ESO Science Archive Facility - Phase 3 Data Release Description
ESO programme The Next Generation Transit Survey, Data Release DR1
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NEXT GENERATION TRANSIT SURVEY DATA RELEASE DOCUMENT

Data release description and supplemental information for the first public data release from the Next Generation Transit Survey (NGTS)

NGTS Consortium

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Acronyms

NGTS The Next Generation Transit Survey

PSF Point-Spread Function

QE Quantum Efficiency

CCD Charged-Coupled device

VLT Very Large Telescope

RMS Root Mean Square

FOV Field of View

FWHM Full Width at Half Maximum

Abstract

The Next Generation Transit Survey (NGTS) is a ground-based exoplanet survey designed to detect Neptune and super-Earth sized planets around bright host stars using the transit method. The NGTS facility consists of 12 fully-robotic telescopes situated at the European Southern Observatory (ESO) site in Paranal, Chile. Each comprises a 20cm f/2.8 telescope, has a field-of-view of $2.8 \times 2.8°$, and is equipped with an Andor iKon-L 936 camera (using a deep depleted CCD42-40 back-illuminated CCD sensor) and a custom NGTS filter. During the first year of science observations, 01-Apr-2016 to 01-Apr-2017, NGTS has completed observing 24 separate fields totalling approximately 204,366 targets and acquiring 31,560,757,282 data points from 3,866,126 images at a 12 second cadence. These data will make up NGTS Data Release 1 (DR1). For each field we are releasing the detrended source lightcurves, a source list with cross-matched identifiers to other surveys, a stacked dithered frame from which the source list was generated and an example science image. The lightcurves are produced using aperture photometry, after each image is reduced and astrometrically solved. Each lightcurve contains between 100,000 to 200,000 measurements made over the course of a season and depending on the field in question.

