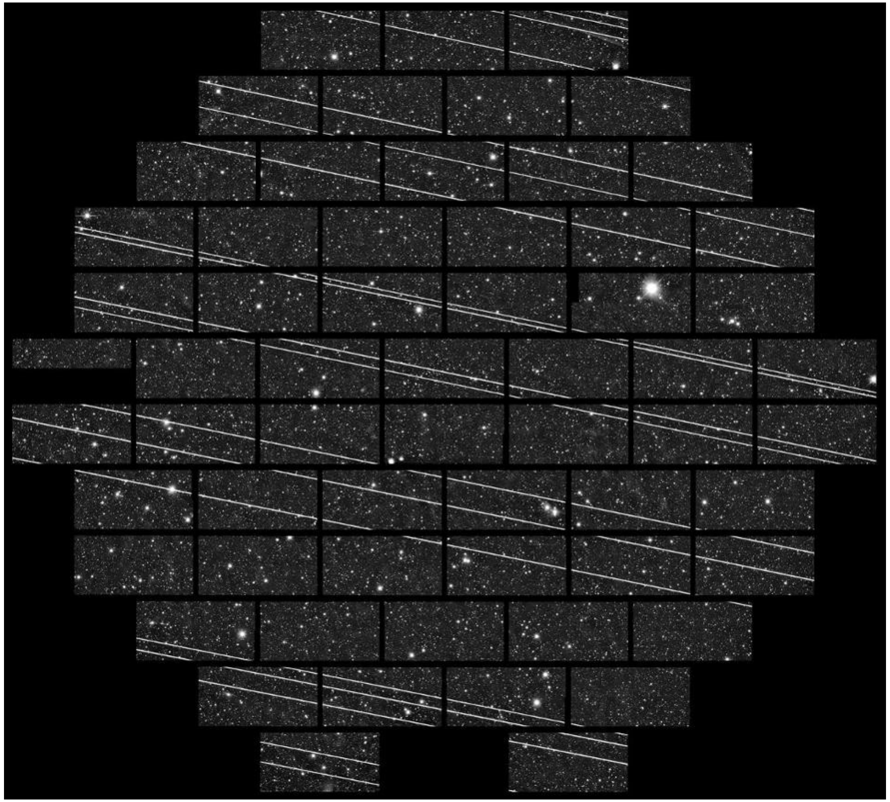
Optical to NIR magnitude measurements of the Starlink LEO satellites & effectiveness of the Darksat darkening treatment

J. Tregloan-Reed, A. Otarola, E. Unda-Sanzana, J. P. Colque, E. Ortiz, V. Molina, J. Anais, and R. González

SATCON1

June 29th 2020

LEO communication satellites



Clara Martínez-Vázquez and Cliff Johnson. NSF's National Optical-Infrared Astronomy Research Laboratory/CTIO/AURA/DELVE

Around 19 Starlink satellites were imaged shortly after launch in November 2019 using the Blanco 4m telescope.

Observations of STARLINK-1113 & 1130 (Darksat)

Chakana 0.6m telescope, Ckoirama
(Universidad de Antofagasta)
http://www.astro.uantof.cl/ckoirama
Observers: J. Tregloan-Reed, J. P. Colque, E. Ortiz, V. Molina, J. Anais, R. González, and E. Unda-Sanzana

VISTA 4.1m telescope, ESO Paranal
Observers: B Haeussler, F. Gaete, A. Otarola

Observations of STARLINK-1113 & 1130 (Darksat)

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VISTA 4.1m telescope, ESO Paranal

Observers: B. Haeussler, F. Gaete, S. Mieske, S. Brilliant, J. Anderson

Forecasting observable LEO satellites

Our Python script downloads the latest TLE data from

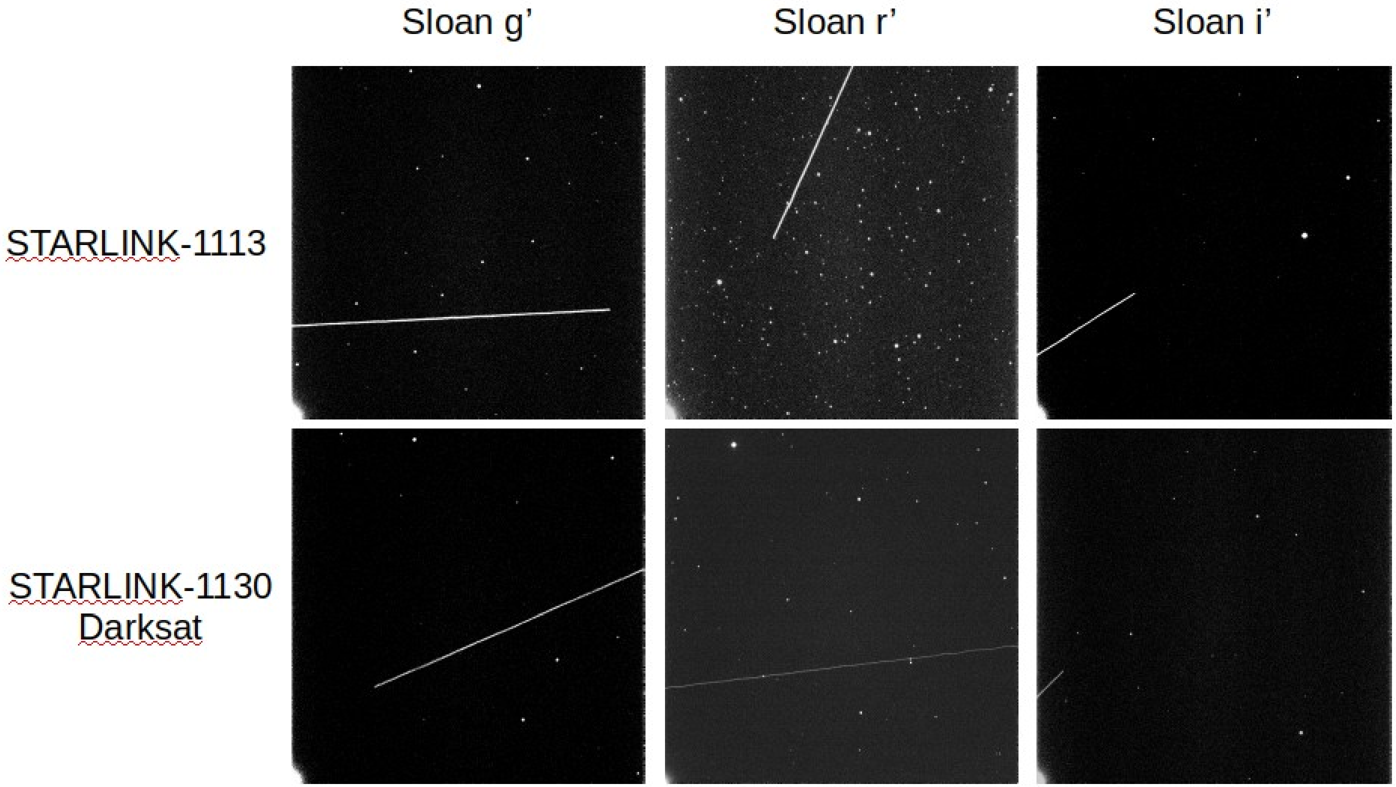
https://celestrak.com/NORAD/elements/supplemental/starlink.txt

