Dark and Quiet Skies for Science and Society

UNITED NATIONS
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IAU International Astronomical Union

INSTITUTO DE ASTROFISICA DE CANARIAS · IAC

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What is the IAU?

- Worldwide union of all professional astronomers

Promote and safeguard astronomy in all its aspects (including research, communication, education, and development) through international cooperation

- Founded in 1919
- 14000+ members with 107 nationalities; 82 member countries
  - Organized in Divisions, Commissions, WGs
  - Increasing diversity, including junior members

New IAU Strategic Plan 2020-2030

IAU — 100 Years: Under One Sky

Posted at
www.iau.org

IAU Offices

- OAE — Education
- OYA / ISYA — Training advancement
- IAU — Knowledge advancement
- OAO — Communication
- IAU OAD (International Astronomical Union | Office of Astronomy for Development) — Development

Links with ISC, COSPAR, URSI, SPIE, CIE,….

Major strength: worldwide networks in >100 countries

Dark & Quiet Skies within the IAU

- WG Dark & Quiet Skies, under Executive Committee
- Commission B7 Protection of Existing and Potential Observatory Sites
- Focus meetings at GAs (including GA2021); SATCON1/2
- Resolution B5 at IAU GA 2009

IAU 2009 RESOLUTION B5

in Defence of the night sky and the right to starlight

resolves that

1. An unpolluted night sky that allows the enjoyment and contemplation of the firmament should be considered a fundamental socio-cultural and environmental right, and that the progressive degradation of the night sky should be regarded as a fundamental loss.

2. Control of obtrusive and sky glow-enhancing lighting should be a basic element of nature conservation policies since it has adverse impacts on humans and wildlife, habitats, ecosystems, and landscapes.

3. Responsible tourism, in its many forms, should be encouraged to take on board the night sky as a resource to protect and value in all destinations.

4. IAU members be encouraged to take all necessary measures to involve the parties related to skyscape protection in raising public awareness – be it at local, regional, national, or international level – about the contents and objectives of the International Conference in Defence of the Quality of the Night Sky and the Right to Observe Stars [http://www.starlight2007.net/], in particular the educational, scientific, cultural, health and recreational importance of preserving access to an unpolluted night sky for all humankind.

Outreach and Education: IYA 2009, IAU100: Dark Skies for All

Dark Skies ambassadors; Distribution Quality Lighting and Dark Skies kits in >50 countries

The Dark and Quiet Skies Presentations Today…

- **Satellite constellations**: not being impacted by light pollution but are doing the impacting
- **Conundrum:** satellite constellations
  - \+ Expand broadband internet service to more remote areas of the world
  - \- Impact strongly astronomical science and discoveries
- **Need mitigation** efforts by astronomers together with industry

- Satellite Constellation Working Group (Satcon WG) worked in four groups: the Observations, Simulations, Mitigations and Recommendations groups

Dark and Quiet Skies for Science and Society

Notes & Introductions

SOC Member/Moderator

Olivier Hainaut

ESO and

SOC Member/Moderator

Sara Lucatello

INAF OAPd/EAS

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Dark and Quiet Skies for Science and Society: Draft Reports

Five Draft Reports are available and open for comments until 16 October

- Download them from http://bit.ly/DQS_reports
- Please comment recommendations at http://bit.ly/DQS_comment

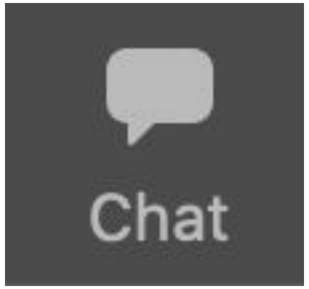
If you registered for today's Workshop then you have received the links on Thursday in an email from UNOOSA-Events@un.org and on Friday in an email from DQSkies@iac.es

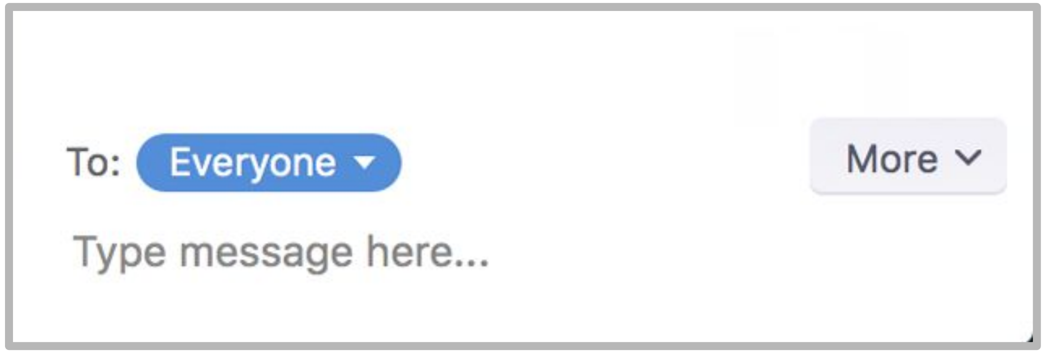
Not received even though you had registered? Please email UNOOSA-Events@un.org

Zoom Meeting Housekeeping

Have a question?

- Use the chat at any time
- Write “QUESTION” so we see it
- Keep it short!





Participants will **not** be unmuted

Q&A monitors will read a subset of questions

Satellite Constellation WG Team

Observations:
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Steve Heathcote, CTIO
Harrison Krantz, U.AZ
Eric Pearce, U.AZ
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Patricia Cooper, SpaceX
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Joel Parriott, AAS
Giuliana Rotola, ESO
Jonathan Williams, NSF
Connie Walker, NOIRLab

(speakers in magenta)

Moderators: Sara Lucatello / Olivier Hainaut

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Observations WG: Results from the Universidad de Antofagasta LEO Satellite Observations Team

Observations of Starlink LEO satellites, including Darksat and Visorsat have been conducted primarily with four telescopes:

- **The Chakana 0.6m telescope at the Ckoirama Observatory, Chile**
  Owned and operated by the Centro de Astronomía, (CITEVA) of the Universidad de Antofagasta.
  Special thanks to E. Unda-Sanzana, J. P. Colque, J. Anais, V. Molina, R. González, and E. Ortiz.

- **The ESO 4.1m VISTA telescope at ESO Paranal Observatory, Chile**
  Special thanks to B. Haeussler, F. Gaete, S. Mieske, S. Brillant, and J. Anderson (European Southern Observatory), C. González-Fernández (Institute of Astronomy, University of Cambridge).

- **The Zeiss 1.23m telescope at the Calar Alto Observatory, Spain**
  Special thanks to L. Mancini (Department of Physics, University of Rome 2, Italy), T. Henning, M. Schlecker, L. Flores, and J. Syed (Max Planck Institute for Astronomy, Heidelberg, Germany).

- **A 0.4m telescope at the LCO Haleakala Observatory, Maui, Hawaii, U.S.A.**
  Special thanks to L. Storrie-Lombardi, R. Street, N. Volgenau. Obtained under proposal: DDT2020B-003.

Observations WG: Results from the Universidad de Antofagasta LEO Satellite Observations Team

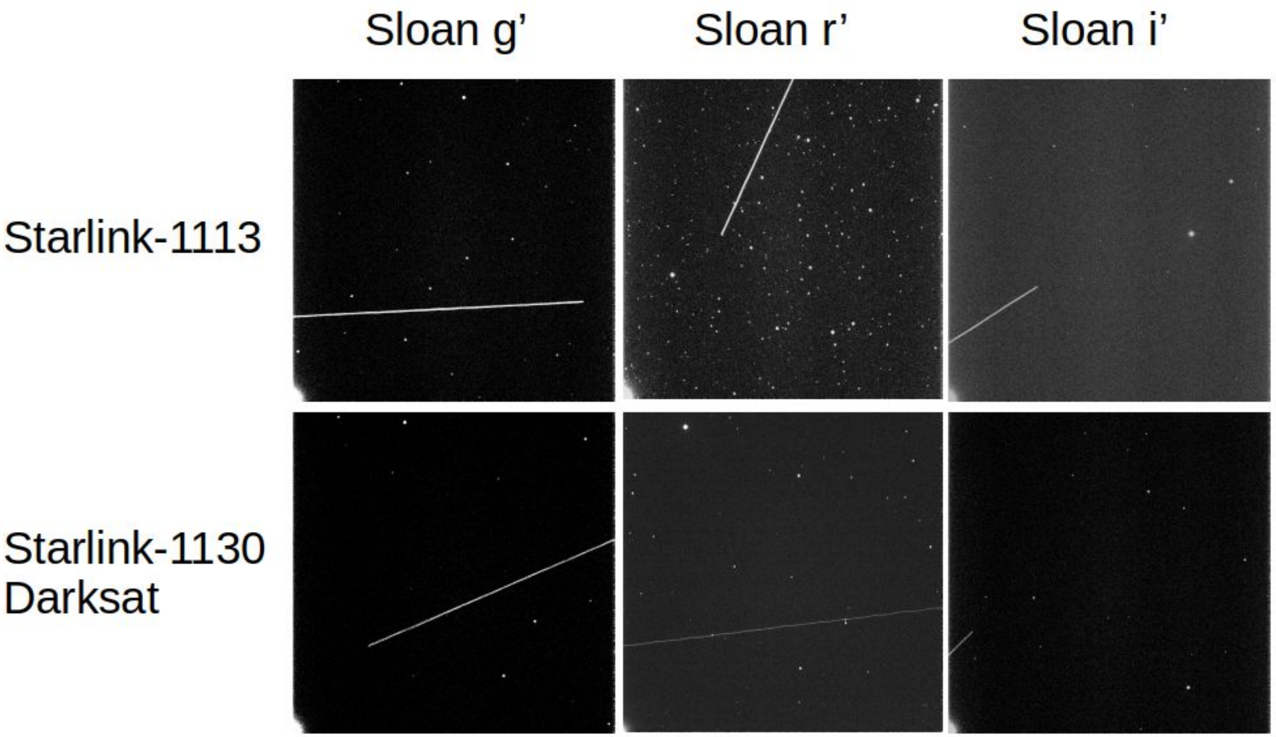
The Chakana 0.6m telescope Observations

Observations of Starlink-1130 (Darksat) and 1113 conducted in early March 2020.

The detector has a 32.4 x 32.4 arcmin FoV

Three passbands were used on three separate nights:

- Sloan g' (475.4 nm)
- Sloan r' (620.4 nm)
- Sloan i' (769.8 nm)



(Tregloan-Reed et al. 2020a, 2020b A&A, under review).

Observations WG: Results from the Universidad de Antofagasta LEO Satellite Observations Team

The ESO 4.1m VISTA telescope Observations

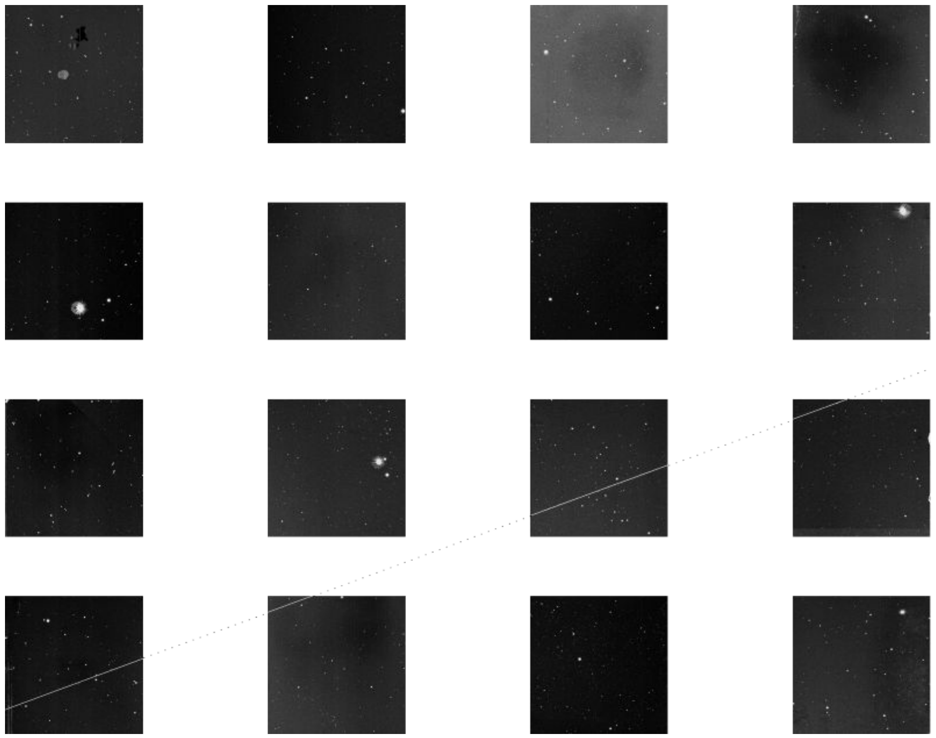
Observations of Starlink-1130 (Darksat) and 1113 conducted in early March 2020.

The Visible and Infrared Survey Telescope for Astronomy (VISTA) telescope used the VISTA InfraRed CAMera (VIRCAM) to obtain observations in the NIR.

Each of the 16 detectors has a 11.6 x 11.6 arcmin FoV

Two NIR passbands were used on two separate nights:

- NIR J-band (1250 nm)
- NIR Ks-band (2150 nm)



NIR image of DarkSat taken using a J filter with VIRCam on the 4.1m VISTA telescope, ESO Cerro Paranal Observatory, Chile (Tregloan-Reed et al. 2020b A&A, under review).

DARK & QUIET SKIES

Jeremy Tregloan-Reed

Observations WG: Results from the Universidad de Antofagasta LEO Satellite Observations Team

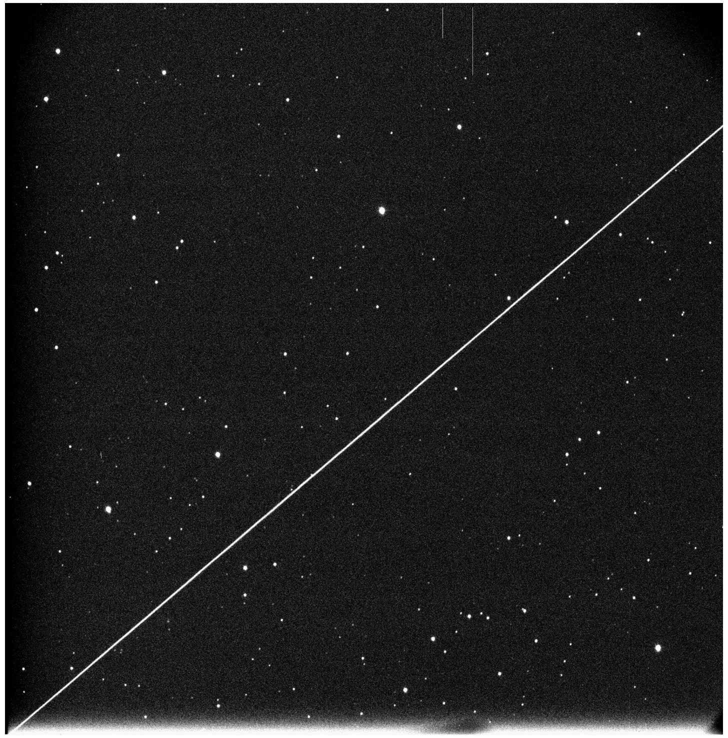
The Zeiss 1.23m telescope Visorsat Observations

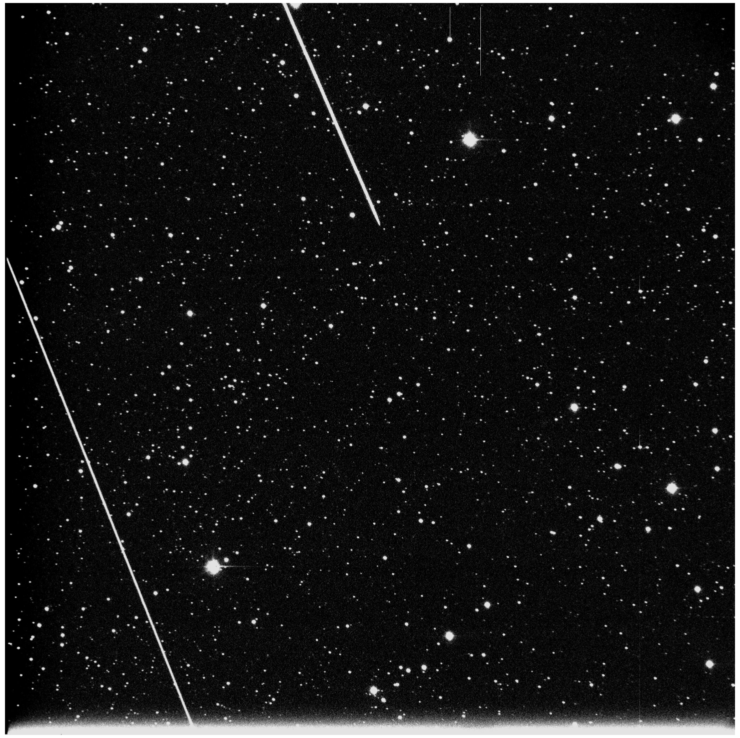
Observations of Starlink-1405 (left) and Starlink-1436, Visorsat (right) conducted in late September 2020.

The detector has a 21.4 x 21.4 arcmin FoV and the observations were conducted using a Johnson V filter (540nm).

The image of Visorsat (right) also shows a serendipitous detection of Starlink-1348 (upper-middle) that at the time of the observation was at 386 km orbital height.

Observations of Visorsat are currently ongoing this week, including observations in the Johnson R (658nm) and I (806nm) passband.



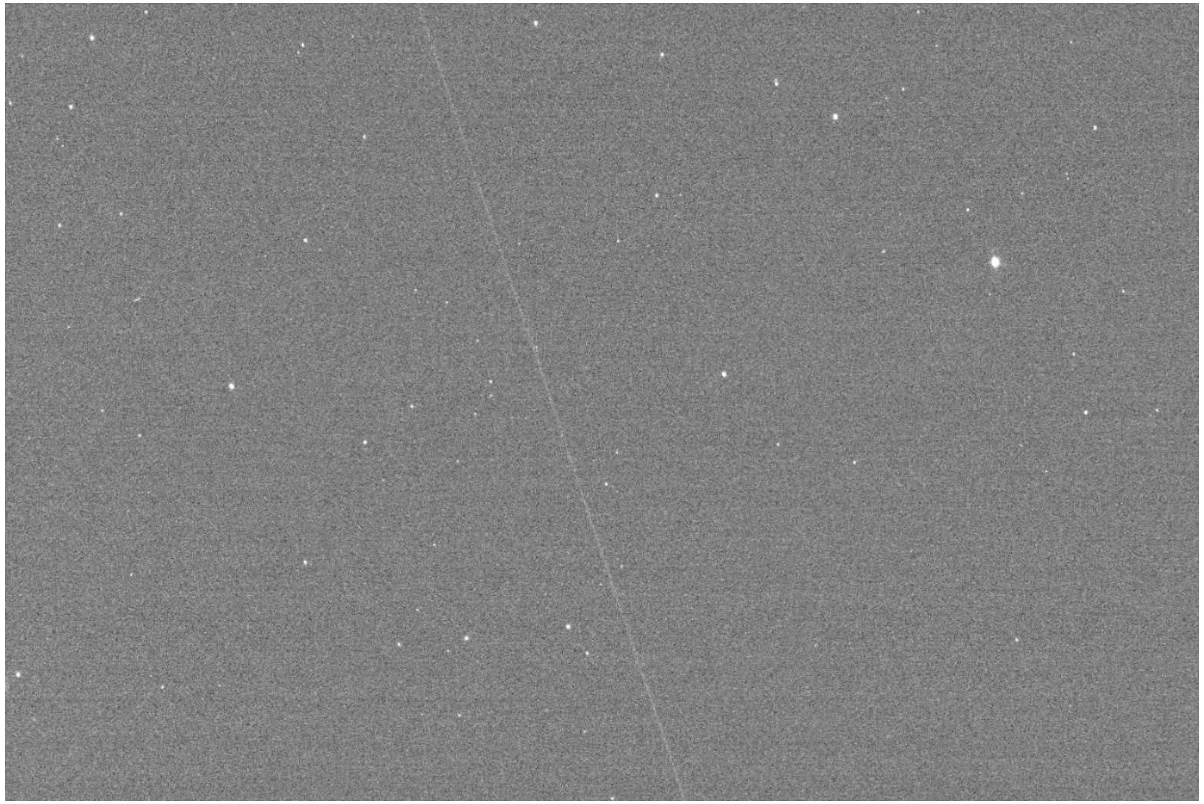


Observations WG: Results from the Universidad de Antofagasta LEO Satellite Observations Team

The LCO Haleakala Observatory Observation

Observation of Starlink-1436 (Visorsat) conducted in late September 2020.