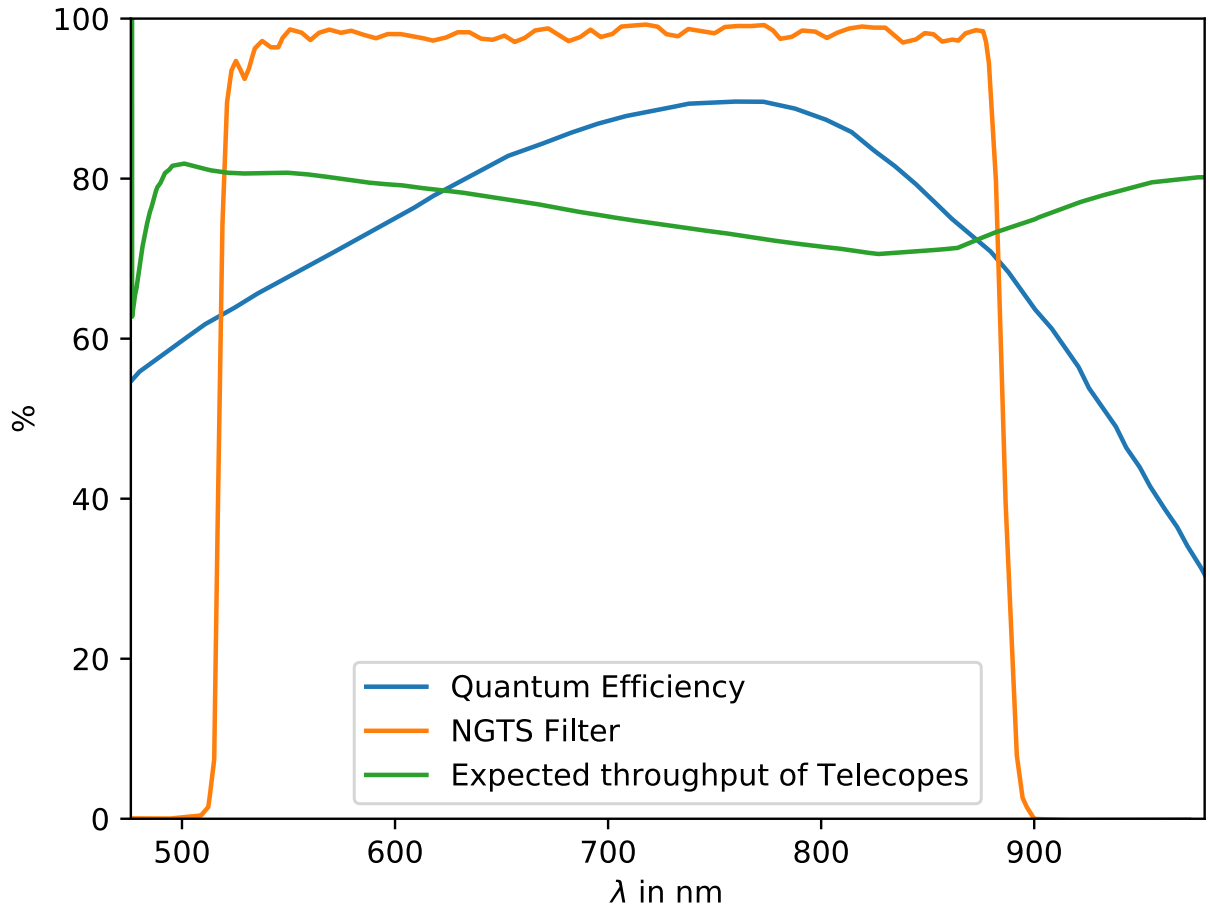


Figure 1: A plot showing the custom NGTS filter, measured QE for the CCD chips and the throughput. This plot has been taken from Wheatley et al. (2018)

1 Overview of Observations

A total of 24 fields of $2.8 \times 2.8°$ have been included in the first data release. These fields have been observed over the course of a year and a half covering the period 22-Sept-2015 to 01-Feb-2017. Fields are included in NGTS DR1 if the final date of observation is before 01-Apr-2017, the one year cut-off for the data release marked from the start of the survey on the 01-Apr-2016. Fields which were not completed during the first year will be included in the next data release, once the observations have finished.

The individual object lightcurves are sampled at approximately 12 second cadence, with a 10 second exposure time and contain between 100,000 to 200,000 data points depending on the field. Observations were conducted by the 12 NGTS telescopes, operating in survey mode. Each telescope is fitted with a custom NGTS filter with a bandpass of 520–890 nm, which increases sensitivity to late-K and early-M stars. Figure 1 shows the NGTS QE, filter and the expected throughput of the telescope.

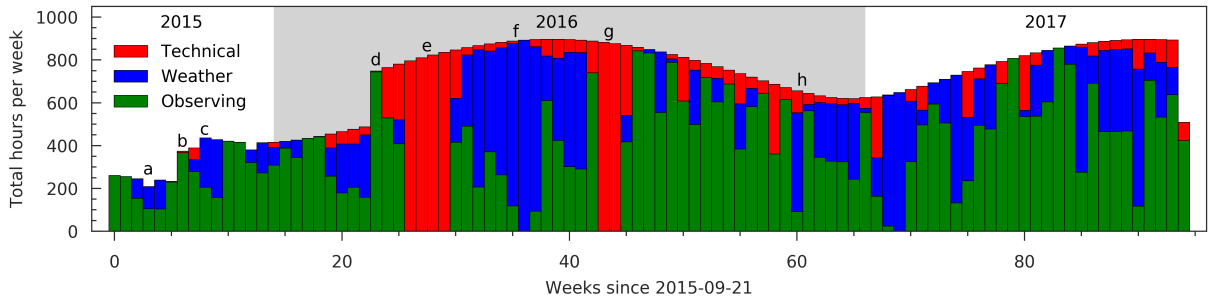


Figure 2: A plot from Wheatley et al. (2018) with a break down of the time spent observing (green), the hours lost due to technical down-time (blue) and the weather (red) since the start of commissioning for the survey. This includes the period covered by DR1. The available hours per night are calculated as the difference between the start and end of astronomical twilight. The letters marking key dates are described in Wheatley et al. (2018). Several key dates are marked on the plot as follows: a) survey commissioning observations began with 4 telescopes; b) 3 more telescope units installed, c) 1 more unit installed, bringing total to 8; d) installation completed for the final 4 telescope units; e) NGTS was invaded by rodents and cabling was destroyed resulting in 1 month of technical downtime; this downtime also marks the end of commissioning observations and the beginning of full survey operations; f) Paranal suffered particularly poor weather during May, June and July due to an El Niño event; g) NGTS suffered a further 2 weeks of technical downtime due to a fault with the enclosure roof; h) individual telescope units were off-sky for extended periods due to on-going camera shutter lifetime issues.