Using the latest TLE data and the location of the observatory, our script (written by A. Otarola) uses the Pyorbital package to determine the time (UTC), RA and DEC of the LEO satellite's position in 1s intervals along with calculating the Sun's position (RA, DEC and zenithal distance) and the angular speed of the satellite across the imaging system for the moment of observation.

```python
    OBSname = sys.argv[1]
    if OBSname == "KPEAK":
        #Kitt Peak Observatory location
        obsName = 'K.P. Observatory'
        (obs_lat, obs_lon, obs_altitude) = (+31.9599, -111.5997, 2.067)
    elif OBSname == "CTIO":
        #CTIO  Observatory location
        obsName = 'CTIO'
        (obs_lat, obs_lon, obs_altitude) = (-30.1690, -70.8063, 2.2)
    elif OBSname == "CKOIRAMA":
        #Ckoirama Observatory location
        obsName = 'Ckoirama Observatory'
        (obs_lat, obs_lon, obs_altitude) = (-24.08913333, -69.93058889, 0.966)
    elif OBSname == "HOME":
        #home location
        obsName = 'Home'
        (obs_lat, obs_lon, obs_altitude) = (+32.2671111, -110.8507778, .753)
    elif OBSname == "VLT":
        #VLT location: Note make sure the coordinates are for the telescope to be used
        obsName = 'VLT'
        (obs_lat, obs_lon, obs_altitude) = (-24.6275, -70.4044, 2.650)
    elif OBSname == "VISTA":
        #VISTA Telescope location:
        obsName = 'VISTA'
        (obs_lat, obs_lon, obs_altitude) = (-24.6157000, -70.3976000, 2.635)
    else:
```

```
UT Date,   UT time,     Sat(lon),      Sat(lat),      Sat(alt), Sat(Azimuth), Sat(Elevation),  SatRA[hr]  SatDEC[deg]  SunRA[hr]   SunDEC[deg]  SunZenithAngle[deg]
2020-03-07 00:26:56    -77.836089     -24.660030      562.17  263.864 30.103 - 02.517723 -16.881320 23.1967429 -5.1706680 109.491
2020-03-07 00:26:57    -77.794766     -24.612873      562.15  264.224 30.268 - 02.535817 -16.639034 23.1967436 -5.1706635 109.495
2020-03-07 00:26:58    -77.753478     -24.565702      562.13  264.587 30.434 - 02.553977 -16.394423 23.1967443 -5.1706590 109.499
2020-03-07 00:27:00    -77.671002     -24.471316      562.09  265.327 30.764 - 02.590498 -15.898202 23.1967458 -5.1706500 109.506
2020-03-07 00:27:01    -77.629815     -24.424103      562.08  265.703 30.929 - 02.608858 -15.646579 23.1967465 -5.1706454 109.510
2020-03-07 00:27:02    -77.588661     -24.376875      562.06  266.083 31.094 - 02.627285 -15.392608 23.1967472 -5.1706409 109.513
2020-03-07 00:27:03    -77.547541     -24.329634      562.04  266.467 31.258 - 02.645778 -15.136284 23.1967479 -5.1706364 109.517
2020-03-07 00:27:04    -77.506454     -24.282378      562.02  266.855 31.422 - 02.664337 -14.877603 23.1967486 -5.1706319 109.521
```

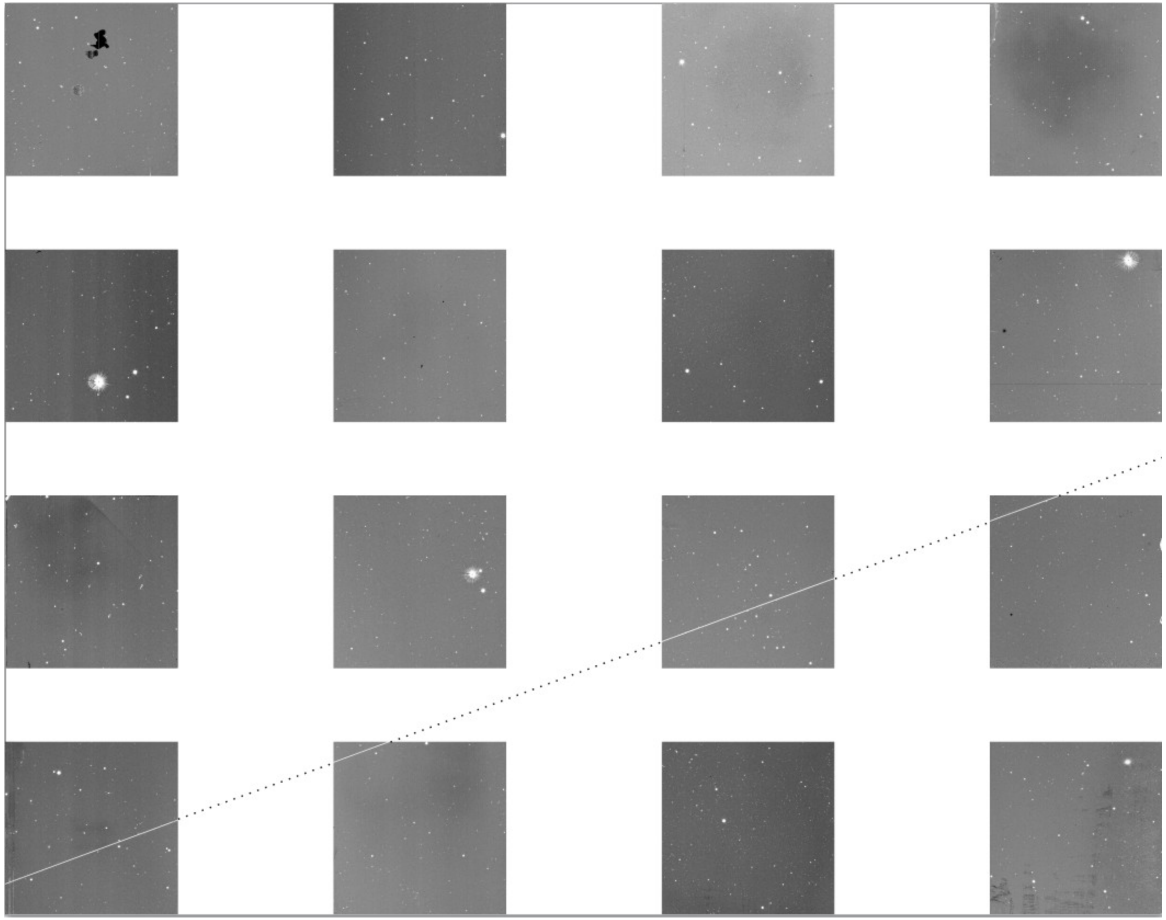
Observing LEO satellites in the optical to NIR