The detector has a 29.5 x 19.7 arcmin FoV and the observations were conducted using a Sloan g’ filter.



Observations WG: Results from the Universidad de Antofagasta LEO Satellite Observations Team

Calibrating observed magnitudes to allow direct comparisons

- The observed reflective brightness of a LEOsat is dependent on the satellite range to the observer (r), the solar incidence angle (θ) and observer angle (Φ) of the satellite, due to the diffused reflected flux.
- Therefore, to allow a direct comparison of the reflective brightness between LEOsats requires a correction for θ and Φ, whilst normalised to a standard range.
- When observed at local zenith (airmass = 1), r is equal to the orbital height (for Starlink LEOsats this is approx 550 km).
- To normalise the magnitude of the Starlink LEOsats to the nominal 550 km requires scaling the magnitudes by:

$$-5\log(r/550)$$

Observations WG: Results from the Universidad de Antofagasta LEO Satellite Observations Team

Calibrating observed magnitudes to allow direct comparisons

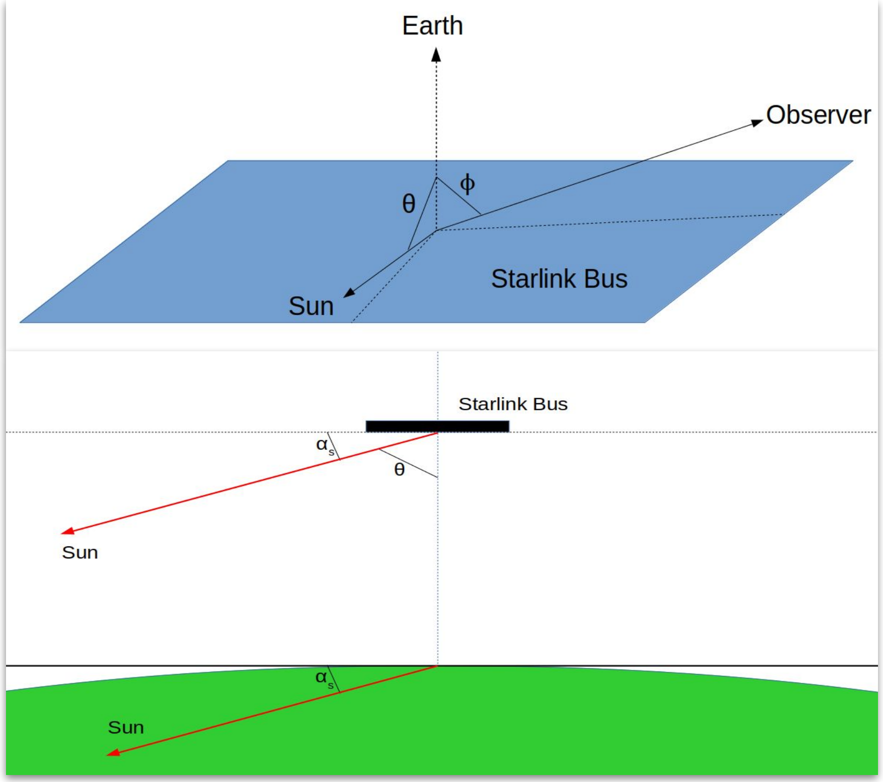
The observer phase angle is the angle between the observer and the unit normal of the Earth facing surface of the satellite.

Tregloan-Reed et al. (2020) gave an equation to approximate observer angle using the straight line distance between the observer and the satellite footprint, nadir (η), LEOsat elevation (ε) and H_{orb}

$$\phi = \arcsin\left(\frac{\eta}{H_{\text{orb}}}\sin\epsilon\right)$$

The solar incidence angle can be calculated by evaluating the solar elevation angle at the satellite nadir.

Therefore, the sum of the solar incidence angle and the solar elevation (when evaluated at the satellite nadir) is equal to 90°.



Jeremy Tregloan-Reed

Observations WG: Results from the Universidad de Antofagasta LEO Satellite Observations Team

Calibrating observed magnitudes to allow direct comparisons

To calibrate the LEOsat magnitudes to local zenith, a parameterised Bidirectional Reflectance Distribution Function (BRDF) model from Minnaert (1941), was used.

Key takeaway results

1. Visorsat while dimmer than its sibling Starlink satellites has an equivalent reflective brightness to Darksat.
2. Darksat is dimmer than Starlink-1113 for all observed wavelengths.
3. Darksat and Starlink-1113 both get brighter towards longer (redder) wavelengths.
4. The effectiveness of the Darksat darkening treatment reduces with increasing wavelength.

Observed and calibrated magnitudes of Starlink LEOsats observed by the Universidad de Antofagasta LEO satellites Observations Team.

Starlink	Facility	Filter	Observed Mag.	Calibrated Mag.
1130 (Darksat)	Chakana 0.6 m	g’	7.46 ± 0.04	6.52 ± 0.04
1130 (Darksat)	Chakana 0.6 m	r’	6.50 ± 0.02	5.64 ± 0.07
1130 (Darksat)	Chakana 0.6 m	i’	6.33 ± 0.03	5.40 ± 0.03
1130 (Darksat)	VISTA 4.1 m	J	5.65 ± 0.01	4.50 ± 0.01
1130 (Darksat)	VISTA 4.1 m	Ks	5.63 ± 0.02	4.50 ± 0.02
1113	Chakana 0.6 m	g’	6.59 ± 0.05	5.75 ± 0.05
1113	Chakana 0.6 m	r’	5.46 ± 0.05	4.90 ± 0.05
1113	Chakana 0.6 m	i’	5.43 ± 0.04	4.82 ± 0.04
1113	VISTA 4.1 m	J	5.10 ± 0.01	4.12 ± 0.01
1113	VISTA 4.1 m	Ks	4.65 ± 0.02	4.15 ± 0.02
1436 (Visorsat)	LCO 0.4 m	g’	7.39 ± 0.18	6.41 ± 0.21
1436 (Visorsat)	CAHA 1.23 m	V	7.20 ± 0.08	6.34 ± 0.08
1405	CAHA 1.23 m	V	6.50 ± 0.09	5.56 ± 0.10
1348	CAHA 1.23 m	V	5.15 ± 0.10	4.29 ± 0.10^{a}

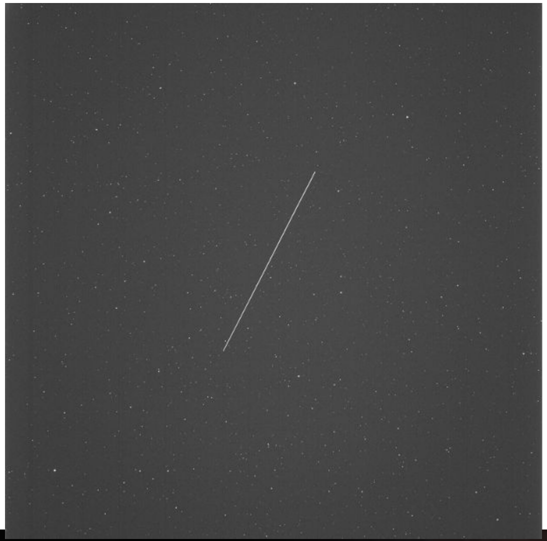
Notes. [a] This value is normalised to a range of 550 km. When normalised to the orbital height at the time of the observation (386 km) the calibrated magnitude becomes $V = 3.23 \pm 0.10$.

DARK & QUIET SKIES

Jeremy Tregloan-Reed

Observations WG: Results from the Pomenis Telescope, University of Arizona Steward Observatory, LEO satellites Observations Team

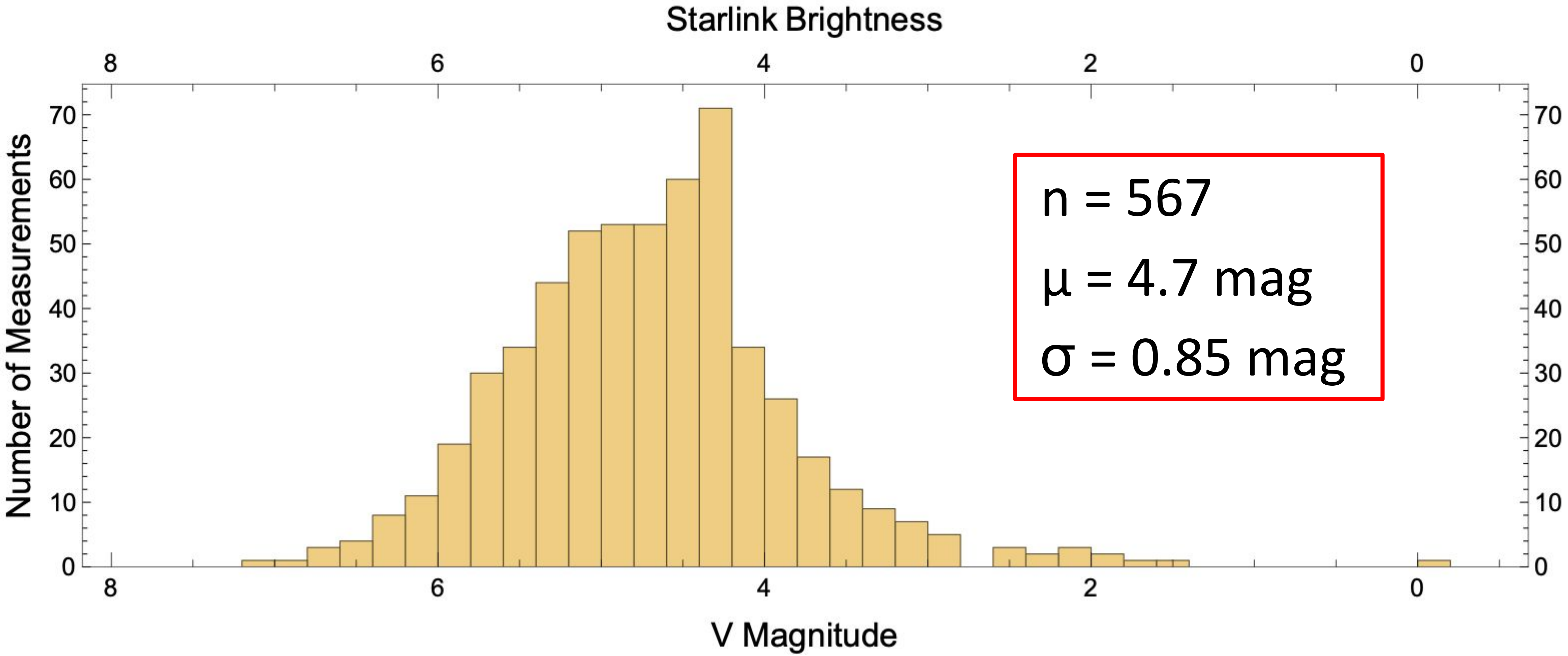
- Telescope system designed for observing satellites
- Small aperture, large field of view
    - 180 mm f/2.8, 4.2° x 4.2°
- Fully robotic and automated
- Automated image processing pipeline



DARK & QUIET SKIES

Harrison R. Krantz

Observations WG: Results from the Pomenis Telescope, University of Arizona Steward Observatory, LEO satellites Observations Team

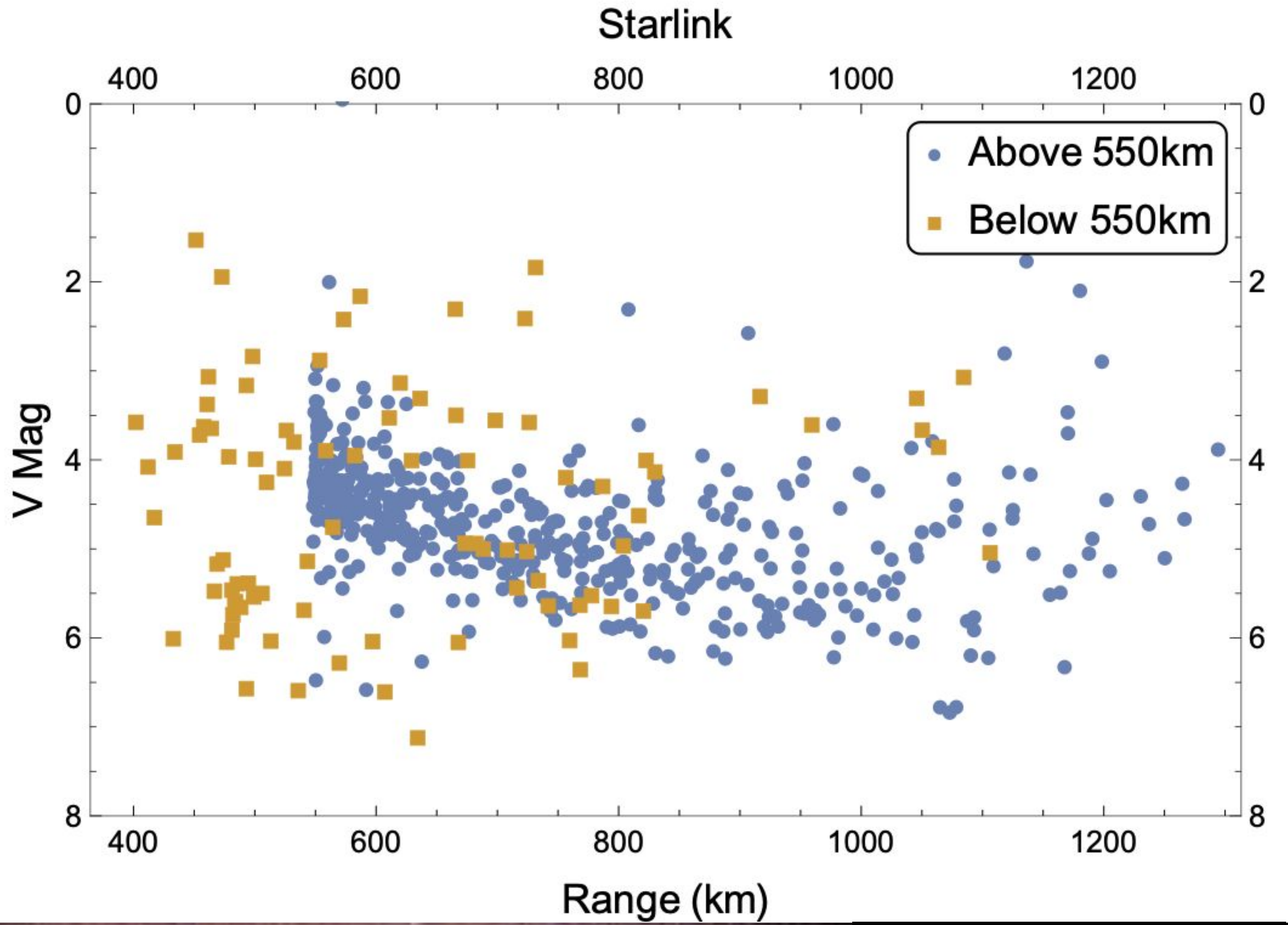


Harrison R. Krantz

DARK & QUIET SKIES

Observations WG: Results from the Pomenis Telescope, University of Arizona Steward Observatory, LEO satellites Observations Team

- Need to use data to test and validate brightness models
- Models need to account for
  - Orbit
  - Sun-observer geometry
  - Satellite attitude
  - Satellite design



Harrison R. Krantz

Observations WG: Results from the Pomenis Telescope, University of Arizona Steward Observatory, LEO satellites Observations Team

- Limited observations so far
- Dimmer than standard Starlink satellites
- Need more observations
- Need a brightness model for satellite attitude and visor position

Pomenis VisorSat Observations

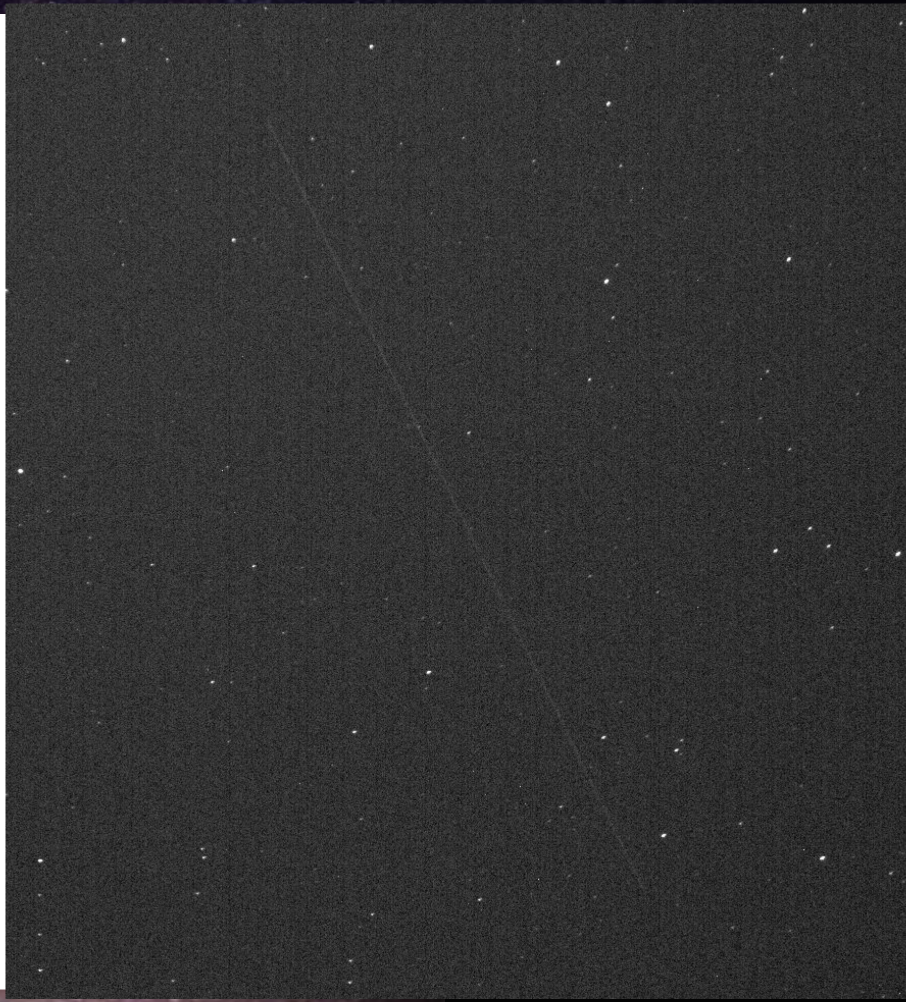
Date	V Magnitude	Range (km)
2020-08-27 02:42:25	6.8±0.81	1005
2020-09-15 11:29:57	7.7±1.21	1057
2020-09-16 11:24:26	7.2±0.77	813
2020-09-17 11:18:54	6.4±0.61	629
2020-09-17 11:20:28	6.1±0.23	923

Harrison R. Krantz

Observations WG: Results from the Pomenis Telescope, University of Arizona Steward Observatory, LEO satellites Observations Team

