VLBI Scheduling and Simulations with VieSched++

<u>Matthias Schartner</u>

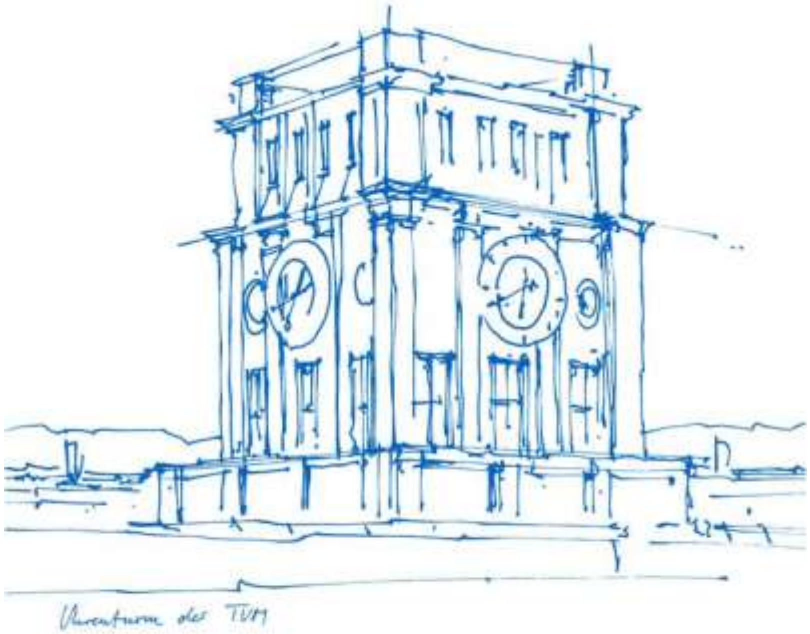
Technical University of Munich

Department of Aerospace and Geodesy

Institute for Astronomical and Physical Geodesy

Professorship of Satellite Navigation

September 16, 2026



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

We will only cover first few topics – rest is for self study

What is VLBI Scheduling?

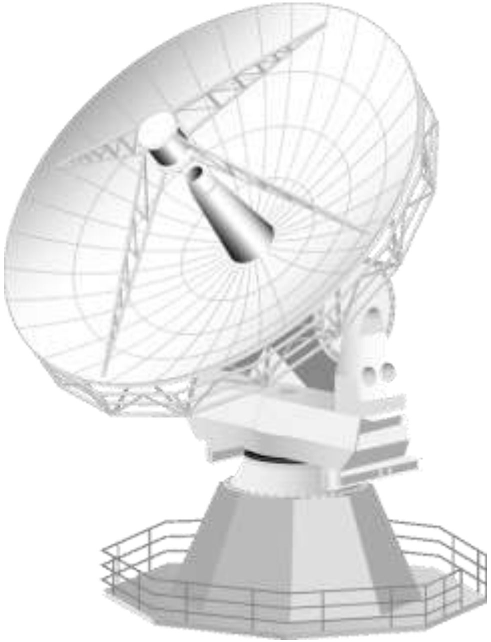
Very Long Baseline Interferometry (VLBI):

Two telescopes observe the same source **simultaneously** to derive an “observation”

- Coordinate observations
- Provide observing plan
- This is what we call a “schedule”

VLBI scheduling

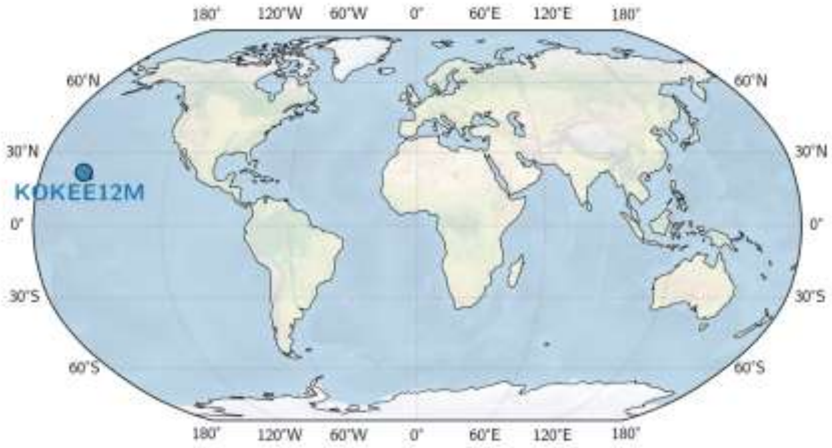
- generation of such an observing plan
- can be seen as an advanced **optimization problem**
- determines observations available during analysis
  - important task

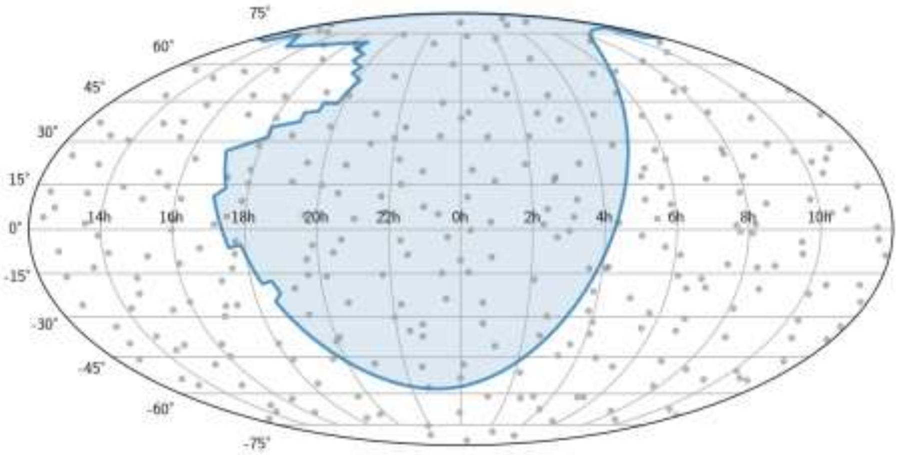


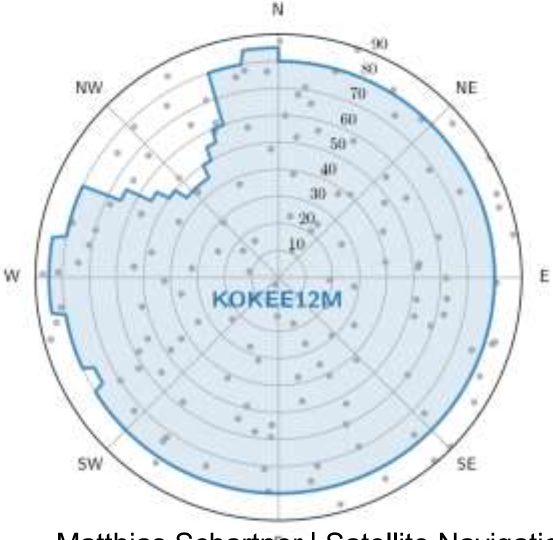
“VLBI Scheduling” in One Sentence

Given a
- **network of radio telescopes**,
- a **time window**,
- and a **list of radio sources**,

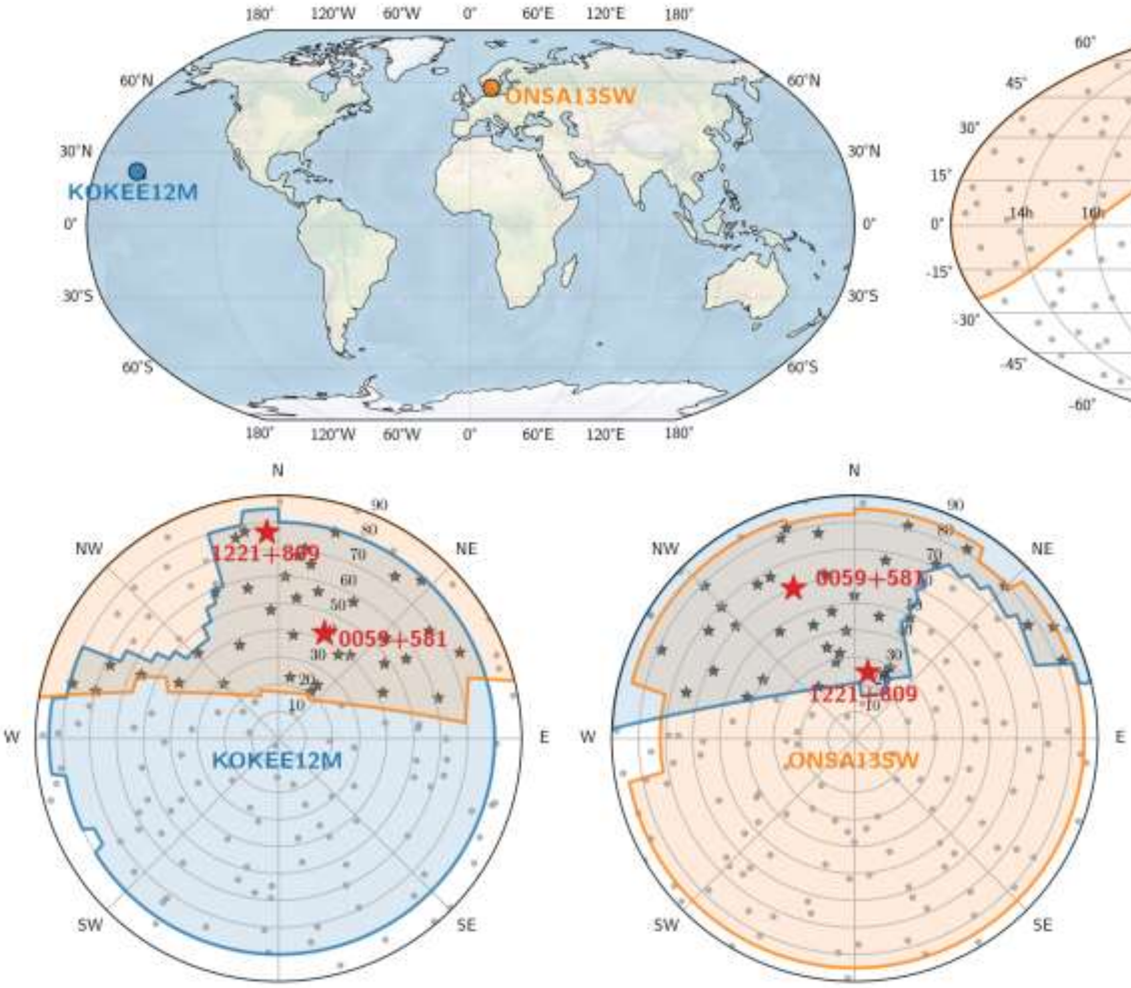
determine the **optimal sequence of observations** that
- **maximizes scientific return**
- under **operational constraints.**



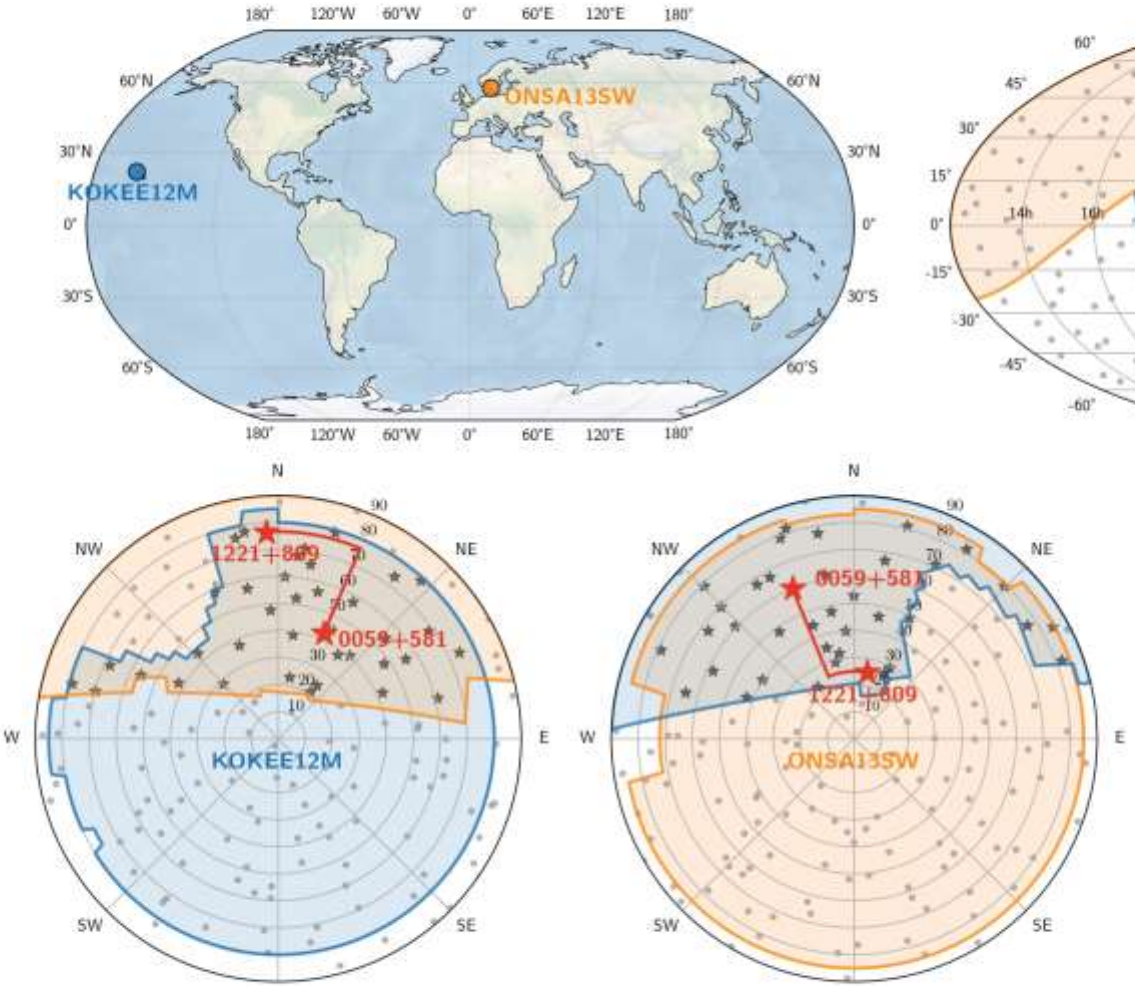




Bottom: sky-coverage (azimuth, elevation)
Date: 2025-05-01 19:00
Visiblity with horizon mask

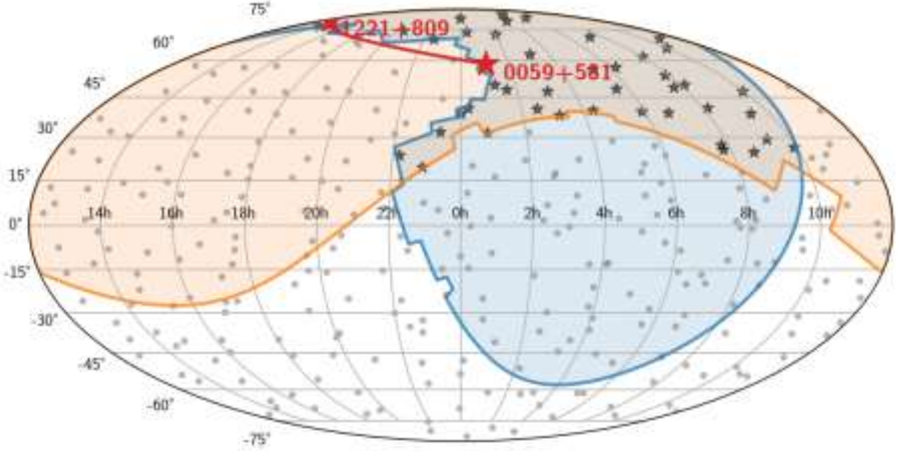


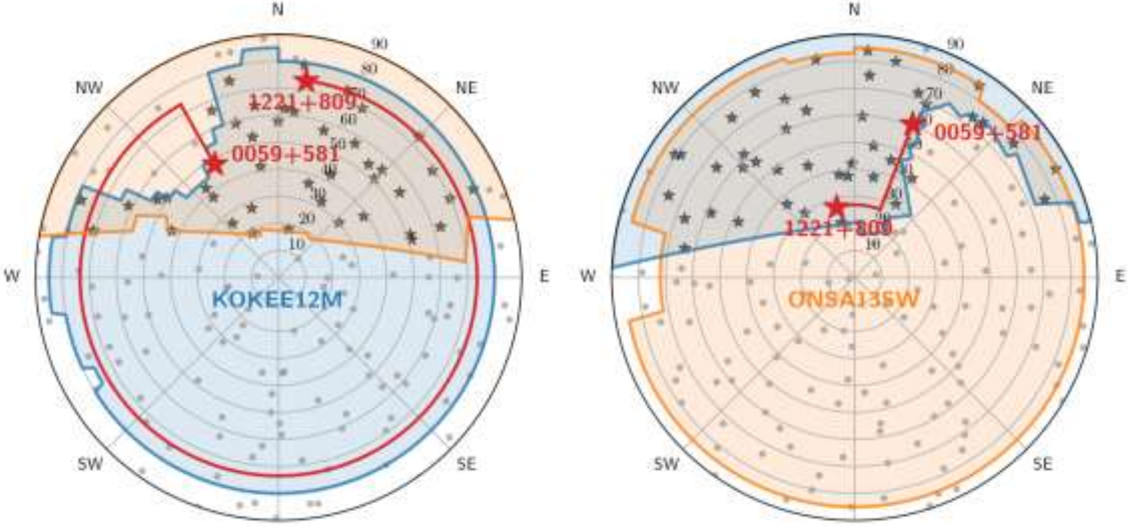
Date: 2025-05-01 19:00
Scan 0059+581
Next scan 1221+809



Date: 2025-05-01 19:00
Scan 0059+581
Next scan 1221+809
Slewing (azimuth, elevation)

- KOKEE12M: 10.7 (7.2, 10.7) [s]
- ONSA13SW: 10.9 (7.8, 10.9) [s]

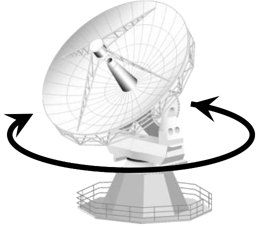


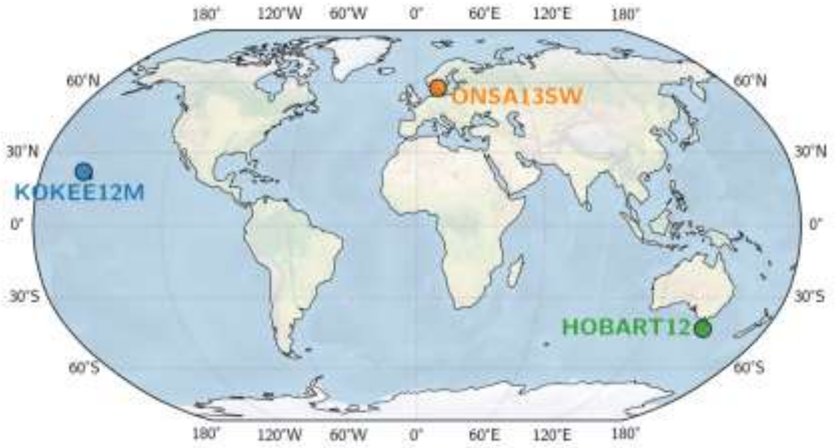


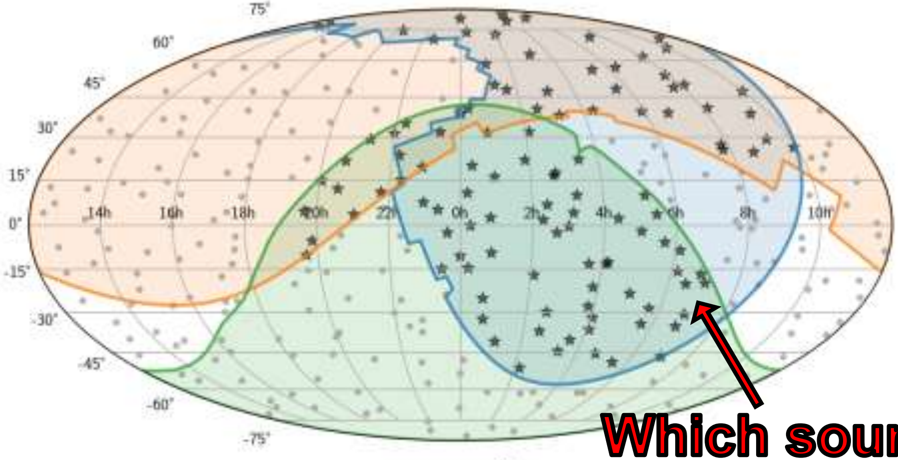
Date: 2025-05-02 00:00
Scan 0059+581
Next scan 1221+809
Slewing (azimuth, elevation)

- KOKEE12M: 38.1 (38.1, 9.2) [s]
- ONSA13SW: 10.6 (8.0, 10.6) [s]

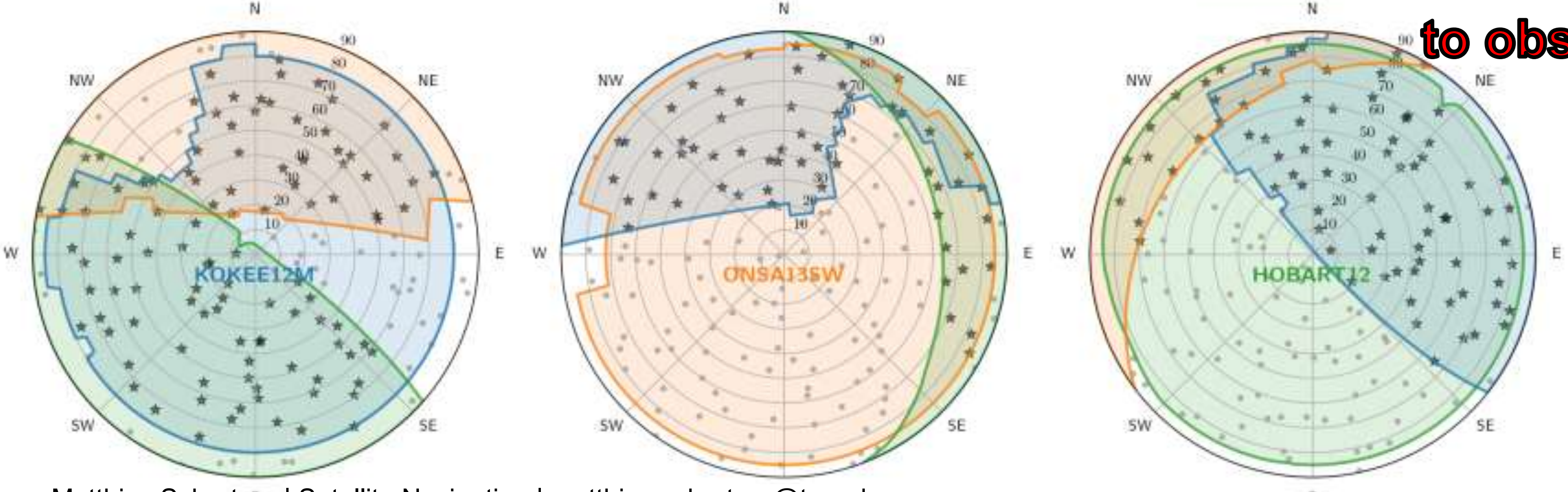
Cable wrap







Which source to observe?