Images of Darksat & STARLINK-1113 observed by the Chakana telescope

- An FLI ProLine 16801 camera is installed on Chakana telescope.
- Currently three filters are available Sloan g', Sloan r', and Sloan I'.
- The detector has a 32.4 x 32.4 arcmin FOV.

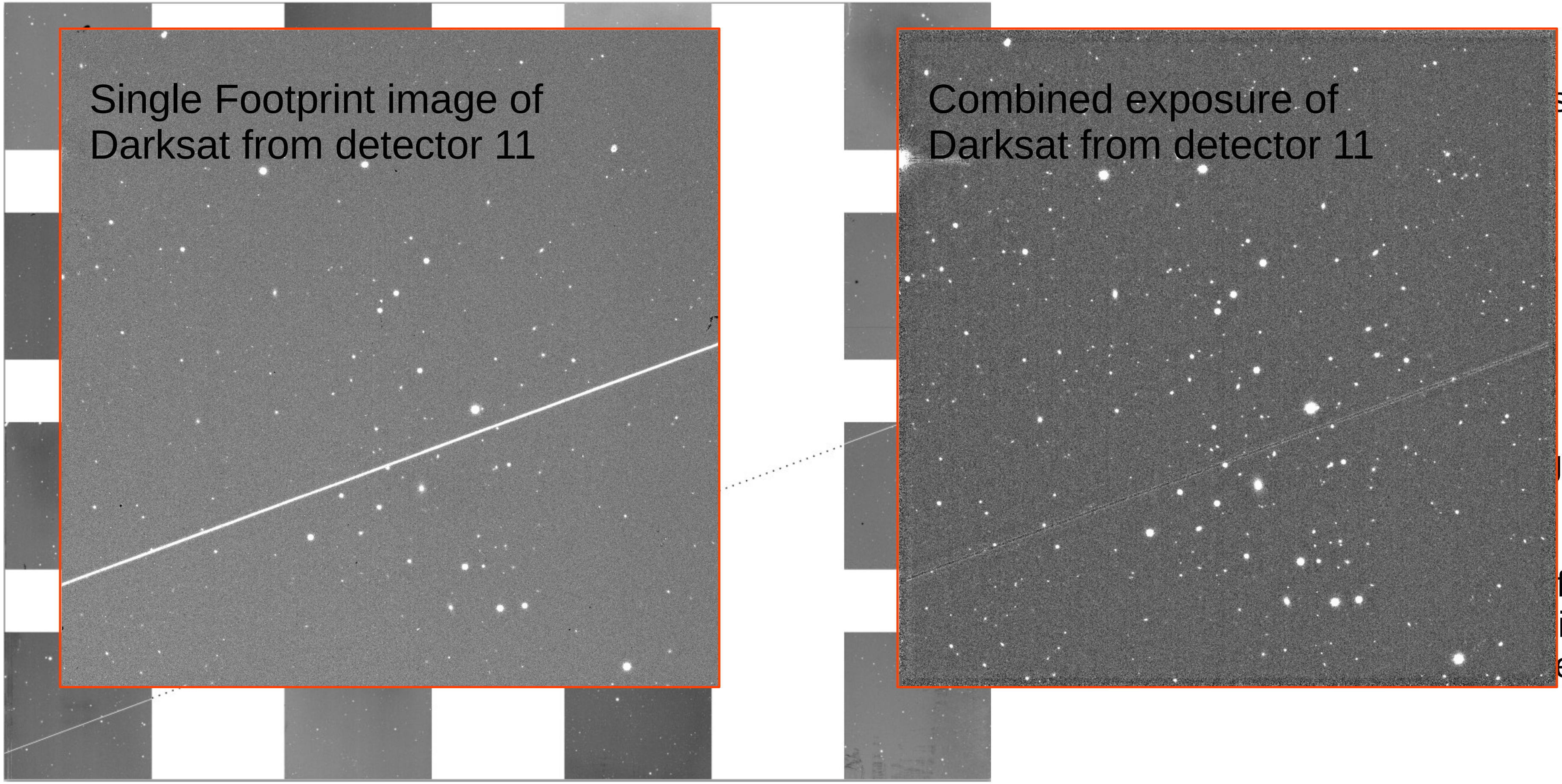
Observing LEO satellites in the NIR



VIRCAM VISTA footprint of Darksat in the J-band, 06-03-2020

- 16 detectors, each with 11.6 x 11.6 arcmin FOV.
- 4.9 arcmin vertical spacing between detector.
- 10.4 arcmin horizontal spacing between each detector.
- Each observation comprises of 4 to 6 footprints, which when combined creates a 1.65° diameter image.