OneWeb Satellites

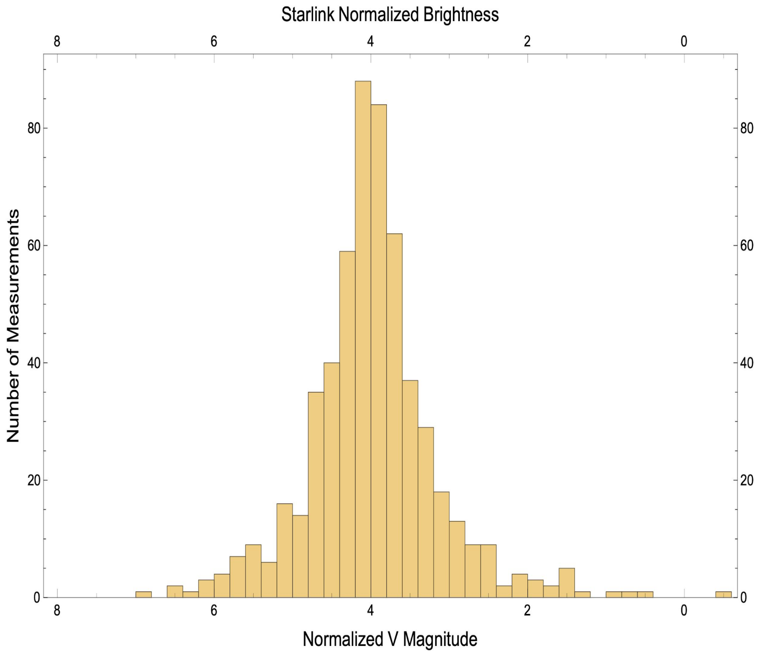
- 100+ observations so far
- Majority are dimmer than 6-7th magnitude
  - Not detected by current algorithm
  - Some outliers as bright as 3rd V magnitude
- Reliably dimmer than Starlink



Harrison R. Krantz

Observations WG: Lessons Learned & Recommendations

- Darksat & Visorsat Mitigation Strategies:
  - In SDSS g’ filter, Darksat and Visorsat observed magnitudes are comparable **(6.3 to 6.5 mag**). After al corrections have been applied.
  - While, both mitigation strategies are a step in the right direction, and they do show a reduction in brightness when compared to standard Starlink satellites, they don’t yet meet Recommendation #5 of the SATCON1 Workshop, stating a magnitude at or fainter than 7 (when satellites are at the zenith, and at 550 km orbital height).
  - Observation of a total of 567 Starlink satellites, **show a distribution of brightness whose peak is centered at about 4.0 mag** when observed using Johnson V filter.
    - **The magnitude distribution goes from -0.4 to ~ 6.2**). This is what a casual observer, or an astronomer, will experience when observing a given field in the sky. In particular, when observing at relatively large zenith angles around the twilights.
    - **This distribution may change, towards fainter satellites, provided that the satellites operator implement effective measures to mitigate the brightness in all of their satellites. (**satellites may could become less visible for naked-eye observers)



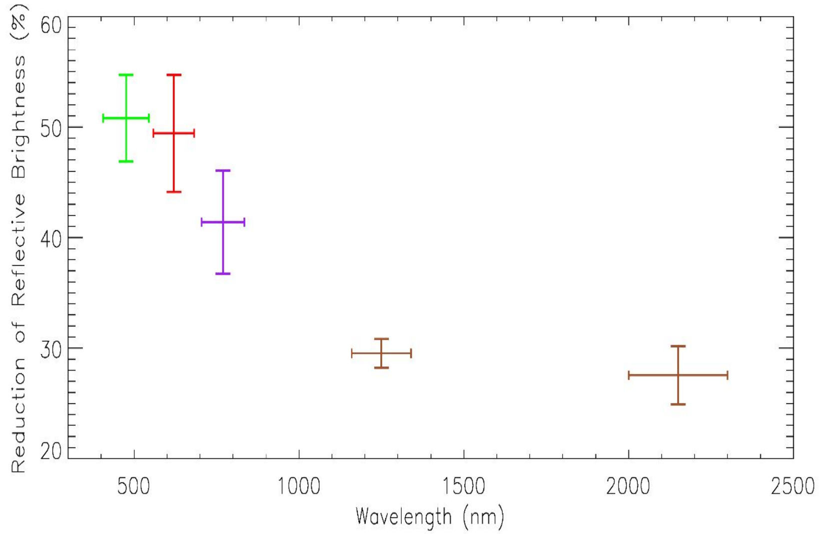
567 Observations: POMENIS Telescope

DARK & QUIET SKIES

Angel Otarola

Observations WG: Lessons Learned & Recommendations

- Darksat Mitigation Strategies:
  - Results from multi-wavelength observations conducted with the help of the Ckoirama Telescope (Universidad de Antofagasta) and the VISTA Telescope (European Southern Observatory) show:
    - **The satellites get brighter at longer wavelengths (from visible into the near infrared).**
    - **The efficiency of the darkening treatment decreased towards the longer wavelengths (from visible into the near infrared).**
    - **Observations of Visorsat at various astronomical spectral bands is yet to be done.** Observations are planned once suitable facilities for simultaneous multi-band observations reopen (***for instance the GROND instrument on the MPG/ESO 2.2m telescope has been identified as a suitable setup for this kind of observations***).



Tregloan-Reed at al., 2020b, A&A under review.

Observations WG: Lessons Learned & Recommendations

- OneWeb Satellites:
  - Several attempts for observing the OneWeb satellites were tried by the POMENIS Telescope team (University of Arizona, Steward Observatory).
    - In most of cases the photometry was limited by the limiting-magnitude in the automatic image processing pipeline used by POMENIS.
    - This implies the brightness magnitude of those satellites were fainter than 6 to 7 mag (in Johnson V filter).
  - Eight OneWeb satellites were detected by the automated software with **magnitudes within the range of 3.3 to 6.5 (Johnson V filter)**, for **satellites observed at a range of 588 to 819 km**.
    - We yet need to secure a set of observations of OneWeb satellites when already at their intended orbital

Observations WG: Lessons Learned & Recommendations

- Recommendation #1: Keep the coordinated effort to observe satellite constellations with the purpose of satellite characterization and better understanding of the impact of the satellite constellations on science. Specially, of Oneweb satellites, and satellites from other operators to be deployed.

- Recommendation #2: We emphasize to the broader community of observers, than when conducting observations of LEOsats, to make every effort to document their observations and calibrate their observations following best practices. This will help our community to accomplish a much better assessment by observing satellites at various times respect to the twilight, and a wider range of zenith angles.

Angel Otarola

Observations WG: Lessons Learned & Recommendations

- Recommendation #3: We adhere to the Recommendation #2 in the SATCON1 Workshop Observations WG report stating that: A comprehensive satellite constellation observing network be formed and sustained, to connect observers with telescopes, provide coordinated observing protocols and data analysis standards. Coordinate ongoing observations of satellite constellations and prepare for the next generation of LEOsats. The design and capabilities of this network should be forward-looking and be prepared for future satellite constellations.

- Recommendation #4: When conducting observations of the LEOsats, our advice is to **perform observations at multiple spectral bands of interest for astronomy from the optical/visible into the infrared**. Conducting observations of the same object at various spectral bands simultaneously **will provide important information to understand the efficiency of technical mitigations strategies (build into the design of the satellites)** across a wider wavelength range.

Angel Otarola

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Richard Green, U.Arizona
Jeffrey Hall, Lowell Obs.
Chris Hofer, Amazon
Kelsie Krafton, AAS
James Lowenthal, Smith Coll.
Robert Massey, RAS, UK
Tim Maclay, Celestial Insight
Charles Mudd Jr, Mudd Law
Joel Parriott, AAS
Giuliana Rotola, ESO
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(speakers in magenta)

DARK & QUIET SKIES

Moderators: Sara Lucatello / Olivier Hainaut

Satellite Constellations Working Group

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With the
support of

Satellite Constellations Working Group

Simulations Group. Team members:

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- **Galadí-Enríquez, D.** (IAU Commission B7; Spanish Astronomical Society SEA)
- Hainaut, O. R. (ESO)
- Kucharski, D. (The University of Texas at Austin)
- McDowell, J. (Center for Astrophysics, Harvard & Smithsonian)
- Seitzer, P. (University of Michigan)
- Siminski, J. (ESA Space Debris Office)
- Walker, C. (NOIRLab; IAU Commission B7 & EC WG on D&QS)

Satellite Constellations Working Group

We will discuss:

1. Objectives
2. Simulations and results:
    - All-sky, bulk satellite counts (what's up, in general)
    - Pointing-oriented simulations (what to expect when you are observing)
    - Spatially resolved simulations (fine structure of on-sky satellite distribution)
3. Flares and glares (reflecting on satellites)
4. Transient orbital phases (ascension and decay)

Satellite Constellations Working Group

1. Simulations Group. Objectives:

- Assessing the impact of satellite large constellations on optical ground-based observations
- Producing realistic estimates of satellite visibility:
  - From orbital dynamics, optics and geometry, to →
  - → Apparent positions, direction of motion, angular velocity, apparent brightness
- Building on the experience of NSF's NOIRLab's SATCON1 Workshop

Satellite Constellations Working Group

2. Simulations and results: the constellation

We use the reference "**SLOW**" constellation: StarLink (**SL**) + OneWeb (**OW**)

StarLink generation 2:

30 000 satellites, altitudes 328 to 614 km, 8 shells

OnewWeb Phase 2:

47 844 satellites, all at 1 200 km altitude, 3 shells

Total: 77 844 satellites (Details in the Appendix to our document)

2. Simulations and results: what is a shell?

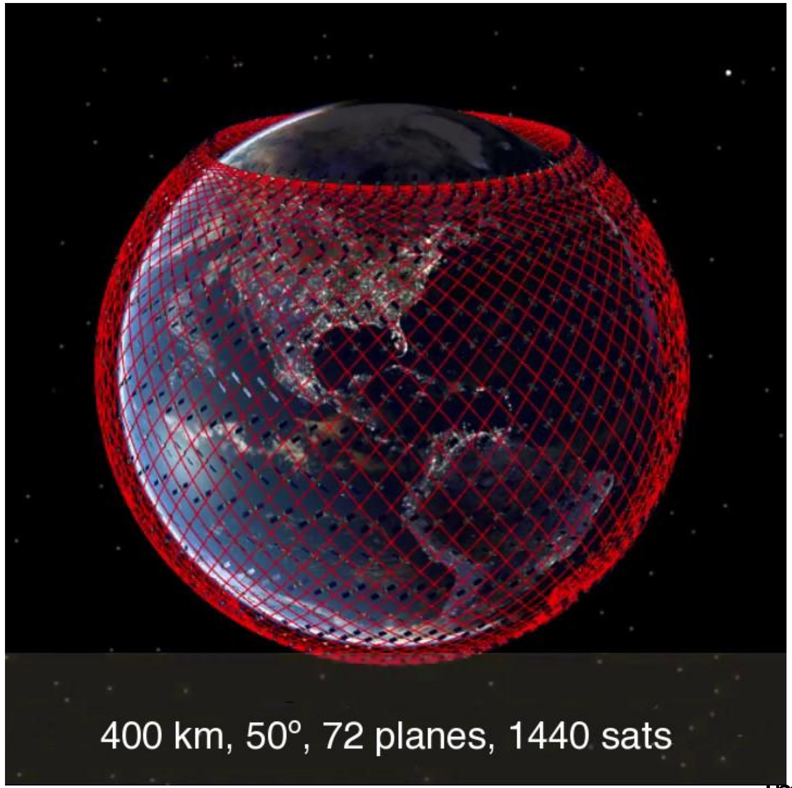


Image: lamid@YouTube

A shell is specified by:

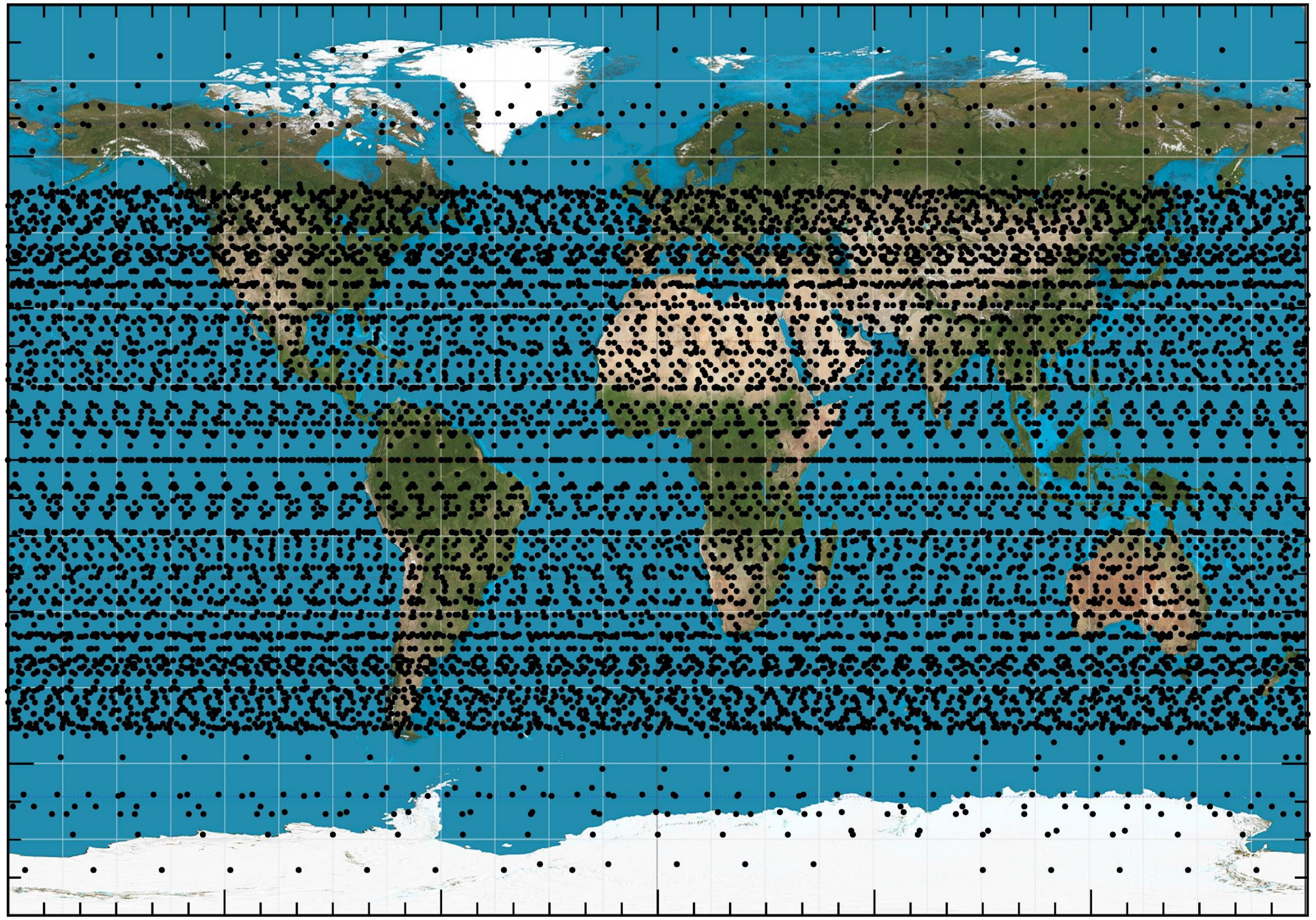
Altitude above the Earth surface

Inclination (same for all orbits in the shell)

Number of planes

Total number of satellites

Satellite Constellations Working Group



12 000 Starlink Generation 1
D. Galadí

2.1. All sky, bulk satellite counts (what's up, in general)

From a location, a satellite is visible (but possibly needing binoculars or telescope to see) if:

It is above the local horizon (i.e., it is "in sight")

AND

It is directly illuminated by sunlight

"Discrete" approach: constellation specification →

individual orbital elements of satellites →

geometry of observation conditions

2.1. All sky, bulk satellite counts

Results are strongly dependent on the configuration of the Earth's shadow on the local celestial sphere →

- Strong dependence with local time
- Strong dependence with the season of the year

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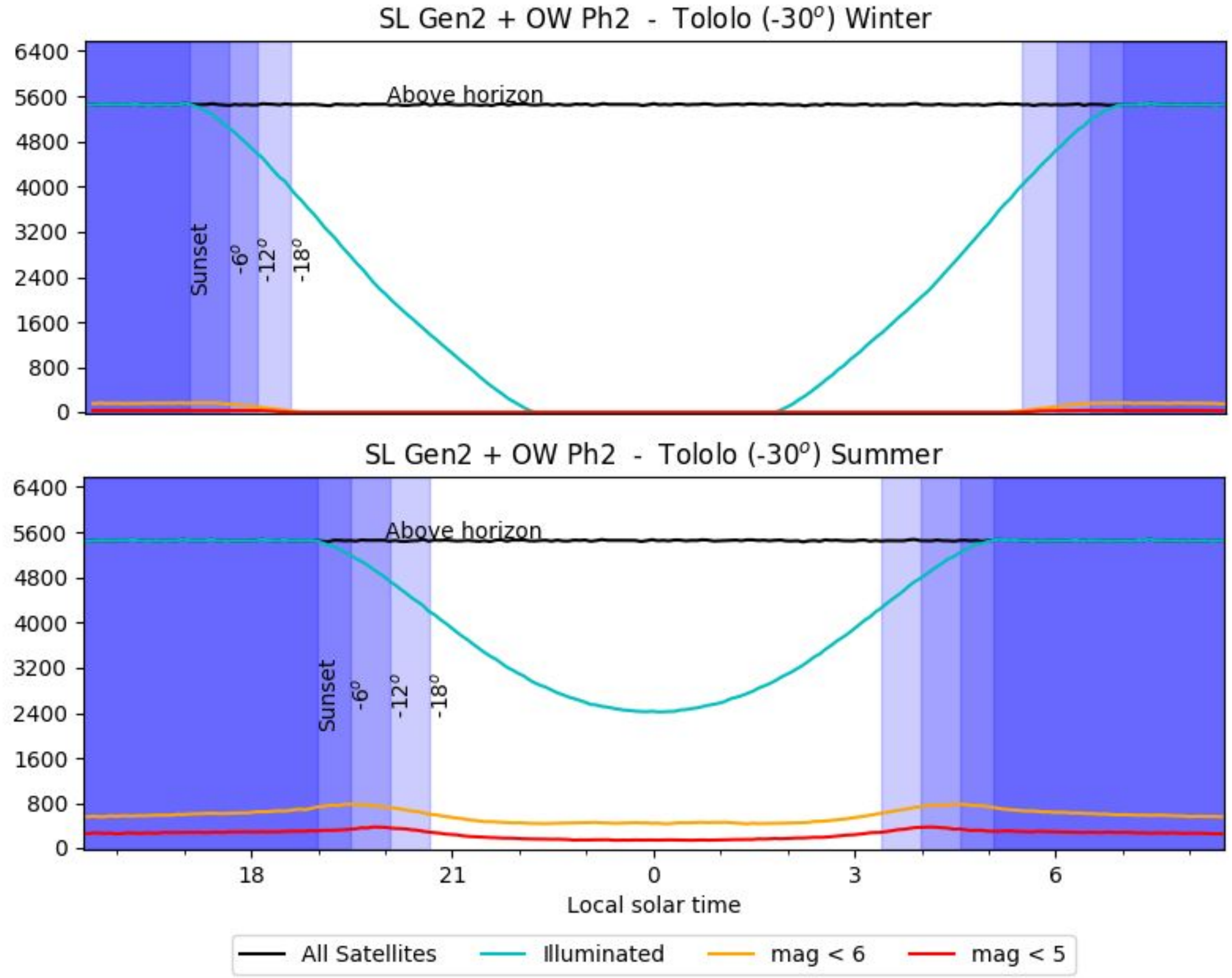
Decay of number of visible satellites towards the centre of the night.