Data Product	PRODCATG Keyword	Naming Convention
Dithered Stack	SCIENCE.IMAGE	DITHERED_STACK_{FIELD}.fits
Example Science Frame	SCIENCE.IMAGE	AG_REFERENCE_{FIELD}.fits
Source Catalogue	SCIENCE.CATALOGTILE	SOURCE_CATALOGUE_{FIELD}.fits
Lightcurve Catalogue	SCIENCE.CATALOGTILE	FLUX_{FIELD}{LETTER}.fits

Table 1: Summary of the data products released for each NGTS field, where {FIELD} denotes the field name. The dithered stacked frame is a high resolution stacked frame from which the source catalogue is derived. The example science frame is a high quality frame for each field taken under good conditions at low airmass. The source and lightcurve catalogues are the source list and the photometric lightcurves for the field respectively. The lightcurves for each field are split on 5 by 5 equal sized grid and each tile has a letter from A to Y assigned to it. This is denoted by {LETTER} in the naming convention.

Each telescope follows one field from the time it rises above 30° elevation to the time it sets below 30°. Once a field has set, another is picked up for the remainder of the night. Fields are chosen to minimize idle time, with each telescope typically observing 2 fields per night. Fields are selected from a discrete mesh of 5,307 mesh centers, and are chosen to maximize expected planetary yield based on the density of stars, expected number of dwarf stars, ecliptic latitude and the presence of bright stars or other extended objects in the field of view (FOV).

The lightcurves have been reduced via the usual procedure, using bias, dark and sky flat-field frames taken over the course of observations. Bias and dark frames are taken at dawn after the telescopes have been stowed and the enclosure is shut. Flat-field frames are taken at dawn and dusk, when the weather is clear, and are carefully processed to remove errant clouds and stars.

2 Release Content

2.1 Overview

NGTS DR1 consists of 4 data products as 28 separate files for each of the fields which have been observed. These data products are summarised in Table 1, and consist of a source catalogue for the field, the stacked image from which the source catalogue is generated and a high quality science image as an example of a typical frame from NGTS. Making the first 3 files. Finally, the primary data product, the lightcurves for the objects in the

Field	Camera ID	Sources	Images	Start Date	End Date
NG0522-2518	802	7554	216839	2015-09-21	2016-05-03
NG0531-0826	806	10472	197151	2015-09-23	2016-04-20
NG0549-3345	805	8924	155909	2016-08-06	2017-01-31
NG0612-2518	805	13430	221621	2015-09-21	2016-05-14
NG0618-6441	801	11479	235266	2015-09-21	2016-05-24
NG1135-2518	809	6597	169344	2015-11-26	2016-08-03
NG1213-3633	810	10690	150489	2015-11-28	2016-08-04
NG1315-2807	812	8207	134312	2016-01-05	2016-08-31
NG1340-3345	808	11427	78516	2016-04-18	2016-08-31
NG1416-2518	806	8569	105573	2016-01-05	2016-09-16
NG1421+0000	805	4341	91077	2016-01-05	2016-08-31
NG1428-2518	802	9030	108918	2016-01-05	2016-09-19
NG1444+0537	801	4226	87151	2016-01-13	2016-09-03
NG2025-1941	813	12901	119157	2016-04-20	2016-11-30
NG2028-2518	809	10962	180854	2016-04-20	2016-12-06
NG2047-0248	810	12872	161769	2016-04-20	2016-12-01
NG2058-0248	803	10805	170323	2016-04-20	2016-12-01
NG2126-1652	804	6967	181379	2016-04-20	2016-12-15
NG2132+0248	805	8623	158453	2016-04-20	2016-12-02
NG2142+0826	801	9228	156463	2016-04-20	2016-12-02
NG2145-3345	808	5739	94332	2016-04-20	2016-09-02
NG2150-3922	812	5750	224159	2016-04-20	2016-12-27
NG2331-3922	806	3580	216979	2016-05-03	2017-01-10
NG2346-3633	802	3421	250092	2016-05-03	2017-01-25

Table 2: Summary of the fields uploaded for DR1. The table contains the field name, unique camera identifier, number of sources for which lightcurves were taken, number of science frames and finally the start and end date for the field observations.

source catalogue are included. For technical reasons each field has been split into an equal 5x5 grid and the lightcurves are provided as 25 separate files. In total the data release consists of 1.67TB of data across 672 files.