Observing LEO satellites in the NIR



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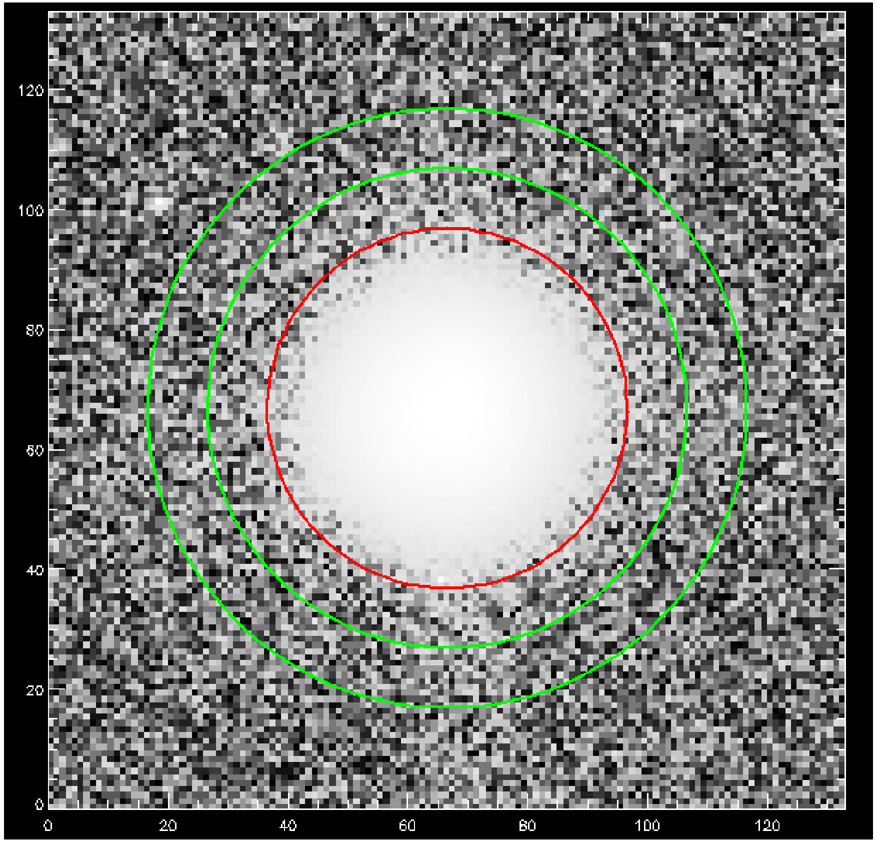
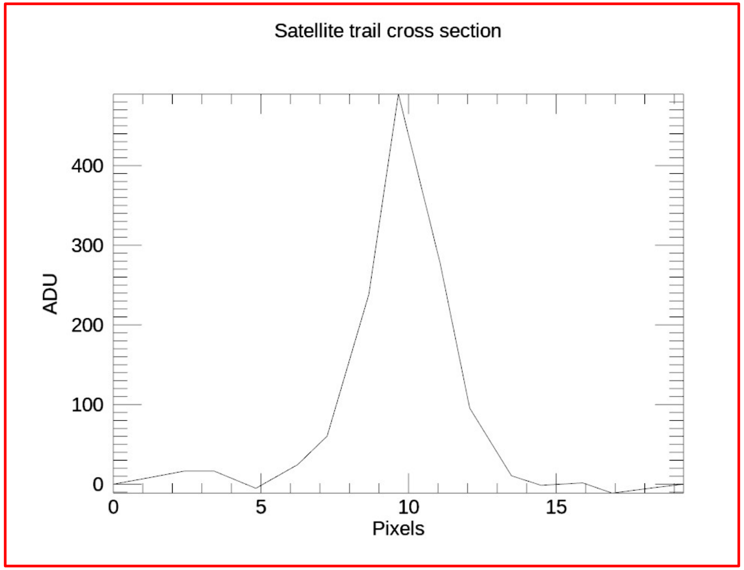
Analysis of LEO satellite observations



Calculating the comparison star fluxes

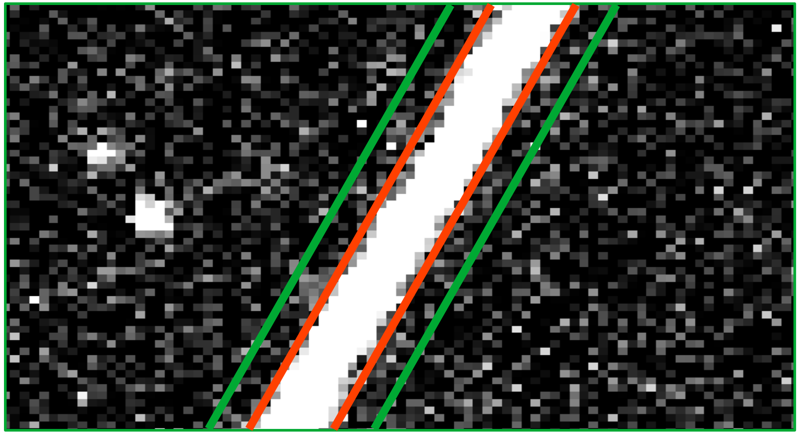
- The pixel average sky-background is calculated from the pixels which lie within the middle and outer aperture rings.
- The pixel average sky-background is subtracted from the source pixels lying within the inner aperture ring.
- The total integrated flux within the inner aperture ring is calculated.

Analysis of LEO satellite observations



Calculating the satellite trail flux

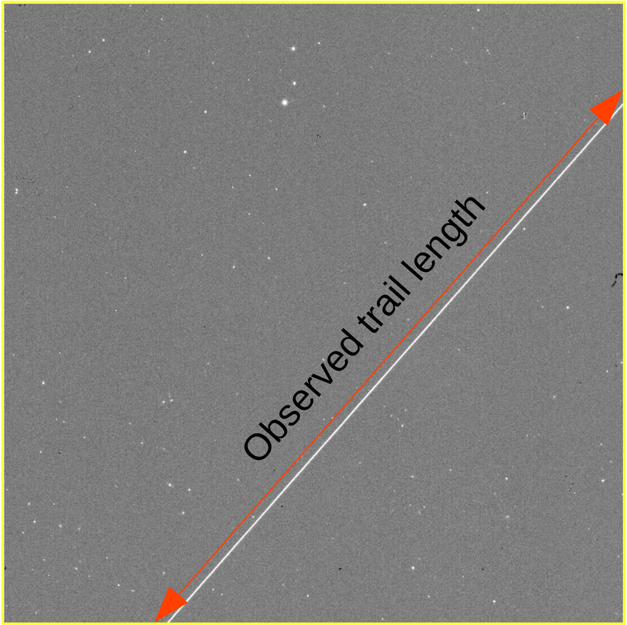
- The satellite trail is highly defined in the images.
- This allows two sets of parallel lines to be fitted along the satellite trail. Where the pixel average sky-background is calculated using the pixels between the inner and outer parallel lines.
- After subtracting the sky-background, the total integrated flux of the satellite trail is calculated using the pixels between the two inner lines.