Winter: some hours with zero satellites visible

Summer: there are satellites visible all the night long



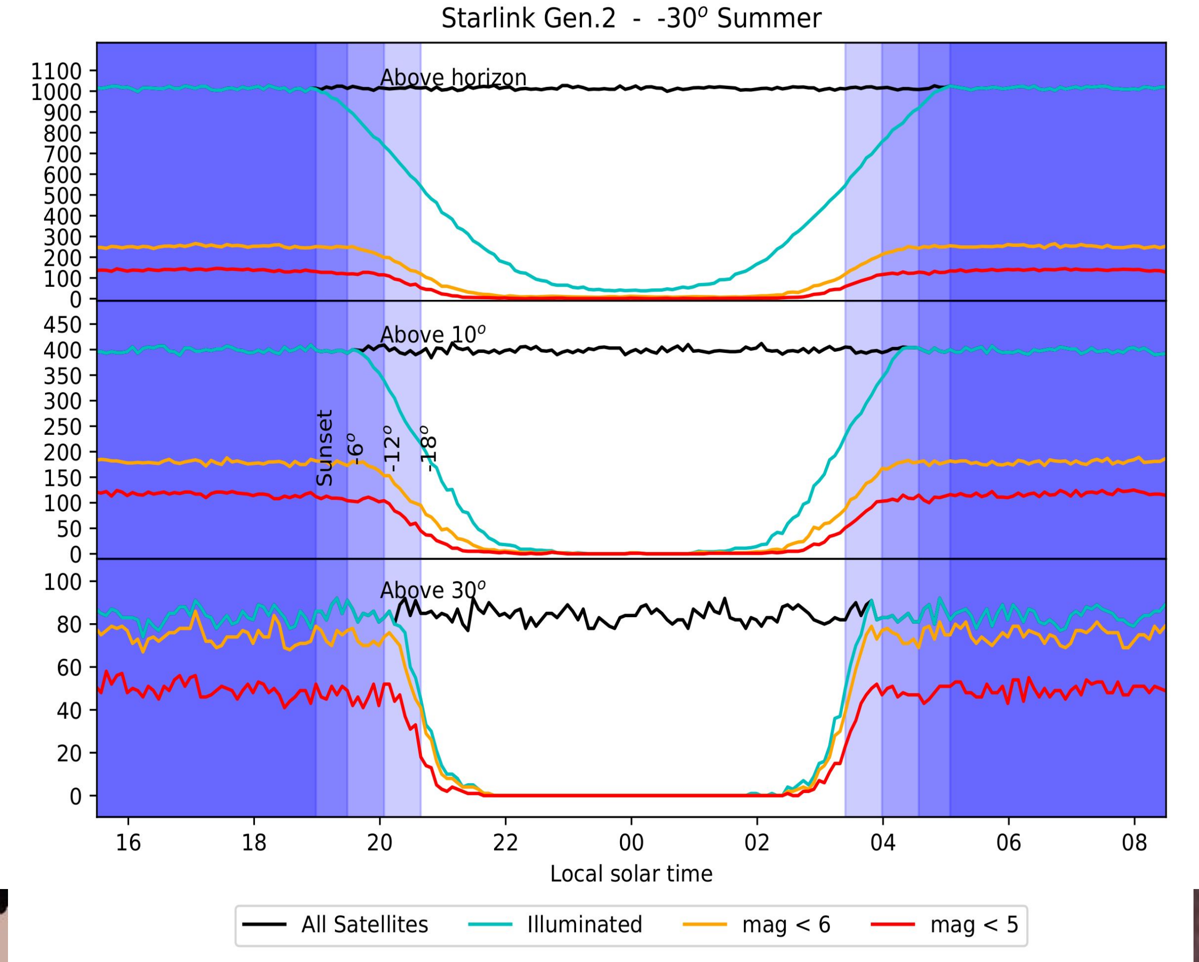
O. Hainaut

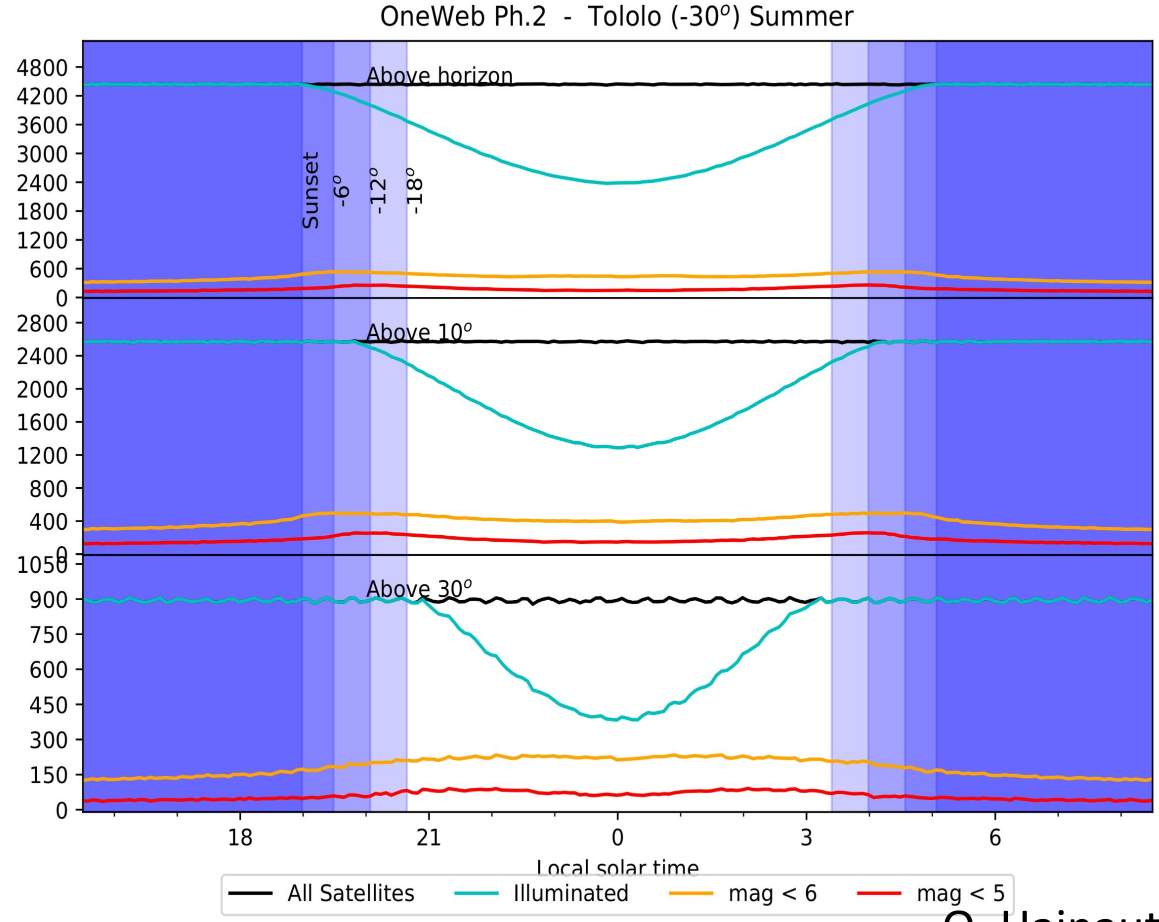
Dark & Quiet Skies

Simulations Group

Satellite Constellations Working Group

Concentration towards horizon AND influence of orbit altitude





O. Hainaut

Simulations Group

2.1. All sky, bulk satellite counts; summary of results:

- Some 5 % of the total constellation is above horizon from most locations (changes with latitude). SLOW → approx 4000 sats
- Higher shells contribute more (550 km → 4 %; 1200 km → 8 %)
- Strong decrease of visible sats towards midnight (even to zero)
- Higher orbits are illuminated more time → weaker & slower decrease
- **Strong** concentration of satellites towards the horizon

2.1. All sky, bulk satellite counts; summary of results:

- **More on the strong** concentration of satellites towards the horizon:

  This effect is strongly dependent on the altitude of the shells

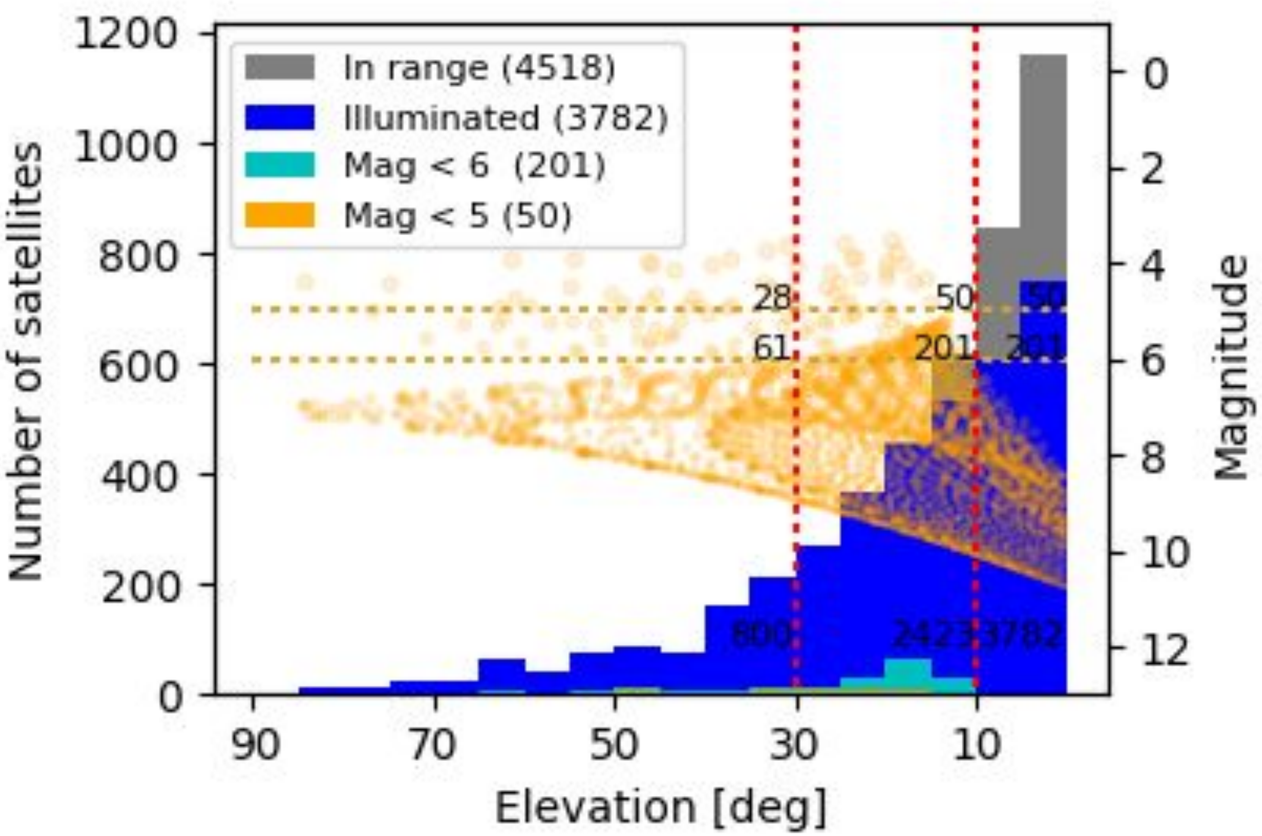
  Lower shells are much more concentrated

  SLOW constellation: 50 % satellites are below 10º elevation, but:

  SL (lower): 60 % below 10º OW (higher): 40 % below 10º

2.1. All sky, bulk satellite counts; summary of results:

- **Apparent brightness and angular speed:**
- For a given shell: closer to the horizon → fainter and slower
- For SLOW constellation, some satellites visible with the naked eye are predicted
- *All* sunlit satellites are detectable by telescopes



2.2. Pointing-oriented simulations (what to expect when you are observing)

From a location, date and time

AND

Given a pointing direction on the sky and a field of view (FOV)

→

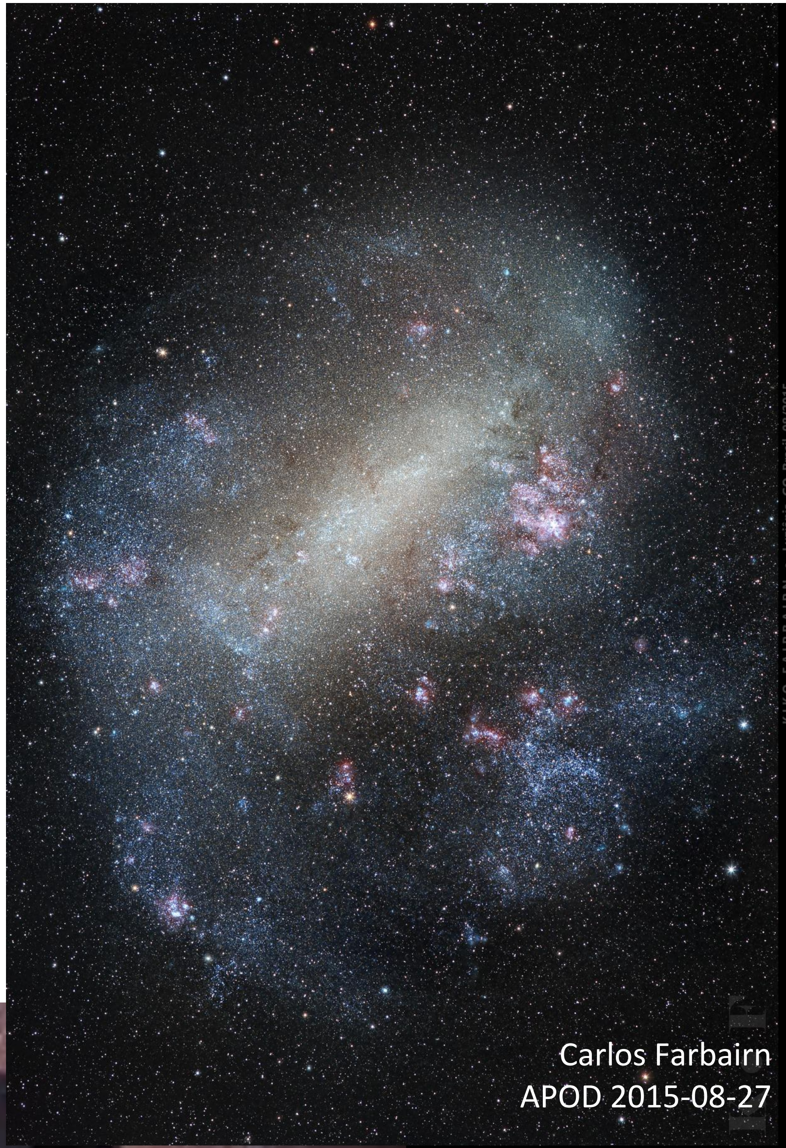
Predict satellites crossing the field, their speed, brightness and orientation

2.2. Pointing-oriented simulations; some results:

High orbit satellites (One Web) are illuminated towards the circumpolar celestial region all the night long in summer.

In this area (circumpolar South): the Magellanic Clouds

Large Magellanic Cloud (LMC) is best visible in local summer



Carlos Farbairn
APOD 2015-08-27

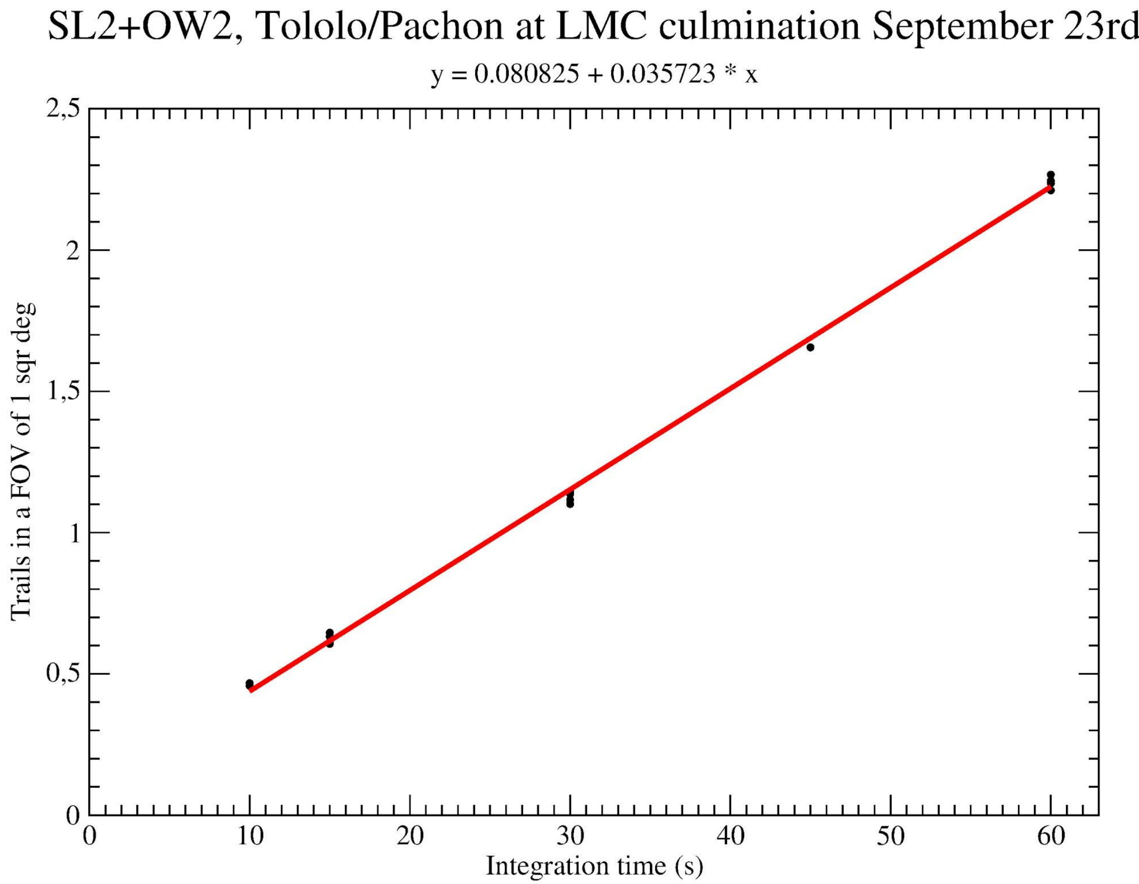
Satellite Constellations Working Group

2.2. Pointing-oriented simulations; some results:

LMC from Cerro Tololo (latitude -30º) in equinox

Field of view one square degree, integration time 60 seconds:

Average of 2.2 trails per shot all night long, most of them (88 % to 100 %, depending on local time) due to high-orbit satellites (One Web).

