Impact of Satellite Mega-Constellations on Astronomical Observations

in the Visible and Infrared Domains

(not radio/sub-mm)

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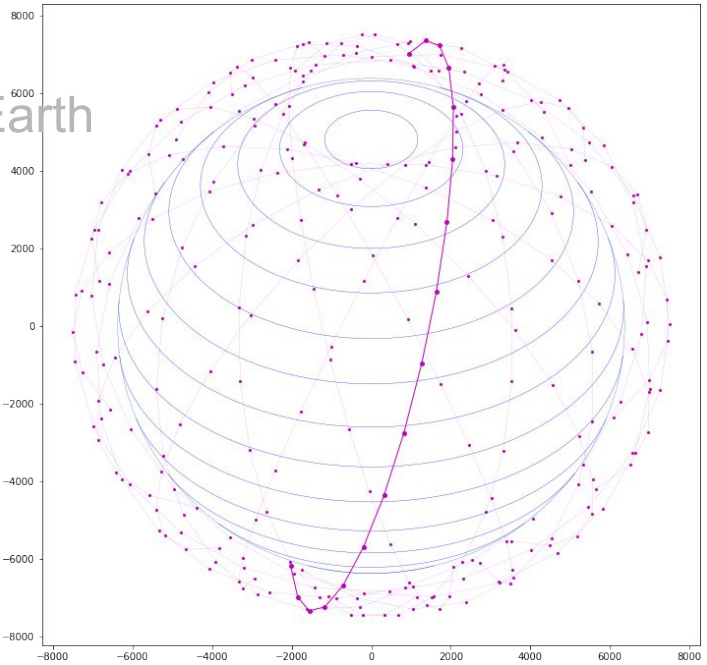
How we simulate a constellation

Simulating a constellation

- Input: Constellation specifications, for each shell:
  - Altitude
  - Inclination
  - Number of planes
  - Number of satellites
- Simplifications:
  - Circular orbits
  - Spherical/flattened Earth, Point-mass Earth
  - Cone (B,G)/cylindrical (H) shadow
- Output:
  - Position (long, lat), (x,y,z)
  - Velocity (v_x,v_y,v_z)
  - Illuminated / in Earth's shadow

Altitude [km]	Inclination [deg]	Planes	Satellites
328	30	84	7178
334	40	84	7178
345	53	84	7178
373	75	20	1998
499	53	40	4000
604	148	12	144
614	116	18	324
360	97	40	2000

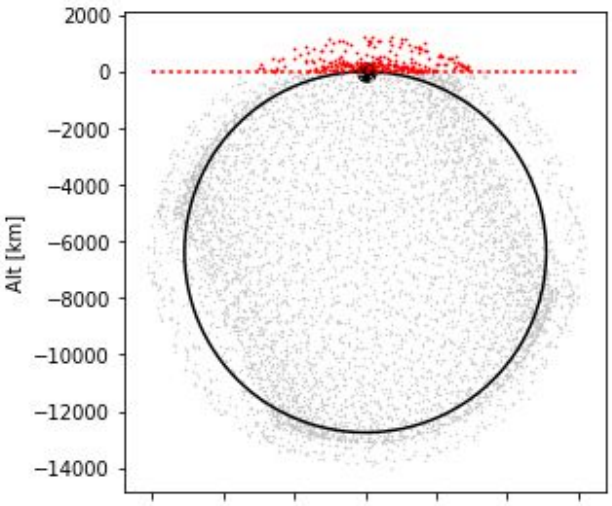
Starlink Generation 2 (from May 2020 filing, JMcD Model III).



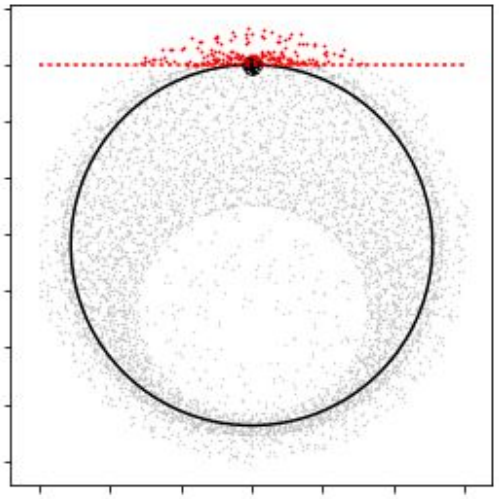
Simulating: position

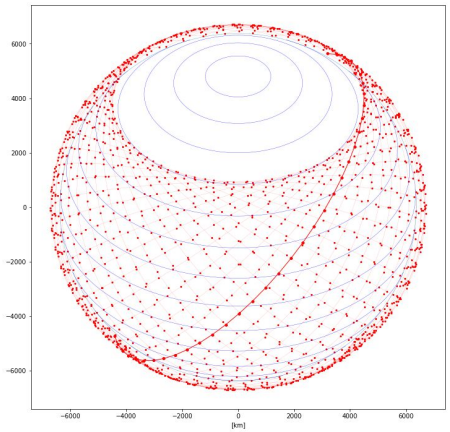
In sight

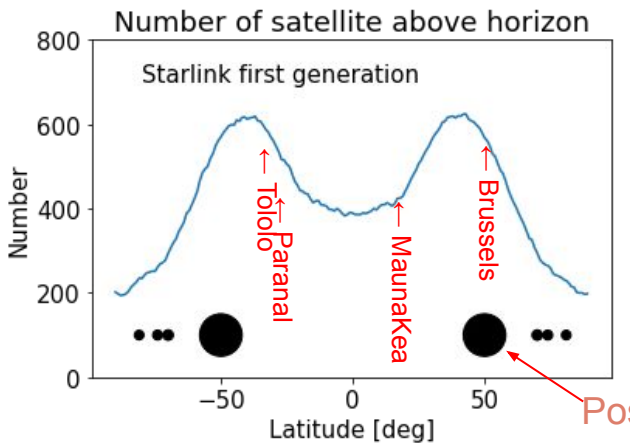
S ⟷ N



W ⟷ E





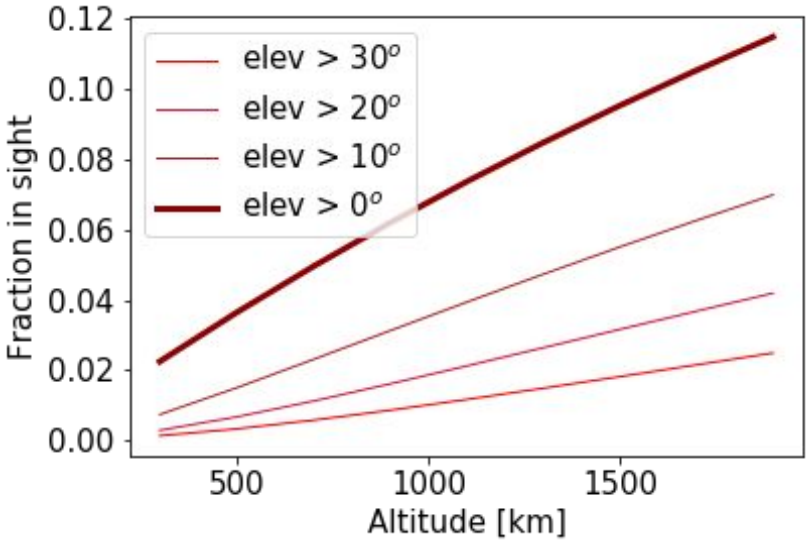


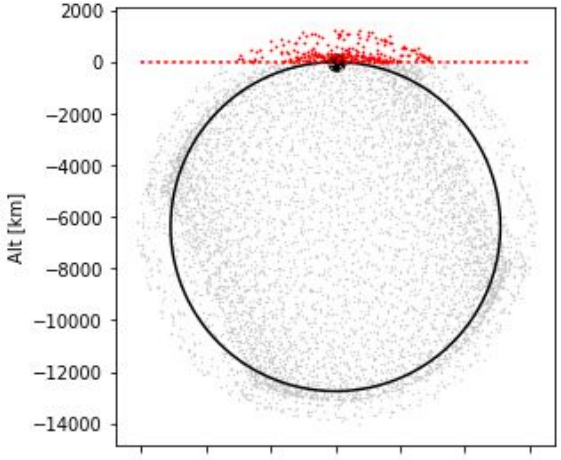
Number of satellites in sight

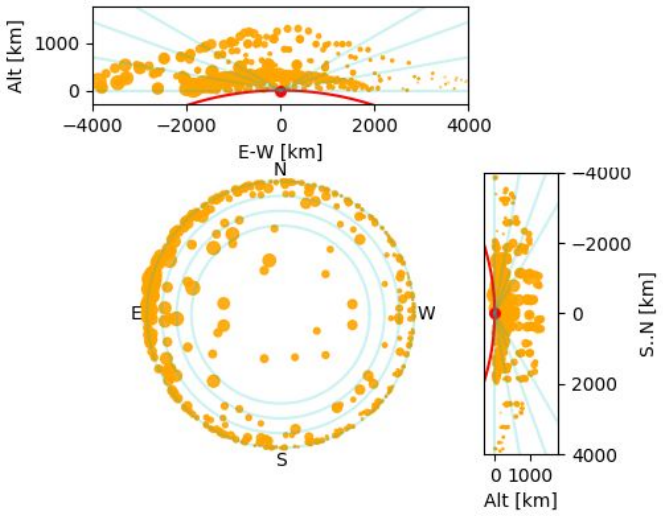
- peaks for observer at latitude = inclination *i* of the constellation
- *i* ~ 30-70° for most constellations