Analysis of LEO satellite observations

Calculating the estimated flux

- The observed satellite trail only gives a partial picture.
- There are two methods to determine the true magnitude of the LEO satellite, both requiring the angular velocity of the LEO satellite, which is calculated by our telemetry code.
- Using the angular velocity and the observed trail length, it is possible to calculate the time it took the LEO satellite to travel across the FOV.
- The flux of the comparison stars can then be multiplied by the ratio between the travel and exposure times.



UT Date,	UT time,	Sat(lon),	Sat(lat),	Sat(alt),	Sat(Azimuth),	Sat(Elevation),		SatRA[hr]	SatDEC[deg]	SunRA[hr]	SunDEC[deg]	SunZenithAngle[deg]
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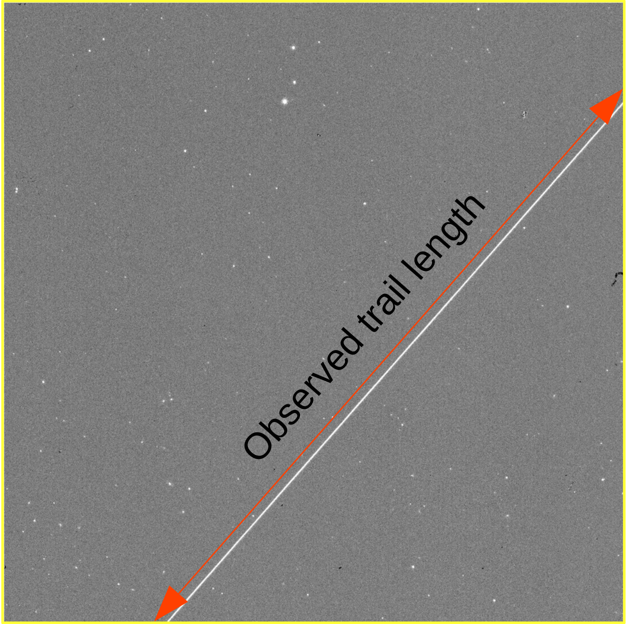
2020-03-07	00:27:01	-77.629815	-24.424103	562.08	265.703	30.929	-	02.608858	-15.646579	23.1967465	-5.1706454	109.510
2020-03-07	00:27:02	-77.588661	-24.376875	562.06	266.083	31.094	-	02.627285	-15.392608	23.1967472	-5.1706409	109.513
2020-03-07	00:27:03	-77.547541	-24.329634	562.04	266.467	31.258	-	02.645778	-15.136284	23.1967479	-5.1706364	109.517
2020-03-07	00:27:04	-77.506454	-24.282378	562.02	266.855	31.422	-	02.664337	-14.877603	23.1967486	-5.1706319	109.521

Analysis of LEO satellite observations

Calculating the estimated flux

- The second method uses the angular velocity to estimate the trail length for the exposure time.
- The flux from the observed trail, is then multiplied by the ratio between the observed and estimated trail lengths.
- For our work on Darksat and STARLINK-1113, the results from both methodologies agree within their 1-σ uncertainties.



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Analysis of LEO satellite observations

Calculating the observed and estimated magnitude

- Once the integrated fluxes of the satellite trail and comparison stars are found, the differential magnitude can be calculated.

  $M_{diff} = -2.5 * \log(F_{sat} / F_{star})$

- When combined with the comparison star magnitude from the literature, the magnitude of the satellite is determined.

  $M_{sat} = M_{star} – M_{diff}$

- The result from each comparison star is then combined by a weighted mean, to determine the LEO satellite magnitude for the observation.

```
Lower Diff Mag of star 1 =       -0.50598358 +/-     0.00065254613
Estimated Diff Mag of star 1 =        -4.5564253 +/-      0.028706782
Observed Magnitude of Sat to compariosn 1 =         8.9420164 +/-       0.023009255
Estimated Magnitude of Sat to compariosn 1 =         4.8915747 +/-      0.036784227
*****************************************************************************************************
Lower Diff Mag of star 2 =        -1.9290569 +/-     0.00098973513
Estimated Diff Mag of star 2 =        -5.9794986 +/-      0.029044030
Observed Magnitude of Sat to compariosn 2 =         9.0519431 +/-       0.024020399
Estimated Magnitude of Sat to compariosn 2 =         5.0015014 +/-      0.037676992
*****************************************************************************************************
Lower Diff Mag of star 3 =        -3.5086086 +/-      0.0017407537
Estimated Diff Mag of star 3 =        -7.5590505 +/-      0.029794856
Observed Magnitude of Sat to compariosn 3 =         9.4353914 +/-       0.024063047
Estimated Magnitude of Sat to compariosn 3 =         5.3849495 +/-      0.038258769
*****************************************************************************************************
Lower Diff Mag of star 4 =        -2.7086225 +/-      0.0012928247
Estimated Diff Mag of star 4 =        -6.7590641 +/-      0.029347053
Observed Magnitude of Sat to compariosn 4 =         9.4813775 +/-       0.023036306
Estimated Magnitude of Sat to compariosn 4 =         5.4309359 +/-      0.037286050
*****************************************************************************************************
Lower Diff Mag of star 5 =        -3.7954378 +/-      0.0019457936
Estimated Diff Mag of star 5 =        -7.8458794 +/-      0.030000044
Observed Magnitude of Sat to compariosn 5 =         9.3705622 +/-       0.024078748
Estimated Magnitude of Sat to compariosn 5 =         5.3201206 +/-      0.038418779
*****************************************************************************************************
Lower Diff Mag of star 6 =        -3.2645962 +/-      0.0015860796
Estimated Diff Mag of star 6 =        -7.3150379 +/-      0.029640342
Observed Magnitude of Sat to compariosn 6 =         9.4964038 +/-       0.023054623
Estimated Magnitude of Sat to compariosn 6 =         5.4459621 +/-      0.037517328
*****************************************************************************************************
Lower Diff Mag of star 7 =        -2.4163473 +/-      0.0011663139
Estimated Diff Mag of star 7 =        -6.4667890 +/-      0.029220566
```

Comparing LEO satellite magnitudes

To directly compare the reflective brightness between LEO satellites requires that the magnitudes to be calibrated and normalised

- The observations conducted of the satellites had different ranges (distances).
- The measured flux follows the inverse square law. By doubling the range, the satellite appears four times fainter.
- We therefore normalise the range to the intended orbital height of the satellites (550km), which is the equivalent of observing the satellite at the local zenith (elevation = 90°) or airmass = 1.
- The magnitude of the satellites is scaled using +5 log(r/550), where r is the range of the satellite, in km at the time of the observation.
- Most of the observed light is diffused, so we need to calibrate for the solar and observer phase angles.