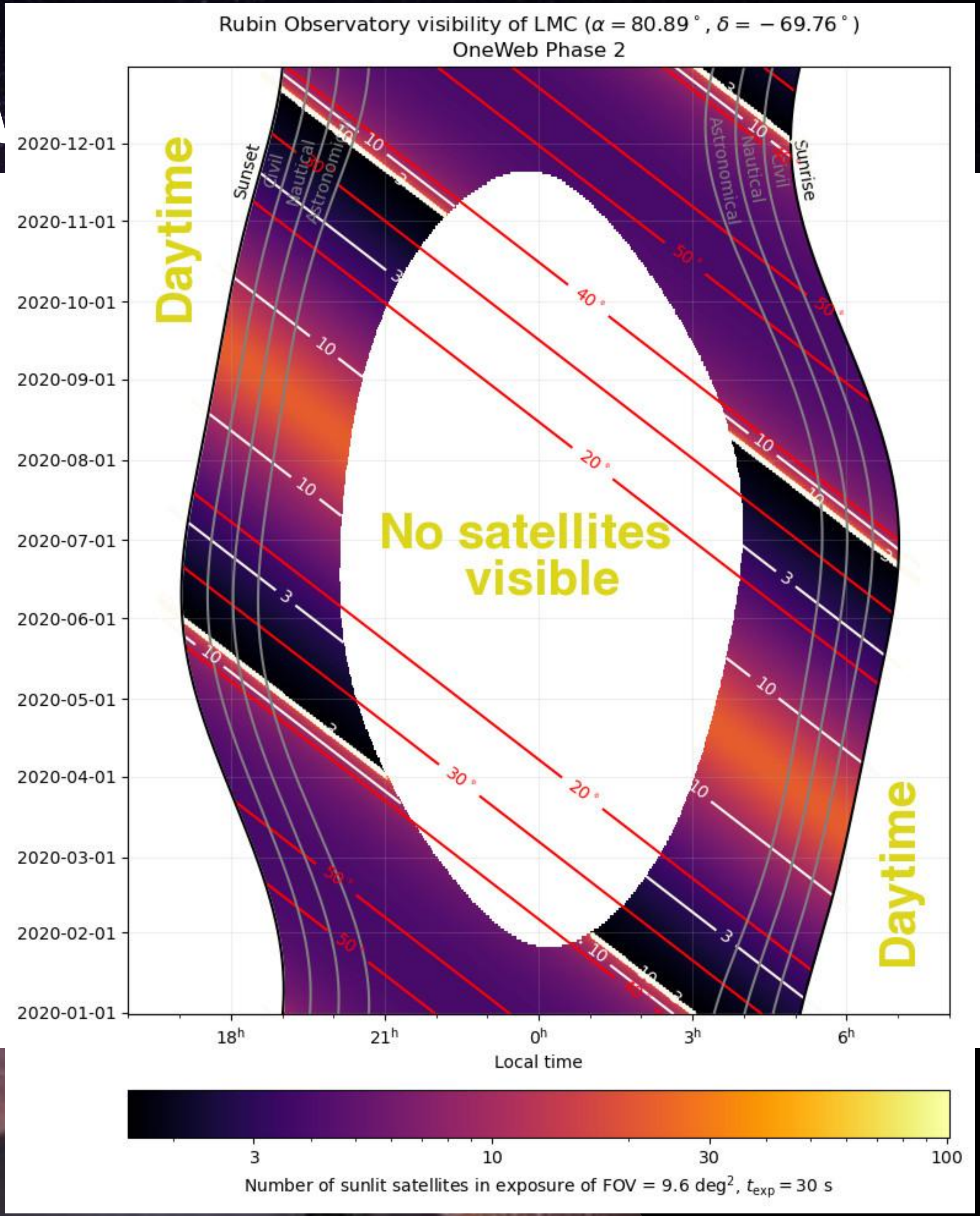


Satellite Constellations V

2.2. Pointing-oriented simulations; some results:

LMC from Tololo/Pachón

Graphs by Cees Bassa by analytical methods

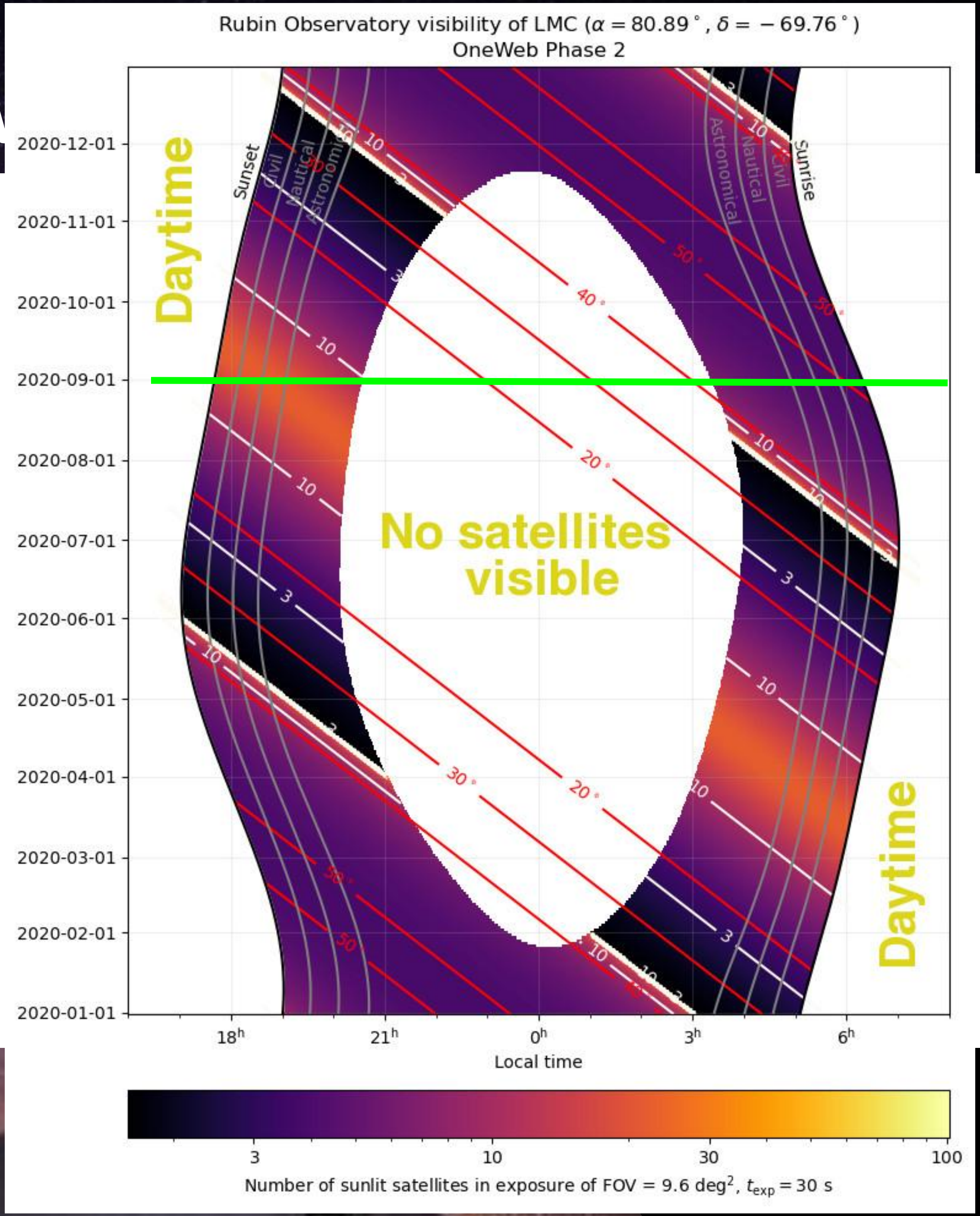


Satellite Constellations V

2.2. Pointing-oriented simulations; some results:

LMC from Tololo/Pachón

Graphs by Cees Bassa by analytical methods



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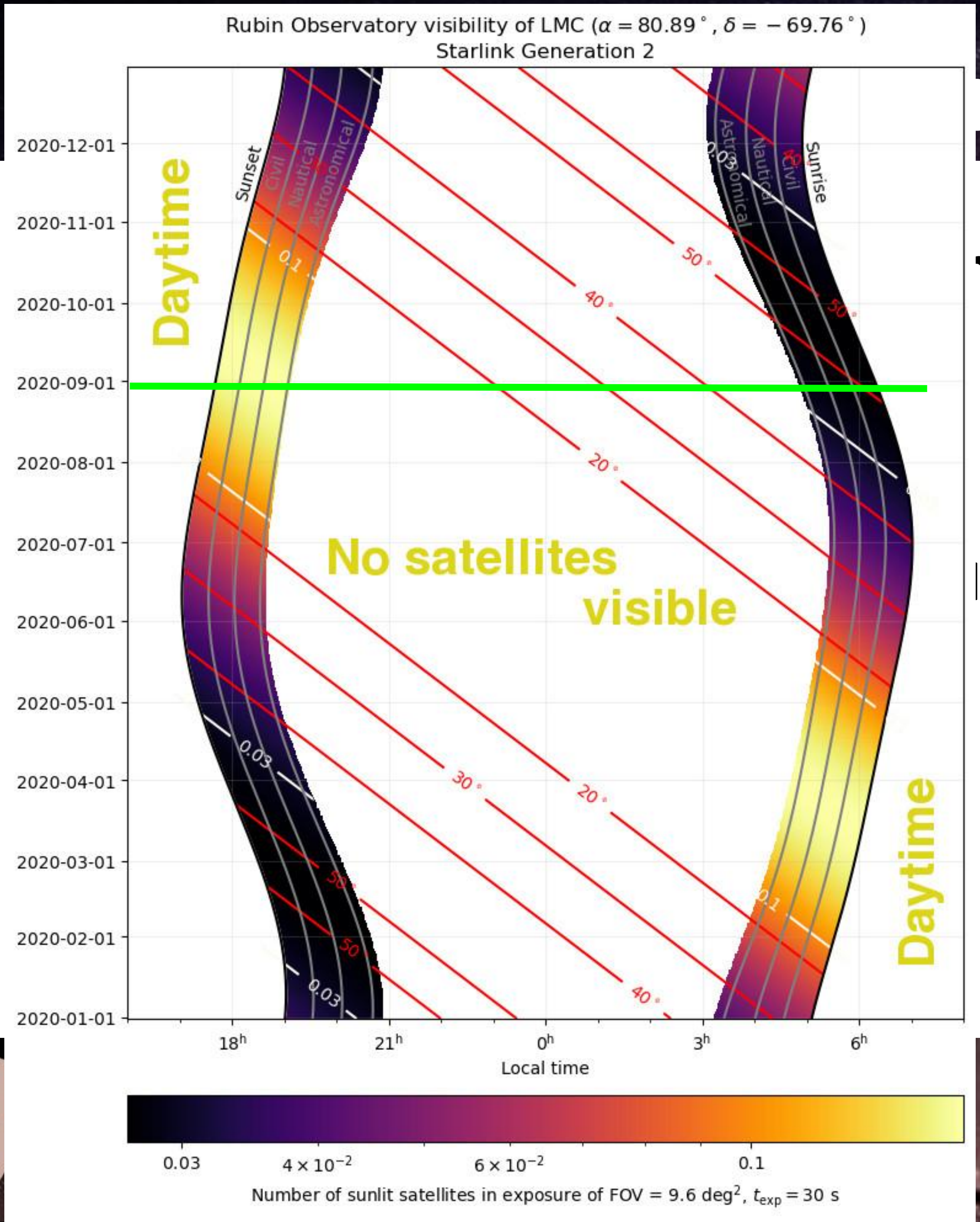
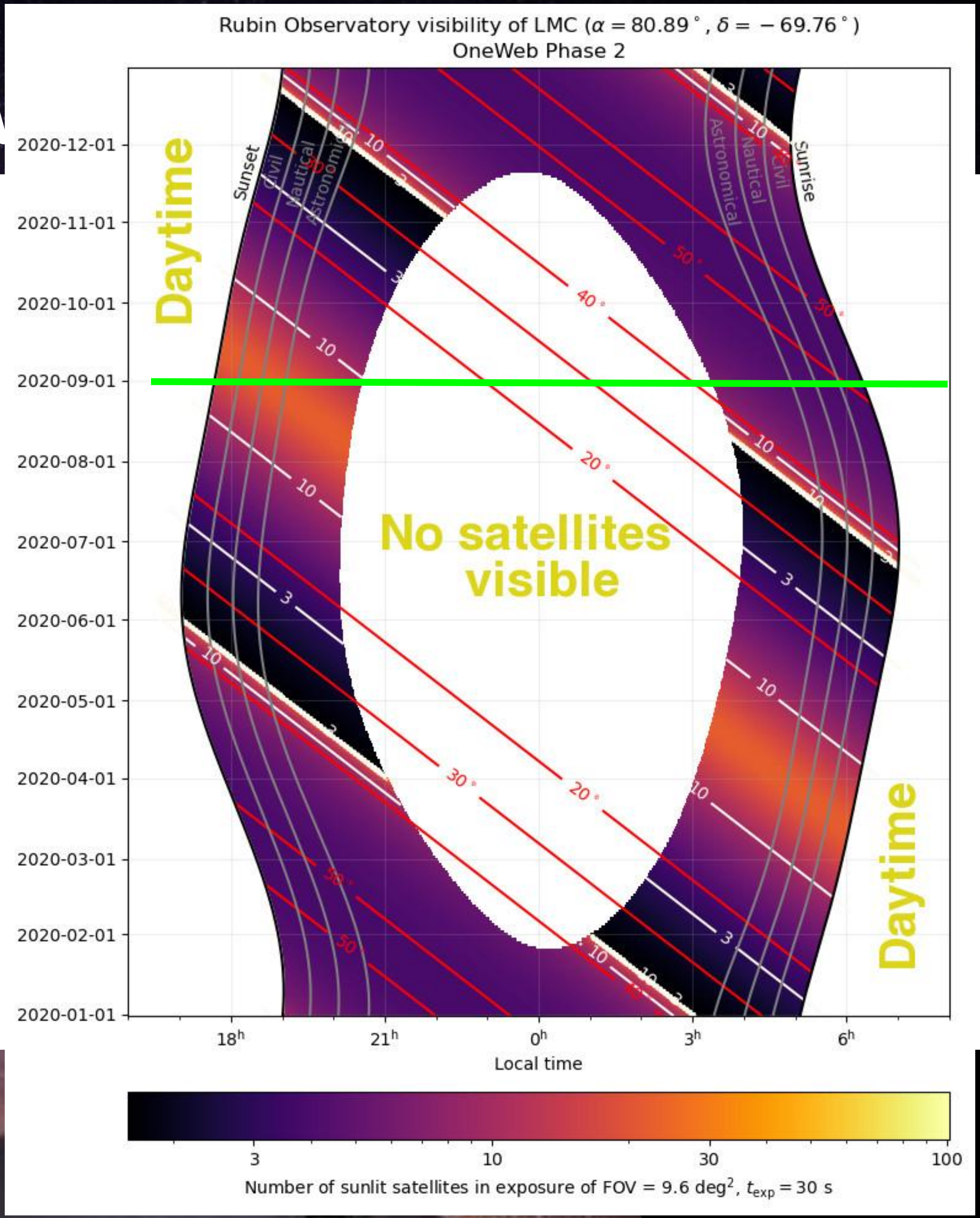


Rubin Observatory visibility of LMC ($\alpha = 80.89^\circ$, $\delta = -69.76^\circ$)
Starlink Generation 2
Daytime
No satellites visible
Daytime
Sunset
Civil
Nautical
Astronomical
Sunrise
Local time
Number of sunlit satellites in exposure of FOV = 9.6 deg^2, $t_{exp} = 30$ s
0.03
4×10^{-2}
6×10^{-2}
0.1



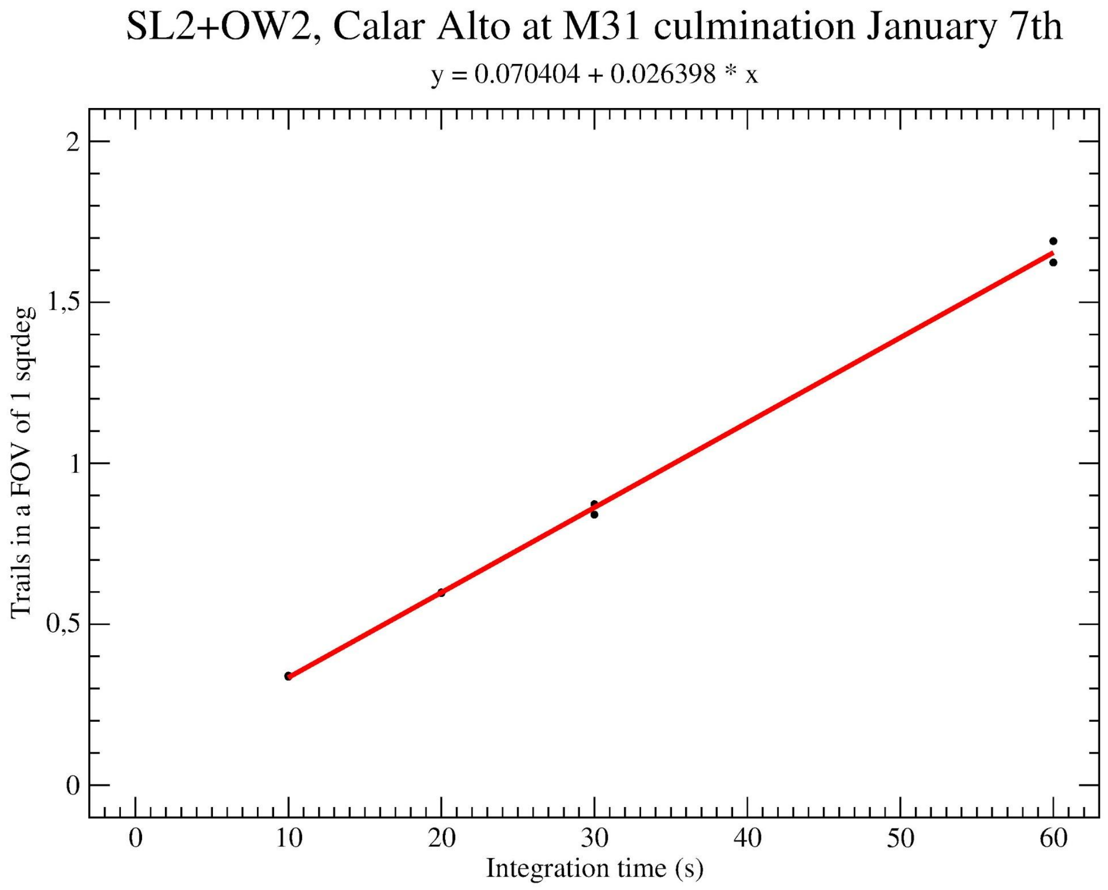
Rubin Observatory visibility of LMC ($\alpha = 80.89^\circ$, $\delta = -69.76^\circ$)
OneWeb Phase 2
Daytime
No satellites visible
Daytime
Sunset
Civil
Nautical
Astronomical
Sunrise
Local time
Number of sunlit satellites in exposure of FOV = 9.6 deg^2, $t_{exp} = 30$ s
3
10
30
100

2.2. Pointing-oriented simulations; some results:

Andromeda Galaxy from Southern Europe or Arizona in local winter

Field of view one square degree, integration time 60 seconds:

Average of 1.6 trails per shot all night long, most of them (88 % to 100 %, depending on local time) due to high-orbit satellites (One Web).



2.2. Pointing-oriented simulations; some results:

Pointing NW from Southern Europe or Arizona in equinox, beginning of night,

FOV 1 square degree, 60 s integration time →

20 deg above horizon: 2 trails per shot, mag 7-10 (mean 9), 11 arcmin/s

10 deg above horizon: 3 trails per shot, mag 9-11 (mean 10), 8 arcmin/s

05 deg above horizon: 4 trails per shot, mag 10-12 (mean 11), 6.5 arcmin/s

2.3. Spatially resolved simulations (fine structure)

Specifying satellite and trail density at each point of the local celestial sphere

Computationally demanding by discrete approaches (following the orbit of each individual satellite through geometry and celestial mechanics)

Analytic approach: each satellite induces a deterministic probability density function over its shell. From densities ⟶ statistics and results

Satellite Constellati

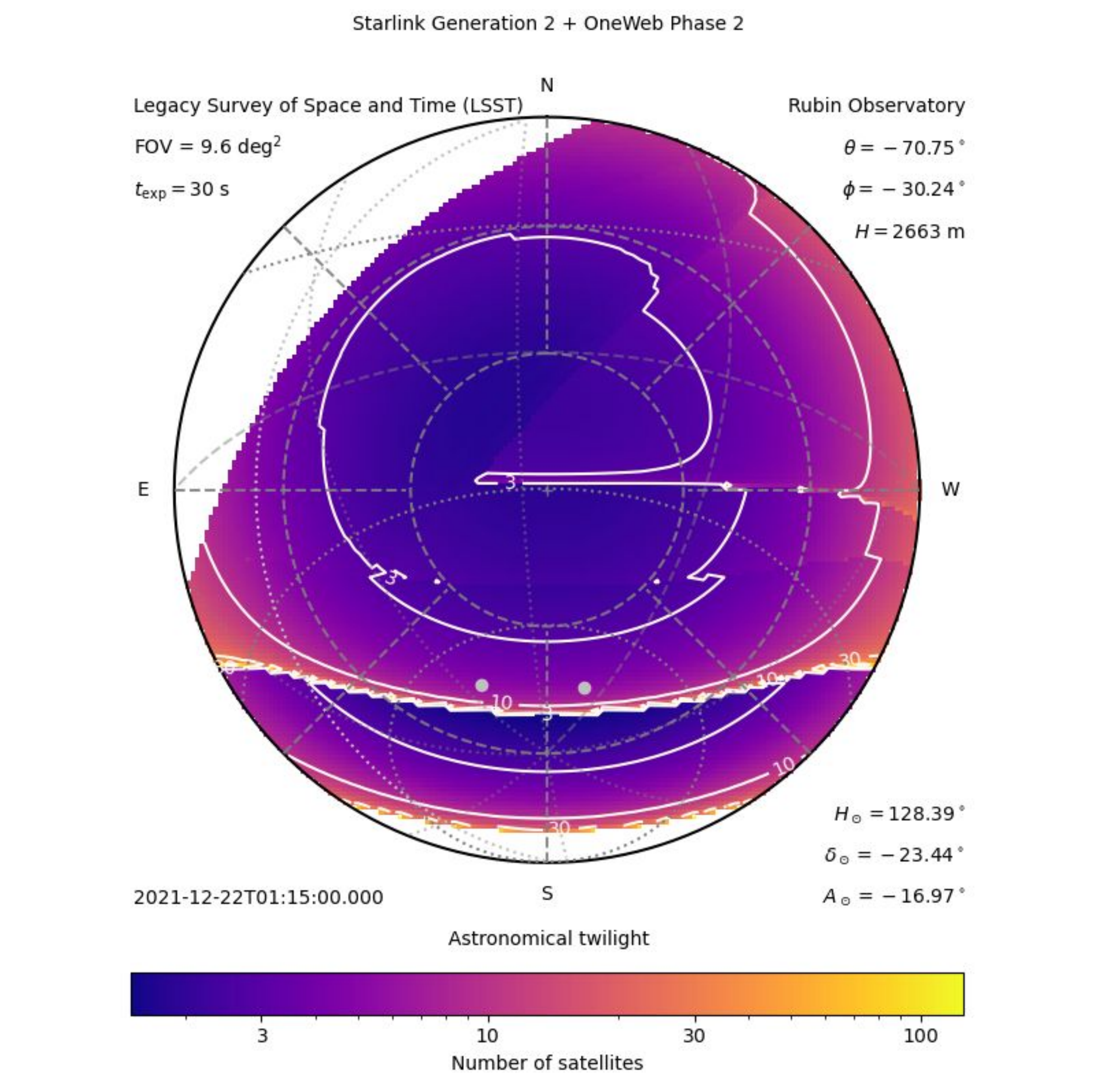
2.3. Spatially resolved simulations; some results:

