LIÈGE université
Astrobiology

Credits: NASA

Introduction to exoplanetology

Practical work

2021-2022

TESS space telescope

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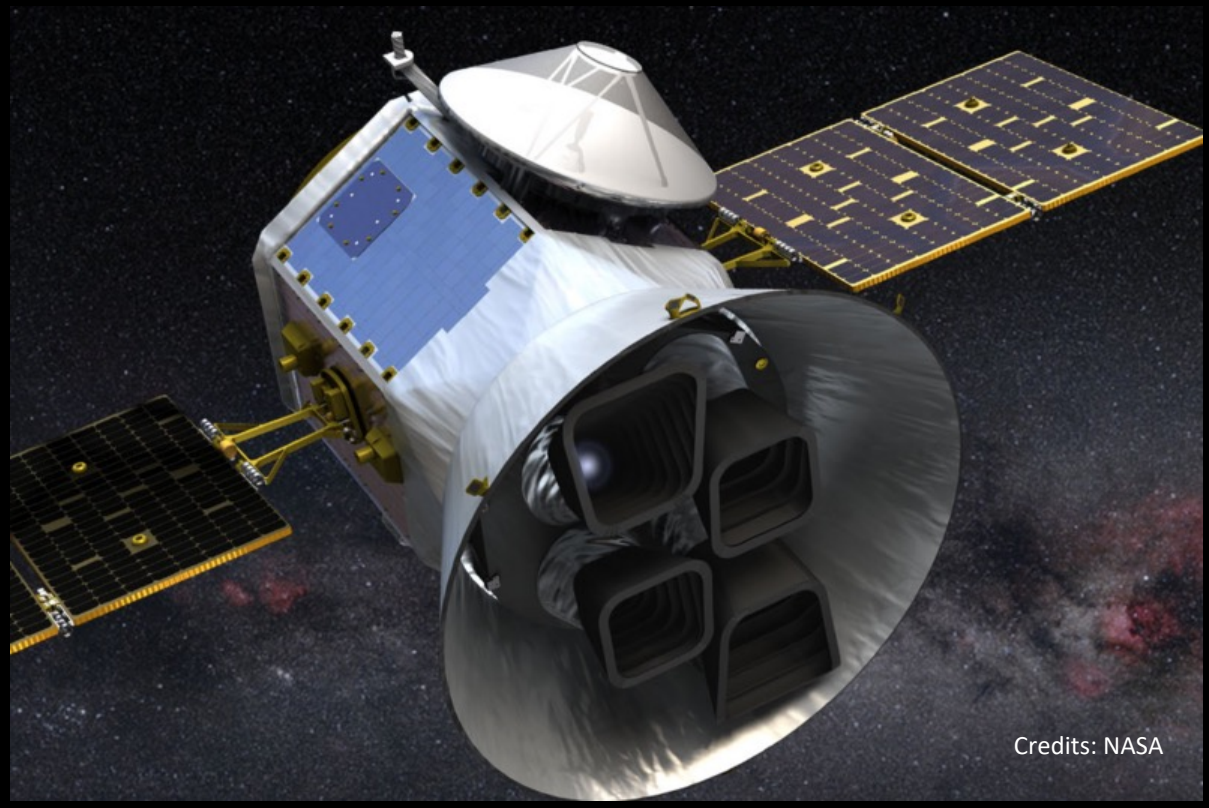
TESS (Transiting Exoplanet Survey Satellite)

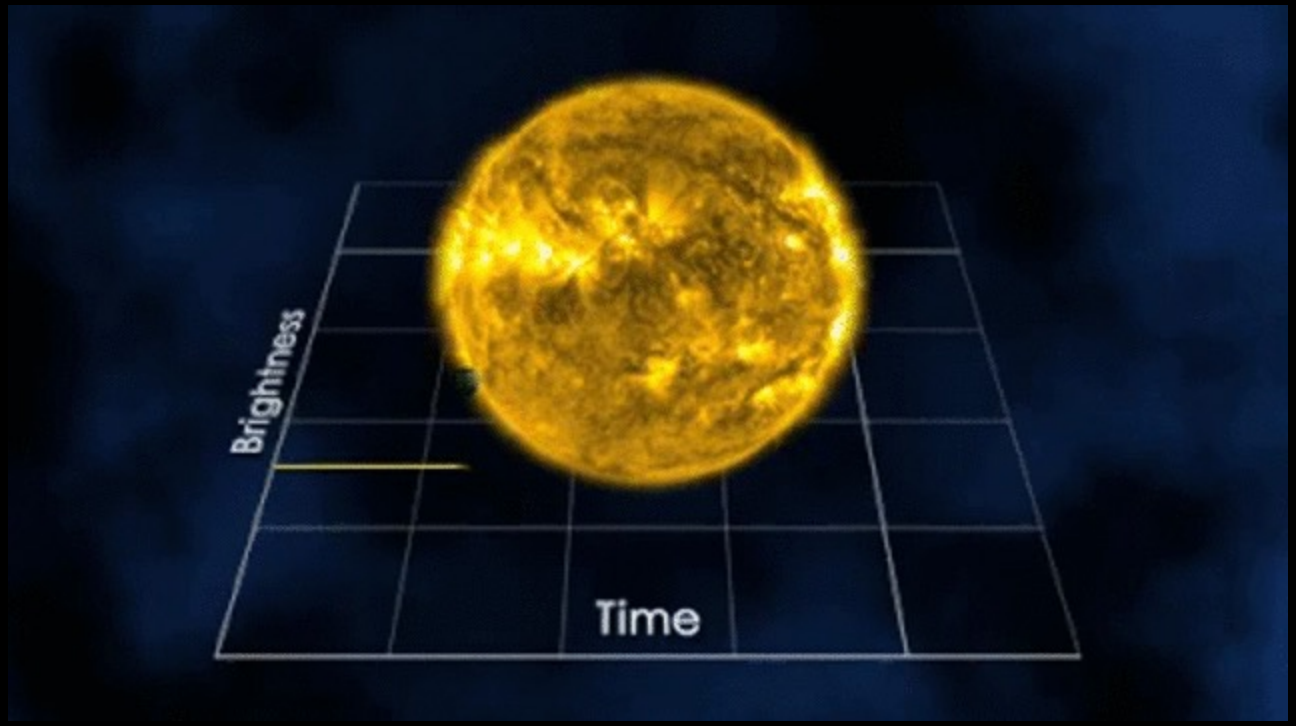
- Photometric all-sky survey
- NASA mission led by MIT
- Primary mission : search for **transiting exoplanets**

  → Earth and super-Earth sized planets



Credits: Harvard University

Exoplanet in transit – indirect detection method



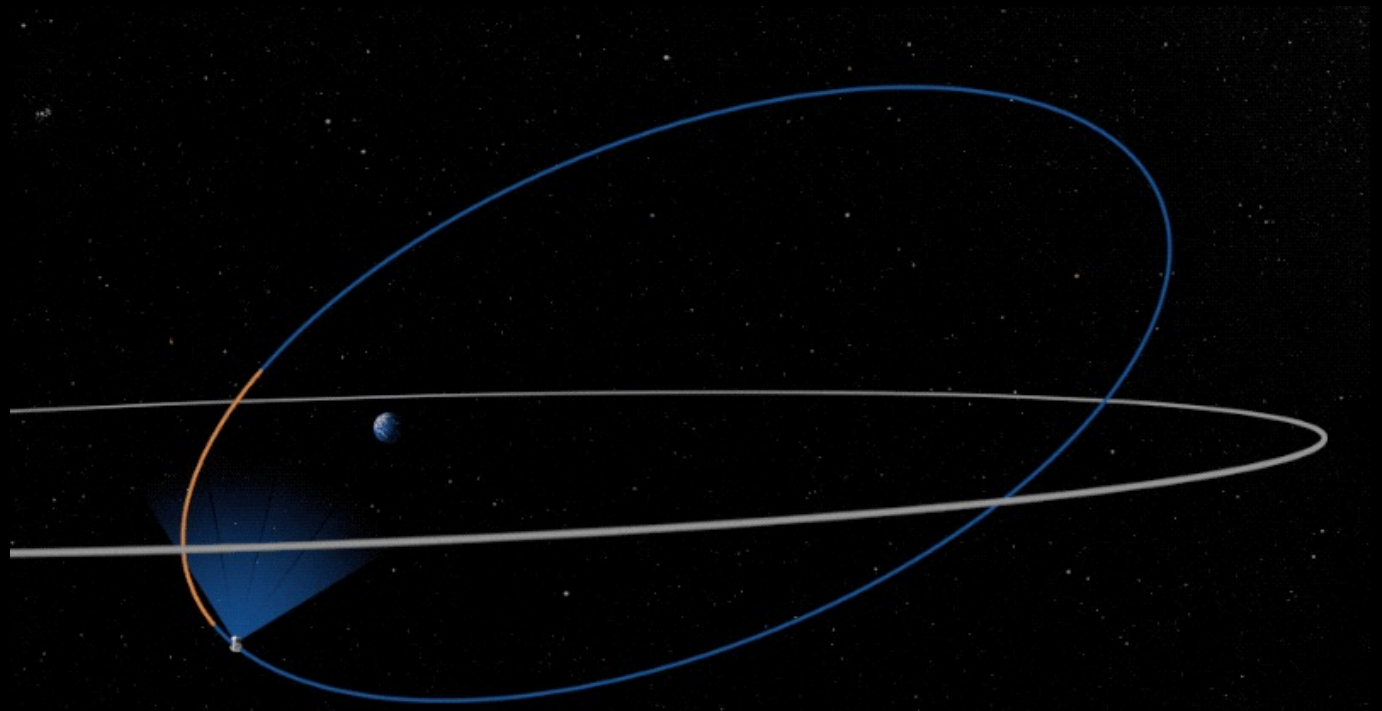
Drop of brightness when the planet passes in front of the star.