Comparing LEO satellite magnitudes

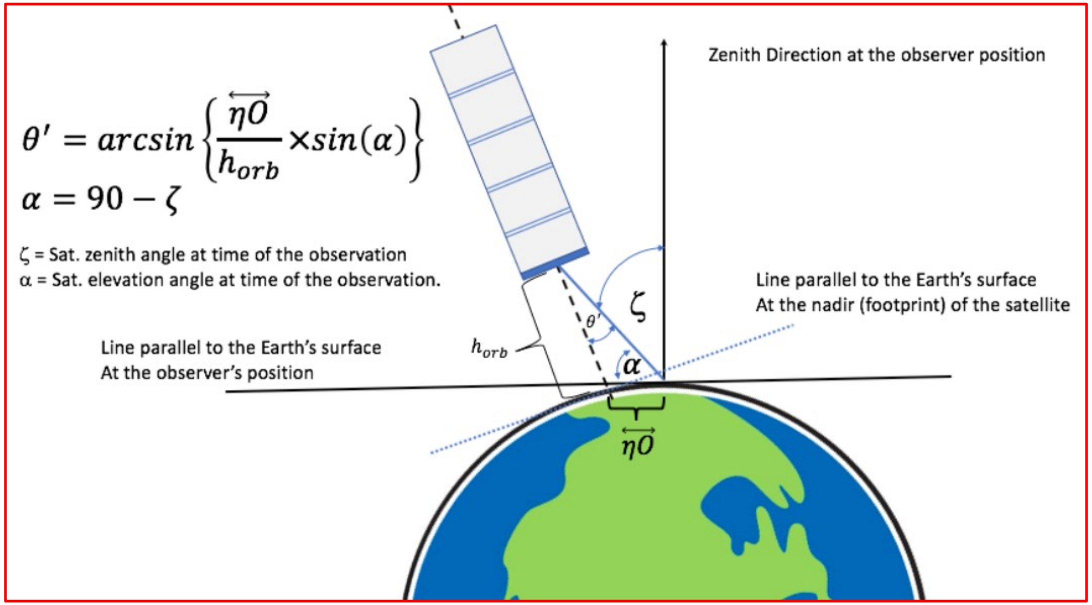
Observer and solar phase angles

- The solar phase angle is computed from the position of the Sun and satellite at the time of the observation and is computed by our telemetry code

- The observer phase angle is the angle between the observer and the unit normal of the Earth facing surface of the satellite and is approximated by:

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

- where η is the straight line distance between the observer and the satellite footprint (nadir) and α is the elevation.



Comparing LEO satellite magnitudes

Estimating the ratio of the solar phase attenuation

- Without empirical observations of the Bidirectional Reflectance Distribution Function (BRDF) for the Starlink satellites, we can only provide an estimated value by using a parametrised BRDF model from Minnaert (1941). Consequently, we estimate the ratio (R) of the solar phase attenuation between Darksat and STARLINK-1113 with:

$$R = \left(\frac{\cos \theta_{1130} \cos \phi_{1130}}{\cos \theta_{1113} \cos \phi_{1113}} \right)^{k-1}$$

- where k is the Minnaert exponent and ranges from 0 to 1 with k = 1 representing a perfect Lambertian surface.

- For our work we set k = 0.5 (e.g. a dark surface Stamnes et al. 1999). The resultant values for R are in agreement to the first order approximation of the solar phase attenuation for a diffusing sphere, (1 + cos θ)/2 given by Hainaut & Williams (2020).

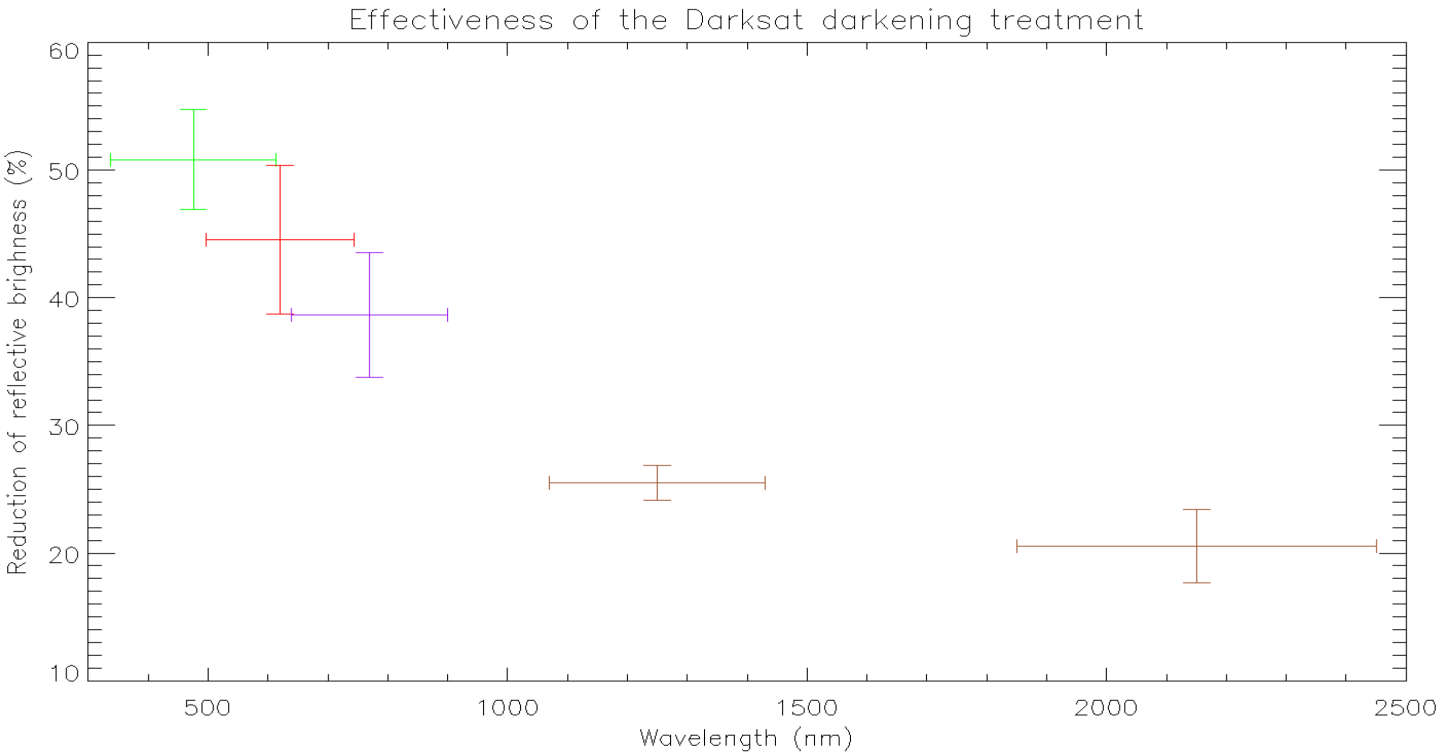
Optical to NIR magnitude measurements of the Starlink LEO satellites

