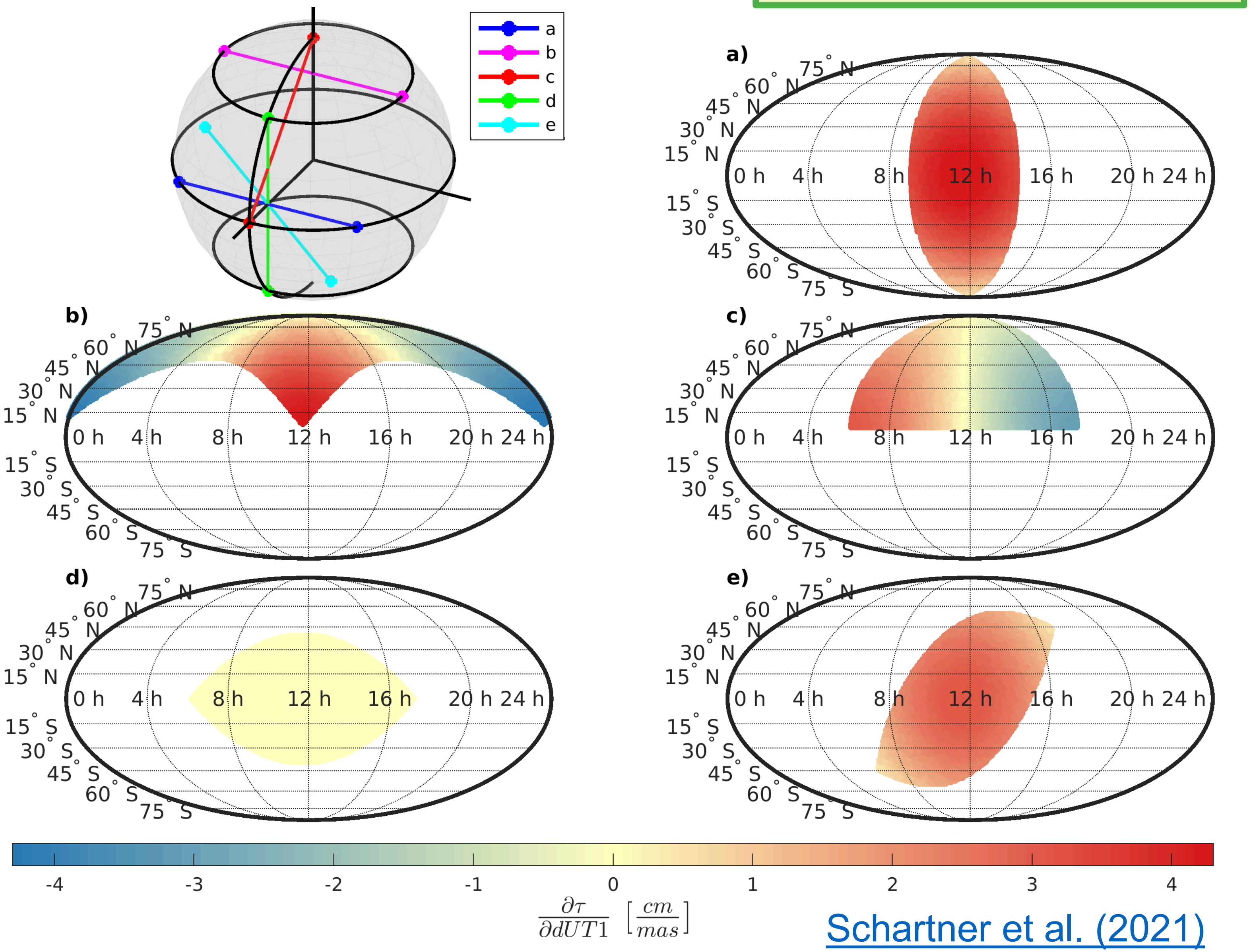
objective: dUT1

baseline geometry?

source selection?

scan distribution?

→ It is beneficial to know how analysis works and what is required or beneficial during analysis



Schartner et al. (2021)

self-study ☺

Example: 24-hour session

24-hour session

self-study ☺

scheduling becomes way more complex

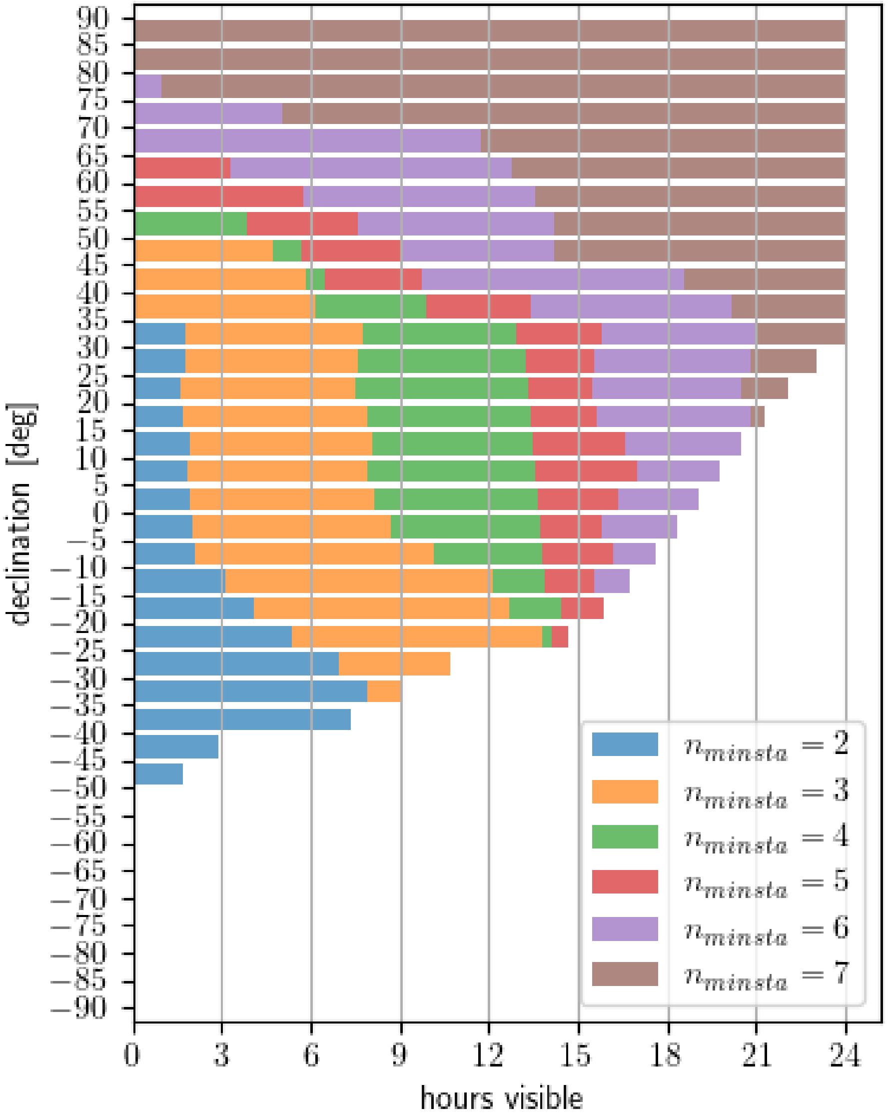
- **dUT1:** observations on long east-west baselines (simplified speaking)
- **polar motion:** observations on long north-south baselines
- **station coordinates:** many scans at different azimuth and elevation angles
- **source coordinates:** good distribution of scans among sources, north-south and east-west baselines
- **source imaging:** good uv-coverage, parallactic angles, etc.

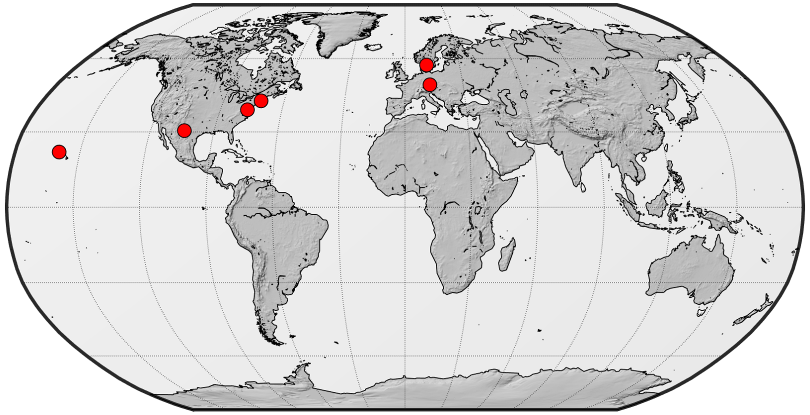
Remember:

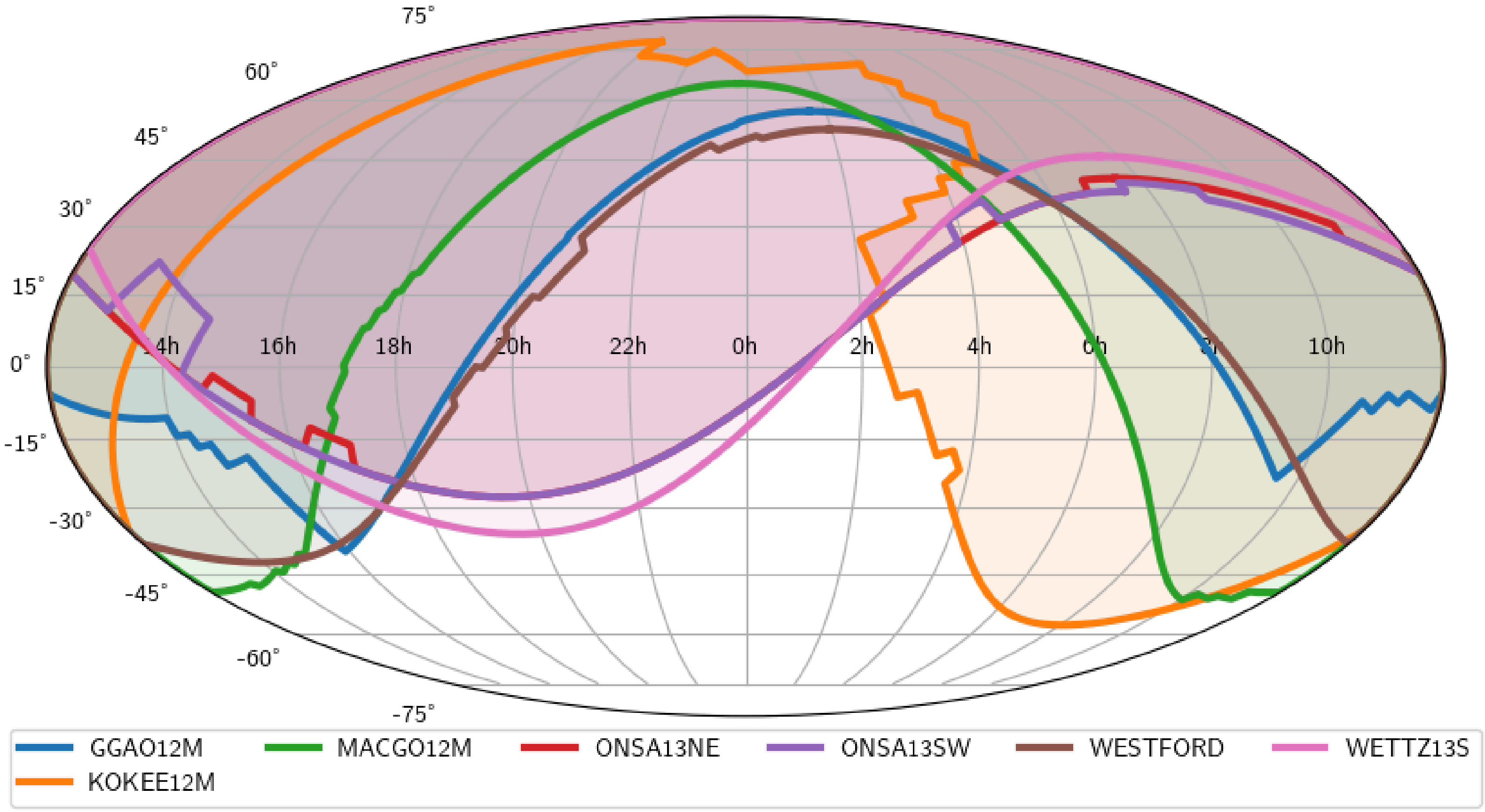
- Observations are not independent
- You always need at least two telescopes to observe together
- Tricky to fulfill all requirements

