# Twinkle Design Update Technical Note

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### **1** Introduction

This technical note captures the recent progress in updating and defining the Twinkle baseline by the Airbus and ABB industrial teams working with Blue Skies Space Ltd (BSSL). Led by scientific requirements, this design makes use of high heritage products and the vast design experience of these two subcontractors. As a result of this industrialisation phase, the performance specifications of the spacecraft have been refined and updated. Here we highlight the key developments, with more detailed information to be provided in future papers and the performance lookup table. The major changes are in the pointing methodology employed, the resolving power of the instrument, and the reduction in the complexity of the optical design. A summary of the key design parameters and any changes from the previous baseline are detailed in Table 1.

Doromator	Old Design		New Design		
Farameter	Channel 0	Channel 1	Channel 2	Channel 0	Channel 1
Wavelength range	0.45 μm - 1.0 μm	1.3 μm - 2.43 μm	2.43 μm - 4.5 μm	0.5 μm - 2.43 μm	2.43 μm - 4.5 μm
Resolving Power	250	250	60	up to 180	up to 80
Detector Temperature	250 K	70 K	70 K	90	Κ
Detector manufacturer	Selex		Teledyne		
Pointing method	FGS		Gyro Inerti	al Pointing	

Table 1: Summary of key design parameters and changes from feasibility study [1].

The next stage of the Twinkle mission is a detailed development study, again with Airbus and ABB as the industrial team. This will bring the design and industrial plan to the stage where the industrial team can progress to the construction of the Twinkle spacecraft.

#### **1.1 Science with Twinkle**

The Twinkle Space Mission is a space-based observatory that has been conceived to measure the atmospheric composition of exoplanets, stars and solar system objects. The satellite payload provides spectroscopy of simultaneous wavelength coverage across  $0.5 - 4.5 \ \mu m$ .

Twinkle will have the capability to provide high-quality infrared spectroscopic characterisation of the atmospheres of hundreds of bright exoplanets, covering a wide range of planetary types. It will also be capable of providing phase curves for hot, short-period planets around bright stars targets and of providing ultra-precise photometric light curves to accurately constrain orbital parameters, including ephemerides and TTVs/TDVs present in multi-planet systems. Twinkle is available for researchers around the globe in two ways:

- 1. joining its collaborative multi-year survey programme, which will observe hundreds of exoplanets and solar system objects; and
- 2. accessing dedicated telescope time on the spacecraft, which they can schedule for any combination of science cases.

Twinkle's rapid pointing and tracking capabilities will enable the observation of solar system objects including asteroids, comets, the outer planets and their moons. Twinkle aims to provide an infrared spectroscopic population study of asteroids and comets to study their surface composition, following up on hundreds of targets detected by surveys such as LSST and NEOSM. Twinkle's instrumentation will be able to obtain high-SNR spectra of major solar system bodies within very brief exposure times. Its wavelength coverage and position above the atmosphere make it particularly well-suited for studying infrared spectral features that are obscured by telluric lines from the ground, including hydration features, organics, silicates and CO2.

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Figure 1: Twinkle will offer two initial survey programmes focusing on exoplanets and solar system objects.

## 2 Design Summary

### 2.1 Spacecraft System Overview

The Twinkle design has been developed around the heritage spacecraft bus 'AstroBus S' which is a repackaging of the 'AS250' with a design lifetime of 10 years. This spacecraft bus is suited for rapid construction and has previously been used for PeruSat<sup>1</sup> and was also adapted for the CHEOPS mission. The spacecraft is designed for a 700 km, sun-synchronous dawn-dusk orbit, to maintain an orbit normal aligned closely to the anti-sun direction for the telescope. The Field of Regard (FoR) available around the anti-sun vector is  $\pm 40^{\circ}$ , constrained throughout the seasons by Earth obstruction in part of the FoR for part of the orbit.

The AstroBus platform requires adaptation for Twinkle in the mechanical design to provide a sun shield of sufficient size. The spacecraft makes use of sunshields to maintain the cool thermal environment by shading the telescope body and payload bay from both Sun and Earth flux across the wide FoR. The cyrogenic temperatures are reached by a combination of space-facing radiators thermally attached to the telescope interface panel and active coolers with a dedicated radiator thermally attached to the inner sanctum and detector.