2.2 Image Data Products

The stacked frame is constructed from 150 images which have been taken using a dithered motion, each with a random offset of around 6 pixels (30 arcsec) from the nominal field centre. These frames are taken at a low airmass during dark time. The images are then reduced, aligned to sub-pixel precision using the same algorithm for the NGTS autoguider (Wheatley et al., 2018) then accumulated into a stacked image that is super-sampled by a factor 8 along each axis. This dithering and super-sampling is performed in order to

counteract the relatively under-sampled telescope PSF, allowing a more accurate source centroiding and improved astrometry. The super-sampling also allows better disambiguation of blended sources resolvable with NGTS.

A second image provided for each field is an example of a typical science frame. The image selected is taken in good conditions at low airmass, and is also used as the autoguider reference image.

2.3 Source Catalogue

The source catalogue is constructed from the dithered stacked frame discussed in Section 2.2. The catalogue is constructed using the IMCORE tool (Mike J. Irwin, 2004) from the CASUTOOLS software package[1]. The source detection will find targets down to an I-mag of 19, but for practical purposes, as well as to focus on the primary scientific aim of the survey, the source catalogue is cut down to only include sources down to 16th magnitude. Lightcurves are only generated for the sources in the catalogue, and so any sources fainter than 16th in our fields will not be included in the data release.

Each source is then cross-matched with various other catalogues including the AAVSO Photometric All-Sky Survey (Henden and Munari, 2014), GAIA (Gaia Collaboration et al., 2016), 2MASS (Skrutskie et al., 2006), UCAC4 (Zacharias et al., 2013), ALLWISE (Cutri and et al., 2014), RAVE (Kunder et al., 2017) and GALEX (Martin et al., 2005). The cross-matched identifiers are provided in the source catalogue to enable easy identification of targets of interest.

Spurious source are removed from the catalogue by checking for multiple detections within what can be resolved using NGTS. This is further discussed in Section 4. A search is performed to check for duplicated sources in overlapping fields, and for those which are found only one entry is left in the catalogue.

Information from the source detection, astrometry and catalogue cross-matching is combined into the DR1 source catalogue. Each entry in the catalogue is for a unique source from one of the fields and is structured as below:

- **SOURCE_ID**: Unique source identifier constructed from the RA and DEC from the astrometric fit
- **RA_NGTS [deg]**: RA coordinate for the source.
- **DEC_NGTS [deg]**: DEC coordinate for the source.
- **NGTS_MAG [mag]**: Magnitude of the source in the NGTS passband.
- **REF_FLUX [ADU/s]**: Reference flux used to calculate the NGTS magnitude, taken from the dithered stacked frame.

[1] `http://casu.ast.cam.ac.uk/surveys-projects/software-release`

- **FLUX_MEAN [ADU/s]**: Mean flux for the source.
- **FLUX_RMS [ADU/s]**: RMS value for the source.
- **CCDX, CCDY [pixel]**: Position of the source as measured on the dithered stack frame for that field.
- **NPTS_TOTAL**: Total number of data points acquired for the source including null and clipped data points.
- **NPTS**: Number of good data points for the source lightcurve.
- **NPTS_CLIPPED**: Number of data points excluded by a 7-sigma clip of the lightcurve.
- **NPTS_NOT_NULL**: Number of data points which are not null.
- **FLAG_CNT0-4**: A value counting the total number of times each of the five data quality flags has been triggered for the source. See Table 3.
- **Cross-matched identifiers**: The source list has been cross-matched against a range of other surveys and where a match has been made the identifier has been provided. The surveys are GAIA_DR1, TWOMASS, PPMXL, UCAC4, NED, GALEX, WISE, RAVE, DENIS and USNOB1.