Position = *i*, size= number of sat

Simulating: position





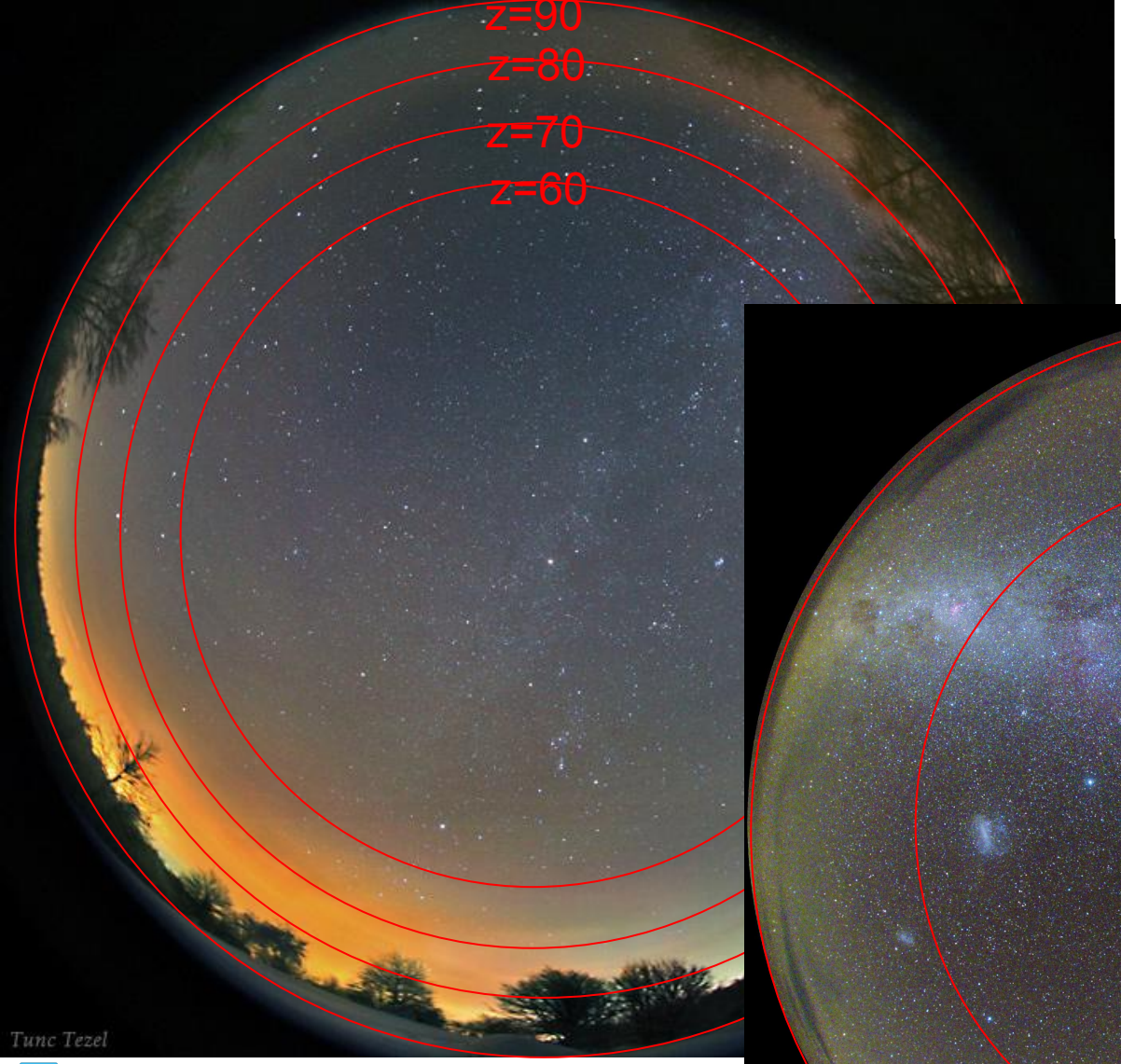


Satellites in sight

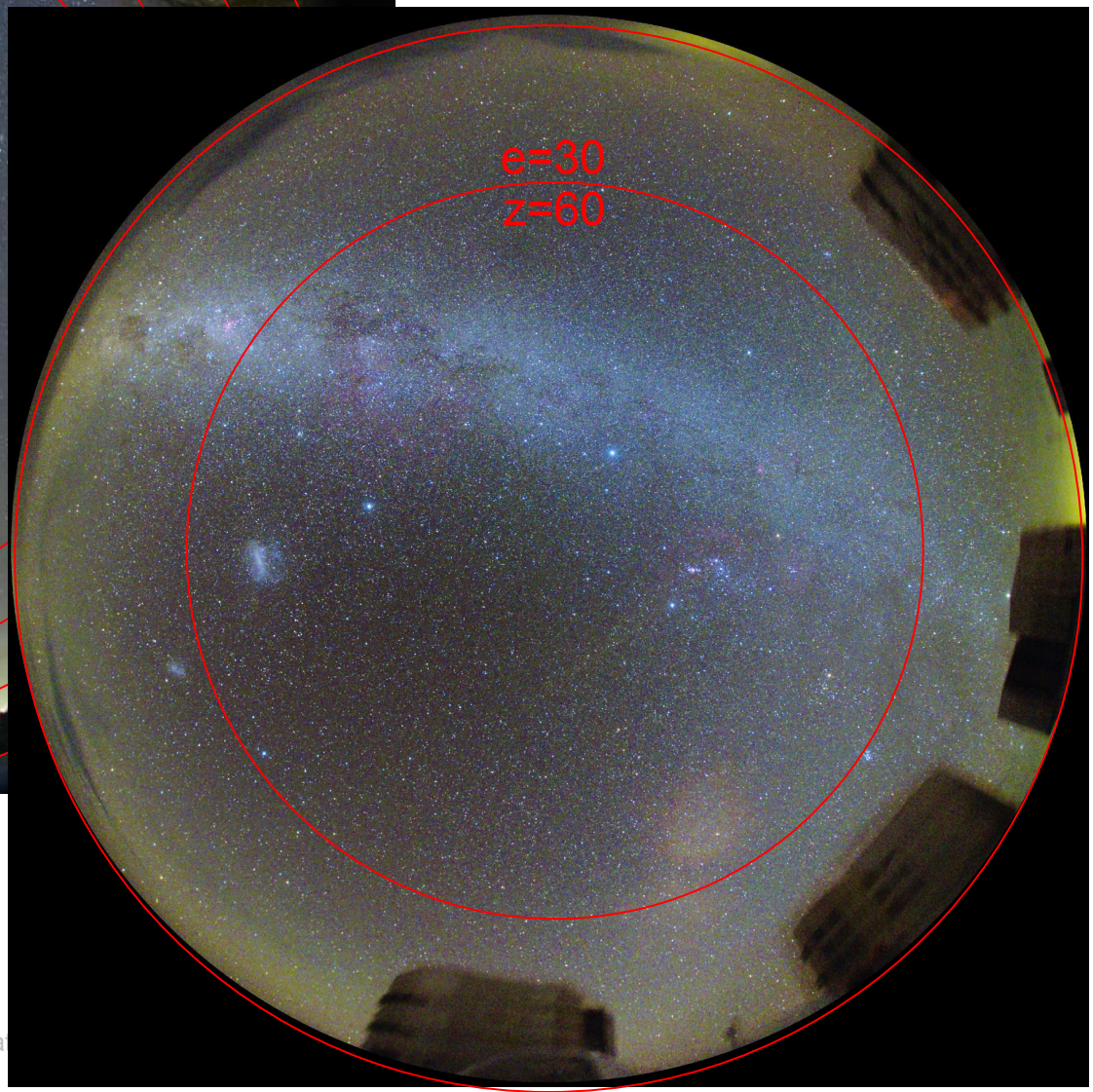
- Fraction of constellation in sight increases with satellite altitude
- > Horizon:
  - 3-10% of constellation
  - half of those below 10° elevation
- > 30° elevation = Airmass 2
  - 0.3 - 1% of constellation
  - or ~10-15% of those in sight

Pro: most observations above 30º elevation (Paranal: 96%)

Amateurs: lowest 10º almost always lost

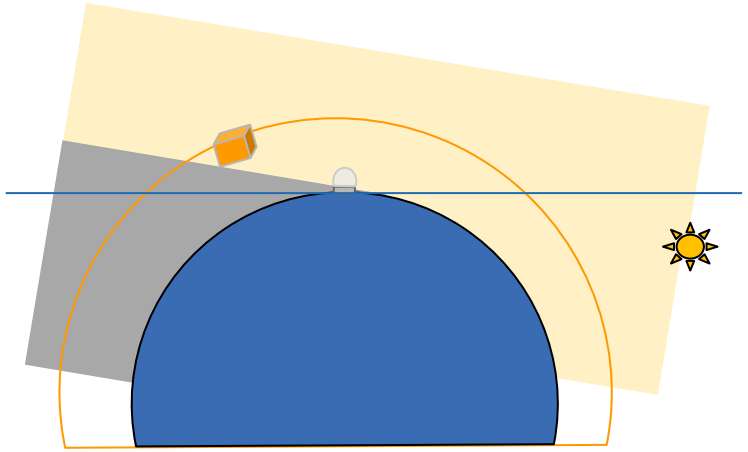


⬆️ Tunk Tezel TWAN.org
(it's a distant freeway junction)



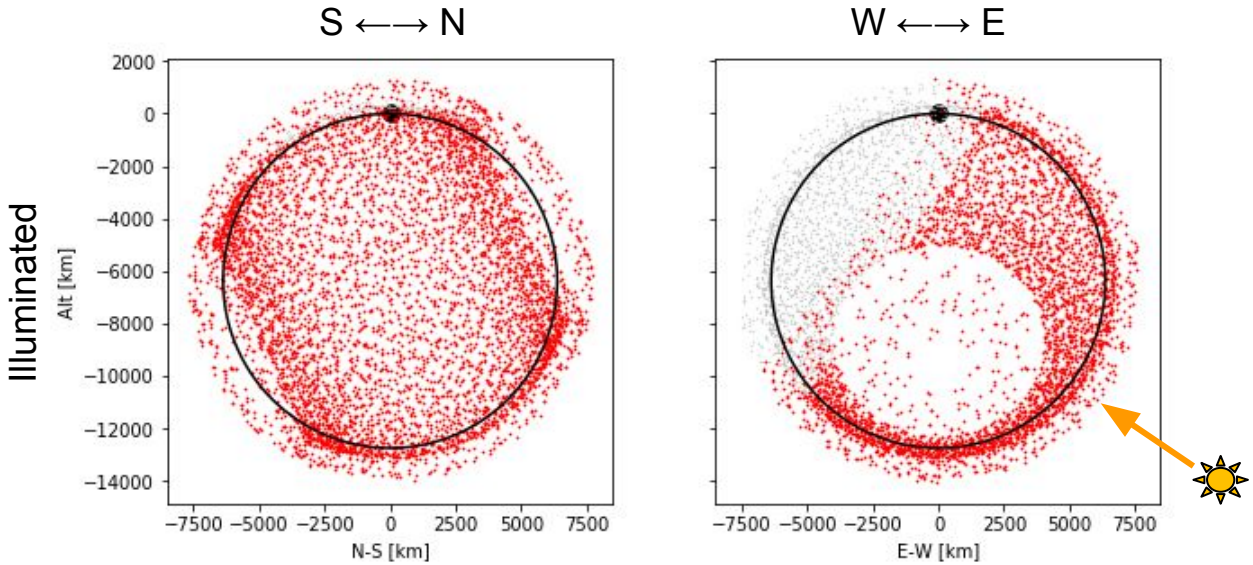
ESO VLT Paranal ➡️

Simulating: Illumination



Illuminated Satellites

- Visible/near-IR:
  Satellites in shadow are not visible
- Thermal IR:
  The satellites are bright all the time
  (It's a different story -
  short version: it does not matter)