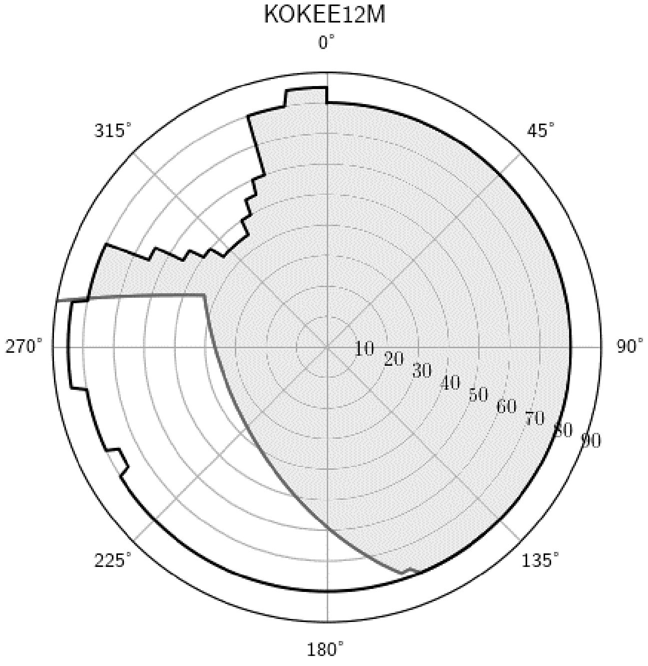
Example VGOS-network

self-study ☺

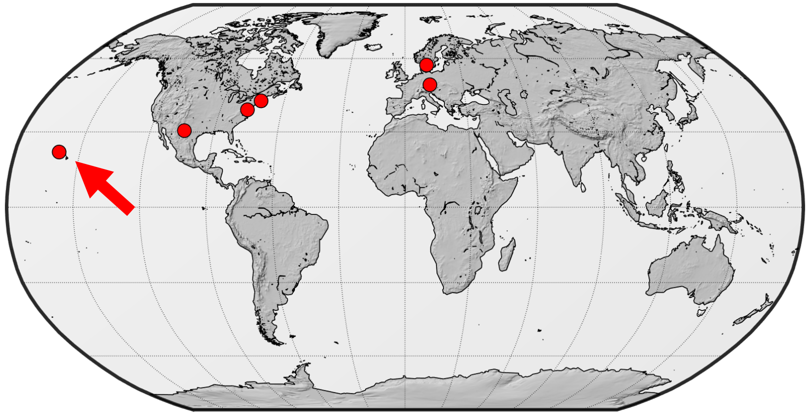


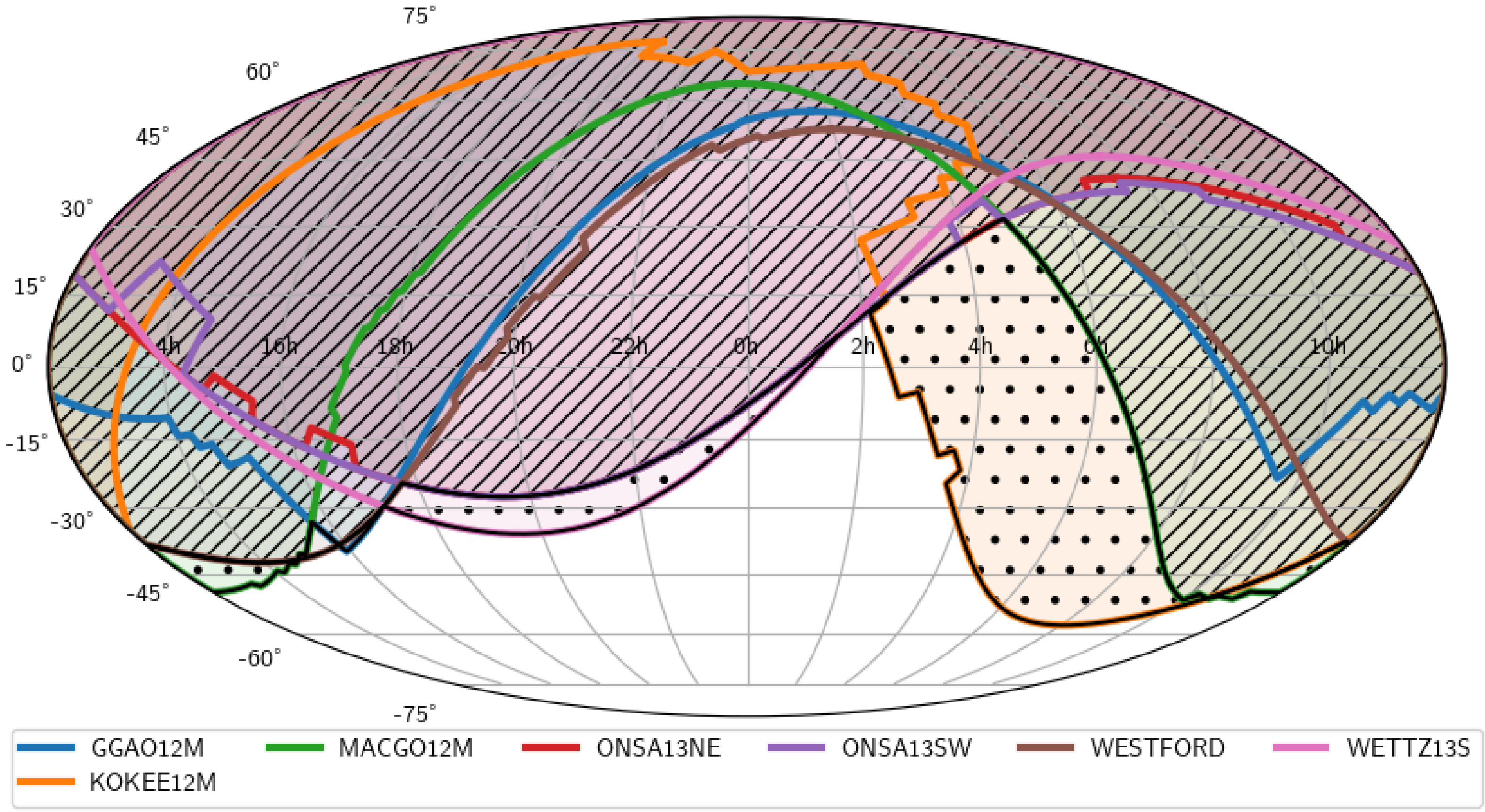






▭ observable by original network

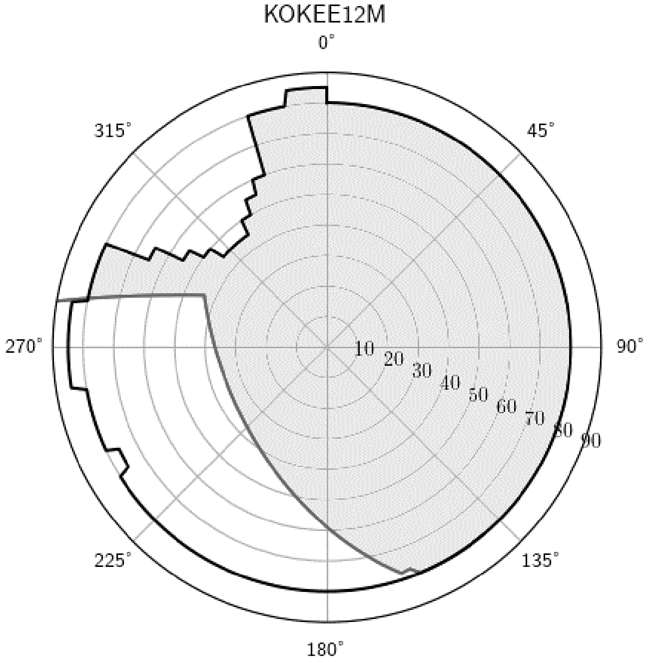




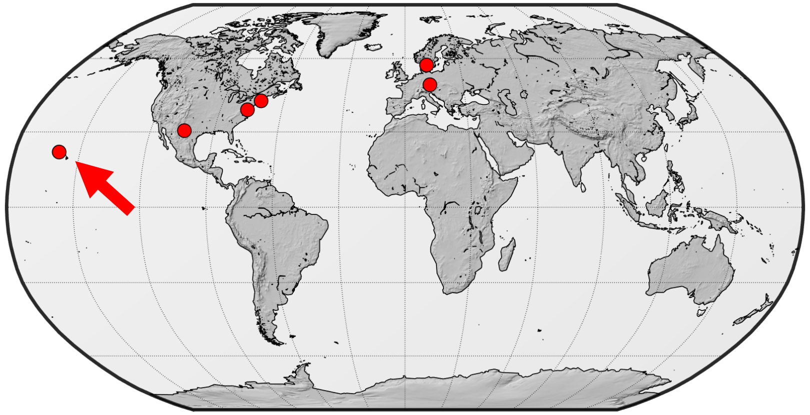
dashed: observable by at least two stations

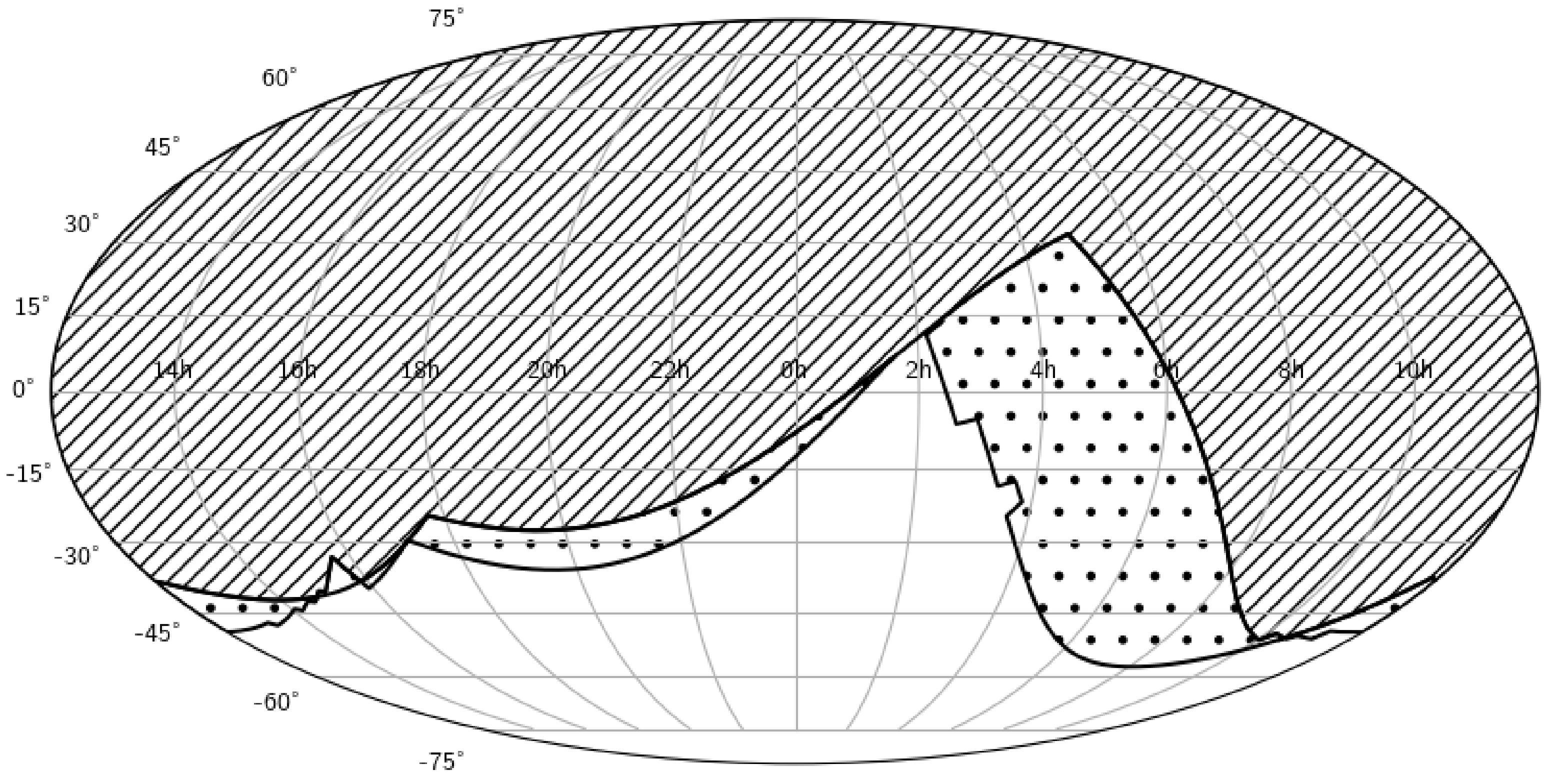
dotted: only observable by one station

self-study ☺



▭ observable by original network





dashed: observable by at least two stations

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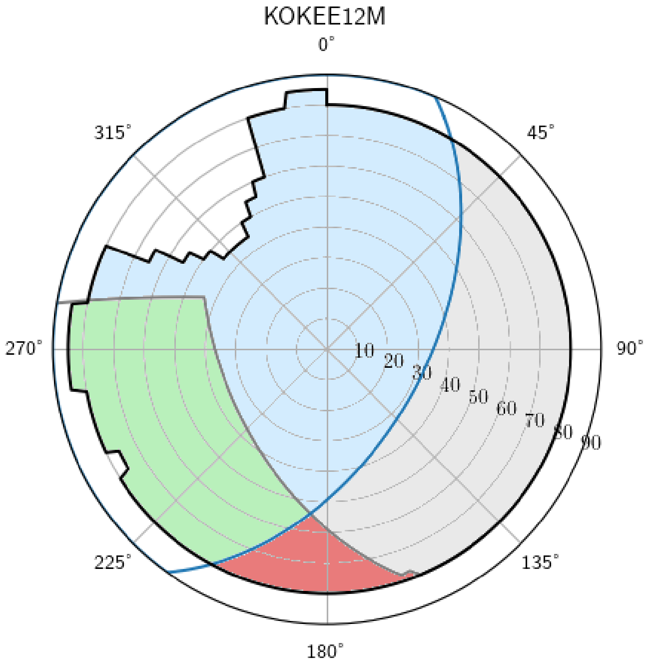
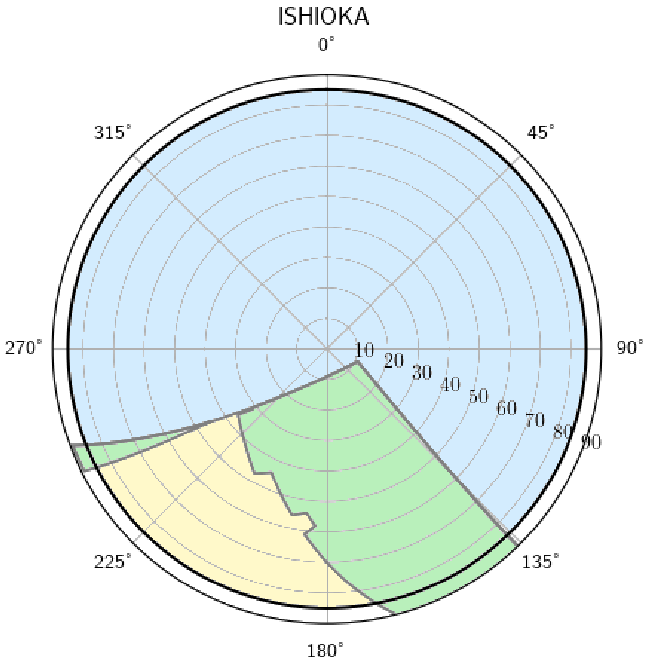
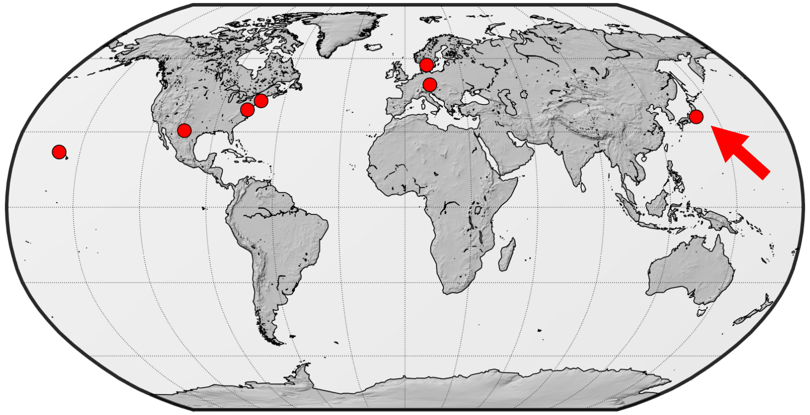
self-study ☺

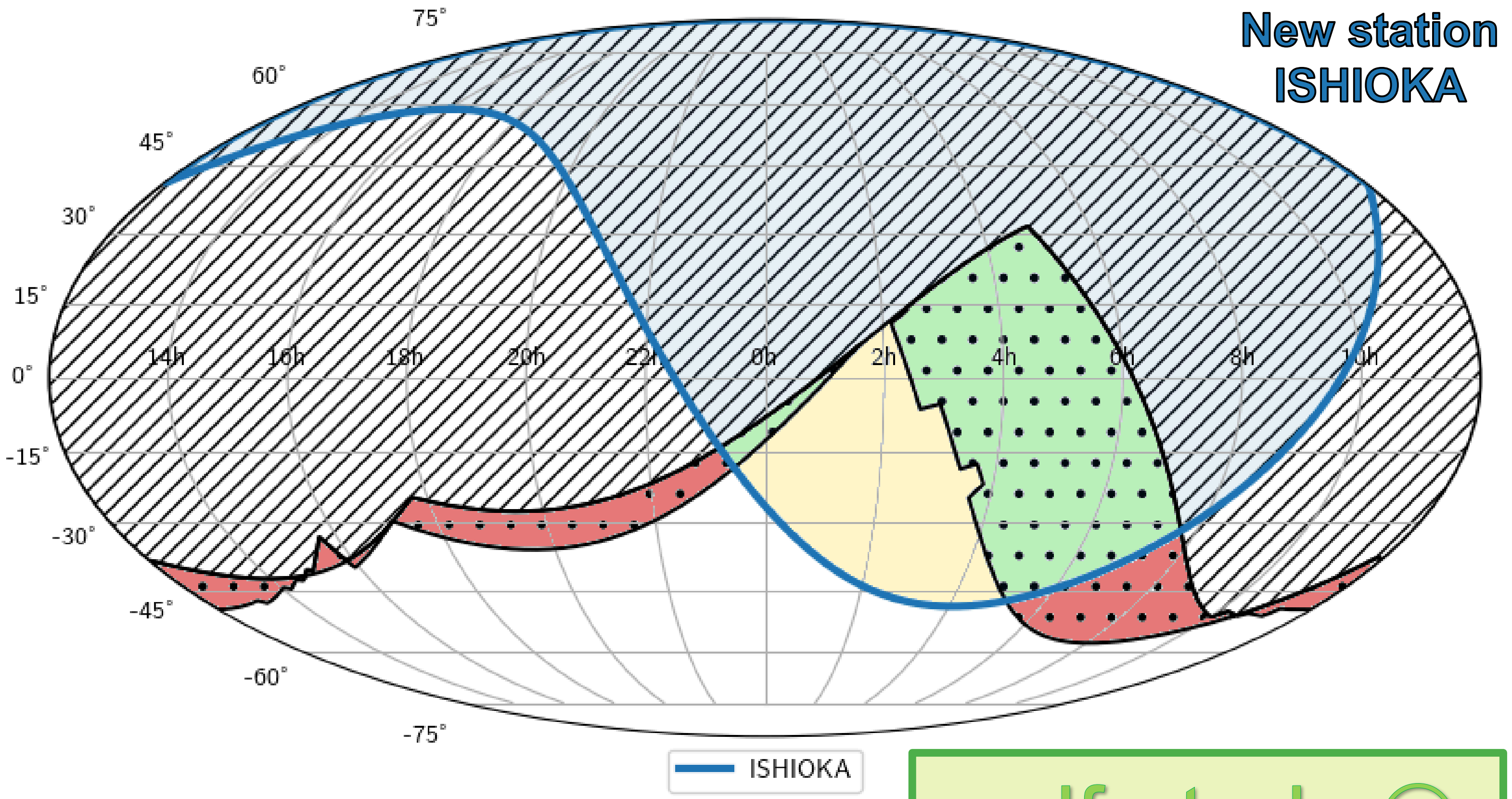




- ⬜ observable by original network
- 🟩 original network now observable
- 🟥 original network not observable
- ⬜ observable with ISHIOKA
- 🟨 not observable (only ISHIOKA)