2.4 Lightcurves

The NGTS DR1 consists of 24 fields worth of data, each covering an area of $2.8 \times 2.8°$. A complete list of fields is included in Table 2. The fields have between 3,000 and 15,000 individual sources, each one of which will have a lightcurve of cadence 12 seconds covering the time for which the field was observed. The lightcurves have been produced using the NGTS pipeline, as described in Section 4, and have been corrected using the SYSREM algorithm (Tamuz, Mazeh, and Zucker, 2005) for removing systematic trends found in multiple stars. SYSREM is a dimensionality reduction algorithm which reduces to running Principle Component Analysis (Pearson, 1901) when the error on each measurement is assumed to be zero. An updated version of SYSREM has been used for the NGTS data, based on the algorithm used by the WASP project (Collier Cameron et al., 2006).

An initial coarse decorrelation removes the most significant trend in the data, which is due to the time-dependent atmospheric extinction as the field rises and sets throughout the night. Four further common trends are then removed from the data.

The errors provided with DR1 are calculated based on counting noise statistics from the source, the image background and other sources of error from the CCD such as read noise. In addition to removing any systematic trends from the data, SYSREM also produces a per-image down-weight based on the intra-image variance of the instantaneous flux of each of the ensemble of stars about their respective global mean fluxes. This down-weight is then propagated through to the error, using the following equation:

$$\sigma_{i,new} = f_i \sqrt{(\sigma_i / f_i)^2 + \sigma_t^2}, \quad (1)$$

where f_i is the flux measurement and σ_i its formal photometric error, and σ_t is the additional down-weight for the image (Collier Cameron et al., 2006).

The final SYSREM-corrected lightcurves are provided in the form of a catalogue. Every entry in the catalogue consists of a single data point of exposure 10 seconds and contains the following information:

- **POINT_ID**: a unique identifier for every data point in the data release.
- **SOURCE_ID**: a unique identifier for each source constructed from it's RA and DEC.
- **HJD [days]**: The time at which the measurement was taken, converted into HJD.
- **SYSFLUX [ADU/s]**: The SYSREM-corrected flux measurement.
- **FLUX_ERROR [ADU/s]**: The SYSREM down-weighted error in the flux measurement.
- **FLAG**: The NGTS data quality flag.

Erroneous flux measurements produced by the pipeline have either been set to not a number (NaN) or to zero. Additionally, the NGTS flagging system is used to identify further data points which are statistical outliers, or which may have been affected by bright stars, airplanes crossing the FOV or other contaminants such as the lasers used by the adaptive optics system of VLT UT4. Each flag consists of a single bit in an 8-bit integer which encodes a unique description of why the data point may have been flagged. The full list of flags can be found in Table 3. Future data releases may include more flags as the NGTS data quality management system improves over time.

3 Release Notes

NGTS is a ground-based exoplanet survey designed to detect Neptune and super-Earth sized planets around bright host stars using the transit method. A detailed description of the project can be found in Wheatley et al. (2018). NGTS observes fields in a custom bandpass from 520–890 nm, which increases sensitivity to late-K and early-M stars. NGTS achieves better than 1 mmag noise for most stars of $I < 12$ in a one hour exposure time (Figure 4). Every NGTS image is calibrated using high quality bias and sky flatfield frames taken before and after the science observations. Source detection is performed on a stack of dithered frames, designed to improve the accuracy of the detection. Each image is solved astrometrically in order to best place the 3 pixel radius aperture used to

Flag Name	Flag Description	Bit
Saturation	The maximum ADU in the aperture exceeds a camera-specific saturation threshold	bit 0
Cosmic	Flagged if a cosmic has hit the CCD in the aperture	bit 1
Crossing	Aperture is intersected by a large pixel-connected region above threshold which also intersects at least two boundaries of the image (most commonly the VLT laser system).	bit 2
Outlier	The data point is found to be a $> 7\sigma$ outlier	bit 3
Spike	Aperture is intersected by a connected-pixel region that contains pixels above saturation (most commonly blooming spikes from neighbouring bright stars)	bit 4

Table 3: Table describing the data quality flags employed by the NGTS pipepline to screen for erroneous data points.

perform photometry. The lightcurves are finally detrended using an updated version of the SYSREM algorithm (Tamuz, Mazeh, and Zucker, 2005; Collier Cameron et al., 2006).