Access to planetary and orbital parameters given stellar parameters.

TESS orbit

Credits: NASA

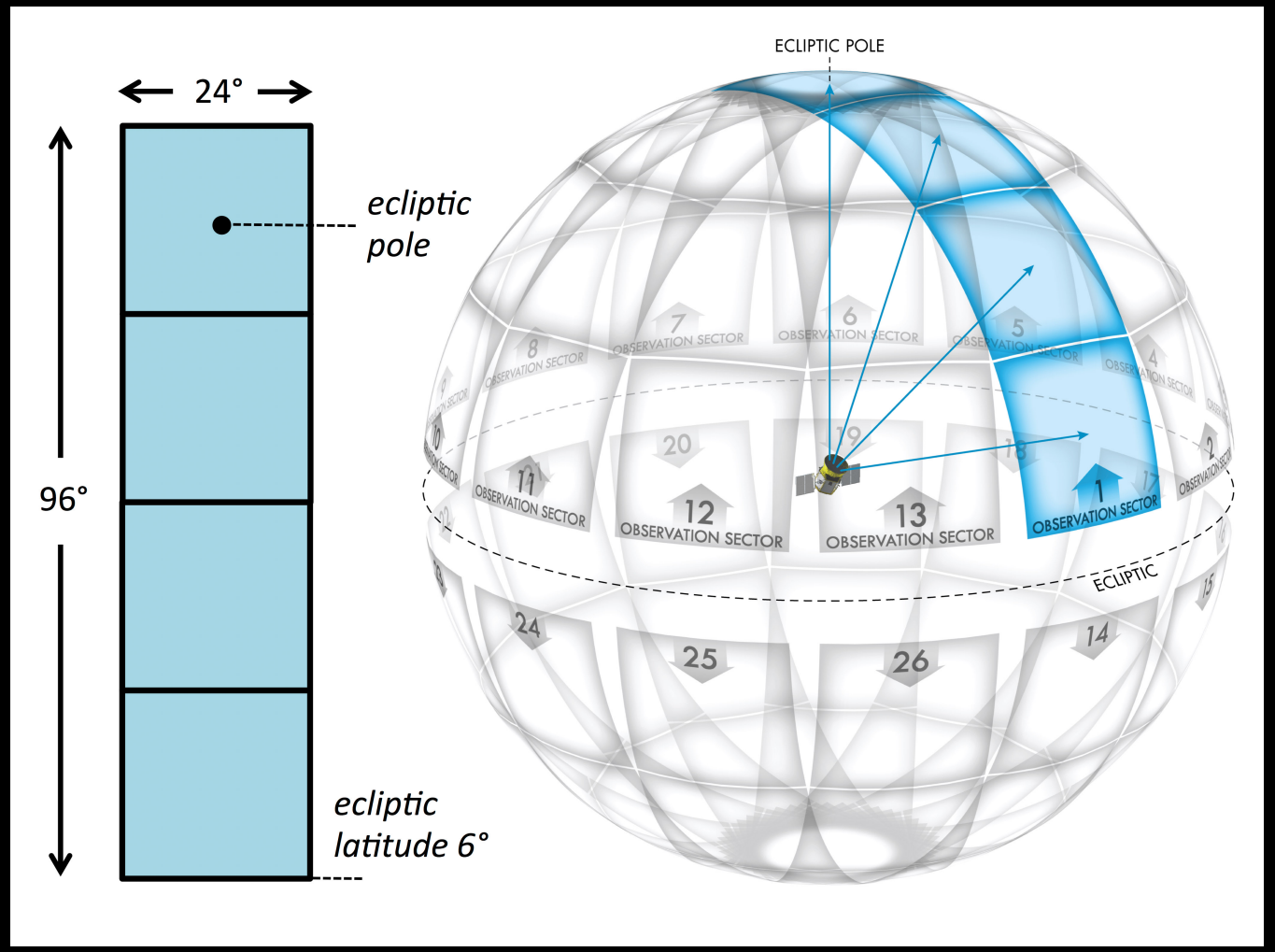
- **Launched in 2018**
- Elliptical orbit
- 2:1 resonance with the moon
- P = 13.7 days
- Data transfer at perigee during 16 hours.



Science instrument

- 4 cameras arranged in a 4x1 array
- f/1.4 lenses
- CCD detectors
- Red/optical band: 600-1000 nm
- 2048 x 2048 pixels

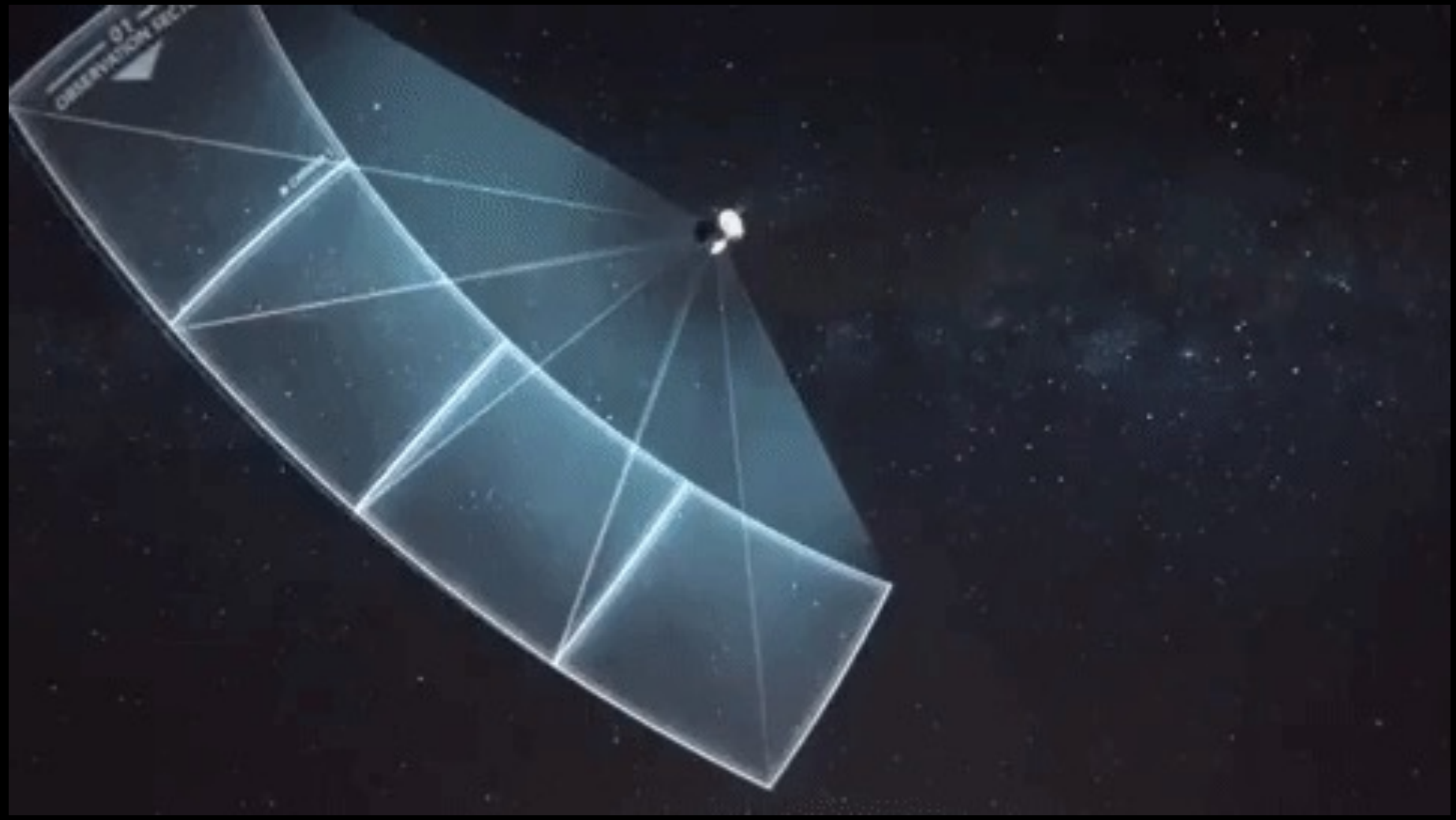
Optimized for main sequence dwarf stars F5-M5



Credits: Ricker et al. (2015)