Normalised magnitude measurements of STARLINK-1113 and 1130 (Darksat). Sloan g' (Tregloan-Reed et al. 2020, A&A, 637, L1). NIR, Sloan r' and Sloan i' (Tregloan-Reed et al. In Preparation).

- In all passbands, Darksat is dimmer than STARLINK-1113.
- The reflective brightness of both satellites increases with increasing wavelength.
- The effectiveness of the Darksat darkening treatment decreases with increasing wavelength.

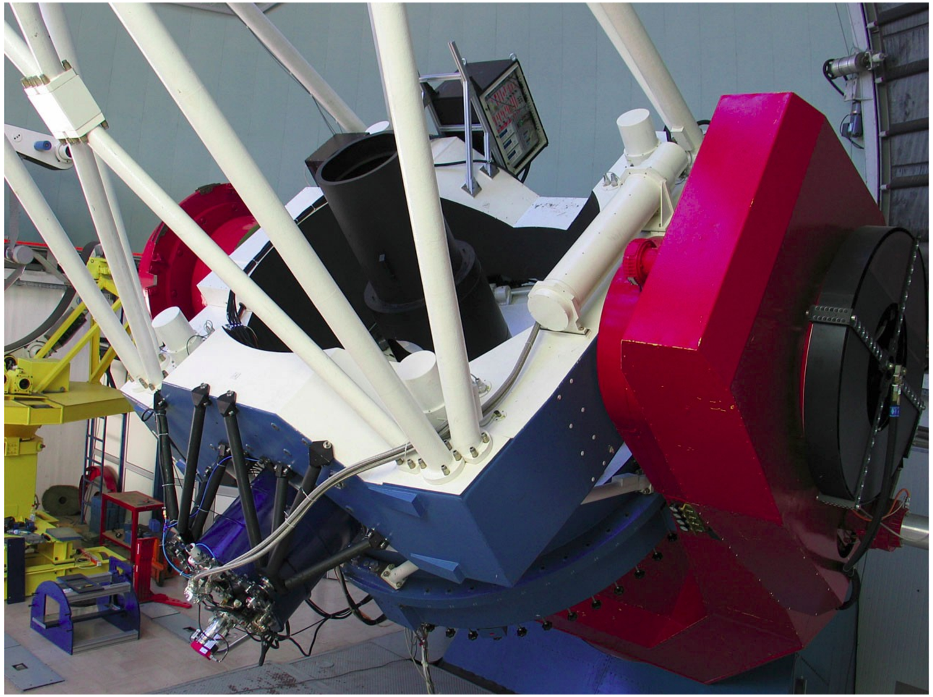
Starlink	Sloan g' Magnitude (475.4 nm)	Sloan r' Magnitude (620.4 nm)	Sloan i' Magnitude (769.8 nm)	NIR J-band Magnitude (1250 nm)	NIR Ks-band Magnitude (2150 nm)
1113	5.33 ± 0.05	4.88 ± 0.05	4.41 ± 0.04	3.93 ± 0.01	3.62 ± 0.02
1130 (Darksat)	6.10 ± 0.04	5.52 ± 0.07	4.94 ± 0.05	4.25 ± 0.01	3.87 ± 0.02

Effectiveness of the Darksat darkening treatment



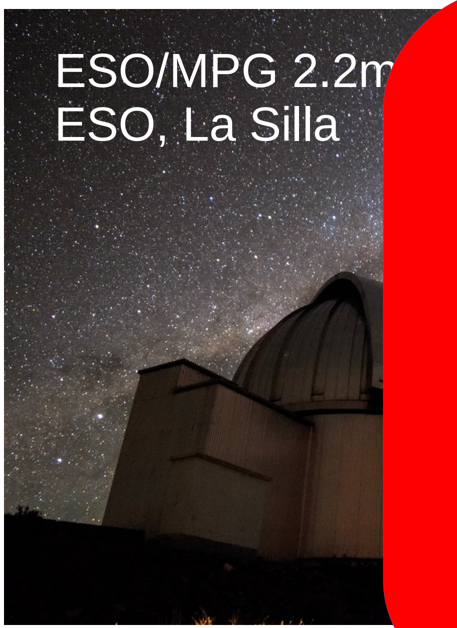
Reduction of reflective brightness between Darksat and STARLINK-1113, for the optical to NIR (*Tregloan-Reed et al. In Preparation*).

Future VisorSat observations



GROND (Gamma-Ray burst Optical/Near infrared Detector)

