An SST-2M Implementation Concept

Response to "Questions of the SST Harmonisation Review Panel to the Teams"

Version

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Foreword

Please see within for answers to all questions posed by the review panel. We note that in section 2 we are given the opportunity to provide an updated requirements section in the RfI Response based on Prod4 results. We thank the panel for this opportunity and have updated the RfI Response appropriately. Rather than submit several documents, we have included the updated section herein. This document therefore exceeds the requested page limit. If this is unacceptable we can remove the updated section and re-submit the RfI response in addition.

1 General

1.A Which are the areas of your proposed design where you think you would benefit most?

Telescope With regard to the mechanical structure and the mirrors assembly, the proposed design of the structure and of the optical system is mature and ready for CDR and production (the structures and mirrors for the array of nine pathfinders are already under production). Therefore, concerning the design, there is no need for new ideas, and a change in the ASTRI design would probably increase risks and costs and introduce delays. On the other hand, the production and deployment of 70 telescopes represents quite a challenging task and there are implementation activities at the observational site that would benefit from the engineering support, solutions and manpower from additional groups (for example telescope AIV and commissioning activities).

Camera We are confident that the current consortium has adequate resources to develop a final camera design and fund 70 cameras for the production phase of CTA. However, the timescales for production and integration into CTA of 70 SSTs cameras will be challenging. We would therefore welcome additional engineering manpower to accelerate the design finalisation and production process.

1.B In the event that your proposal does not form the basis for the final SST design, in which areas do you foresee continued contribution to CTA?

Telescope Team In case the proposal will not be selected, INAF will not participate to the SST program apart, maybe, a symbolic and small participation (e.g. related to the production of the mirrors). INAF will in any case implement the mini-array of nine pathfinders based on the ASTRI telescopes using funds different from the money engaged for the CTAO ERIC. Therefore, most of the available budget engaged for the ERIC for will be redirected in other areas of the CTA project. INAF main interest would be then readdressed to the leadership in some of the software work packages, in particular those related to the data handling process (i.e. DPSS, SUSS). Other areas of interests would be the participation in the development and production of the LSTs for the southern site.

Camera Team In the event that the proposed design is not chosen as the basis for the SST camera, most of the current CHEC groups would endeavour to continue contributing to CTA, either to the SST or elsewhere. The exact area of contribution will depend on individual group expertise and national funding constraints. We expect some loss of funding completely (20-30%), 50% that would be moved to other CTA areas, and upward of 5M€ could potentially still be available for SST camera production.

2 Performance

NOTA BENE: the performance of the different subsystems and of the telescope have been measured, whenever possible, using the existing working prototype installed in the INAF astronomical site of Serra La Nave on the slope of Etna volcano. In the following, several of the answers are based on the results of these direct experimental tests. See the documentation cited in the text for extended reports.

2.A Seismic acceleration: Have the seismic accelerations expected at the camera interface during the maximum seismic event been evaluated? Which methods, assumptions and simplifications have been used or are planned for that assessment? Which verification methods have been performed or are planned to verify sufficient resistance of the camera to such accelerations?

The finite element model applied for ASTRI telescope (Figure 1) permits to calculate the transfer spectrum of the accelerations on the barycentre of the camera (ASTRI-DES-GEC-3100-030b). While the resistance at the camera interface has been already verified by a proper analysis (see **Error! Reference source not found.**), these values will be delivered to the CHEC collaboration in order to verify the resistance of the camera and to implement a proper mechanical structure in the final camera design.

Due to the compact nature of the camera vibration tests can be performed on the complete camera using an industrial "shaking" machine. We plan to use the aforementioned acceleration spectrum from the telescope FMEA as input to these tests. Due to the potential risk of damage to the prototype camera these tests will only be performed once all other tests are complete. After completion of the vibration tests, the camera will undergo visual examination for loose screws or connectors. Illumination tests will be performed before and after the vibration tests to identify the pixels damaged during the tests.

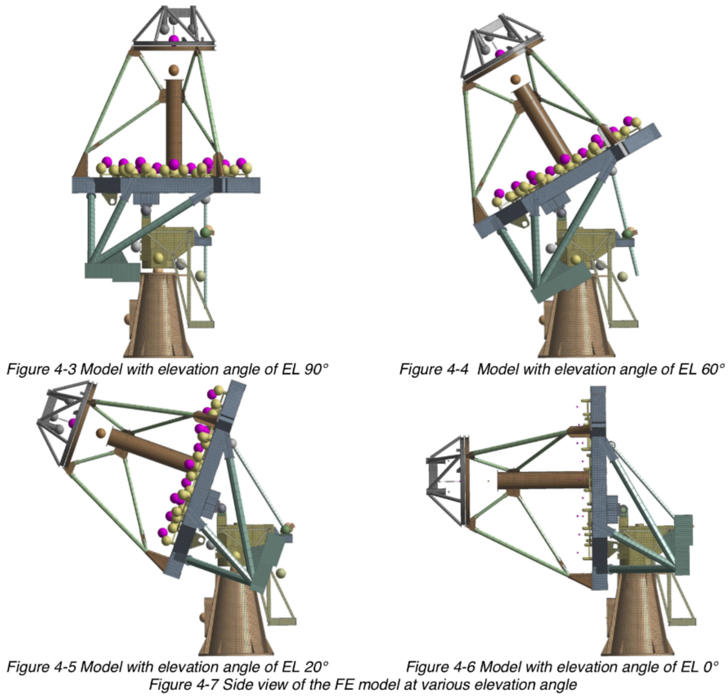

Figure 1: Model used for the FEM analysis.

2.B Astrometric accuracy: Please provide an error budget which summarizes the contributions of the various components and subsystems to the achievable astrometric accuracy. Disturbances from environmental conditions should also be considered

Telescope Structure

The telescope has been designed to fulfil CTA astrometric accuracy requirements following two parallel strategies: the on-line astrometric calibration and a post-facto calibration astrometry. A good astrometric accuracy is important in order to correct pointing errors mainly due to the factors listed hereafter:

1. Gravity flexures
2. Mechanical errors (i.e. encoders systematics)
3. Thermal flexures
4. Wind loads flexures.

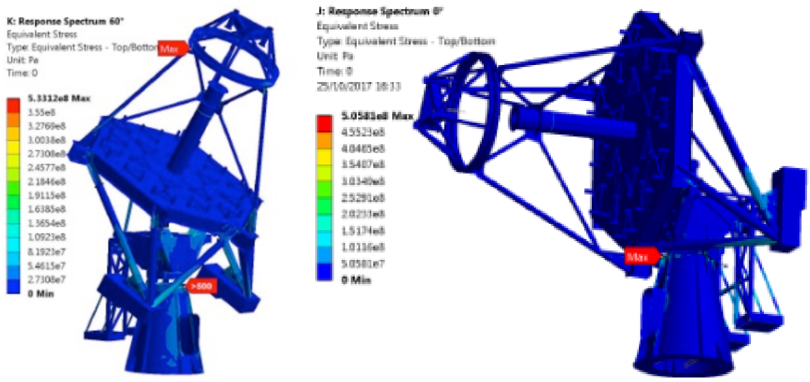

Figure 2: Results of the FEM analysis for the structure: Left) elevation 60°. Right) Elevation 0°.