Observing strategy

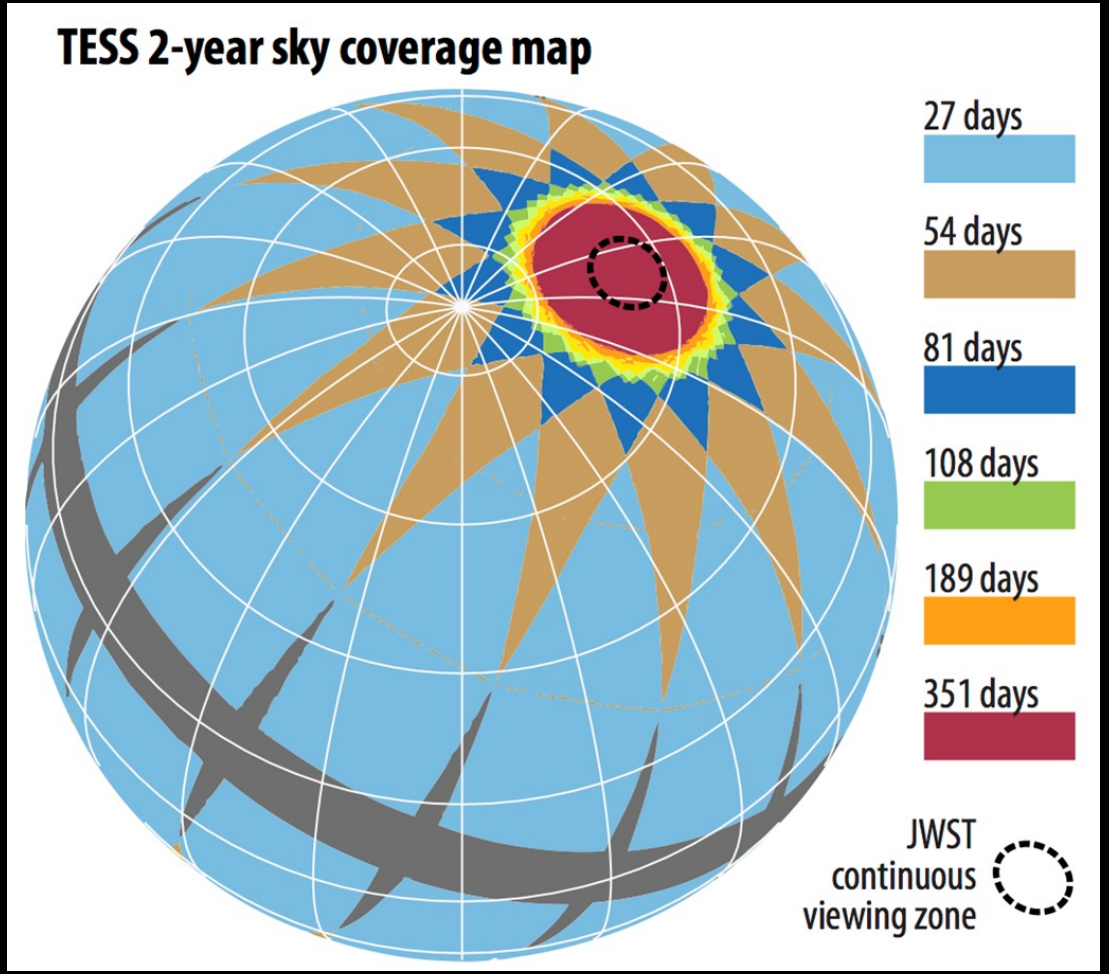
Credits: NASA



Observing strategy

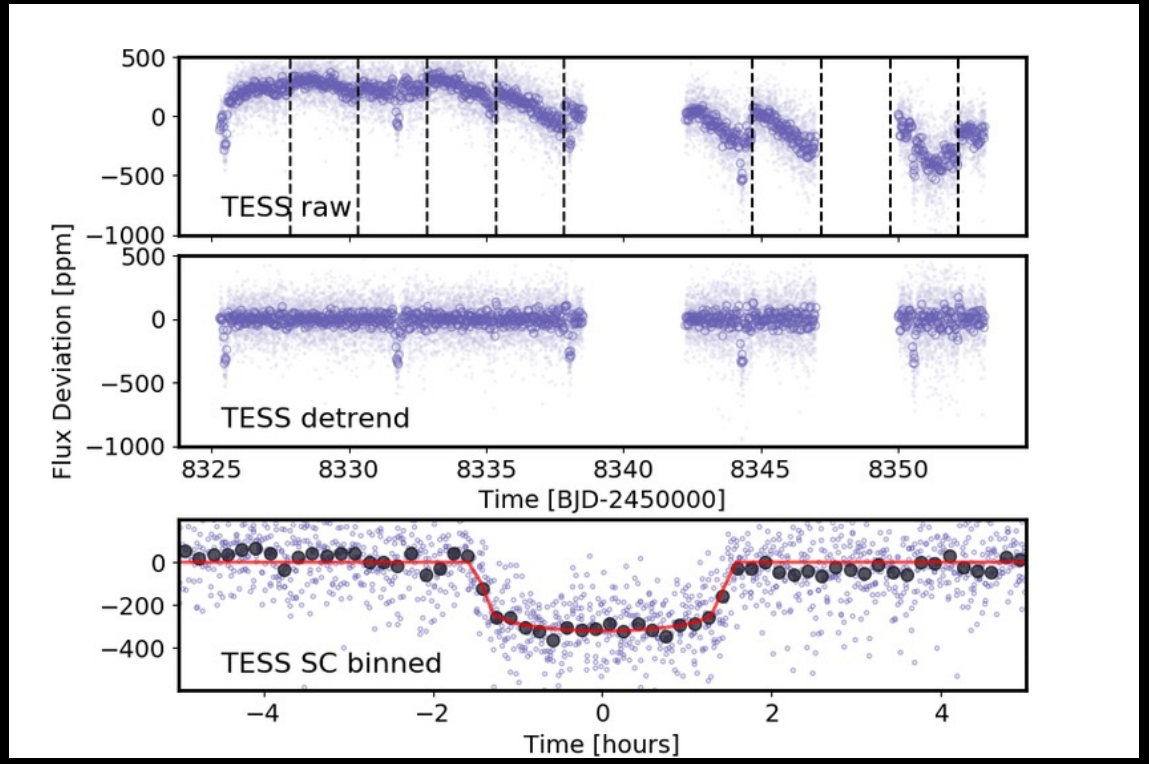
- Tess Input Catalogue (TIC): more than 200.000 stars.
- Exposure time = 2s.
- Short cadence → 2 min.
- Full Frame Images → 30 min.
- **Two years to scan the whole sky** → close to the ecliptic poles: nearly constant coverage.
- **26 sectors of 24° x 96° field of view**.

Credits: TESS/MIT



Observing strategy

- Transit signal detected by the automatic pipeline → **TESS Object of Interest (TOI).**
- Public data release every 4 months.



Huang et al. (2018)

All transit-like signals are not due to planets
→ Need for follow-up observations

Follow-up observations

- **TESS Follow-up Observing Program (TFOP) Working Group (WG)**

→ SG1 : Seeing-limited photometry

→ SG2 : Recon Spectroscopy

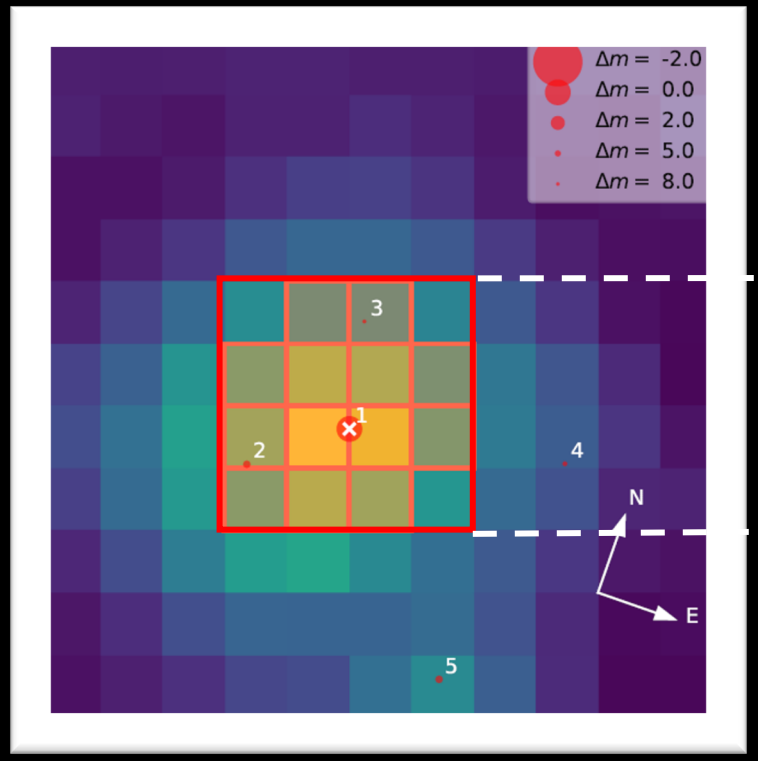
→ SG3 : High-resolution Imaging with adaptive optics