The spacecraft instrument is a spectrometer operating from 0.5 to 4.5  $\mu m$  using two spectral channels (with the split at 2.4 $\mu m$ ) and a single HXRG series detector. The telescope and optical element will be maintained at less than 160K and the primary aperture of the telescope will be greater than 0.45m. The design is being developed by Airbus and ABB and makes use of heritage components where possible and the product lines and supply chains of both companies.

Twinkle's Low Earth Orbit (LEO) enables the use of an X-band downlink signal capable of downloading all payload data via an isotropic antenna. This will allow the spacecraft to maintain scientific operations during downlink sessions.

The spacecraft is being designed to fit a range of small satellite launch vehicles including the new Small Satellite Launch Vehicle (SSLV), the VEGA launch system and the SpaceX Falcon 9. We note that several other launch vehicles are also suitable for Twinkle and consider the driving case for size and mass to be the SSLV.

### 2.2 Pointing Performance

The pointing performance of the spacecraft is a key parameter that determines the viable resolving power of the instrument as well as jitter noise. The industrial team reviewed the science requirements of the mission against the previous pointing performance and the spacecraft buses available. Three distinct pointing solutions were identified and these options were reviewed against the impact on the scientific analysis. The three possibilities considered were:

- 1. A Fine Guidance Sensor.
- 2. A Gyroscope sensor incorporated into the AS250 baseline.
- 3. An AS250 platform baseline of Star Tracker only pointing.

<sup>1</sup>www.airbus.com/space/earth-observation/perusat.html

#### 2.2.1 Fine Guidance Sensor (FGS)

The FGS would provide the finest pointing performance, with previous FGS units modelled to achieve a performance criteria of ~0.13" (1 $\sigma$  APE). The performance estimate of the Phase A design was approximately 0.04" (1 $\sigma$  APE). However, for any FGS design, the performance is inherently dependent on the total flux delivered to the FGS detector. In order to achieve a sufficiently high read-out rate this would place a brightness limit in that band for tracking to be successful, restricting the targets which could be observed. The inclusion of an FGS also adds complexity to the optical design, requires an additional detector, and introduces an additional thermal consideration on the optical bench. The industrial team focused its efforts on reviewing the viability of less optically complex solutions.

#### 2.2.2 Gyroscope and Star Tracker solutions

The scientific implications of two non-FGS solutions were explored with the help of Cardiff University: 1) a system using Star Trackers as the primary pointing measurement sensor and 2) a configuration incorporating a Gyroscope module. ExoSim [2], a generic time domain simulator that can be used across a number of astrophysics missions [3, 4, 5], has been used to create TwinkleSim which models the instrument's performance and noise sources due to thermal emissions of the system, detector dark current and read noise, astrophysical sources (e.g. zodical light) and jitter. Using Power Spectral Density functions (PSDs) provided by Airbus for the modified AstroBus-S designs, Cardiff University and BSSL conducted simulations for a number of exoplanetary targets. The time-domain aspect of this tool allows for the consideration of pointing jitter noise and the effects of spreading the spectral image on the detector. Given the early stage of the mechanical properties of the spacecraft a conservative pointing rms was selected in each case. To  $1\sigma$ , the modelled PSD for the Star Tracker was 1.25" rms while for the gyroscope solution the analysis used a magnitude of 0.5" rms.

The analysis was run across a range of detector read-out apertures and for various scaled versions of the PSDs to explore the sensitivity of the mission performance to the jitter noise source. The investigation highlighted the relationship between resolving power and jitter. While the Star Tracker may be viable it reduces the range of acceptable values for the detector dark current and read noise, with more pixels being required to read out the signal. The analysis showed that the Gyroscope solution, with jitter decorrelation, will be sufficient to squash high frequency pointing noise in the system. At low wavelengths, where the PSF is largest relative to the airy disc, the readout aperture must be increased in order to manage clipping with the readout aperture which can cause considerable uncertainty on the stellar flux received.