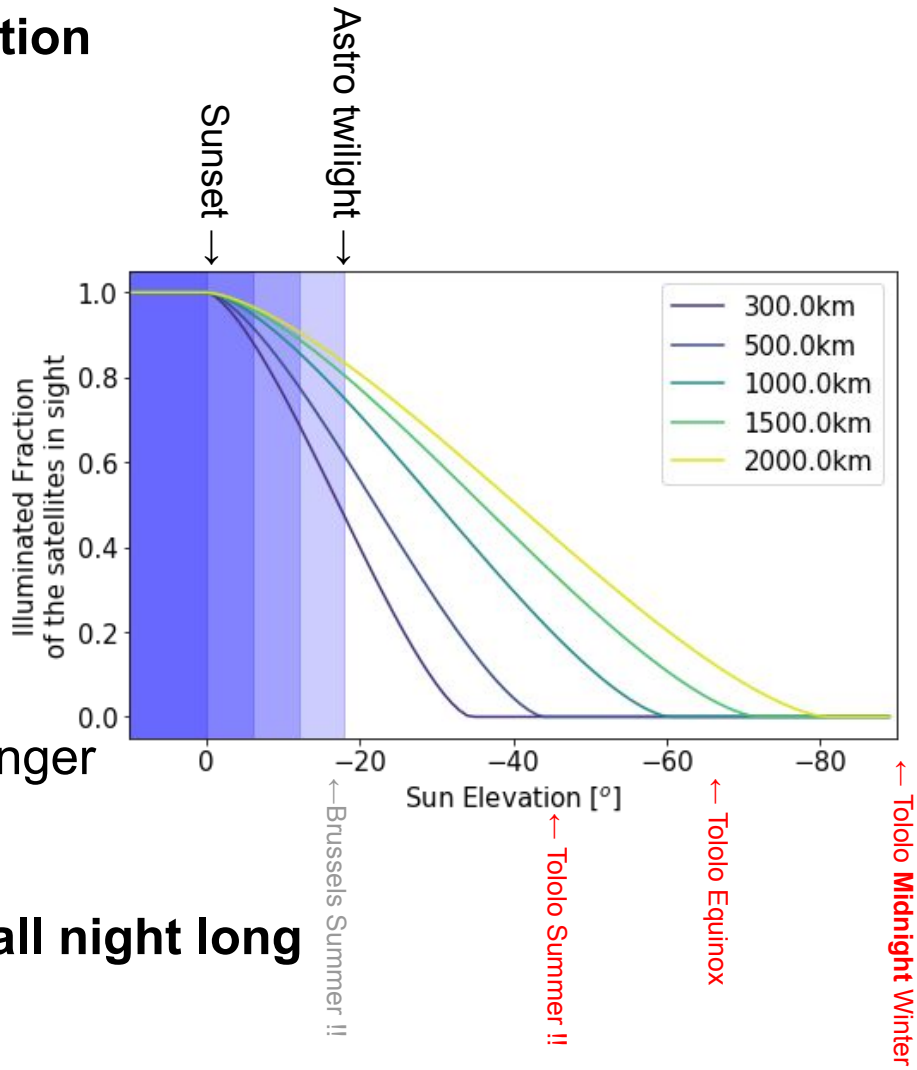


Simulating: Illumination

Illuminated fraction of the constellation
is a function of

- **Elevation of the Sun**
  is a function of
  - Latitude
  - Time of year (season)
  - Time of night

- **Altitude of the satellites**
  - Higher Sat stay illuminated longer

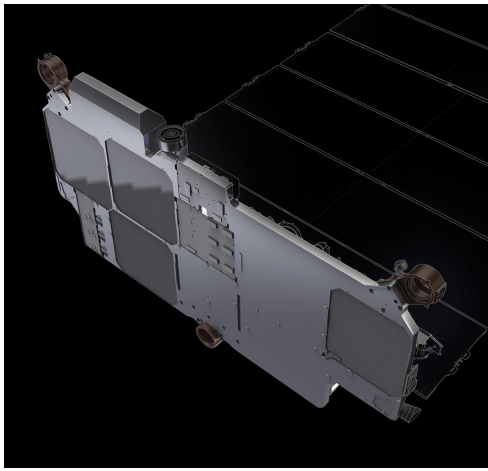


⇒ **High sat *can* remain illuminated all night long**
(eg: the Moon :-)

Simulating: Magnitude

- Reality
  - Complex shape
  - Complex surface properties

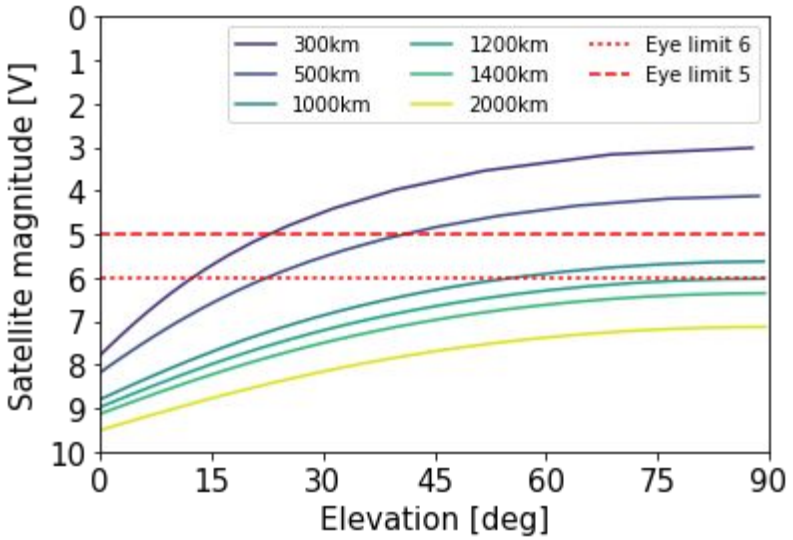
  ⇒ very complex, not characterized, impossible to model (as of today → see later talk for the future)



- **Lambertian sphere:**
  - Geometric diffusion
  - Geometric solar phase function $f(\alpha)$
  - Cross section (albedo p and radius r) set from observations
    (obs of SL normalSat, not DarkSat, not VisorSat)

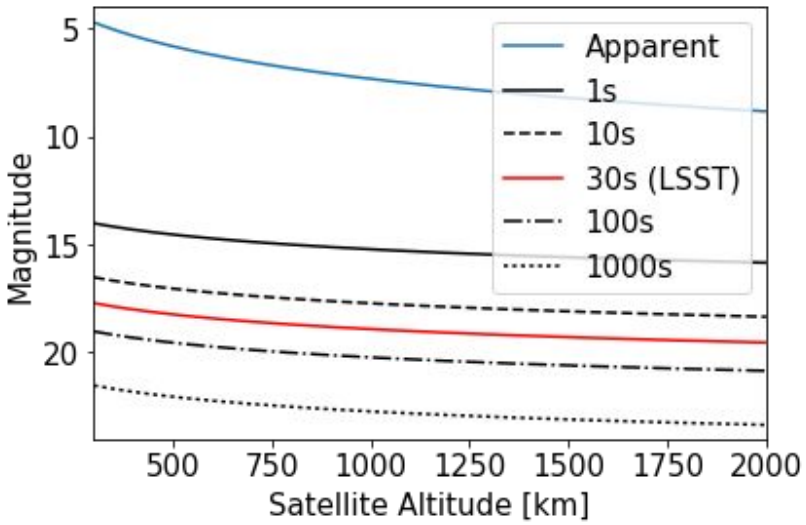
$$M = M_{Sun} - 2.5\log(r^2 p) - 2.5\log(f(\alpha)) + 5\log(R) + x\chi$$

  - Simple, but good for many purposes
  - ... room for improvement
    (no glare, no flare...)



Simulating: effective magnitude

- M = Apparent (real) magnitude of the satellite
- Apparent motion of the satellite: v (10 … 80°/min)⟶ trailing
- t_{eff} Effective Exposure Time for a satellite
  - t_{eff} = time to cross a resolution element
    - t_{eff} ~ 0.0002 - 0.002 s for seeing-limited telescope
  - t_{eff} independent of the actual exposure time t
- Effective magnitude of a sat.:
  - Trail has the same peak brightness as an object with $M_{eff} = M - 2.5 \log(t_{eff} / t)$
  - Low dependency on elev.
  - Caveat: satellite can (will) be resolved/out-of-focus with large tel.

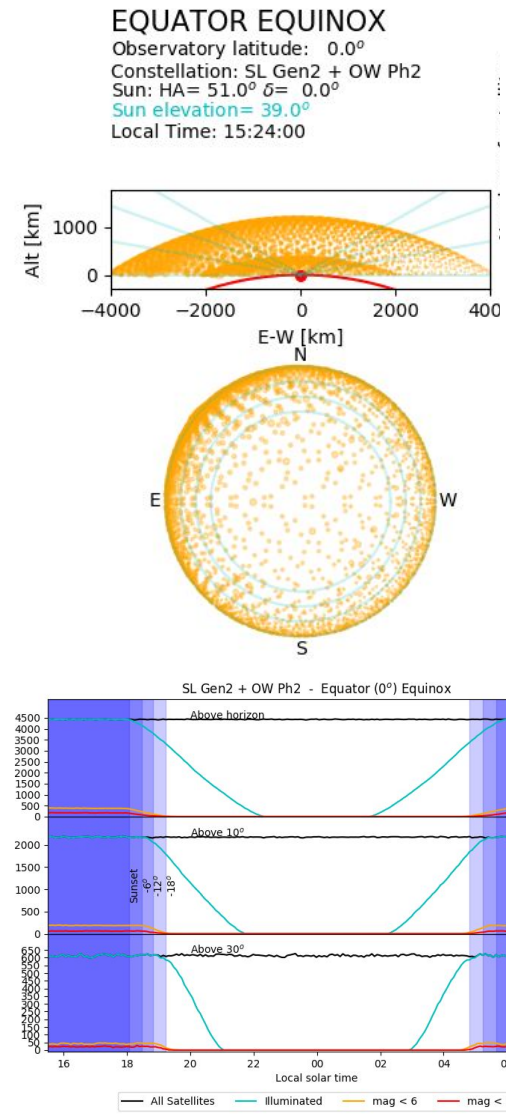


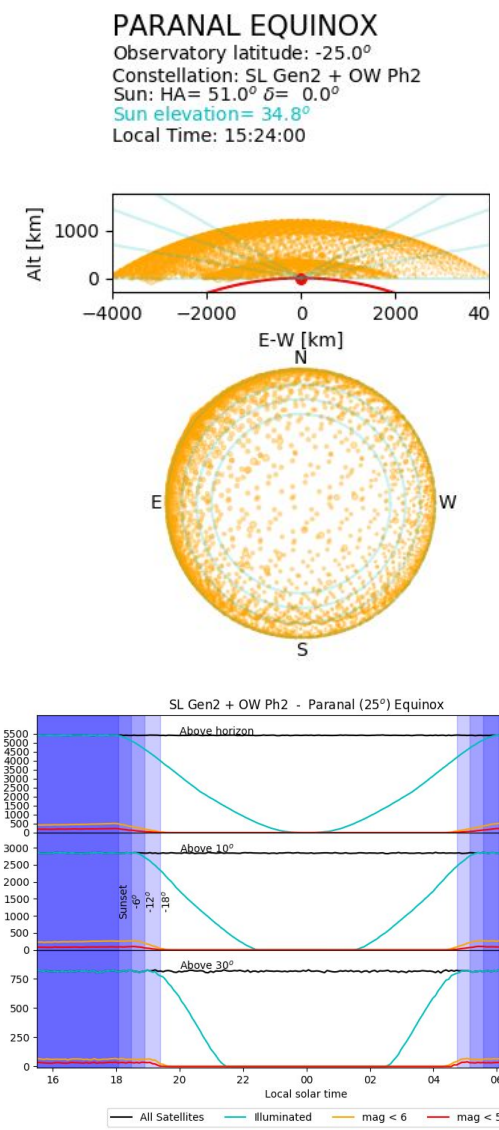
Simulating: How?