The sky over Cerro Pachón/Tololo

Local summer solstice, 20:30 solar local time, “SLOW” constellation

Colour code: number of satellite trails inside the field of view of the Simony Survey Telescope (for LSST project) for an integration time of 30 seconds

C. Bassa



Satellite Constellati

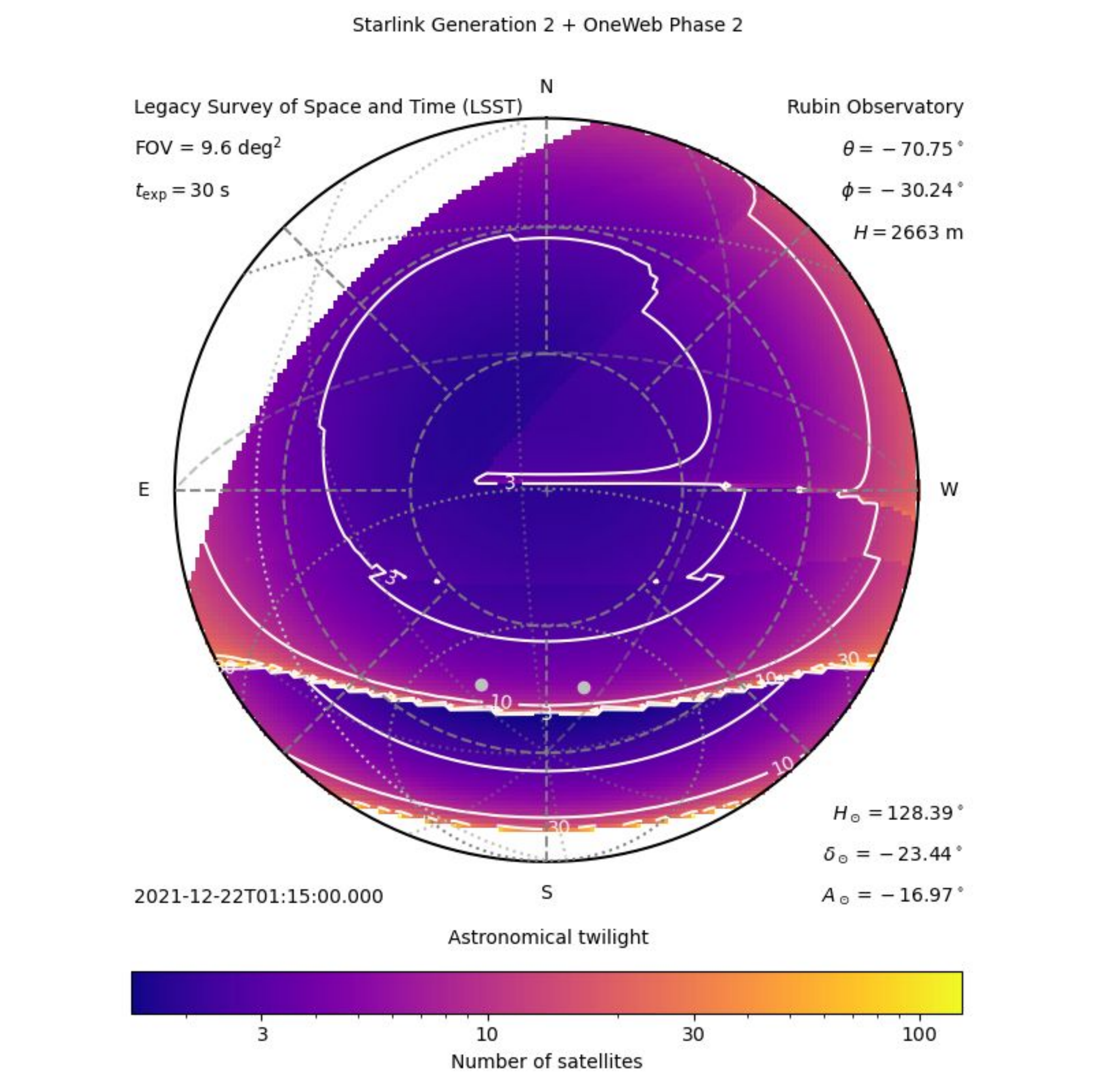
2.3. Spatially resolved simulations; some results:

Huge amount of spatial fine structure

Shell boundaries are relevant

Dots: Magellanic Clouds; LMC (left) and SMC (right)

C. Bassa



Satellite Constellati

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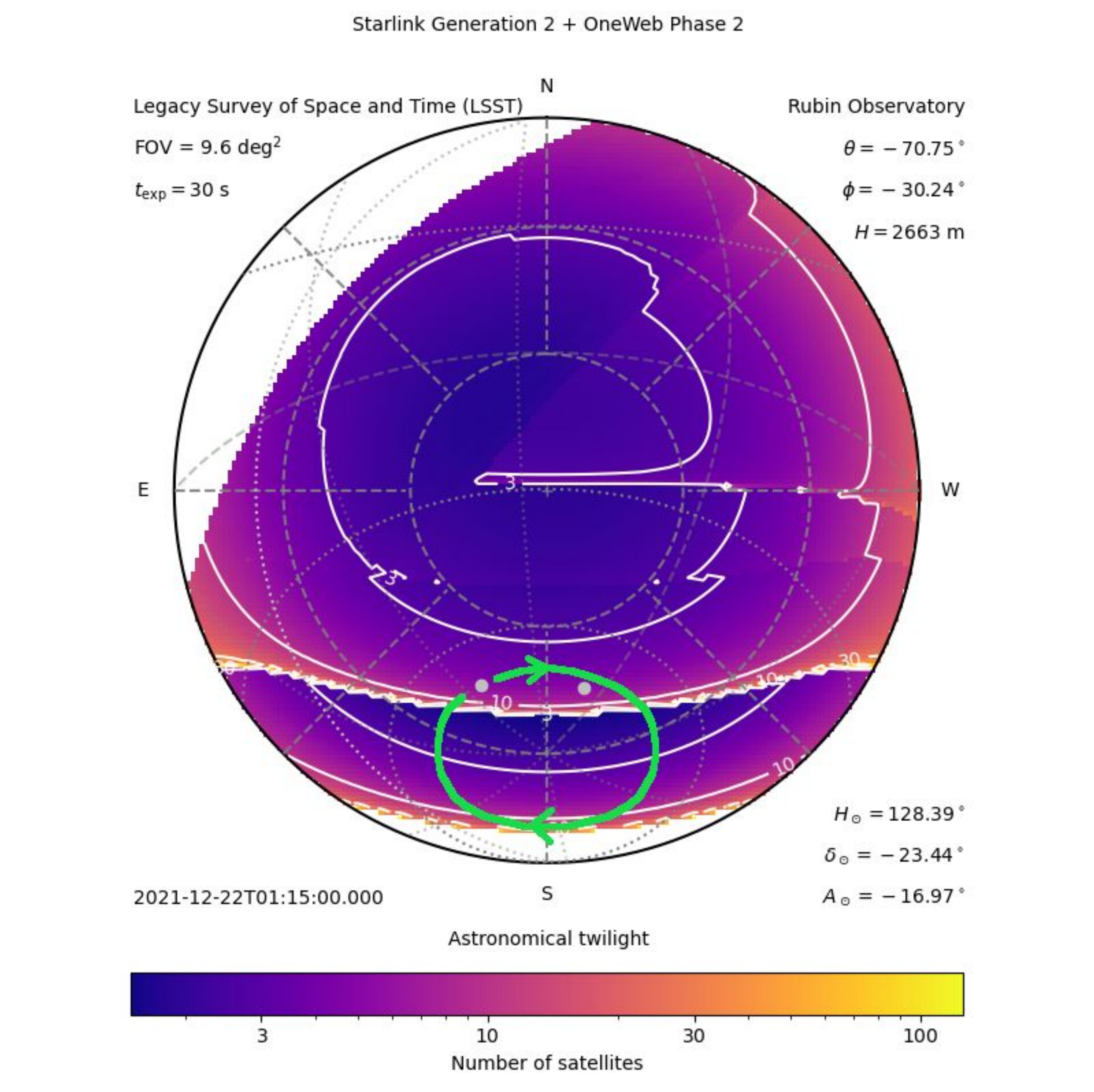
C. Bassa



Satellite Constellati

2.3. Spatially resolved simulations; some results:

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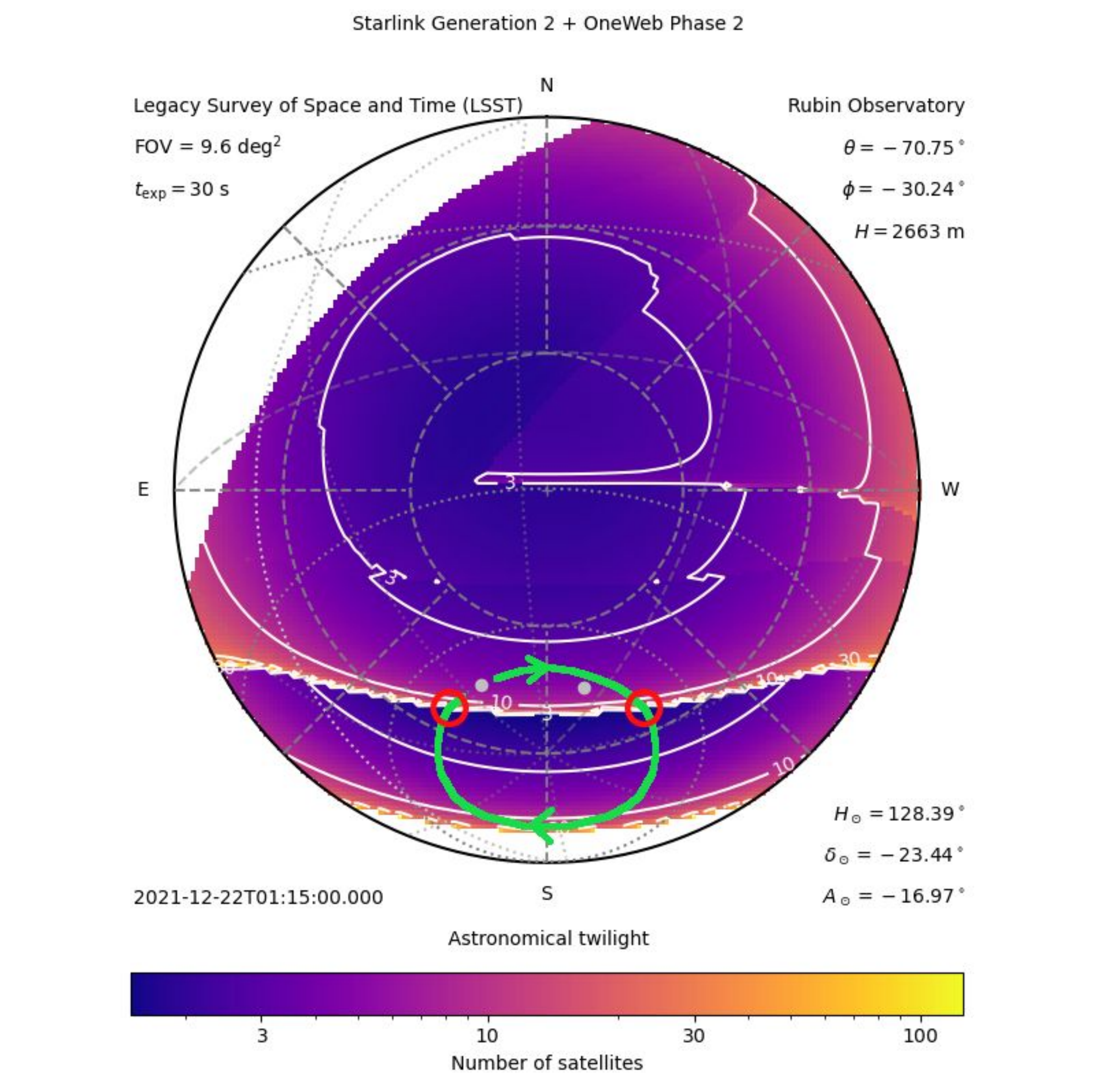

Satellite Constellations Working Group

3. Flares and glares (reflecting on satellites)

Flares:

Specular reflections from flat surfaces

Computation tools available (Iridium satellites of first generation)

Glares:

Similar reflections from non-flat surfaces

Less bright, longer in time

J. C. Casado

Satellite Constellations Working Group

3. Flares and glares; some results:

Specular reflections are expected to happen

Will be (much) less bright than Iridium flares (Iridium: -8 mag; SL maybe -5 mag at worst)

Never will appear as point-like sources: they will leave a brighter trail

The frequency will be very low, most probably not an issue for most observations (but: all-sky cameras for meteors and the alike)

Highly predictable in advance, even better results in retrospect, if ephemeris and tools are provided

4. Transient orbital phases (ascension and decay)

From launch to operation: lower orbits, train formation, different (brighter) attitude

Transient phase, but for large constellations there will be a significant fraction of spacecraft at this stage (3 % … 5 %)

→

Need to minimise **duration** and **brightness** in these stages

Alamy Live News

4. Transient orbital phases:

Orbit decay; active and passive:

Natural orbit decay will happen: If active de-orbiting is not foreseen

If the satellite is lost

Space debris mitigation guidelines are not always fulfilled

Orientative time scales for natural orbit decay: 350 km altitude, less than one year

550 km altitude, 12-18 years

beyond 1000 km altitude takes centuries,

if not millenia (in practice, forever)

Satellite Constellations Working Group

4. Transient orbital phases:

Orbit decay; active and passive:

Even active de-orbiting may lead to lower orbits where satellites may remain for years and without attitude control

Starlink first de-orbiting maneuvers: from operational orbit to re-entry in 4-9 months

Estimation: 5 yr active life, 6 months of active decay aiming re-entry (not to parking orbit for later, natural decay)

→ 10 % of the constellation would be in this phase

Satellite Constellations Working Group

Summary / conclusions:

1) Threat to naked eye sky *can* be mitigated (but see below)
2) Deep sky astronomy is severely affected by high orbit constellations (even more in local sumer)
3) Twilight/near-horizon astronomy is severely threatened by all constellations

Industry: Provide information about constellation projects
Limit number of spacrecraft (optimum number: zero)
Reduce orbit altitude
Provide orbital elements and tools (avoidance, flare prediction)
Satellite darkening

Industry & community: Improving photometric models (information, observation, simulation)

Regulation: Enforcing active de-orbiting aiming re-entry

Community: Improving simulations

Satellite Constellation WG Team

Observations:

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Lorri Allen, NOIRLab
Steve Heathcote, CTIO
Harrison Krantz, U.AZ
Eric Pearce, U.AZ
Lisa Storrie-Lombardi, Las Cumbres Obs.
Jeremy Tregloan-Reed, U.Antofagasta
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Moriba Jah, U Texas
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Satellite industry engineers, SpaceX, Kuiper, et al.
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Recommendations:

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Patricia Cooper, SpaceX
Roger Davies, EAS/U.Oxford
Richard Green, U.Arizona
Jeffrey Hall, Lowell Obs.
Chris Hofer, Amazon
Kelsie Krafton, AAS
James Lowenthal, Smith Coll.
Robert Massey, RAS, UK
Tim Maclay, Celestial Insight
Charles Mudd Jr, Mudd Law
Joel Parriott, AAS
Giuliana Rotola, ESO
Jonathan Williams, NSF
Connie Walker, NOIRLab

(speakers in magenta)

DARK & QUIET SKIES

Moderators: Sara Lucatello / Olivier Hainaut

Mitigating the impacts of satellite constellations on astronomy

Genoveva Micheva

Meredith Rawls

on behalf of the
Satellite Mitigations WG

8 October 2020

UNITED NATIONS
Office for Outer Space Affairs

IAU International Astronomical Union

INSTITUTO DE ASTROFISICA DE CANARIAS · IAC

With the support of NOIRLab

Purpose and Aims of Mitigations WG

- Satellite constellations are affecting astronomical observations
- Several are currently launching, many more are approved to launch
- What can be done to **mitigate** their effects?
- We focus on broad-scope technical solutions
- Our work builds on NSF & NOIRLab’s SATCON1 Mitigations Report (Appendix C)

https://aas.org/satellite-constellations-1-workshop-report

Mitigations Working Group

Genoveva Micheva, chair (Leibniz-Institute for Astrophysics Potsdam and AIP, DE)
Michele T. Bannister (University of Canterbury, NZ)
Piero Benvenuti (IAU, IT)
Daniel Devost (University of Hawaii/CFHT, USA)
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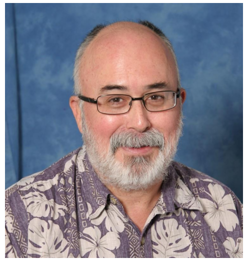
Meredith Rawls (University of Washington and Rubin Observatory, USA)
Rob Seaman (Catalina Sky Survey, University of Arizona, USA)
Rachel Street (Las Cumbres Observatory Global Telescope, USA)
Tony Tyson (University of California, Davis and Rubin Observatory, USA)
Richard Wainscoat (Institute for Astronomy, University of Hawaii, USA)





Satellite industry engineers from SpaceX, Amazon Kuiper, and others

SPACEX

amazon | project kuiper

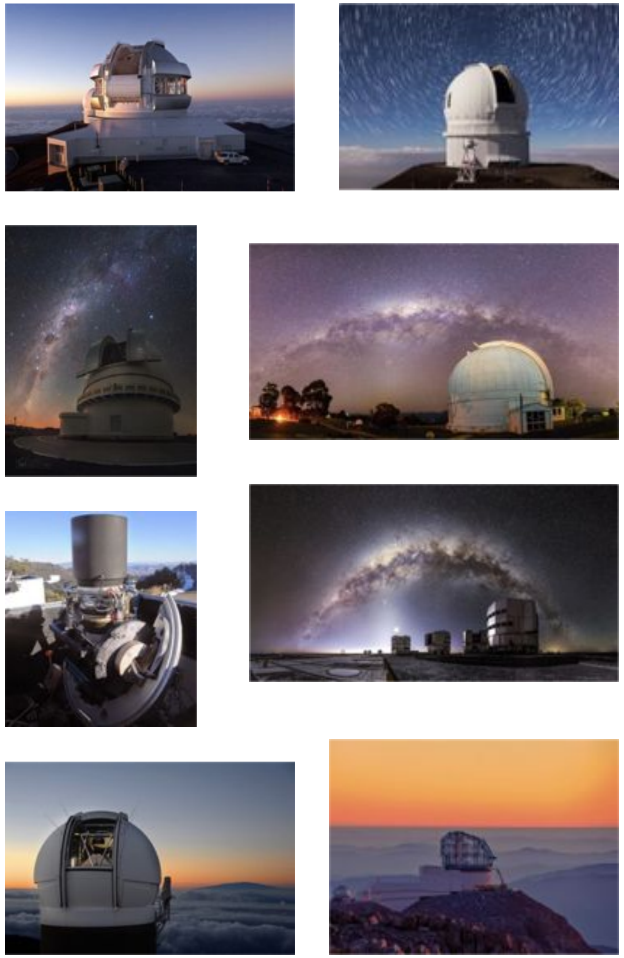
SATCON1: a need for mitigations

"If the 100,000 or more LEOsats proposed by many companies and many governments are deployed, no combination of mitigations can fully avoid the impacts of the satellite trails on the science programs of current and planned ground-based optical-NIR astronomy facilities."