#### 2.2.3 Summary of Findings

The detailed analysis of the impact of the jitter achieved with the gyroscope on the performance of Twinkle has confirmed that science will be achieved. This analysis covered spectral retrievals across a range of target exoplanets and atmospheres, with examples shown in Section 3. As a result of this analysis the Gyro configuration will be carried forward as the baseline for the next phase of missions design and simulations provided by BSSL will consider this case, with the wavelengths previously dedicated to the FGS now available to science. A more detailed description of this pointing performance analysis is in preparation for submission to a peer reviewed journal [6] and a comparison of the science performance for a few cases is given Section 3.

#### 2.3 Thermal Solution

There are three key thermal parameters that drive the scientific performance of the mission; the temperatures of the telescope and optical chain, the inner instrument sanctum and the detector. The primary sources of flux to reject are the Sun and the Earth. In order to reject solar flux the design considered a number of different thermal configurations. An important consideration when reviewing different thermal configurations is the attitude allowance of each thermal solution.

A sun-synchronous orbit was selected to help constrain the Earth-Sun-Spacecraft geometry and hence the impact of Earth flux on the spacecraft design. A series of sun shields designs were considered with the telescope either side mounted or top-mounted relative to the spacecraft bus. No significant thermal preference between the two designs approaches (side mounted or top-mounted) was identified so for mechanical considerations the top-mounted orientation was selected.

The lowest costs, lowest risk, implementation of a thermal solution for a missions such as Twinkle would be an all passive system. This was assessed for anti-sun pointing and a range of other attitude cases. While the analysis showed the system to be potentially viable there was insufficient confidence to take forward as the baseline, reverting instead to making use of an active cooler. The industrial team have performed an analysis of low cost, low lift, cyrocoolers which has been incorporated into the design in order to provide the low temperature for the detector and, crucially, the temperature stability.



Figure 2: Thermal configurations considered for feasibility

### 2.4 Optical Design

The spacecraft optical design has been developed with the ABB team to reduce complexity and to consider industrialisation. Key developments are the change from using narrow science and background slits to instead a wider field stop. The optical paths of the channels have been consolidated onto a single detector, as opposed to two separate spectrometers, with now only two diffracting elements as opposed to three. This also simplifies the thermal isolation considerations of the optical bench.

Each optical path consists of 6 mirrors, one dichroic and a grism element to produce the spectra. The detector on the optical plane is baselined as the Teledyne H1RG detector which will be actively cooled to a achieve a maximum temperature of 90 K (with a design target of 85 K). The telescope will be at least 0.45m in diameter and cooled below 168 K while the inner sanctum will be cooled to have maximum of operating temperature of 110K (baseline temperatures of 158 K and 100 K respectively).

This optical design reduces the complexity of the Twinkle mission by allowing for the consideration of one detector and a single optical plane. In the previous design the incorporation of the UVIS detector, while a heritage solution, introduced complexity into the optical layout and a thermal operating constraint much higher than the rest of the optical bench. The H1RG electrical interface and performance are well known and often used for astrophysics applications.

### 2.4.1 Wavelength Range

The updated industrial design now maintains two channels, with continuous wavelength coverage from 0.5 to  $4.5\mu m$  with a split at 2.43  $\mu m$ . This continuous coverage across the wavelength range is a distinct improvement on the previous design where some light (1.0-1.3  $\mu m$ ) was sequestered to the FGS. The previous design maintained three separate channels covering 0.4 - 1.0  $\mu m$ , 1.3 - 2.43  $\mu m$ , and 2.43 - 4.5  $\mu m$ .

A combination of considerations led the short wavelength cutoff to be relaxed, including detector and mirror performance, to maintain a cost-effective mission. Different telescope providers and processes were considered and each presented similar issues. The wavelength range was relaxed to remove this driver; the change was considered against the scientific impact and, while there are some interesting features at these wavelengths to examine (e.g. Sodium, Lithium), the resolving power required to accurately constrain the abundance is beyond the scope of Twinkle.

#### 2.4.2 Resolving Power

The most demanding science application of Twinkle is transmission and emission spectroscopy performed to characterise exoplanetary atmospheres. In order to avoid over-engineering the mission, a detailed analysis of this science case was performed to constrain the design. This in turn highlighted that the resolving power baselined previously could be reduced and allowed for changes and updates to the spacecraft platform design. The optical design of the Twinkle mission will provide spectral resolution powers of up to 180 and 80 in channel 0 and 1 respectively, and the effective readout resolving power is a function of pointing performance. Once accounting for the pointing performance the effective resolving power of the system is 70 in channel 0 and 50 in channel 1.