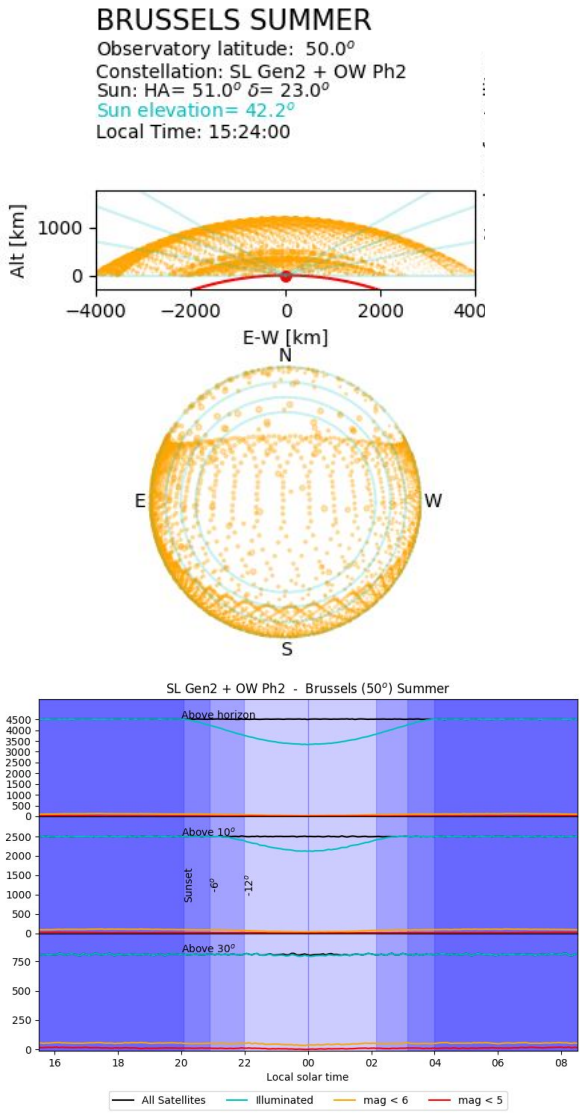
- Numerically
  1. Compute the position (and mag) of each satellite
  2. Count the satellites in the sky (or region of interest)
  3. GOTO 1 (iterate to get better statistics)

  (CPU intensive, with tricks to optimize)
- Analytically
  - Cees Bassa worked out the (non-trivial) geometrical problem
  - Being implemented with great success and very promising prospects
  - *Lightning fast!*
- Cross validation:
  - Numerical models: all within <% ✔
    Us: Oli's + Cees' + David's (3 independent)
    Others': Jonathan McD's + Jan Siminski's (2 independent)
  - Cees' analytical model: within <% ✔

Simulating a constellation

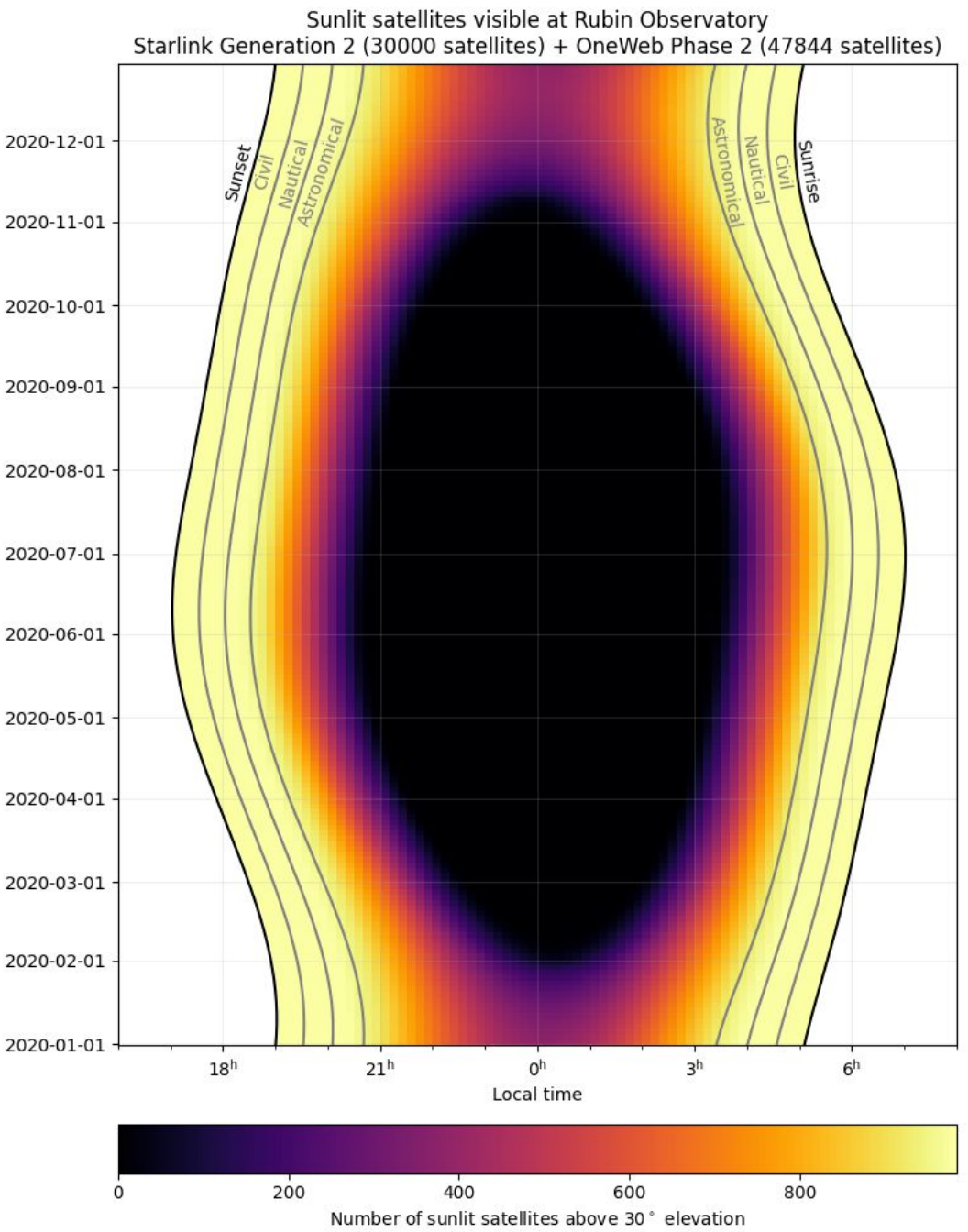






Simulating a constellation

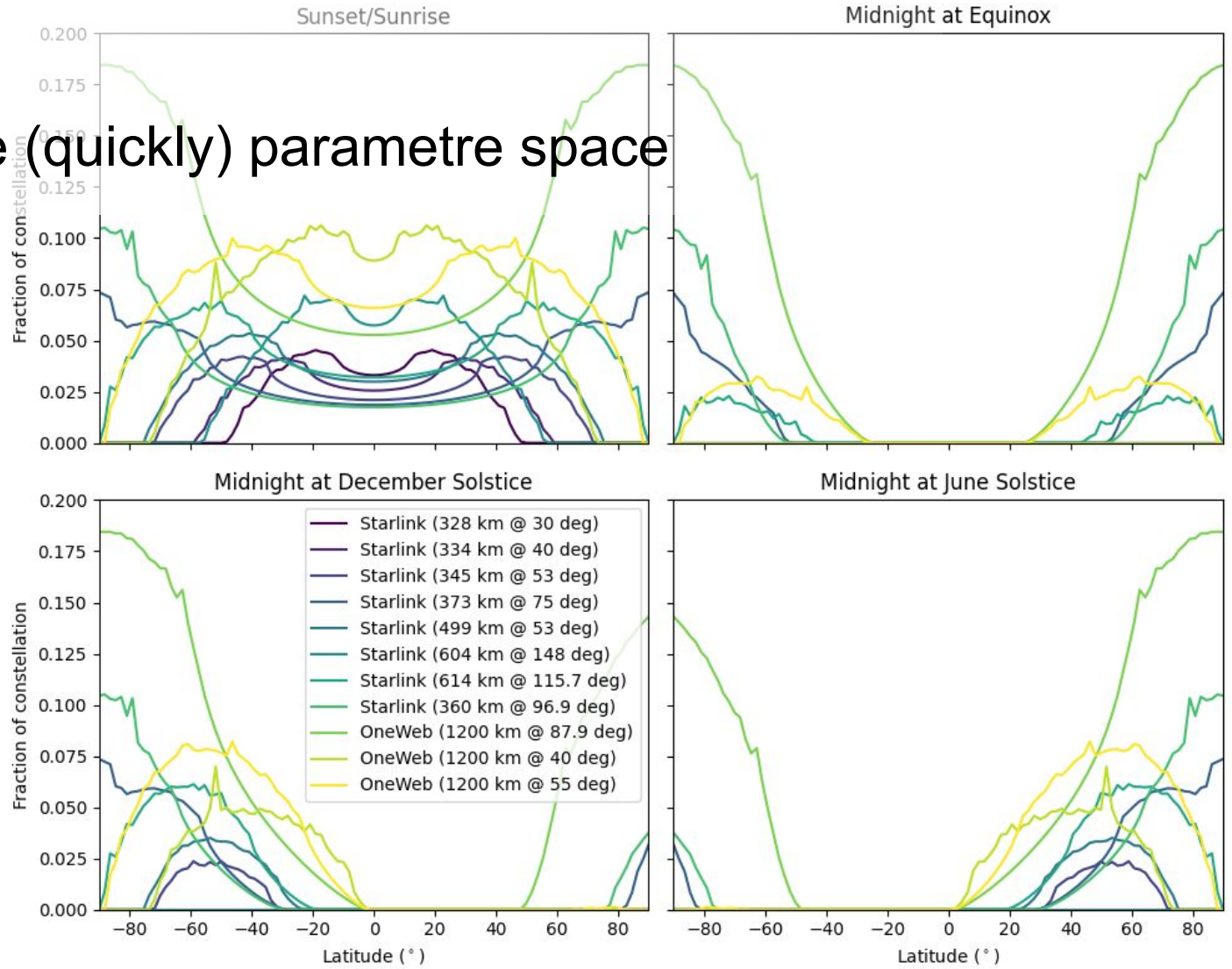
- Whole year at a glance
  - Analytically