→ SG4 : Precise Radial Velocity Work

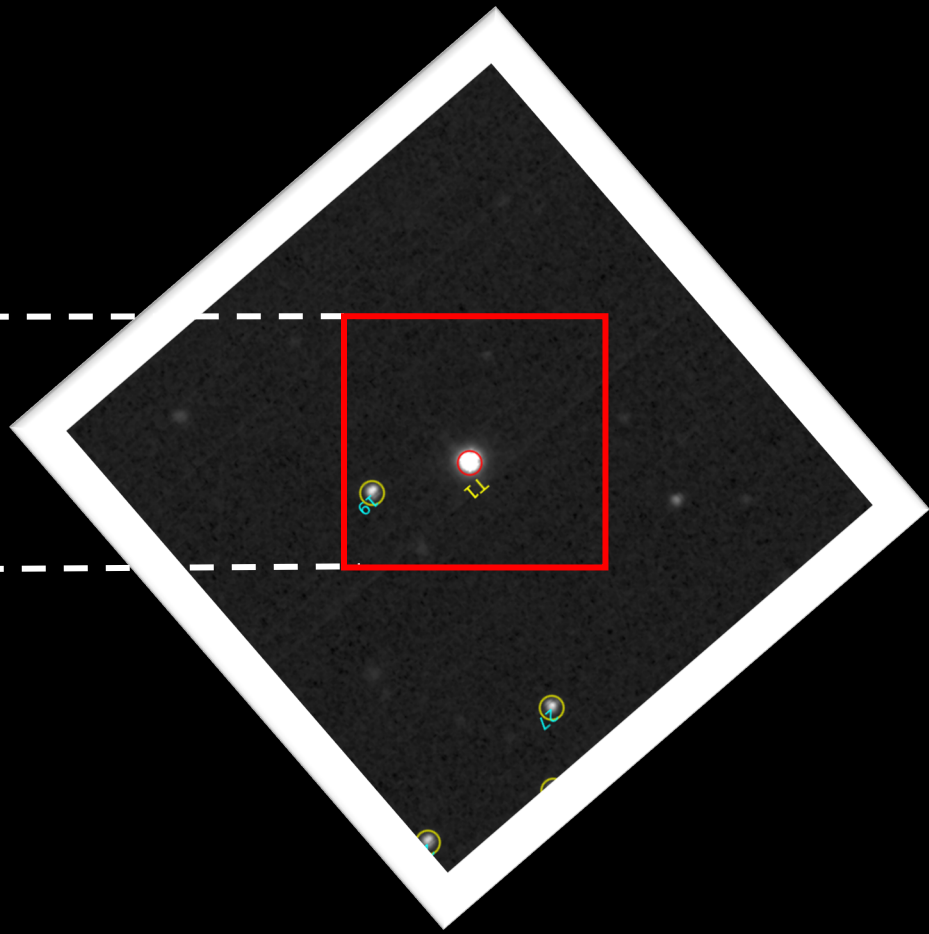
→ SG5 : Space-based photometry

Seeing-limited photometric follow-up

TESS – TOI-1266 (Sector 22)



TRAPPIST-North – TOI-1266



Search for signal dilution or false positives

Credits: Demory et al. (2020)

Possible cases

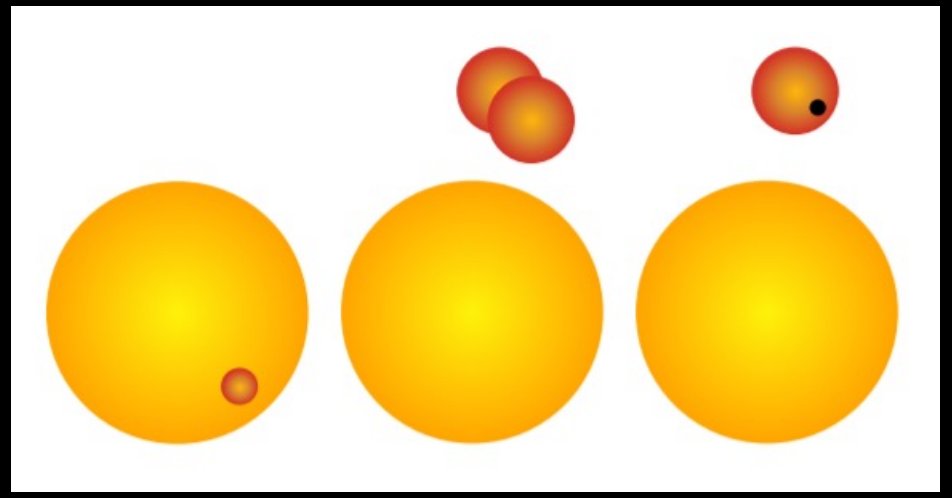
- **Transiting planet on target or around a nearby star**.
- **Eclipsing binaries :** often V shaped + chromaticity.

→ On target

→ Background star (blend)

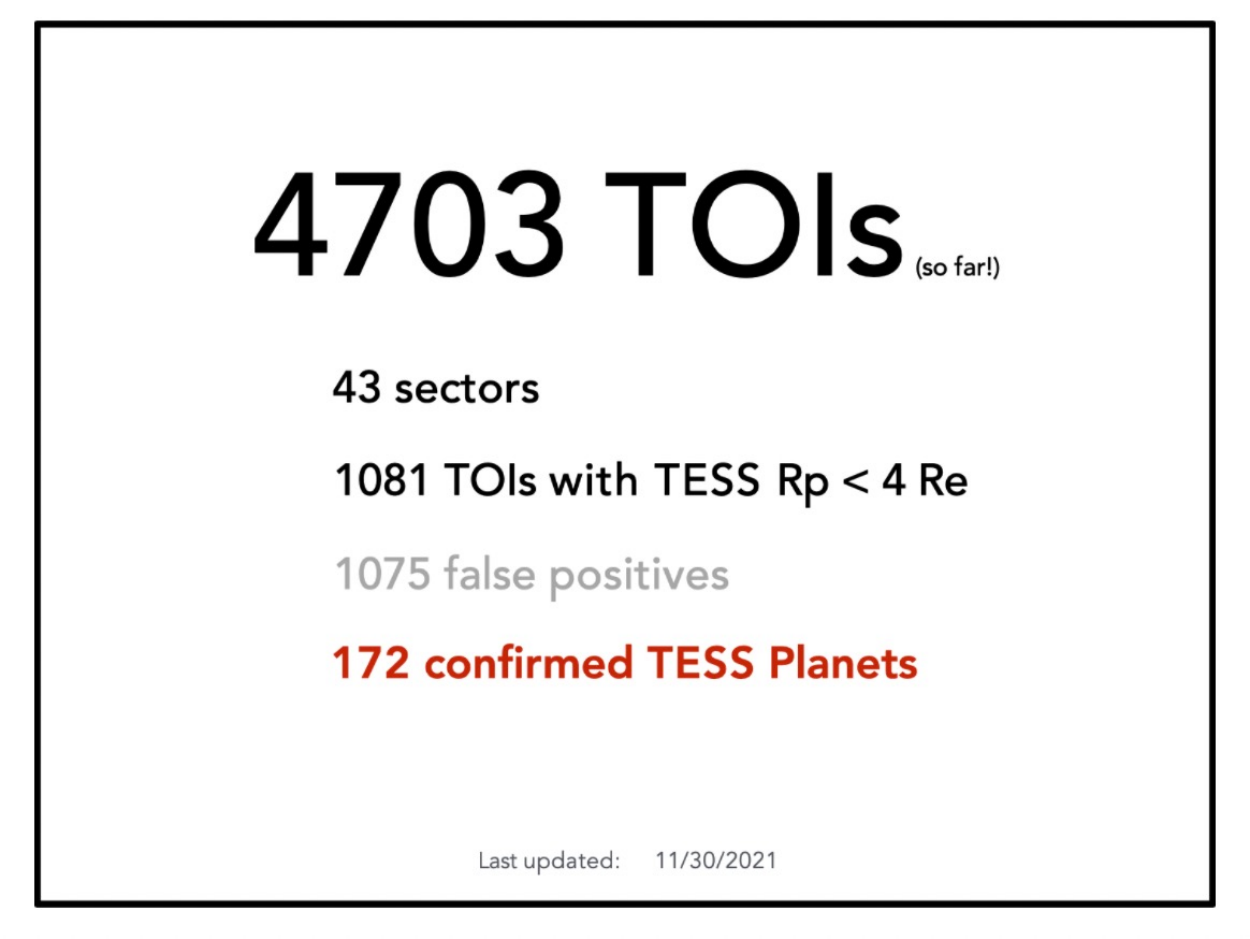
→ Bound star (triple system)

- **False positives**



Credits: Santerne et al. (2013)

Current status



Credits: TESS/MIT

Important discoveries – some examples

- **TOI-700 d : Earth-sized planet in the habitable zone of M2 dwarf star**

  Gilbert et al. (2020). The First Habitable Zone Earth-sized Planet from TESS. I: Validation of the TOI-700 System.

- **TOI-1338 b : circumbinary planet**

  Kostov et al. (2020). TOI-1338: TESS' First Transiting Circumbinary Planet

- **TOI-451 : three planets in a triple system**

  Newton et al. (2021). TESS Hunt for Young and Maturing Exoplanets (THYME). IV. Three Small Planets Orbiting a 120 Myr Old Star in the Pisces–Eridanus Stream*

- **TOI-178 : six planets in Laplace resonances**

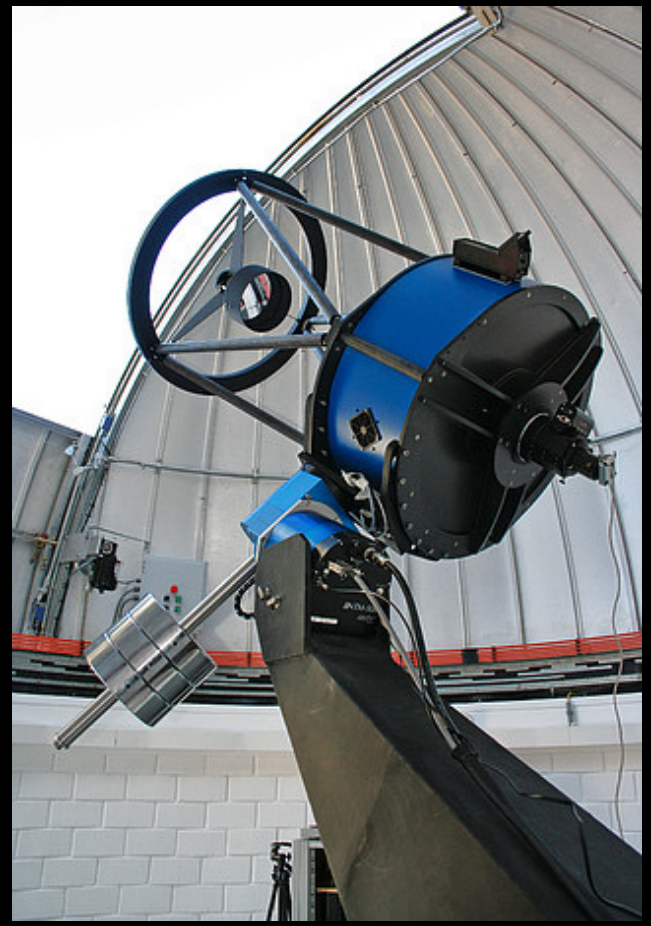
  Leleu et al. (2021) Six transiting planets and a chain of Laplace resonances in TOI-178