The previous design maintained a native resolution of up to 250 for wavelengths shorter than  $2.43\mu m$ . This was a natural extension of the Attitude and Orbit Control System (AOCS) performance of the platform available and the need to consider a FGS and a Tip-Tilt Mirror (TTM) in the design. This resolving power is not necessary for the considered science cases and, having consulted scientists interested in the Twinkle mission, the value was reassessed as part of the industrial phase. Through a series of spectral retrievals, the Twinkle science team determined that a resolving power of 20-70 would recover spectral features and these values were subsequently fed into the industrial design. With the previously discussed Gyro pointing solution as the baseline, the instrument was designed such that this resolving power requirement could confidently be met.



Figure 3: Simulated results of noise contributions with a selective readout aperture and conservative gyro pointing performance for HD 209458 b.

## **3** Performance Analysis

The radiometric tool used to access the capability of the previous design [7] has been updated and enhanced to incorporate the changes in the Twinkle design including PSFs from the ABB design and the jitter noise described in Section 2.2. Calculations by BSSL on the expected scientific performance for targets are provided in Table 2. This table details the error on the transit depth expected for a selection of exoplanet targets, including faint, small and cool targets as well as bright and hot Jupiters.

Table 2 also characterises the range currently considered for the performance of the Twinkle spacecraft with respect to the required transits to achieve the shown transit depth error. This reflects the engineering trade-offs and development work left in the design which will be refined throughout future work. The lookup table will be updated to reflect design milestones up to, and after, launch.

For exoplanet spectroscopy, the retrieval of the atmospheric chemistry and thermal structure is the primary aim of most pursuing scientists. In order to verify the viability of the pointing solutions, and the changes to the optical design, a number of atmospheric compositions were simulated and the performance of the mission design assessed via Bayesian retrievals using TauREx 3 [8]. The targets simulated represent a diverse range of planets, with a variety of atmospheric compositions, in an attempt to cover the expected parameter space and identity any loss of scientific potential due to a design decision.

HD 209458 b is a well-known reference to the exoplanet community and is one of the planets chosen to highlight the performance of the Twinkle spacecraft. Figure 3 shows a breakdown of the noise sources for this target while Figure 4 displays the resulting spectra after 3 transits have been stacked for both pointing solutions. By performing a retrieval on these simulated spectrum, we evaluated the ability of Twinkle to recover the input parameters. The posterior distributions are shown in Figure 5. Both pointing methods



Figure 4: Example recovered spectra for modelled HD 209458 b (3 stacked transits) which have been offset for clarity.



Figure 5: Comparing retrieval solutions for a single observation of HD 209458 b assuming different pointing performances.

accurately recover the water (H<sub>2</sub>O) abundance and the cloud deck. However, the Star Tracker solution derives a higher temperature and does not well constrain the ammonia (NH<sub>3</sub>). Both designs, in this case, can only put an upper limit on the methane content of the atmosphere which was modelled at  $log(CH_4) = -8$ .

### 4 Asteroid science analysis

The prospect of Twinkle as an observatory for asteroid and solar system bodies has been reviewed against the updated design and highlights more areas of study where the spacecraft can provide excellent data. The extended wavelength range compared to analogous past missions allows for water features at around 3.5  $\mu m$  to be observed. Additionally the removal of the spectral gap between 1-1.3  $\mu$ m provides additional science cases such as the characterisation of mafic silicates, olivine and pyroxene on the surfaces of stony asteroids [9].

In order to review the potential performance of Twinkle, the ephemerides of over several hundred thousand asteroids from the JPL Horizons database were reviewed and the brightness of the asteroids considered in a radiometric tool. This initial review shows that, considering how bright these targets are, a high SNR can be achieved with relatively short observations. Additionally, as on target tracking is no longer used, fainter objects are now accessible to the mission as shown in Figure 6 (a previous limit had been place at Vmag = 15). Setting a conservative inertial pointing tracking rate of 30 mas/s there are many asteroid targets available to Twinkle.