For each one of these effects, the error budget foreseen by the ASTRI design is the following (all values are rms):

1. Up to 70 arcsec (in the 30 ° – 90° elevation range)
2. up-to 20 arcsec
3. <5 arcsec outside transition conditions (thermal gradients below 3 °/h)
4. < 5 arcsec inside *precision pointing conditions* (wind < 11 km/h), about 13 arcsec up to 50 km/h

The first two sources of errors are easily modelled and removed after a proper simulation (e.g. using a TPOINT model) due to the fact they are systematics.

In principle, the last two effects could be tracked and corrected using the data from a look-up table, due to the fact they are just marginally effective in determining the *precision pointing conditions*. However, in order to adopt a more conservative approach, we have chosen the strategy to limit, by an accurate and proper design, their amplitudes below the astrometric requirement. As above mentioned, the on-line calibrations deal with all the systematic effects affecting the astrometry, i.e. the gravity flexures and encoder errors. In principle, during observations in *precision pointing conditions,* these are the only sources of errors to be considered. After the application of a proper model using a TPOINT treatment of the parameters, it is possible to push down these systematic errors at a level < 10 arcsec for each single structure of the array (see Figure 3).

In the ASTRI telescope, the TPOINT model parameterization is obtained using a Pointing Monitoring Camera (PMC) mounted on the top of the M2 support structure. This tool permits to track the errors with a frequency lower than 0.1 hertz to an accuracy of about 4 arcsec. This is obtained using an automatic asterisms recognition approach in the pointing field of view of the PMC (2° x 2.5°). The only effects that cannot be account for are the M2 - M1 relative tilts. However, these errors are by design well below the astrometric requirements. Moreover, it should be noted that a cross-check calibration between the telescope focal plane and PMC values during the AIV phase can be done using a dedicated CCD camera placed at the centre of it.

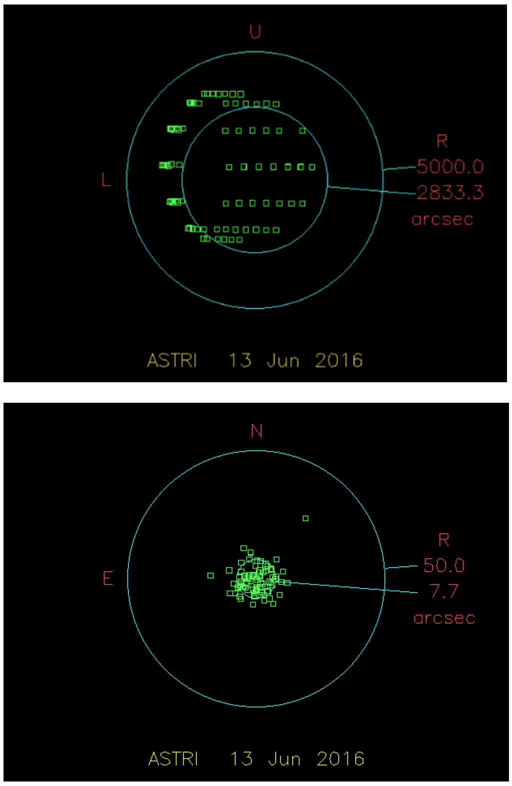

Figure 3: Example of the results of the TPOINT analysis for the ASTRI prototype telescope.

A post-calibration correction can also be performed in order to improve the astrometric accuracy. This can be obtained acquiring images with the PMC during the scientific runs. This procedure assures an astrometric accuracy of about 4 arcsec for all effects with frequencies below 0.1 hertz as it has been clearly demonstrated with the ASTRI prototype (see section 3.1.1 of the RfI Response). Higher frequencies effects are well below astrometric accuracy.

Camera Positioning The camera must be positioned stably and accurately with respect to the ideal focal-plane position. Systematic rotations about the optical axis along the focal plane radius of curvature are unimportant for online performance. Shifts along the optical axis are important and deteriorate the PSF as seen by the camera. Shifts perpendicular to optical may be considered to contribute to a shift along the optical axis from the ideal position of a given pixel centre. To ensure a degradation of no more that 10% in PSF all pixels must be positioned to within 1 mm in of the focal plane along the optical axis.

The camera enclosure is rigid and holds the focal plane position stable to ±0.2 mm. Measurements on the camera mechanics indicate that the centre of all photosensor tiles may be placed to within 0.35 mm of the ideal position in the direction of the optical axis. This misalignment may be compensated for by a translation and rotation at the rear of the camera when installed on-telescope via adjustment of telescope secondary reflector (M2), but is not essential. This would reduce the spread to 0.035 mm for an ideal set of detectors. The tolerance in detector depth and tiling of the curved focal plane with flat sensor tiles creates an additional maximum shift of 0.55 mm from the ideal position for pixels at the edge of photosensor tiles.

Camera continuous pointing monitoring. As noted in section 1.1.3 ii of the RfI Response the camera contains a signal chain to monitor star brightness continuously in addition to Cherenkov observations. All stars brighter than Vmag = 9 may be tracked, implying that the system may be used to continuously monitor telescope pointing during all observations. A post-calibration accuracy of 4-5 arcseconds was achieved in simulations under 'new moon' conditions. The exposure time to record enough photons to track each star is ~100 ms. As the PSF is on the order of the pixel size the system is most sensitive to stars transiting pixels, and thus requires a few minutes to reach high precision. The continuous pointing monitoring system thus requires that telescope vibrations and variations in PSF across the focal plane (due to position or environmental conditions) are negligible on such timescales. If the PSF varies on shorter time scales, the error in the determination of the PSF location will go linearly with the size of the PSF, and is approximately 4 arcseconds per percent PSF change. In precision pointing mode the CTA requirement on post-calibration astrometric accuracy is 7 arcseconds, implying a <2% change in PSF could be tolerated. In the standard pointing mode, the CTA requirement on post-calibration astrometric accuracy increases to 20 arcseconds, so a 5% change in PSF could be tolerated. It should be noted that typically there will be up to 10 stars in the field that are tracked simultaneously, which means that errors can average out, depending on the kind of changes in the PSF so the above budget is only applicable in extreme cases. The system is in principle self-calibrating without external references required; an observation while the telescope is stationary will provide information regarding the PSF due to the known drifting of stars through the FoV. Once self-calibrated the system may be used to monitor not only pointing but also changes in the telescope PSF, and misalignment of mirrors therein.

The ASTRI camera prototype have also verified pointing on the ASTRI telescope using continuous monitoring of the pixel variance. This can also be tested with CHEC during normal operations using the waveform readout (see section 3 "Pixel baseline and fluctuations") and if appropriate can be used instead / as well as the above method.

Environmental effects such as wind and temperature do not create distortions on the timescales (10 – 100 ns) of Cherenkov data capture. Effects on longer timescales can be corrected off-line using the continuous pointing system. Effects on the 10 - 100 ms scale may well limit the accuracy of the continuous pointing system. The continuous pointing system is due for first on-telescope tests this spring with the specific goal of understanding the limitations of the concept.

2.C As the Monte Carlo Prod4 with the more accurate telescope models was not available to the teams at the time of writing, we invite the teams to update their responses to the SST requirements in the light of prod4 results, if desired.

Herein we re-produce RfI Response Section 1.1.3 'Requirements verification' updated in light of Prod4 results. Only subsections that have changed are included here. Plots have been provided by the ASWG working group. As requested by the panel, we discuss results for a single choice of camera pixel size. A baseline of 6 mm pixels has been chosen. In plots where all SST options are shown the appropriate curve to examine is "sst-astri+chec-s" (blue triangular points).

i. **B-SST-0010 Monte-Carlo Verification**. MC simulations are used to demonstrate that the SST sub-system fulfils performance requirements. As requested, here a sub-set of these performance requirements are addressed. In all cases results from the Prod4 MC production run are presented.

