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Active mitigation of spaceborne radio frequency interference for VLBI

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Background

- VLBI equipment very sensitive
- ground-based **radio frequency interference** (RFI) is already a severe problem (WiFi, 5G…)
- last years, tremendous **increase of satellites** in space

- some will emit signals in VLBI frequency range
  → spaceborne RFI
- can cause **non-linearities** in our observations or might **saturate receivers**
- also planned InSAR mission that will emit strong radiation that can potentially be **damaging**

Investigated Starlink evolutions

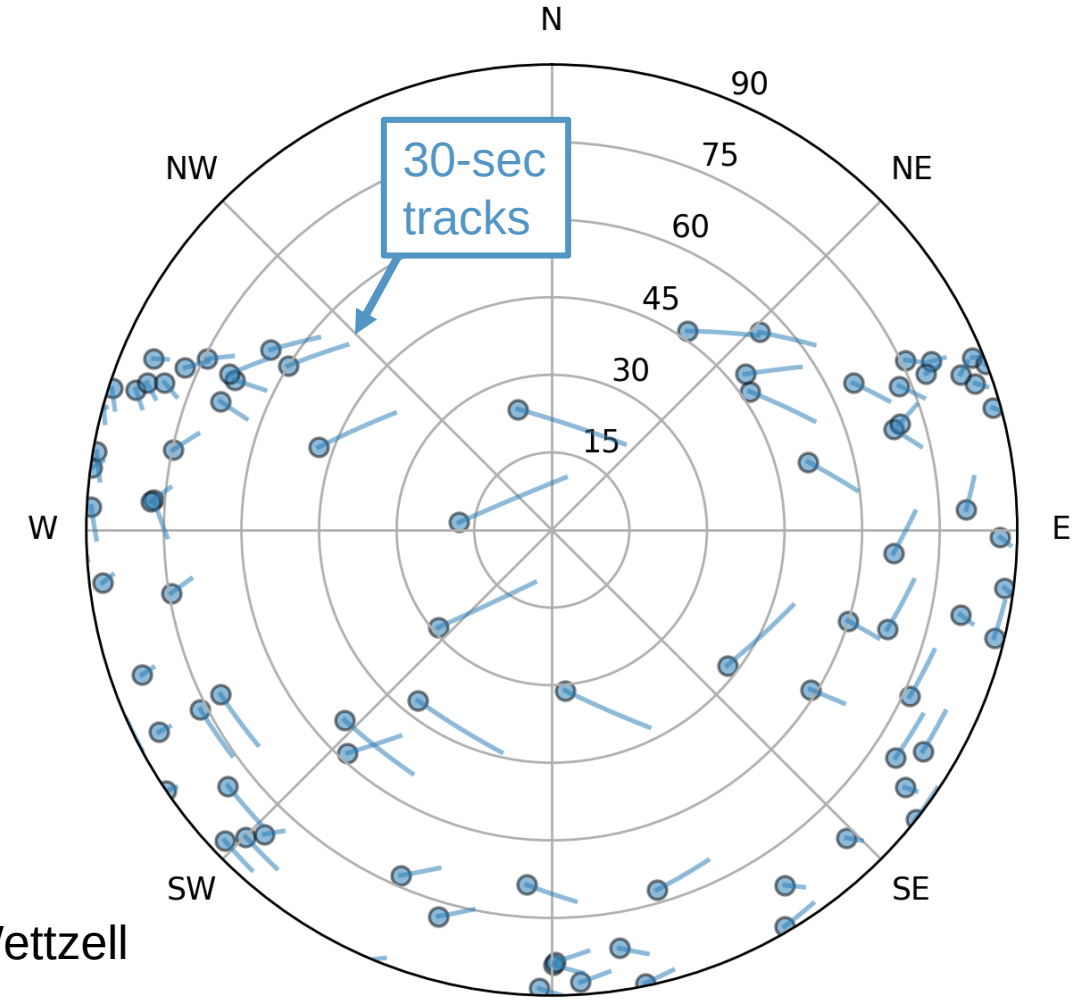
- Three phases*
  - Phase 1: **1584** satellites
  - Phase 2: **4408** satellites
  - Phase 3: **34408** satellites

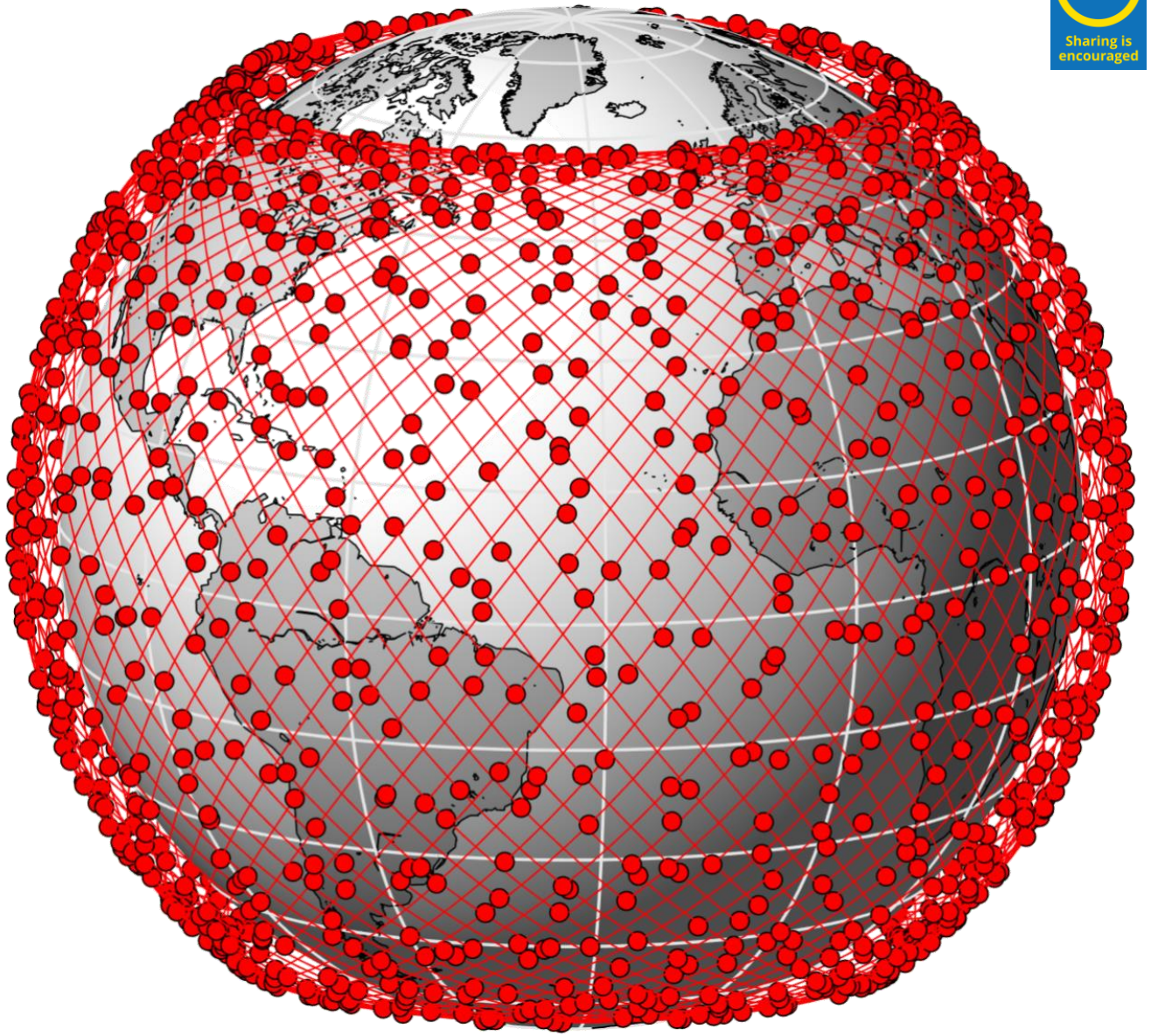
*currently, there are around 3360 Starlink satellites in orbit

	P.1	Phase 2				Phase 3							
orbits	72	72	36	6	4	7178	7178	7178	40	1998	4000	12	18
sat/orbit	22	22	20	58	43	1	1	1	50	1	1	12	18
satellites	**1584**	2824 (→ **4408** total)				30000 (→ **34408** total)							
altitude [km]	550	540	570	560	560	328	334	345	360	373	499	604	614
inclination [°]	53	53.2	70	97.6	97.6	30	40	53	96.9	75	53	148	115.7