Finally, in Figure 7 we show an example spectra for two asteroids, with magnitudes of 14 and 16, after 1 hour and 10 hours of integration respectively assuming a Ceres-like composition. Given the sensitivity of Twinkle's instrumentation, a population of several thousand asteroids could be studied in a three year survey.

## 5 Conclusions and Way forward

The industrialisation phase of the mission has shown that the design of Twinkle is valid and able to use a large amount of industrial heritage. The scientific analysis has been performed with greater detail and shown Twinkle to be capable of observing many exoplanets and an extensive asteroid populations. The scientific analysis captures the design trade-offs that will form the immediate future work, most notably a detailed thermal design of the optical path, the selection of a cyrocooler supplier and a detailed mechanical model of the spacecraft.

The Twinkle mission is entering a mature stage of technical design with advanced simulations of the scientific performance. BSSL would like to again thank the industrial team and contributing scientists for their work in progressing the spacecraft design. The aim of the Twinkle mission is to provide excellent science from an observatory that reflects the needs of scientists. We invite those who would like more information to get in touch.

### 6 Acknowledgements

Blue Skies Space would like to thank Subhajit Sarkar and Matthew Griffin of Cardiff University for their support and analysis of the impact of jitter on the spacecraft performance and on the forthcoming paper. This work has been immensely valuable in validating the Twinkle design. Additionally, we thank Andy Rivkin for supplying the spectrum of Ceres.

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Figure 6: Asteroids observable by Twinkle sorted by type - assuming a maximum tracking rate of 30mas/s. The grey region shows brightness limit of previous the FGS design on trackable objects, a restriction which no longer exists. Figure adapted from [9].



Figure 7: Example recovered spectra for asteroids modelled with a Ceres-like composition highlighting the abundance of features within Twinkle's spectral coverage.

[Rank] <sup>†</sup> HD 209458 b [4]							ין שקיים וופווה	, midd minoill	mmn centra			TIATINTAGAN		IVAILES OF	FOICIIII #
HD 209458 b [4]	$[R_J]$	Mag	[mdd]	$0.5$ - $1.0\mu m$	$1.0-1.5 \mu m$	$1.5-2.0\mu m$	$2.0-2.5\mu m$	$2.5-3.0 \mu m$	$3.0-3.5\mu m$	$3.5-4.0\mu m$	$4.0-4.5 \mu m$		of Transits	Transits	Transits Per Year
	1.39	6.3	14700	27	29	43	60	46	58	85	112	Full	3	2-4	$\sim 17$
WASP-74 b [19]	1.83	8.2	9800	47	52	82	119	89	115	177	242	Full	5	4-7	$\sim 35$
KELT-7 b [21]	1.6	7.54	8650	27	32	52	76	57	74	114	154	Full	5	4-7	$\sim 25$
<u>55 Cnc e [28]</u>	0.17	4.02	450	20	20	26	34	27	33	44	57	Full	3	3-4	~
GJ 3470 b [14]	0.408	7.99	6600	61	46	53	67	57	64	83	105	Half	5	4-7	$\sim 23$
GJ 1214 b [15]	0.254	8.782	17000	174	86	105	134	116	122	150	199	Half	10	6-16	$\sim 39$
WASP-80 b [38]	1.0	8.351	29650	68	61	69	66	6L	94	147	202	Half	10	6-17	$\sim 24$
	1.41	9.693	9800	39	47		131	94	$-\frac{126}{}$	220	$\frac{319}{2}$			8-29	~
KELT-17 b [41]	1.525	8.646	8950	21	26	47	69	50	64	103	142	Quarter	5	3-8	$\sim 25$
WASP-34 b [54]	1.0	8.792	12500	26	28	45	69	50	99	109	155	Quarter	10	6-17	$\sim 13$
GJ 9827 b [83]	0.145	7.193	700	26	21	26	35	27	34	48	63	Quarter	10	8-13	$\sim 67$
LHS 1140 b [117]	0.154	8.82	5600	58	36	44	56	47	51	65	85	Quarter	10	7-16	~ 3
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