   A-PERF-1210 SST Sub-system Sensitivity: Figure 4 shows the SST sensitivity for 50 hr, 5 hr and 0.5 hr of observations. In all cases the requirement is met.

   A-PERF-0030 Gamma-ray field of view: The gamma-ray FoV (defined as twice the angular offset at which the 50-hour differential point-source sensitivity is degraded by a factor of two) is required to be >3° from 3 - 300 TeV. Figure 4 (bottom-right) shows the SST sensitivity relative to on-axis for several offset angles. The requirement is fulfilled for all results above a ratio of 0.5. The 3.5° offset result is within the requirement for all but a single point, and the gamma-ray FoV is therefore just under 7°.

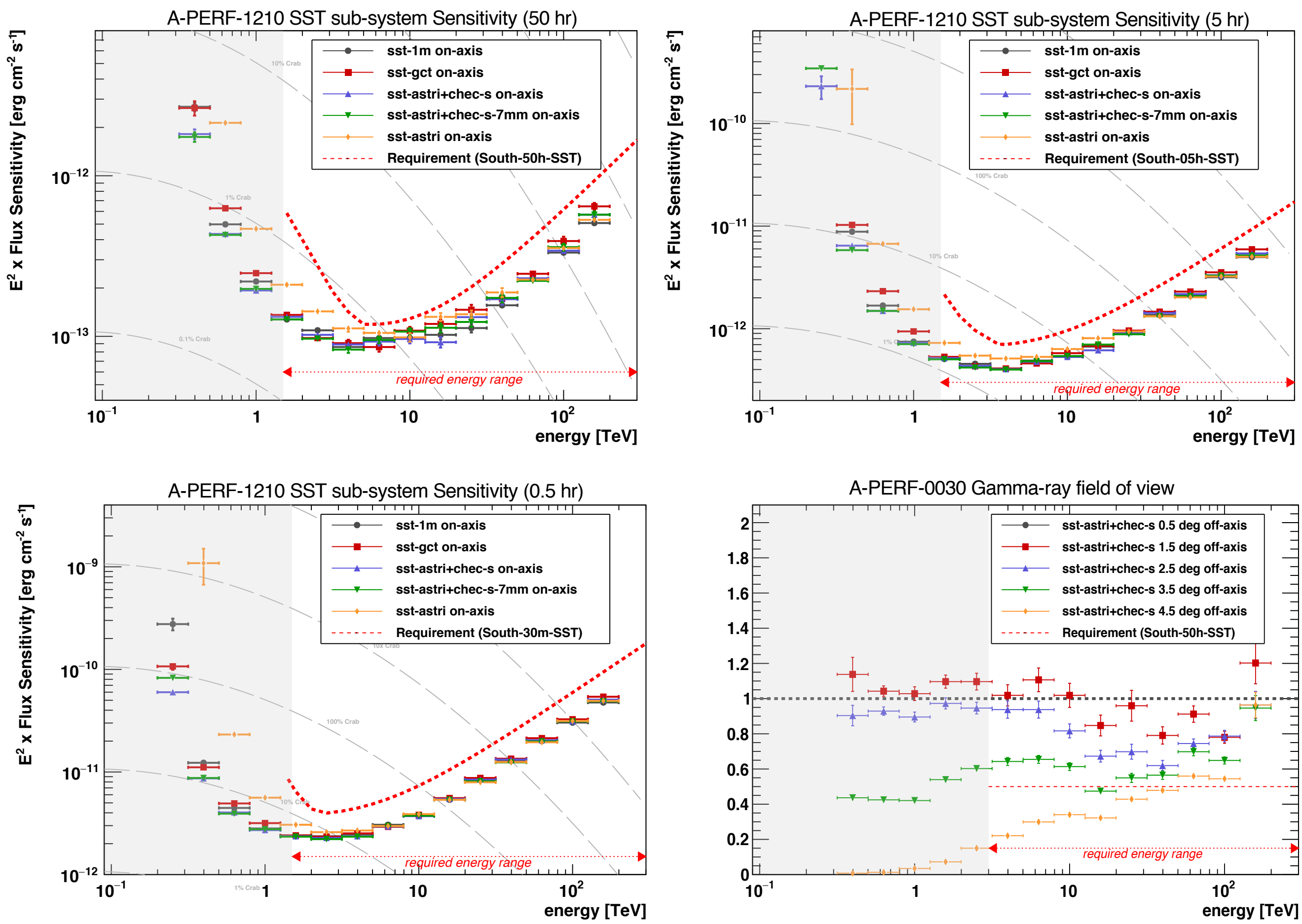

Figure 4 Sensitivity requirements for the SST Subsystem together with the Prod4 MC simulation results.

A-PERF-1250 SST Sub-system Angular Resolution: Figure 5 shows the angular resolution for the SST Subsystem. Note that this analysis is not optimised to provide best angular resolution, but rather best point-source sensitivity. All SST results in Figure 5 therefore violate the CTA requirement at some energies. The violation should be assigned to deficits in the reconstruction methods, and not to the design of the SSTs. Therefore, ASWG chose not to include the requirement curve in this figure. As noted in the original response, a significantly better angular resolution is possible at expense of some collection area and sensitivity. Image template or model-based analysis schemes, for example, are known to provide an improved angular resolution, in particular when images start getting truncated at the edge of the field-of-view – a situation not uncommon at the highest energies. An example of the improvement possible was given in Figure 5 of the original RfI Response.

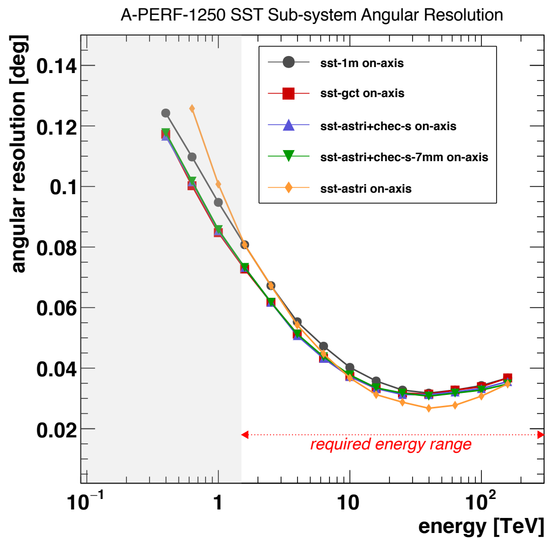

Figure 5 Angular resolution results from Prod4 MC simulations.

ii. **B-SST-0120 Mirror Reflectivity**. No update

iii. **B-SST-0130 Optical PSF quality**. No update

iv. ***B -TEL-1010 Intensity Resolution.*** Figure 6 shows the intensity resolution requirement and the Prod4 performance. The large error bars at high illumination levels are due to the limited statistics in the Prod4 simulations at these image amplitudes.

v. **B-SST-1130 Field of View Diameter.** The FoV is required to be at least 8°. By design, with 6×6 mm^2 pixels the proposed camera will have a FoV of 8.84°.

vi. **B-SST-1150 Angular Pixel Pitch.** The pixel pitch is required to be <0.23° for pixels on a square grid. 6×6 mm^2 pixels correspond to a pixel pitch of 0.16°.