It's complicated

Calibration

UV-Plane

Imaging

Baseline orientation

Polar Motion

UT1-UTC

Celestial Pole Offsets

Astrometry

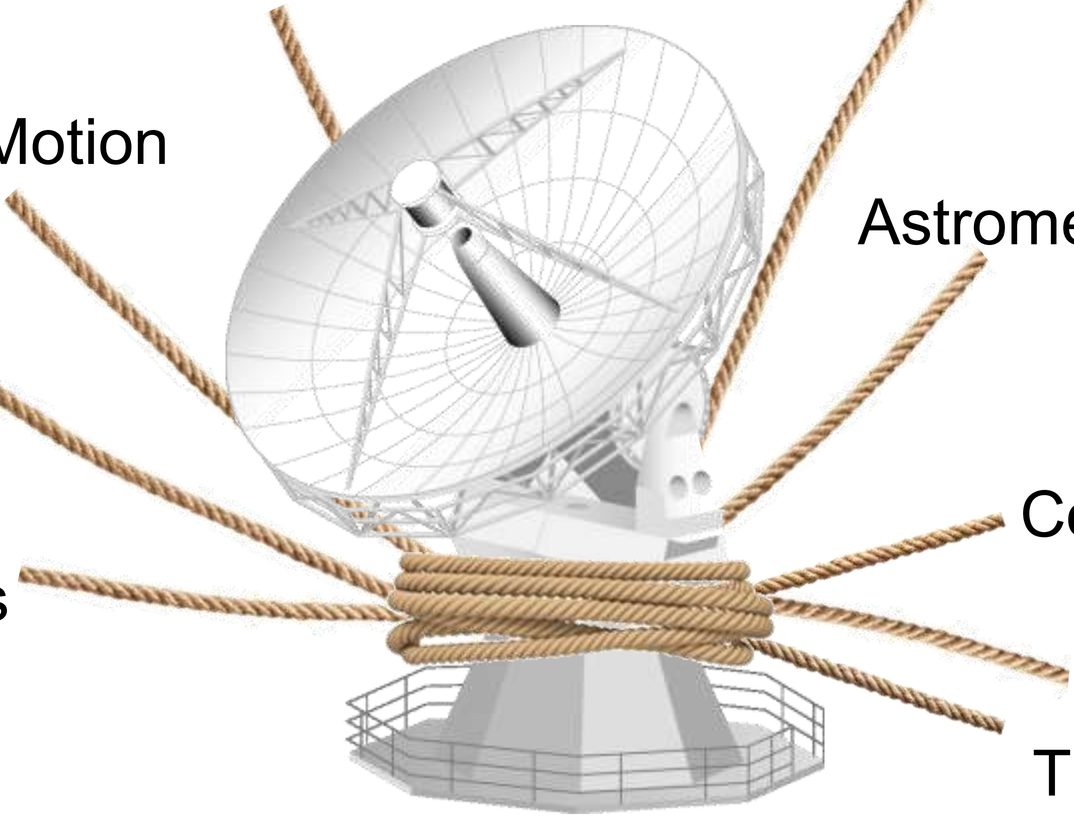
scans per source or station

Station Coordinates

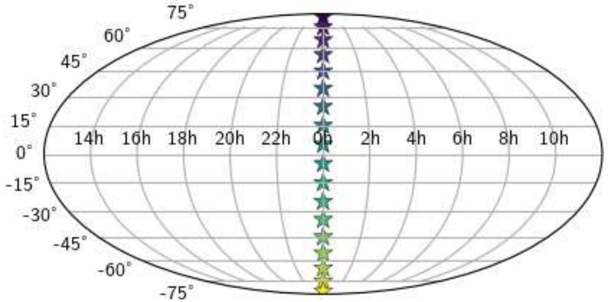
CRF

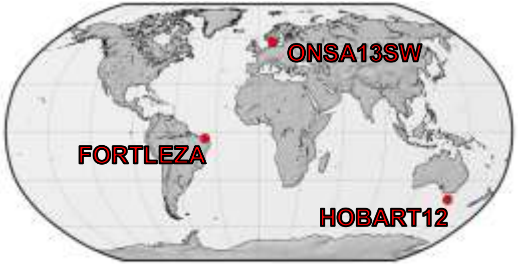
TRF

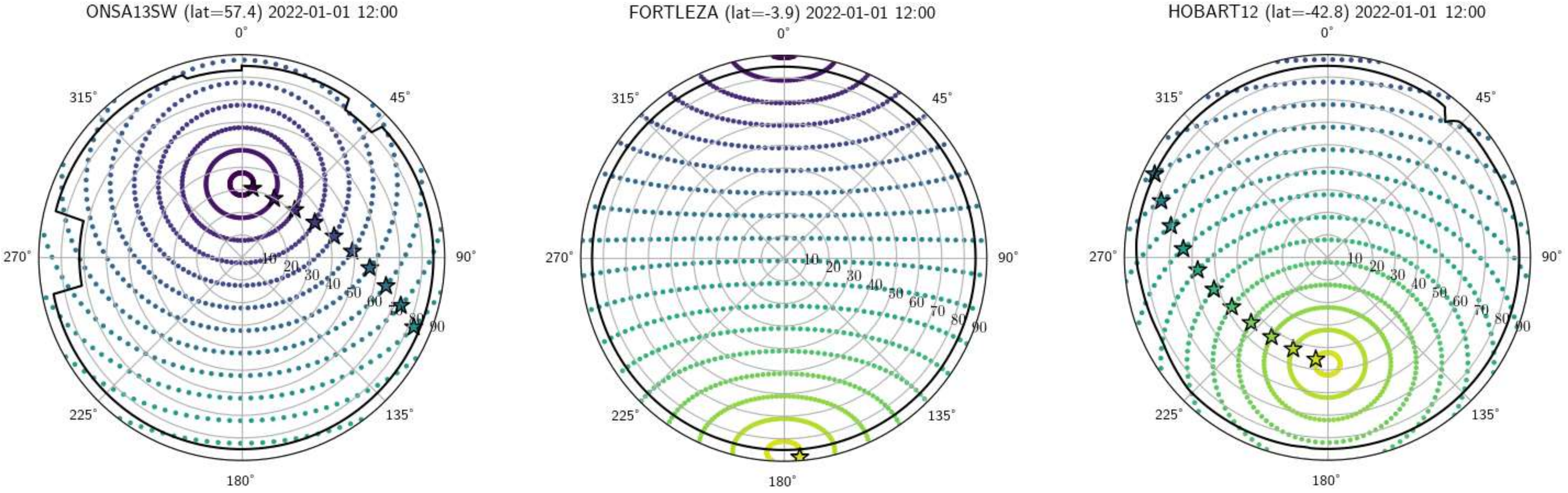
long-term



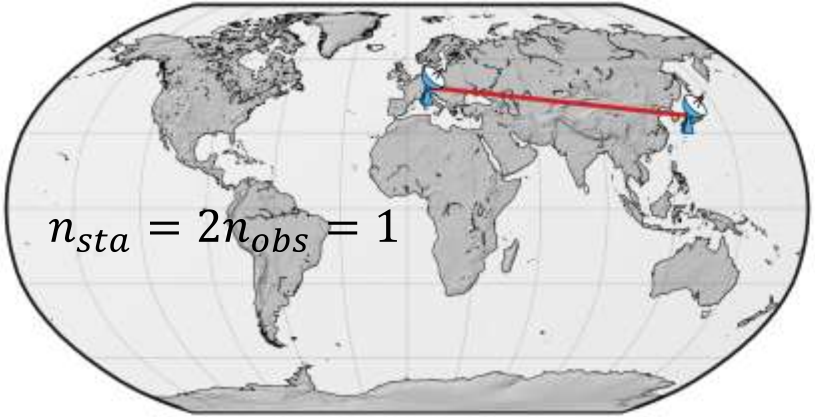
Source visibility:

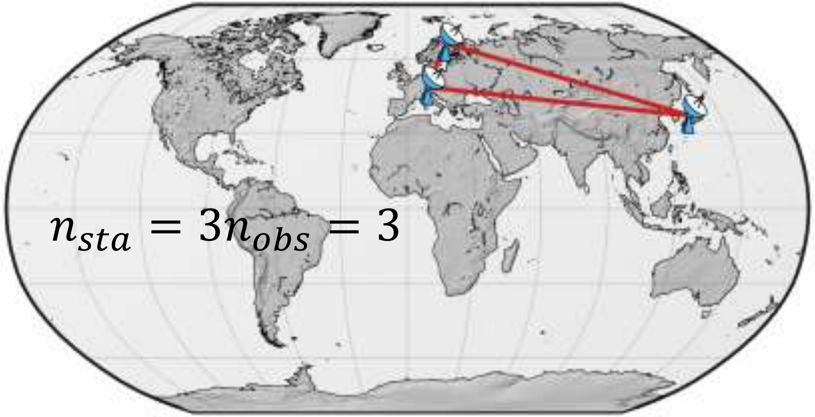


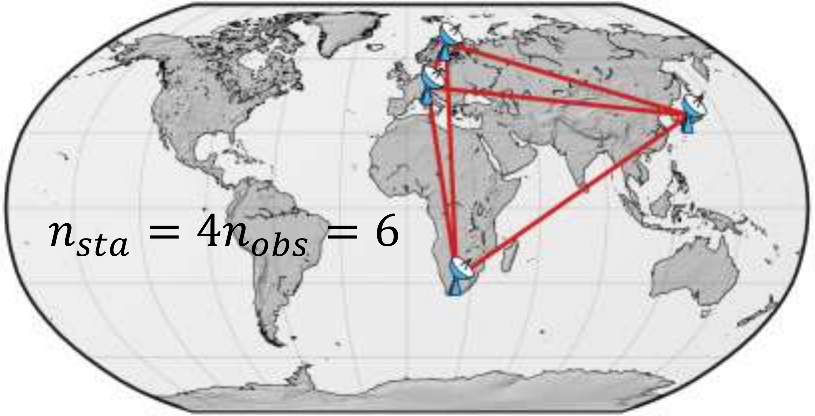


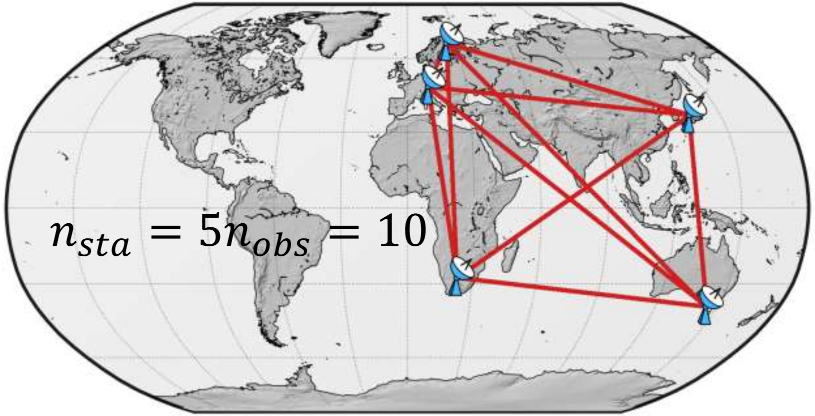


Number of observations per scan



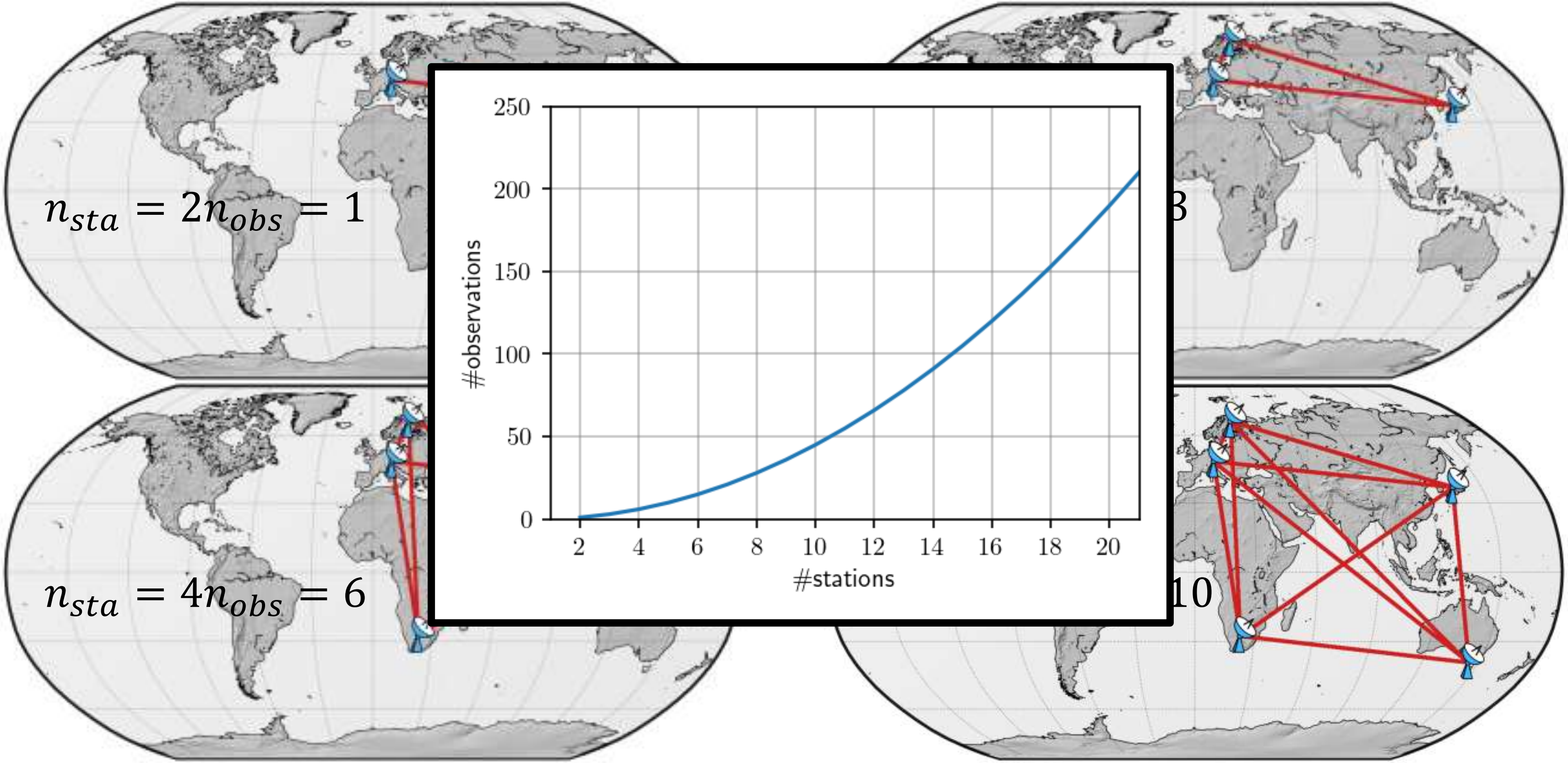






Number of observations per scan

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



$n_{sta} = 2 \quad n_{obs} = 1$

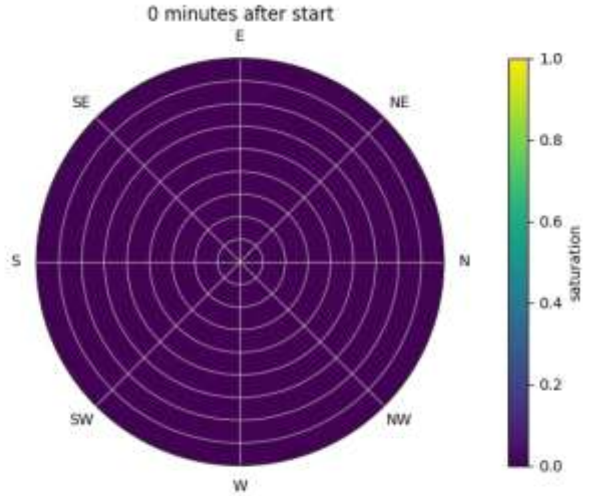
3

$n_{sta} = 4 \quad n_{obs} = 6$

10

Scan Selection

TU WIEN VieSched++
Vienna VLBI and Satellite Software



Via many optimization criteria

Sky-coverage □ troposphere

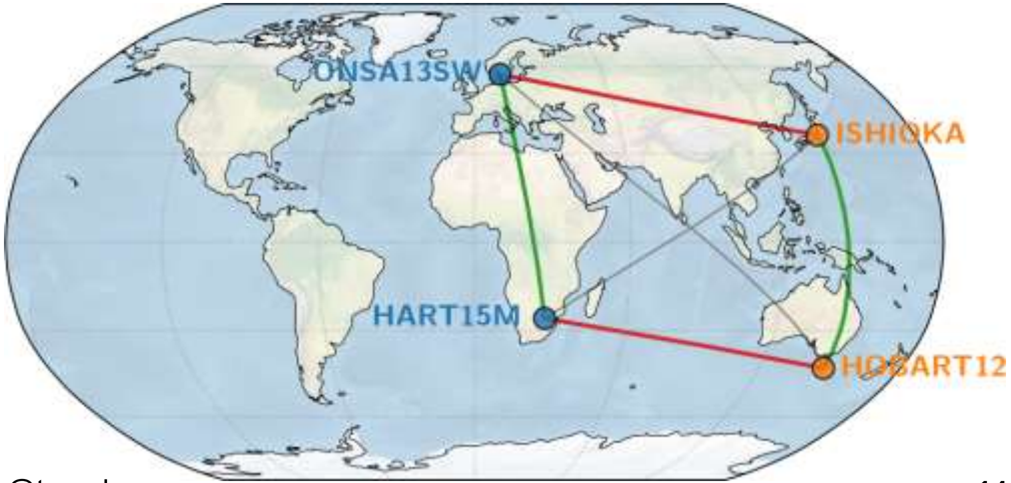
Number of observations □ redundancy

Distribution of observations

- Stations □ Coordinates / TRF
- Sources □ Astrometry / CRF
- Baselines □ N-S (Polar Motion)
  □ E-W (UT1-UTC)

and many more…

The "art" is to balance these criteria
□ scheduling software



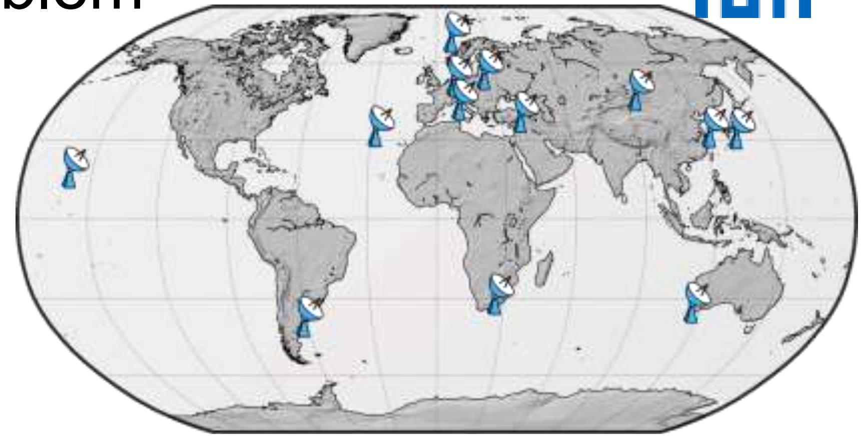
Scheduling is an optimization problem

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
IVS-R41032	R41032	2022-01-06 18:30	6	24:00	Ht Is Kk Ns Ny Sa Yg Ys
IVS-R11033	R11033	2022-01-10 17:00	10	24:00	Ag Ht Is Ma Ns Nt Ny On Sa Wz Yg