Simulating a constellation

Analytically:

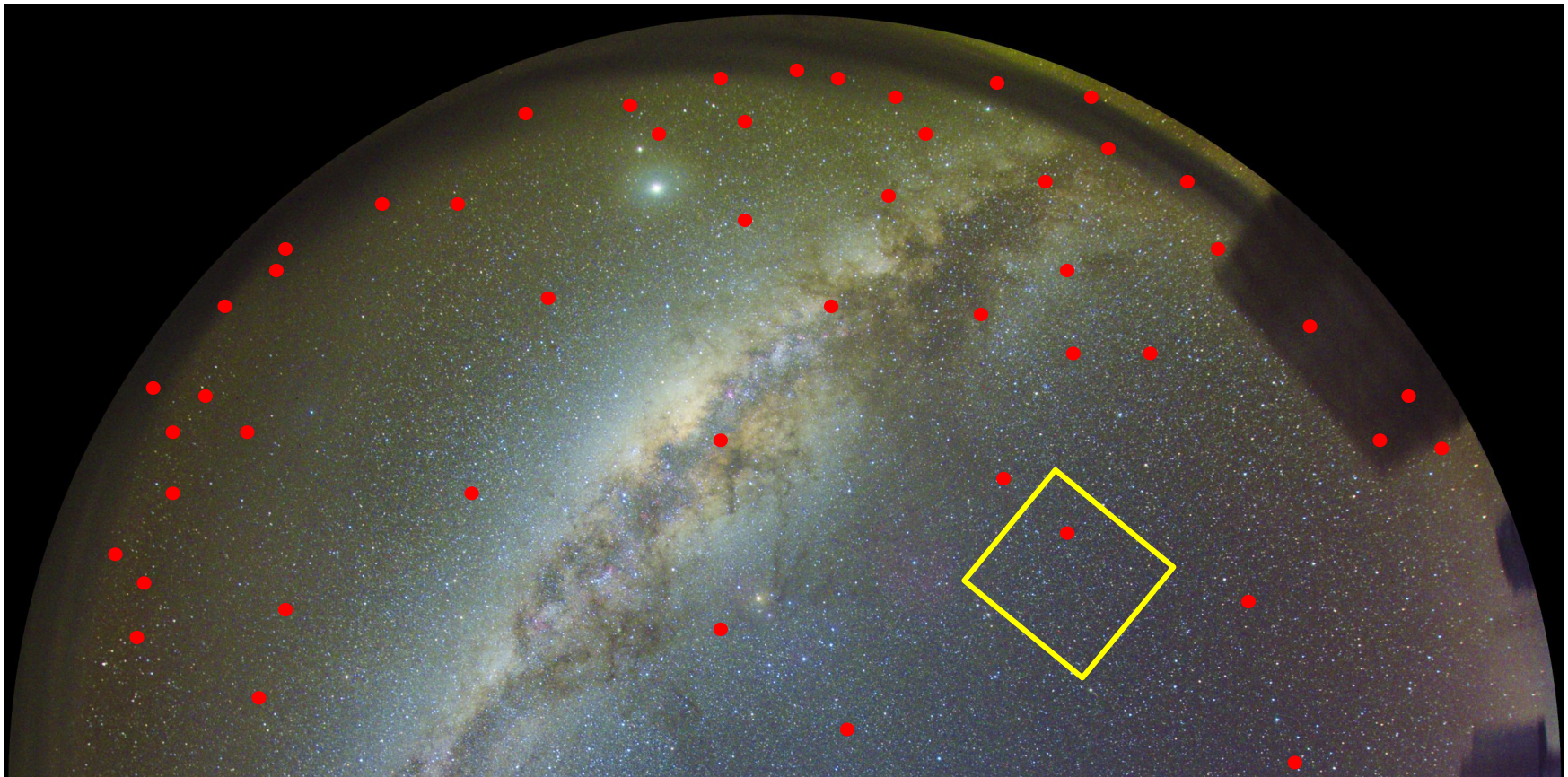
- Explore (quickly) parametre space



How we simulate the effect on the observations

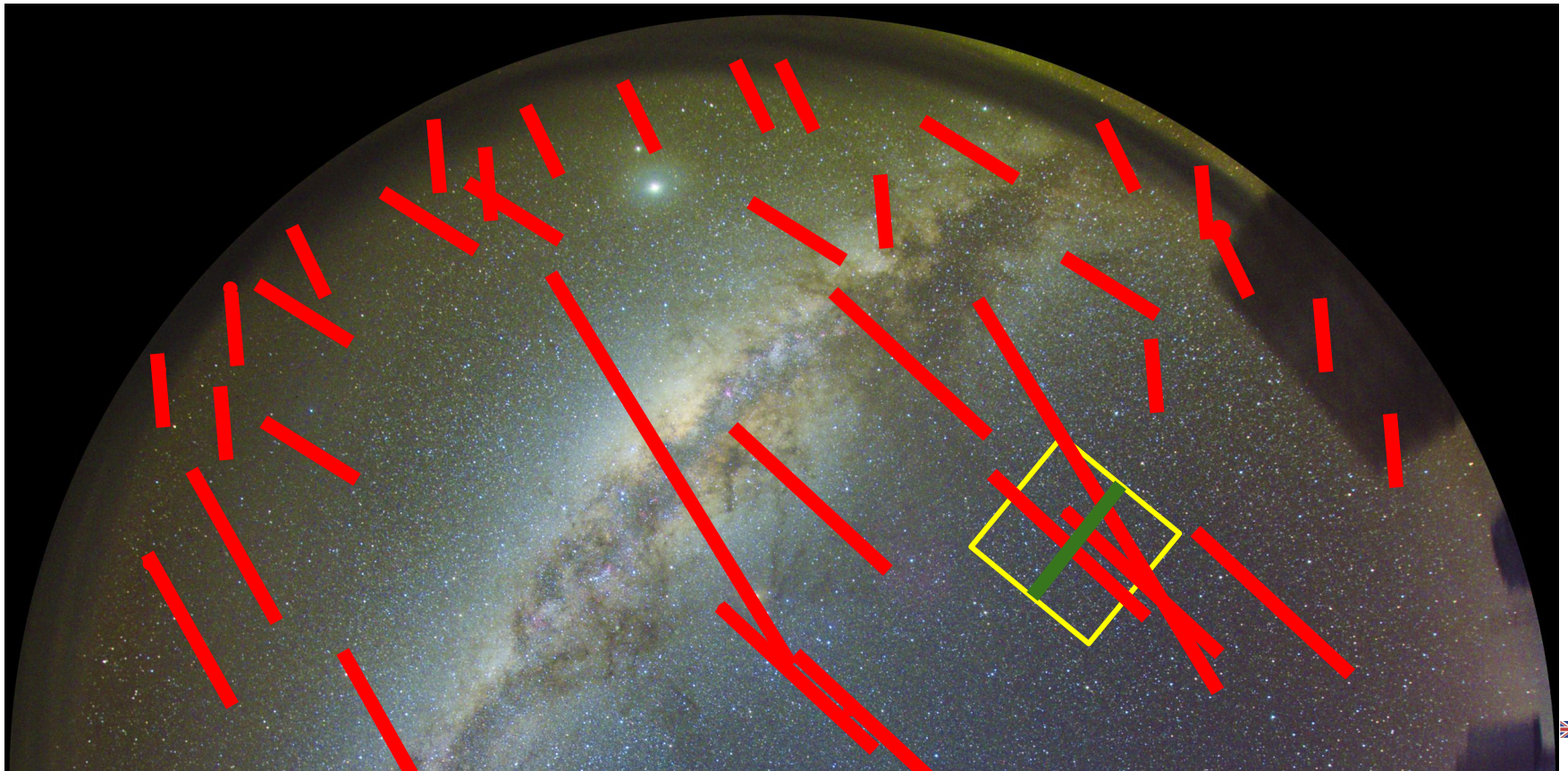
Effect on the observations

- “Instantaneous” Observation
  - Number of satellites = Density of sat. x (FoV size)^2



Effect on the observations

- “Long” Observation
  - Number of trails = Density of trails x FoV size x Exp.Time
  - With Density of trails = ∑ Density of sat. x Apparent Velocity



Effect on the observations

- General expression for Number of satellites in a field:

A = FoV solid angle [square^o]

L = FoV cross section [^{o}]

δ = instantaneous density of satellites [(square^o)$^{-1}$]

ρ = trail density [(^{o})$^{-1}$ s^{-1}]

T = integration time [s]

$$N = A\,\delta + L\,T\,\rho$$

Often: $A = L^2$ (or $A = \pi/4\, L^2$) $\rightarrow$

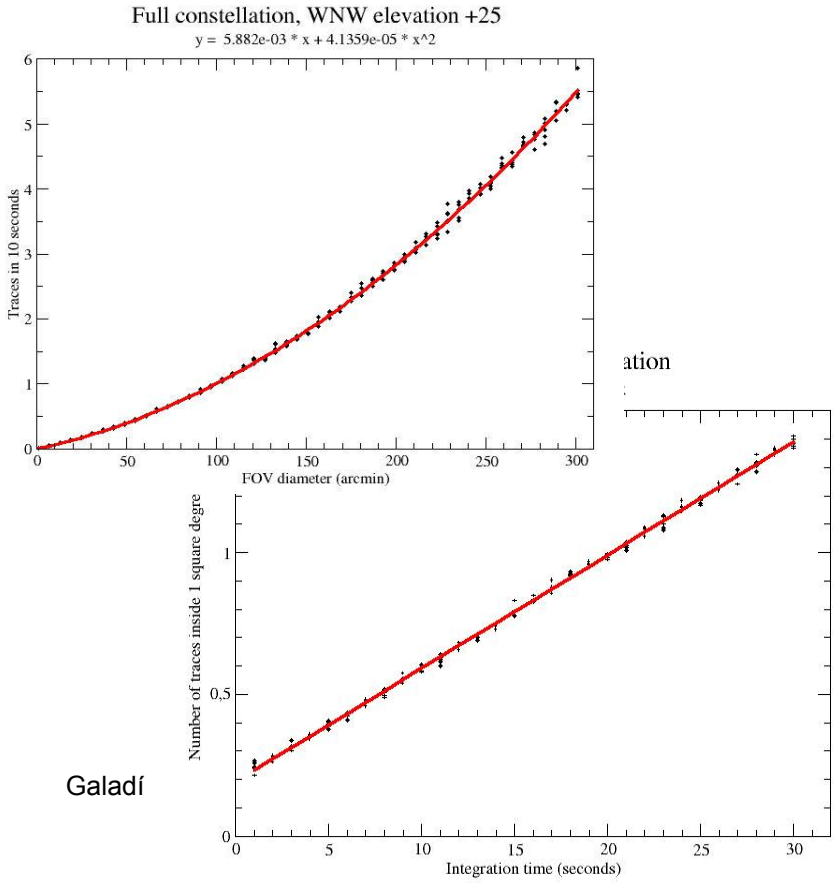
$$N = L^2\,\delta + L\,T\,\rho$$

- N is
  - a quadratic function of FoV cross-section L
  - a linear function of integration time T