vii. **B-SST-1230 Minimum Image Amplitude.** The camera is required to trigger with 50% efficiency on gamma-ray images of less than 250 photons in amplitude (300-550 nm) for a nominal 'dark' NSB level. Analysis of Prod4 shows the proposed camera will reach 50% trigger efficiency by an image size of 153 photons.

viii. **B-TEL-1260 Deadtime.** No update

ix. **B-SST-1280 Event Rate.** No update

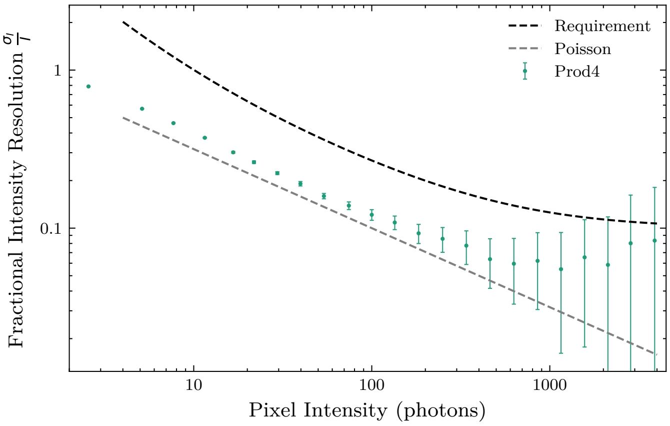

Figure 6 Intensity resolution derived from Prod4 simulations (6 mm pixels). The large error bars are due to limited statistics available.

2.D Please also address the following points

2.D.i Off-axis PSF

Figure 7 shows the PSF of the ASTRI prototype measured across the focal plane using a dedicated CCD camera. See also section 3.2.1 for more details on the measurements and results.

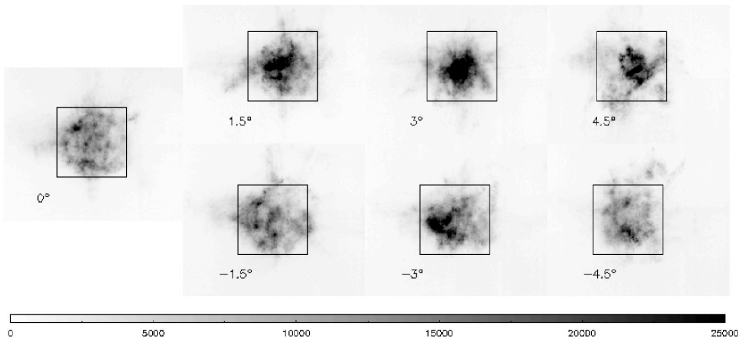

Figure 7: ASTRI prototype Telescope measured across the focal plane. The pixel of the Cherenkov camera is over plotted (from: Giro et al., "First optical validation of a Schwarzschild Couder telescope: the ASTRI SST-2M Cherenkov telescope", Astronomy

2.D.ii Effective mirror area

In Figure 8 we show the profile of the effective area of each telescope as a function of the wavelength, for different off-set angles with respect to the optical axis. It should be noted that the reflectivity of the two mirrors and the filter transmission have been included in the simulations.

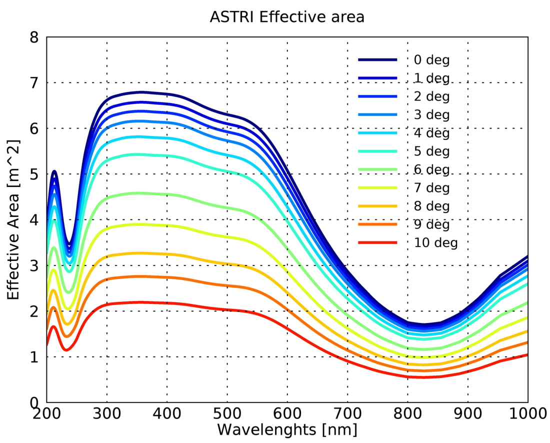

Figure 8: Effective Area of the ASTRI telescope as a function of the wavelengths for different off-set angles (the reflectivity of the two mirrors and the filter transmission have been included in the simulations).

2.D.iii Angular pixel size

The angular pixel size is 0.16°.

2.D.iv Number of readout channels and readout scheme

The number of readout channels is 2048. In each channel an SiPM signal is amplified and shaped to be optimal for the SSTs (~10 ns FWHM – determined by early MC simulations). This shaped signal is sent to 3 locations on the Front-End Electronics (FEE) modules:

- A TARGET-T5TEA trigger ASIC
- A TARGET-C digitisation ASIC
- A slow-signal ADC used to monitor NSB and telescope pointing – not for Cherenkov readout. See section 2.B.

The TARGET-T5TEA ASIC provides the first level of camera trigger. Each ASIC accepts 16 input channels. Sets of 4 neighbouring SiPM channels are summed and discriminated (via a settable threshold) in each ASIC. The resulting digital output is sent to an FPGA on the Backplane. The Backplane thus receives 512 digital signals from the 2048 camera channels. The width of these digital signals is configurable on the ASIC and set to 8 ns. The Backplane FPGA implements a next-neighbour logic and produces a positive camera trigger if the digital signals from two neighbouring sets of camera pixels overlap. This camera trigger is timestamped and sent both to the FEE modules and a central trigger system within CTA.

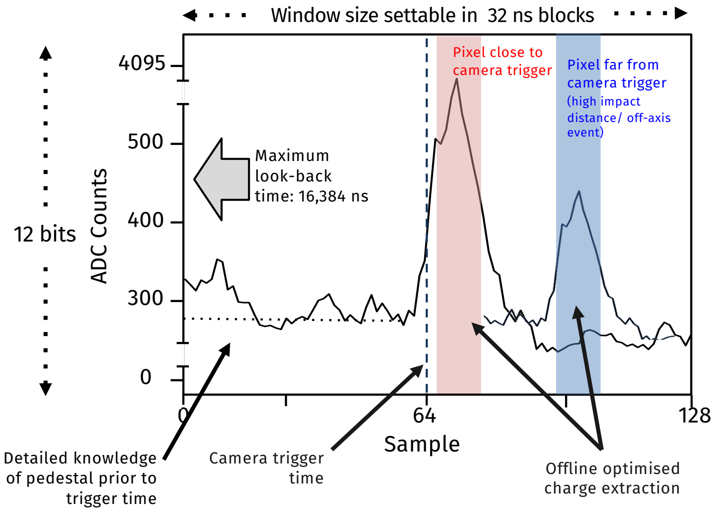

Figure 9: Overview of the waveforms obtained from camera readout. 2048 channels of readout lead to 1 waveform per channel per event.