Phase 1

1584 satellites





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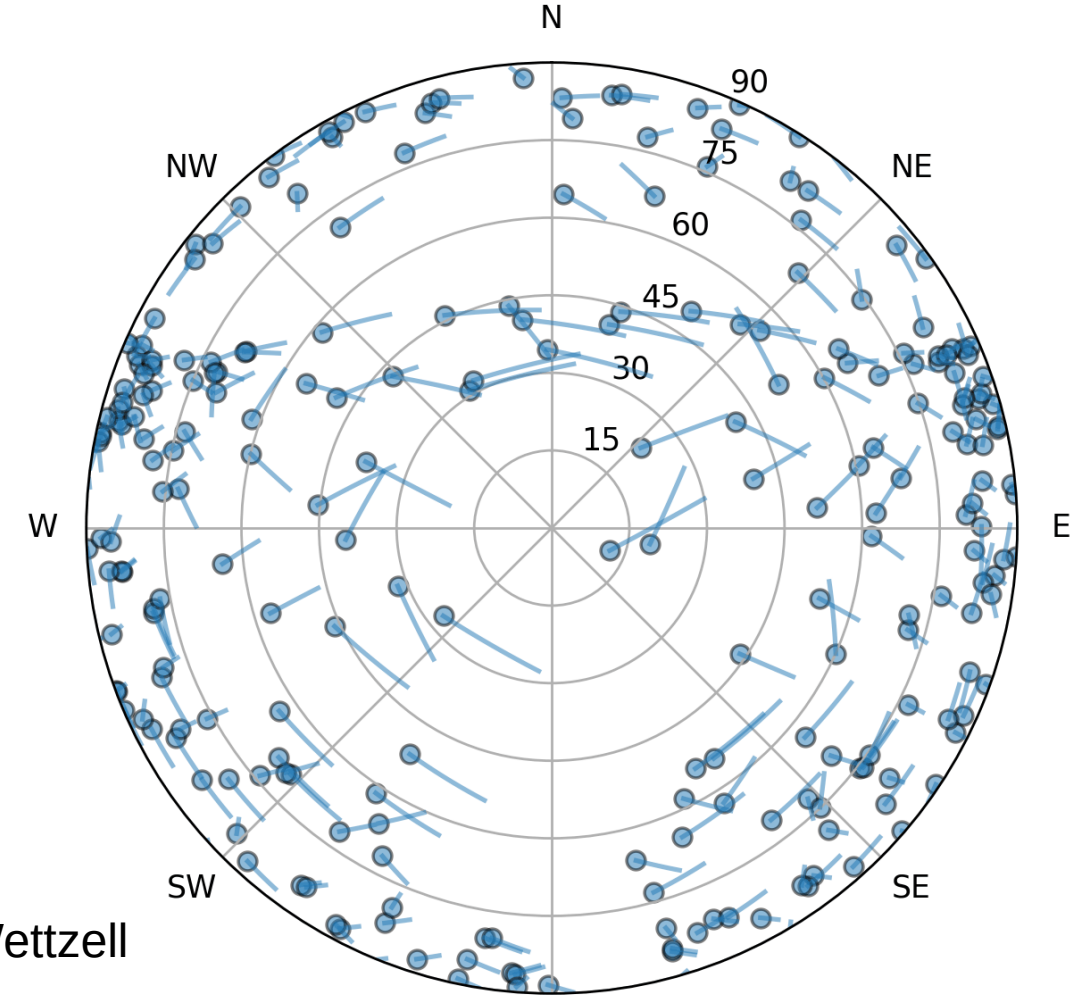
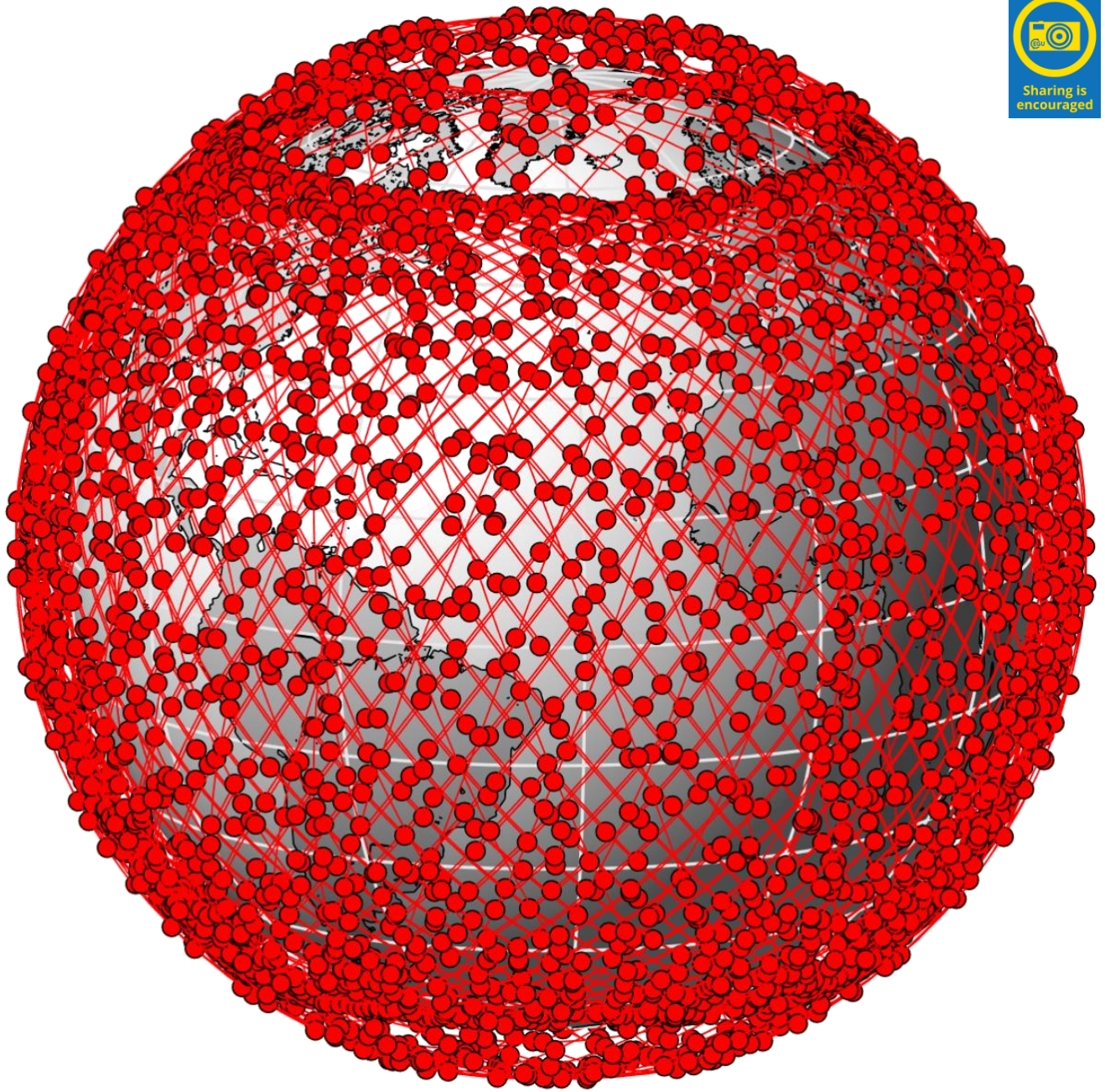
Phase 2

4408 satellites





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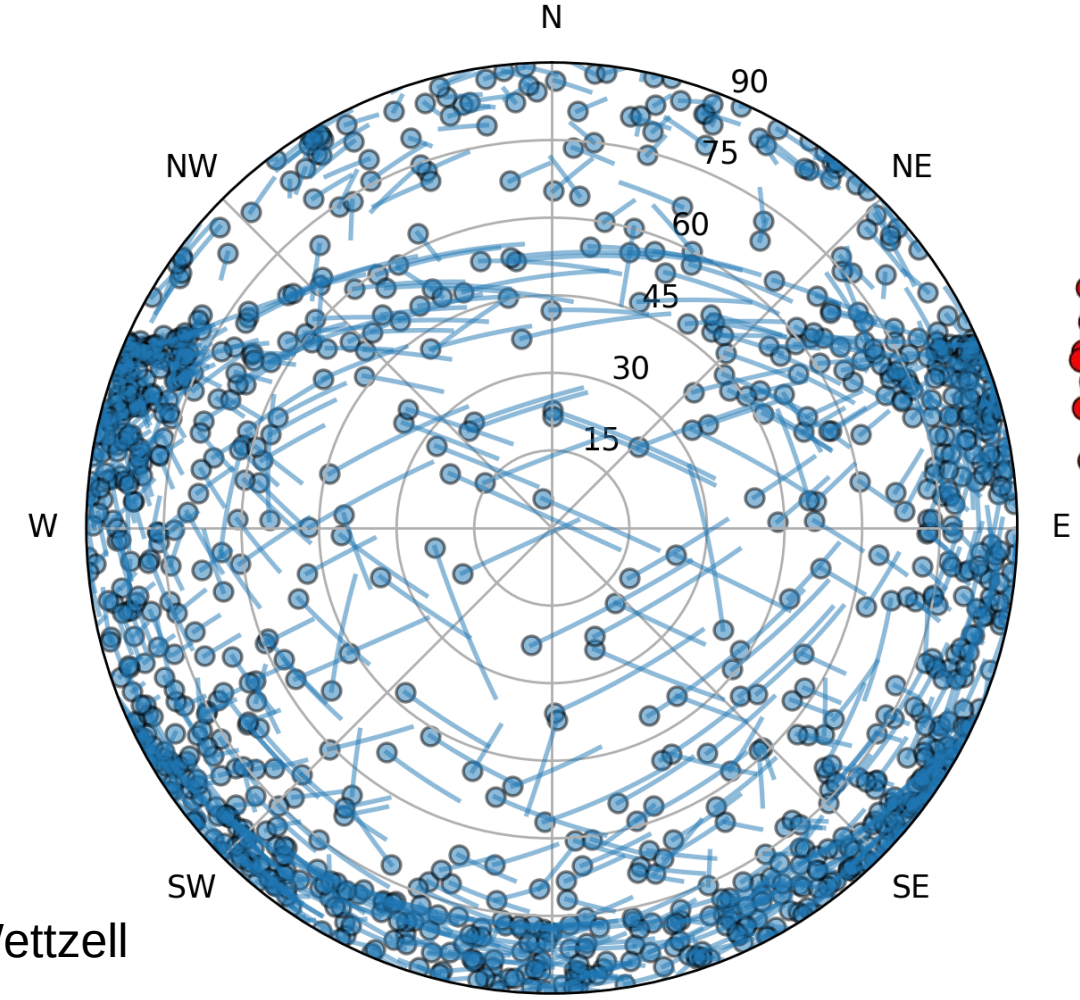
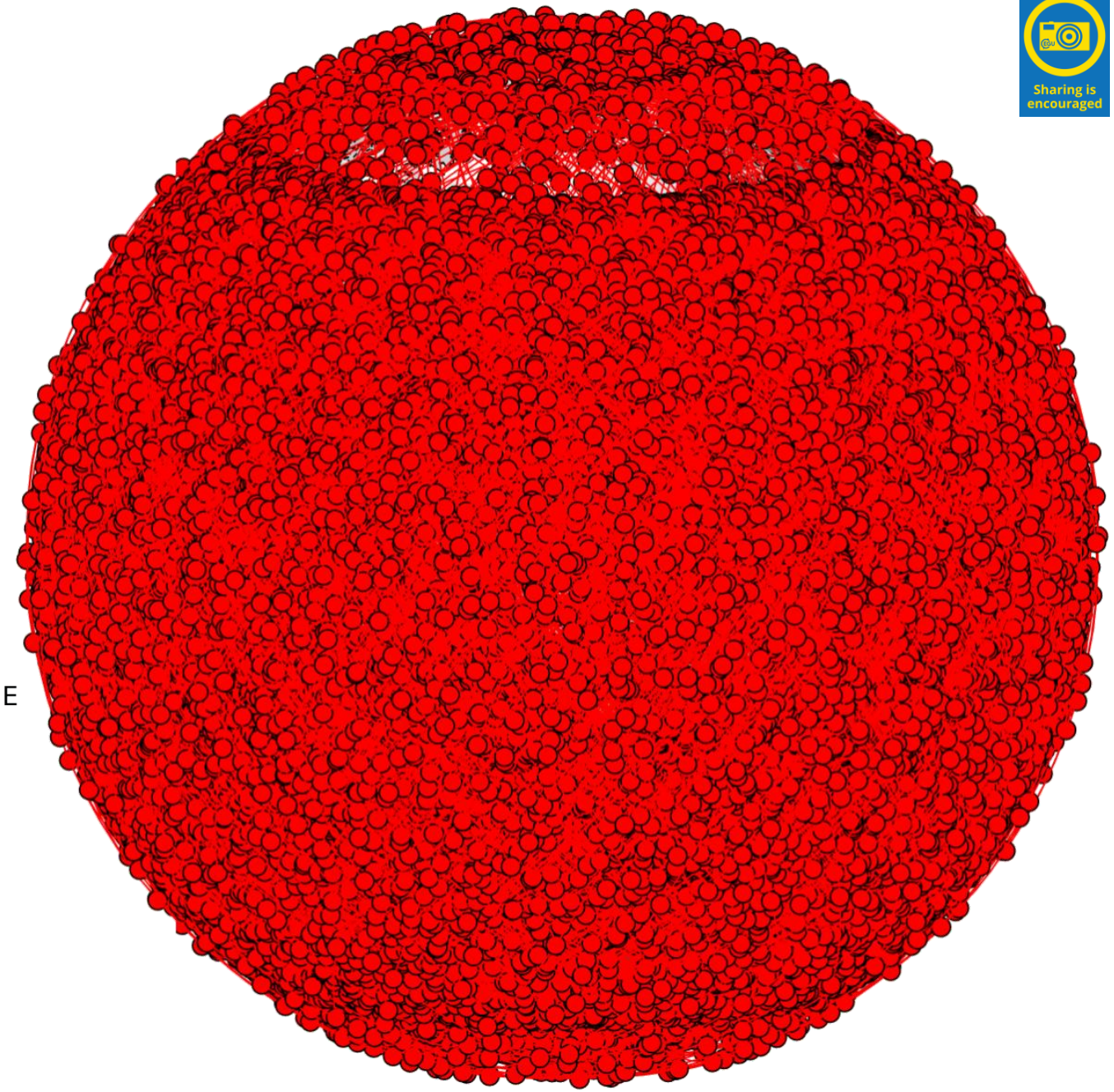
Phase 3