4 Data Reduction and Calibration

The NGTS pipeline is designed to take raw images, both science and calibration, and produce detrended high-quality lightcurves for each detected source. The full structure of the pipeline is shown in Figure 3 as a schematic diagram. The calibration frames are processed through Bias-, Dark-, FlatPipe respectively and then finally through Calpipe to produce high quality master frames.

PhotPipe processes the science images, performing image reduction, astrometry and aperture-based photometry. Each science frame is trimmed to remove the overscan and then is bias and flat-field corrected in the usual way. A model of the radial distortion of the cameras is calculated once using a custom MCMC code and only updated if any changes are made to the telescope hardware. The distortion is stable over time so it is not necessary to update the model. In PhotPipe each image is solved astrometrically so that an aperture can be placed precisely, in order to not introduce any additional noise into the photometry. Each image is background subtracted by calculating an interpolated value for the background on a 64 by 64 pixel grid using a k-sigma clipped median. This improves the signal to noise of the background measurement while preserving some of the local structure.

MergePipe collates the raw photometry for each field into a single data product covering the entire observing season, which is then passed through SysremPipe to produce the corrected lightcurves that make up the bulk of DR1. These are created as discussed in

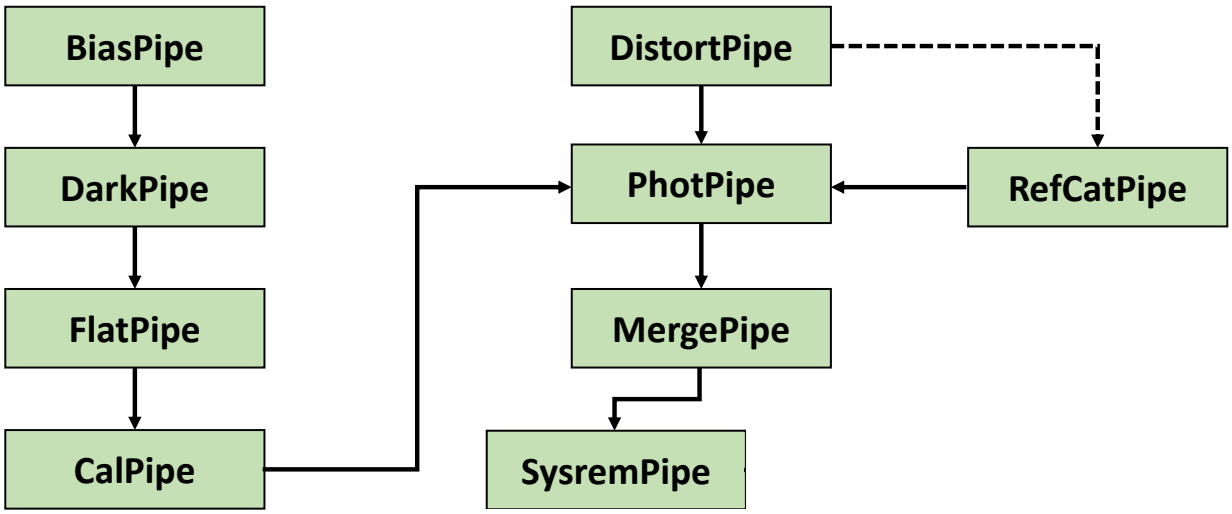


Figure 3: A schematic illustration of the NGTS photometric pipeline. Each box represents a distinct component in the NGTS pipeline and a single step in the processing of the data. BiasPipe, DarkPipe, FlatPipe and CalPipe are responsible for the production of high quality bias, dark and flatfield calibration frames. DistortPipe and RefCatPipe produce the astrometric calibration and source catalogue respectively. PhotPipe, MergePipe and SysremPipe produce the raw and then detrended lightcurves.

section 2.4 using an updated version of the SYSREM algorithm (Tamuz, Mazeh, and Zucker, 2005; Collier Cameron et al., 2006). Four trends are removed including the atmospheric extinction.