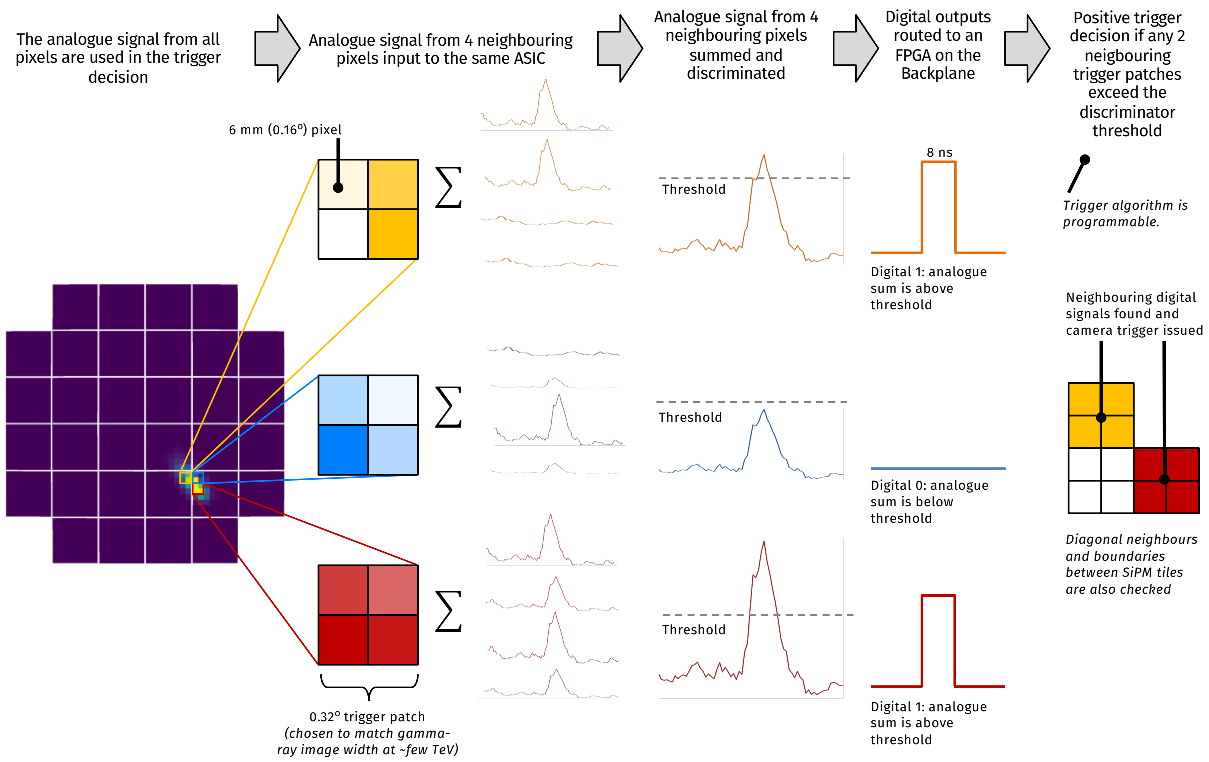

Figure 10: Overview of the camera trigger scheme.

Following a camera trigger from the Backplane at the FEE modules, all channels are read out. This is achieved via the TARGET-C ASICs. One ASIC contains 16-channels, each with a depth set to 4096 cells (of a possible 16384). Each cell stores 1 ns of incoming charge. Following instruction from an FPGA on the FEE module a selected set of cells are digitised and read out. The result for every channel is a 1 GSa/s waveform of 128 samples in length with a 12-bit per sample resolution. The ASIC sampling speed, look back time, and readout / waveform length are all configurable. The high-channel density of the TARGET ASIC leads to a cost-optimised readout solution. Storage of incoming charge may continue during read out of other cells following a camera trigger. In this way dead-time is minimised (see RfI Response section 3.3 & Figure 18).

The camera contains 32 FEE modules, each with 64 channels. Each FEE module buffers digitised data and sends it via 1 Gbps UDP to a single data acquisition board, known as the XDACQ. The XDACQ acts effectively as a switch, routing all traffic to a single 10 Gbps link out of the camera. The XDADQ has a second Gbps link that can increase readout rate in the future.

Off-camera data is processed and built into full events by a Camera Server Process (running on the CTA farm). The CTA central trigger system processes the list of camera triggers (and timestamps) and sends a list of events to retain to the Camera Server Process. The camera and Camera Server Process may also flag a certain fraction of events to keep regardless of the central trigger decision (such as for calibration).

2.D.v Pixel calibration and stability
Pixel calibration and the stability therein is covered in section 3. If some particular aspect is missing we will be happy to provide further information.

2.D.vi Pixel baseline measurement and pedestal subtraction
Pixel baseline measurement and subtraction in CTA is regarded as part of regular calibration / monitoring. Please see section 3 for details.

2.E Provide information about the following additional points

2.E.i Flexibility of the proposed trigger scheme, including integration window.

The proposed trigger scheme is shown in Figure 10. The algorithm used to form a camera trigger is implemented in an FPGA and is therefore flexible. The current algorithm requires any two neighbouring camera trigger patches to overlap by ~3 ns. This scheme was chosen following MC optimisation. Implementing a more complicated algorithm would simply require a firmware (FW) update. Other flexible aspects of the trigger scheme:

- the analogue sum threshold is settable to allow for a flat trigger response across the camera and to limit the trigger rate appropriately for a given NSB rate;
- the width of the digital pulses used to make a trigger decision is settable, allowing control over the telescope coincidence time;
- the digital pulses used to make a trigger decision may be individually delayed in the Backplane FPGA to minimise the coincidence resolving time of the camera.

The integration window is not part of the trigger system. Analogue signals are split to two distinct ASICS – one for triggering and one for readout. Figure 9 shows the flexible aspects of the readout window (size, position and sampling rate). Signal extraction takes place off-line, and in the most basic form an “integration window” may be used. However, due to the availability of full waveform data more advanced techniques are possible (including applying custom filters, cross-correlation with a reference pulse, and even extracting the time and number of every photon in the waveform via e.g. machine learning).

2.E.ii Optical system alignment monitoring procedures and frequency, including PSF across the FoV

Due to the stiffness of the opto-mechanical structure, no active correction of the mirror tilts is needed. This has been proven with the prototype, where no change of the mirror alignment was observed after 6 months of operations (Figure 11, left & centre). For this reason, the alignment system is considered an AIT/maintenance tool to be mounted at the telescope only when necessary, i.e. in case our monitoring systems give a signal of misalignment and for the periodical maintenance (e.g. once per year).

Alignment of the mirrors can be considered as a maintenance operation and its monitoring is a fully-fledged part of the predictive maintenance. This operation is obtained all the nights during scientific shifts using the waveform variances (implemented in both the ASTRI and CHEC cameras) or the slow-signal chain (implemented in the CHEC camera – see section 2.B). This acquisition mode allows the PSF to be monitored across the entire focal plane in in parallel with scientific data acquisition. It should be noted that this approach has been already successfully proven with the ASTRI prototype in order to test if some mirror is misaligned and it has to be corrected (see Figure 11, right).

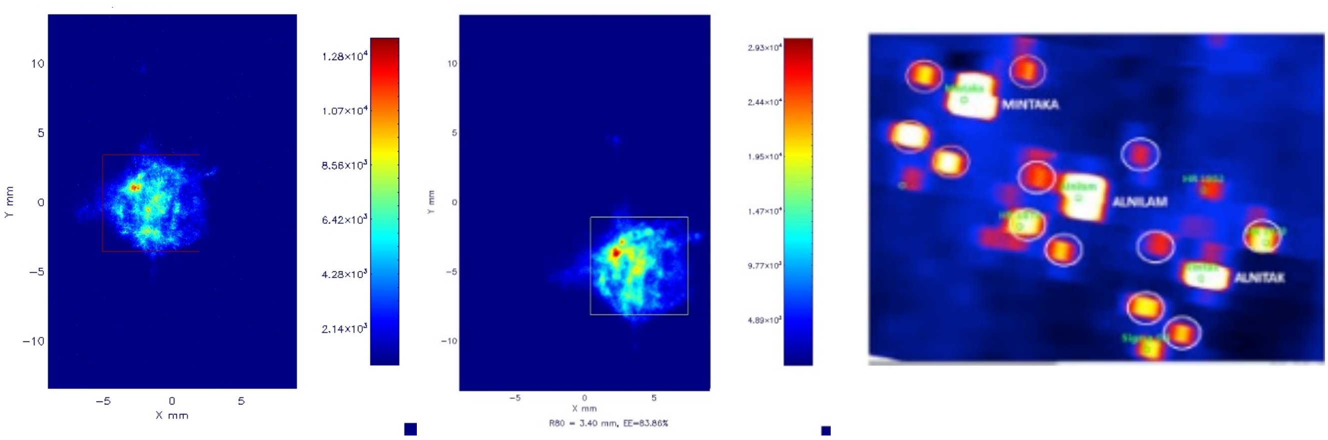

*Figure 11: **Left & Centre:** The two images of the Polaris acquired in October 2016 (left) and March 2017 (right) obtained with the ASTRI prototype. The two images are almost identical while the mirror alignment was not touched. **Right:.** Variance image of the Orion belt showing the ghost spots due to the misalignment of a few panels of the M1 mirror.*

2.E.iii Upgradability of the FoV and pixels: For your optical design, what is the minimal reasonable pixel size for an 8 degree FoV? What is the maximum FoV supported by your optics?