Scheduling is an optimization problem

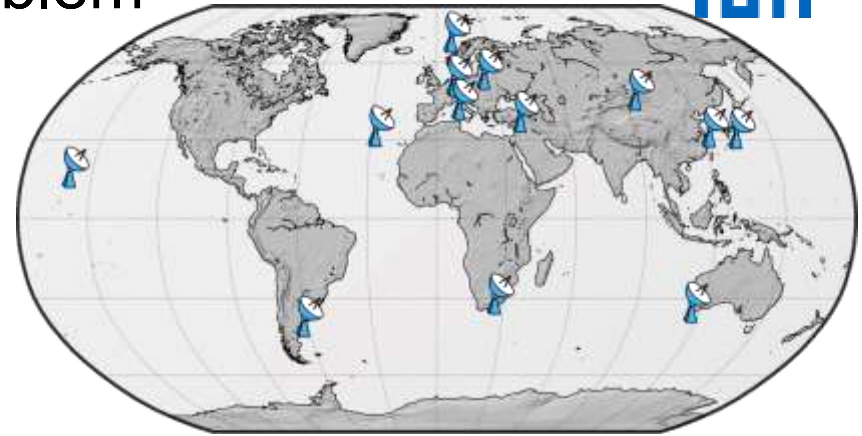


What you have:

- session (time…)
- station network

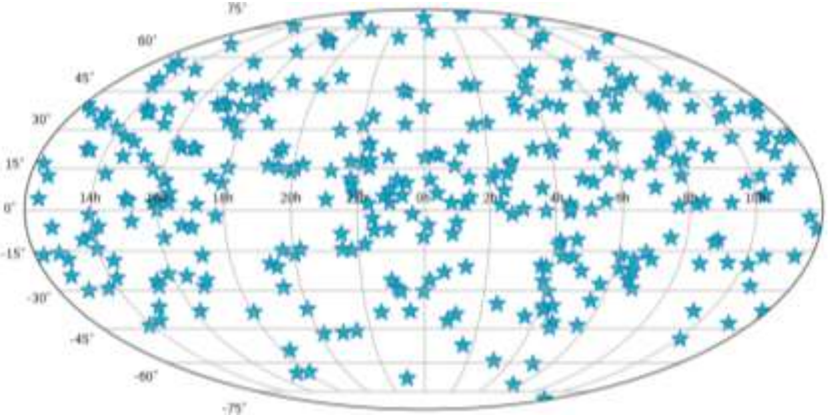
Name	Code	Start	DOY	Dur	Stations
January					
IVS-R11032	R11032	2022-01-03 17:00	3	24:00	Ht Is Kv Ma Ns Nt Ny On Sa Wz Yg Ag
IVS-R41032	R41032	2022-01-06 18:30	6	24:00	Ht Is Kk Ns Ny Sa Yg Ys
IVS-R11033	R11033	2022-01-10 17:00	10	24:00	Ag Ht Is Ma Ns Nt Ny On Sa Wz Yg

Scheduling is an optimization problem



What you have:

- session (time…)
- station network
- source list

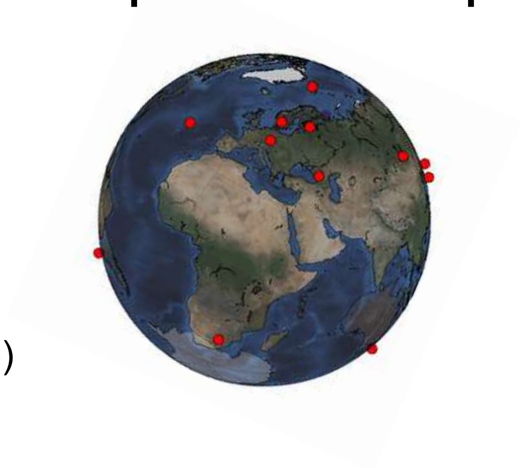


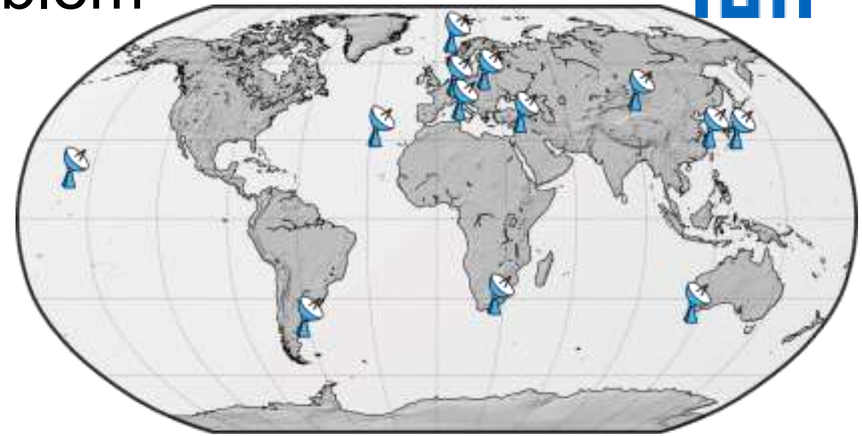
Name	Code	Start	DOY	Dur	Stations
January					
IVS-R11032	R11032	2022-01-03 17:00	3	24:00	Ht Is Kv Ma Ns Nt Ny On Sa Wz Yg Ag
IVS-R41032	R41032	2022-01-06 18:30	6	24:00	Ht Is Kk Ns Ny Sa Yg Ys
IVS-R11033	R11033	2022-01-10 17:00	10	24:00	Ag Ht Is Ma Ns Nt Ny On Sa Wz Yg

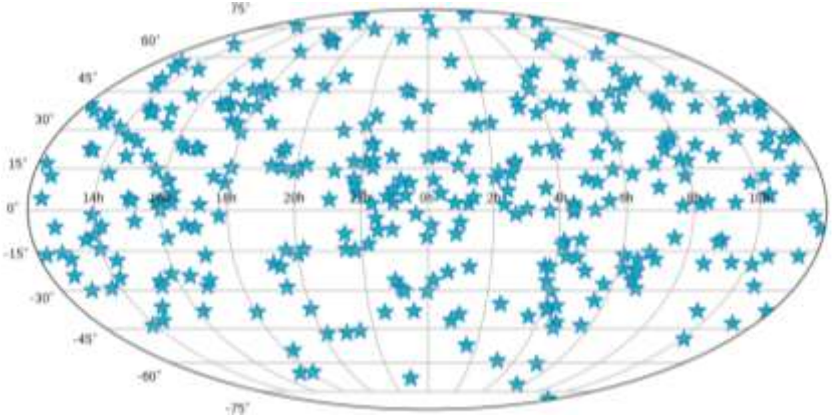
Scheduling is an optimization problem

What you have:

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





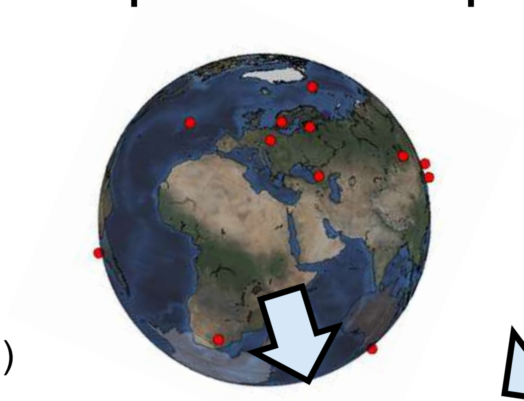


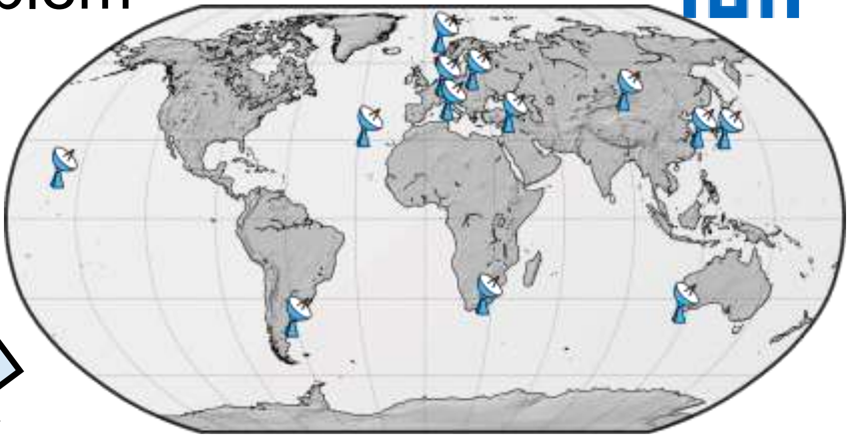
Name	Code	Start	DOY	Dur	Stations
January					
IVS-R11032	R11032	2022-01-03 17:00	3	24:00	Ht Is Kv Ma Ns Nt Ny On Sa Wz Yg Ag
IVS-R41032	R41032	2022-01-06 18:30	6	24:00	Ht Is Kk Ns Ny Sa Yg Ys
IVS-R11033	R11033	2022-01-10 17:00	10	24:00	Ag Ht Is Ma Ns Nt Ny On Sa Wz Yg

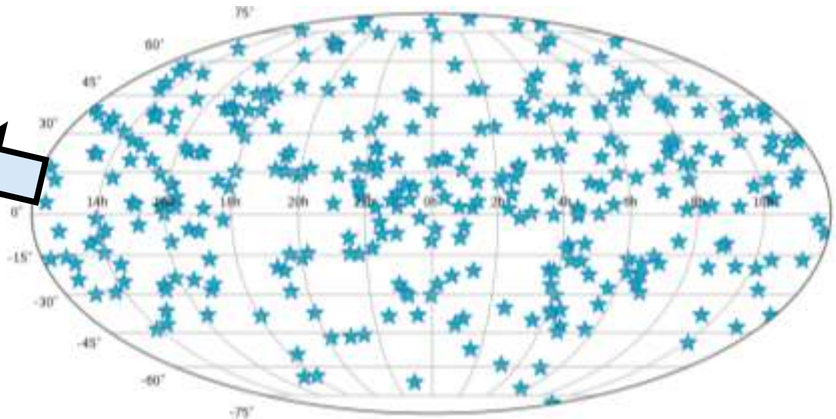
Scheduling is an optimization problem

What you have:

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



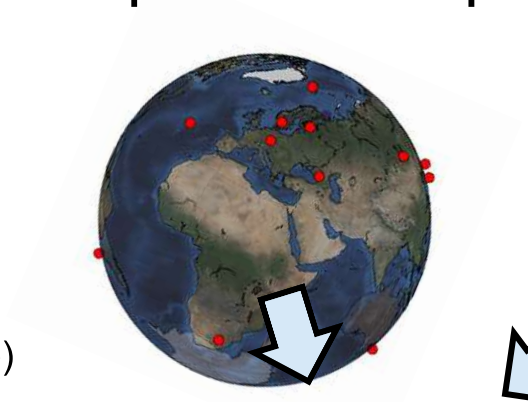


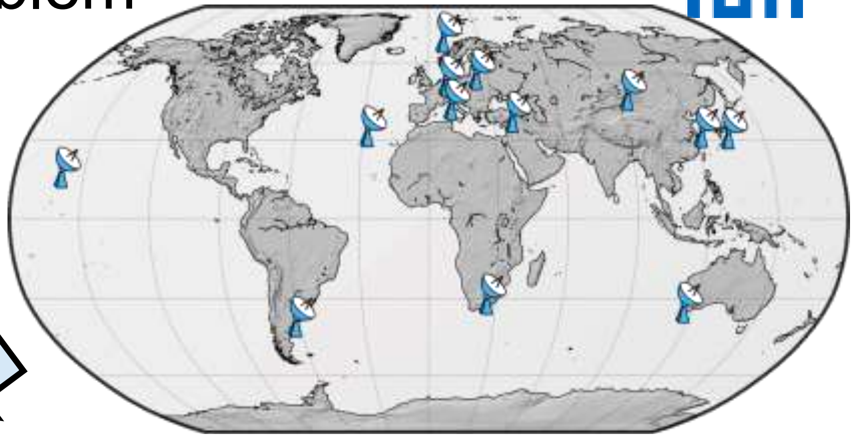


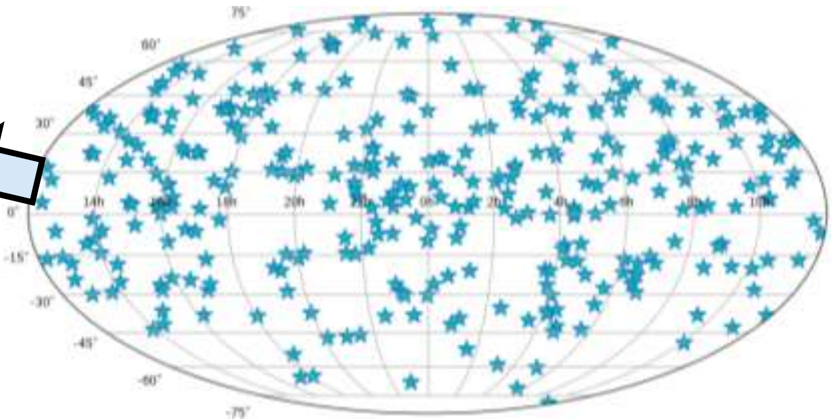
Name	Code	Start	DOY		
January					
IVS-R11032	R11032	2022-01-03 17:00	3	24:00	Ht Is Kv Ma Ns Nt Ny On Sa Wz Yg Ag
IVS-R41032	R41032	2022-01-06 18:30	6	24:00	Ht Is Kk Ns Ny Sa Yg Ys
IVS-R11033	R11033	2022-01-10 17:00	10	24:00	Ag Ht Is Ma Ns Nt Ny On Sa Wz Yg

Scheduling is an optimization problem

What you have:
- session (time…)
- station network
- source list
- objective (EOP, scale)



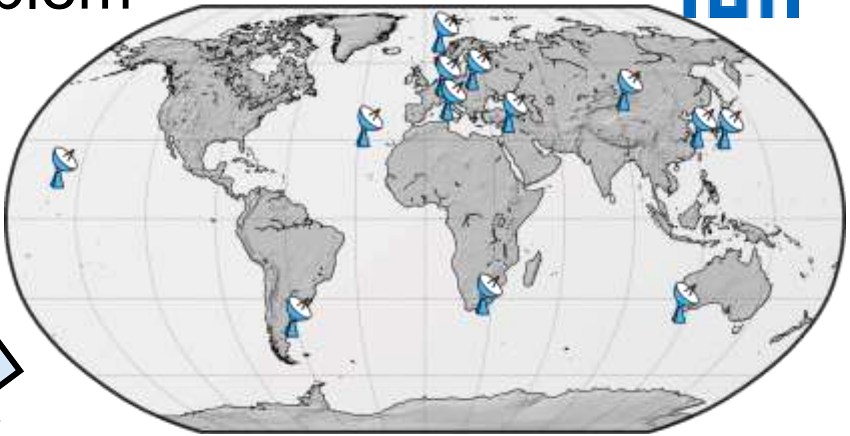


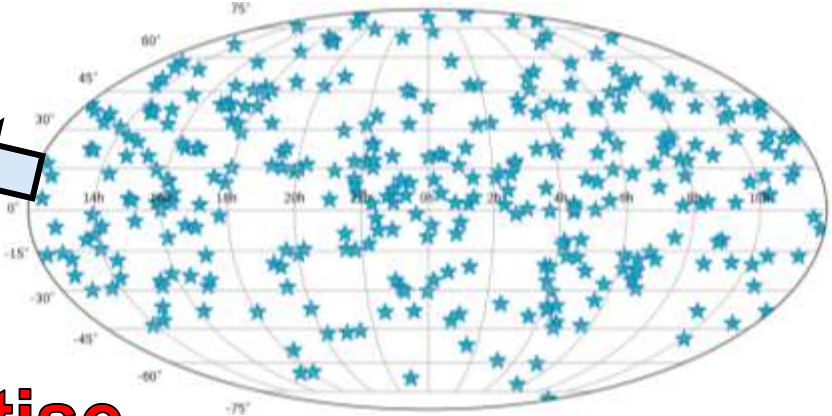


Name	Code	Start	DOY		Star
January					
IVS-R11032	R11032	2022-01-03 17:00	3	24:00	Ht Is Kv Ma Ns Nt Ny On Sa Wz Yg Ag
IVS-R41032	R41032	2022-01-06 18:30	6	24:00	Ht Is Kk Ns Ny Sa Yg Ys
IVS-R11033	R11033	2022-01-10 17:00	10	24:00	Ag Ht Is Ma Ns Nt Ny On Sa Wz Yg

Scheduling is an optimization problem

What you have:
- session (time…)
- station network
- source list
- objective (EOP, scale)





Name	Code	Start	DOY		[illegible]
January					
IVS-R11032	R11032	2022-01-03 17:00	3	24:00	Ht Is Kv Ma Ns Nt Ny [illegible] Yg Ag
IVS-R41032	R41032	2022-01-06 18:30	6	24:00	Ht Is Kk Ns Ny Sa Yg Ys
IVS-R11033	R11033	2022-01-10 17:00	10	24:00	Ag Ht Is Ma Ns Nt [illegible]

Expertise

Example: from objective to schedule

1-hour VGOS Intensive | WETTZ13S–KOKEE12M | Objective: rapid UT1–UTC

1 DEFINE

Network: 2 VGOS stations
Window: 1 hour
Target: UT1–UTC precision

2 CONSTRAINS

Common visibility
5° cutoff + horizon masks
Cable wrap, slew and SNR

3 SCHEDULING

Favor east-west geometry
Mix high and low elevations
Low declination scans

4 COMPARE

Schedule A: more scans
Schedule B: better sky-coverage
Keep both for evaluation

5 EVALUATE

Check observations and idle time
Simulate UT1-UTC formal error and repeatability
Select best schedule

6 EXPORT

Release selected schedule
SKD → stations
VEX → correlator

Takeaway: one scientific objective drives every scheduling choice.
Evaluation closes the loop before release.

What is a VLBI schedule in practice?