Source Catalogue

The source detection is run using the IMCORE tool from the CASUTools software package (Mike J. Irwin, 2004). It is run on the dithered stacked frame from the field in order to better sample the stellar profile and produce a more accurate source position and fewer spurious sources.

There were several overlapping survey tiles in the data release. Duplicate sources were identified by searching for objects with the same coordinates. The duplicate entries were then removed from the catalogue leaving only one unique source.

Astrometric Solution

For each science image an astrometric solution was found in order to accurately place the photometric aperture on each of the sources. Each image taken by NGTS has a non-linear radial distortion due to the telescopes used, and so a zenith polynomial projection is used (Calabretta and Greisen, 2002). A 7th order polynomical is used with the distortion

described by the 3rd, 5th and 7th order terms (Wheatley et al., 2018). The distortion parameters are calculated using a custom Markov chain Monte-Carlo code.

Photometry

NGTS photometry is performed using the IMCORE package with a 3 pixel radius soft-edged aperture which is placed on the source based on the derived astrometric solution. The PSF FWHM is approximately 1.6–1.8 pixels and so less than 1% of light is lost due to the finite aperture size. The NGTS pipeline performs only relative photometry as an absolute photometric calibration is not necessary by the primary science goal of the survey. No explicit corrections are applied to the photometric measurements due to seeing variations over time, as given the pixel scale and size of the photometric aperture used, the effects of variable seeing should be minimal.

5 Data Quality

Various data quality checks were carried out automatically within the calibration pipelines, particularly for flat field frames, to reject: saturated frames, frames afflicted by clouds and frames containing residual stars. In addition, all master calibration frames (from CalPipe) were visually inspected for quality, as well as applying statistical tests e.g. signal-to-noise etc.

A full astrometric calibration is performed on each autoguider reference image, including terms that encapsulate the optical distortions. PhotPipe uses the appropriate DistortPipe parameters as an initial guess of the astrometric solution for each science image. The astrometric fitting in PhotPipe only varies the WCS parameters that encode the pointing position (including rotation), but not the distortion. The RMS error of the DistortPipe fit is recorded and if this value is above a pre-determined threshold, PhotPipe falls back on the astrometric solution from RefCatPipe, which was used during compilation of the source catalogue. Although the best possible result for each astrometric fit is assured, fitting is carried out on a field-by-field basis and residuals may vary by camera and by field.

During compilation of the source catalogue in RefCatPipe, contamination due to spurious objects was mitigated by cross-matching the results from the source detection with multiple external catalogues, as set out in Section 2.3. We placed empirically defined limits on colour and separation to improve the accuracy of the cross-matching and screened for known variable stars and extra-galactic sources. The Gaia cross-match was used to determine whether each NGTS source is a single object or a blend that is unresolved in NGTS images. Objects fainter than 16th magnitude in the NGTS band (I-band) were cut from the catalogue, thus this is the completeness limit at the faint end. RefCatPipe outputs were manually checked for quality assurance.

The quality of the final photometry was assessed both visually and via statistical metrics, e.g. by comparing fractional RMS flux vs stellar magnitude, see Fig. 4. Each flux data point has an associated data quality flag - see Section 2.4 for a full description.

6 Known Issues

Two fields were excluded from DR1 despite meeting the date cut-off. These are NG1318-4500 and NG2152-1403, for which we were unable to produce lightcurves as the astrometry failed to solve for the pipeline run used to produce the DR1 products. These will be provided in the next NGTS data release.

There are currently no known issues with the lightcurves provided in DR1, though the NGTS consortium is continuously working toward reducing any residual systematic trends which may be present in the data.

7 Acknowledgements

Any publications making use of this data, whether obtained from the ESO archive or via third parties, must include the following acknowledgement: "Based on data collected under the NGTS Project at the ESO La Silla Paranal Observatory."

If the access to the ESO Science Archive Facility services was helpful for you research, please include the following acknowledgment: "This research has made use of the services of the ESO Science Archive Facility."