34408 satellites





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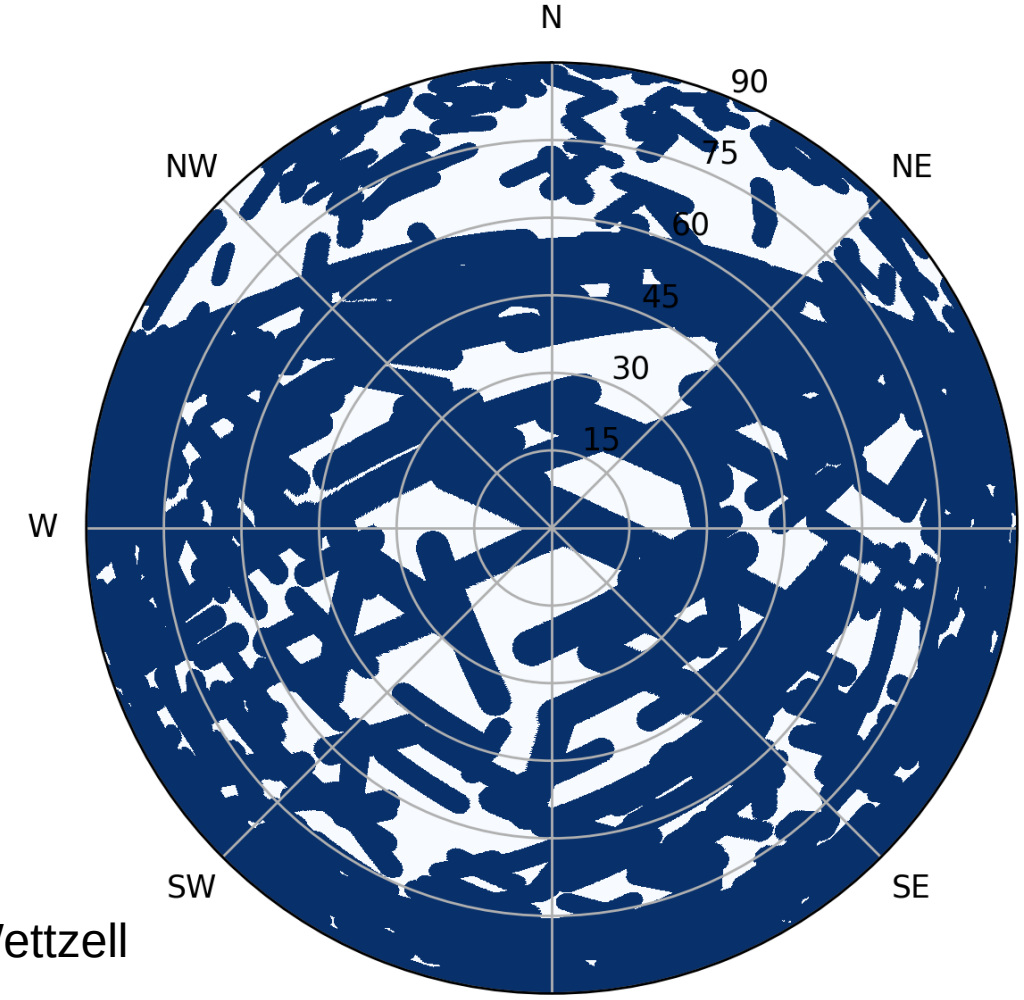
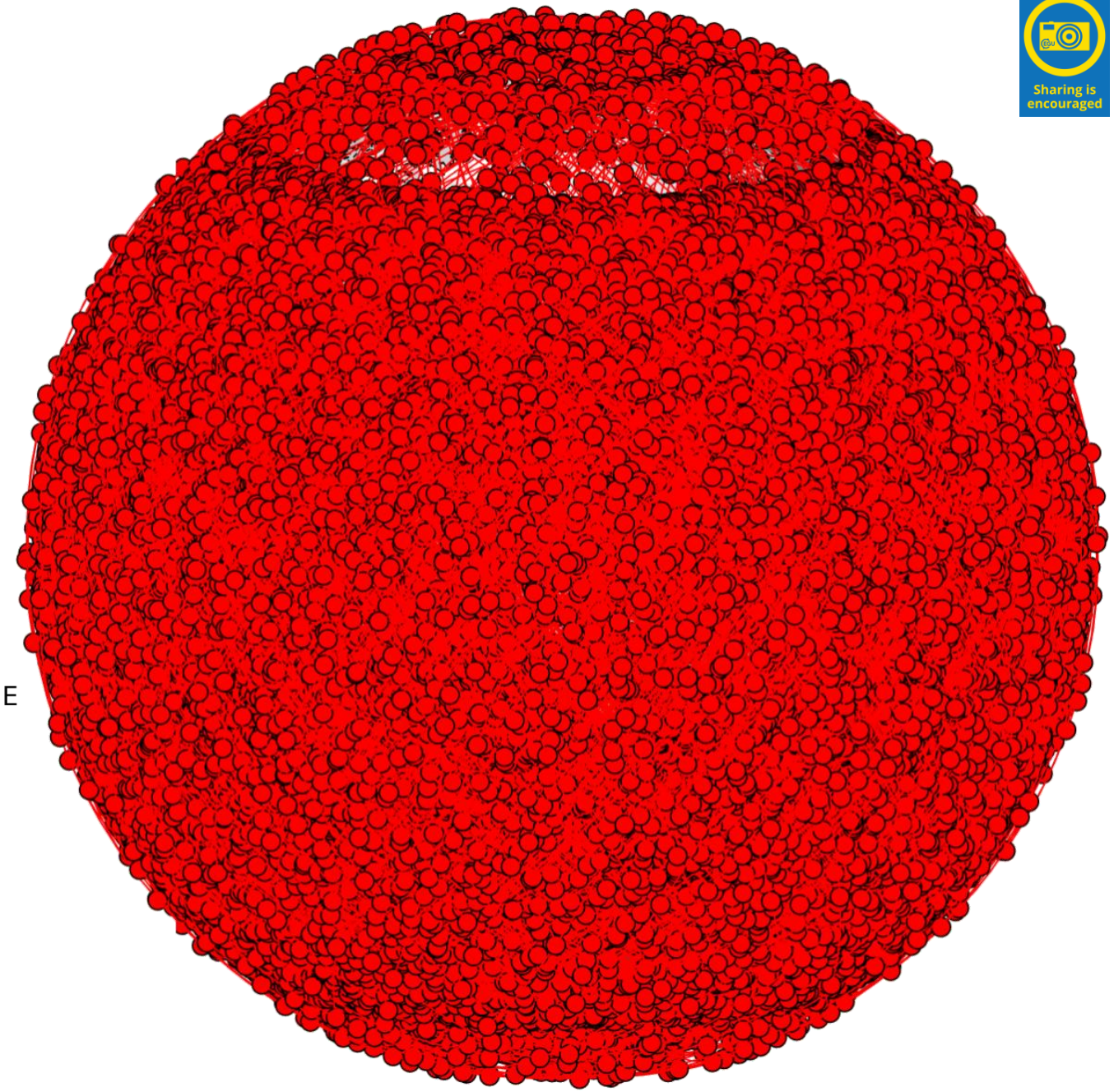
Phase 3
Avoidance mask for 30 sec scan