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
https://github.com/TUW-VieVS/VieSchedpp_AUTO

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

- **Session:** VLBI experiment
- **Station:** A given VLBI antenna/telescope together with all the electronics and recording equipment
- **Baseline:** A pair of two stations
- **Site:** A location with one or more stations in close proximity
- **Network:** All participating stations within a VLBI session
- **Source:** Something that is observed by VLBI (AGN, satellite, spacecraft…)
- **Source list:** All available sources that could potentially be scheduled in this session
- **Scan:** Two or more VLBI stations simultaneously observing the same source
- **Observation:** The result of cross-correlating the signal from two VLBI stations within a scan

Models and Concepts

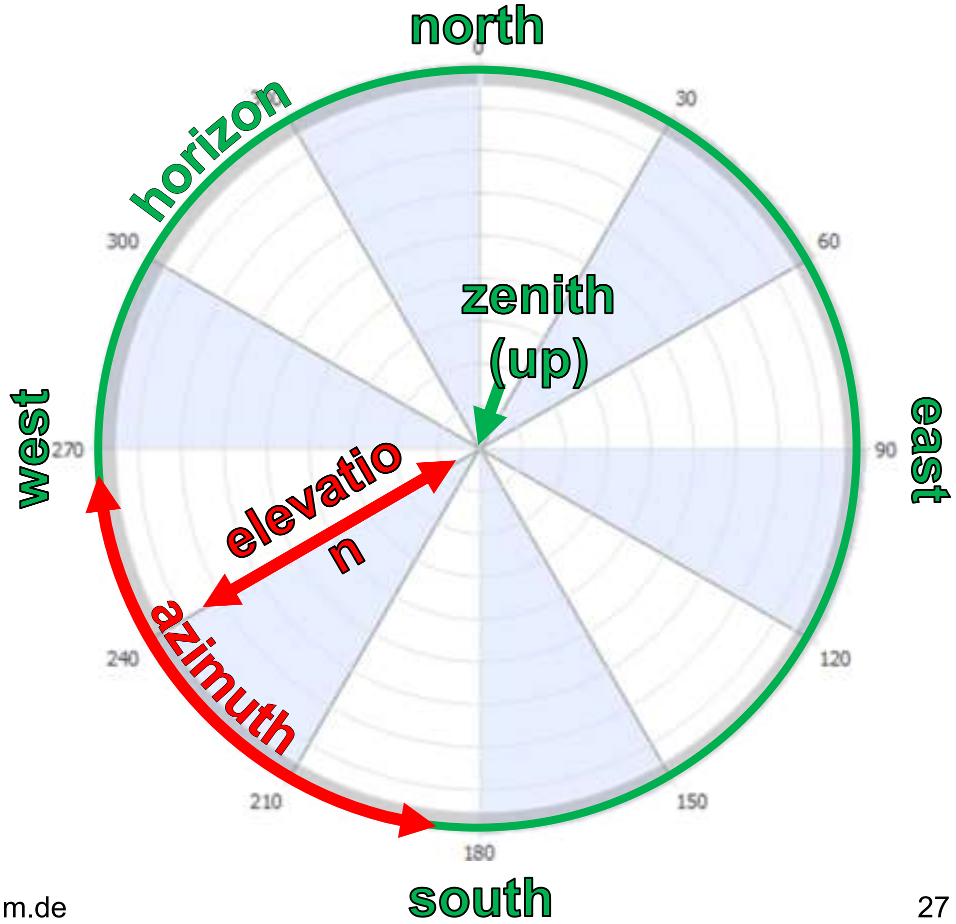
Sky-coverage

Problem

- 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



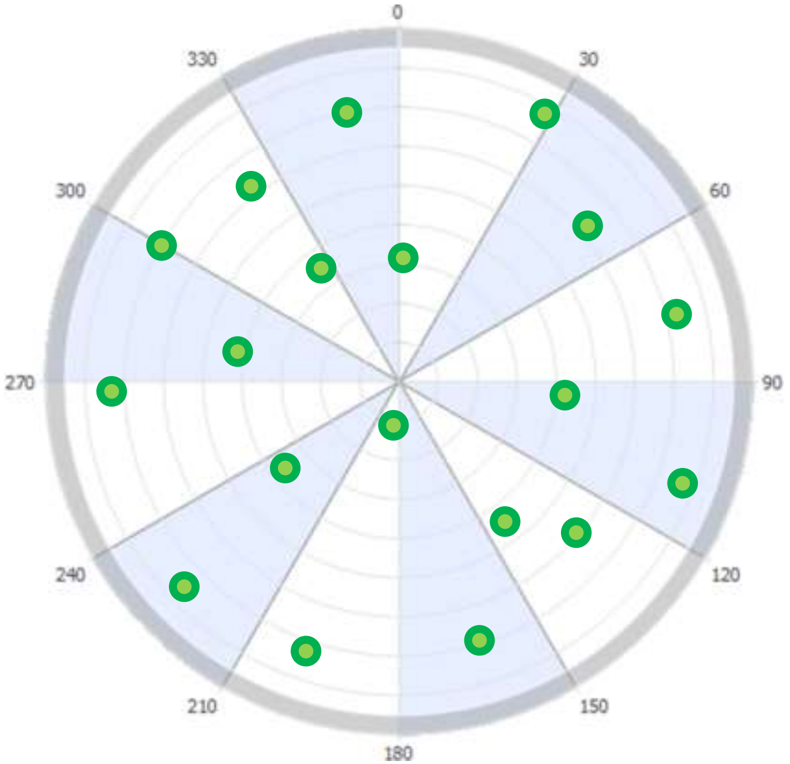
Sky-coverage

For estimating **ZWD**:

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

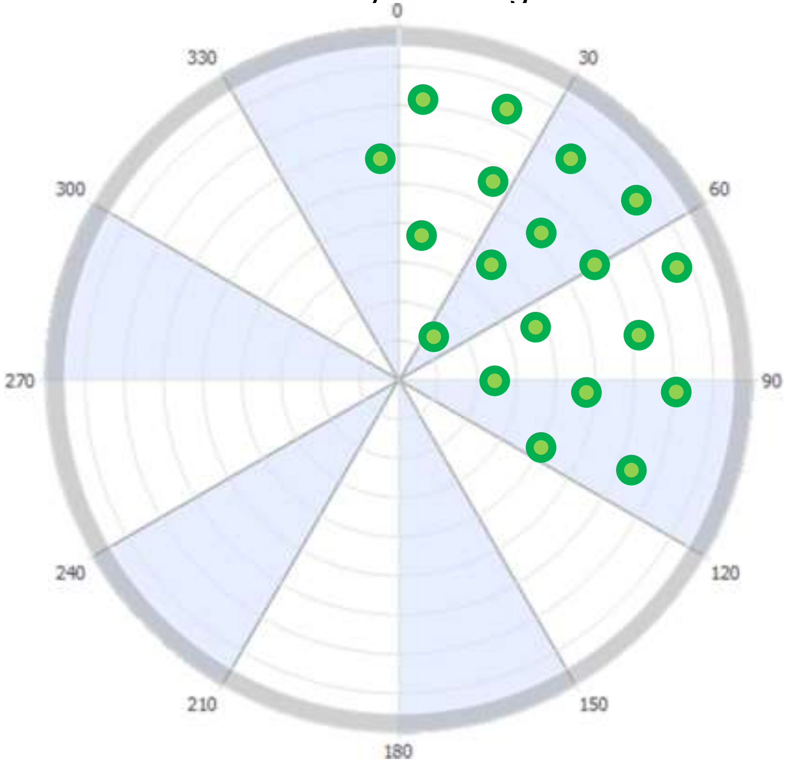
For estimating tropospheric **gradients**:

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

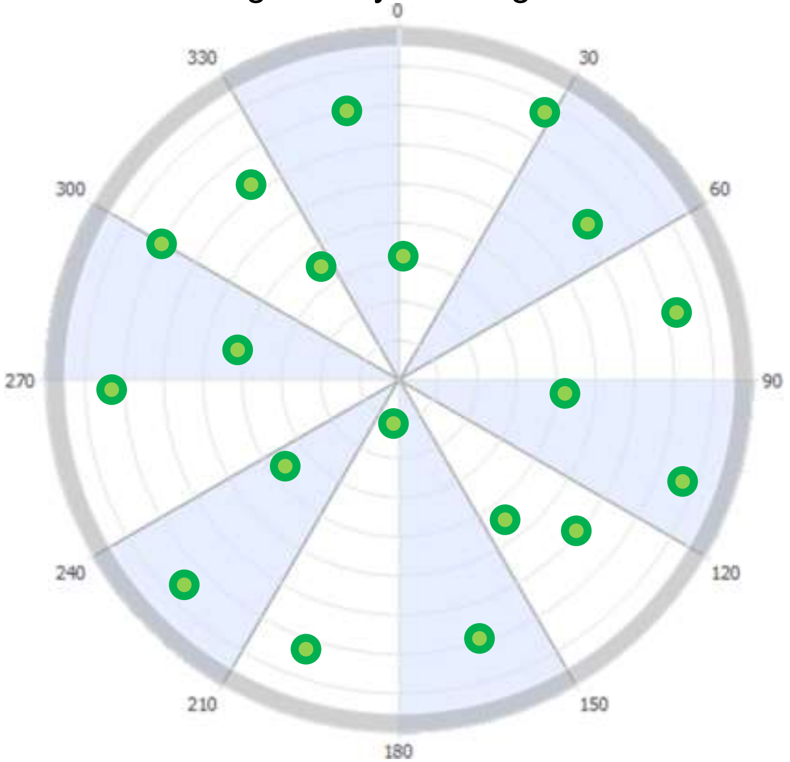


Sky-coverage

bad sky-coverage



good sky-coverage



One challenge in 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)

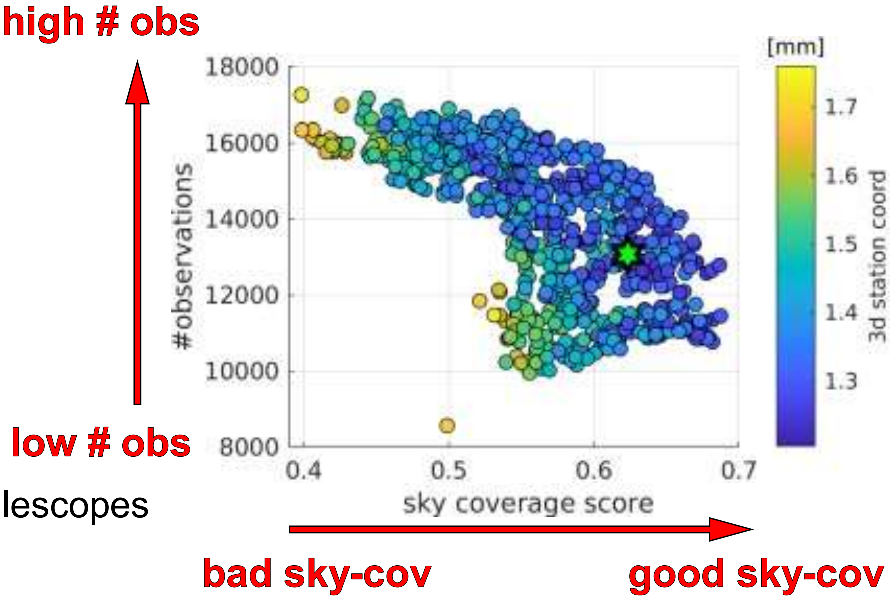
One challenge in VLBI scheduling

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)



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

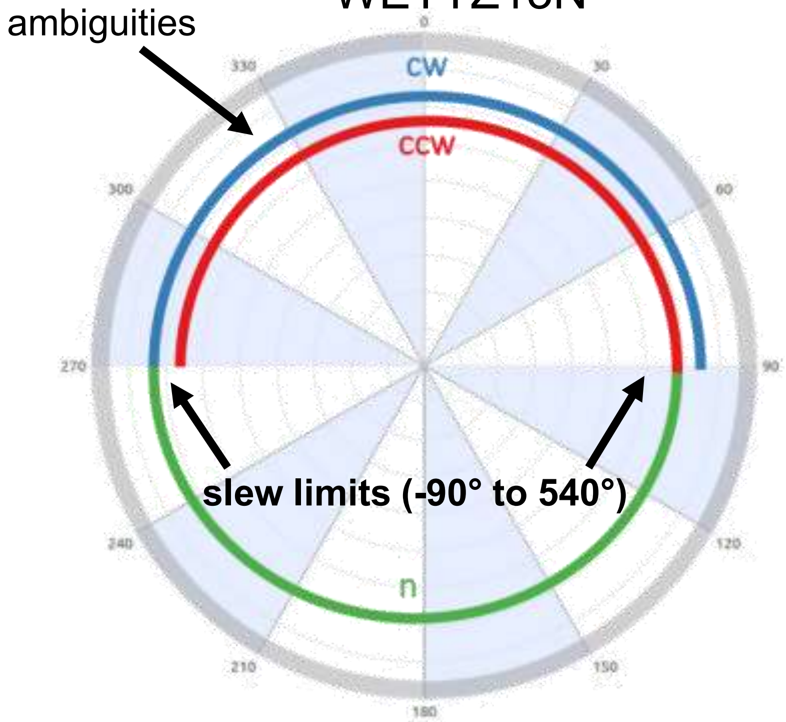
three sections:

ccw: counter cw

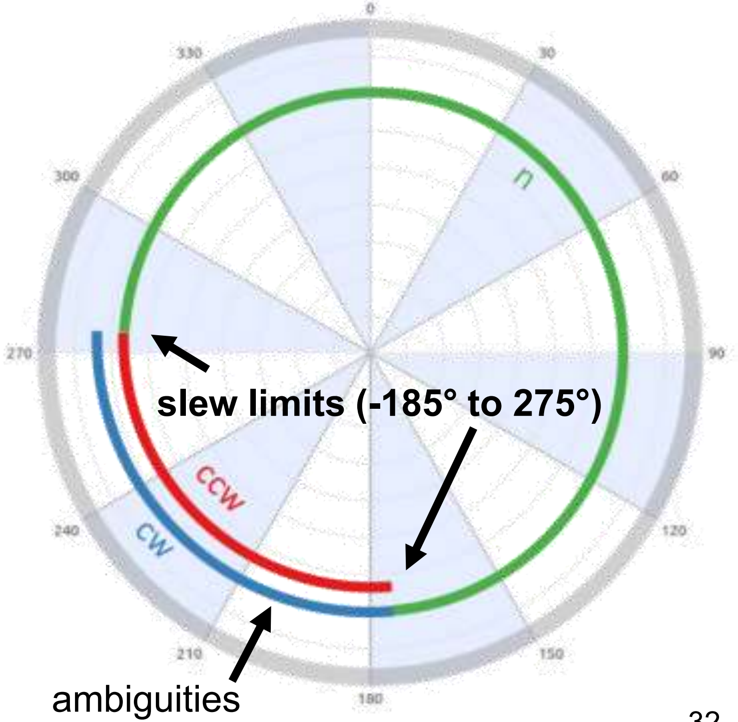
n: neutral

cw: clock-wise

WETTZ13N



HART15M



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
*											
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

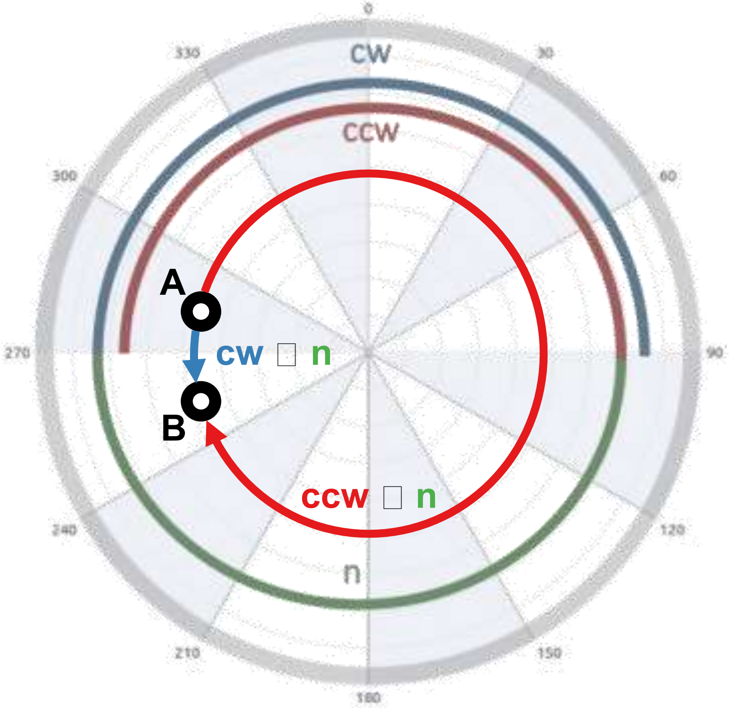
three sections:

ccw: counter cw

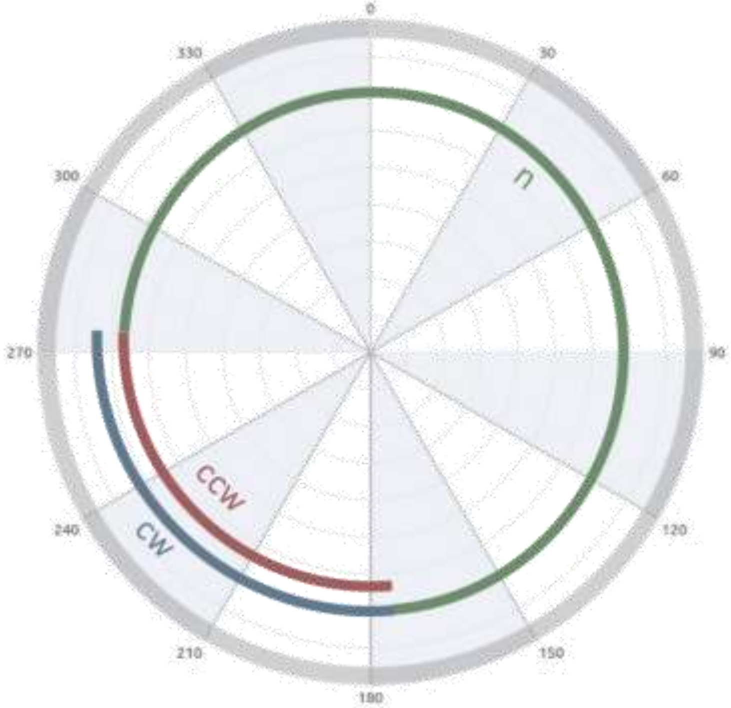
n: neutral

cw: clock-wise

WETTZ13N



HART15M

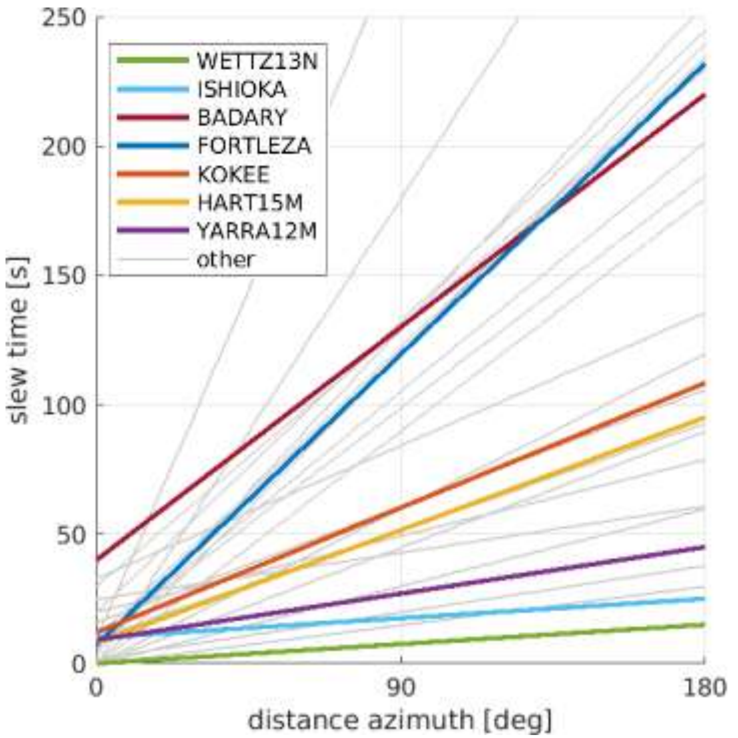


Slew time

*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

- 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



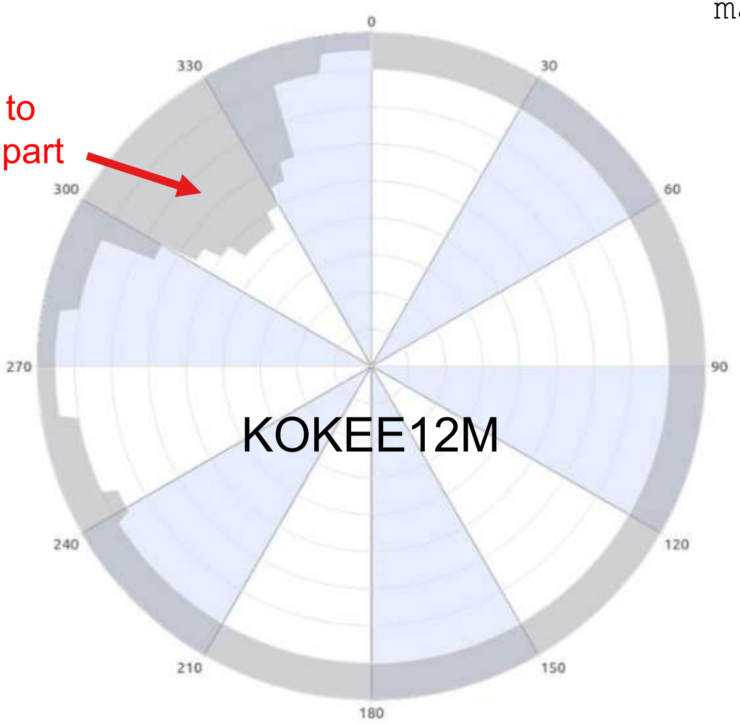
Horizon mask

```
*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)

Not possible to observe this part of the sky



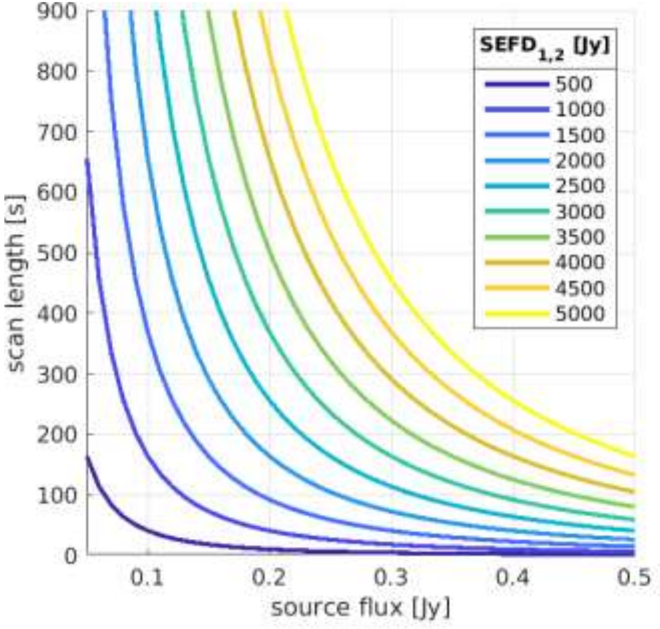
Required observation duration

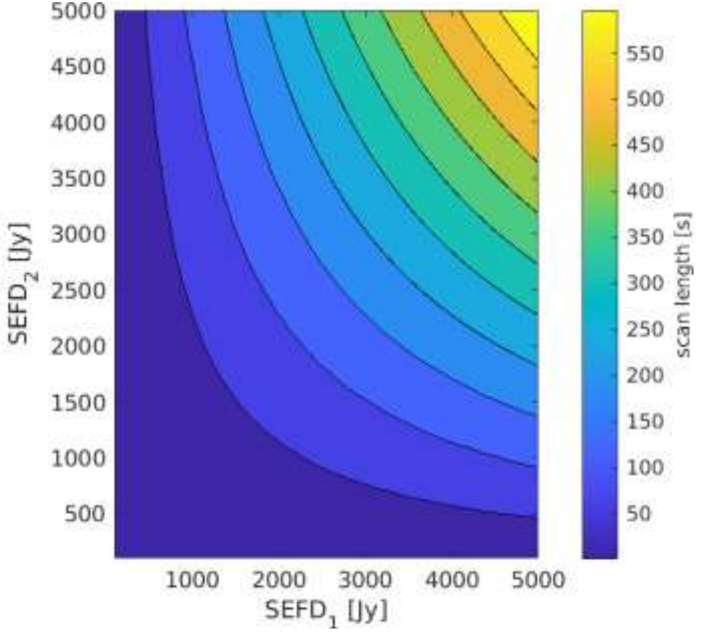
$$\mathrm{T}_{band,1,2} = \left(\frac{SNR_{band}}{\eta F_{band}}\right)^2 \cdot \left(\frac{SEFD_{band,1} \cdot SEFD_{band,2}}{rec_{band}}\right)$$

$T_{band,1,2}$ = observation duration between station 1 and 2 on this band
SNR_{band} = target signal to noise ratio for this band
η = efficiency factor ($\sim$0.7 or lower)
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

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





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

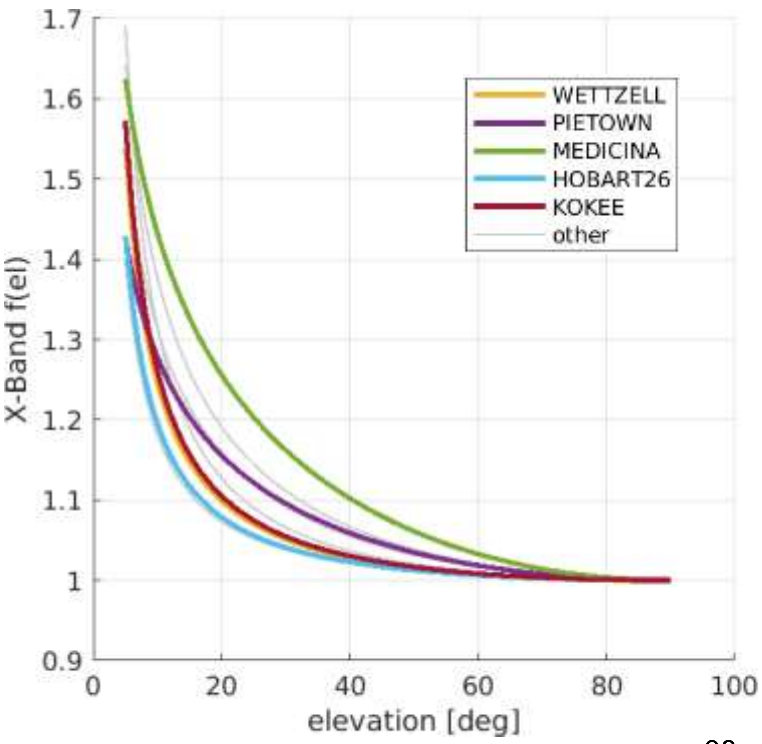
$A_e = \eta_A A_g =$ effective aperture

η_A = aperture efficiency factor

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

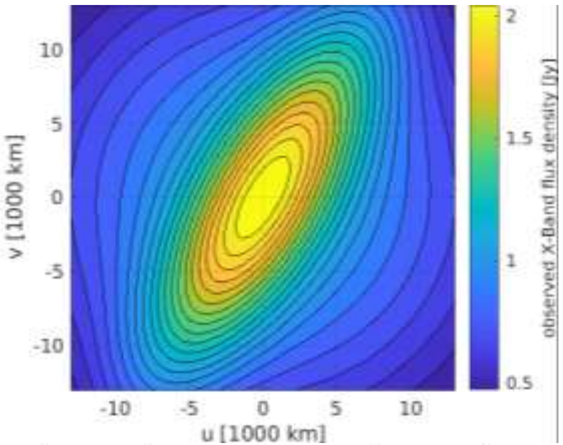
D = antenna diameter

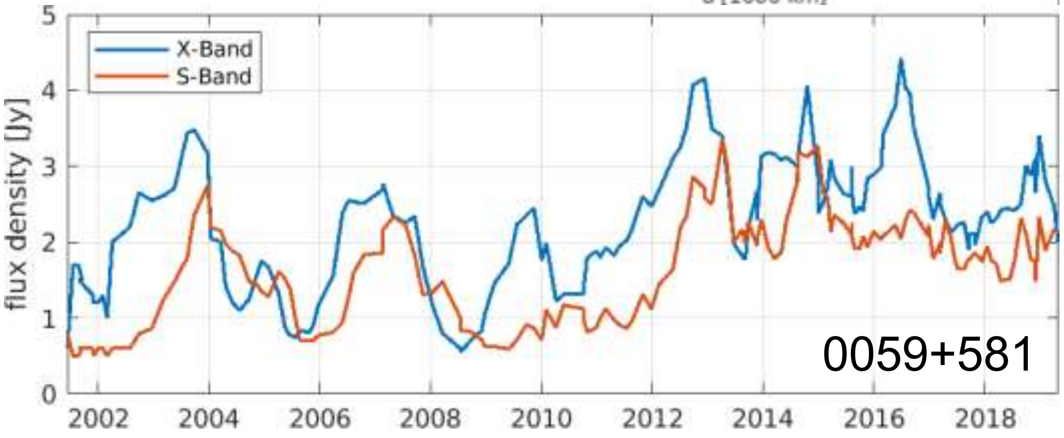
- SEFD is function of frequency, elevation, time, …
  - regular SEFD measurements
  - elevation dependent correction



Source brightness

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





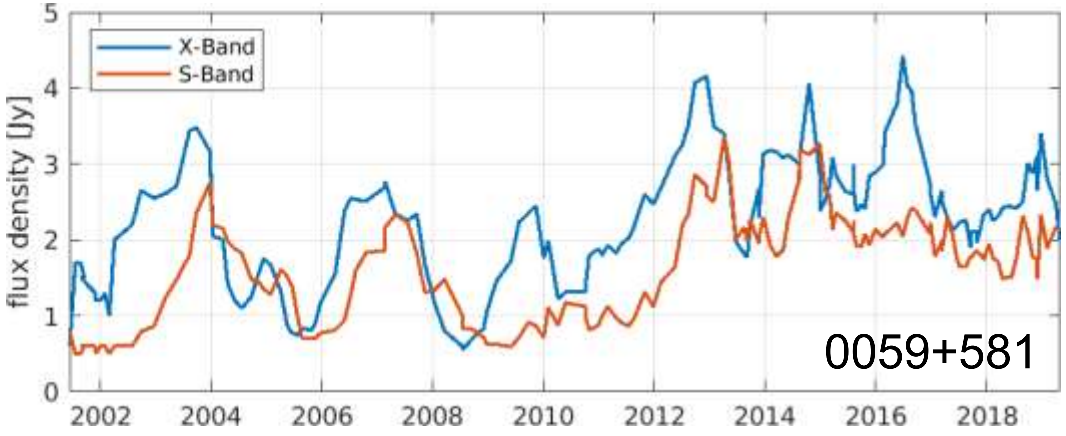
Source brightness

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

```
* 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



VLBI Session types

Intensive sessions

characteristics

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

Objectives

- rapid determination of UT1-UTC

24-hour sessions

characteristics

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

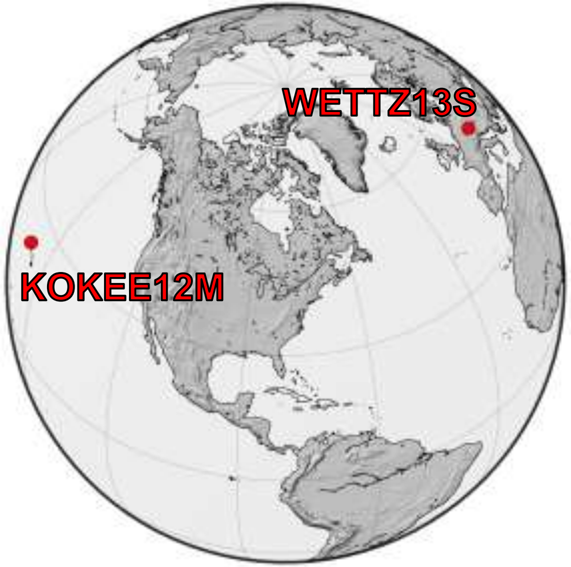
Objectives

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

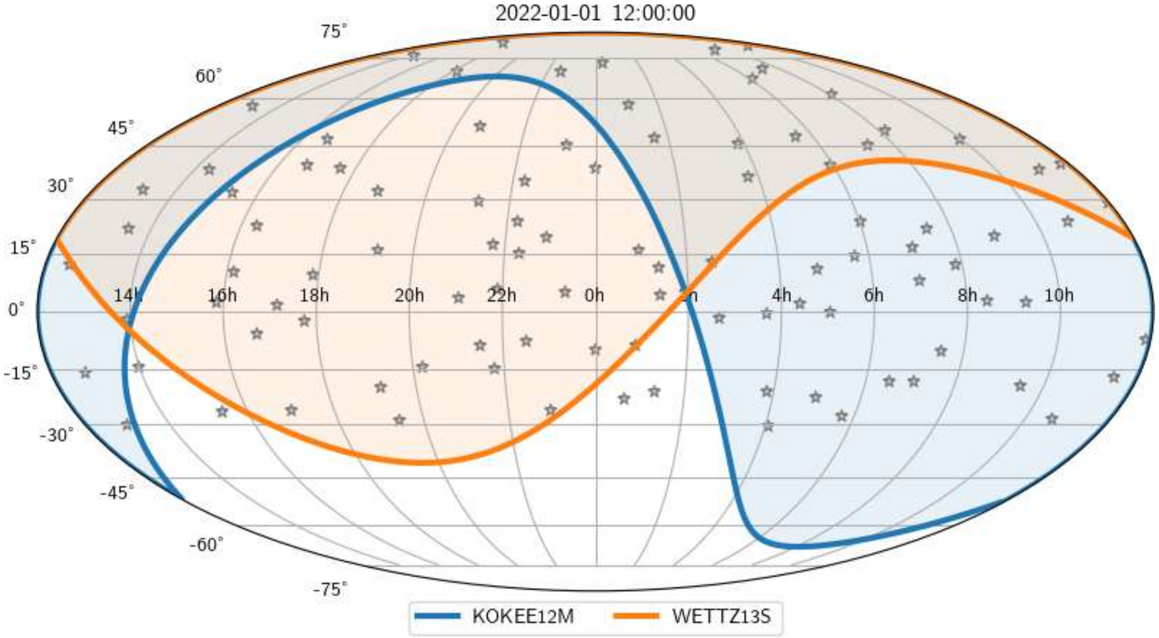
Example VGOS Intensive baseline

suitable baseline

- WETTZ13S
- KOKEE12M

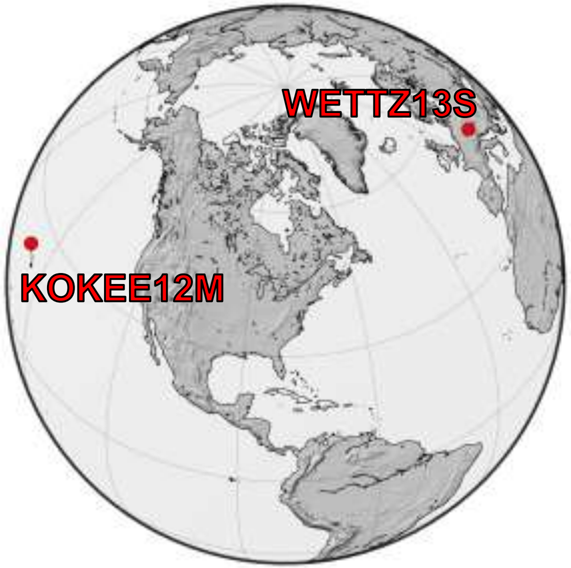


theoretically possible observable sky

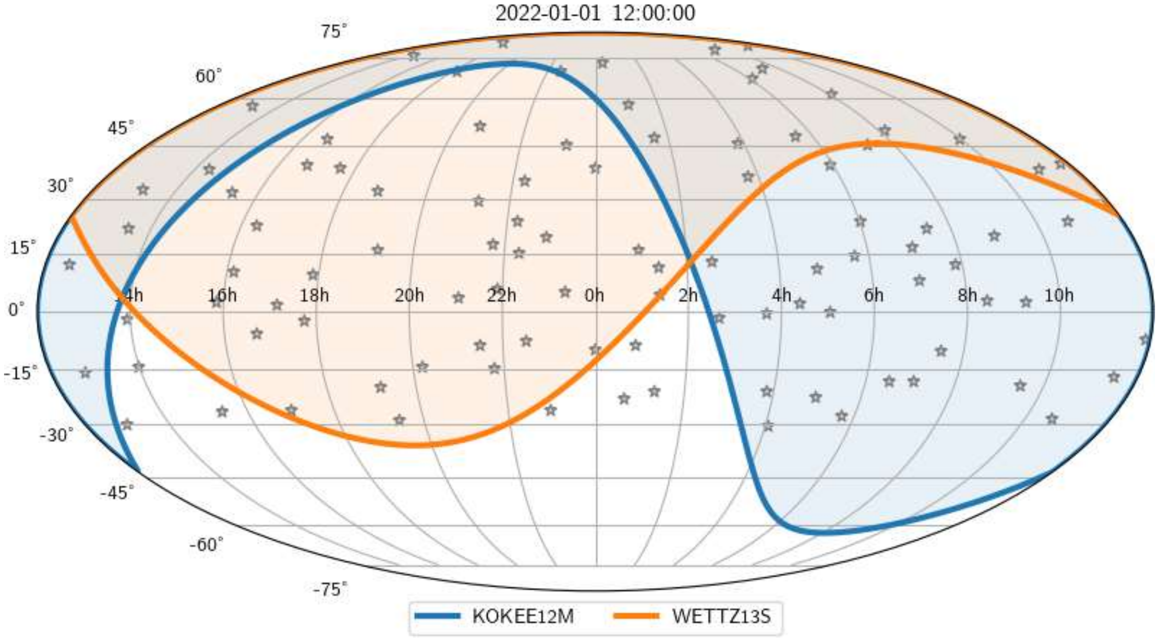


Example VGOS Intensive baseline

suitable baseline
- WETTZ13S
- KOKEE12M



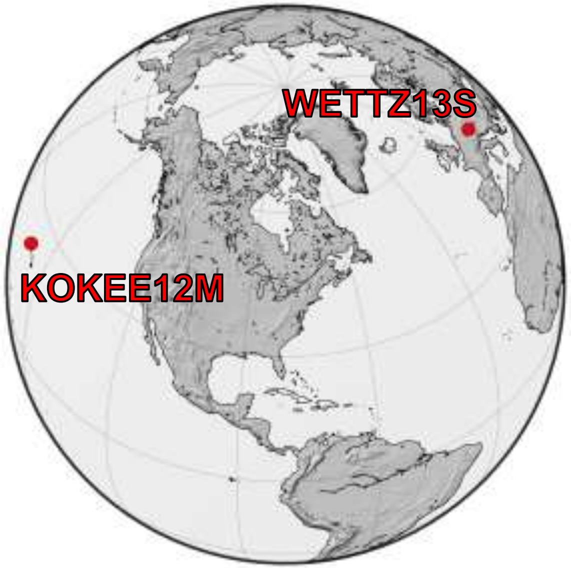
theoretically possible observable sky + 5° cutoff elevation