The minimal pixel reasonable size that could be envisaged is 6 x 6 mm^2. This corresponds to an angular pixel size of 0.16°. The ASTRI optical design exhibits excellent off-axis performance and the CTA SST optical performance requirement of is satisfied up to 6° off-axis. The maximum FoV supported by the proposed optics is therefore 12°. The ASTRI optical system has a plate scale of 37.6 mm/$^\circ$, and hence a 12° FoV would correspond to a 0.45 m focal plane (increased from 0.33 m with the current 8.84° FoV). The ASTRI dual mirror telescope is prone to the vignetting by the secondary mirror (M2) and by the structure. To investigate the FoV upgradability we simulated the ASTRI geometrical area as a function of off-axis angle (see Figure 12, right). For each off-axis angle above 4.5° the camera size is set to that corresponding to a FoV equal to twice the off-set angle. An increase from a FoV of 9° to 12° results in a drop in geometric area from ~6 m^2 to 5 m^2. Rather coincidentally the CTA requirement for the minimum area of an SST is 5 m^2.

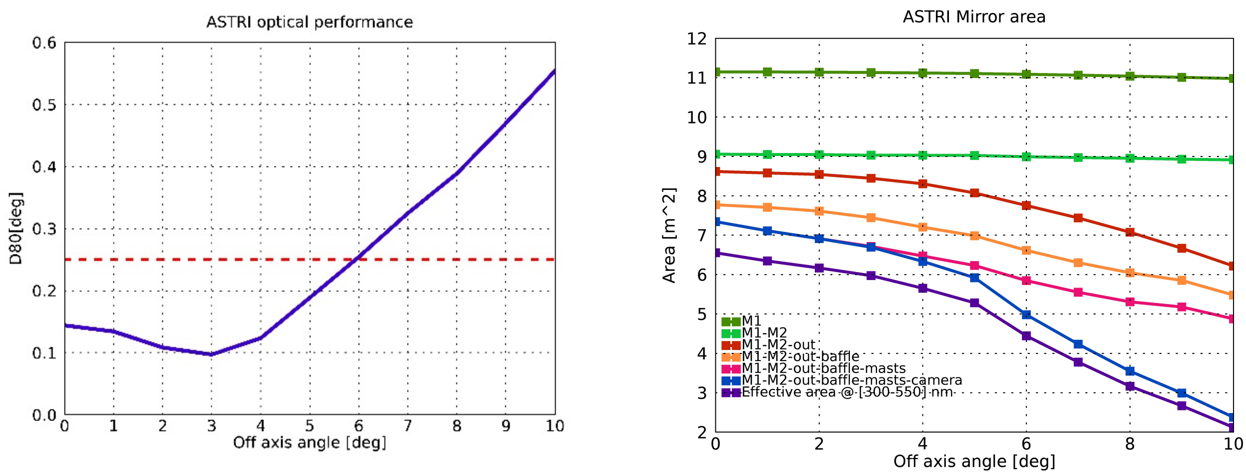

Figure 12. Left: D80 as function of off axis angle. CTA requirement is satisfied up to FoV of 6 degrees in radius: Right: geometrical area vs off axis angle. Blue curve shows the effect of the vignetting of the camera. Points below 4.5 degrees are for the current camera geometry. For larger angles a camera with increasing diameter is considered. In violet colour it also shown the average area in the 300-550 wavelengths region as a function of the off-set angle taking into account the reflectivity of the two mirrors and the transmission of

2.E.iv Comment on the energy range, particularly recovery of large signal events (including both on and off-axis events).

The proposed SST design meets CTA sensitivity requirements on all timescales across the required energy range of 1.5 TeV to 300 TeV.

At low energies performance if first limited by the ability of telescopes to trigger on the amount of Cherenkov light produced in showers. The proposed design features reflector collection area, mirror reflectivity and camera efficiency specified to meet CTA requirements. Coupled with an efficient trigger scheme a desirably low energy threshold is met. Energy threshold is defined by the ability to trigger, but does not necessarily translate directly to sensitivity due to the thresholds set by image analysis. Cherenkov signal must be isolated from NSB and gamma-ray showers correctly separated from hadronic showers. Waveform readout is essential to optimise Cherenkov signal capture and minimise NSB contamination. This becomes increasingly important at high NSB rates (e.g. in moonlight). To this end the proposed design features 1 GSa/s digitisation. Fine pixilation improves the image quality and therefore the ability to reject hadrons. With the standard Hillas analysis used in Figure 4 the effect of a finer pixel size in the proposed design compared to the 1M is only evident in the regime where the width of gamma-ray images is less than the 1M pixel size (< ~2 TeV). However, with a better analysis the improvement should exist up to higher energies.

The dominant factor in the 50-hour point-source sensitivity curve (Figure 4) above 10 TeV is the area covered on the ground. In this regime over 50 hours and for a point source CTA is essentially background free. Since the array layout is fixed the effective area and therefore 50-hour point-source sensitivity for all SSTs is similar at high energies. In reality high-energy sources are extended and will be observed for longer than 50 hours – so will not be background free. Here the point-source sensitivity plots are not a good general judge of performance. It will not only be the sensitivity but also the angular resolution that will be key to achieving meaningful scientific return, rather than simply source detection. Fine pixilation (>30% finer than the 1M) improves angular resolution is therefore important for high-energy science.

Recovery of large signal events at high energies:

At the highest energies, on-axis events produce extremely bright, fully contained, images in telescopes illuminated at small impact distances. Pixel saturation can occur, which can in turn limit the quality of the charge and directional information in the corresponding telescopes. Compliance of the proposed design with the applicable CTA requirement (intensity resolution) ensures acceptable performance up to 4000 photons (see Figure 6). Such large showers produce enough Cherenkov light to trigger telescopes many 100s of metres away (see Figure 13 left) and so will inevitably also be captured by many more cameras, and therefore excellent resolution is achievable. As events are captured at increasingly large impact distances the image centroid moves radially outwards from the camera centre as images become elongated and eventually truncated by the finite FoV (see Figure 13 – middle). At high energies, the effective collection area for a fixed telescope spacing is therefore limited by the size of the FoV, rather than by mirror area / telescope throughput (or equivalently photon density). It is a CTA requirement that the SST features a FoV of at least 8^{o} to ensure acceptable performance in this regime. The proposed design exceeds this (8.8^{o}). For a fixed telescope layout there is a limited benefit to be gained by increasing the FoV further for on-axis events landing inside the array. For high-energy events landing outside the array, the collection area increases approximately linearly with the FoV as telescopes trigger on showers landing further away (assuming enough light remains to trigger the telescope) (consider Figure 13 - left at 50 TeV). This does affect the sensitivity (though as a fraction of the total on-axis sensitivity for all event the increase is small).