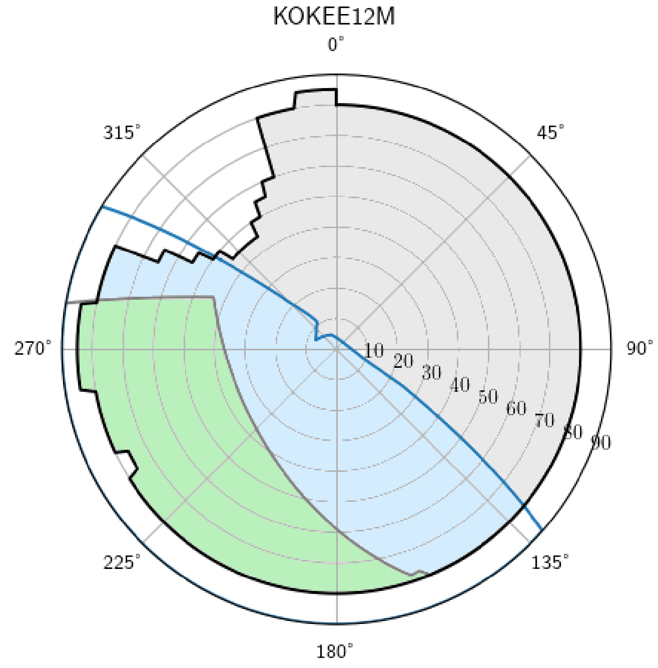


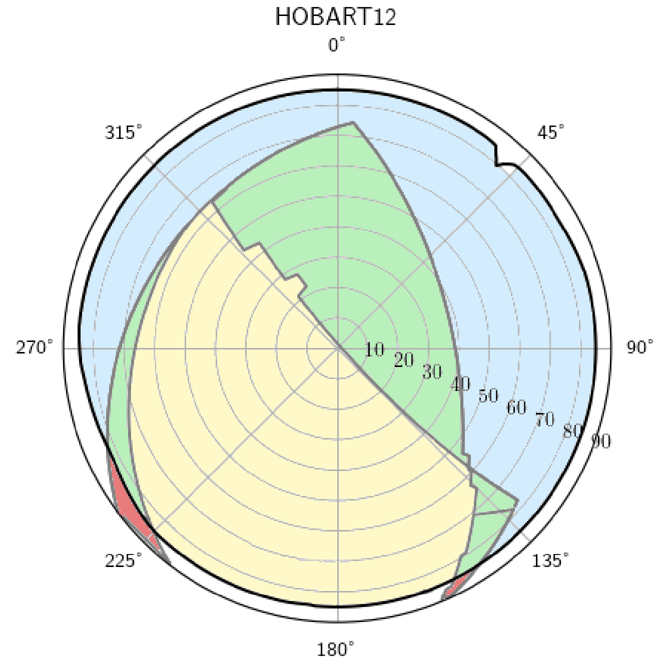
New station ISHIOKA



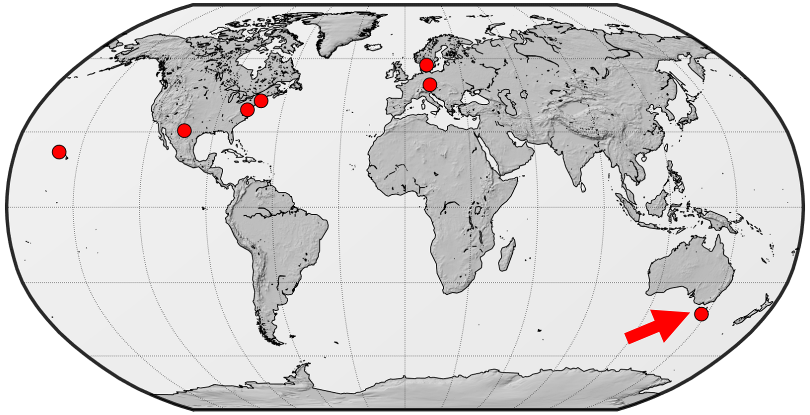
self-study ☺

Matthias Schartner – mschartner@ethz.ch

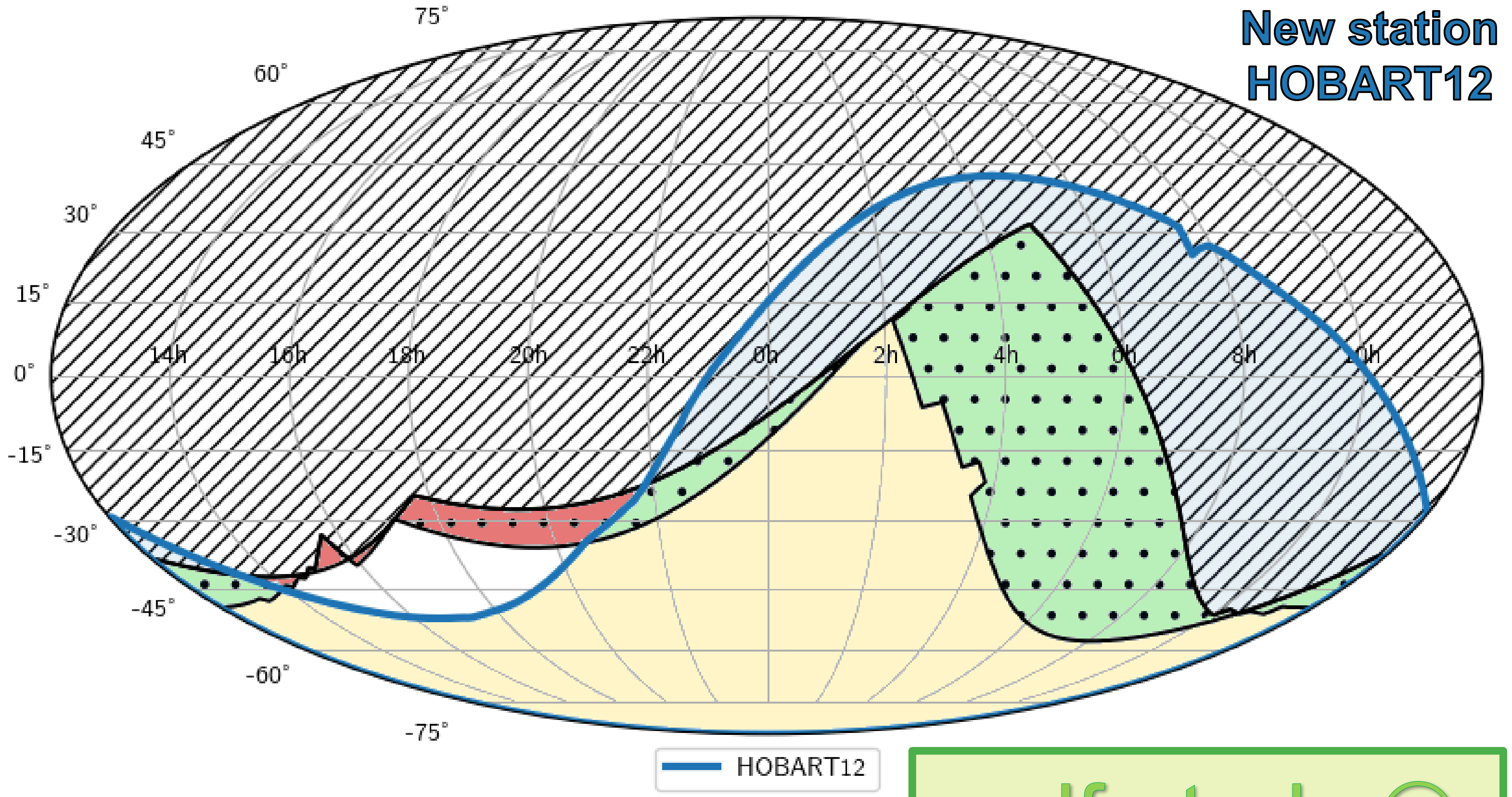




▢ observable by original network
🟩 original network now observable
🟥 original network not observable
▢ observable with HOBART12
🟨 not observable (only HOBART12)



New station HOBART12



self-study ☺

Matthias Schartner – mschartner@ethz.ch

mostly for self-studying ☺

Schartner 2019

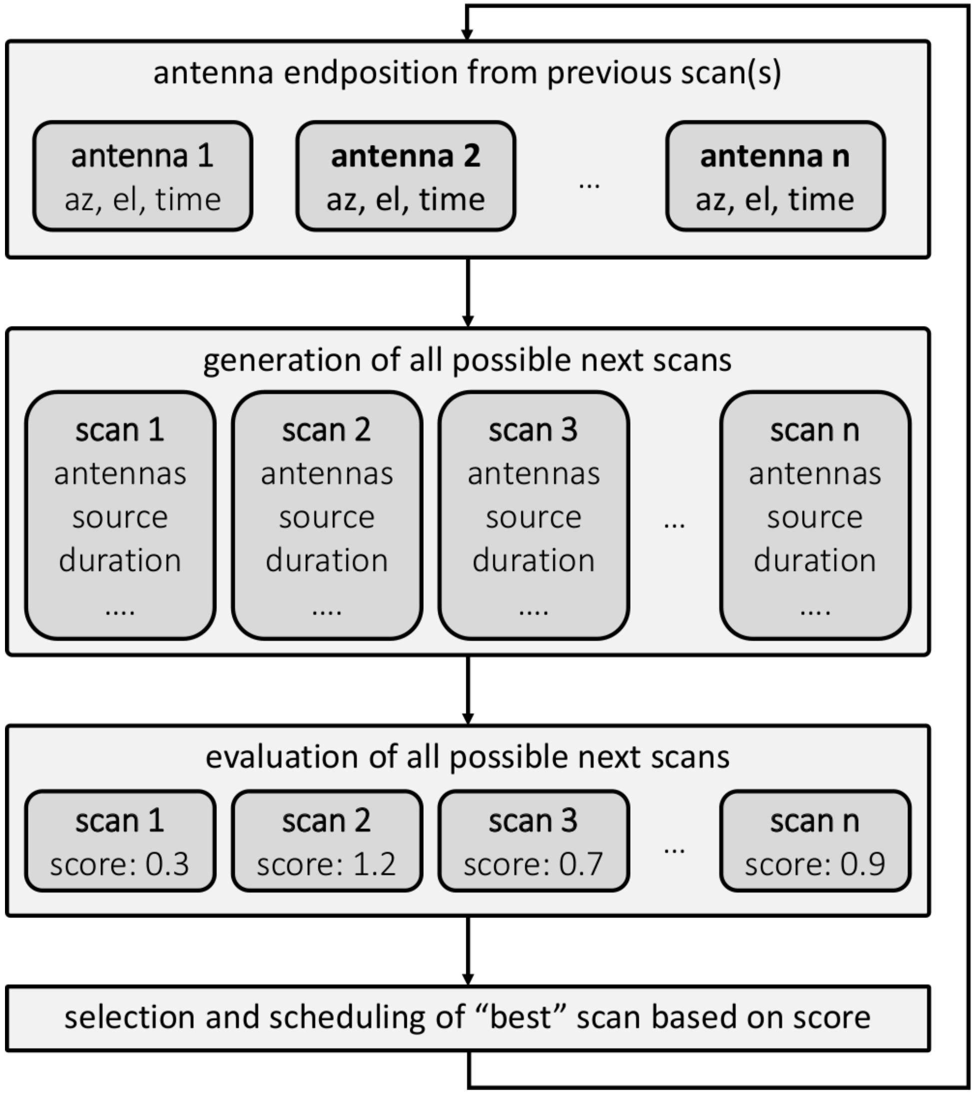
Algorithms

Scheduling

self-study ☺

24-hour VGOS session: 1000 – 4000 scans
1-hour VGOS intensive: 50 – 100 scans

- Schedule is generated scan after scan
- Every (reasonable) scan is evaluated based on various optimization criteria
  - improvement in sky-coverage
  - number of observations
  - scan duration (FS-commands, slew, idle, preob, observing…)
  - idle time
  - …
- Define certain “weights” of these optimization criteria
- Selection of “best” scan based on weighted sum from optimization criteria (score)



antenna endposition from previous scan(s)

antenna 1 az, el, time | **antenna 2** az, el, time | … | **antenna n** az, el, time

generation of all possible next scans

scan 1 antennas source duration …. | **scan 2** antennas source duration …. | **scan 3** antennas source duration …. | … | **scan n** antennas source duration ….

evaluation of all possible next scans

scan 1 score: 0.3 | **scan 2** score: 1.2 | **scan 3** score: 0.7 | … | **scan n** score: 0.9

selection and scheduling of “best” scan based on score

Scheduling

self-study ☺

24-hour VGOS session: 1000 – 4000 scans
1-hour VGOS intensive: 50 – 100 scans

- Schedule is generated scan after scan
- Every (reasonable) scan is evaluated based on various optimization criteria
  - **improvement in sky-coverage**
  - number of observations
  - scan duration (FS-commands, slew, idle, preob, observing…)
  - idle time
  - …
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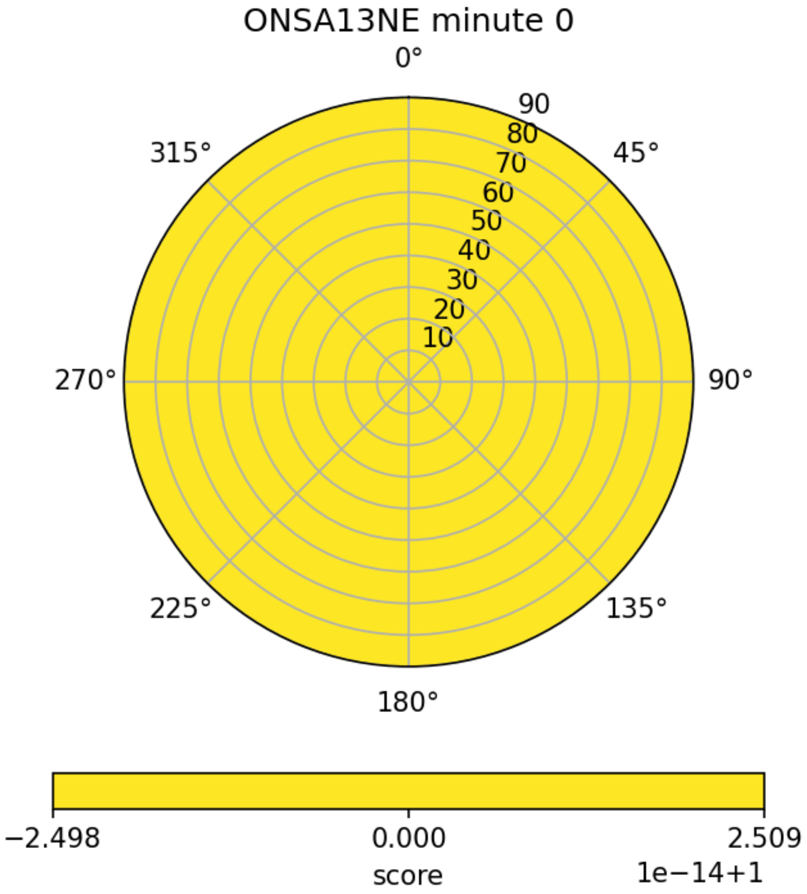
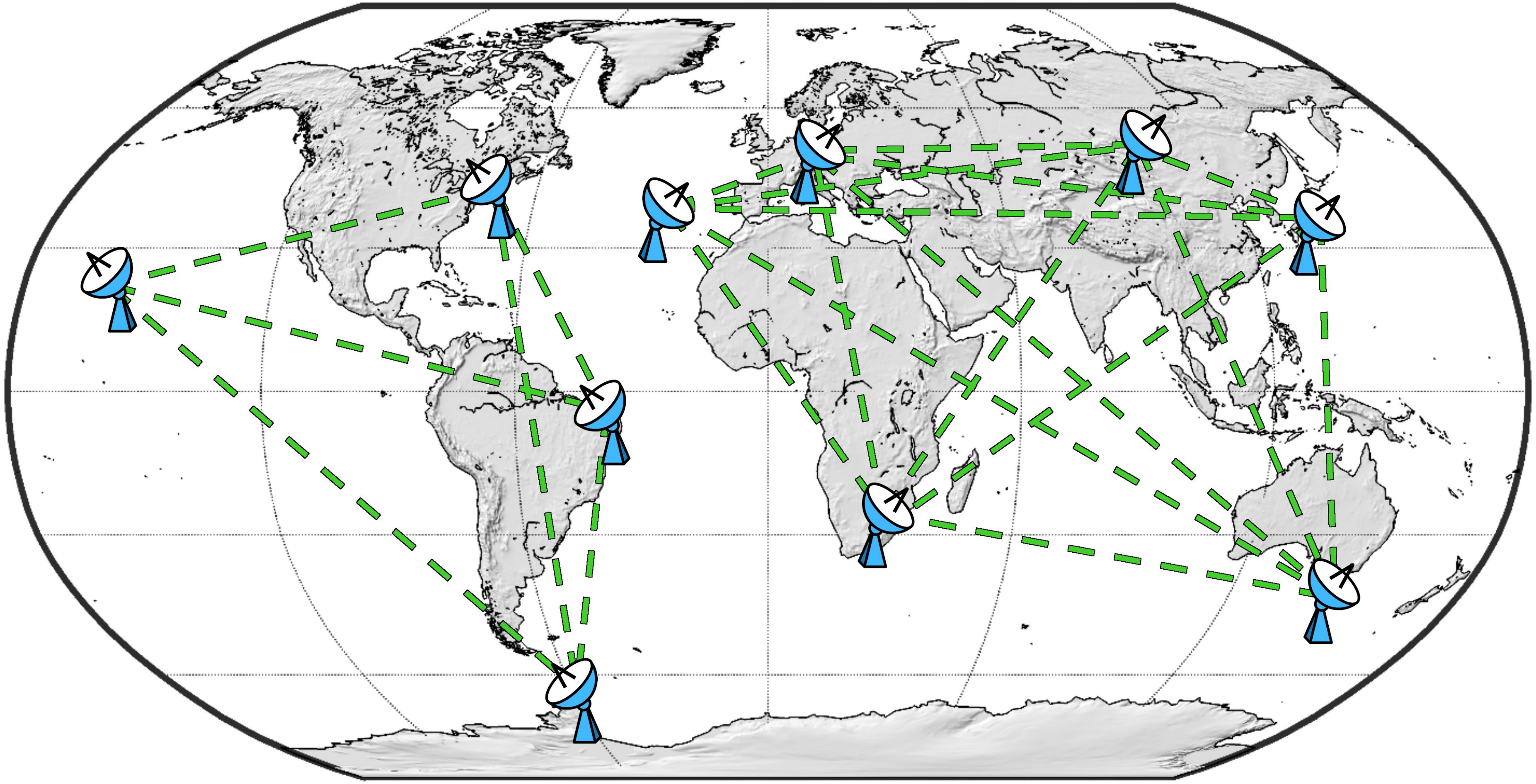