- **LTT 1445Ab**

  Winters et al. (2019) Three Red Suns in the Sky: A Transiting, Terrestrial Planet in a Triple M Dwarf System at 6.9 Parsecs

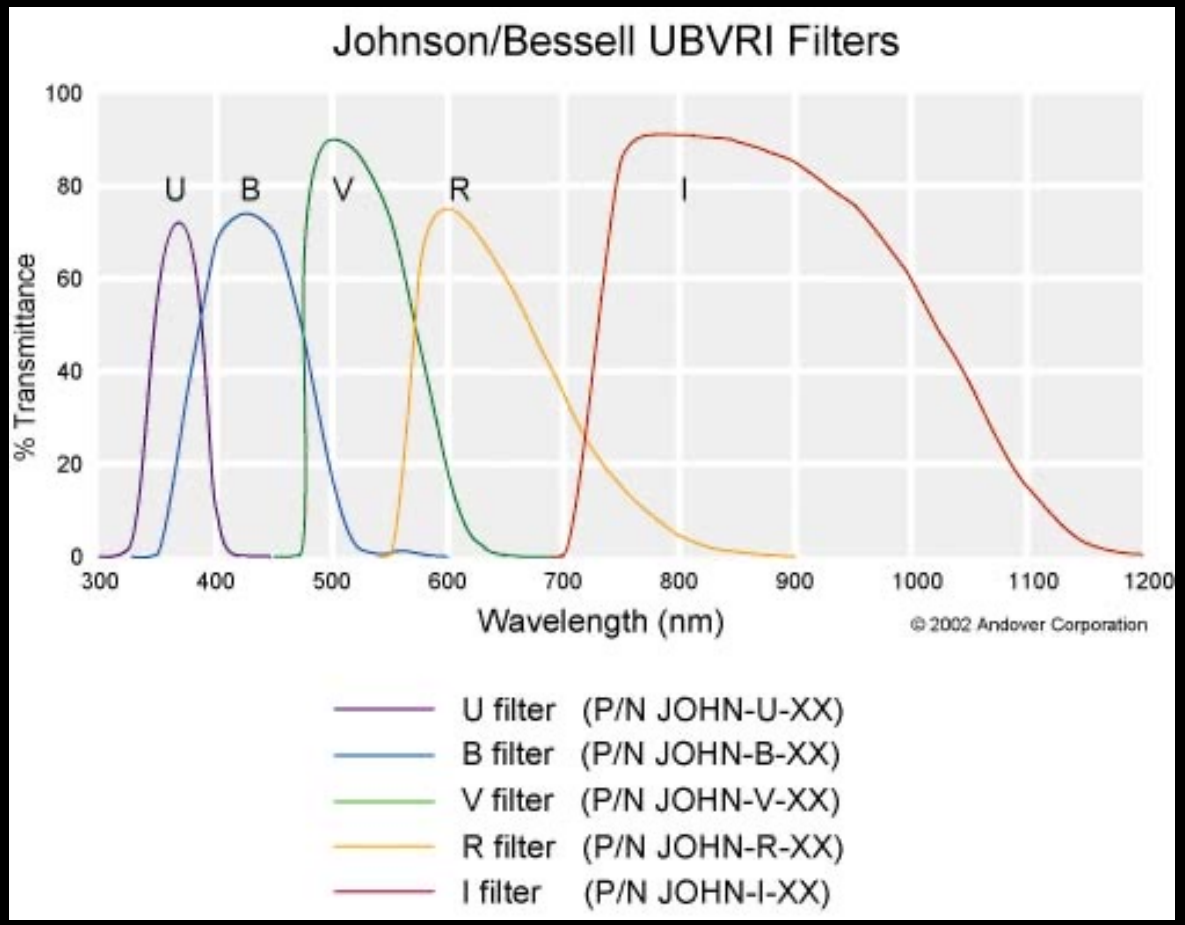
TRAnsiting Planets and PlanetesImals Small Telescopes (60 cm)

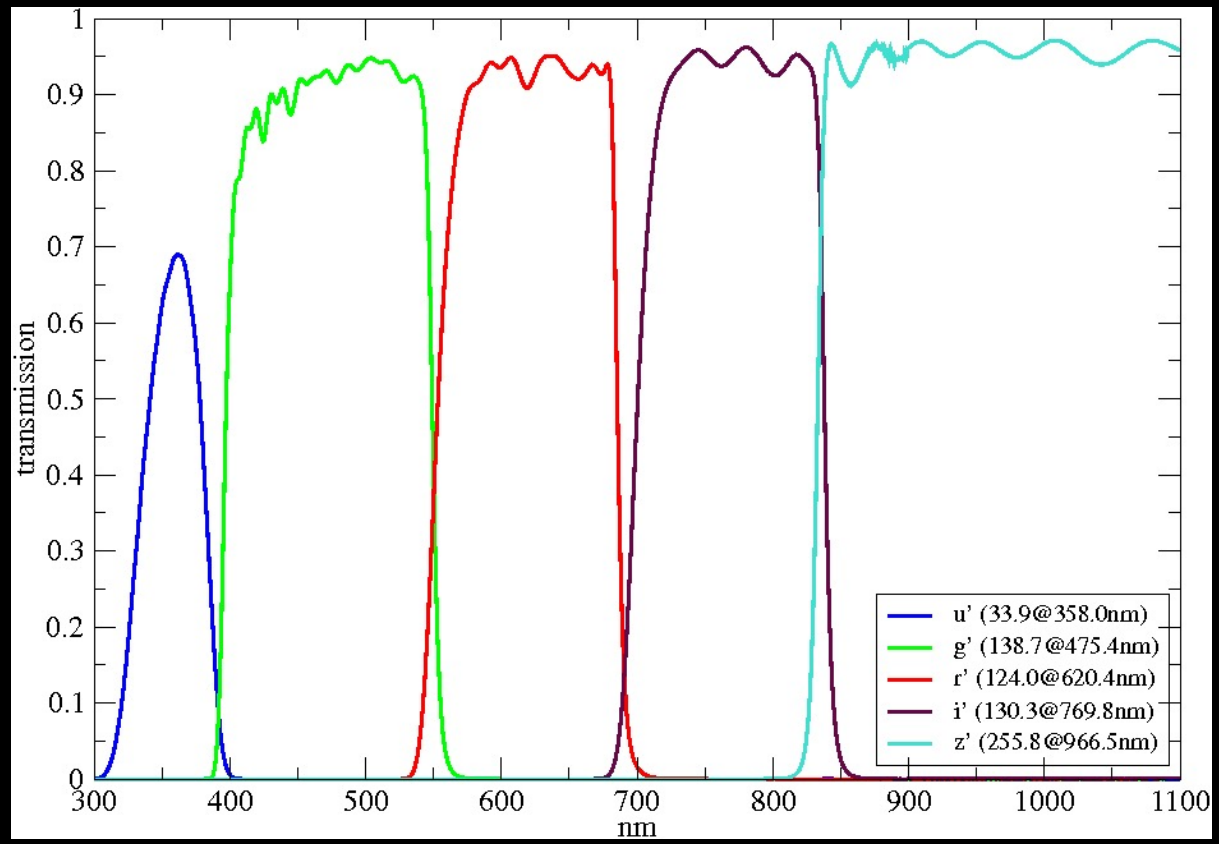
	TRAPPIST-North	**TRAPPIST-South**
Observatory:	Oukaïmeden Observatory, Morocco	La Silla Observatory, Chile
Altitude:	2751 m	2315 m
Latitude:	31°12’33’’ N / 31.2061° N	29°15’40’’ S / 29.2546° S
Longitude:	7°52’52’’ W / 7.8664° W	70°44’52’’ W / 70.7394° W
Camera CCD:	2048 x 2048 pixels	2048 x 2048 pixels
Pixel scale:	0.60‘’/pixel	0.64’’/pixel
Field of view:	20’ x 20’	22’ x 22’



Credits: E. Jehin

TRAPPIST filters





TRAPPIST robotic telescopes

Credits: L. Van Laeken

Credits: E. Jehin

Working with science images

- Images = **FITS** (Flexible Image Transport System) files.
- Contains all the information about the observation and telescope you need.
- To read them: **AstroImageJ or Prose.**