34408 satellites





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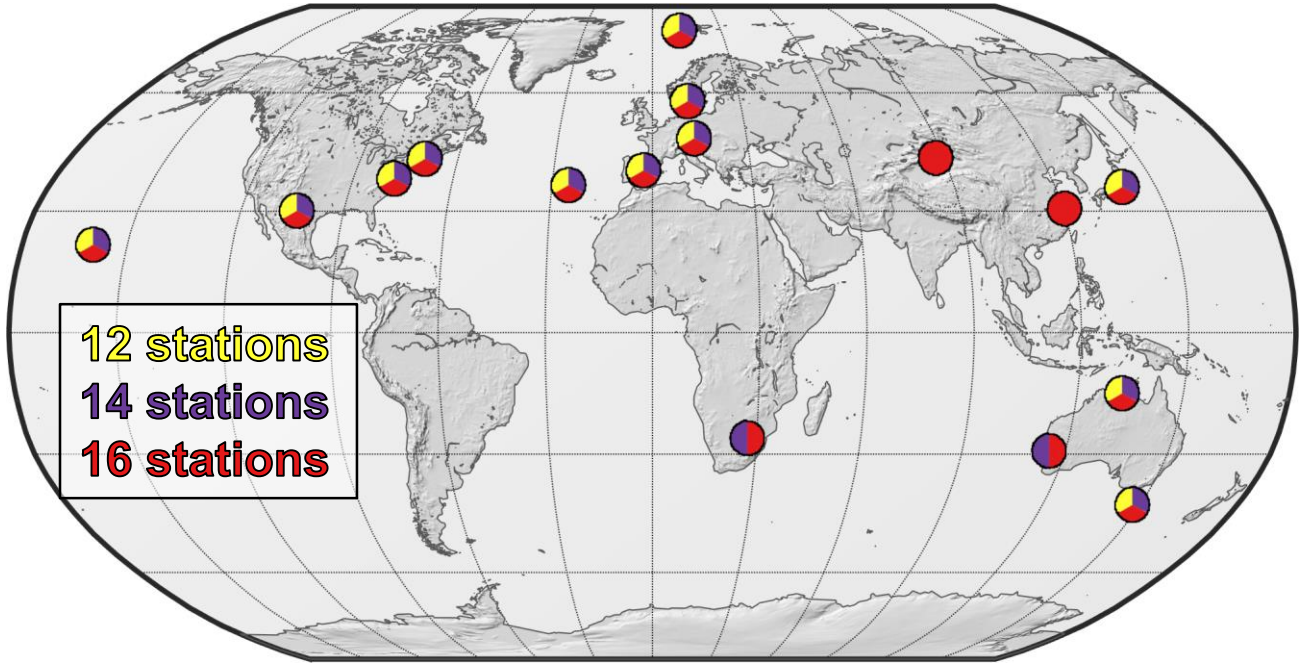
Impact on VLBI observations?

- How many observations are affected?
- Effect on geodetic products?

Method

- Generate VLBI observing plans
  - **no satellites: reference** without satellites
  - **active avoidance:** do **not schedule** sources close to satellites
  - **no active avoidance:** no active avoidance but **removal of affected observations**
- Monte-Carlo simulation

Repeated for three VLBI networks
and for three Starlink network phases
→ **nine combinations**



How close is too close?

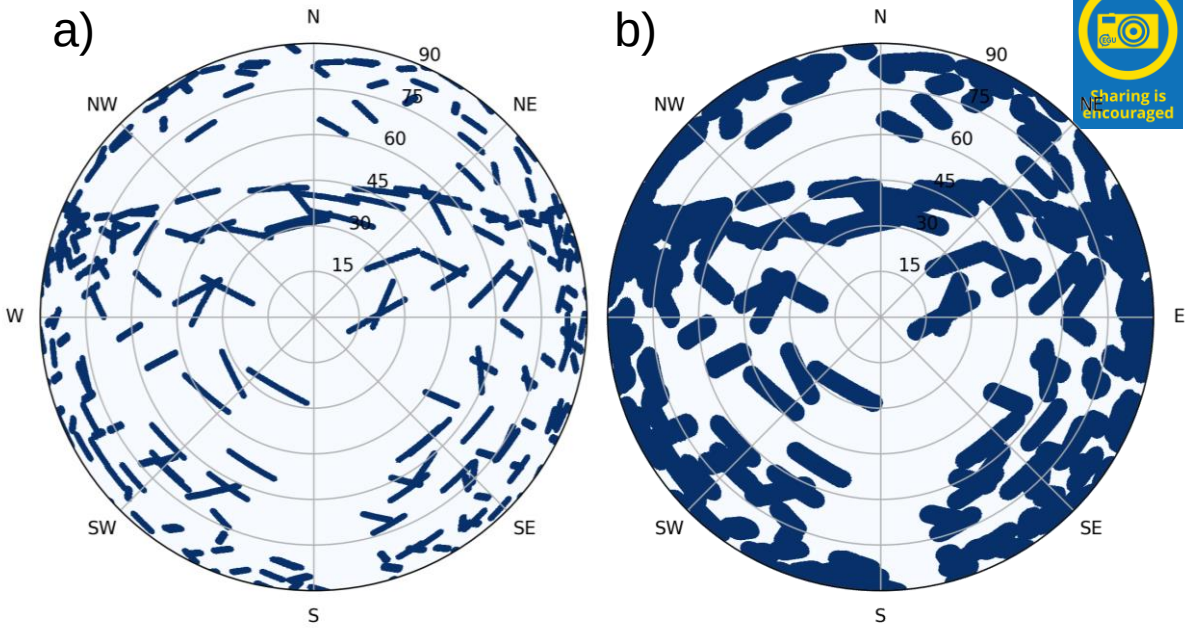
Two terms: constant offset + error in orbits

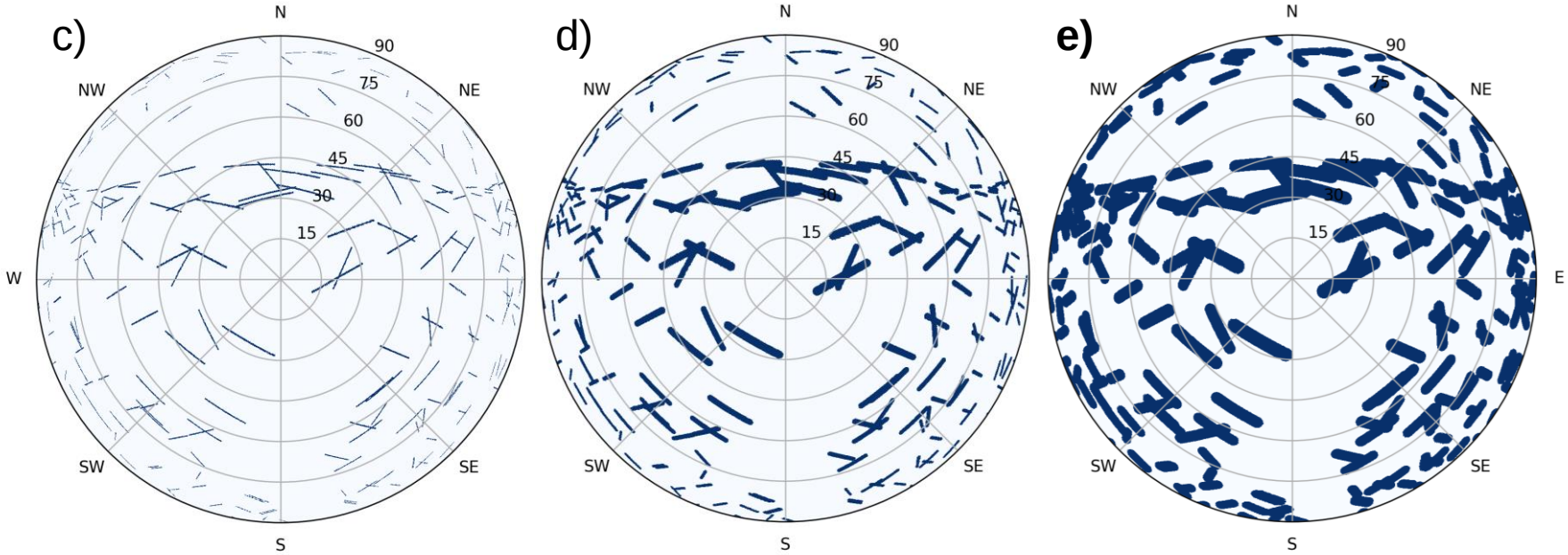
$$\epsilon = c + f(e_0, e_i, d)$$

c = constant factor [deg]
e_0 = orbital error at epoch 0 [km]
e_i = increase of orbital error per day [km]
d = days till session start

a) $c = 1$
b) $c = 3$
c) $e_0 = e_i = 2; d = 1$
d) $e_0 = e_i = 2; d = 7$
e) $\boldsymbol{c = 1;\ e_0 = e_i = 2; d = 7}$