Subnetting

Global network means that it is **not possible** for all stations to observe the same source simultaneously – they all see different parts of the sky

Approach:
Divide network into two sub-networks – each observing a different source simultaneously



Subnetting

self-study ☺

- Remember: $n_{obs} = \frac{n_{sta} \cdot (n_{sta} - 1)}{2}$
- If you have 10 stations, you get a maximum of 45 observations
- If you divide your network into $5 + \ 5$ station scans, you get $10 + 10 = 20$ observations
- If you divide your network into $6 \ + 4$ station scans, you get $15 + 6 = 21$ observations
- If you divide your network into $7 \ + 3$ station scans, you get $21 + 3 = 24$ observations
- If you divide your network into $8 \ + 2$ station scans, you get $28 + 1 = 29$ observations

Based on number of observations, it is best to perform an “imbalanced” subnetting

Subnetting

self-study ☺

Example:

- 10 station network
- 3 see exclusively **source 1**
- 3 see exclusively **source 2**
- 4 see both, **source 1** and **source 2**

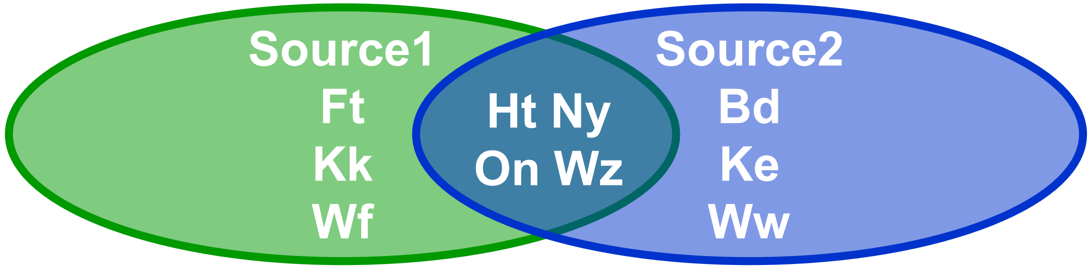
→ increased complexity through increased number of possibilities

pros and cons:

necessary for scheduling global network

too much subnetting leads to low #obs

higher complexity

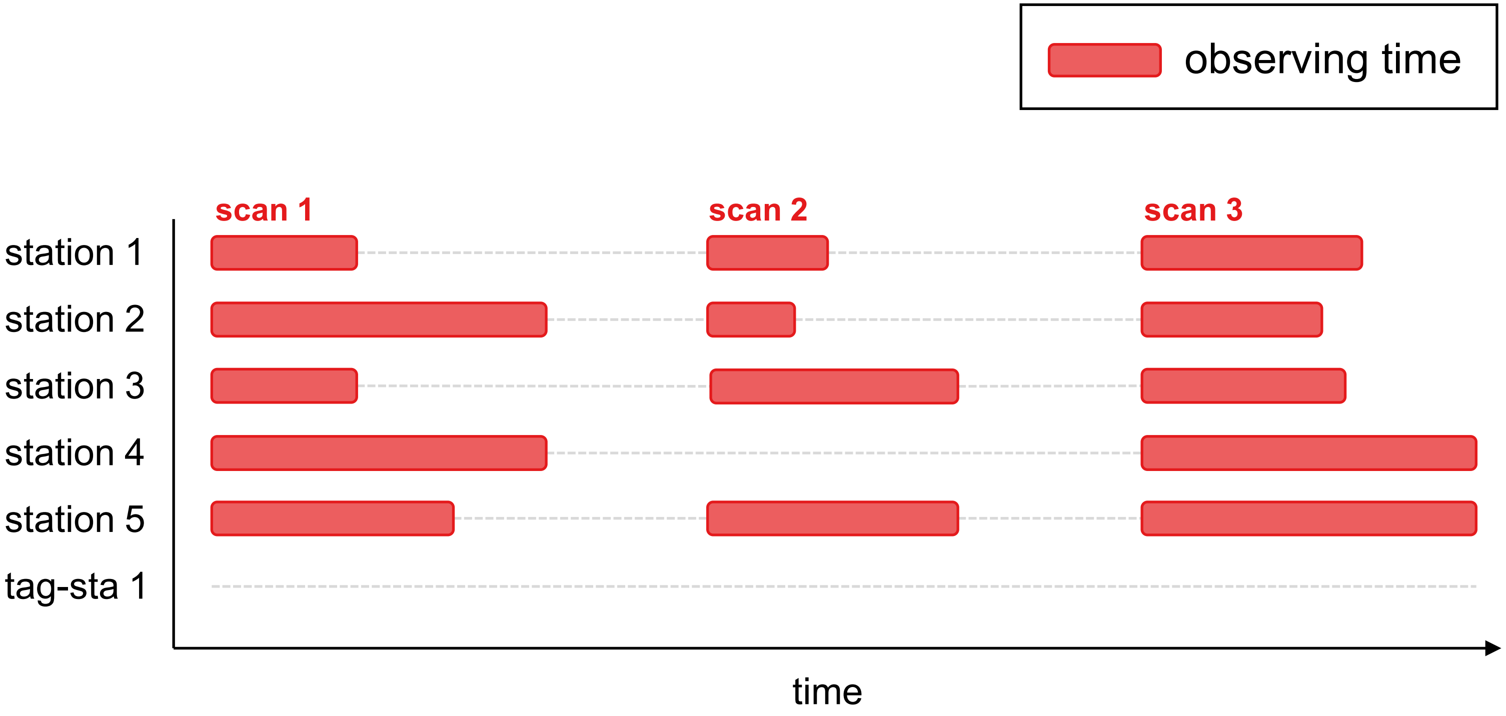


version	scan of source 1	scan of source 2
1	Ft Kk Wf Ht Ny On Wz	
2		Bd Ke Ww Ht Ny On Wz
3	Ft Kk Wf Ht Ny On Wz	Bd Ke Ww
4	Ft Kk Wf Ht Ny On	Bd Ke Ww Wz
5	Ft Kk Wf Ht Ny Wz	Bd Ke Ww On
6	Ft Kk Wf Ht On Wz	Bd Ke Ww Ny
7	Ft Kk Wf Ny On Wz	Bd Ke Ww Ht
8	Ft Kk Wf Ht Ny	Bd Ke Ww On Wz
9	Ft Kk Wf Ht On	Bd Ke Ww Ny Wz
10	Ft Kk Wf Ht Wz	Bd Ke Ww Ny On
11	Ft Kk Wf Ny On	Bd Ke Ww Ht Wz
12	Ft Kk Wf Ny Wz	Bd Ke Ww Ht On
13	Ft Kk Wf On Wz	Bd Ke Ww Ht Ny
14	Ft Kk Wf Ht	Bd Ke Ww Ny On Wz
15	Ft Kk Wf Ny	Bd Ke Ww Ht On Wz
16	Ft Kk Wf On	Bd Ke Ww Ht Ny Wz
17	Ft Kk Wf Wz	Bd Ke Ww Ht Ny On
18	Ft Kk Wf	Bd Ke Ww Ht Ny On Wz

Tagalong mode

Sometimes it is not clear if station can participate in a session or will produce meaningful observations
- new, untested stations
- stations with known problems
- station under maintainance
- …

1. generate schedule without this station



Tagalong mode

Sometimes it is not clear if station can participate in a session or will produce meaningful observations

- new, untested stations
- stations with known problems
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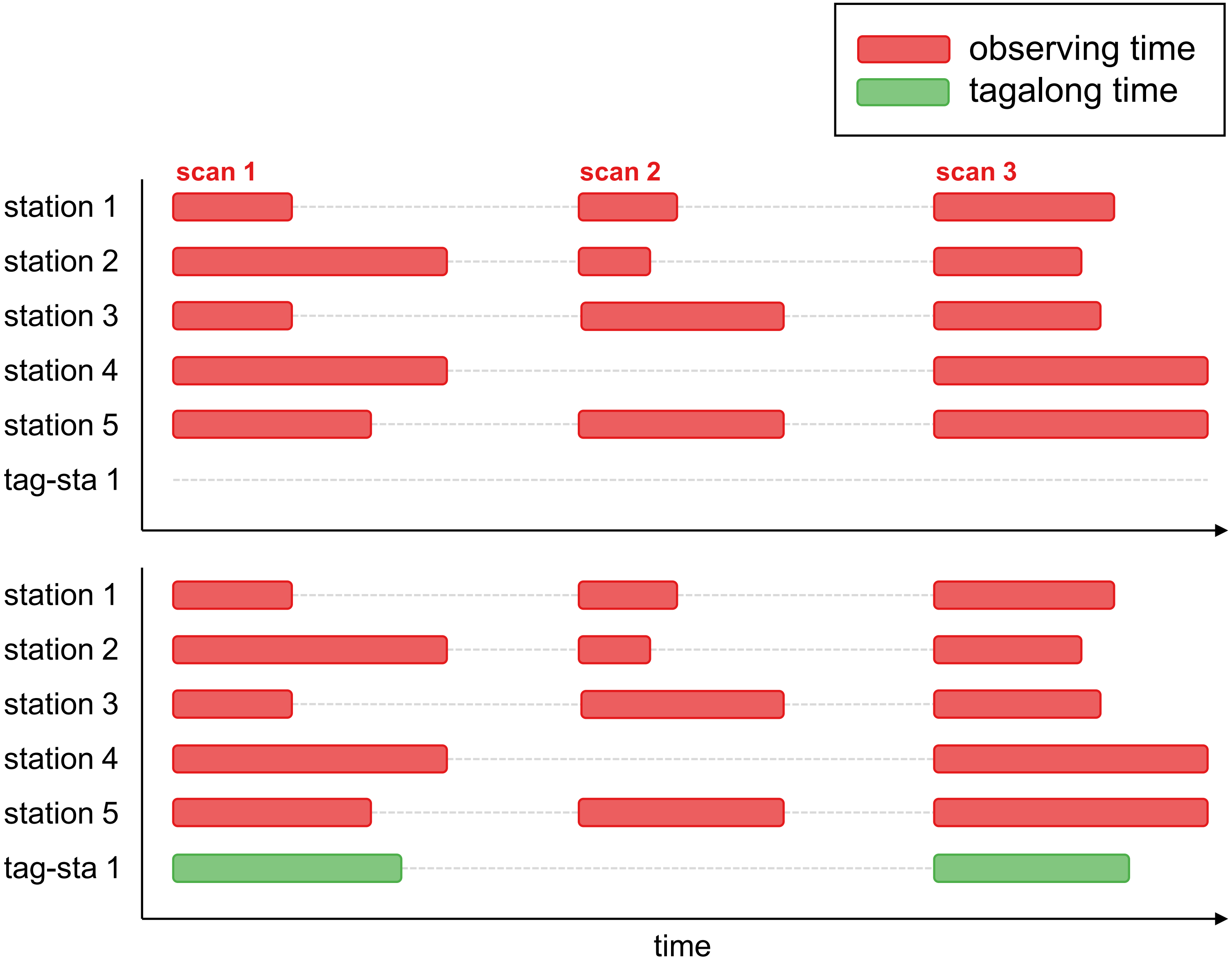
- …

1. generate schedule without this station
2. add station to as many scans as possible

Problematic for remote station or station with poor sensitivity



Tagalong mode

Sometimes it is not clear if station can participate in a session or will produce meaningful observations

- **new, untested stations**
- **stations with known problems**
- **station under maintainance**
- …

1. generate schedule without this station
2. add station to as many scans as possible

Problematic for remote station or station with poor sensitivity

please report errors

Fillin mode

self-study ☺

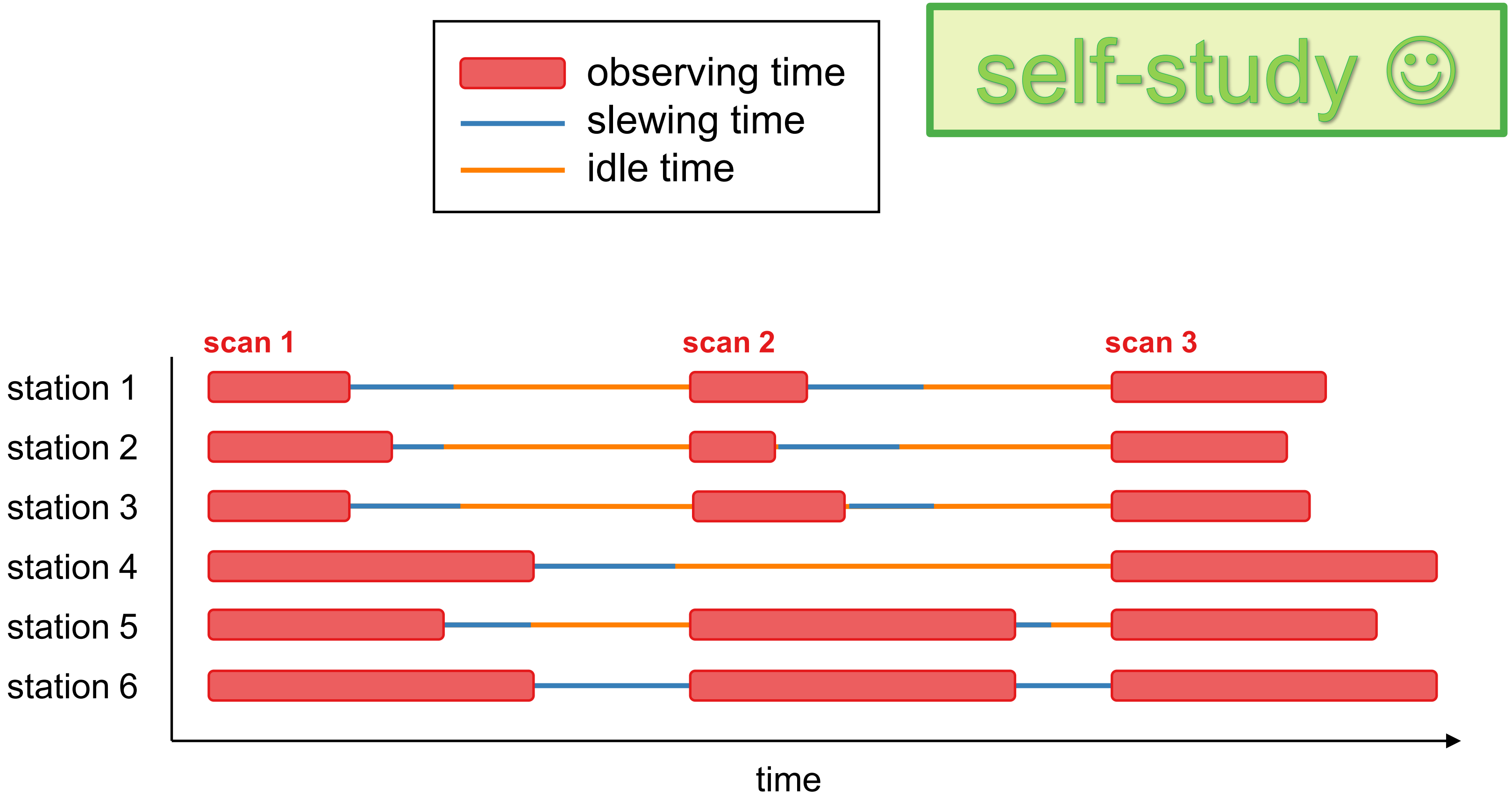
antennas have different characteristics:

- slew rate
- sensitivity

→ different scan start/stop times

convention:
all antennas start at the same time

→ different stop times



Fillin mode

🟥 observing time
— slewing time
— idle time
🟩 fillin-mode

self-study ☺

antennas have different characteristics:

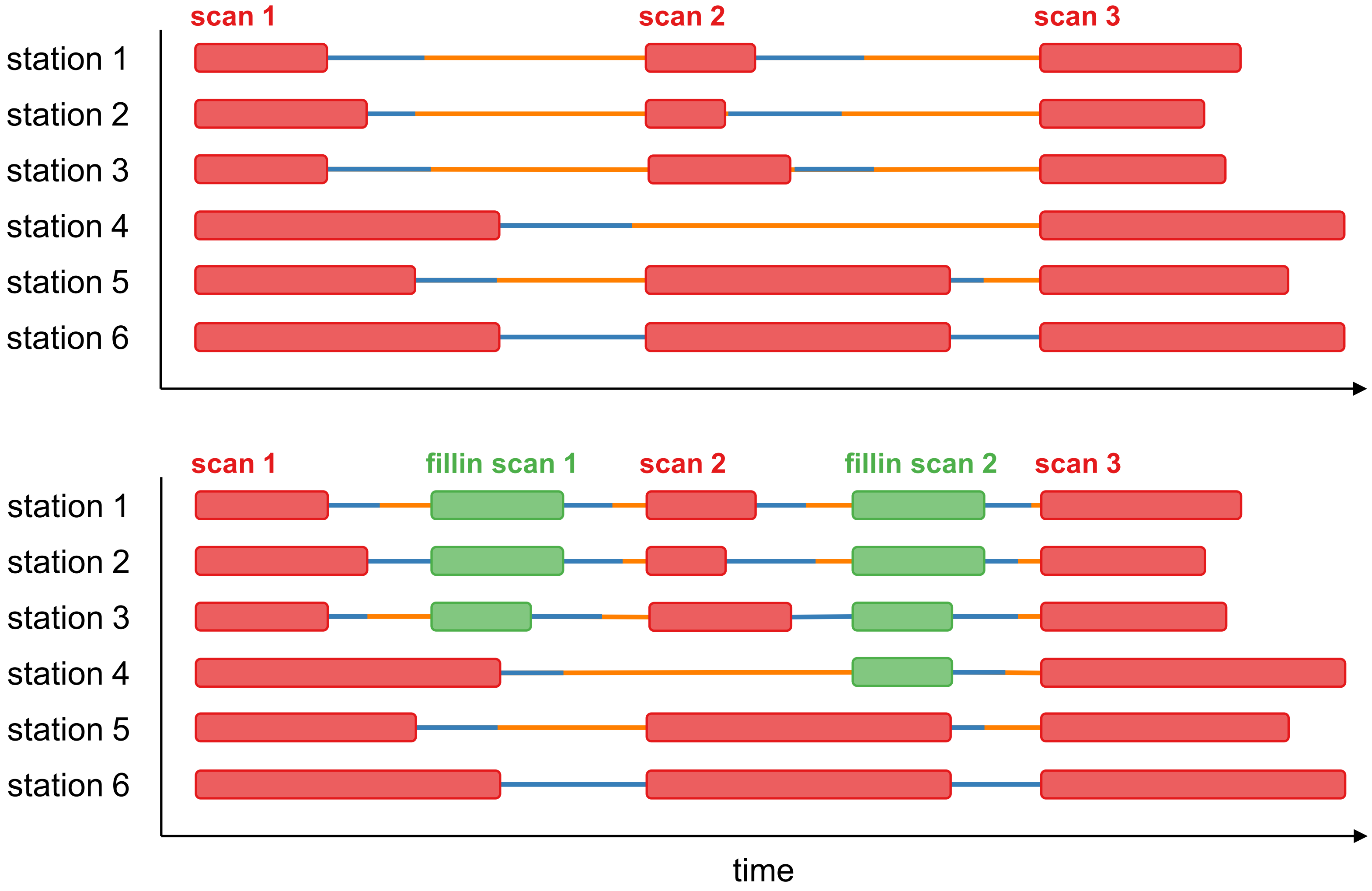
- slew rate
- sensitivity

→ different scan start/stop times

convention:
all antennas start at the same time

→ different stop times

pros and cons:
more scans but reduced number of stations per scan and thus reduced impact (but better sky-coverage)



Extend observing time

self-study ☺

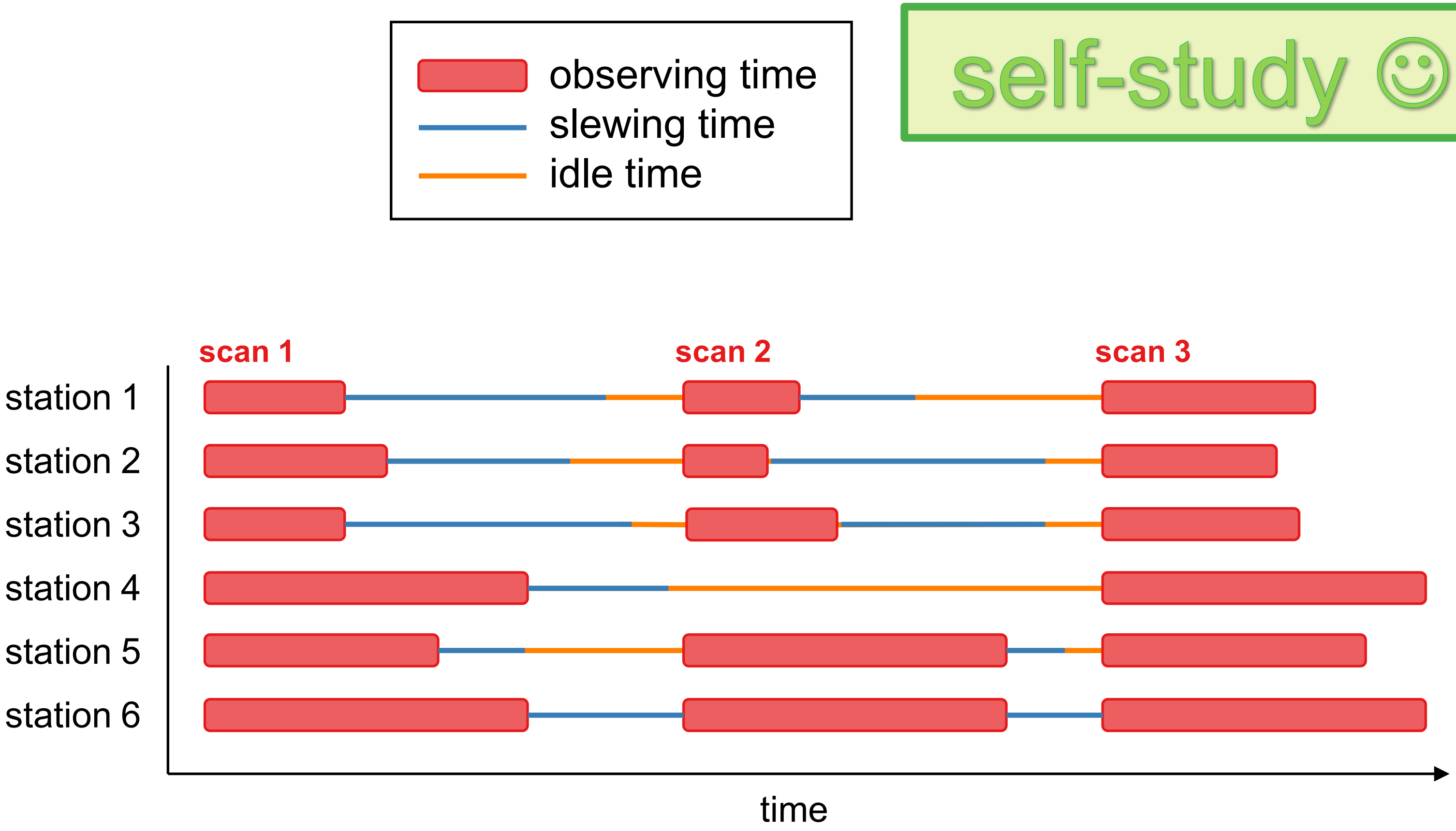
antennas have different characteristics:

- slew rate
- sensitivity

→ different scan start/stop times

convention:
all antennas start at the same time

→ different stop times



Extend observing time

self-study ☺

antennas have different characteristics:

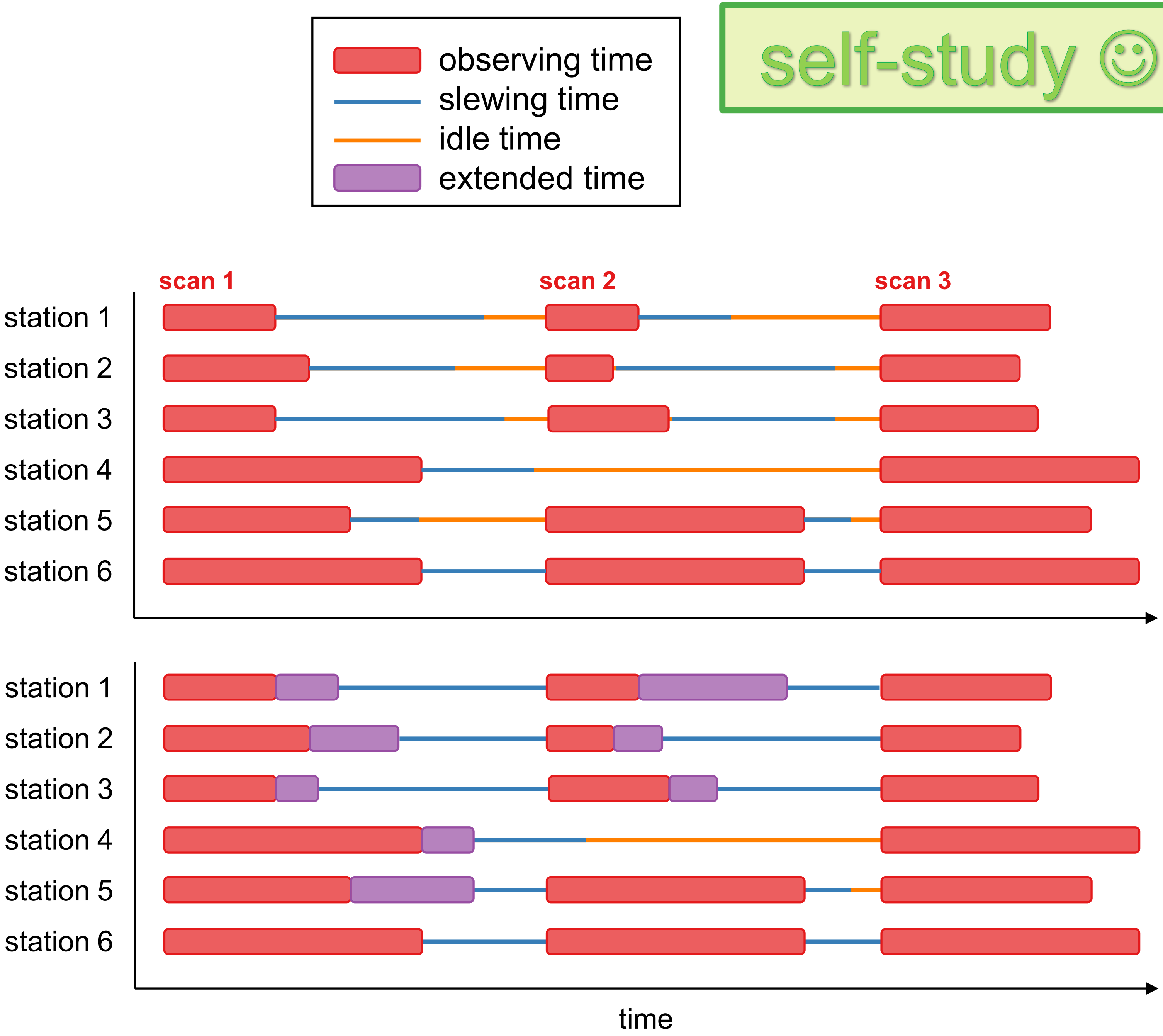
- slew rate
- sensitivity

→ different scan start/stop times

convention:
all antennas start at the same time

→ different stop times

pros and cons:
higher SNR per scan at the cost of more recorded bits



remaining slides are for self-studying ☺

Schedule evaluation

First hints

Look at statistical metrics

- number of scans (in total and per station)
- number of observations (in total and per station)
- idle time (per station)
- number of scans/observations (per source, baseline, station)
- station sky-coverage
- number of 2-station, 3-station … n-station scans
- …

First hints

Look at statistical metrics

- number of scans (in total and per station)
- number of observations (in total and per station)
- idle time (per station)
- number of scans/observations (per source, baseline, station)
- station sky-coverage
- number of 2-station, 3-station … n-station scans
- …

no direct access to session objectives (EOP, station coordinate, source coordinates …)

(→ first hint)

First hints

Look at statistical metrics

- number of scans (in total and per station)
- number of observations (in total and per station)
- idle time (per station)
- number of scans/observations (per source, baseline, station)
- station sky-coverage
- number of 2-station, 3-station … n-station scans
- …

maximise number of observations:

- focus on strong sources visible by many stations
  → imbalanced source distribution
  → no good sky-coverage

maximise number of scans:

- only observe two-station scans
  few observations
  poor network interconnection

no direct access to session objectives (EOP, station coordinate, source coordinates …)

(→ first hint)

Simulations

simulate VLBI observations (delays) and perform standard VLBI analysis

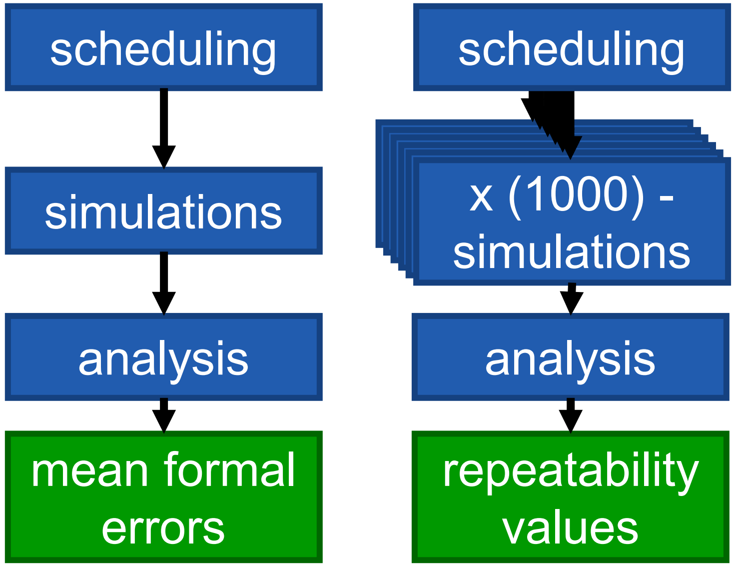
→ Provide direct access to session objective (EOP, coordinates) via

- mean formal errors (from least-squares adjustment)
- repeatabilities (from Monte-Carlo simulations)

Simulations contain observation (delay)
+ most important error sources

- troposphere
- clock drifts
- white noise
- (source-structure effects)

opportunity



Tropospheric simulations

stochastic behaviour of wet refractive index
Nilsson et al. (2007) (Treuhaft and Lanyi (1987), Kolmogorov (1991))

Idea:
spatial and temporal correlation between observations

Parameters:
- refractive index structure constant C_n
- effective tropospheric height H
- wind velocities v_e, v_n
- …

Clock simulations

Can be modelled as:
- sum of random walk and integrated random walk

Parameters:
- Allan standard deviation (ASD)

Measurement error

Can be modelled as:
- white noise

Parameters:
- amplitude

More information regarding VGOS simulations: Pany et al. (2010)

Best practices

Best practices

- **scheduling is an iterative approach**
- generate multiple schedules
- look at the statistics
- simulate your schedules
- look at #scans and #obs per station, source, baseline
- look at idle time per station
- look at number of x-station scans
- look at sky-coverage
- Intensives: obs at corners of visible sky
- Intensives: high, low elevation scans
- get in contact with stations/correlator and other schedulers

We will see and discuss this later

VGOS scheduling
current status and future perspectives

VGOS scheduling

- Lack of models and information (catalogs)
  - no SEFD models
  - no source flux density models
  - → today, most VGOS sessions are scheduled with fixed 30 second integration time
    (some attempts with SNR-based scheduling have been done, VR, EU-VGOS, VGOS-B, VGOS-S…)
  - improved slew models
  - understanding other delays that occur

VGOS scheduling

- Lack of models and information (catalogs)
- Hardware limitations
  - some sessions are scheduled with 30 second “buffer-flush” time between scans
  - record on one module or two modules (or FlexBuff)
  - → you can slew during this time, but not record new observations
  - move from 8 Gbps to 16 Gbps, impact on scheduling

VGOS scheduling

- Lack of models and information (catalogs)
- Hardware limitations
- Poor support of current file formats/software w.r.t. VGOS
  - .skd file is not able to properly define VGOS-observing mode
  - $CODES section lists 256 Mbps mode
  - $PROCS section with field-system commands
  - → have a look at latest VGOS schedule, get in contact with PI/stations/other schedulers
  - VEX/VEX2 would work but there are software limitations

VGOS scheduling

- Lack of models and information (catalogs)
- Hardware limitations
- Poor support of current file formats/software w.r.t. VGOS
- Twin telescopes
  - main concept of VGOS was to use twin-telescopes for improved sky-coverage
  - limited support in (some) scheduling software packages
  - limited support in (some) analysis software packages

VGOS scheduling

- Lack of models and information (catalogs)
- Hardware limitations
- Poor support of current file formats/software w.r.t. VGOS
- Twin telescopes
- Source selection
  - poor knowledge of sources in VGOS frequencies
  - compactness, brightness…
  - distribution of scans among sources (CRF)

VGOS scheduling

- Lack of models and information (catalogs)
- Hardware limitations
- Poor support of current file formats/software w.r.t. VGOS
- Twin telescopes
- Source selection
- Automation
  - most VGOS sessions are not yet automatically generated
  - in contrast to SX observations where automation is already widely established

VGOS scheduling

- Lack of models and information (catalogs)
- Hardware limitations
- Poor support of current file formats/software w.r.t. VGOS
- Twin telescopes
- Source selection
- Automation
- VEX2 support
  - some required software packages do not support the (modern) VEX2 format
  - operational VGOS observing requires to be able to produce procedures based on VEX2
  - currently, making changes to VGOS setup requires great expert knowledge
  - limiting for VGOS R&D

VGOS scheduling

- Lack of models and information (catalogs)
- Hardware limitations
- Poor support of current file formats/software w.r.t. VGOS
- Twin telescopes
- Source selection
- Automation
- VEX2 support

Opportunities for (young) scientists to contribute to VGOS development and performance

VGOS scheduling

- Lack of models and information (catalogs)
- Hardware limitations
- Poor support of current file formats/software w.r.t. VGOS
- Twin telescopes
- Source selection
- Automation
- VEX2 support

Opportunities for (young) scientists to contribute to VGOS development and performance

How?