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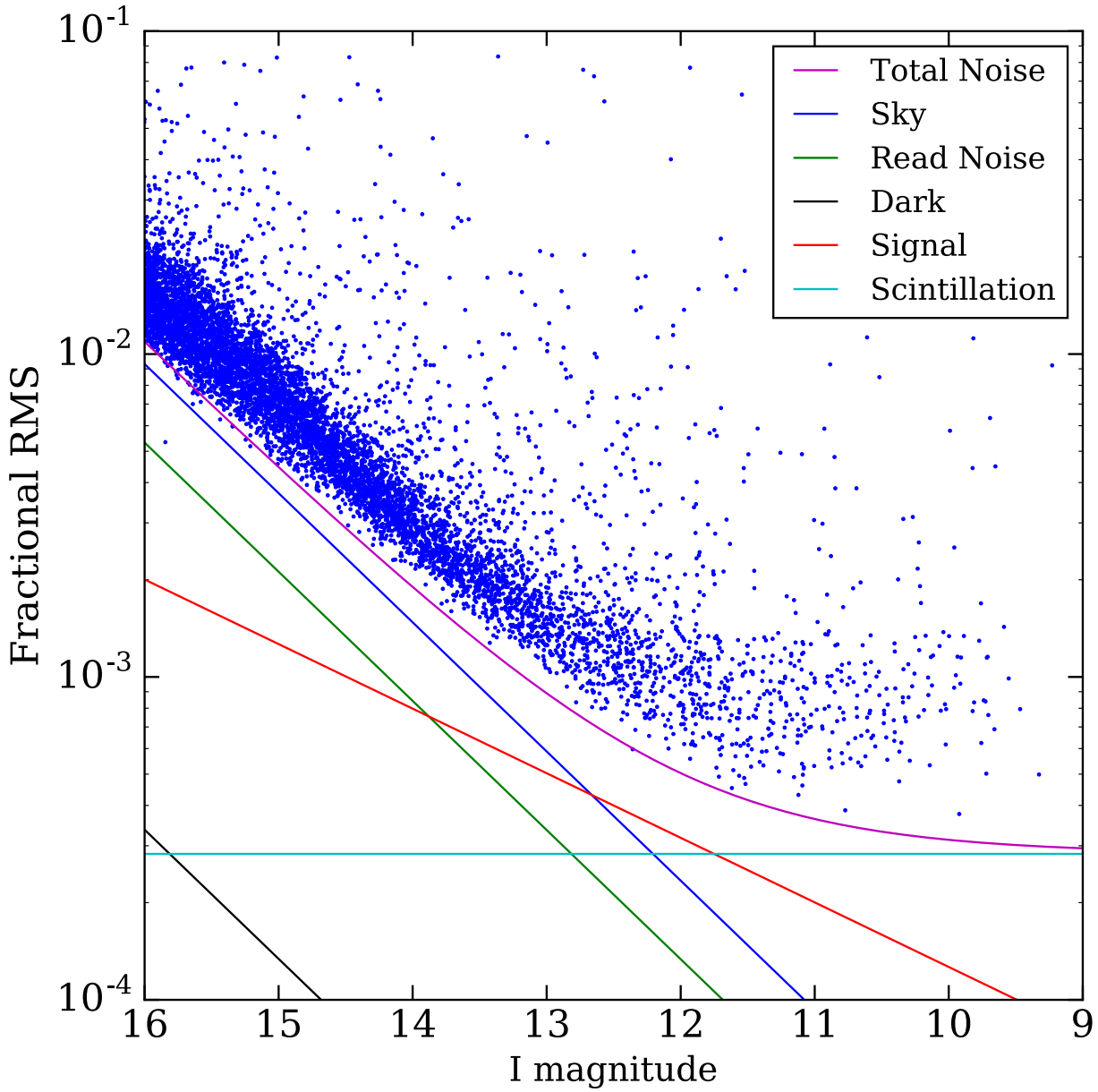


Figure 4: A comparison of the measured fractional RMS noise level of a single NGTS field compared with a theoretical model of the expected noise contributions. The NGTS data is detrended and has been binned to 1 hour exposure time. This plot has been taken from Wheatley et al. (2018). The data points diverge from the expected theoretical model as not all sources of error can be accurately accounted for, particularly the low-level correlated noise often seen in transit surveys.

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