**with min elevation of 20°*

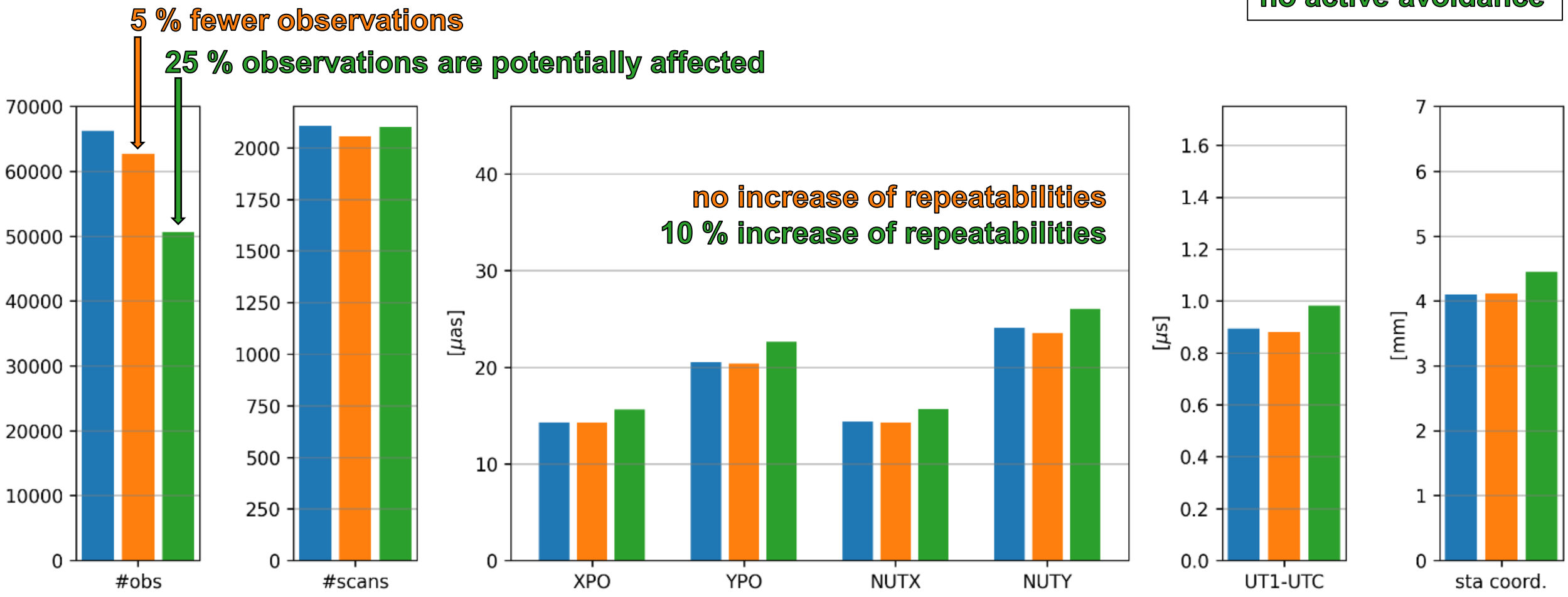




Example results*

16 station VLBI network with Starlink phase 2 (4408 satellites)

no satellites
active avoidance
no active avoidance



*all results are in the appendix

Increase of repeatability based on Monte Carlo simulations

		active avoidance				no active avoidance			
		PM	NUT	UT1	STA	PM	NUT	UT1	STA
1584 sat	12 sta. **phase 1**	0 %	0 %	-1 %	0 %	3 %	3 %	3 %	3 %
	14 sta. **phase 1**	0 %	0 %	0 %	0 %	3 %	3 %	4 %	3 %
	16 sta. **phase 1**	-1 %	-1 %	-1 %	0 %	4 %	3 %	4 %	3 %
4408 sat	12 sta. **phase 2**	0 %	1 %	0 %	1 %	9 %	9 %	10 %	8 %
	14 sta. **phase 2**	-1 %	0 %	-1 %	1 %	8 %	9 %	9 %	8 %
	16 sta. **phase 2**	-2 %	-1 %	-2 %	0 %	9 %	9 %	10 %	9 %
34408 sat	12 sta. **phase 3**	6 %	13 %	14 %	16 %	75 %	65 %	80 %	62 %
	14 sta. **phase 3**	13 %	23 %	18 %	18 %	76 %	90 %	80 %	63 %
	16 sta. **phase 3**	17 %	29 %	21 %	19 %	78 %	93 %	89 %	63 %

Increase of repeatability based on Monte Carlo simulations

		active avoidance				no active avoidance			
		PM	NUT	UT1	STA	PM	NUT	UT1	STA
1584 sat	12 sta. **phase 1**		0 %				3 %		
	14 sta. **phase 1**								
	16 sta. **phase 1**								
4408 sat	12 sta. **phase 2**		0 %				9 %		
	14 sta. **phase 2**								
	16 sta. **phase 2**								
34408 sat	12 sta. **phase 3**		20 %				80 %		
	14 sta. **phase 3**								
	16 sta. **phase 3**								

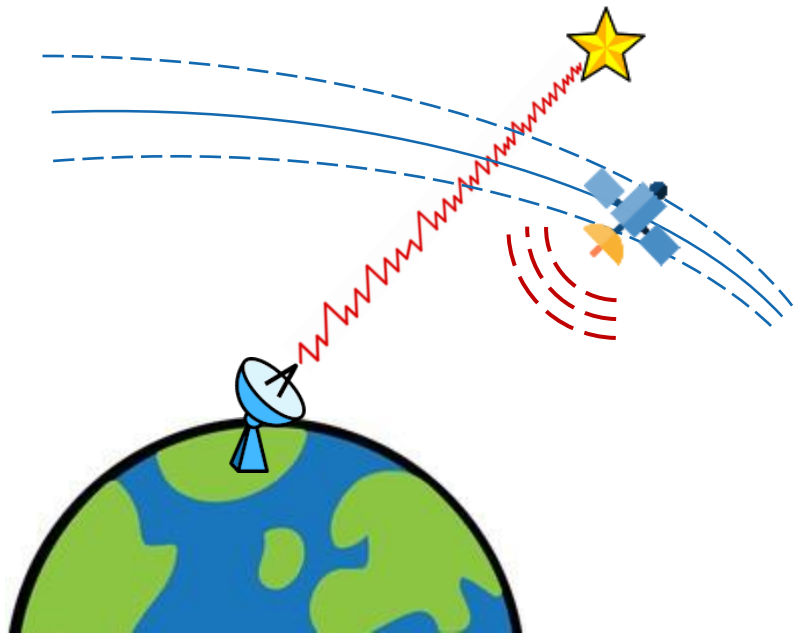
Current bottlenecks

- **Implementation**
  - track thousands of satellites (every second)
  - computationally expensive
- Scheduling is an optimization problem
  - relies to some extend on brute-force testing
  - performance is critical

```
void Scan::checkSatelliteDistance( Station &sta, const shared_ptr<const AbstractSource> &source, ofstream &of ) {
    boost::optional<unsigned long> oidx = findIdxOfStationId( sta.getId() );
    int idx = oidx.get();
    unsigned int startTime = getTimes().getObservingTime();
    vector<unsigned int> times;
    unsigned int t = getTimes().getObservingTime( idx );
    while ( t < getTimes().getObservingTime( idx, Timestamp::end ) ) {
        times.push_back( t );
        t += AvoidSatellites::frequency;
    }
    times.push_back( getTimes().getObservingTime( idx, Timestamp::end ) );

    for ( auto tt : times ) {
        pair<double, double> rade_src = source->getRaDe( tt, sta.getPosition() );
        for ( const auto &sat : AvoidSatellites::satellitesToAvoid ) {
            auto rade_sat = sat->calcRaDeDistTime( tt, sta.getPosition() );
```

- **Affected area / safety margin**
  - more study needed to properly measure and quantify requirements (under way)
- Satellite orbit data and predictions
  - tens of thousands of satellites
  - launched database of TLE files at ETH
  - https://satdb.ethz.ch/



Conclusion

- Number of satellites in space is rising dramatically
- VLBI must **prepare** for potential threats from space borne RFI
- Presented in this work: **active mitigation strategy**
  - avoid observations close to satellites
  - passive strategies (e.g. filters) also exist
- **Few thousand** satellites can be **handled effectively** by this approach
  - no noticeable effect on the geodetic products based on simulations
- **Orbit prediction accuracy** drives safety margin size
  - Currently based on TLE files
  - problematic if schedules need to be posted 7 days in advance
- **More work is required**