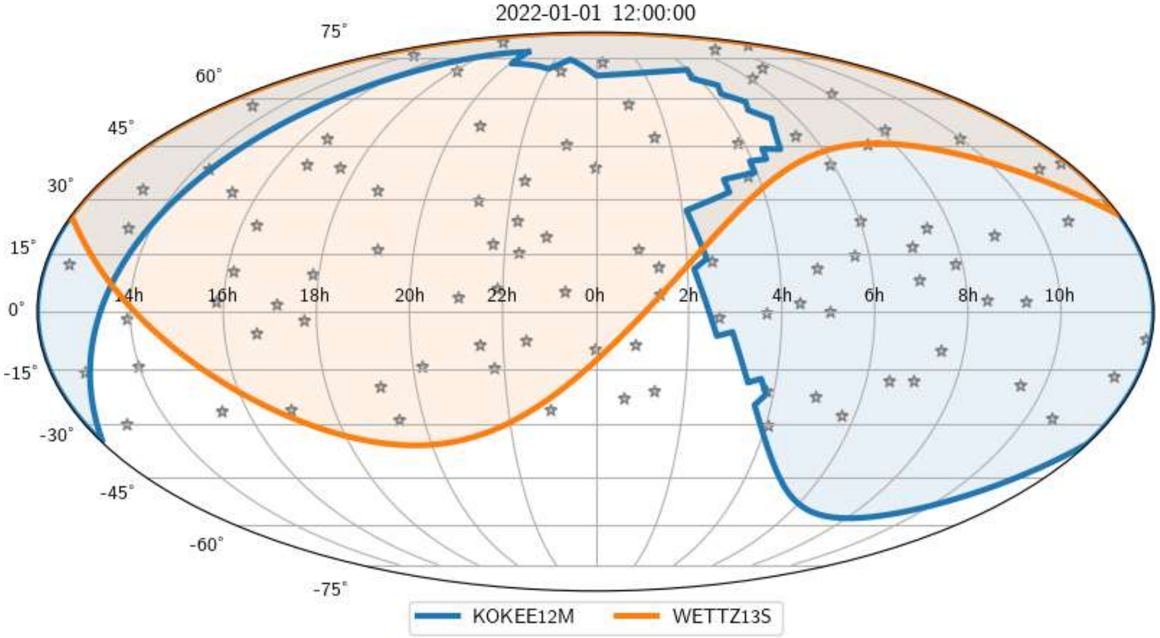
Example VGOS Intensive baseline

suitable baseline

- WETTZ13S
- KOKEE12M

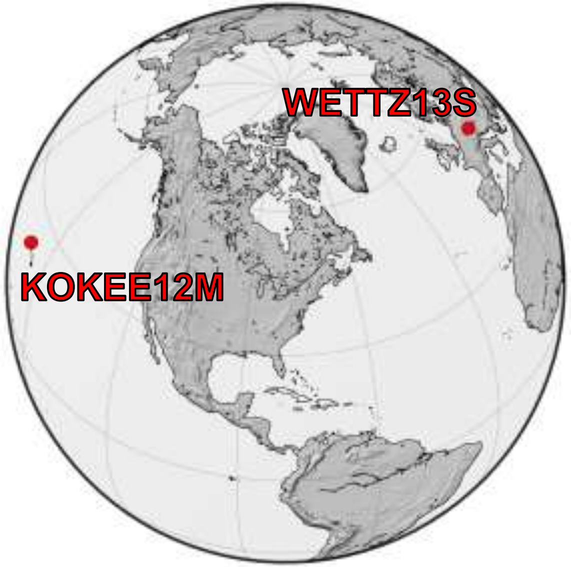


theoretically possible observable sky + 5° cutoff elevation + horizon mask

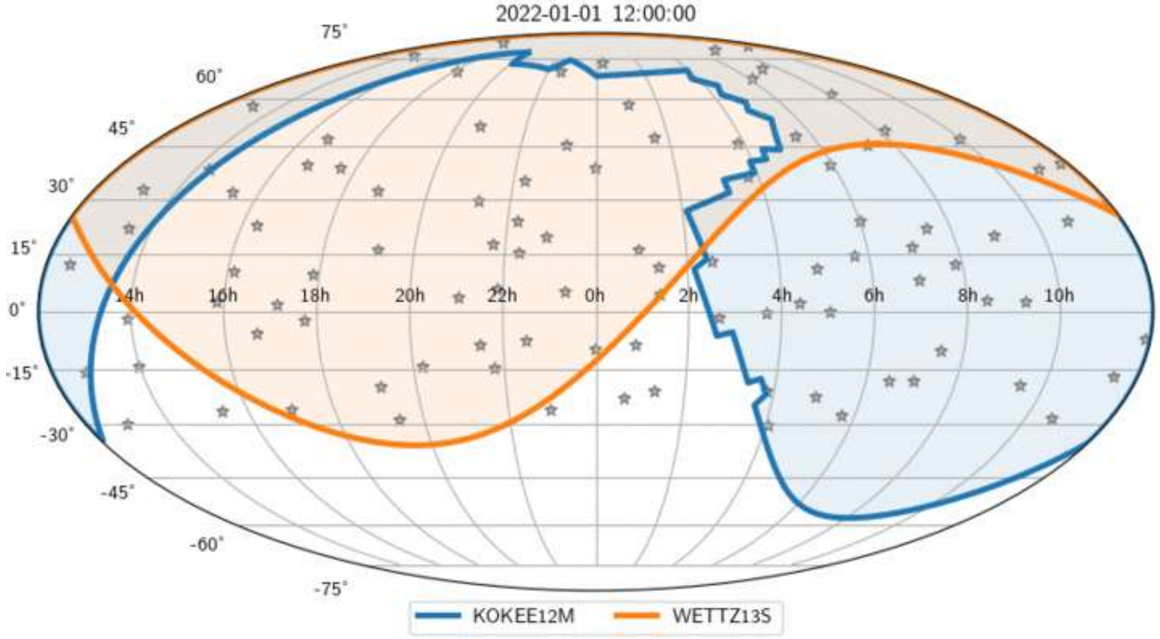


Example VGOS Intensive baseline

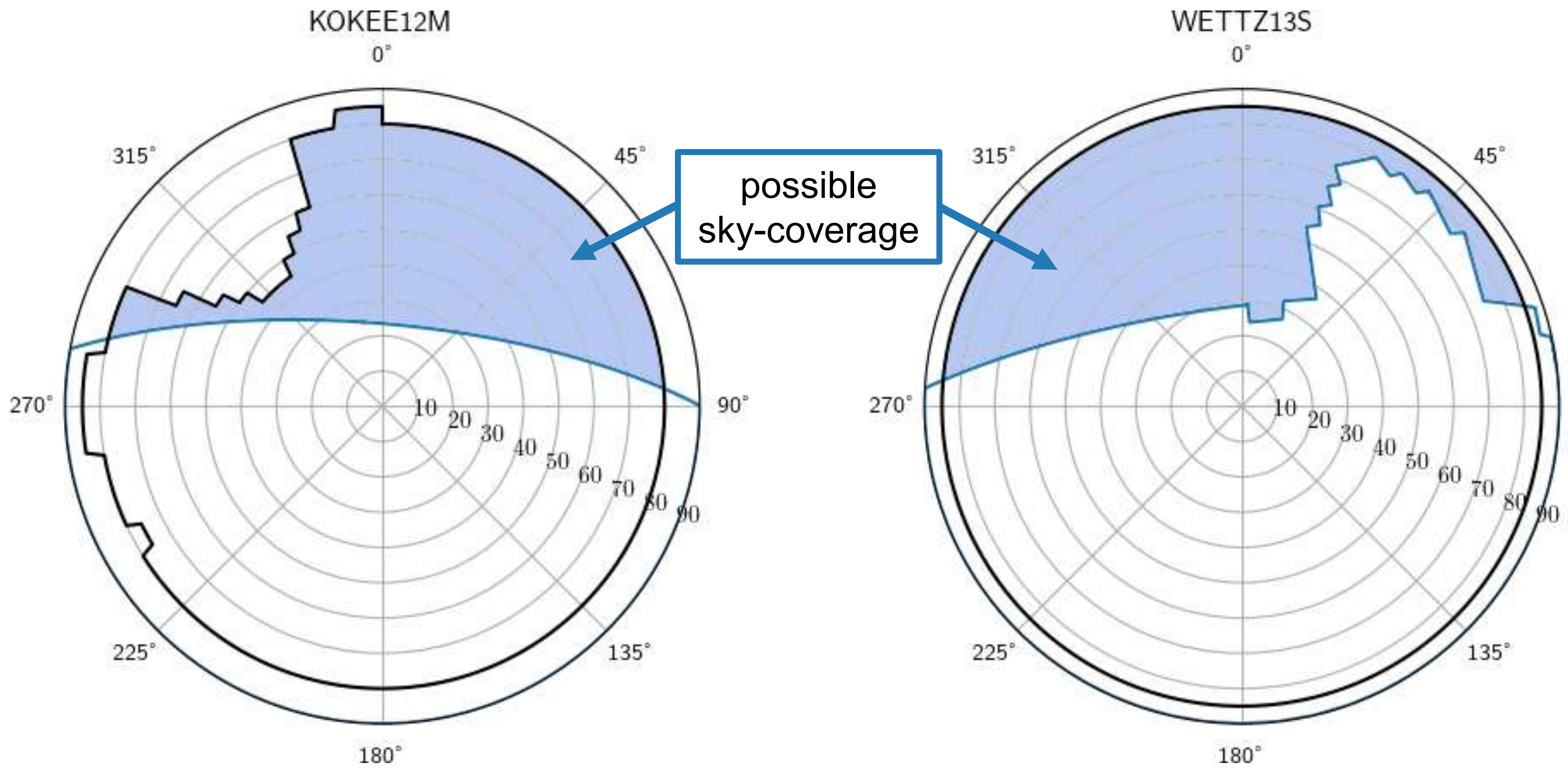
suitable baseline
- WETTZ13S
- KOKEE12M



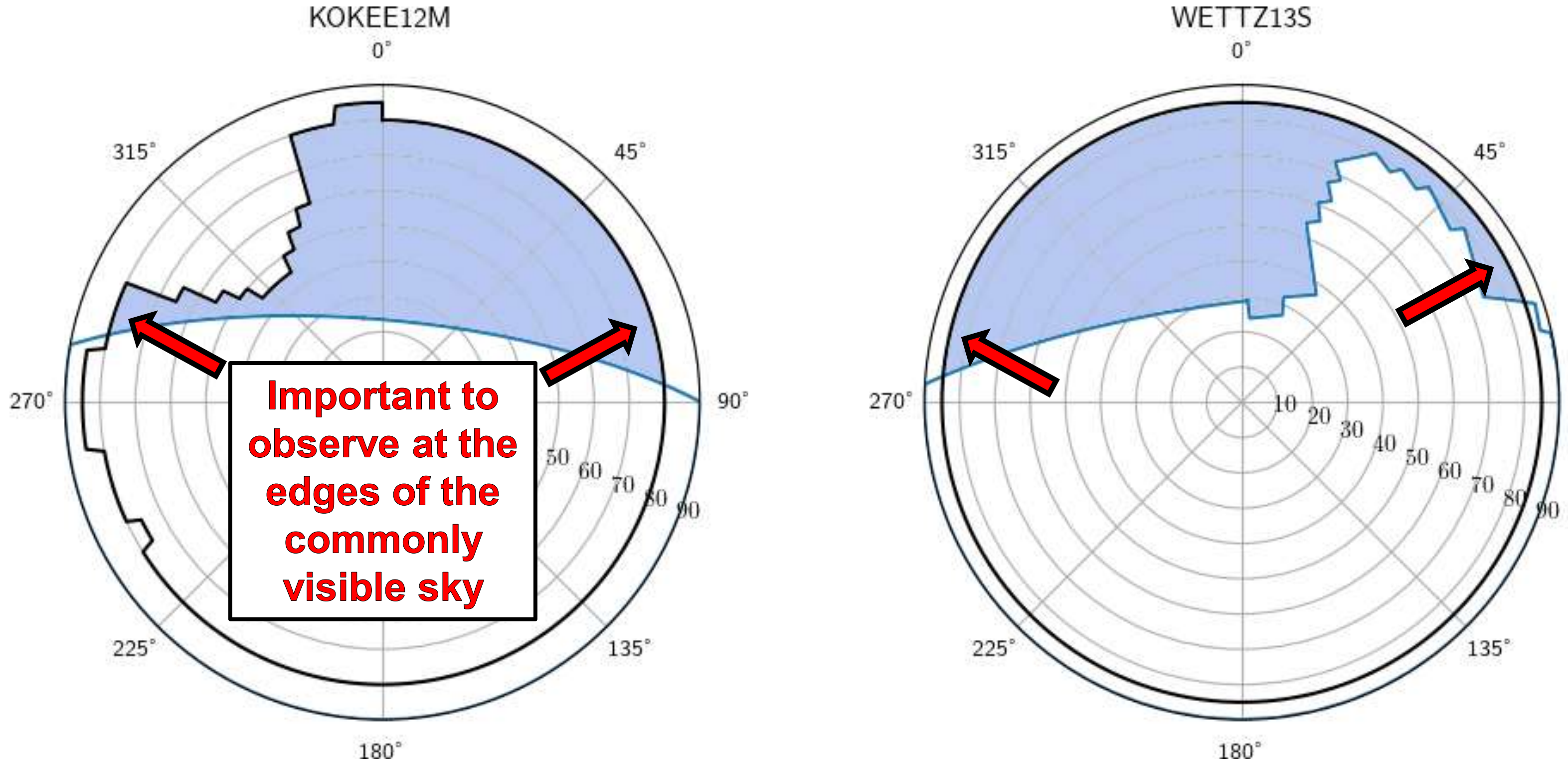
theoretically possible observable sky + 5° cutoff elevation + horizon mask



Example VGOS Intensive baseline

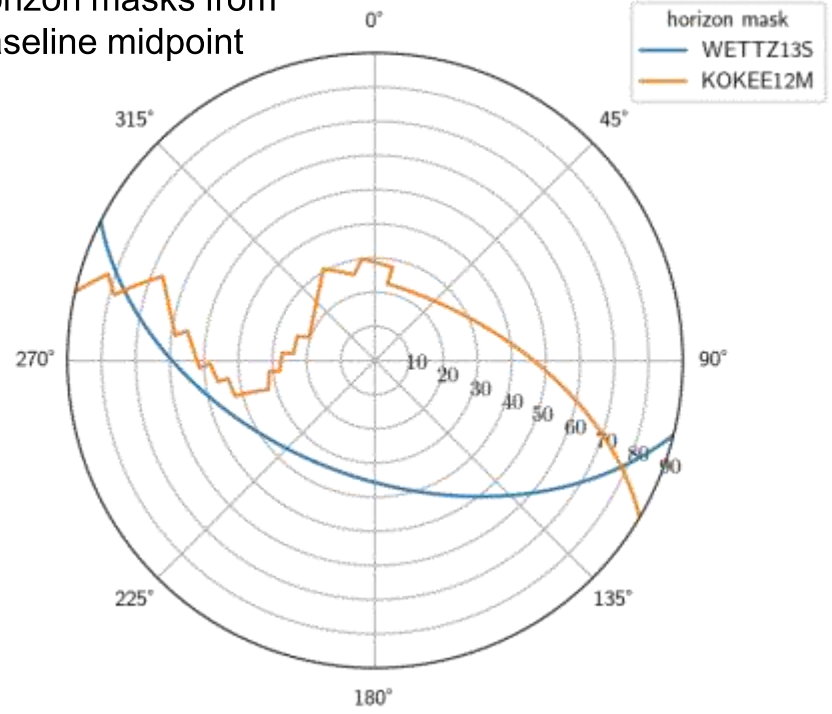


Example VGOS Intensive baseline



Example VGOS Intensive baseline

horizon masks from
baseline midpoint



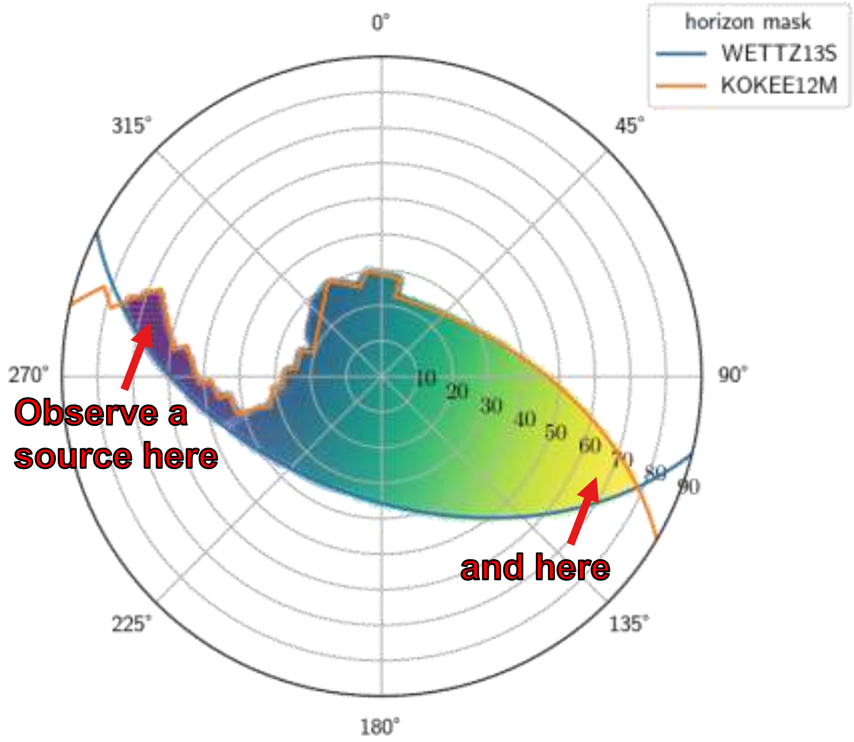
Example VGOS Intensive baseline

color-coded partial derivatives of UT1-UTC

- beneficial to put observations at corners of mutually visible sky
- but UT1-UTC 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)



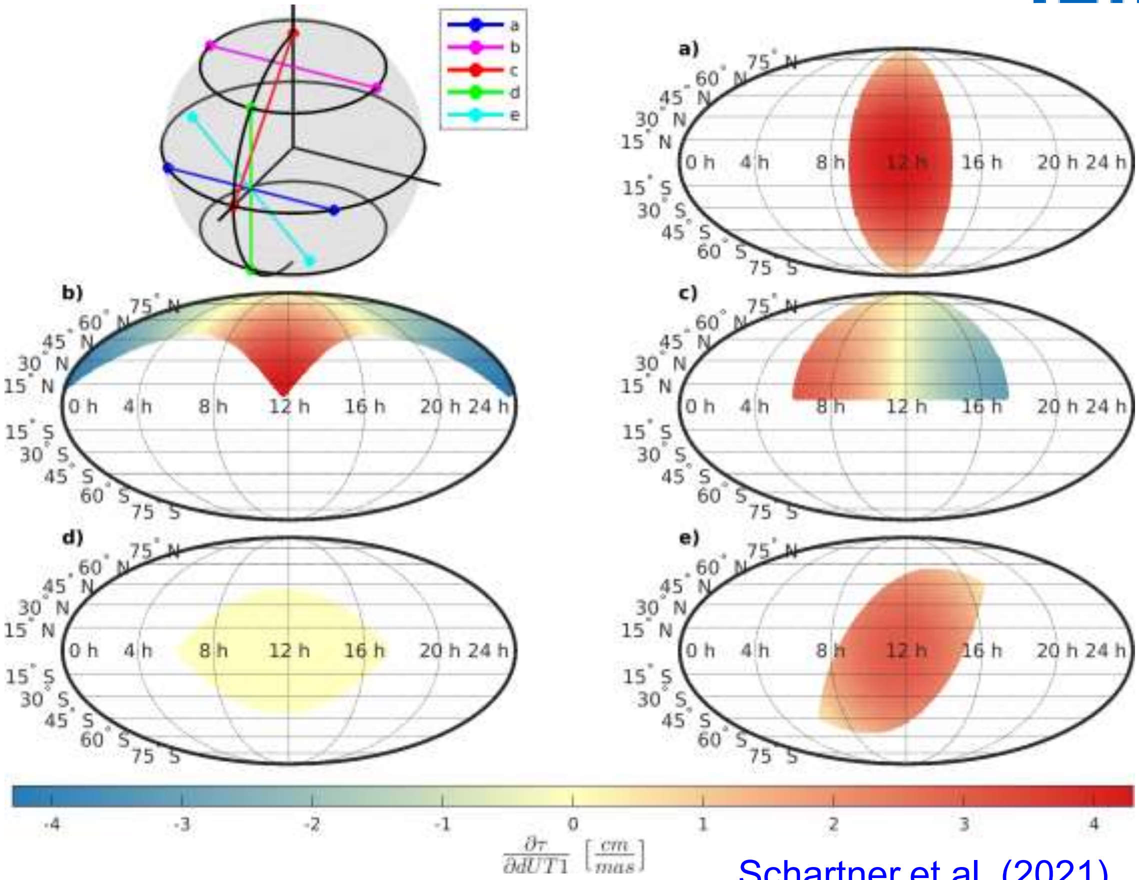
Know your objective

Intensive session

objective: UT1-UTC

- 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)](#)

24-hour session

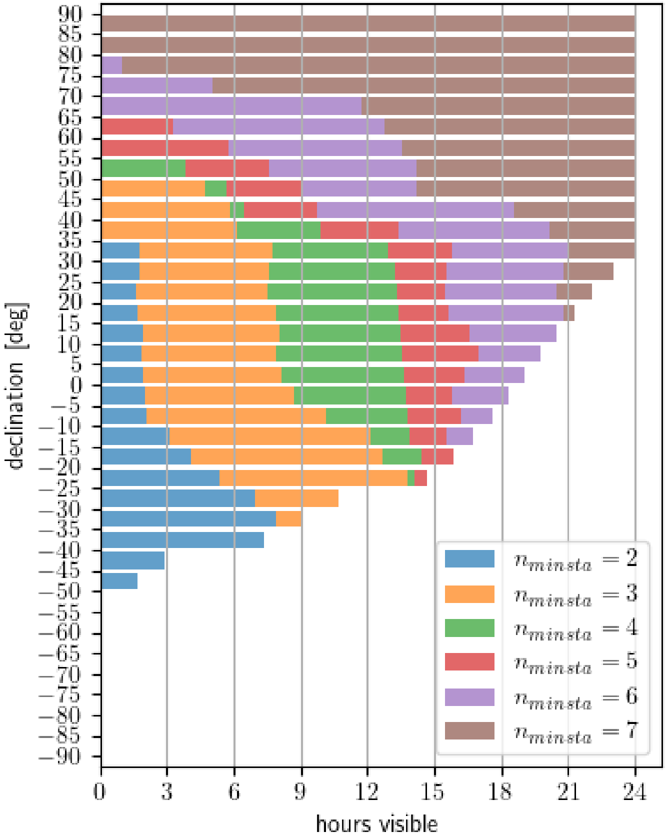
scheduling becomes way more complex

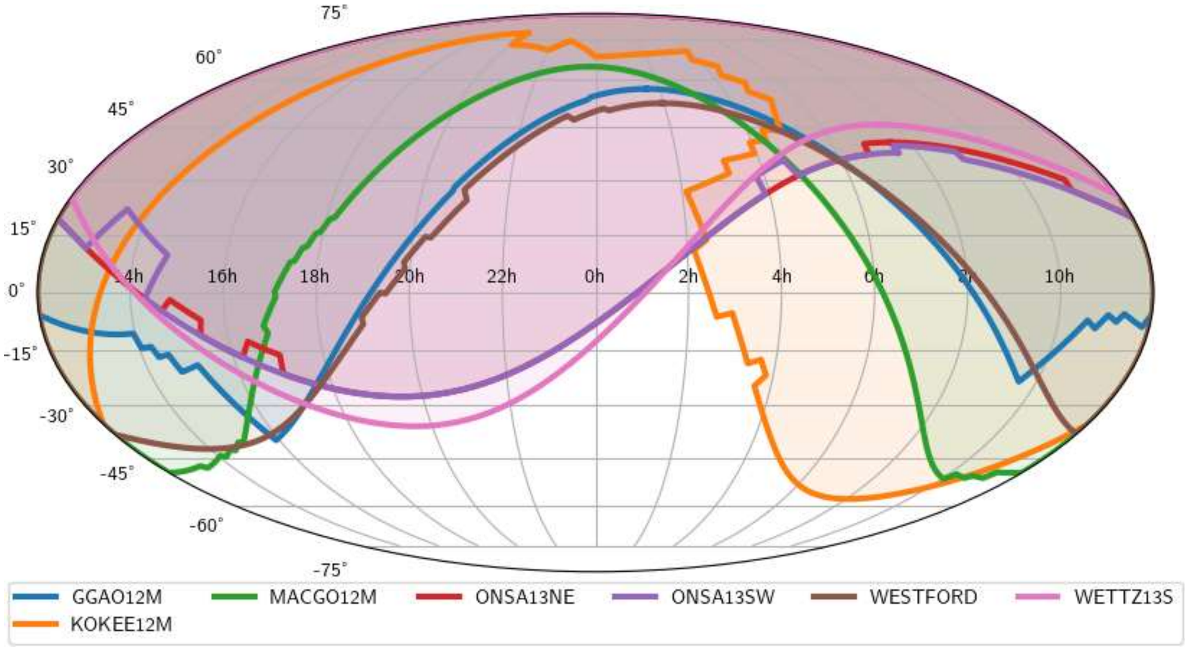
- **UT1-UTC:** observations on long east-west baselines
- **polar motion:** observations on long north-south baselines
- **station coordinates:** many scans at different azimuth and elevation angles
- **source coordinates:** good distribution of scans among sources, north-south and east-west baselines
- **source imaging:** good uv-coverage, parallactic angles, etc.