For high-energy off-axis events, images move away from the camera centre and again elongate with increasing off-axis-angle. For such events an increased FoV not only increases the telescope multiplicity with which a shower is seen but also allows more images to be fully contained within a camera. An increased telescope multiplicity results in improved angular resolution and reducing truncation improves image quality resulting in better background rejection (and in-turn better off-axis sensitivity). This improved off-axis performance translates to an increased gamma-ray FoV, and is the dominant improvement to be found when increasing FoV beyond the CTA requirement (assuming fixed telescope spacing). The proposed optical design can support a camera with a FoV of up to 12^{o}. In section 9 we discuss upgrading the FoV and the scientific implications.

In the same way that events may be truncated in, or miss, the camera due to the finite FoV, they can also be missed by the camera readout window. The amount of time taken for an image to propagate across a camera increases with the energy of the shower and with the impact distance from the shower. Figure 13 – right shows the propagation time for high energy gamma rays and protons as a function of impact distance.

To ensure that the events that produce enough light to trigger telescopes at large impact distances also result in complete captured images requires a long readout window. It is important for background rejection to not only fully capture images from gamma-rays, but also from protons. The proposed design features an adaptable readout window, nominally set to 128 ns to ensure recovery of events at large impact distances.

Design choices in considering the recovery of large signals:

One may then consider increasing the FoV. This can potentially be achieved at fixed cost by increasing the angular pixel size. However, as previously mentioned, this also degrades the resolution, and correspondingly the gamma-hadron separation and the sensitivity. There is a clear trade-off between FoV, angular pixel size and cost. The conclusion that may be drawn is that one should immediately aim for a low cost per channel, thereby enabling a large FoV with fine pixilation. This was the motivation for the proposed camera design, which offers a similar FoV to the 1M (8.8° vs 9°) with 60% more pixels (2048 vs. 1296) and a correspondingly finer pixelisation.

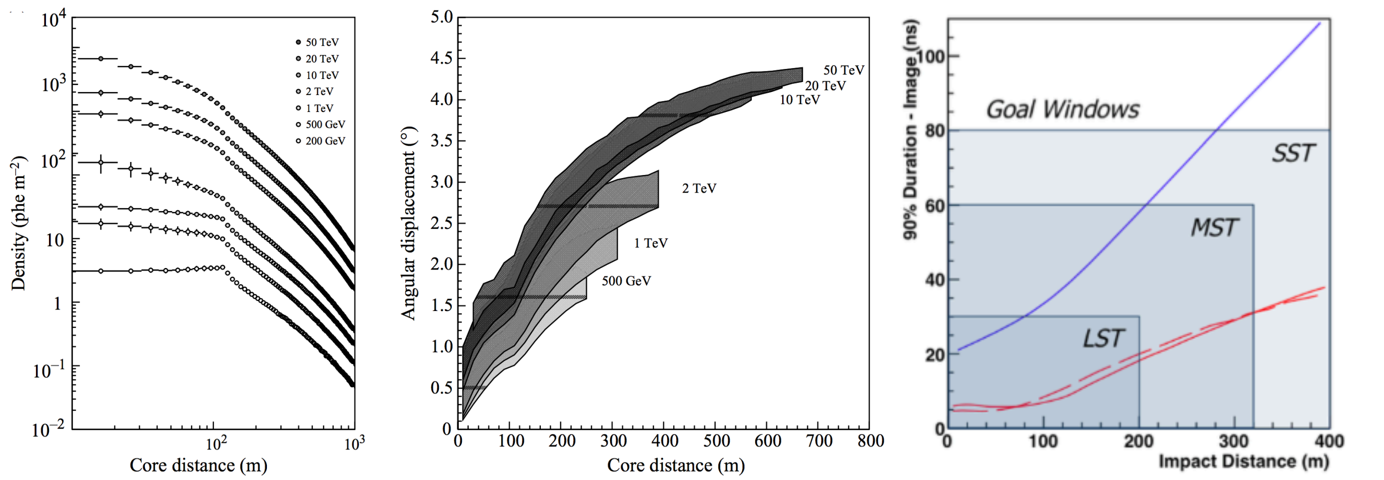

Figure 13: Left: Density of Cherenkov photons on the ground as a function of impact distance for several gamma-ray energies. Middle: Displacement of images in a camera as a function of impact distance. Right: Duration of Cherenkov images as a function of impact distance for gamma rays (red-dashed: 10 - 100 TeV, red-solid: 0.3 - 3 TeV) and protons (1 – 10 TeV). Left and Middle image reproduced from de La Calle Pérez I and Biller S D 2006 Astropart. Phys. 26 69.

3 Performance monitoring:

3.A A. Please describe the performance monitoring strategy for a typical day, week and month during normal operations. Include estimates of the time, manpower and equipment necessary. The strategy should include monitoring of the optical PSF, telescope pointing, optical reflectivity and camera performance.

3.A.i Optical PSF

As reported before, due to the high stiffness of the structure, we assume that no use of actuators to re-align the mirror is needed during normal operations. For this reason, only corrective maintenance is foreseen just in case that some event able to move the mirrors from the correct position occurs (earthquake, strong winds, etc.). Monitoring is assured by the use of the continuous camera pointing system (see 2.E.ii). Therefore, daily monitoring of the PSF is permitted without having to spend devoted time. An automated pipeline will raise an alarm in case of any serious deterioration of the PSF.

3.A.ii Telescope Pointing

A Pointing Monitoring Camera (PMC) can be installed routinely on the telescope structure, in order to map the flexure deformations of the telescope during observation and performing a monitoring of possible errors by checking the pointed field. Images are taken during the scientific acquisition both for calibration of the data acquired and increase the TPOINT model accuracy. Astrometry is automatically performed in parallel with the acquisition of the Cherenkov scientific data, so no devoted time in data reduction is necessary.

See section 2.B for a description of the continuous pointing system. Using this system, the pointing of the telescope may be monitored continuously during normal observations. The system itself may require self-calibration no more than once per month requiring 5 – 20 minutes of dark time.

3.A.iii Optical Reflectivity

Using data rate observations an estimation of the throughput of the telescope can be estimated. This can be used as red flag for a visual and instrumental inspection on the local reflectivity of the mirror. Moreover, the direct measurement of the local reflectivity of the mirrors will be done using a portable reflectometric device (e.g. Ocean Optics USB2000 equipped with integrating sphere and reflectance standard, an IRIS 908RS2 or a Minolta spectrophotometer already used e.g. for MAGIC). For a single telescope, the time and manpower needed to do that are reported in the maintenance section. As discussed below muons also provide a measure of throughput (including optical reflectivity).

3.A.iv Camera Performance

All aspects of camera performance, such as per-pixel charge calibration and time correction factors, pixel linearity, and pixel gain will be characterised prior to camera deployment. However, due to aging effects of the camera components and variations in ambient conditions such as temperature or NSB, this initial characterisation will need to be routinely updated during camera operation. When possible, this continual updating of the camera calibration should be undertaken with two or more independent and complementary methods to allow for cross-checking of results, and an estimation of systematic uncertainties, as well as to provide a level of redundancy. In the proposed camera this is possible via the in-camera flasher calibration system and by using images of local muon rings from extended air showers.