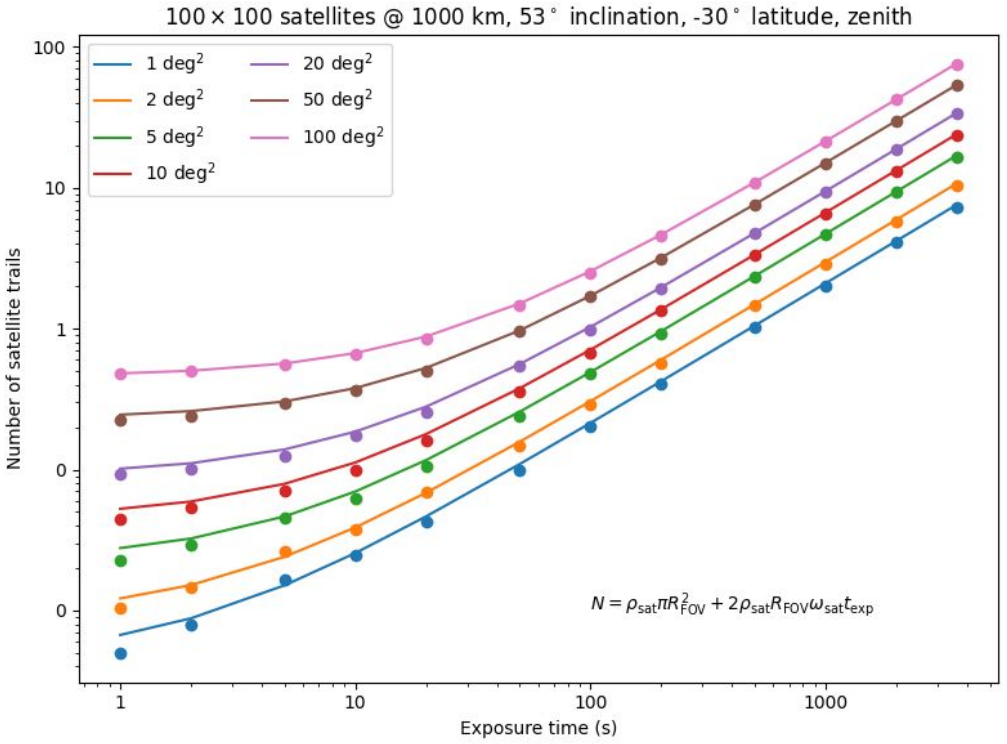
Effect on the observations

Validated ✓

- Dots: actual “measurements” on simulations
- Lines: using quadratic and linear fits



Galadí



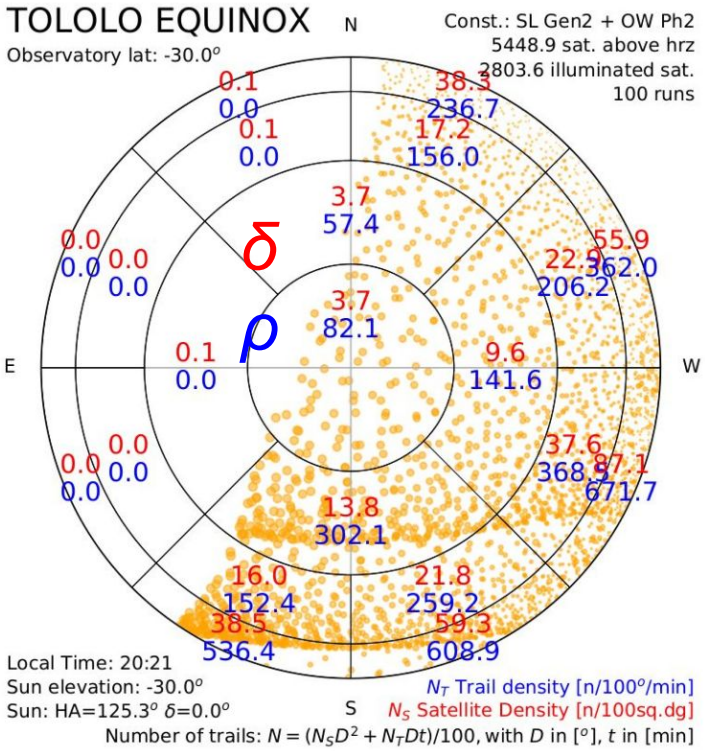
Bassa

Effect on the observations

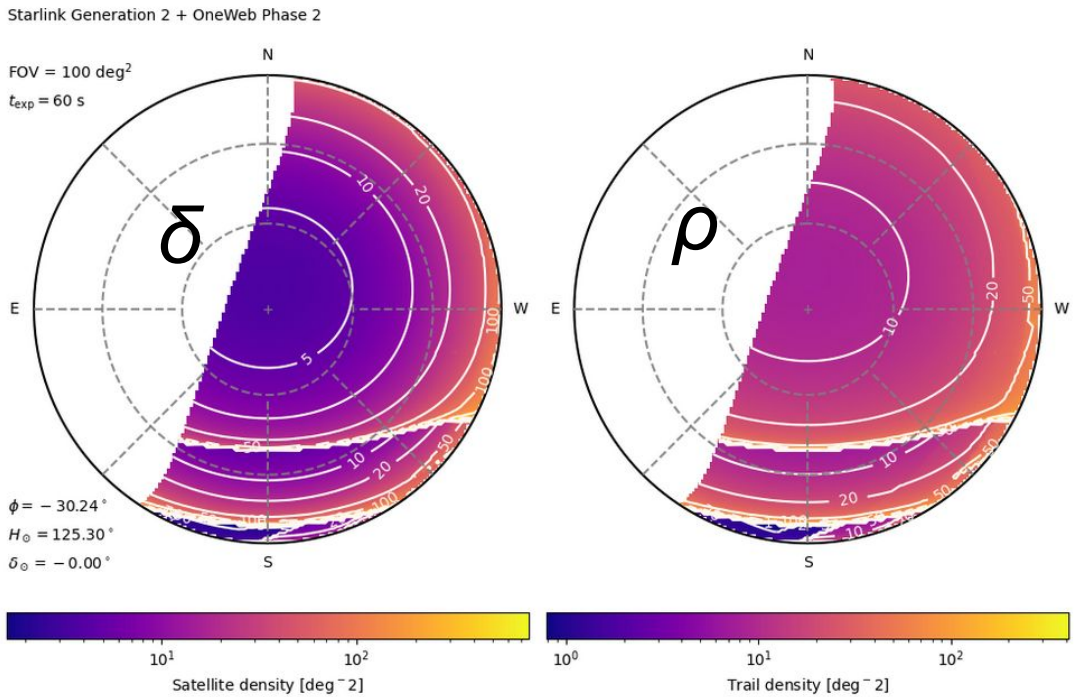
⟶ Effect maps

- for given latitude, date, time,
- for unit FoV, exp.t

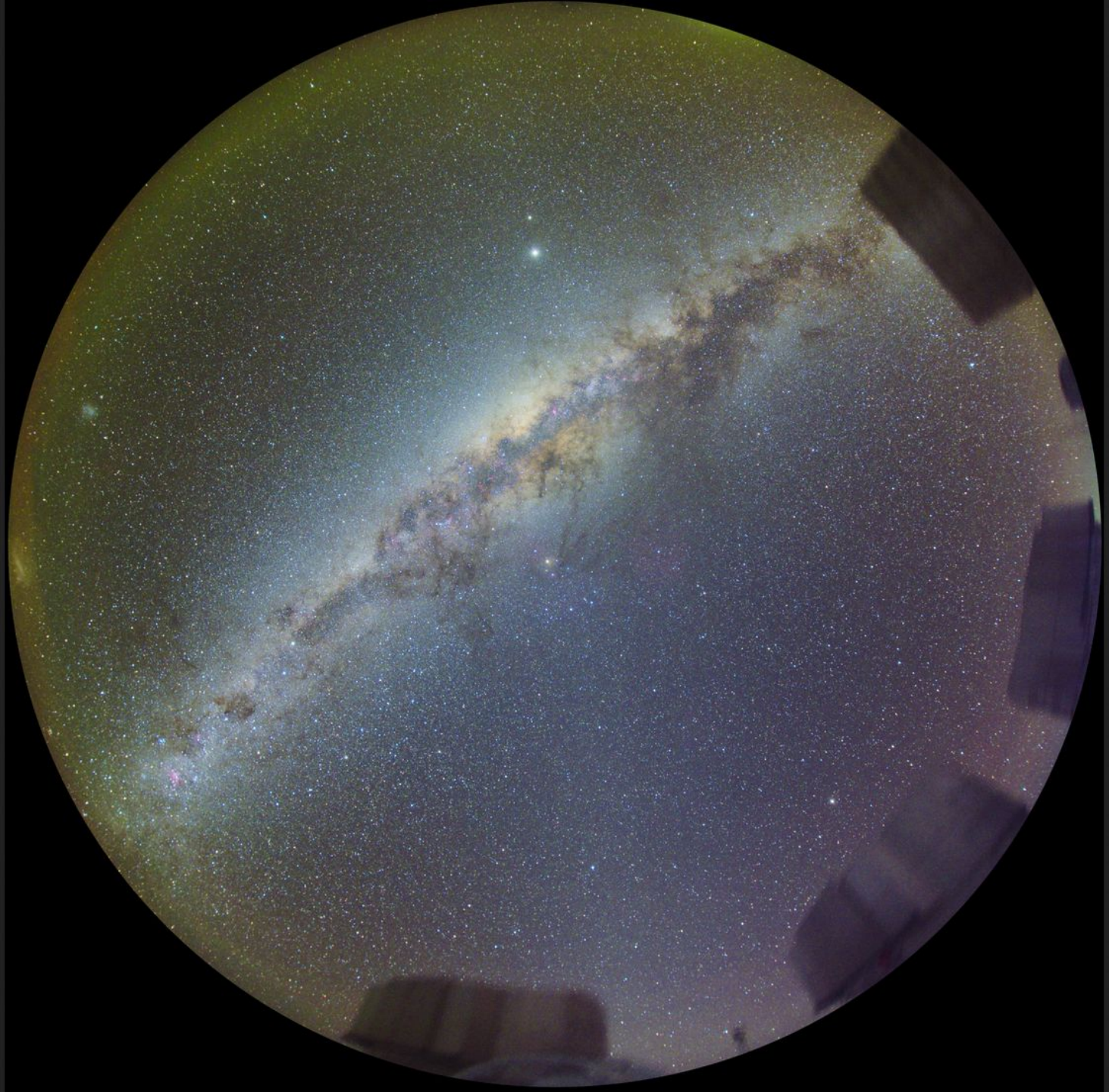
$$N = L^2 \delta + L T \rho$$



Numerically



Analytically



Effect on the observations

...for some examples...