#	Keyword	Value	Comment	Type
1	SIMPLE	T	Created by ImageJ FITS_Writer	B
2	BITPIX	16	number of bits per data pixel	I
3	NAXIS	2	number of data axes	I
4	NAXIS1	2096	length of data axis 1	I
5	NAXIS2	2080	length of data axis 2	I
6	BZERO	32768.0	data range offset	R
7	BSCALE	1.0	scaling factor	R
8	DATE-OBS	'2021-02-18T00:27:37.759'	[ISO 8601] UTC date/time of exposure start	S
9	EXPTIME	4.000000000000E+001	[sec] Duration of exposure	R
10	EXPOSURE	4.000000000000E+001	[sec] Duration of exposure	R
11	SET-TEMP	-30.000000000000000	CCD temperature setpoint in C	R
12	CCD-TEMP	-30.000000000000000	CCD temperature at start of exposure in C	R
13	XPIXSZ	15.000000000000000	Pixel Width in microns (after binning)	R
14	YPIXSZ	15.000000000000000	Pixel Height in microns (after binning)	R
15	XBINNING	1	Binning level along the X-axis	I
16	YBINNING	1	Binning level along the Y-axis	I
17	XORGSUBF	0	Subframe X position in binned pixels	I
18	YORGSUBF	0	Subframe Y position in binned pixels	I
19	READOUTM	'2MHz 1CH'	Readout mode of image	S
20	FILTER	'I+z '	Filter name	S
21	IMAGETYP	'LIGHT '	Type of image	S
22	SITELAT	-29.256666666666668	geographic latitude of observatory	R
23	SITELONG	-70.73	geographic longitude of observatory	R
24	JD	2459263.5191870369	Julian Date at start of exposure	R
25	FOCALLEN	4740.000000000000	Focal length of telescope in mm	R
26	APTDIA	600.00000000000000	Aperture diameter of telescope in mm	R
27	APTAREA	282743.34669113159	Aperture area of telescope in mm^2	R
28	SWCREATE	'MaxIm DL Version 5.22 120424 2TU52'	Name of software	S
29	OBJECT	'TOI-2441.01'	Target object name	S
30	TELESCOP	'TRAPPIST-S'	Telescope name	S
31	INSTRUME	'TRAPPISTS'	Detector instrument name	S
32	OBSERVER	'trappist'	Observer name	S
33	NOTES	' '		S
34	FLIPSTAT	' '		S
35	CSTRETCH	'Medium '	Initial display stretch mode	S
36	CBLACK	2422	Initial display black level in ADUs	I
37	CWHITE	3070	Initial display white level in ADUs	I
38	PEDESTAL	0	Correction to add for zero-based ADU	I
39	PIERSIDE	'WEST '		S
40	DATE	'2021-02-18T00:28:17.759'	UTC date/time when this file was written	S
41	TIME-OBS	'00:27:37'	[old format] UTC time of exposure start	S
42	UT	'00:27:37'	[old format] UTC time of exposure start	S
43	TIMESYS	'UTC '	Default time system	S
44	AIRMASS	1.0863690779321673	Target airmass at mid-exposure	R
45	LAT-OBS	-2.92546083333E+001	[deg +N WGS84] Geodetic latitude	R
46	LONG-OBS	-7.07393944444E+001	[deg +E WGS84] Geodetic longitude	R
47	ALT-OBS	2.31500000000E+003	[metres] Altitude above mean sea level	R
48	OBSERVAT	'TRAPPIST'	Observatory name	S
49	RA	6.102376769736265	EOD right ascension of target (hours)	R
50	OBJCTRA	6.094036111111105	J2000 right ascension of target (hours)	R
51	DEC	-51.68713560309148	EOD declination of target (degrees)	R
52	OBJCTDEC	-51.680166666666665	J2000 declination of target (degrees)	R
53	CLRBAND	'R '	[J-C std] Std. color band of image or C=Color	S
54	FWHM	3.38145400286E+000	[pixels] Mean Full-Width-Half-Max of image star	R
55	ZMAG	2.30243875560E+001	Mag zero point for 1 sec exposure	R
56	EQUINOX	2000.0	Equatorial coordinates are J2000	R
57	PA	177.9795730411862	[deg, 0-360 CCW] Position angle of plate	R
58	CTYPE1	'RA--TAN'	X-axis coordinate type	S
59	CRVAL1	9.1410348943E+001	X-axis coordinate value	R
60	CRPIX1	1.0480000000E+003	X-axis reference pixel	R
61	CTYPE2	'DEC--TAN'	Y-axis coordinate type	S
62	CRVAL2	-5.16802753860E+001	Y-axis coordinate value	R
63	CRPIX2	1.0400000000E+003	Y-axis reference pixel	R
64	CD1_1	1.82192318629E-004	Change in RA along X-Axis	R
65	CD1_2	-6.42997098506E-006	Change in RA along Y-Axis	R
66	CD2_1	6.42733076831E-006	Change in DEC along X-Axis	R
67	CD2_2	1.82267159527E-004	Change in DEC along Y-Axis	R
68	HIERARCH E...	'TRAPPISTS'	Instrument name	S
69	HIERARCH E...	'60.A-9901(A)'	ESO program identification	S
70	ORIGIN	'TS-LASILLA'	TRAPPIST-South	S
71	HIERARCH E...	'SCIENCE '	Observation category	S
72	HIERARCH E...	'OBJECT '	Observation type	S
73	HIERARCH E...	'IMAGE '	Observation technique	S
74	RADESYS	'FK5 '	Equatorial coordinate system	S
75	BUNIT	'adu '	Physical unit of array values	S
76	LST	337.488	LST at start [sec]	R
77	UTC	1657.759	UTC at start [sec]	R
78	MJD-OBS	59263.01918703	Modified Julian Date of start of exposure	R
79	MJD-END	59263.01964999	Modified Julian Date of end of exposure	R
80	DATE-END	'2021-02-18T00:28:17.759'	UTC date/time of end of exposure	S
81	ORIGFILE	'TRAPPS.2021-02-18T00_27_37.759.fits'	Original File Name	S
82	ARCFILE	'TRAPPS.2021-02-18T00:27:37.759.fits'	Archive File Name	S
83	CHECKSUM	'NAKJO5khNAKhN3Kh'	HDU checksum updated 2021-02-18T14:54:21	S
84	DATASUM	'324361550'	data unit checksum updated 2021-02-18T14:54:21	S
85	JD_SOBS	2459263.51918703?	Julian Date at start of exposure	R
86	JD_UTC	2459263.5194185185	Julian Date (UTC) at mid-exposure	R
87	HJD_UTC	2459263.5202412284	Heliocentric JD (UTC) at mid-exposure	R
88	BJD_TDB	2459263.5210504164	Barycentric JD (TDB) at mid-exposure	R
89	ALT_OBJ	66.96501695421513	Target altitude at mid-exposure	R
90	AZ_OBJ	168.74198676940208	Target azimuth at mid-exposure	R
91	HA_OBJ	-0.47200075235424954	Target hour angle at mid-exposure	R
92	ZD_OBJ	23.03498304578487	Target zenith distance at mid-exposure	R
93	HISTORY	Previous Filename = TRAPPS.2021-02-18T00:27:37.759.fits		H
94	HISTORY	Bias corrected with mbias.fits		H
95	HISTORY	Dark corrected with mdark.fits		H
96	HISTORY	and exposure time scaling factor = 2.6666666666666665		H
97	HISTORY	Flat corrected with mflat.fits		H
98	END			E

Image calibration

- **Raw image:**

→ Very noisy

→ Big dust particles or trails

Need for calibration images !

Calibration images

1. Bias subtraction

Removes an offset related to the electronics that is pixel-dependant.

Taken with zero exposure time and shutter closed.

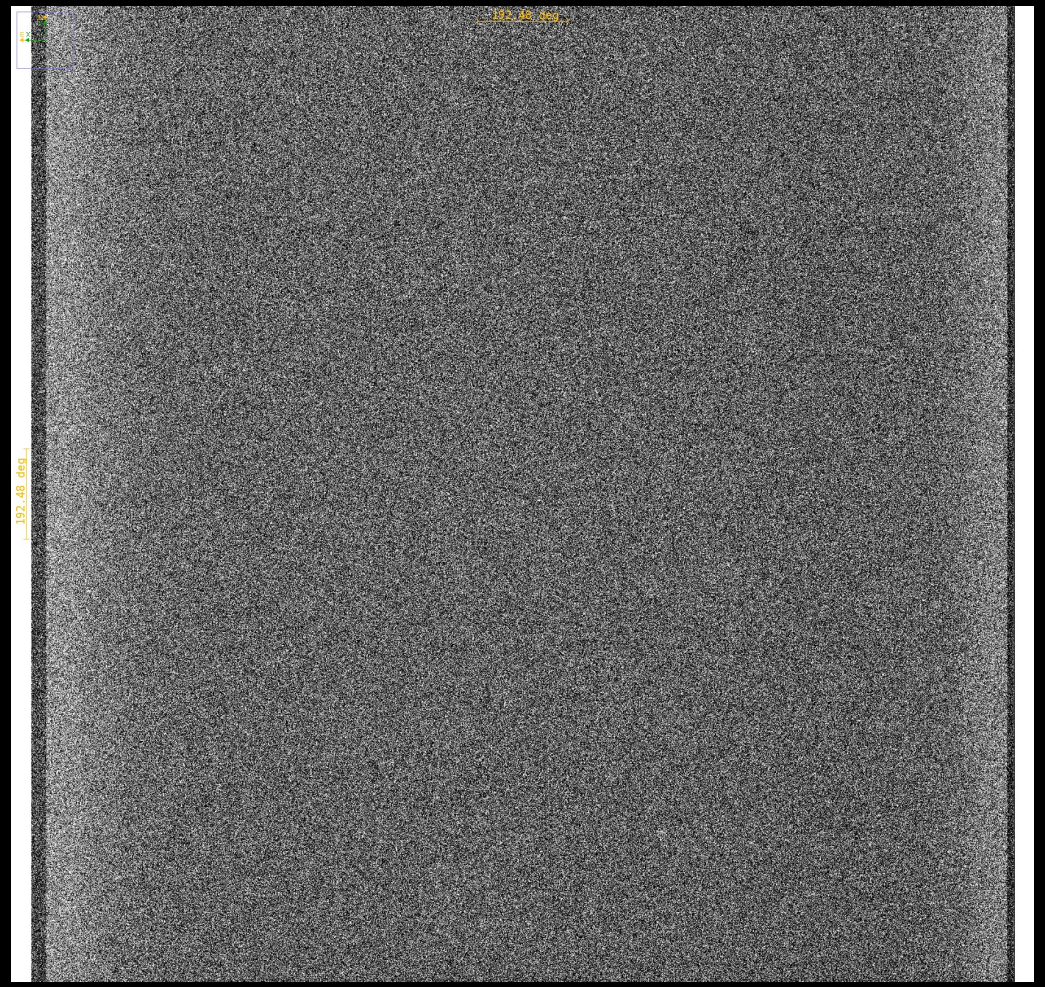
2. Dark subtraction

Removes the dark current produced by thermal excitation of the electrons in the detector.