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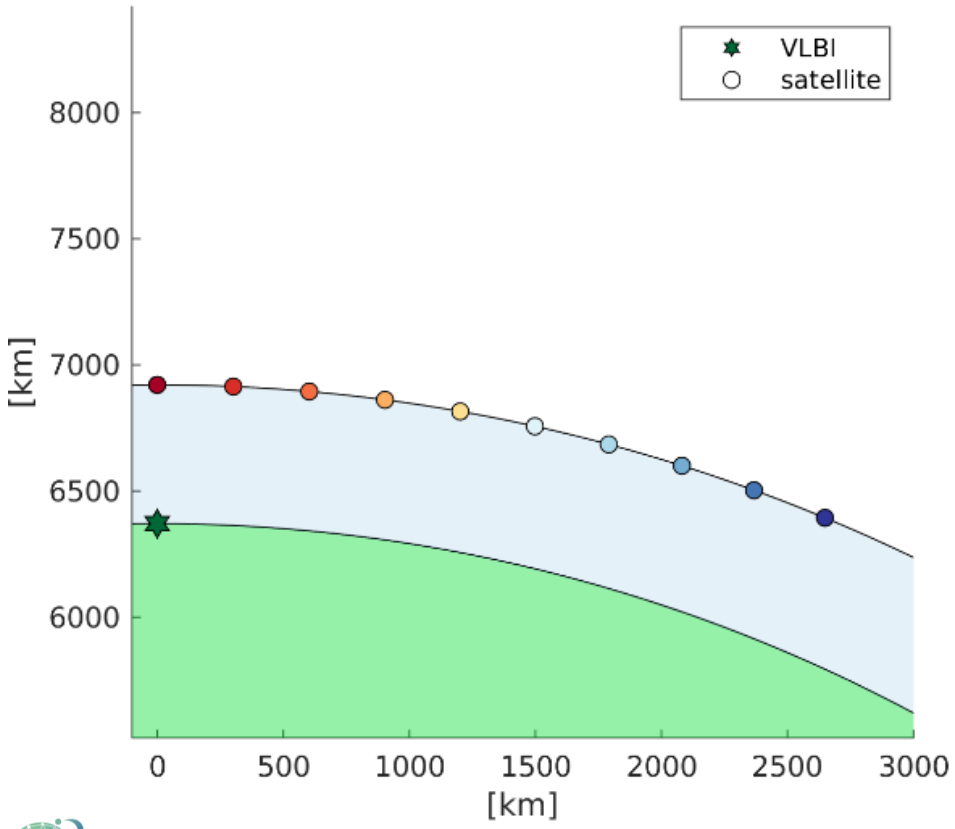
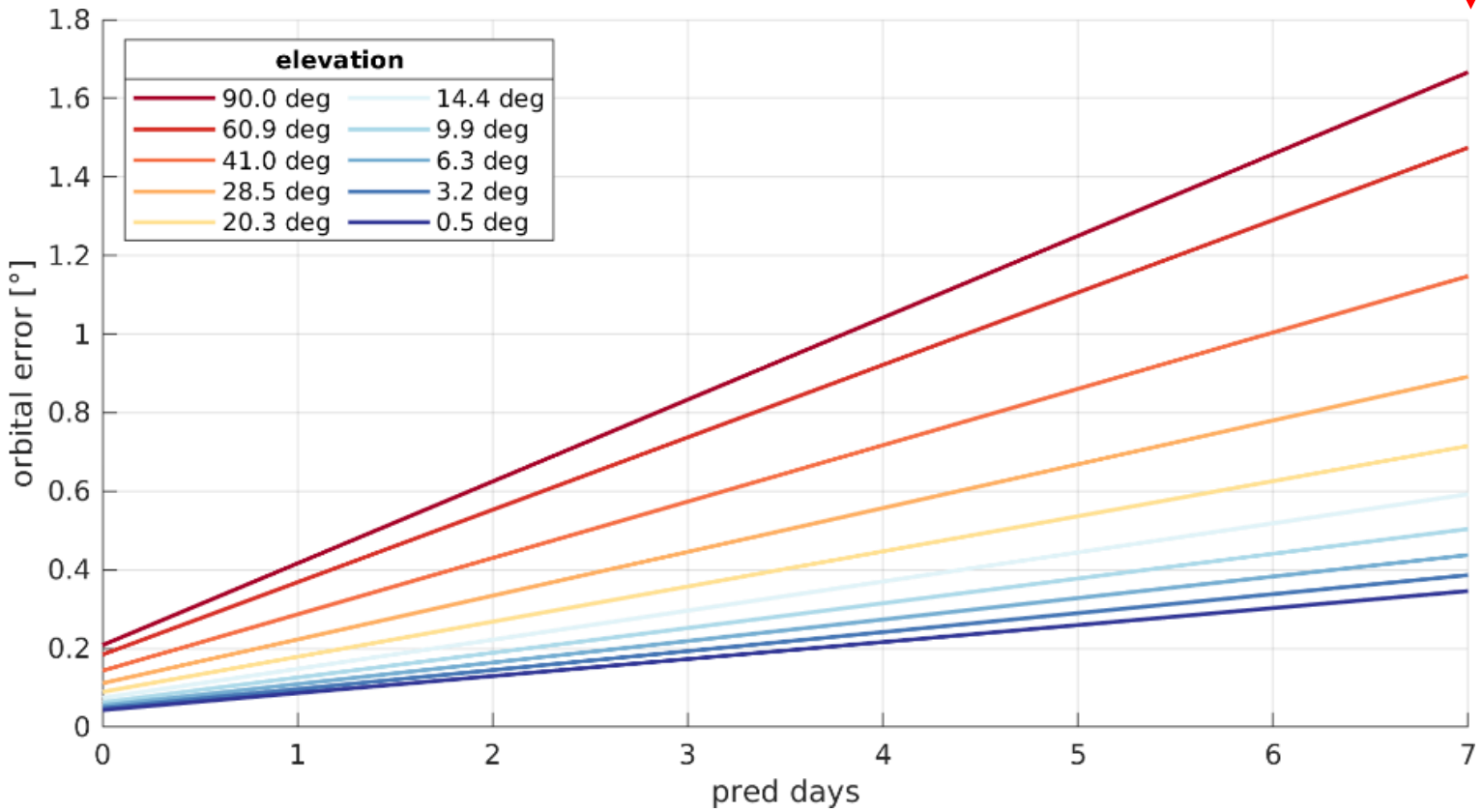
When are observations affected?
Safety margin for active avoidance?