Walker & Hall et al. 2020

S#. SATCON1 Mitigations

S#. Additional Mitigations

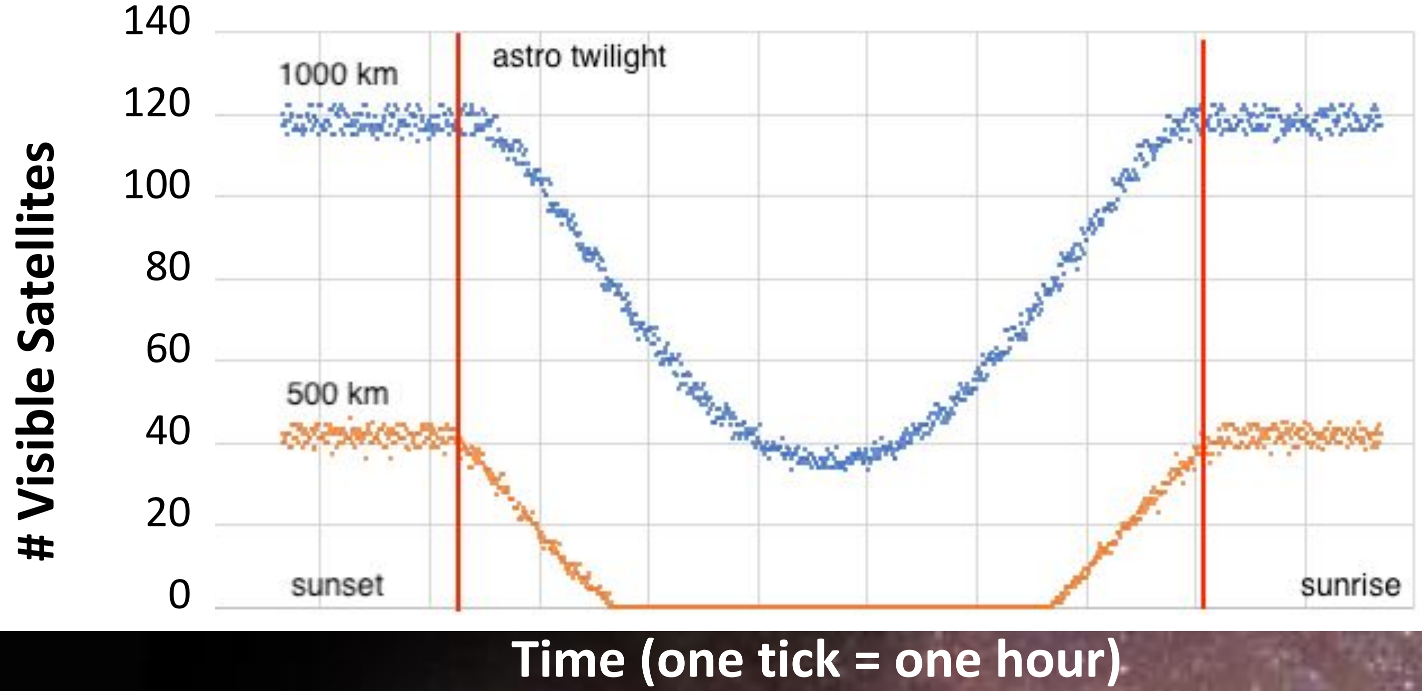


Fewer and lower satellites

S1. Fewer satellites

- If satellite operators can achieve their goals with fewer satellites, this is the simplest mitigation

S4. LEO satellites on orbits as *low* as possible



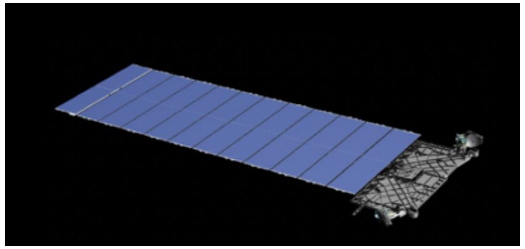
- Satellites at 1200 km will be visible all night in summer
- Satellites < 600 km yield some satellite-free dark time

Figure courtesy P. Seitzer
10k satellites, 30° lat, summer

Darkened, dimmable and quiet satellites

S2 & S3. Darken satellites in all phases of the orbit

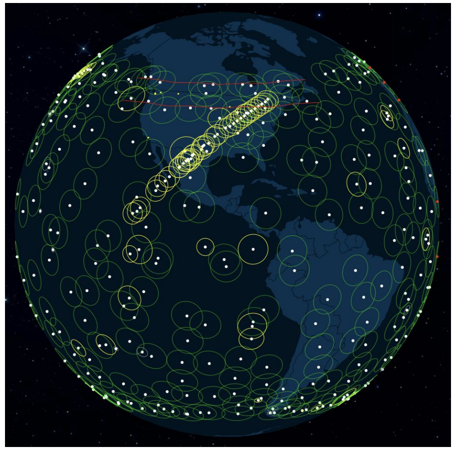
- Orbit raise, parking, and de-orbit are relatively short, but significant
- Darken to fainter than 7th visual mag at 550 km altitude, and preferably 8th mag
  - 7th mag ≈ 44 Watts per steradian (Tyson et al. 2020, arXiv:2006.12417)
- Satellites at higher altitudes move more slowly and must be darkened further



SpaceX Starlink in "open book" configuration

S12. Mitigations for radio astronomy

- Satellites: small beam sizes (low orbits), transmitter on/off, sharp bandpass filters
- Observatories: new pre-amplifiers, fully digital receivers
- Keep satellite ground stations far from observatories — more on radio tomorrow!

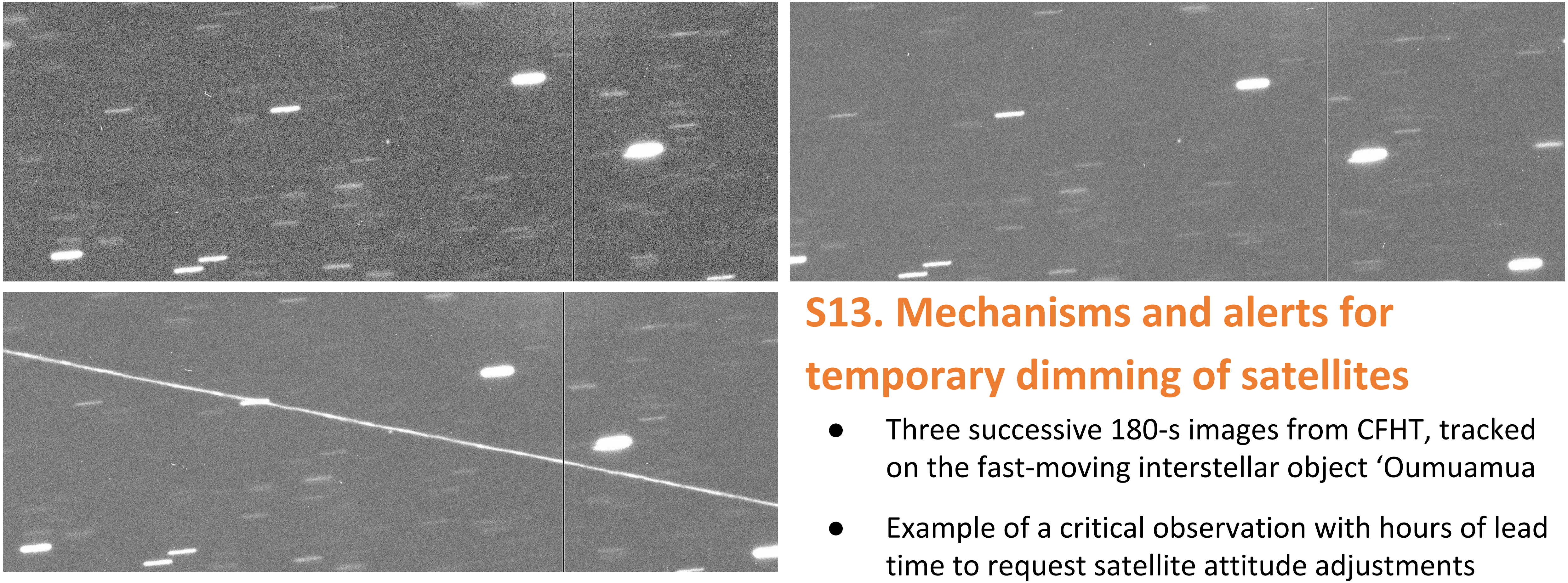


From satellitemap.space

S13. Mechanisms and alerts for temporary dimming of satellites

- Temporary satellite orientation change for crucial observations, especially at twilight

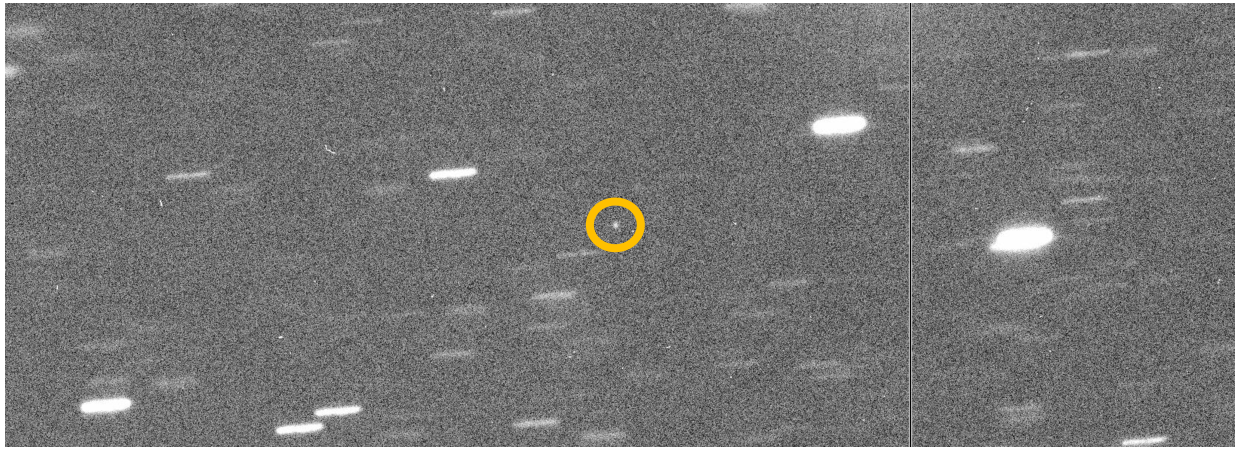
Observations of ‘Oumuamua in 2017

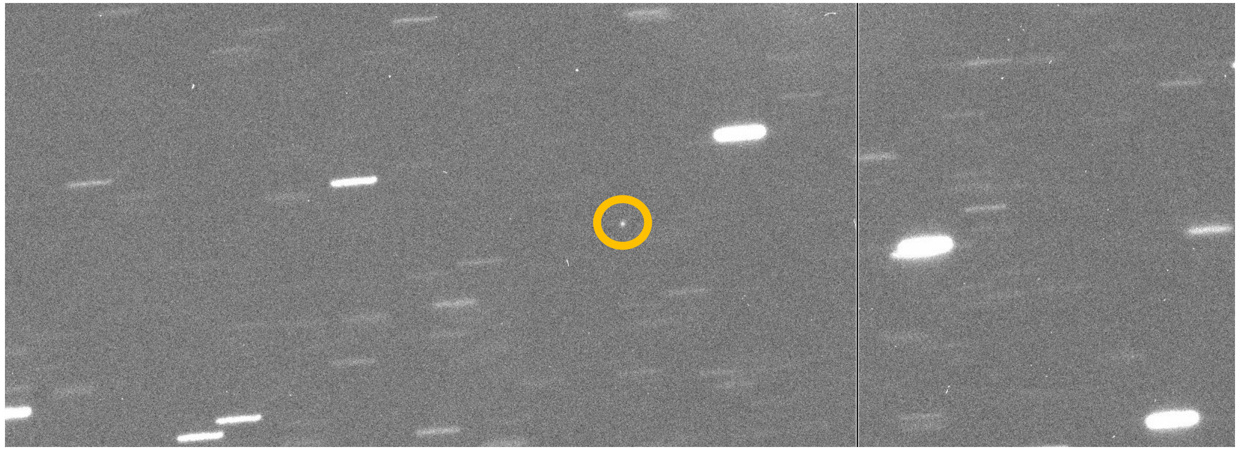


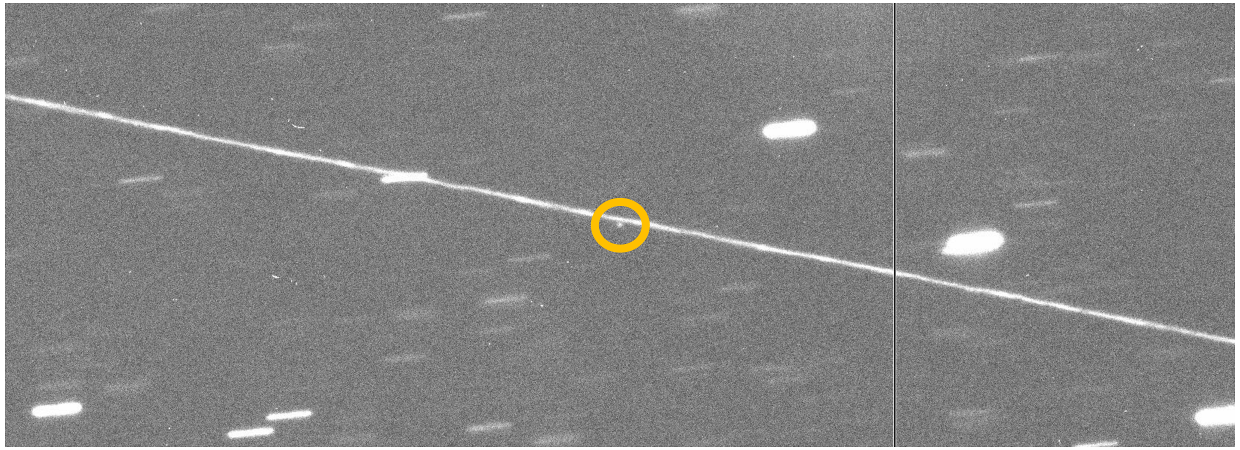
S13. Mechanisms and alerts for temporary dimming of satellites

- Three successive 180-s images from CFHT, tracked on the fast-moving interstellar object ‘Oumuamua
- Example of a critical observation with hours of lead time to request satellite attitude adjustments

Observations of ‘Oumuamua in 2017







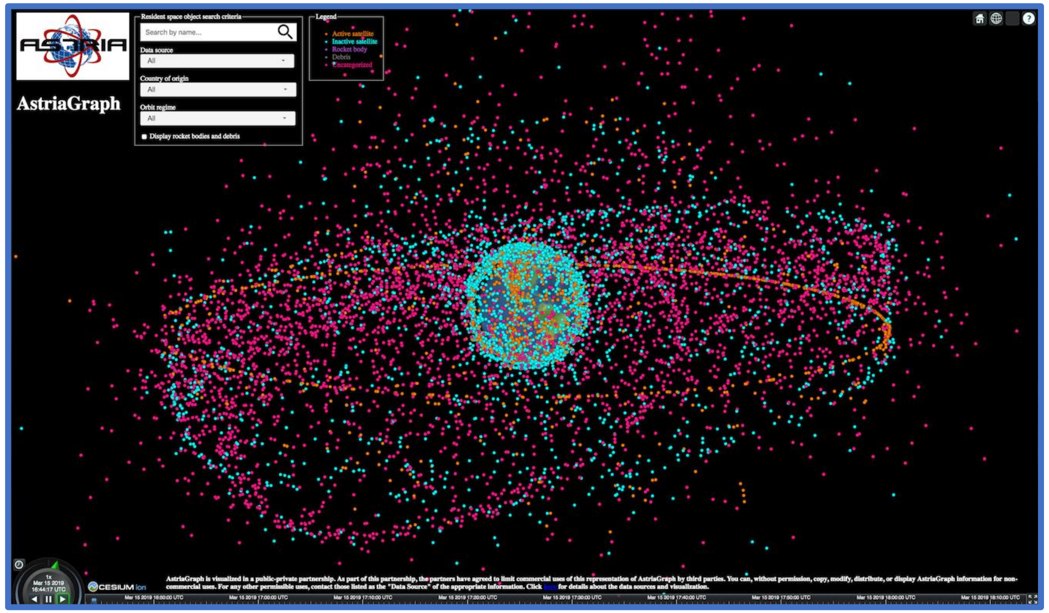
S13. Mechanisms and alerts for temporary dimming of satellites

- Three successive 180-s images from CFHT, tracked on the fast-moving interstellar object ‘Oumuamua
- Example of a critical observation with hours of lead time to request satellite attitude adjustments

Satellites: locate, locate, locate

S5 & S6. Public, updated, accurate satellite orbits and locations as a public service

- ASTRIAGraph is a step toward this, providing access to standard-formatted updated Orbit Ephemeris Messages for IRIDIUM, FLOCK, INTELSAT, GALAXY, TDRS, GALILEO objects
- See http://bit.ly/astriagraph

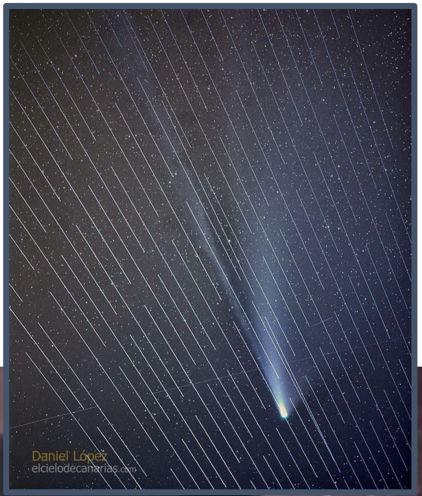


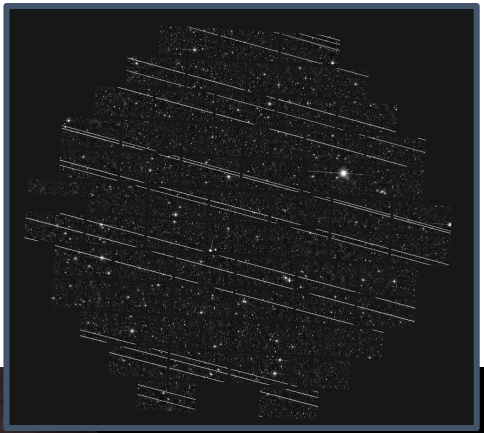
S17. "Gravity-Only" satellite trajectories

- Future locations are more predictable if one can invoke Newton's Principle of Determinacy