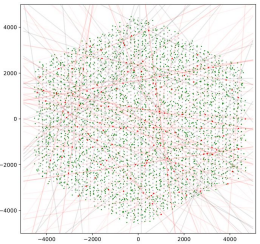
no observations ←

StarLink Ph2				h>30	Sunset	Civil	Nautical	Astron.	Night ...									
		Sun Elevation		[deg]	0	-6	-12	-18	-24	-30	-36	-42	-48	-54	-60	-66	-72	-78	-84	-88
Summer	FoV	x FoV	Exp.t	Local time	18:45	19:15	19:46	20:18	20:53	21:31	22:18	24:00	-	-	-	-	-	-	-	-
Equinox	FoV	x FoV	Exp.t	Local time	18:00	18:26	18:53	19:19	19:46	20:13	20:41	21:10	21:40	22:13	22:51	24:00	-	-	-	-
Winter	FoV	x FoV	Exp.t	Local time	17:14	17:43	18:11	18:39	19:07	19:34	20:01	20:28	20:55	21:22	21:48	22:15	22:41	23:08	23:35	24:00
Number of illiminated sat. with h>30deg				Nsat all	74.5	74.8	75.1	42.4	3.9	0.1	0	0	0	0	0	0	0	0	0	0
				Nsat bright	19.8	20	21.2	3.1	0	0	0	0	0	0	0	0	0	0	0	0
FORS/IMG	6 arcmin	6 arcmin	5 min		1.11%	1.11%	1.12%	0.63%	0.06%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%			
FORS/Sp	6 arcmin	2arcsec	30 min		2.16%	2.16%	2.19%	1.23%	0.12%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%			
UVES	10 arcsec	2 arcsec	30 min		0.06%	0.06%	0.06%	0.03%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%			
VST	1 deg	1 deg	5 min		78.10%	78.40%	78.75%	44.45%	4.10%	0.10%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%			
QMOST	2.3 deg	2.3 deg	20 min		4.27	4.29	4.31	2.43	0.22	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number of fibers				5.4	5.4	5.4	3.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	% of fibers				0.22%	0.22%	0.22%	0.13%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
LSST all	3 deg	3 deg	30 s		671.58%	674.28%	677.00%	382.22%	35.16%	0.90%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
LSST Ruined	3 deg	3 deg	30 s		178.49%	180.29%	191.12%	27.95%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Classical imager
Long-slit spectrograph
Hi-res spectrograph
Wide-field imager
Multi-fibre spectrograph
Rubin Observatory LSST mode

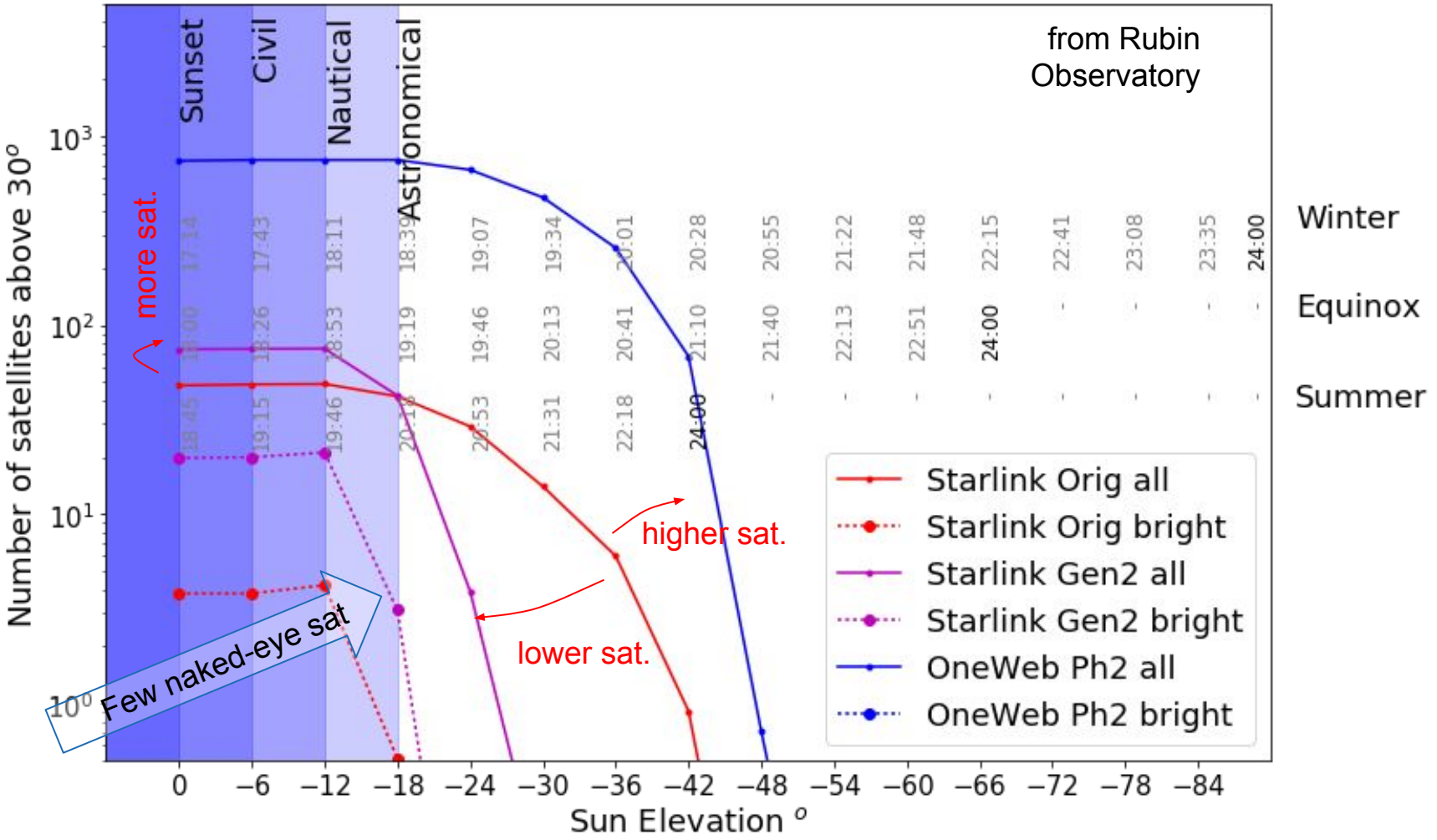
- Fraction of frames hit by a trail
  - Any magnitude, even if faint
  - > 100%: number of trails / frame
- LSST:
  - all: as above
  - ruined: effective mag brighter than 15

QMOST:
2400 fibres in 2.3°
1.3 fibre hit per trail



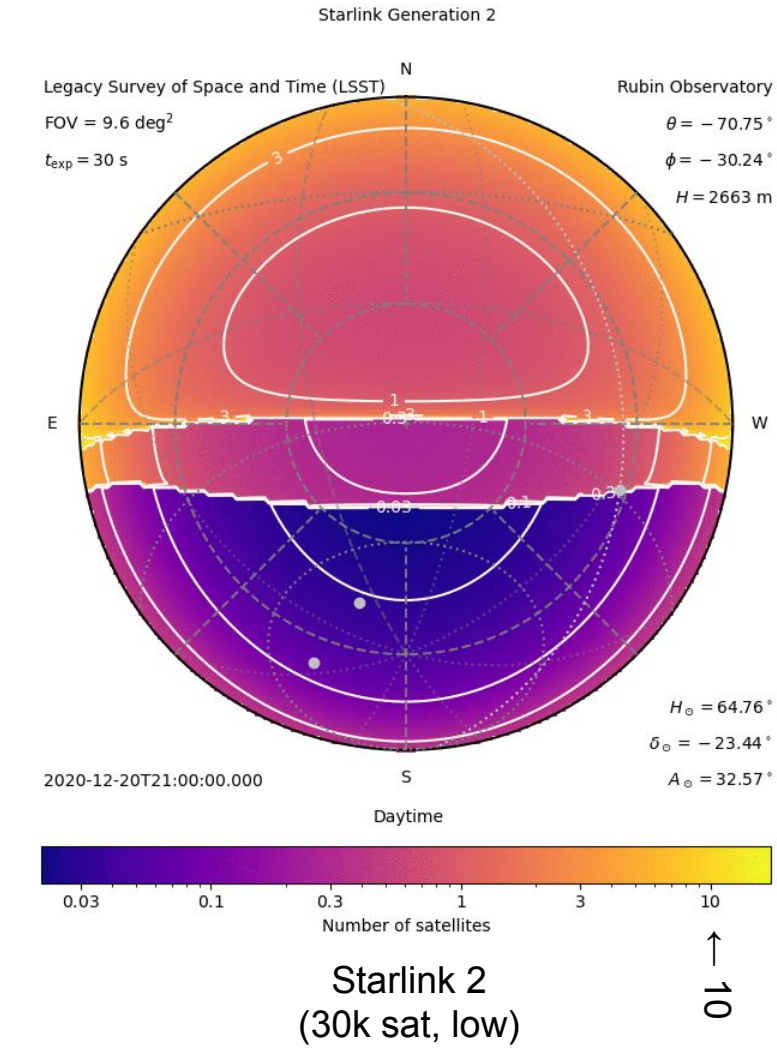
Comparison:
StarLink & OneWeb2

Comparisons



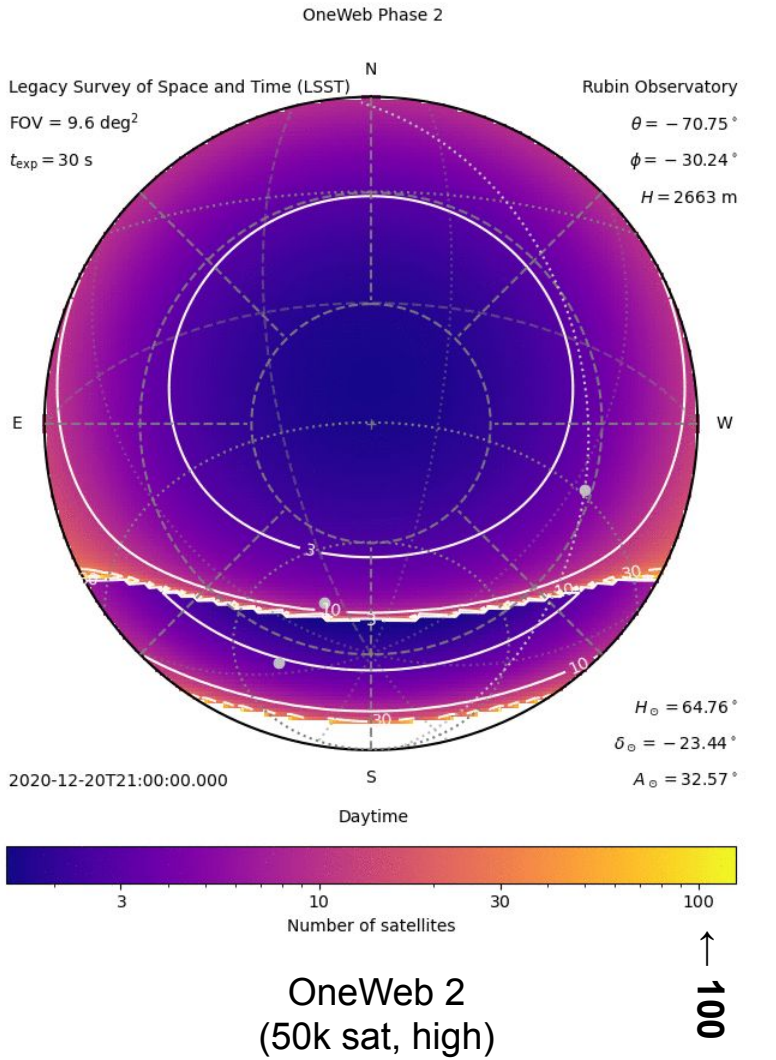
StarLink Orig: 12k sat, low and high | **SL Gen 2**: 30k sat, low | **OneWeb2**: 50k sat, high