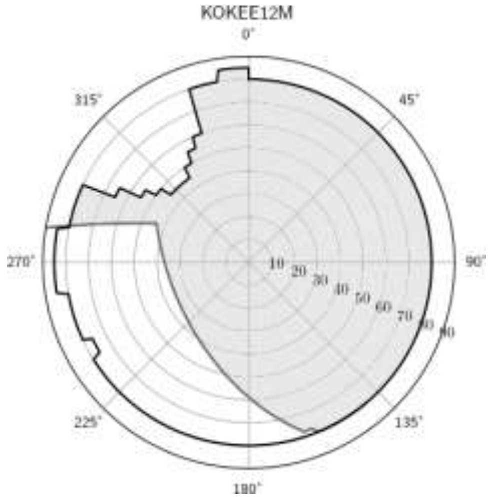
Remember:

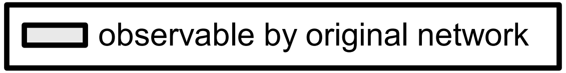
- Observations are not independent
- You always need at least two telescopes to observe together
- Tricky to fulfill all requirements

Example VGOS-network



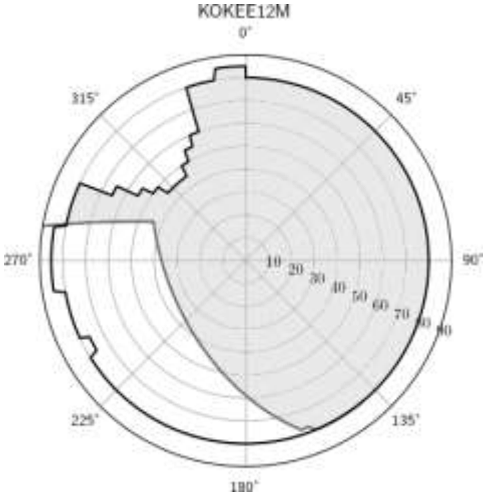




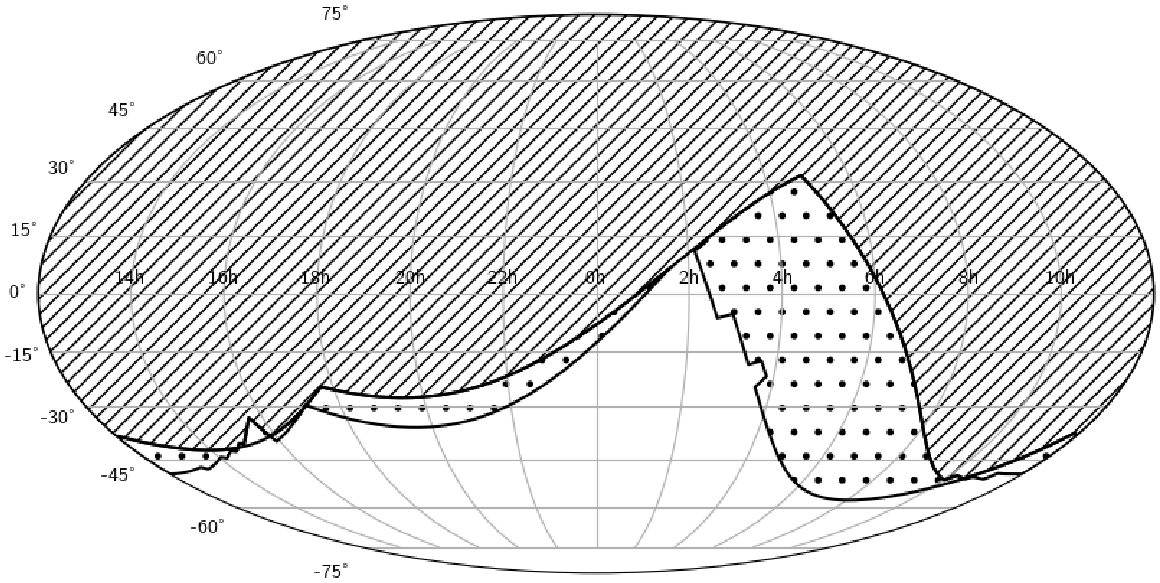


dashed: observable by at least two stations

dotted: only observable by one station

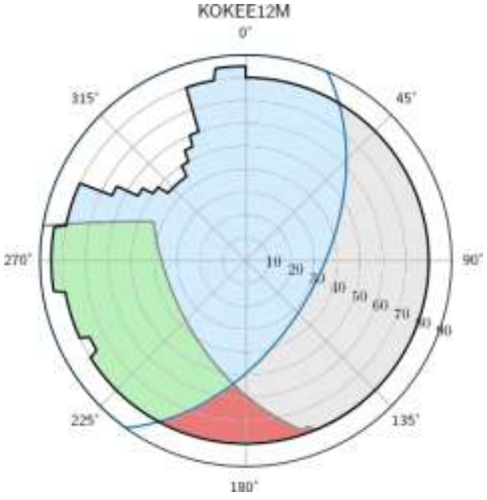


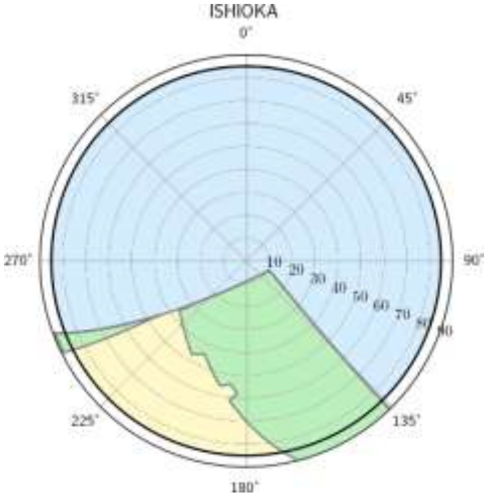
observable by original network



dashed: observable by at least two stations

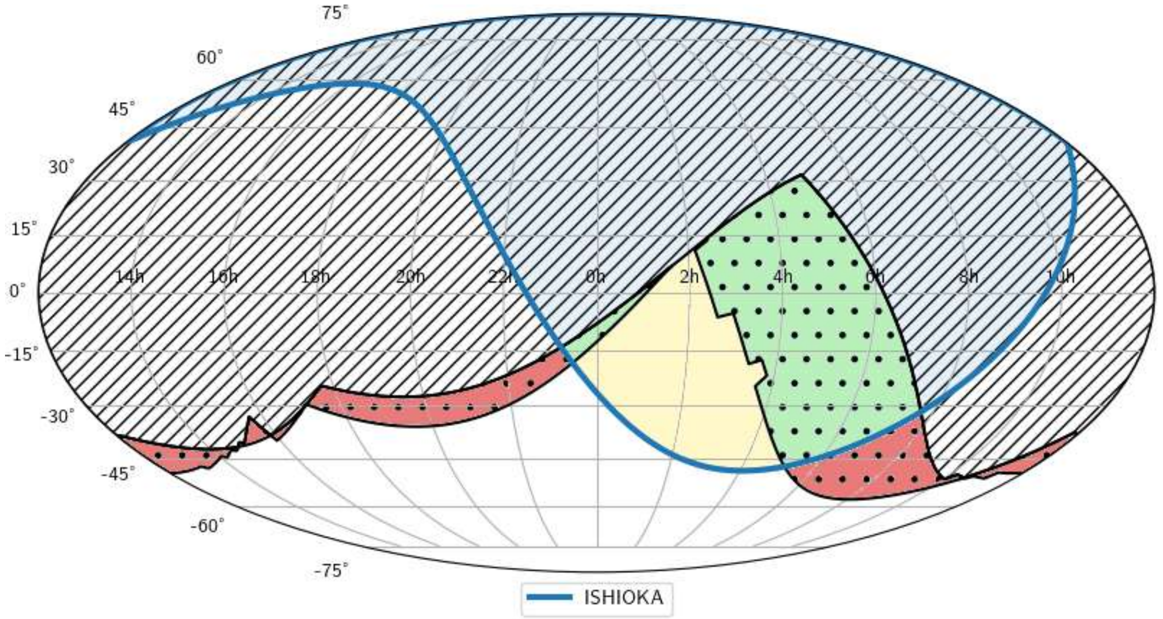
dotted: only observable by one station

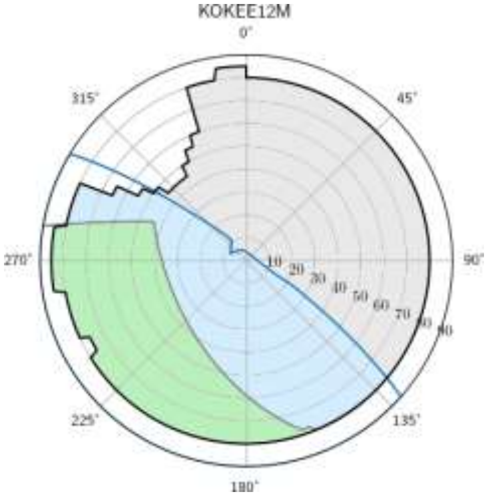


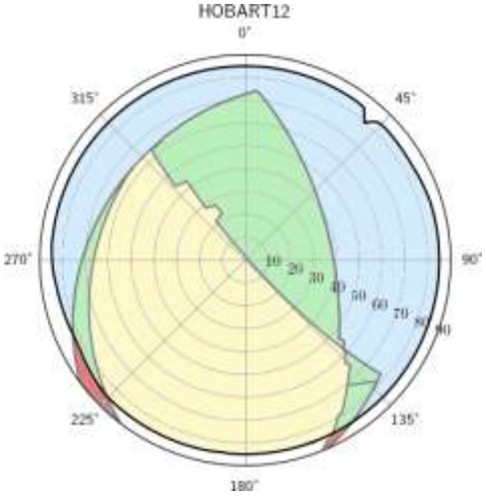


- observable by original network
- original network now observable
- original network not observable
- observable with ISHIOKA
- not observable (only ISHIOKA)

New station ISHIOKA

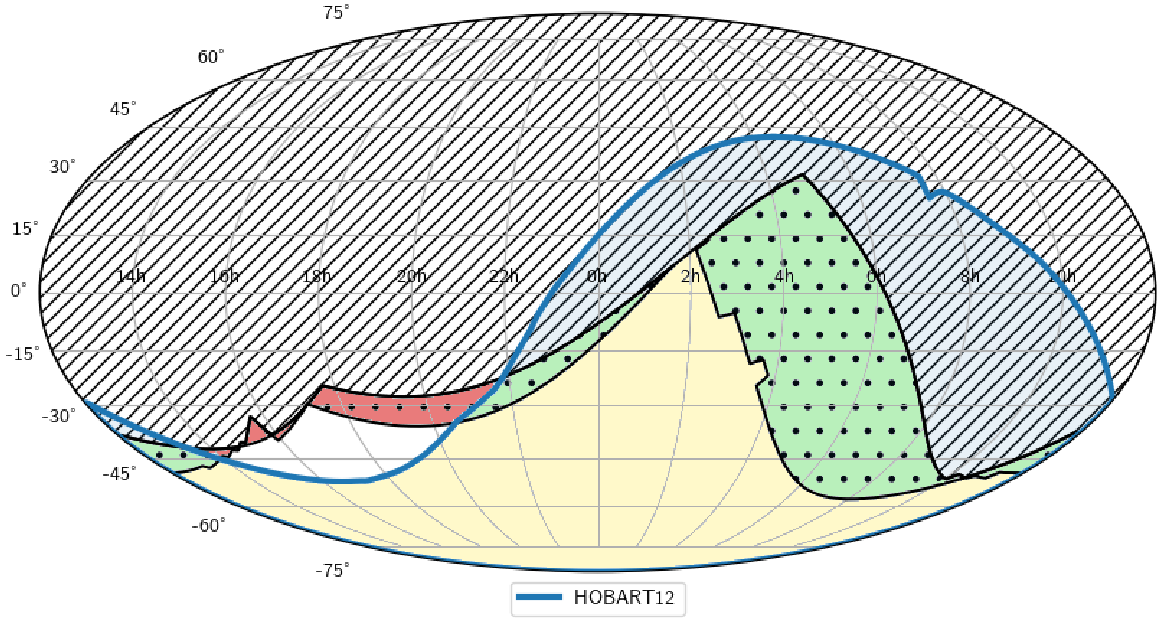






observable by original network
original network now observable
original network not observable
observable with HOBART12
not observable (only HOBART12)

New station HOBART12



Algorithms

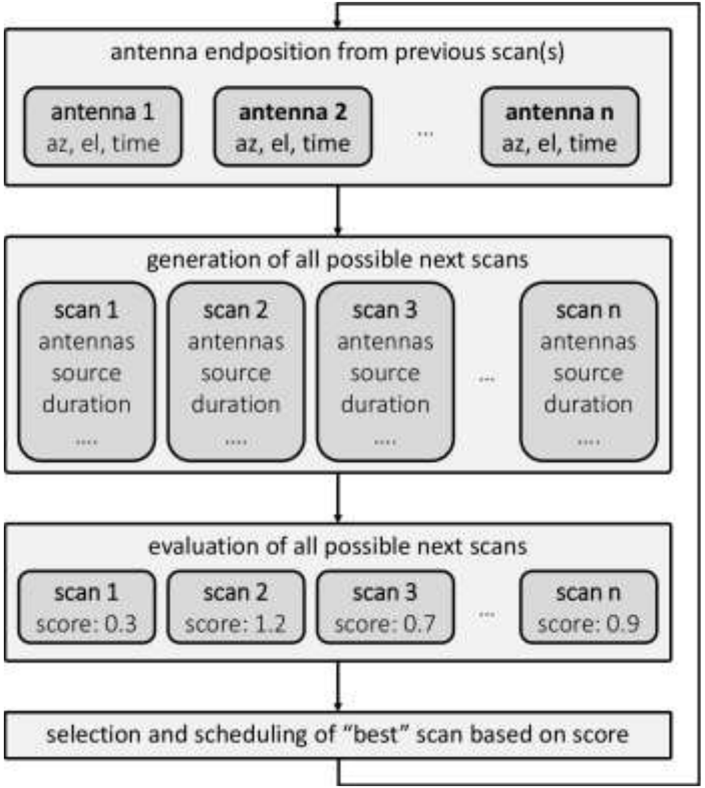
Scheduling

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 of optimization criteria (score)



Scheduling

24-hour VGOS session: 1000 – 4000 scans

1-hour VGOS intensive: 50 – 100 scans

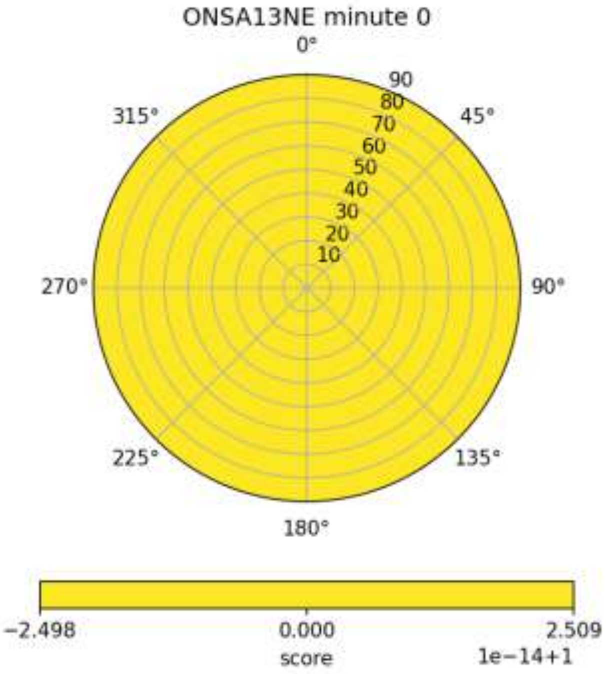
Schedule is generated scan after scan

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

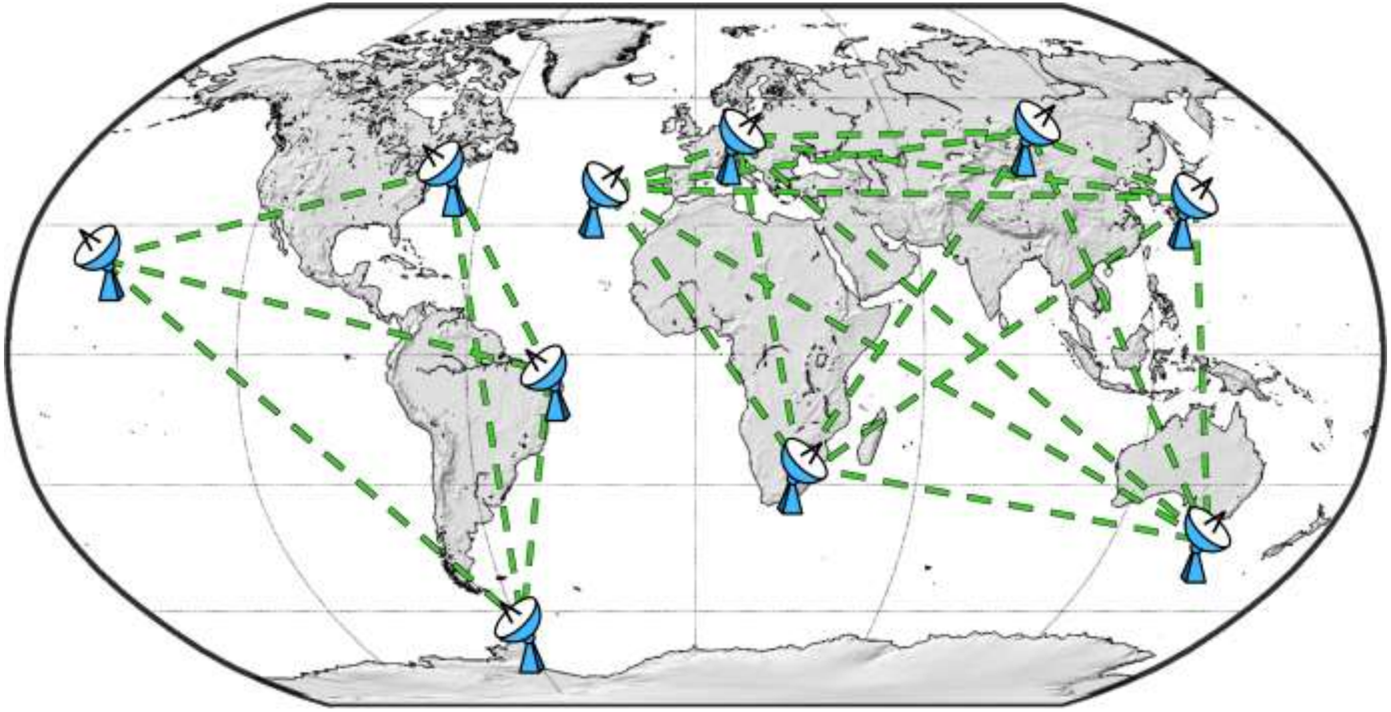
Selection of “best” scan based on weighted sum of optimization criteria (score)



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



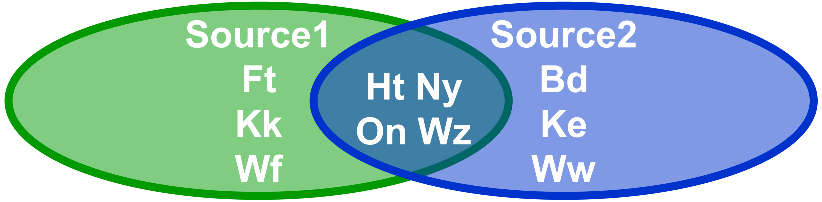
Subnetting

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



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

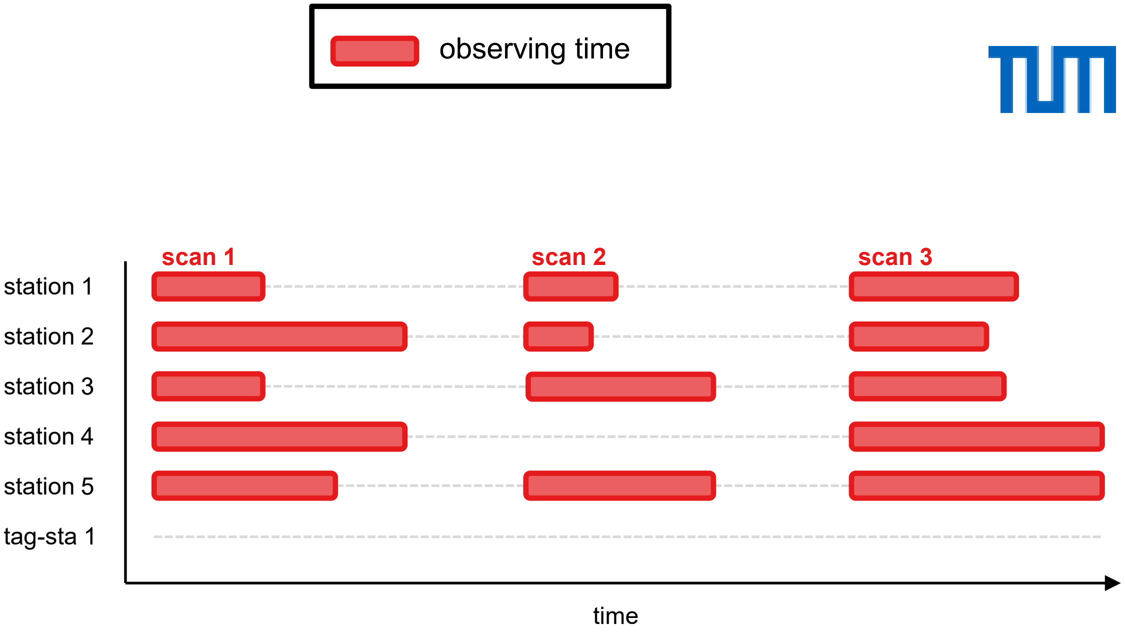
version	scan of source 1	scan of source 2
1	Ft Kk Wf Ht Ny On Wz	
2		Bd Ke Ww Ht Ny On Wz
3	Ft Kk Wf Ht Ny On Wz	Bd Ke Ww
4	Ft Kk Wf Ht Ny On	Bd Ke Ww Wz
5	Ft Kk Wf Ht Ny Wz	Bd Ke Ww On
6	Ft Kk Wf Ht On Wz	Bd Ke Ww Ny
7	Ft Kk Wf Ny On Wz	Bd Ke Ww Ht
8	Ft Kk Wf Ht Ny	Bd Ke Ww On Wz
9	Ft Kk Wf Ht On	Bd 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 maintenance