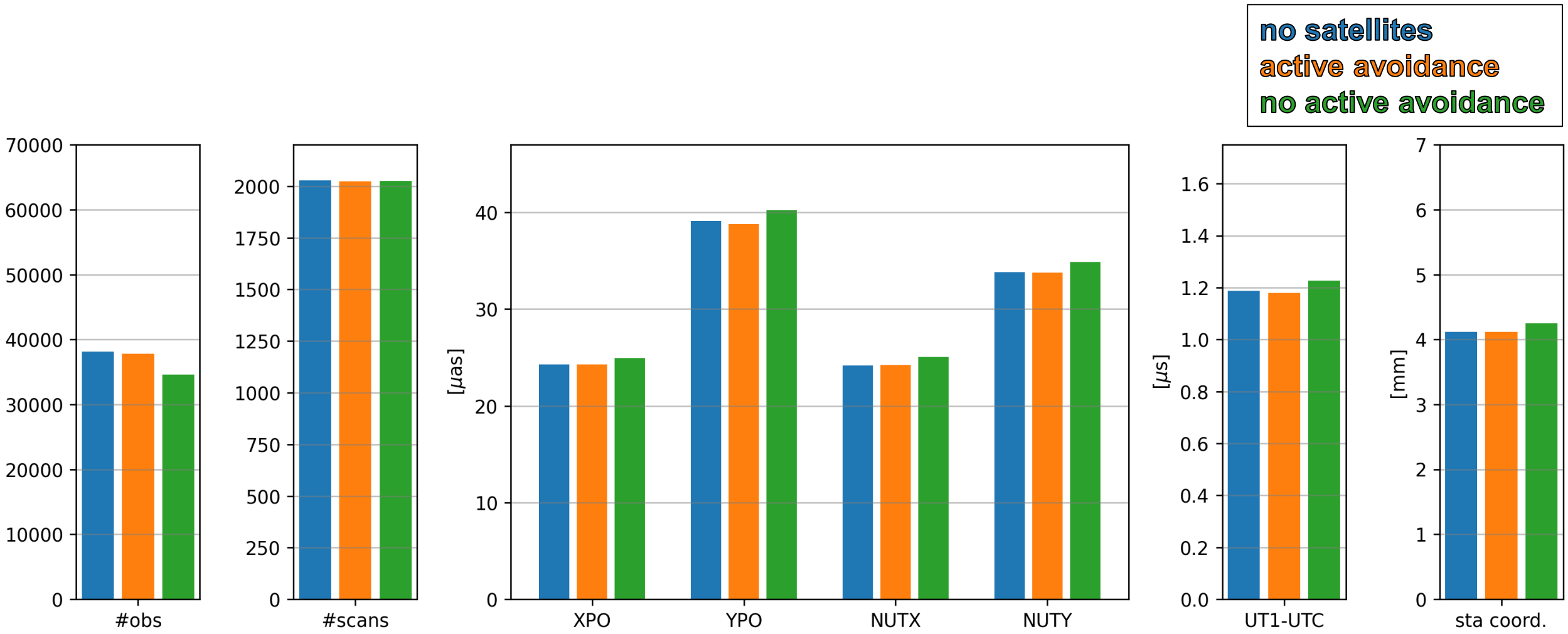
Big part is orbit prediction accuracy

assumption: 500 km altitude, error at epoch 0 is 2 km, increased by 2 km per day

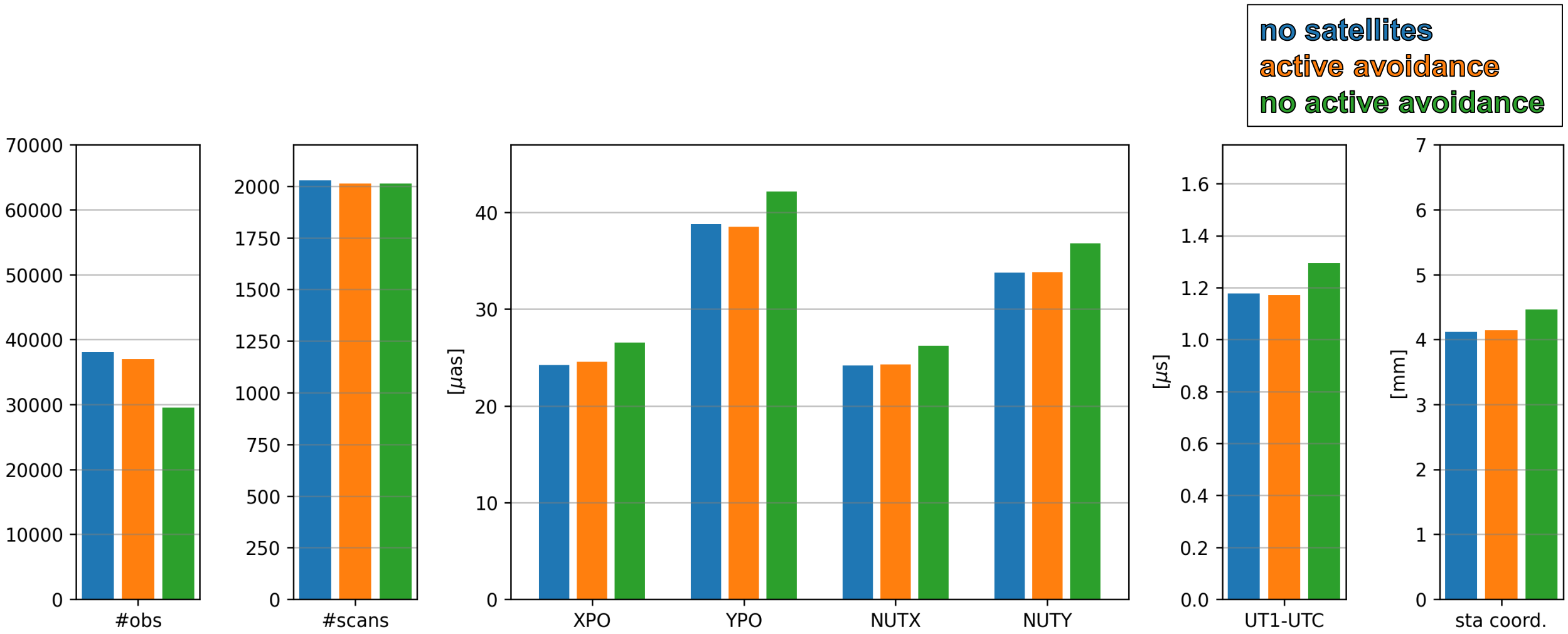




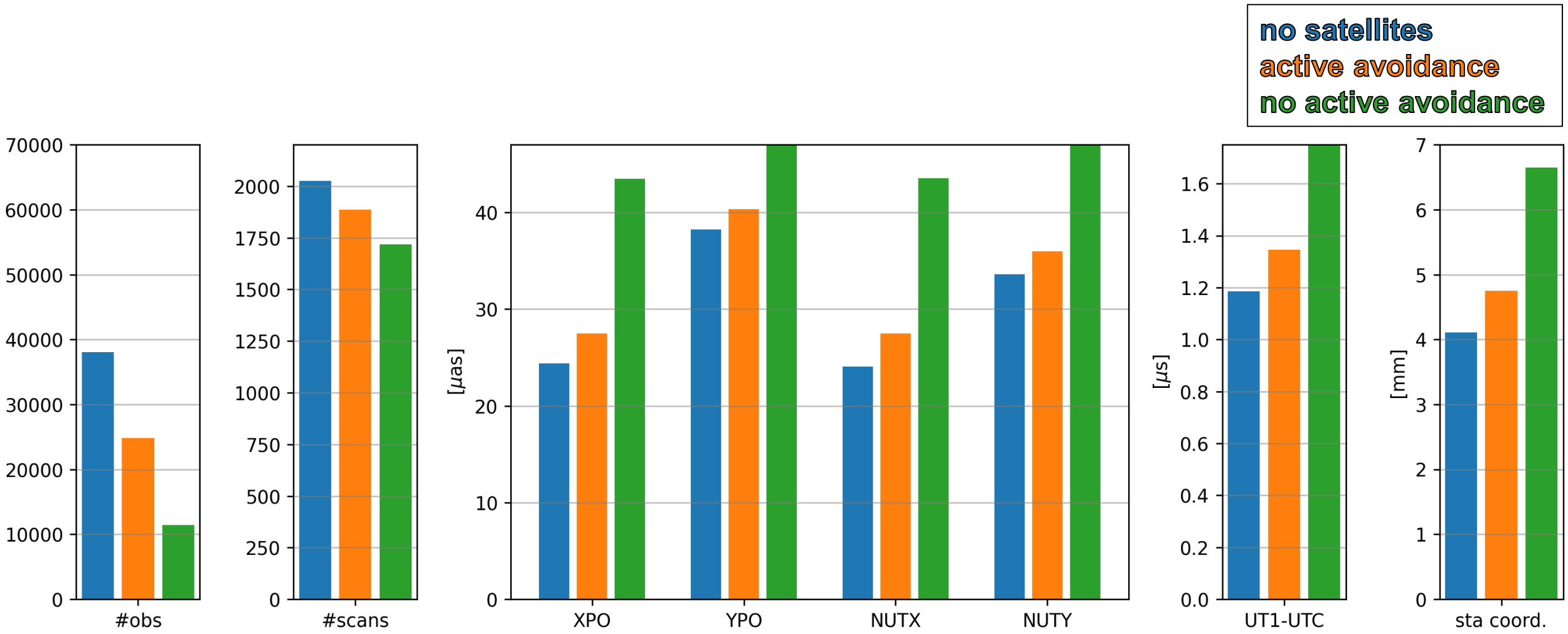
12 station VLBI network + Starlink phase 1 (12 sta. phase 1)



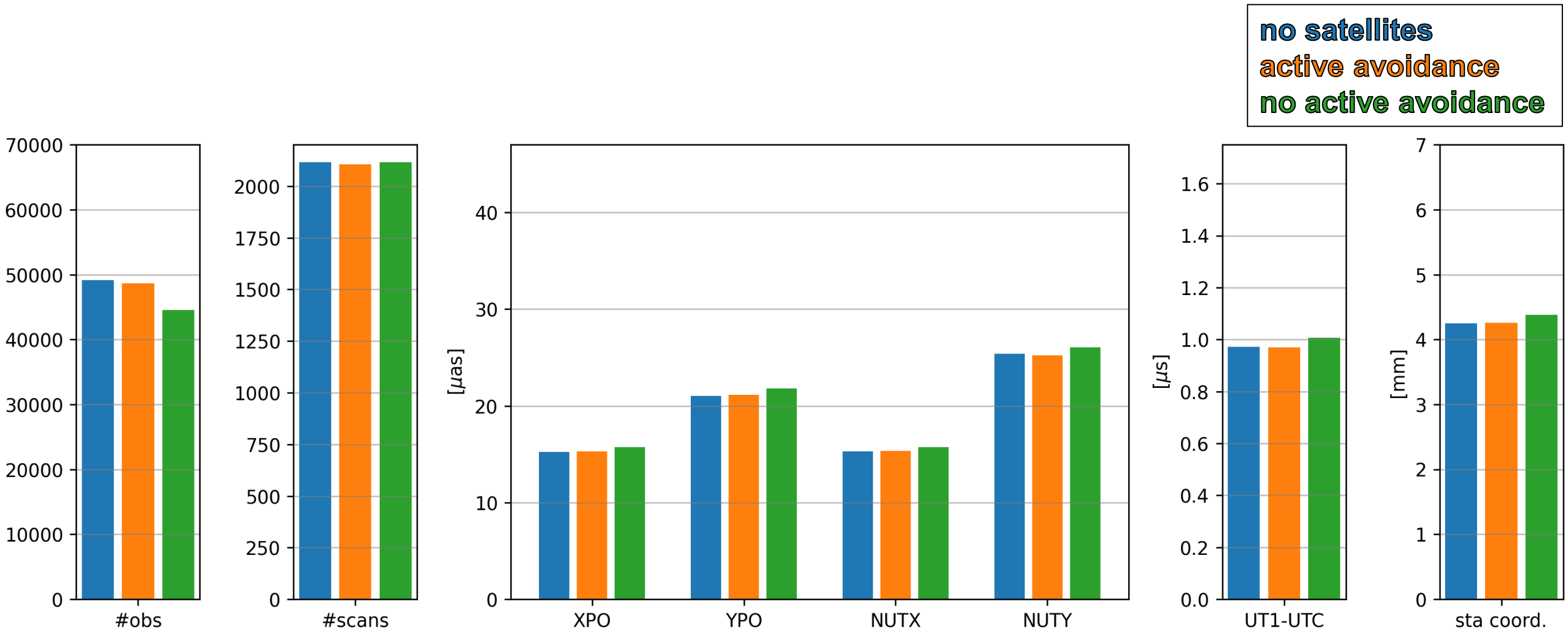
12 station VLBI network + Starlink phase 2 (12 sta. phase 2)



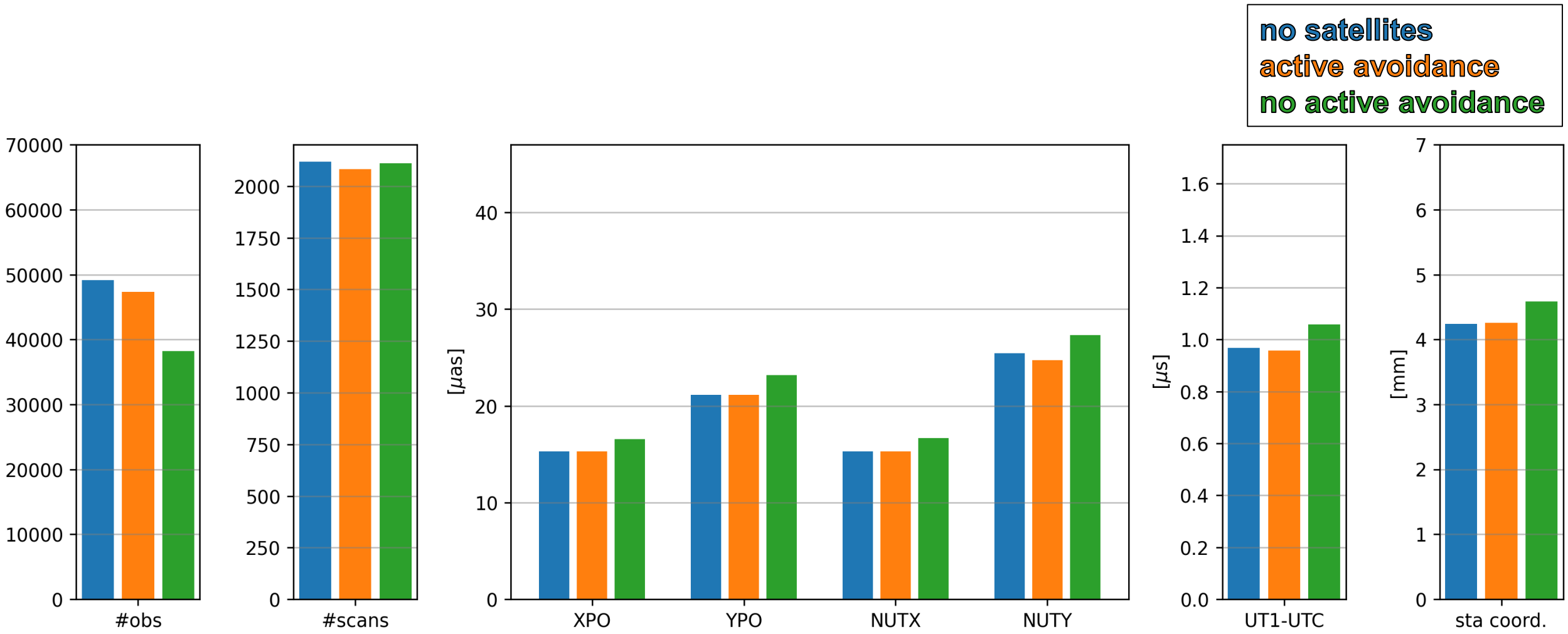
12 station VLBI network + Starlink phase 3 (12 sta. phase 3)