Comparison



Starlink 2
(30k sat, low)

10



OneWeb 2
(50k sat, high)

100

LSST at Rubin Obs, ~Tololo, Summer night

StarLink Ph2

				h>30	Sunset	Civil	Nautical	Astron.	Night ...											
		Sun Elevation		[deg]	0	-6	-12	-18	-24	-30	-36	-42	-48	-54	-60	-66	-72	-78	-84	-88
Summer	FoV	x FoV	Exp.t	Local time	18:45	19:15	19:46	20:18	20:53	21:31	22:18	24:00	-	-	-	-	-	-	-	-
Equinox	FoV	x FoV	Exp.t	Local time	18:00	18:26	18:53	19:19	19:46	20:13	20:41	21:10	21:40	22:13	22:51	24:00	-	-	-	-
Winter	FoV	x FoV	Exp.t	Local time	17:14	17:43	18:11	18:39	19:07	19:34	20:01	20:28	20:55	21:22	21:48	22:15	22:41	23:08	23:35	24:00
Number of illiminated sat. with h>30deg				Nsat all	74.5	74.8	75.1	42.4	3.9	0.1	0	0	0	0	0	0	0	0	0	0
				Nsat bright	19.8	20	21.2	3.1	0	0	0	0	0	0	0	0	0	0	0	0
FORS/IMG	6 arcmin	6 arcmin	5 min		1.11%	1.11%	1.12%	0.63%	0.06%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
FORS/Sp	6 arcmin	2arcsec	30 min		2.16%	2.16%	2.19%	1.23%	0.12%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
UVES	10 arcsec	2 arcsec	30 min		0.06%	0.06%	0.06%	0.03%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
VST	1 deg	1 deg	5 min		78.10%	78.40%	78.75%	44.45%	4.10%	0.10%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
QMOST	2.3 deg	2.3 deg	20 min		4.27	4.29	4.31	2.43	0.22	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number of fibers				5.4	5.4	5.4	3.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	% of fibers				0.22%	0.22%	0.22%	0.13%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
LSST all	3 deg	3 deg	30 s		671.58%	674.28%	677.00%	382.22%	35.16%	0.90%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
LSST Ruined	3 deg	3 deg	30 s		178.49%	180.29%	191.12%	27.95%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

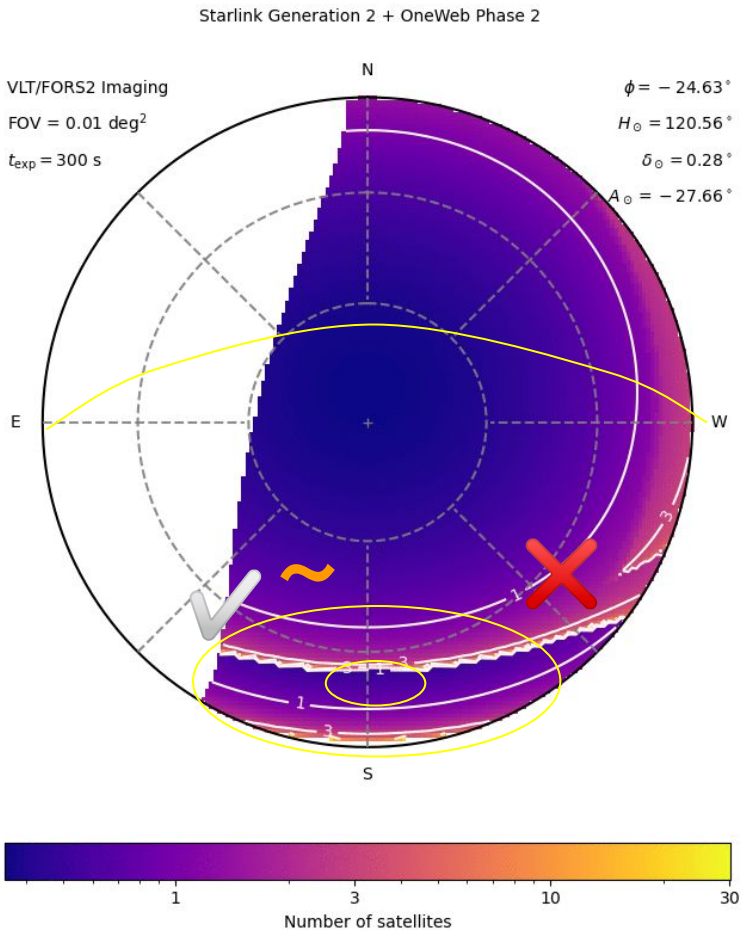
OneWeb Ph2

					Sunset	Civil	Nautical	Astron.	Night ...											
		Sun Elevation		[deg]	0	-6	-12	-18	-24	-30	-36	-42	-48	-54	-60	-66	-72	-78	-84	-88
Summer	FoV	x FoV	Exp.t	Local time	18:45	19:15	19:46	20:18	20:53	21:31	22:18	24:00								
Equinox	FoV	x FoV	Exp.t	Local time	18:00	18:26	18:53	19:19	19:46	20:13	20:41	21:10	21:40	22:13	22:51	24:00				
Winter	FoV	x FoV	Exp.t	Local time	17:14	17:43	18:11	18:39	19:07	19:34	20:01	20:28	20:55	21:22	21:48	22:15	22:41	23:08	23:35	24:00
Number of illiminated sat. with h>30deg				Nsat all	739.6	747.3	747.4	747.7	663	473.4	256.1	68.4	0.7	0	0	0	0	0	0	0
				Nsat bright	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FORS/IMG	6 arcmin	6 arcmin	5 min		11.0%	11.1%	11.1%	11.1%	9.8%	7.0%	3.80%	1.01%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
FORS/Sp	6 arcmin	2arcsec	30 min		21.6%	21.8%	21.8%	21.8%	19.3%	13.8%	7.5%	1.98%	0.03%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
UVES	10 arcsec	2 arcsec	30 min		0.60%	0.61%	0.61%	0.61%	0.54%	0.38%	0.21%	0.06%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
VST	1 deg	1 deg	5 min		775%	784%	784%	784%	695%	496%	269%	72%	0.75%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
QMOST	2.3 deg	2.3 deg	20 min		42.42	42.87	42.87	42.89	38.03	27.15	14.69	3.92	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number of fibers				53.2	53.8	53.8	53.8	47.7	34.1	18.4	4.9	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	% of fibers				2.18%	2.21%	2.21%	2.21%	1.96%	1.40%	0.76%	0.20%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
LSST all	3 deg	3 deg	30 s		6667%	6737%	6737%	6740%	5977%	4267%	2309%	617%	6.3%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
LSST Ruined	3 deg	3 deg	30 s		0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Next steps

Mitigation scheduling

- Real-time analytical trail density map
  - Point where density is lower
  - Queue-mode schedule optimization
- However
  - Not for all science cases
    - Twilight surveys?!!
  - Not for all FoV
    - Rubin Obs/LSST :(



Next Steps

- Publish...
- Better photometric model
  - Observers: get us magnitudes! see WG Observations
  - Sat. operators: please please please give us models
  - Advanced modellers: give us photometric models
- Handling of Magnitude in the effect maps
  - Saturation threshold
  - Detection threshold
- Consider effect of the flares? (although very small)
- Integrate in observations short-term scheduling
  - where possible
    - VLT: it will help
    - Rubin Observatory: slewing time dominates

FINAL WORDS

We have

- (validated) methods to simulate constellations
  - Numerical
  - Analytical (to be published soon, stay tuned)
- a very simple photometric model
- a (validated) formalism to evaluate impact on observations
  - $N = L^2 \delta + L T \rho$
  - L: FoV cross-section, T: exp.time
  - δ: Sat. density, ρ: Trail density ← from simulations
    - for latitude, date, time

Simulation outcome ...in 1 slide

- Number of sat. in sight:
  - 3 - 10% above horizon (for alt = 350-2000km)
  - 0.3 - 1% above 30° elevation
  - Fewer is better!
- Illuminated sat.:
  - at the end of twilight: 50% - 85%
  - alt > 600km: illuminated all night (summer from Tololo)
  - Fewer is better! (low!)
- Brightness (and effective brightness)
  - brighter ←→ fainter
  - fast ←→ slow
  - faint:
    - blessing for imaging surveys
    - concern for spectroscopy (Meff ~ Mag of science targets)
  - Fainter is better! (small, dark, shaded, high)
- **Effect on observations:**
  - **“Traditional” imaging and spectro: ~% frames affected at twilight**
  - **Wide-field: 10-50% frames affected at twilight**
  - **LSST/Rubin Obs:**
    - ***all* frames affected at twilight,**
    - **many during whole summer night by high-alt.**
    - ***many* frames *ruined* at twilight.**

ADDITIONAL MATERIAL

References

- Hainaut & Williams 2020: “On the impact of Satellite Constellations on Astronomical Observations with ESO Telescopes in the Visible and Infrared Domains”, *A&A* 636, A121 (https://doi.org/10.1051/0004-6361/202037501, available here and on ArXiv)
  See also corresponding ESO press release at https://www.eso.org/public/news/eso2004/
- Hainaut 2020: "Simulation of Starlink Satellites" http://www.eso.org/~ohainaut/satellites/
- Soon: the paper from this presentation
  - Cees’ code: https://github.com/cbassa/satconsim