Taken with several exposure times and shutter closed.

Need to be corrected for bias.

This is then subtracted to the science images.



Calibration images

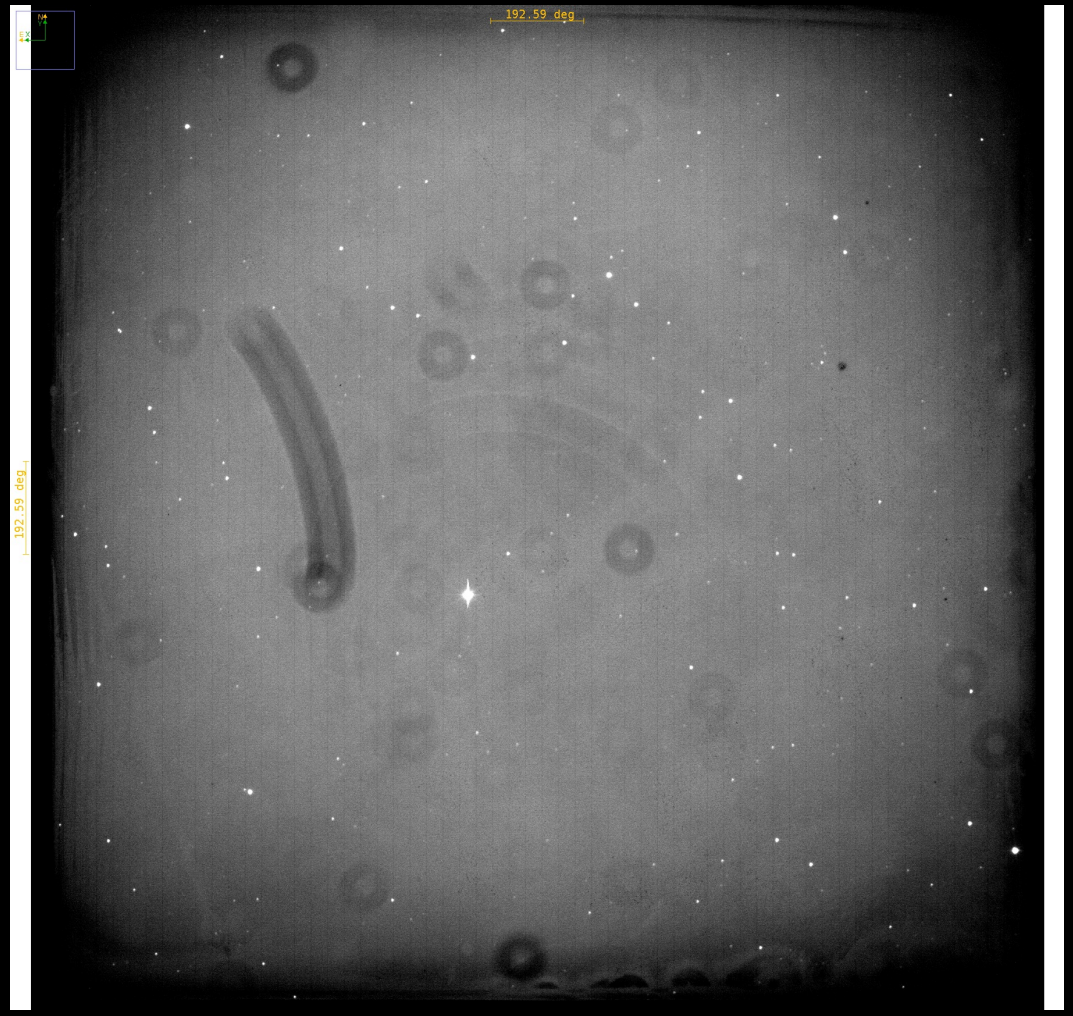
3. Flat field division

Corrects for the pixel to pixel sensitivity variation, dust particles, imperfections, and vignetting effect.

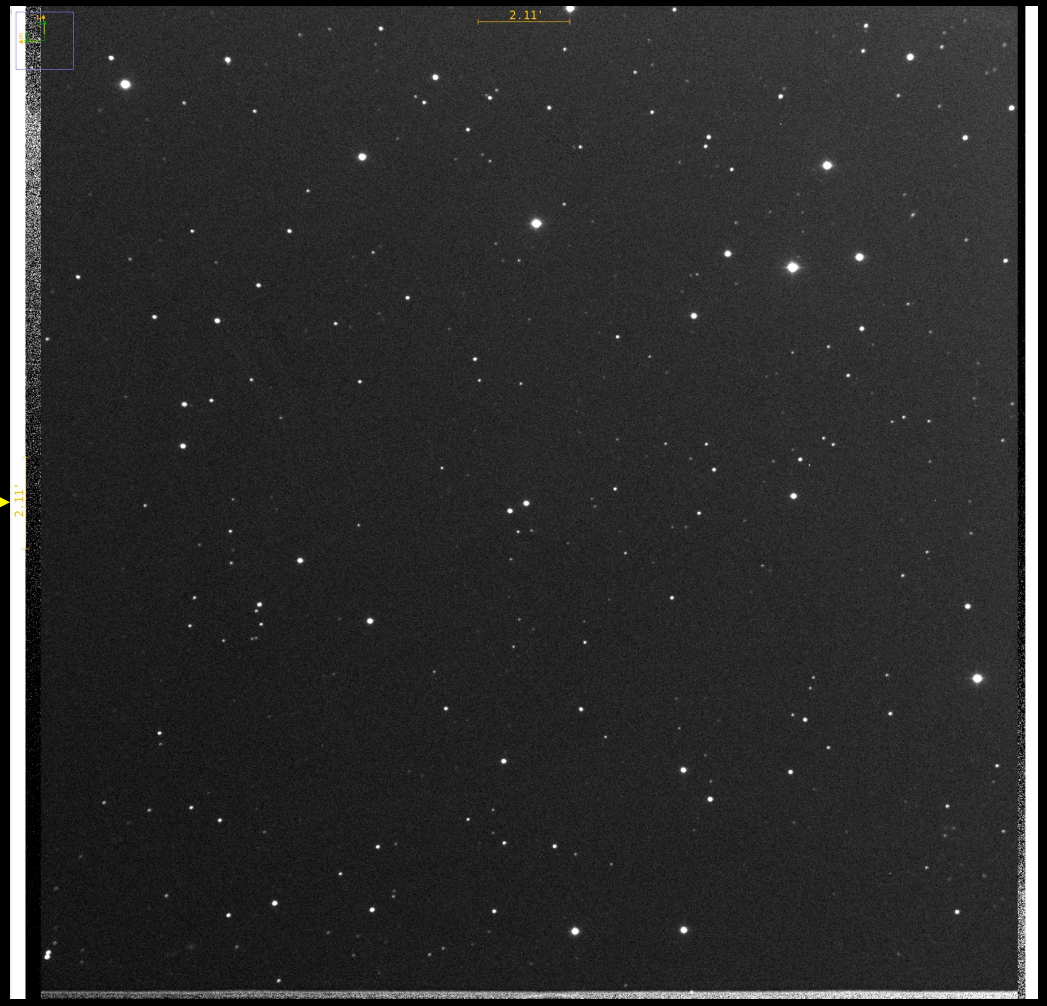
Taken at dusk or dawn for uniform light and in different filters.

Must be corrected for bias and darks.

Division of the science images by the corrected median of the flats.



Science images



Differential photometry

Goal : remove systematic effects in the target star.