S15. Clump satellites in parking and orbit raise

- Fewer discrete interfering events when satellites are brightest





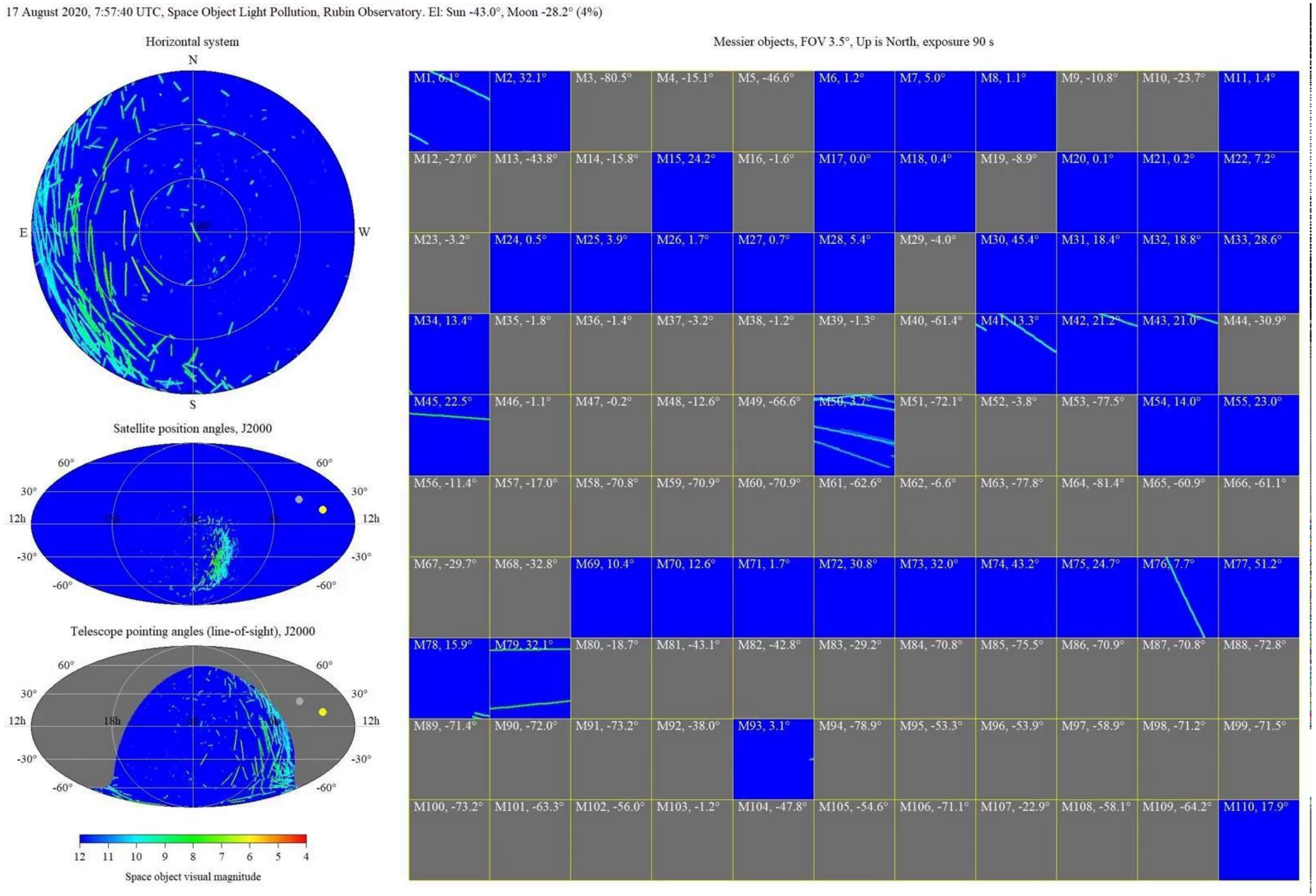
Satellite prediction and avoidance

S7. Advanced algorithms for avoidance of bright satellites

- Dodging is not feasible for all situations
- Movie shows one night from Rubin Observatory with present-day population of satellites (17 Aug 2020)

S8. A predictive model for satellite brightness

- Analyze observed satellite trails
- Measure reflectance in satellite design
- Simulate how satellites reflect light

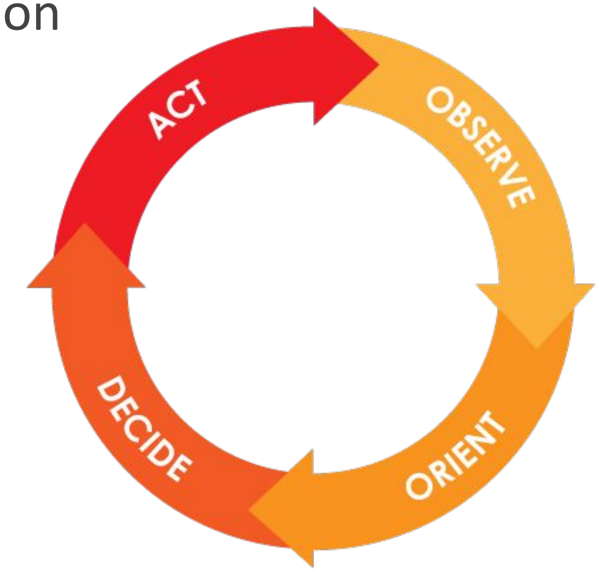


Simulation by Moriba Jah

Understand space environment & satellites

S11. Develop a "digital twin" of the space environment and its satellites

- Virtual replica to enable automatic decision-making (Observe, Orient, Decide, Act)
- Satellite size/shape/materials, location/velocity, environment, sensors & information systems
- Data engineering, statistical inference, physical models, information curation



S9. "End-to-end" simulations of broad science impacts

- Once we model satellite effects on astronomy data, more work to turn this into concrete science impacts
- e.g., Deciding where a satellite trail's edge is
- e.g., False transient events in archival data

Ground-based refinements

S10. More telescopes and telescope networks

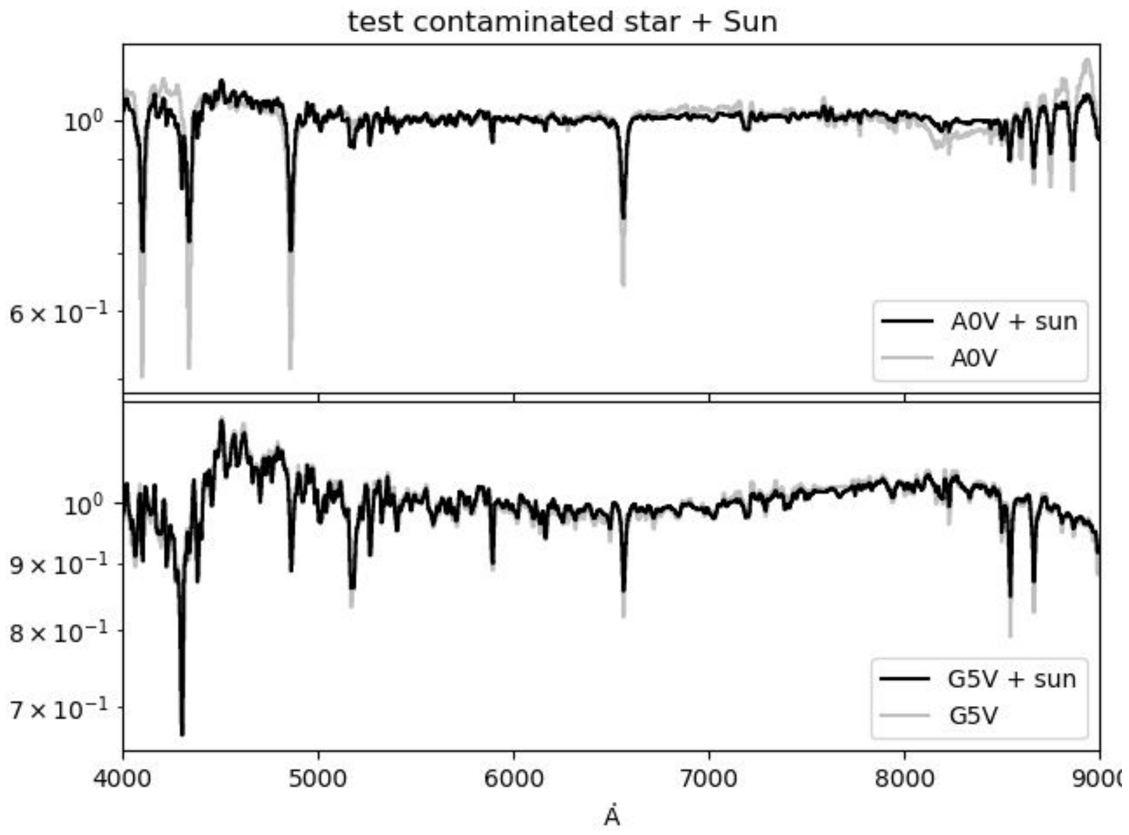
- Astronomers rely on facilities around the world and in space
  - Often combining data from multiple facilities
  - Observations are often scheduled in real time
- A single satellite trail can cause a cascade of failed follow-ups
  - Satellite constellations will cause **frequent** interruptions
  - Effectively shortens every night & endangers complex observations
- Increased access to telescope facilities can benefit *some* science
  - Optical/IR telescopes up to 6.5 m are available off-the-shelf
  - Equipped with software and high-quality CCD cameras
- Funding needed for operations as well as construction

A turnkey 6.5m observatory
Kingsley et al.
https://doi.org/10.1117/12.2313889

Ground-based refinements

S14. Knowing which spectra to throw out

- With spectroscopy, cannot separate scientific target spectrum from satellite contamination
- Quality control pipelines will *not* detect this in post-processing
- Mitigation: Detect contamination via an additional, smaller telescope with an imager — see satellite streaks — calculate which fibers are hit — throw away those spectra



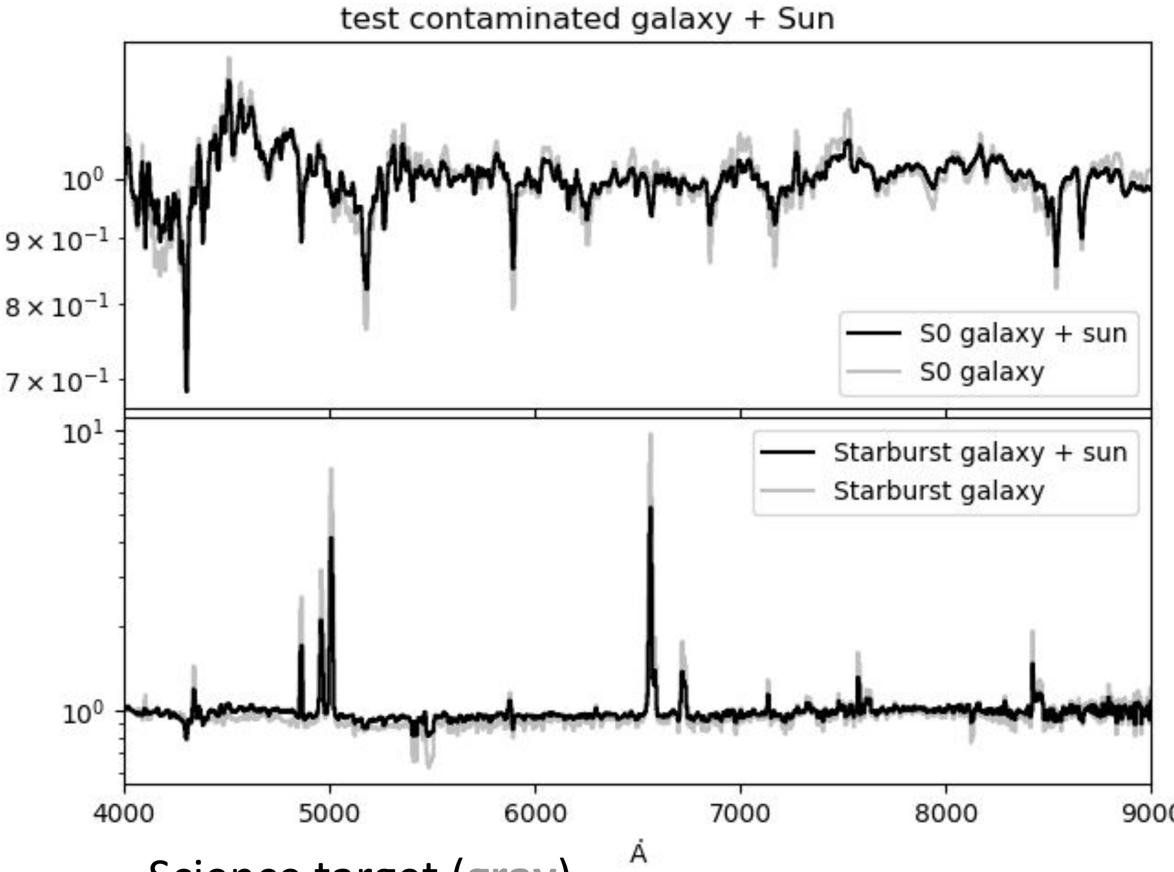
Science target (gray)

Science target + satellite contamination (**black**)

Ground-based refinements

S14. Knowing which spectra to throw out

- With spectroscopy, cannot separate scientific target spectrum from satellite contamination
- Quality control pipelines will *not* detect this in post-processing
- Mitigation: Detect contamination via an additional, smaller telescope with an imager — see satellite streaks — calculate which fibers are hit — throw away those spectra



Science target (**gray**)

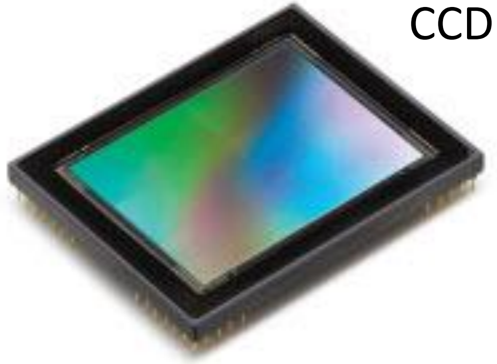
Science target + satellite contamination (**black**)

Ground-based refinements

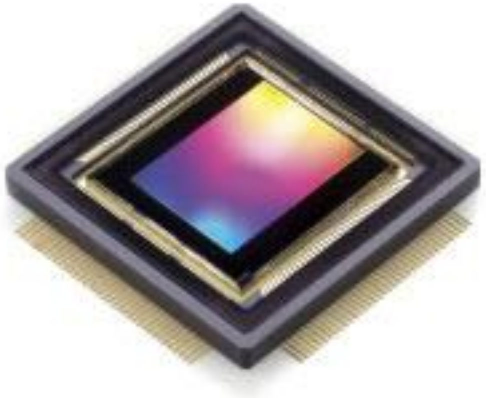
S16. Development of smarter instruments

- sCMOS (Scientific Complementary Metal Oxide Semiconductor)
    - Extremely fast readout speeds for time domain studies
    - "Active" shuttering
- Many problems with using sCMOS for science applications
    - Each pixel has a readout circuit, each column has an ADC
    - Lower-quality ADCs than in CCDs (lower image quality)
    - No on-chip binning, correlated neighbor pixels, and pixels glow
- This is a *long-term* mitigation (> 10 years)
- sCMOS would not be useful for most Rubin/LSST science

CCD



CMOS



There is much we still don’t know

Are space telescopes going to be affected?

- Hubble will not be significantly affected
- Unclear for future space telescopes
- It is not a mitigation to put all our telescopes into space
  - Ground-based observatories do science that cannot be done from space
  - Service and maintenance would be a problem
  - Lifetime of space observatory ~5 years (without service and upgrades)

There is much we still don’t know

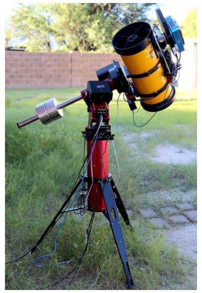
Broader impacts on astronomy that are without mitigations

- The impact on astronomy is planet-wide, all observatories affected (to different degrees)
- Impossible to estimate the impact of lost science opportunities and missed discoveries
- Systematically contaminated data archives will lead to bogus “detections” and wrong calibrations of simulations
- Decreased dark time available — increased telescope oversubscription — fewer proposals get observing time — early-career astronomers disproportionately impacted







BREAK:

WE WILL START AT 16:45 UTC

Satellite Constellation WG Team

Observations:
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Harrison Krantz, U.AZ
Eric Pearce, U.AZ
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Satellite industry engineers, SpaceX, Kuiper, et al.
Connie Walker, NOIRLab

Recommendations:
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Giuliana Rotola, ESO
Jonathan Williams, NSF
Connie Walker, NOIRLab

(speakers in magenta)

DARK & QUIET SKIES

Moderators: Sara Lucatello / Olivier Hainaut

Satellite Constellations Working Group

Recommendation Group

Industry perspectives

Patricia Cooper (Space X)

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UNITED NATIONS
Office for Outer Space Affairs

International Astronomical Union

With the support of NOIRLab

Satellite Constellations Working Group

Recommendation Group

Astronomy community, industry and policymaker recommendations

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Astronomical
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Recommendations process

Goal: Provide summarised and structured set of recommendations for the overall satellite constellation working group.

Inputs:

- NSF/AAS SATCON1 Report
- D&QS Working Groups Reports
  - Satellite Constellation Working Groups (Observations, Simulations, Mitigations)
  - Radio Astronomy Working Group
- Initial review of international law and existing regulatory frameworks
- Group expertise

Andrew Williams ESO

Policy Recommendations Framework

<u>Recommendation Owner</u>

- Observatories
- Industry
- Astronomy Community
- Science Funding Agencies
- National policymakers and regulatory agencies
- International policymakers

<u>Supporting Stakeholders</u>

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Recommendations: Observatories

Software development

- Scheduling observations,
- Predictive brightness models
- Removing image artifacts
- Analysis of systematics
- EFPD predictions for radio observations

Facility, hardware, instrumentation development

- Additional telescopes or new requirements for designs
- Technology development in instrumentation

Recommendations: Industry

Mission design

- Altitudes, satellite no., deorbiting and raising

Satellite design

- Brightness limits, reflectance analysis, antenna parameters

Satellite operations

- Positional and timing data in advance and at high precision
- Observatory avoidance
- Collaborative efforts in modelling

Raise awareness amongst key astronomy stakeholders

Corporate social responsibility initiatives

Andrew Williams ESO

Recommendations: Astronomy Community

Raise awareness amongst key astronomy stakeholders

- Conduct outreach and advocacy campaigns, engage in regulatory and licensing proceedings, and represent astronomy interests in satellite industry and professional working groups

Develop skill base to operate in the satellite constellation era

- Support development of educational materials and courses

Include satellite constellation considerations in strategic planning

- Consider satellite constellations in national strategic plans, decadal surveys and solicitation processes for new instruments and telescopes, including these considerations in developing science cases

Support collection of observational data (partnership with Industry and observatories)

- Support coordinated effort for observations of LEOsat constellation members, involving amateur astronomy community in data collection and impacts understanding

Recommendations: Science Funding Agencies

Provide support for understanding impacts on astronomy and the increased overheads in terms of additional observing time or science loss

- Instruments to help astronomy communities and observatories develop software, hardware and facility mitigations
- Identify necessary technological developments to mitigate impacts
- Evaluate impacts on funding instruments and capital investments, and report to political levels of governments

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Recommendations: National Policymakers and Regulatory Agencies

Licensing Requirements

- Satellite licensing requirements and guidelines that take into account
  - impact on multiple stakeholders
  - radio frequency issues (tomorrow!)

National Standards Agencies

- Spacecraft systems and operational standards that take into account the impacts on astronomy

National economic and space policymakers

- Space domain decision intelligence
- Investigate negative externalities of space industrial activities, and develop incentives and inducements for industry and investors.

Andrew Williams ESO

Recommendations: International Policymakers

Existing International Law Addressing Astronomy and Science

- Outer Space Treaty (1967): freedom of scientific exploration, non-interference, cooperation, and the environmental protection
- Regulatory framework in similar domains:
    - International regulation, guidelines, and national laws protecting radio astronomy and on mitigation of space debris
    - National laws on space advertising

Recommendations for Development of International Law

- Develop international agreements and national laws related to the impact of electromagnetic radiation from satellites on science
- Make efforts to mitigate or eliminate harmful aspects of such impacts
- Develop capacity-building measures and outreach efforts to encourage the discussion between stakeholders

Andrew Williams ESO

Policy challenges

- Balancing government responsibility and public interest in
    - Conserving Earth's pristine natural landscapes
    - Growing national space industries and a global space economy
    - Conducting and supporting fundamental scientific research

- Interconnected problems in space governance:
    - LEO as a common pool resource
    - Negative externalities (debris, astronomy impacts, interference etc)
    - Integration with existing policy landscape of radio regulation
    - Challenge to develop international agreements

The way ahead: Shared Stewardship

Scientific Organising Committee of the D&QS Workshop seeks a COPUOS endorsement, in order to:

- Raise awareness of astronomy as part of the space community
- Encourage States, Industry, Astronomers, and other affected stakeholders to collaborate on principles, rules and information sharing
- Guide the development of future national policy to create a level playing field for industry and norms of responsible operation

Andrew Williams ESO

Dark and Quiet Skies for Science and Society

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Dark and Quiet Skies for Science and Society: Draft Reports

Five Draft Reports are available and open for comments until 16 October

- Download them from http://bit.ly/DQS_reports
- Please comment recommendations at http://bit.ly/DQS_comment

If you registered for today's Workshop then you have received the links on Thursday in an email from UNOOSA-Events@un.org and on Friday in an email from DQSkies@iac.es

Not received even though you had registered? Please email UNOOSA-Events@un.org

Dark and Quiet Skies for Science and Society

Closing Remarks
SOC member
Piero Benvenuti
IAU EC Advisor

UNITED NATIONS
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Thank you!

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