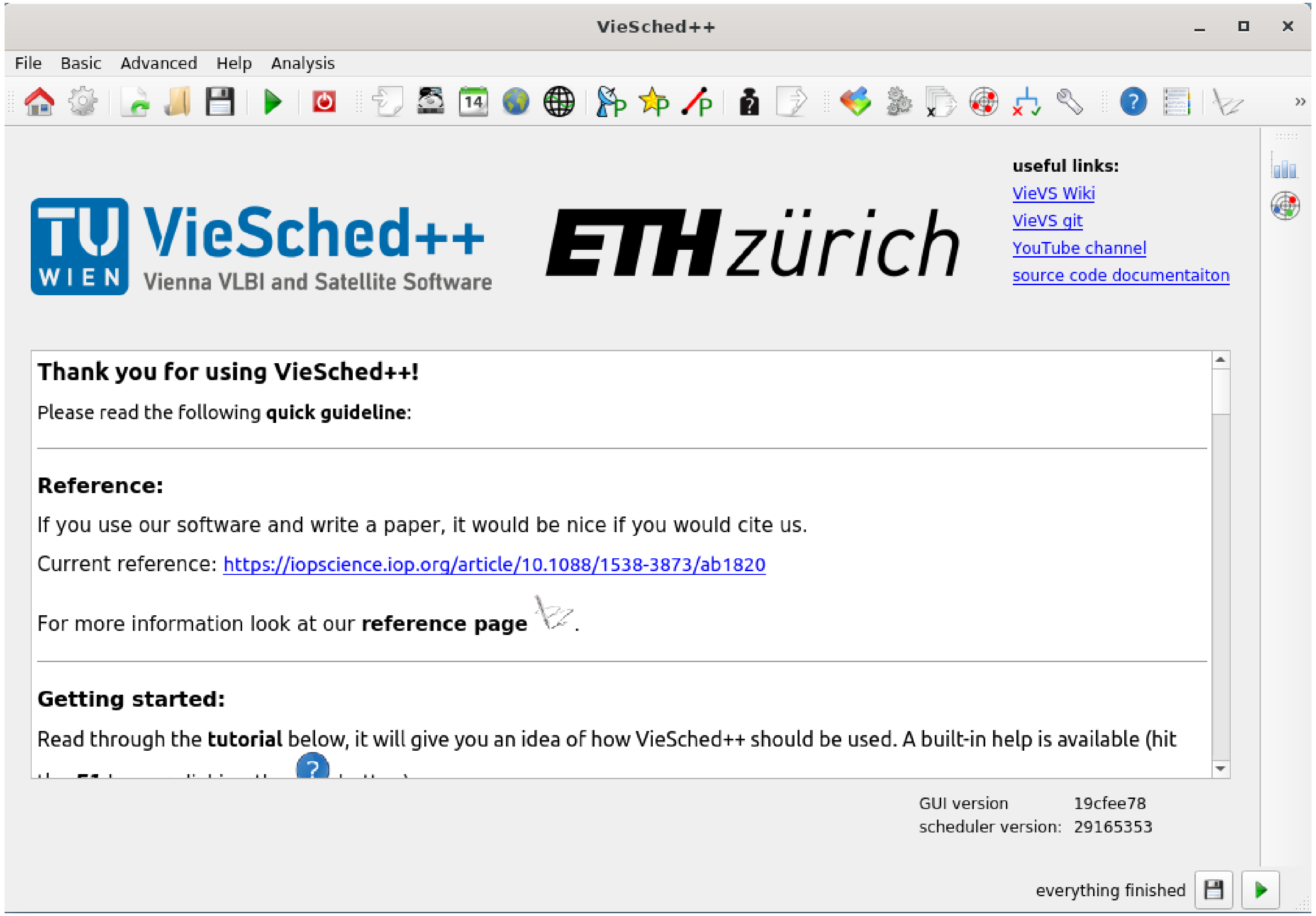
- Learn to use state of the art scheduling software packages
- Understand scheduling and test different (new) approaches
- Conduct simulation studies

→ Exercise today

VieSched++

VieSched++

- VLBI scheduling and simulation software
- Developed at TU Wien
- Easy to use
  - optional graphical user interface
  - manuals and tutorial videos
- Versatile
  - many options and parameters
  - flexible parameterization
  - support of many algorithms
  - different optimization criteria
  - special scheduling modes
- Powerful
  - generate high-quality schedules
  - test many scheduling approaches automatically
  - VGOS support



useful links:
VieVS Wiki
VieVS git
YouTube channel
source code documentaiton

Thank you for using VieSched++!

Please read the following **quick guideline**:

Reference:

If you use our software and write a paper, it would be nice if you would cite us.

Current reference: https://iopscience.iop.org/article/10.1088/1538-3873/ab1820

For more information look at our **reference page** .

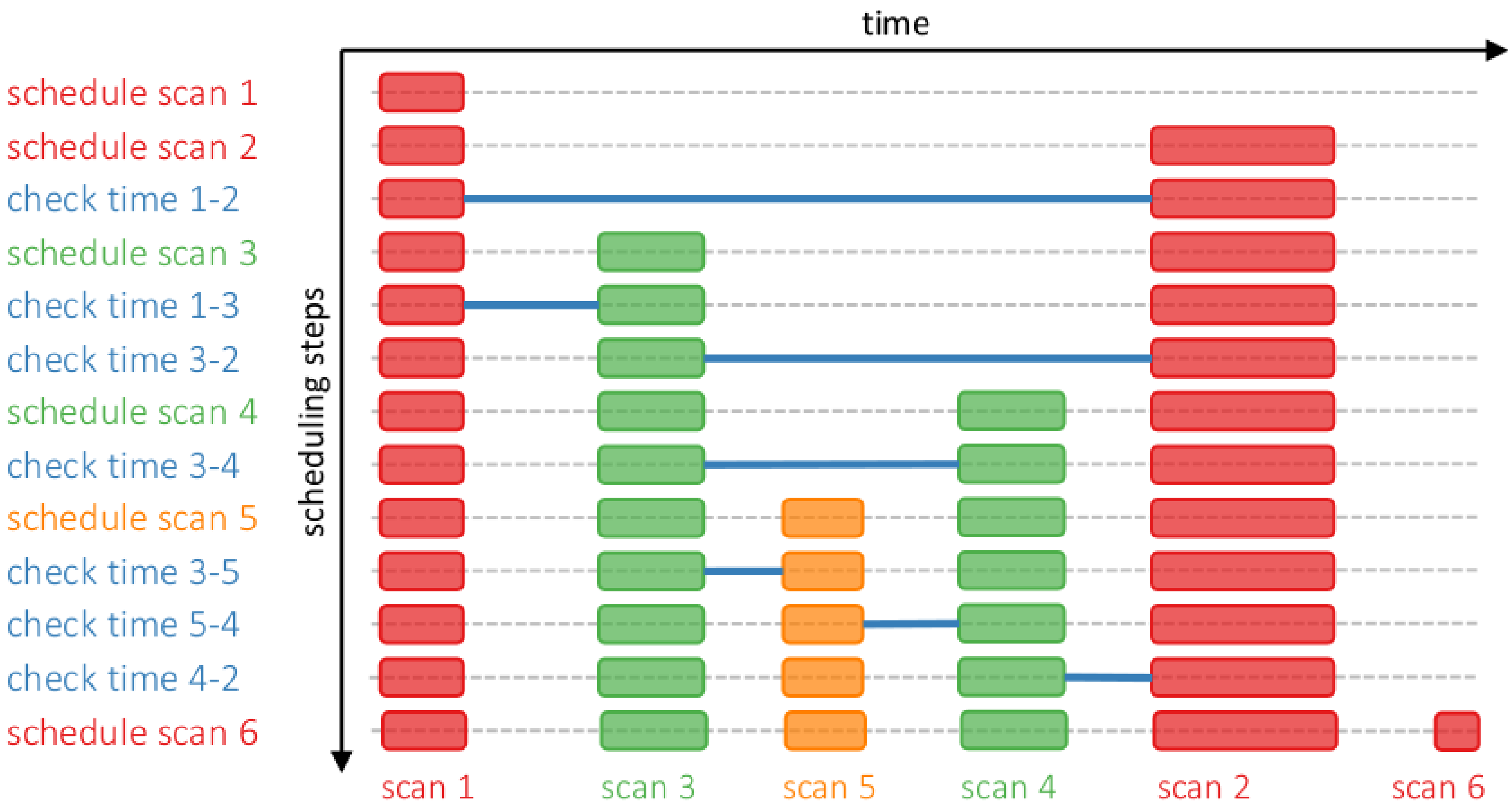
Getting started:

Read through the **tutorial** below, it will give you an idea of how VieSched++ should be used. A built-in help is available (hit

GUI version 19cfee78
scheduler version: 29165353

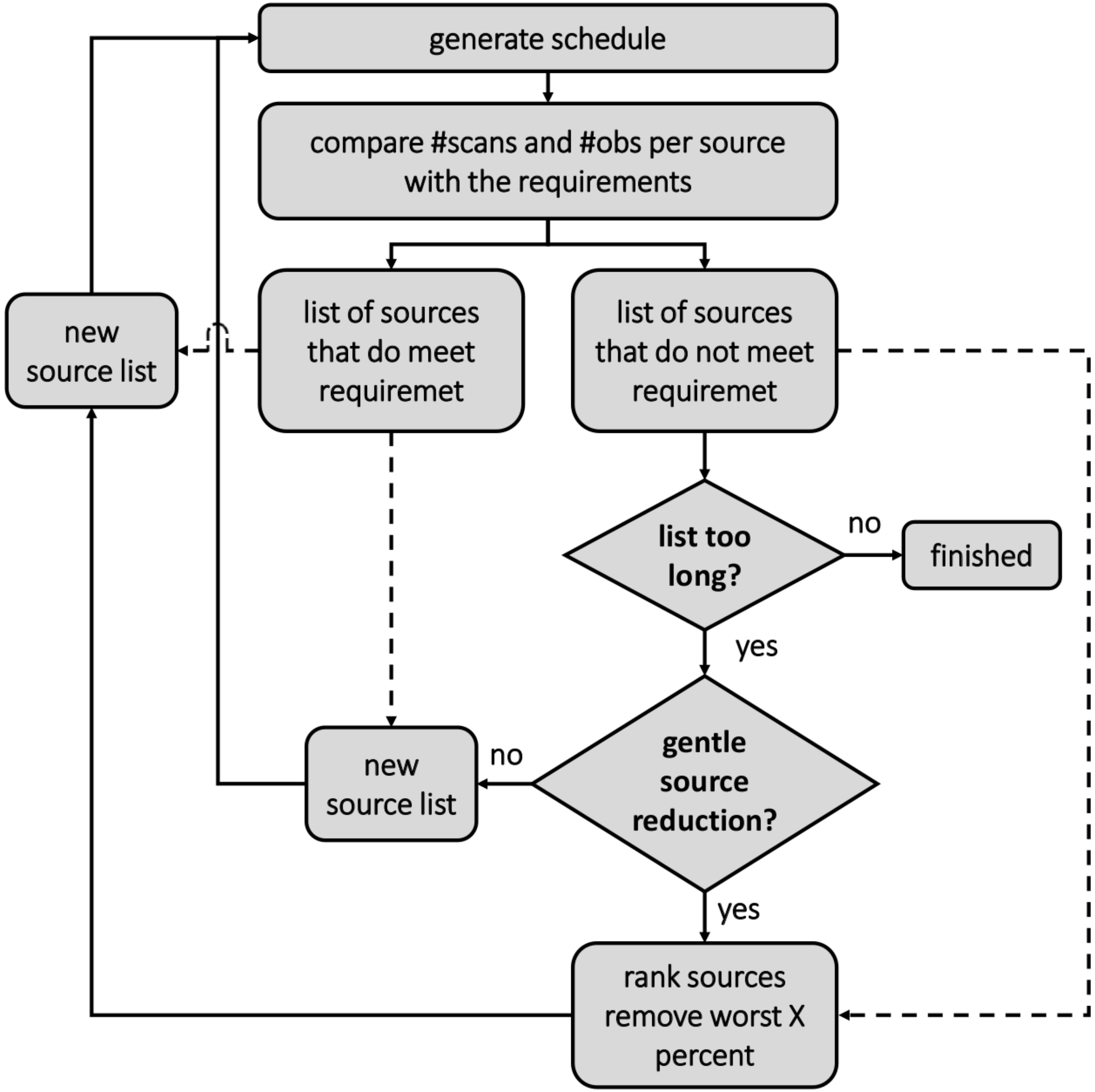
everything finished

Recursive scan selection



Iterative source selection

- Define minimum number of scans/observations per source
- Generate schedule with full source list
- Sources with fewer scans/observations as required are removed from source-list
- There are methods to fine-tune approach (gentle source reduction)



Multi-scheduling

- There are various scheduling paramameters and optimization criteria
  - task is to find a good set of scheduling parameters and a good balance between optimization criteria
  - problem: best parameters change based on network, observing mode, source list…
- VieSched++ multi-scheduling tool allows to easily test different combinations
  - provide a list of parameters and values to test
  - generate all combinations of these parameters
  - generate a schedule for every combination
- Finally, you get a large number of different schedules (e.g. 1000+)
  - based on statistics or simulation results, best schedule is selected

Matthias Schartner – mschartner@ethz.ch

Matthias Schartner
mschartner@ethz.ch

ETH Zürich
Space Geodesy
Robert-Gnehm-Weg 15
8093 Zürich

Appendix

SKD file

```
$EXPER VR2201
$PARAM
DESCRIPTION VGOS-R&D01
SCHEDULING_SOFTWARE VieSched++
SOFTWARE_VERSION 2bee4f99b90697fb002ecd67781e35ceee7dd66f
SCHEDULER DACH CORRELATOR HAYS START 22020180000 END 22021180000 ...
$SOURCES
0003-066 $          00 06 13.892888    -06 23 35.335330 2000.0 0.0 2010a glob
0016+731 $          00 19 45.786419    +73 27 30.017440 2000.0 0.0 ICRF2 def ...
$FLUX
0003-066  X    M   6.91  0.80  0.40  10.  0.0  0.0
0003-066  S    M   1.54  6.00  1.00   0.  0.0  0.0
0003-066  S    M   0.71  1.00  1.00   0.  0.0  0.0
0016+731 S B 0.0  1.01   900.0  1.01  1530.0  0.92  2600.0  0.82  4420.0  0.82  7520.0  0.80 10400.0  0.82 12800.0
0016+731 X B 0.0  2.43   900.0  2.36  1530.0  2.17  2600.0  1.61  4420.0  1.06  7520.0  1.06 10400.0  1.15 12800.0 ...
$STATIONS
A  G GGAO12M  AZEL  0.00000   300.0   7  180.0  720.0   66.0   4    6.5   88.0  12.0   Gs  Gs  Gs
A  L HOBART12 AZEL  0.00000   300.0   9   90.0  630.0   75.0   9    5.0   88.0  12.0   Hb  Hb  Hb
P Gs GGAO12M      1130729.8766   -4831245.9720    3994228.2998   71025302   76.83   39.02 2020c
P Hb HOBART12  -3949991.0936    2522421.2592   -4311707.7211  73741201   212.56 -42.80 2020c ...
$SKED
0133+476 2 SX PREOB 22020180000 7 MIDOB 0 POSTOB G-M-1-2-RCE-SC ...     7     7     7     7     7     7     7
0059+581 2 SX PREOB 22020180025 7 MIDOB 0 POSTOB G-M-1C2CRCE-SC ...     7     7     7     7     7     7     7
0224+671 2 SX PREOB 22020180050 9 MIDOB 0 POSTOB G-M-E- ...     9     9     9 ...
$CODES
F GEOSX SX GGAO12M HOBART12 KOKEE12M ONSA13NE ONSA13SW RAEGYEB WESTFORD WETTZ13S
C SX X 8212.99 10000.0  1 Mk341:1  8.00 1(-1,7)
C SX X 8252.99 10000.0  2 Mk341:1  8.00 1(0)
C SX X 8352.99 10000.0  3 Mk341:1  8.00 1(1)
C SX X 8512.99 10000.0  4 Mk341:1  8.00 1(2) ...
R SX 16
B SX
L G SX  X 1N     8080   1 U
L G SX  X 1N     8080   2 U ...
```