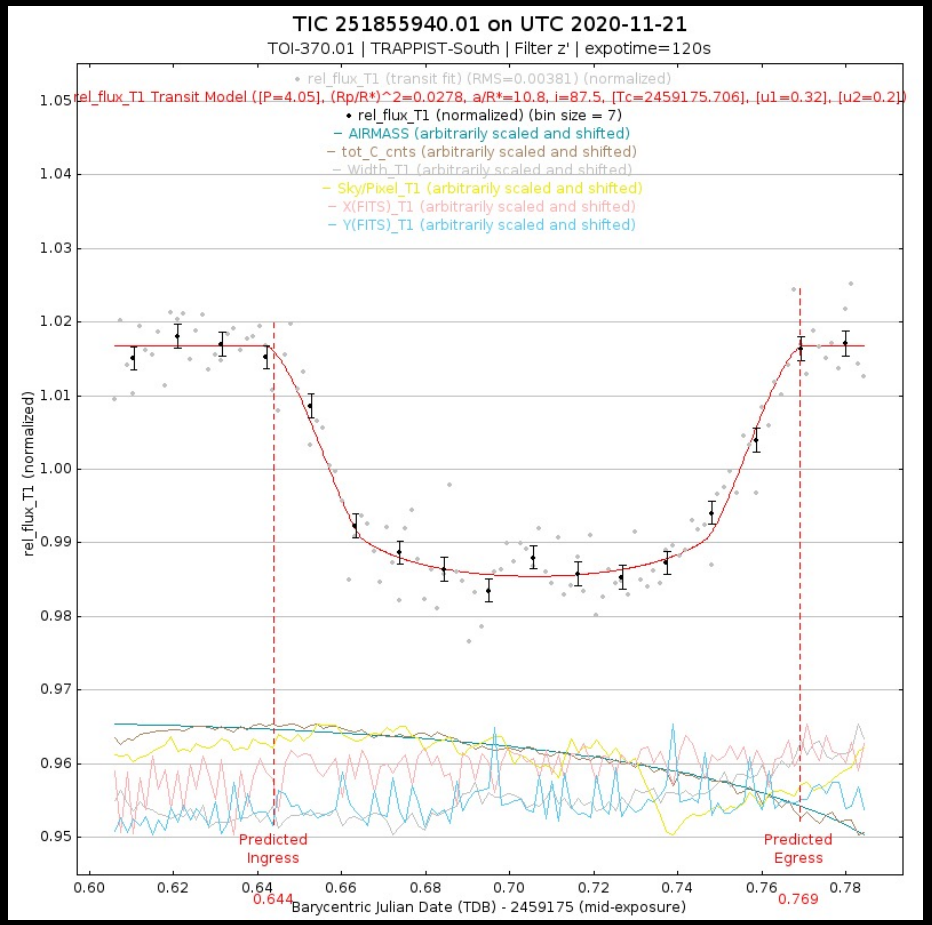
- **Aperture photometry**:

  Flux measurement inside the aperture by summing the pixel values and subtracting the background contribution (outer ring).

Differential photometry

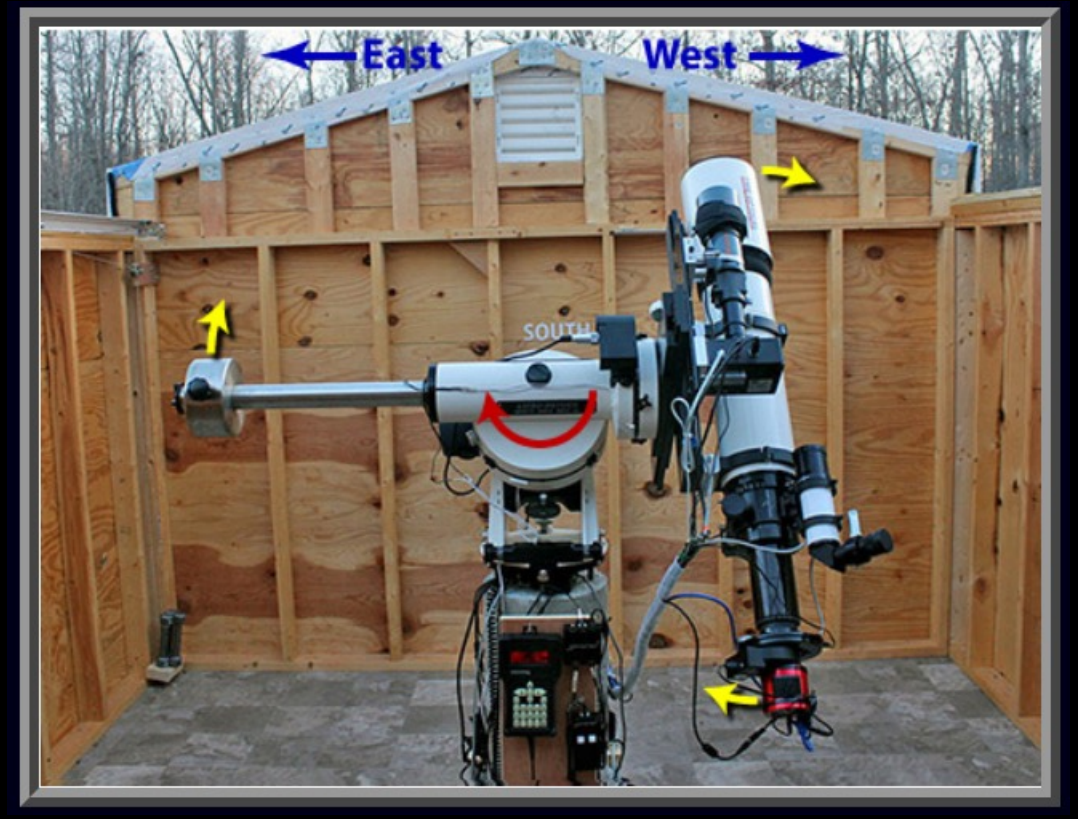
- Choose a set of **comparison stars** which have similar brightness (delta mag) and constant throughout the observation.
- **Differential flux** :

$$F_{diff} = \frac{F_{T1}}{\sum_i F_{c,i}}$$



Meridian flip

- Encountered with German equatorial mounts.
- Change the side of the mount on which the telescope is to avoid it crashing into the mount.

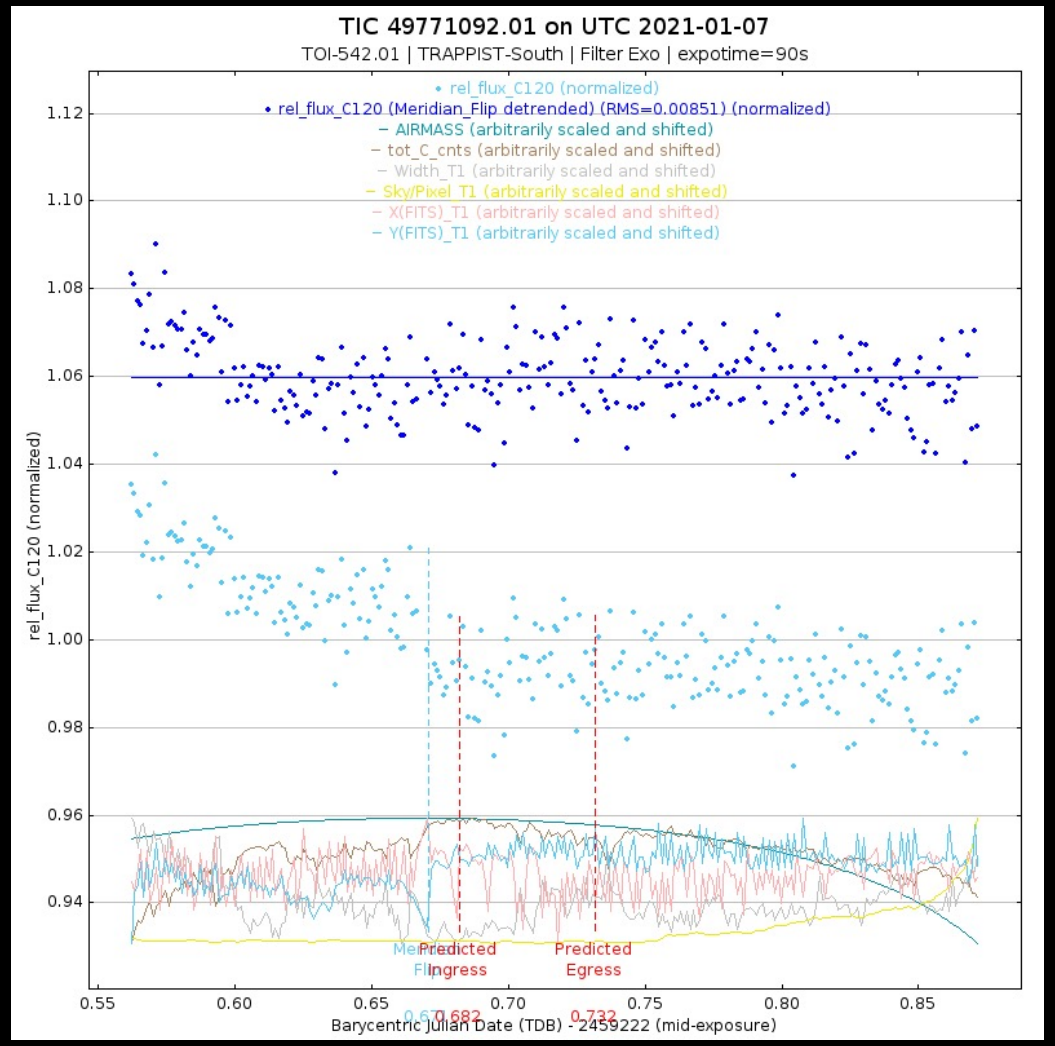


Credits: https://astronomy.mdodd.com/gem_movement.html

Meridian flip

- Encountered for German equatorial mounts.
- Change the side of the mount on which the telescope is to avoid it crashing into the mount.
- **Result** : Flip of 180° of the dec and ra axes. The positions of the stars on the detector change !

  → Offset in the light curve.



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Astrobiology

Credits: NASA

Thanks for your attention !

Do not hesitate to contact us with your questions

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