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
- station under maintenance

generate schedule without this station add station to as many scans as possible

Problematic for remote station or station with poor sensitivity

Fillin mode

antennas have different characteristics:

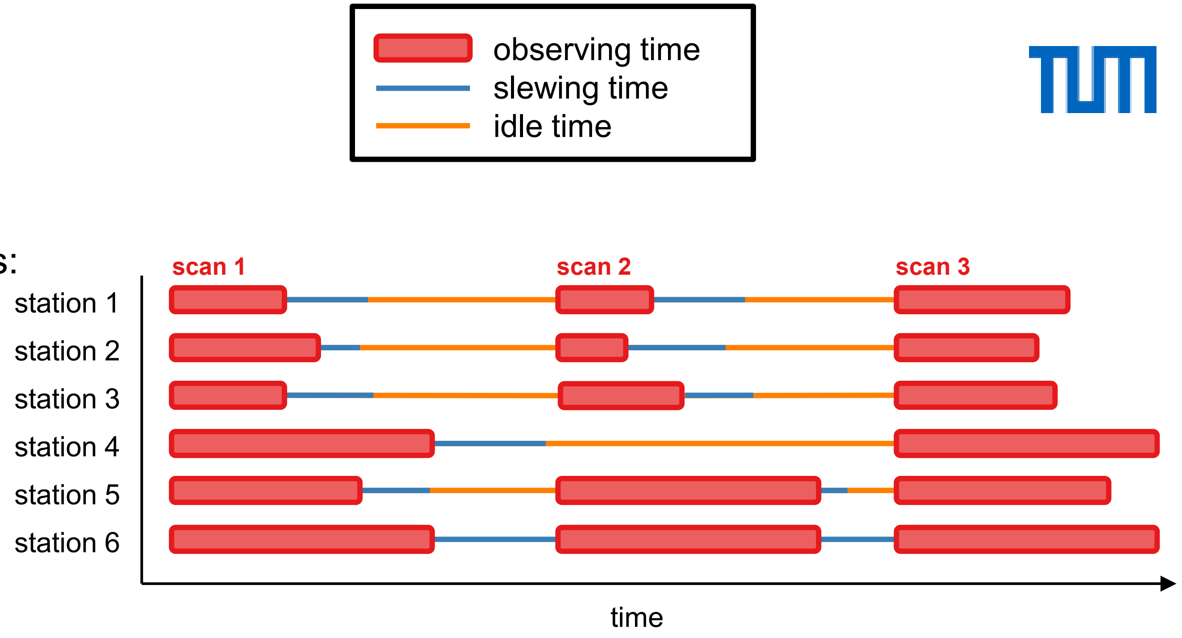
- slew rate
- sensitivity

→ different scan start/stop times

- convention:

  all antennas start at the same time

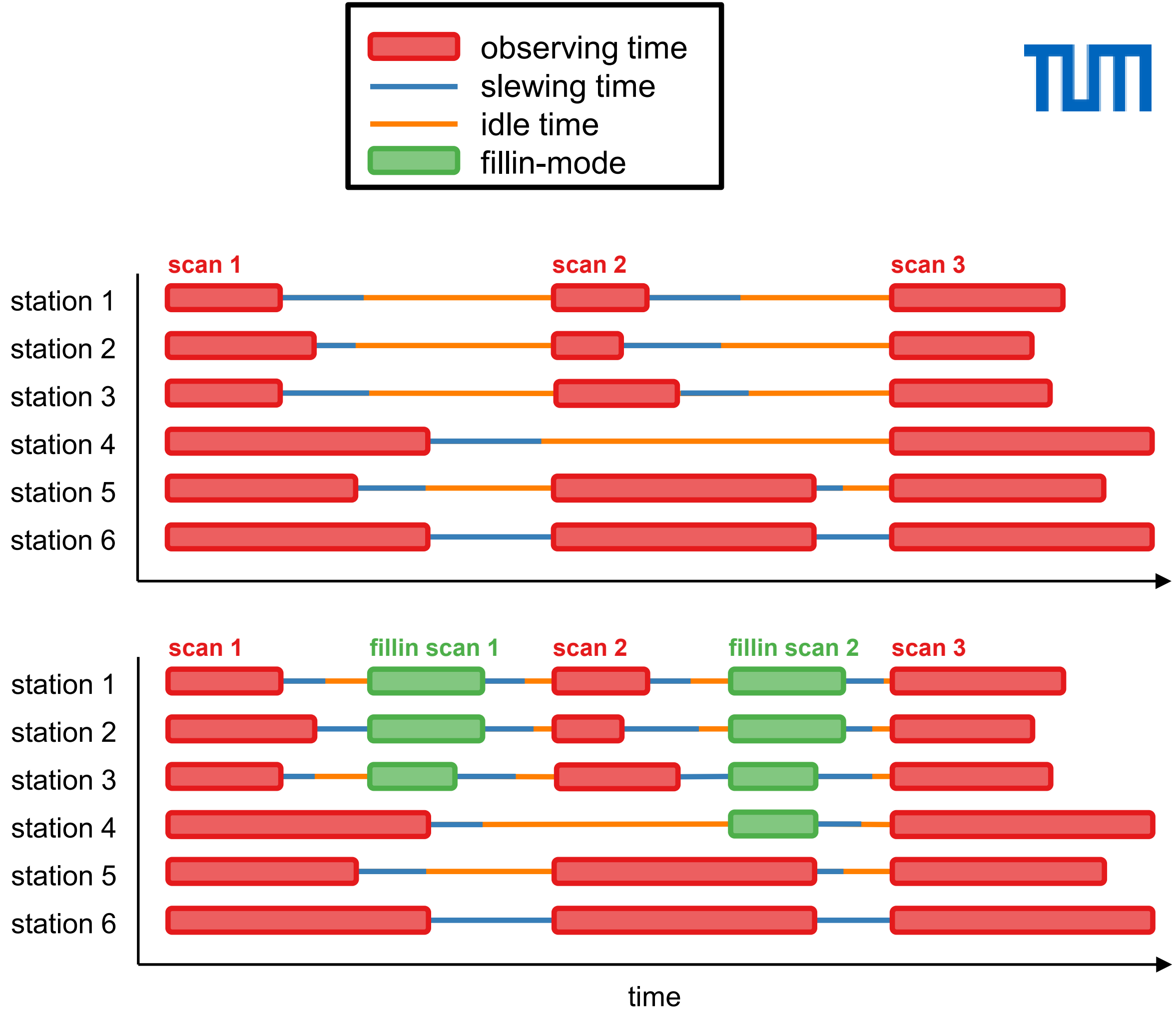
→ different stop times



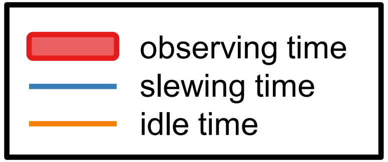
Fillin mode

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



antennas have different characteristics:

slew rate

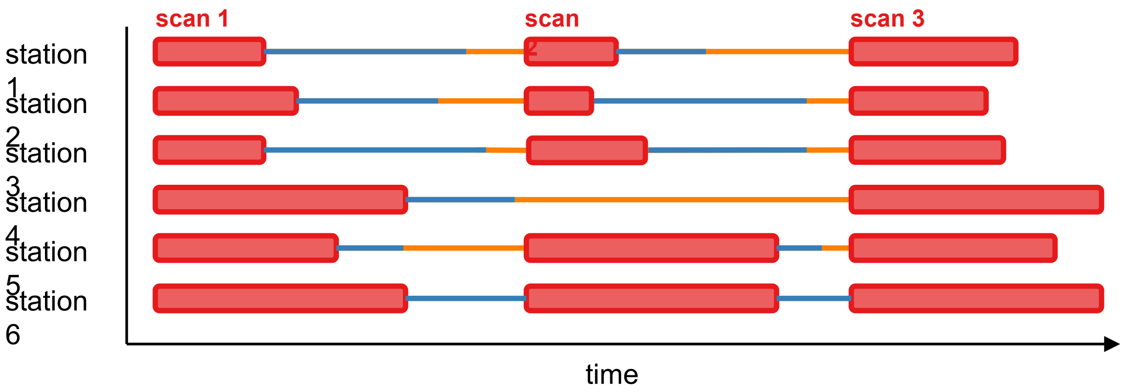
sensitivity

→different scan start/stop times

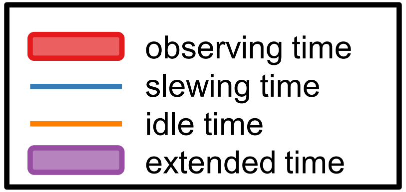
convention:

all antennas start at the same time

→different stop times



Extend observing time



antennas have different characteristics:

slew rate

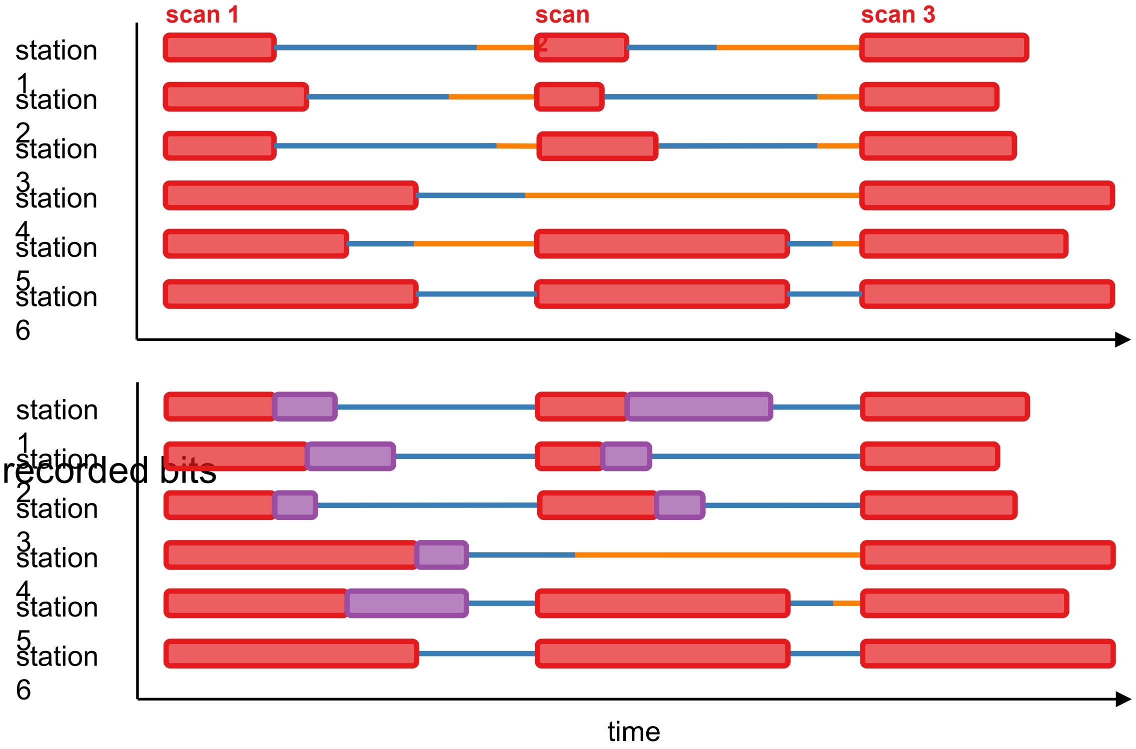
sensitivity

→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

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
- …

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

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

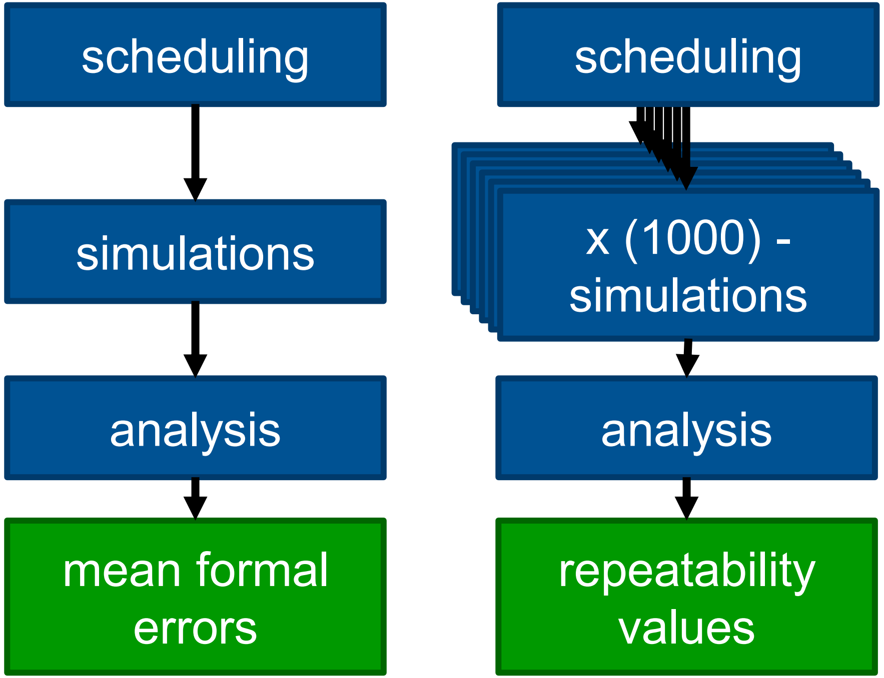
Simulations

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 observations (delay) and the most important error sources

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



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

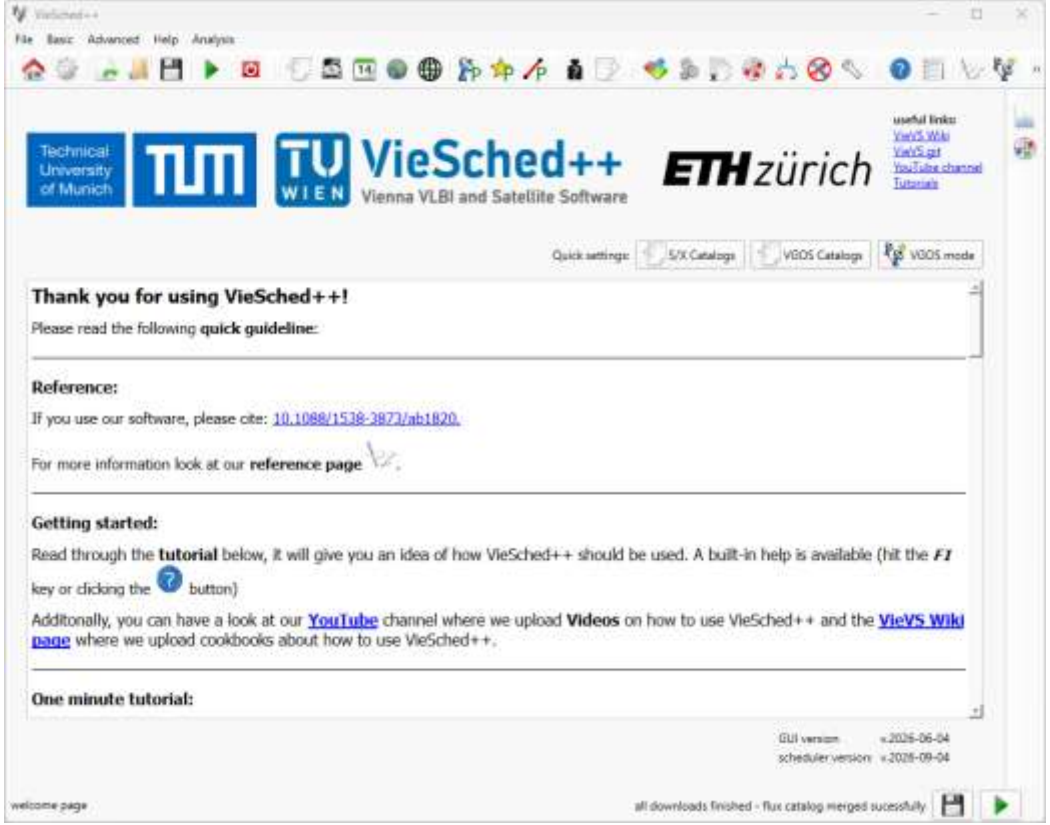
scheduling is an iterative approach

- 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

VieSched++

VieSched++

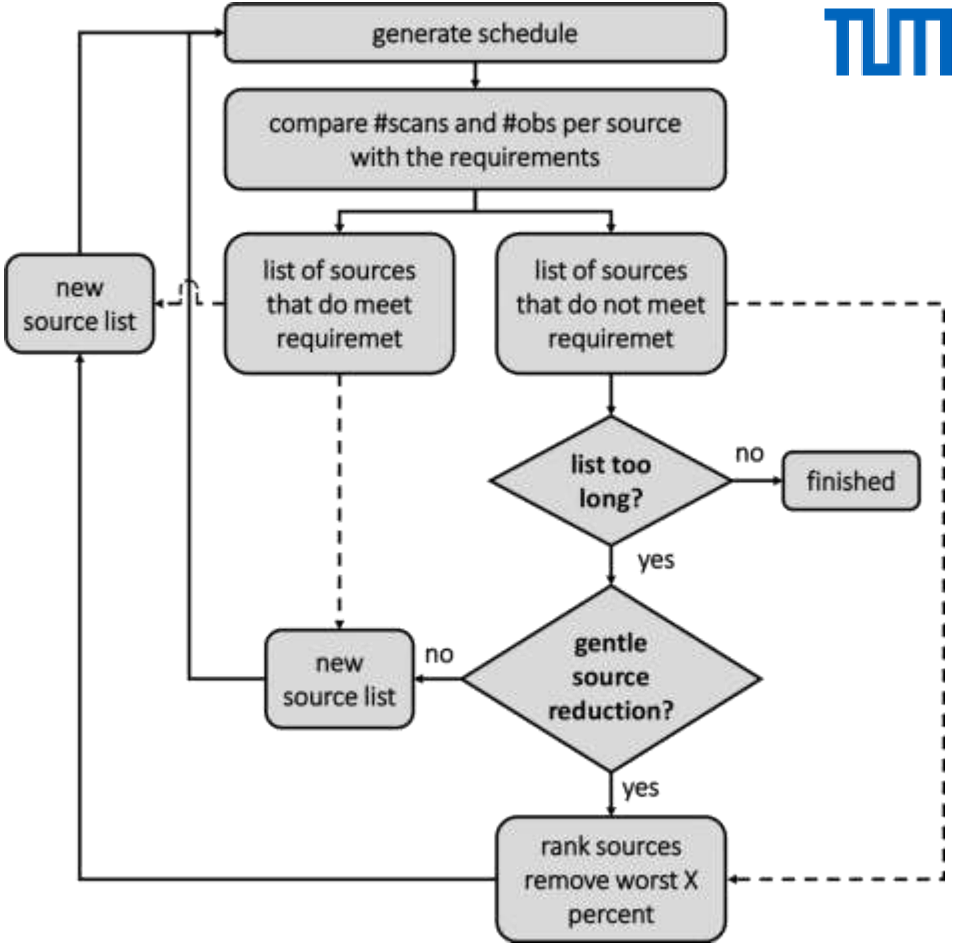
- VLBI scheduling and simulation software
- Easy to use
  - optional graphical user interface
- Versatile
  - many options and parameters
  - flexible parameterization
  - support of many algorithms
  - different optimization criteria
  - special scheduling modes
- Powerful
  - generate high-quality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



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 than required are removed from source-list
- There are methods to fine-tune approach (gentle source reduction)



Multi-scheduling

- There are various scheduling parameters 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 makes it easy to 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

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
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  I 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-F-  ...      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 ...
```

RA (h m s)

Dec (d m s)

band

Flux model type

One-letter code (OLC)

start time

obs-dur

OLC+cable wrap

observation duration per station

preob time

sky-frequency

BW

tracks

[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

Observing mode

List of scans

List of sources

[VEX Definition]

[VEX2 Definition]