SKD file

```
$EXPER VR2201
$PARAM
DESCRIPTION VGOS-R&D01
SCHEDULING_SOFTWARE VieSched++
SOFTWARE_VERSION 2bee4f99b90697fb002ecd67781e35ceee7dd66f
SCHEDULER DACH CORRELATOR HAYS START 22020180000 END 22021180000 ...
$SOURCES
0003-066 $          00 06 13.892888    -06 23 35.335330 2000.0 0.0 2010a glob
0016+731 $          00 19 45.786419    +73 27 30.017440 2000.0 0.0 ICRF2 def ...
$FLUX
0003-066  X    M   6.91  0.80  0.40  10.  0.0  0.0
0003-066  S    M   1.54  6.00  1.00   0.  0.0  0.0
0003-066  S    M   0.71  1.00  1.00   0.  0.0  0.0
0016+731 S B 0.0  1.01   900.0  1.01  1530.0  0.92  2600.0  0.82  4420.0  0.82  7520.0  0.80 10400.0  0.82 12800.0
0016+731 X B 0.0  2.43   900.0  2.36  1530.0  2.17  2600.0  1.61  4420.0  1.06  7520.0  1.06 10400.0  1.15 12800.0 ...
$STATIONS
A  G GGAO12M  AZEL  0.00000   300.0   7  180.0  720.0   66.0   4    6.5   88.0  12.0   Gs  Gs  Gs
A  L HOBART12 AZEL  0.00000   300.0   9   90.0  630.0   75.0   9    5.0   88.0  12.0   Hb  Hb  Hb
P Gs GGAO12M      1130729.8766   -4831245.9720    3994228.2998   71025302    76.83   39.02 2020c
P Hb HOBART12  -3949991.0936    2522421.2592   -4311707.7211  73741201    212.56 -42.80 2020c ...
$SKED
0133+476 2 SX PREOB 22020180000 7 MIDOB 0 POSTOB G-M-1-2-RCE-SC ...     7     7     7     7     7     7     7
0059+581 2 SX PREOB 22020180025 7 MIDOB 0 POSTOB G-M-1C2CRCE-SC ...     7     7     7     7     7     7     7
0224+671 2 SX PREOB 22020180050 9 MIDOB 0 POSTOB G-M-E- ...     9     9     9 ...
$CODES
F GEOSX SX GGAO12M HOBART12 KOKEE12M ONSA13NE ONSA13SW RAEGYEB WESTFORD WETTZ13S
C SX X 8212.99 10000.0  1 Mk341:1  8.00 1(-1,7)
C SX X 8252.99 10000.0  2 Mk341:1  8.00 1(0)
C SX X 8352.99 10000.0  3 Mk341:1  8.00 1(1)
C SX X 8512.99 10000.0  4 Mk341:1  8.00 1(2) ...
R SX 16
B SX
L G SX  X 1N     8080   1 U
L G SX  X 1N     8080   2 U ...
```

General information

List of sources

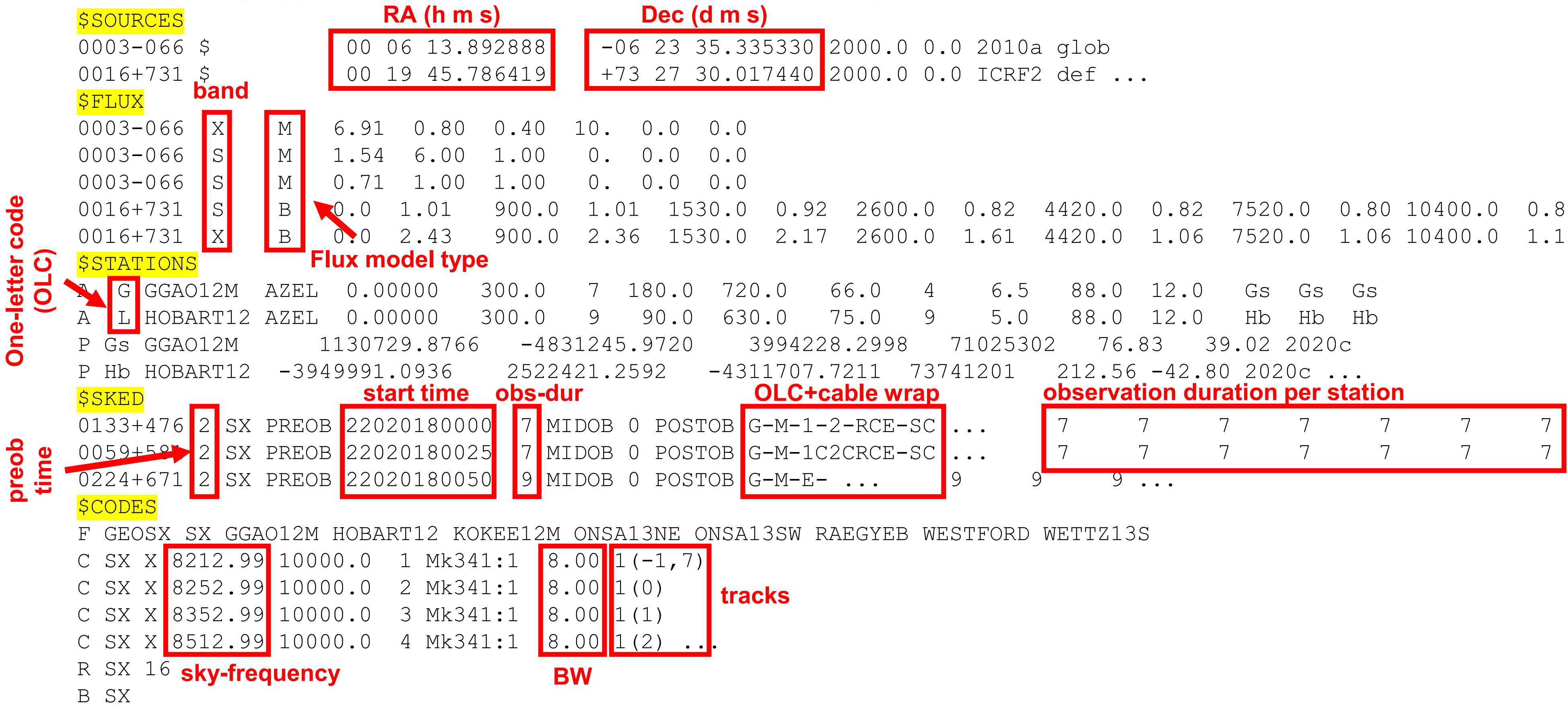
Source flux information

List of stations

List of scans

Observing mode

SKD file



```
$EXPER VR2201
$PARAM
DESCRIPTION VGOS-R&D01
SCHEDULING_SOFTWARE VieSched++
SOFTWARE_VERSION 2bee4f99b90697fb002ecd67781e35ceee7dd66f
SCHEDULER DACH CORRELATOR HAYS START 22020180000 END 22021180000 ...
$SOURCES
0003-066 $          00 06 13.892888    -06 23 35.335330 2000.0 0.0 2010a glob
0016+731 $          00 19 45.786419    +73 27 30.017440 2000.0 0.0 ICRF2 def ...
$FLUX
0003-066  X    M   6.91  0.80  0.40  10.  0.0  0.0
0003-066  S    M   1.54  6.00  1.00   0.  0.0  0.0
0003-066  S    M   0.71  1.00  1.00   0.  0.0  0.0
0016+731  S    B   0.0  1.01   900.0  1.01  1530.0  0.92  2600.0  0.82  4420.0  0.82  7520.0  0.80 10400.0  0.82 12800.0
0016+731  X    B   0.0  2.43   900.0  2.36  1530.0  2.17  2600.0  1.61  4420.0  1.06  7520.0  1.06 10400.0  1.15 12800.0 ...
$STATIONS
A  G GGAO12M  AZEL  0.00000   300.0   7  180.0  720.0   66.0   4    6.5   88.0  12.0   Gs  Gs  Gs
A  L HOBART12 AZEL  0.00000   300.0   9   90.0  630.0   75.0   9     5.0  88.0  12.0   Hb  Hb  Hb
P Gs GGAO12M      1130729.8766   -4831245.9720    3994228.2998   71025302    76.83   39.02 2020c
P Hb HOBART12  -3949991.0936    2522421.2592   -4311707.7211  73741201   212.56 -42.80 2020c ...
$SKED
0133+476 2 SX PREOB 22020180000  7 MIDOB 0 POSTOB G-M-1-2-RCE-SC ...     7     7     7     7     7     7     7
0059+58  2 SX PREOB 22020180025  7 MIDOB 0 POSTOB G-M-1C2CRCE-SC ...     7     7     7     7     7     7     7
0224+671 2 SX PREOB 22020180050  9 MIDOB 0 POSTOB G-M-E- ...     9     9     9 ...
$CODES
F GEOSX SX GGAO12M HOBART12 KOKEE12M ONSA13NE ONSA13SW RAEGYEB WESTFORD WETTZ13S
C SX X 8212.99 10000.0  1 Mk341:1  8.00 1(-1,7)
C SX X 8252.99 10000.0  2 Mk341:1  8.00 1(0)
C SX X 8352.99 10000.0  3 Mk341:1  8.00 1(1)
C SX X 8512.99 10000.0  4 Mk341:1  8.00 1(2) ...
R SX 16
B SX
L G SX  X 1N      8080   1 U
L G SX  X 1N      8080   2 U ...
```

SKED manual

Schartner (2019)

VEX file

```
VEX_rev = 1.5;
$GLOBAL;
    ref $EXPER = VR2201;
$EXPER;
    def VR2201;
        exper_name = VR2201;
        exper_nominal_start = 2022y020d18h00m00s;
        exper_nominal_stop = 2022y021d18h00m00s;
    enddef;
$STATION;
    def Gs;
        ref $SITE = GGAO12M;
        ref $ANTENNA = GGAO12M;
    enddef;
$MODE;
    def type;
        ref $FREQ   = VGOS : Gs : Hb : K2 : Mg : Oe : Ow : Yj : Wf : Ws ;
        ref $BBC    = VGOS : Gs : Hb : K2 : Mg : Oe : Ow : Yj : Wf : Ws ;
        ref $IF     = VGOS : Gs : Hb : K2 : Mg : Oe : Ow : Yj : Wf : Ws ;
        ref $TRACKS = VGOS : Gs : Hb : K2 : Mg : Oe : Ow : Yj : Wf : Ws ;
    enddef;
$SCHED;
    scan 020-1800a;
        start = 2022y020d18h00m00s;
        mode = type;
        source = 0133+476;
        station = Gs :    0 sec :    7 sec : 0 ft : 1A :   &n : 1;
        station = Mg :    0 sec :    7 sec : 0 ft : 1A :   &n : 1;
        station = Oe :    0 sec :    7 sec : 0 ft : 1A :   &n : 1;
    endscan;
$SOURCE;
    def 0113-118;
        source_type = star;
        source_name = 0113-118;
        IAU_name = 0113-118;
        ra = 01h16m12.52203s;
        dec = -11d36'15.43426";
    enddef;
```

VEX file

```
VEX_rev = 1.5;
$GLOBAL;
    ref $EXPER = VR2201;
$EXPER;
    def VR2201;
        exper_name = VR2201;
        exper_nominal_start = 2022y020d18h00m00s;
        exper_nominal_stop = 2022y021d18h00m00s;
    enddef;
$STATION;
    def Gs;
        ref $SITE = GGAO12M;
        ref $ANTENNA = GGAO12M;
    enddef;
$MODE;
    def type;
        ref $FREQ   = VGOS : Gs : Hb : K2 : Mg : Oe : Ow : Yj : Wf : Ws ;
        ref $BBC    = VGOS : Gs : Hb : K2 : Mg : Oe : Ow : Yj : Wf : Ws ;
        ref $IF     = VGOS : Gs : Hb : K2 : Mg : Oe : Ow : Yj : Wf : Ws ;
        ref $TRACKS = VGOS : Gs : Hb : K2 : Mg : Oe : Ow : Yj : Wf : Ws ;
    enddef;
$SCHED;
    scan 020-1800a;
        start = 2022y020d18h00m00s;
        mode = type;
        source = 0133+476;
        station = Gs :    0 sec :    7 sec : 0 ft : 1A :    &n : 1;
        station = Mg :    0 sec :    7 sec : 0 ft : 1A :    &n : 1;
        station = Oe :    0 sec :    7 sec : 0 ft : 1A :    &n : 1;
    endscan;
$SOURCE;
    def 0113-118;
        source_type = star;
        source_name = 0113-118;
        IAU_name = 0113-118;
        ra = 01h16m12.52203s;
        dec = -11d36'15.43426";
    enddef;
```

General information

List of stations

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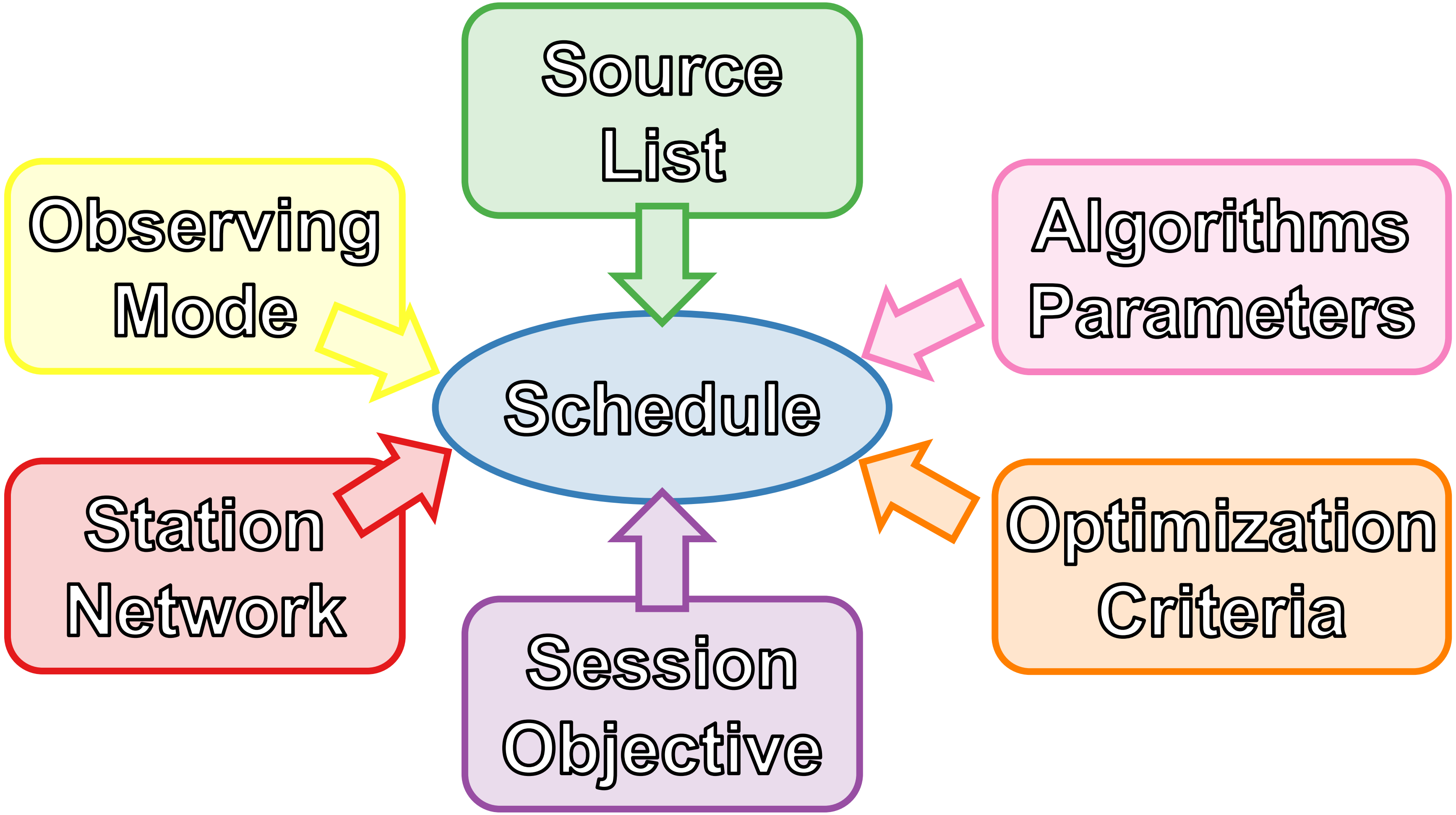
List of scans

List of sources

VEX Definition

VEX2 Definition

Scheduling



Source List

Observing Mode

Algorithms Parameters

Schedule

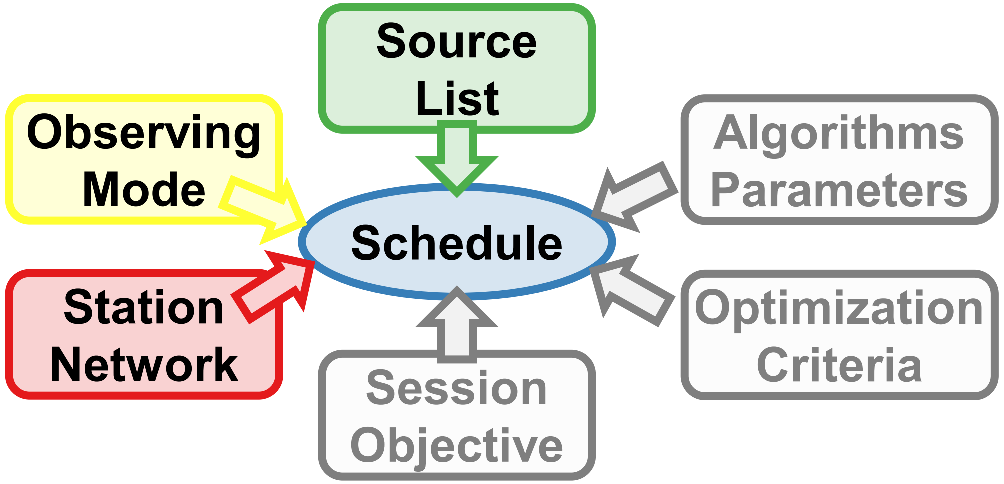
Station Network

Optimization Criteria

Session Objective

Matthias Schartner – mschartner@ethz.ch

Scheduling



Station network:

- depending on availability/capabilities
- typically given

Observing mode:

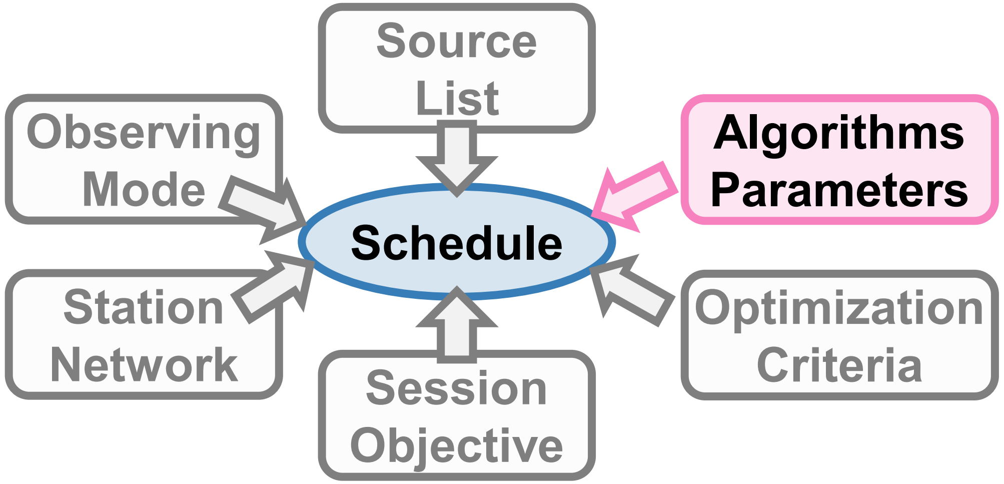
- depending on participating stations
- typically given

Source List:

- depending on visibility, brighness, compactness…
- some room for flexibility

Matthias Schartner – mschartner@ethz.ch

Scheduling



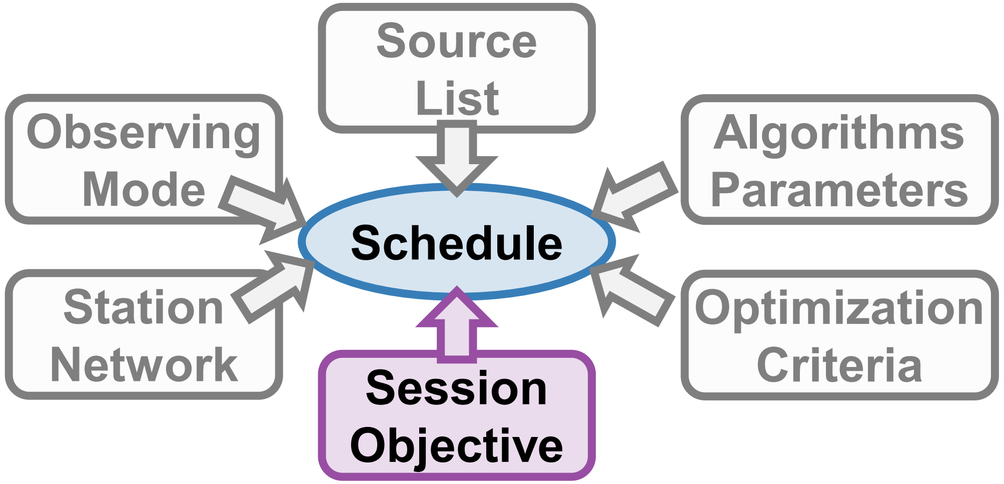
Algorithms:

- subnetting
- fillin-mode
- extend observing time
- …

Parameters:

- minimum time between two scans to same source
- minimum/maximum observing time
- minimum/target number of scans per source
- minimum number of stations per scan
- …

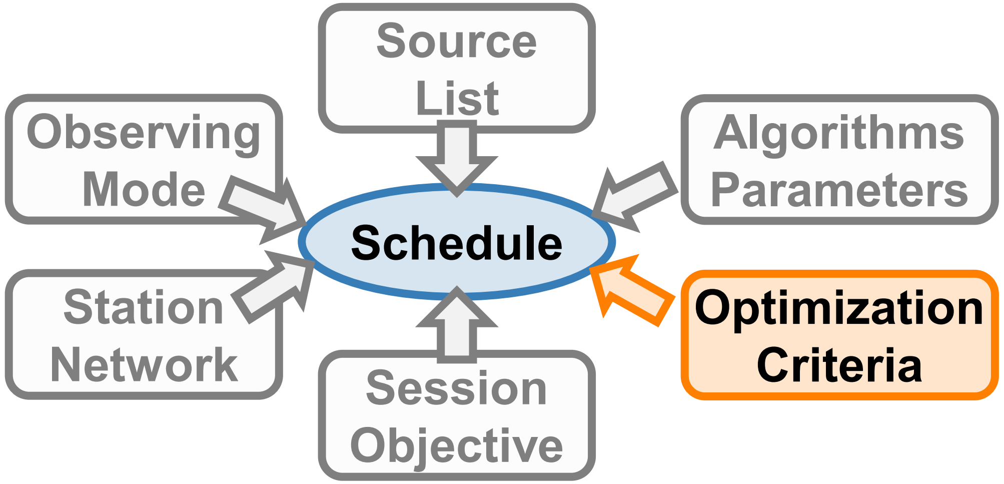
Scheduling



Session Objective

- station coordinates
- source coordinates
- full set of EOP
- dUT1
- source imaging
- …

Scheduling



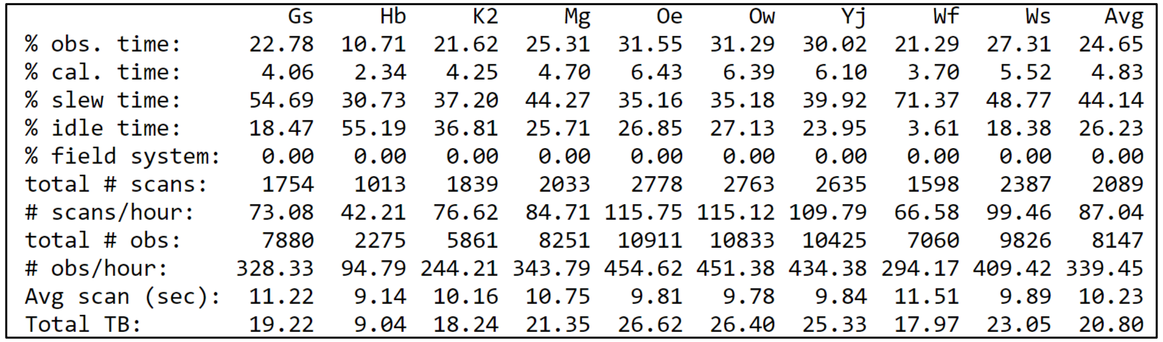
Optimization criteria:

- number observations (per scan)
- scan duration
- station idle time
- number of closures
- sky-coverage improvement
- average observations among stations/sources/baseline
- low elevation scans
- source declination

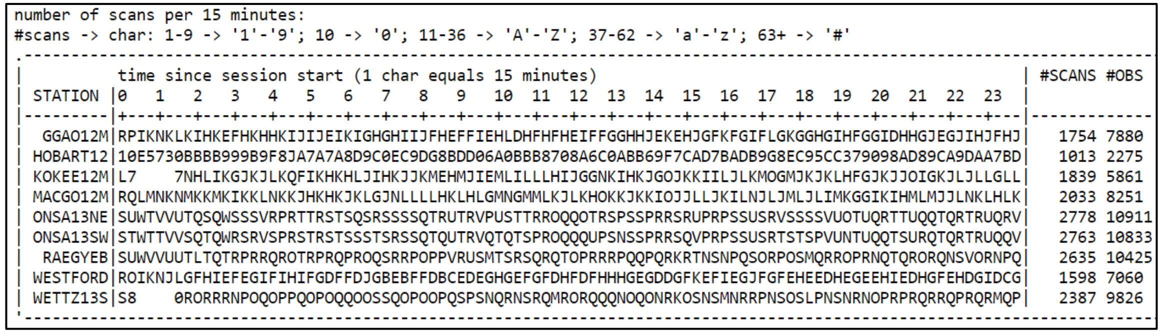
(combination of optimization criteria)

How to get session statistics

- Have a look at the operation notes file (*sessioncode.txt*)

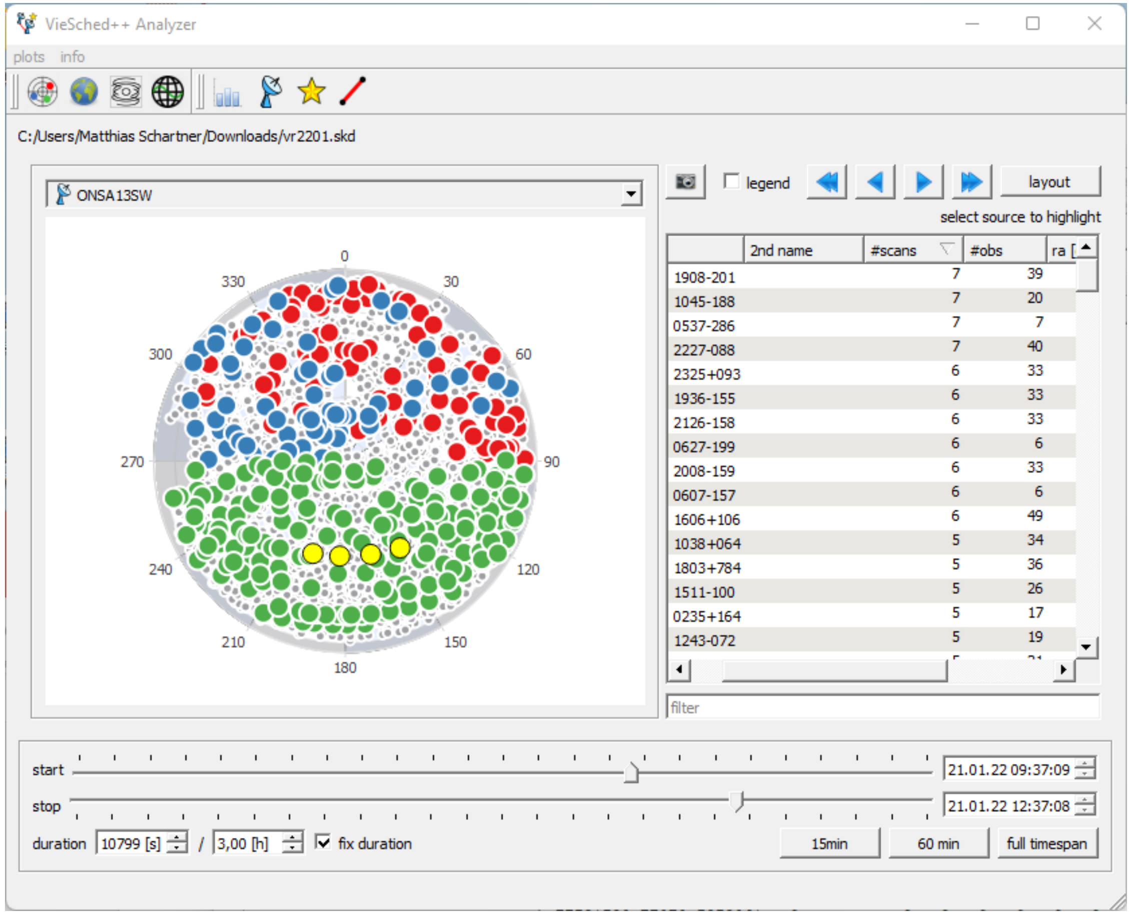


```
                    Gs      Hb      K2      Mg      Oe      Ow      Yj      Wf      Ws     Avg
% obs. time:     22.78   10.71   21.62   25.31   31.55   31.29   30.02   21.29   27.31   24.65
% cal. time:      4.06    2.34    4.25    4.70    6.43    6.39    6.10    3.70    5.52    4.83
% slew time:     54.69   30.73   37.20   44.27   35.16   35.18   39.92   71.37   48.77   44.14
% idle time:     18.47   55.19   36.81   25.71   26.85   27.13   23.95    3.61   18.38   26.23
% field system:   0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
total # scans:    1754    1013    1839    2033    2778    2763    2635    1598    2387    2089
# scans/hour:    73.08   42.21   76.62   84.71  115.75  115.12  109.79   66.58   99.46   87.04
total # obs:      7880    2275    5861    8251   10911   10833   10425    7060    9826    8147
# obs/hour:     328.33   94.79  244.21  343.79  454.62  451.38  434.38  294.17  409.42  339.45
Avg scan (sec):  11.22    9.14   10.16   10.75    9.81    9.78    9.84   11.51    9.89   10.23
Total TB:        19.22    9.04   18.24   21.35   26.62   26.40   25.33   17.97   23.05   20.80
```



```
number of scans per 15 minutes:
#scans -> char: 1-9 -> '1'-'9'; 10 -> '0'; 11-36 -> 'A'-'Z'; 37-62 -> 'a'-'z'; 63+ -> '#'
.------------------------------------------------------------------------------------------------------------------
|          time since session start (1 char equals 15 minutes)                                  | #SCANS #OBS
| STATION |0   1   2   3   4   5   6   7   8   9   10  11  12  13  14  15  16  17  18  19  20  21  22  23  |
|---------|+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---|-------------
|  GGAO12M|RPIKNKLKIHKEFHKHHKIJIJEIKIGHGHIIJFHEFFIEHLDHFHFHEIFFGGHHJEKEHJGFKFGIFLGKGGHGIHFGGIDHHGJEGJIHJFHJ|   1754 7880
| HOBART12|10E5730BBBB999B9F8JA7A7A8D9C0EC9DG8BDD06A0BBB8708A6C0ABB69F7CAD7BADB9G8EC95CC379098AD89CA9DAA7BD|   1013 2275
| KOKEE12M|L7    7NHLIKGJKJLKQFIKHKHLJIHKJJKMEHMJIEMLILLLHIJGGNKIHKJGOJKKIILJLKMOGMJKJKLHFGJKJJOIGKJLJLLGLL|   1839 5861
| MACGO12M|RQLMNKNMKKMKIKKLNKKJHKHKJKLGJNLLLLHKLHLGMNGMMLKJLKHOKKJKKIOJJLLJKILNJLJMLJLIMKGGIKIHMLMJJLNKLHLK|   2033 8251
| ONSA13NE|SUWTVVUTQSQWSSSVRPRTTRSTSQSRSSSSQTRUTRVPUSTTRROQQOTRSPSSPRRSRUPRPSSUSRVSSSSVUOTUQRTTUQQTQRTRUQRV|   2778 10911
| ONSA13SW|STWTTVVSQTQWRSRVSPRSTRSTSSSTSRSSQTQUTRVQTQTSPROQQQUPSNSSPRRSQVPRPSSUSRTSTSPVUNTUQQTSURQTQRTRUQQV|   2763 10833
|  RAEGYEB|SUWVVUUTLTQTRPRRQROTRPRQPROQSRRPOPPVRUSMTSRSQRQTOPRRRPQQPQRKRTNSNPQSORPOSMQRROPRNQTQRORQNSVORNPQ|   2635 10425
| WESTFORD|ROIKNJLGFHIEFEGIFIHIFGDFFDJGBEBFFDBCEDEGHGEFGFDHFDFHHHGEGDDGFKEFIEGJFGFEHEEDHEGEEHIEDHGFEHDGIDCG|   1598 7060
| WETTZ13S|S8    0RORRRNPOQOPPQOPOQQOOSSQOPOOPQSPSNQRNSRQMRORQQQNOQONRKOSNSMNRRPNSOSLPNSNRNOPRPRQRRQPRQRMQP|   2387 9826
'------------------------------------------------------------------------------------------------------------------
```

- Use external tools (VieSched++)



C:/Users/Matthias Schartner/Downloads/vr2201.skd

ONSA13SW

	2nd name	#scans	#obs	ra
1908-201		7	39	
1045-188		7	20	
0537-286		7	7	
2227-088		7	40	
2325+093		6	33	
1936-155		6	33	
2126-158		6	33	
0627-199		6	6	
2008-159		6	33	
0607-157		6	6	
1606+106		6	49	
1038+064		5	34	
1803+784		5	36	
1511-100		5	26	
0235+164		5	17	
1243-072		5	19	

start 21.01.22 09:37:09

stop 21.01.22 12:37:08

duration 10799 [s] / 3,00 [h] ☑ fix duration