Future VisorSat observations



Simultaneously observe in seven passbands

Optical to NIR

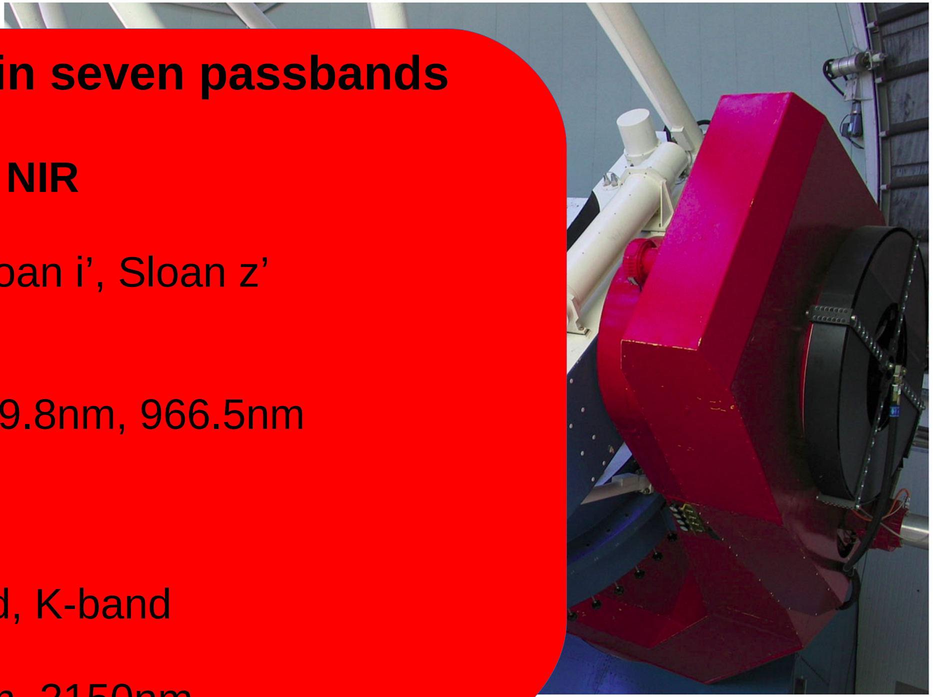
Sloan g’, Sloan r’, Sloan i’, Sloan z’

475.4nm, 620.4nm, 769.8nm, 966.5nm

NIR

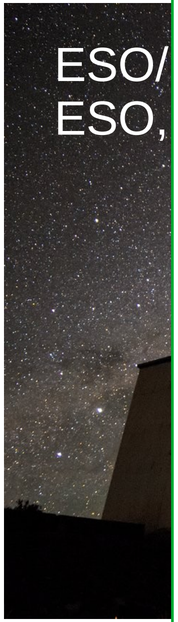
J-band, H-band, K-band

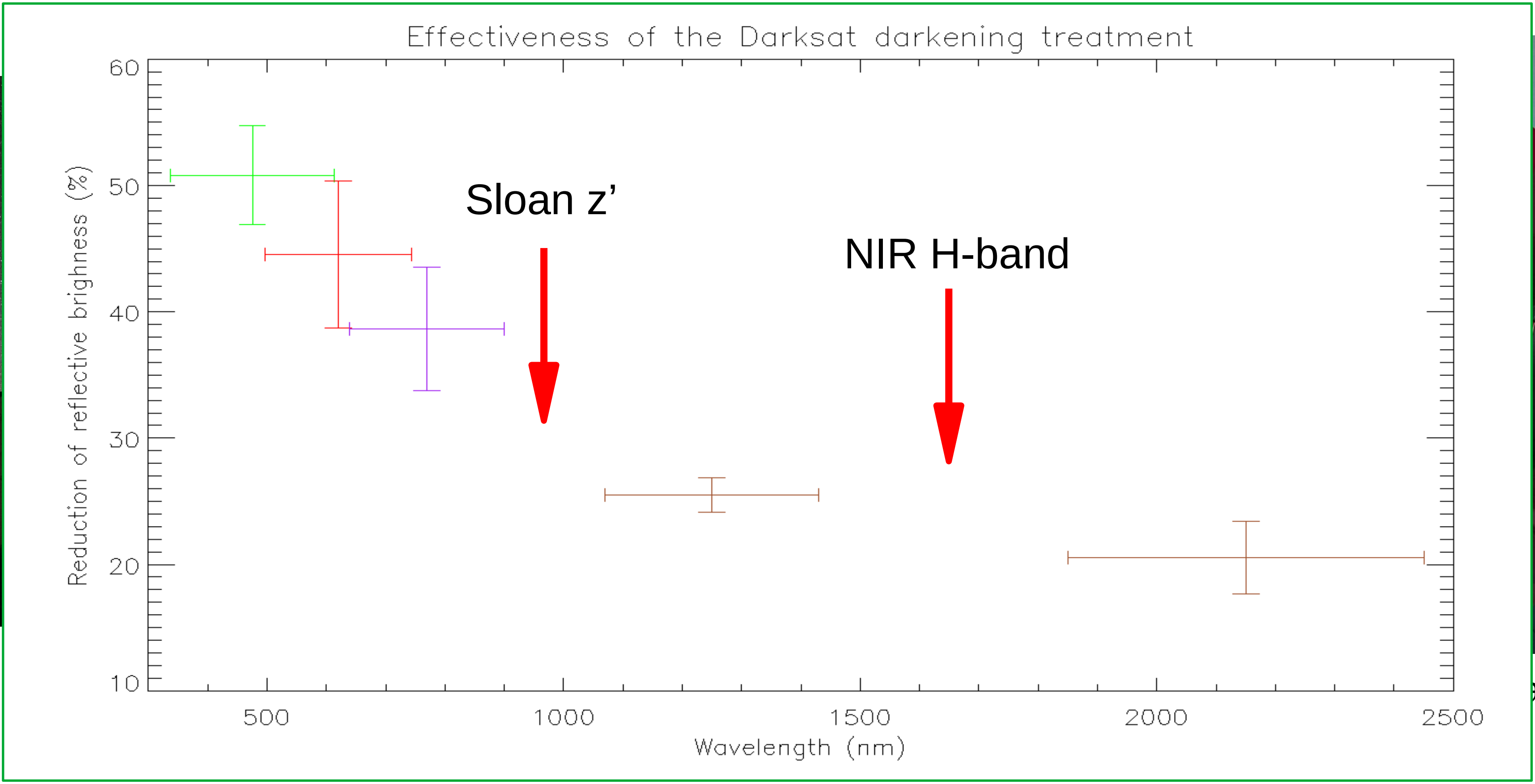
1250nm, 1650nm, 2150nm

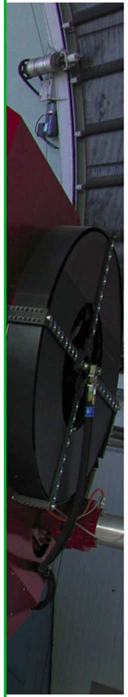


GROND (Gamma Ray burst Optical/Near infrared Detector)

Future VisorSat observations







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Special thanks to our team members and observers!

Centro de Astronomía (CITEVA) Universidad de Antofagasta
E. Unda-Sanzana, J. P. Colque, E. Ortiz, V. Molina, J. Anais, R. González

TMT International Observatory
A. Otarola

ESO Paranal
B. Haeussler, F. Gaete, S. Mieske, S. Brilliant, J. Anderson

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