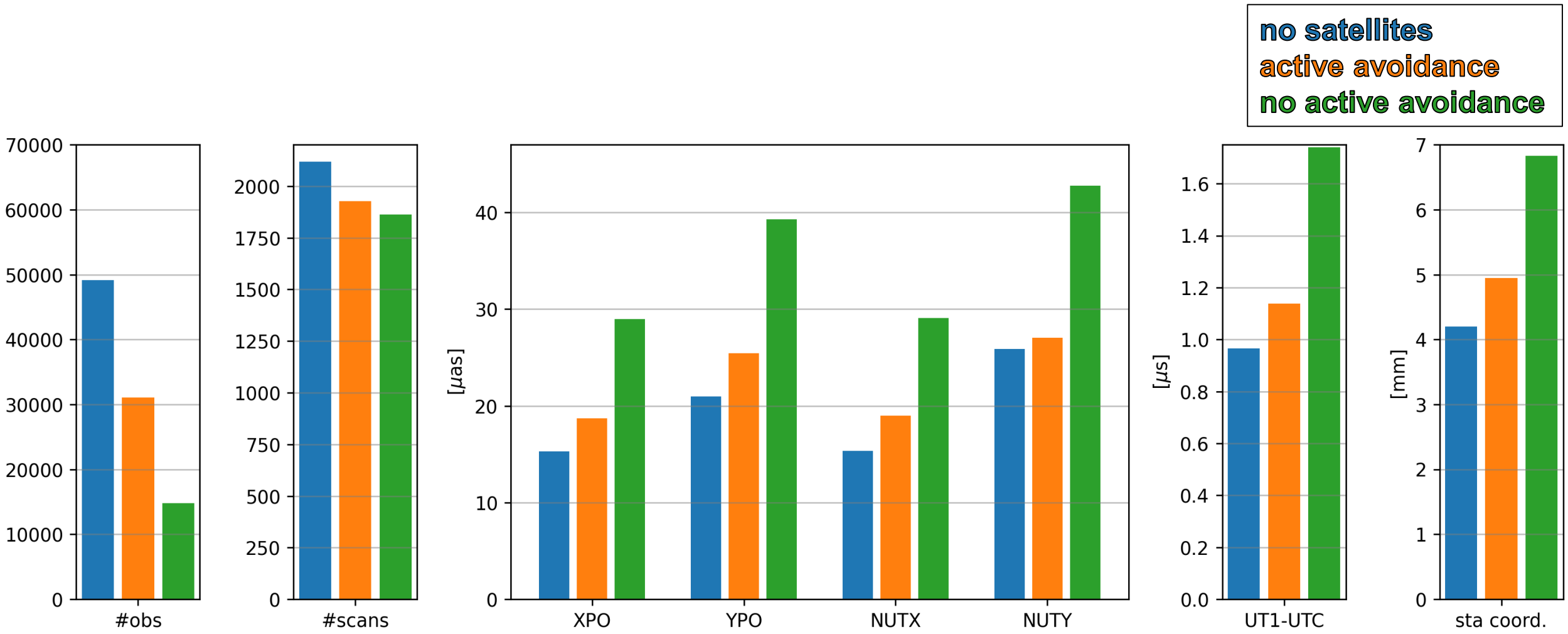
14 station VLBI network + Starlink phase 1 (14 sta. phase 1)



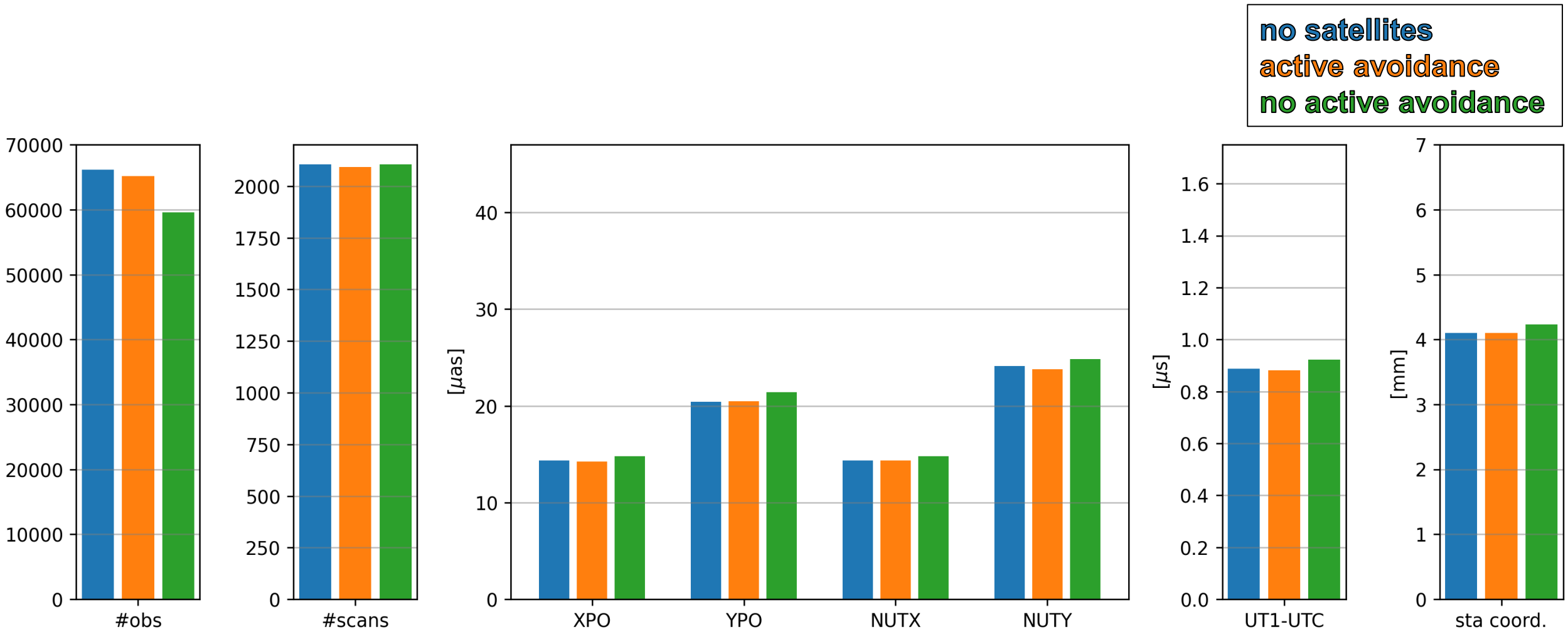
14 station VLBI network + Starlink phase 2 (14 sta. phase 2)



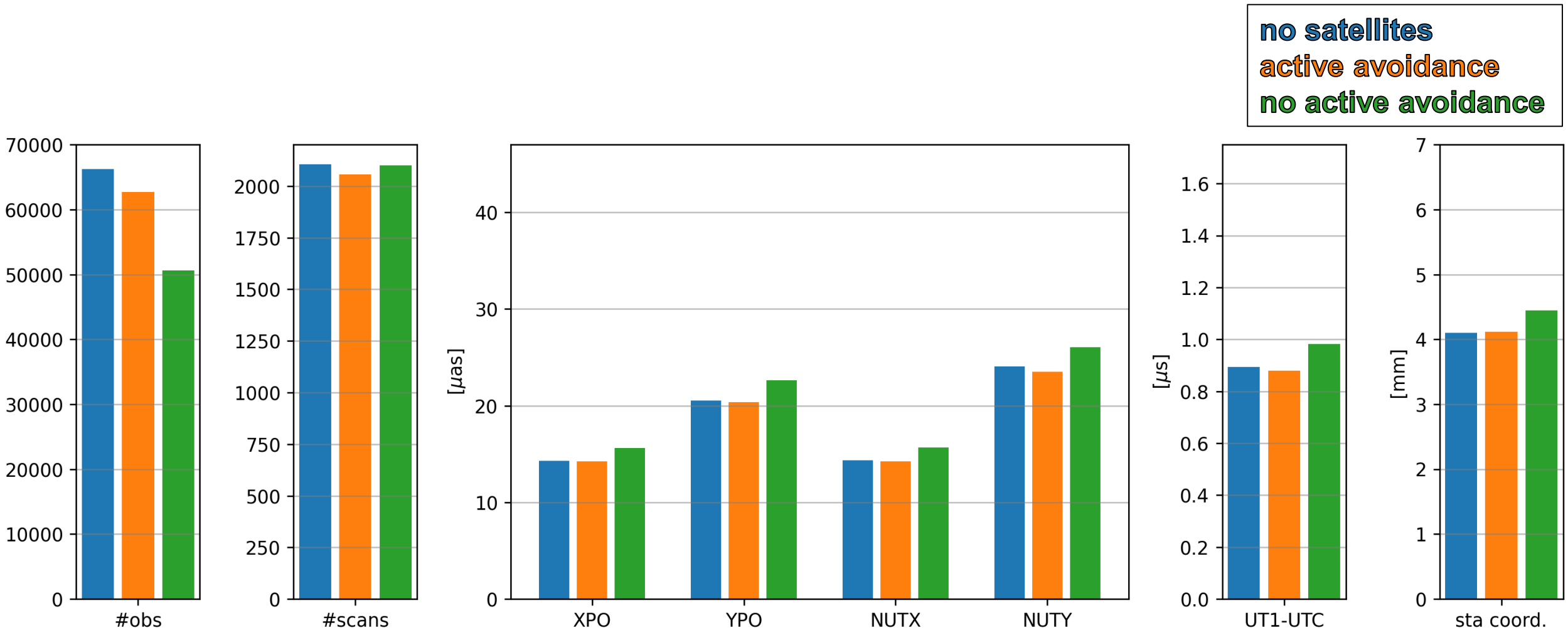
14 station VLBI network + Starlink phase 3 (14 sta. phase 3)



16 station VLBI network + Starlink phase 1 (16 sta. phase 1)



16 station VLBI network + Starlink phase 2 (16 sta. phase 2)



16 station VLBI network + Starlink phase 3 (16 sta. phase 3)