As noted in the RfI Response, the camera includes an internal system to provide calibration via fast, variable intensity, flashes. In the CHEC prototype this system is implemented as four flasher units, located in the corners of the focal plane. Each unit includes 10 LEDs and a diffuser emit a diffused light front that is reflected from the secondary mirror back on to the camera focal plane. The illumination intensity is varied between 0.1 to 1000 p.e. by turning off/on different LED combinations, allowing linearity and saturation effects to be determined as well as extraction of relative PDE via charge-spectrum fitting. By design it is intended that the LED flashers produce a well understood and stable output.

No equipment other than the camera itself is needed to calibrate and monitor the camera performance. No man power at the telescope is required and all data acquisition and analysis can be incorporated into routine and automatic operations.

Each night the HV of each pixel will be set to a nominal data-base value pre-determined to minimise the spread in response across the camera. Continuous monitoring of critical calibration coefficients will take place nightly interleaved with Cherenkov events. Nominal data-base values may be updated using this information, and / or following dedicated runs at regular intervals. Offline, data may be calibrated (quickly) using the nominal data-base values or, to a potentially higher precision, using the values derived from the continuously monitored data (slower – requiring iterative data passes).

ASIC Calibration: The TARGET-C sampling ASICs contain a buffer of 4096 capacitive cells per pixel used to store the signal whilst a camera trigger decision is made. Each cell requires calibration. The majority of the calibration (transfer functions and temperature dependence) is required only once (at commissioning). During operation the cell 'pedestal' values, corresponding to the number of digital counts per cell resulting from zero input, will be routinely measured and stored to obtain the best possible performance. A TARGET-pedestal run is expected to be required at most once per hour, but at 1kHz requires only ~5 s of data.

Pixel baseline and fluctuations: Random triggered events can be injected into the data stream to establish the pixel baseline values and fluctuations therein. Alternatively, baselines can be determined from blank regions of shower images, or from samples preceding the trigger in the waveforms. The electronics baseline (i.e. independent of NSB or SiPM dark-count contribution) can be determined by force triggering the camera with the HV off – note this can be derived for “free” from the TARGET-pedestal run data.

Pixel On-line Amplitude Matching & Monitoring: During normal observations the response the pixels will be monitored using the internal illumination system by interleaving medium-brightness flashes (e.g. 200 photons) during normal Cherenkov data taking (at a few – tens of Hz). Following a drift in response exceeding some threshold (nominally 10%) the amplitude will be stabilised via HV adjustment. Temperature and NSB level SiPM gain dependence are expected to be the dominant reasons that the HV would need to altered during observations. The amplitude of recorded pulses may also drift on longer timescales due to changes in some combination of M2 reflectivity and camera window transmission. To correct for such effects, it makes sense to update the nominal HV settings in the data base. A dedicated set of runs using the internal illumination system (at 1.25kHz) may be used to re-establish the nominal HV values with high precision, such a measurement would take 5 – 10 min and be is expected to be required no more than once a month. It should be noted that re-establishing the HV settings by using a medium brightness LED requires that the LED be stable. Alternatively, a low brightness LED may be used to measure charge spectra and extract pixel gains. The latter has the advantage that the absolute LED brightness is not important as long as the single p.e. response can be measured.

Pixel Off-line Amplitude Matching (Intensity Flat Fielding): A relative correction is applied to the extracted charge per pixel to correct for any differences remaining after amplitude-matching the camera. Flat-field coefficients can be obtained by illuminating the camera with medium-brightness pulses and deconvolving the known illumination pattern. In this case the absolute brightness of the illuminating LED is not important. The flat-field coefficients include relative differences in PDE, OCT and gain between pixels. If the absolute illumination level of the LED is known and stable this measurement can also be used to determine the absolute conversion of measured charge to photoelectrons.

Pixel Off-line Time Matching (Time Flat Fielding): Given uniform synchronous illumination the skew between the pulses recorded in the camera waveforms can be used to correct for systematic timing offsets per pixel (dominated by PCB trace-length differences). Whist it is unlikely that these values will drift significantly (investigation is on-going), correction factors can be extracted from data as the flat-field coefficients.

Broken / Malfunctioning Pixels: Pixels can be easily identified as broken or malfunctioning continuously during normal data taking via the aforementioned interleaved flasher pulses.

Pixel linearity: The calibration measurements mentioned so far utilise a medium-illumination level. The performance as a function of illumination level (<1 to >1000 p.e.) will be monitored during operation via the LED flashers in dedicated runs expected to take place weekly. It should be noted that it is of course possible to continuously flash the camera with varying illimitation levels during normal Cherenkov data taking if beneficial.

Single-photo electron response: The LED flashers units are capable of illuminating the camera at the single p.e. level. By fitting the resulting charge spectrum, the gain, relative illumination level, and optical cross talk of each pixel may be monitored (see Figure 17 left of the RfI Response). The mean relative illumination level as compared to that expected gives an indication of the degradation to the combination of M2 reflectivity, camera entrance window transmission, SiPM PDE (assuming a stable LED brightness). The variation between pixels in extracted illumination level indicates the relative PDE of each pixel (assuming this dominates over non-uniformity of the illumination pattern – specified to be 2% over the camera). Due to the high number of events (10 – 20 k) needed to produce a well resolved single p.e. spectrum it is unlikely that low-illumination flashes are interleaved with normal data taking. Therefore, dedicated runs of ~80 s are expected nightly. It should be noted that gain and optical cross talk may also be established independently of the LED flashers via dark counts. The use of this in routine monitoring is yet to be established.

Total Optical Throughput Efficiency: Reliable calibration and monitoring of the telescope optical throughput efficiency is required to convert the recorded image intensity from p.e. to photons. The total throughput is a combination of: mirror reflectivity, shadowing, camera window transmission and SiPM PDE and can be extracted from the ring–like images generated by background muons. Ring-like images are fitted to extract geometrical parameters which can then be used to calculate the amount of light emitted by a muon. Comparing the extracted image size in p.e. to the theoretical expectation for the same ring geometry enables the telescope–wise optical throughput efficiency to be determined.

4 Maintenance

4.A Provide details of the access for maintenance and handling of line replaceable units, including Camera, Camera components, all mirrors, auxiliary equipment.

Primary mirror panel assembly. It is composed by the panel, and its holder. Since alignment motors are not permanently mounted at the telescope, motor failure is not considered. Typical failures are coating and/or support damage. M1 is inside specification when up 3 mirrors over 18 are damaged, so only in case of 3 or more panel failures, corrective maintenance has to be applied. The overall change of the M1 surface requires three days.
Three operators, a crane and a cherry picker are needed. Failure rate could be considered moderate (> 6 years). After daytime functional tests, alignment is necessary in night-time.

Secondary mirror assembly. It is composed by M2 support structure, M2 supports and M2 mirror. When a problem arises in one of these three components the assembly is fully removed and changed. Main sources of concern are M2 coating degradation and M2 motor actuator failure. Failure occurrence rate could be considered moderate (> 10 years). The operations of M2 replacement need of a crane (load > 1 Ton), four operators and a cherry picker. The shift to complete operation is 1 day. Calibrations of the M2 optics and of M2 servos are performed before M2 assembly mounting and this assures no calibration of the LRU at the telescope but only functional tests before normal operations.

Camera assembly. Access to the camera for maintenance is feasible via manlift or secured ladder. To replace the camera requires a manlift and a custom handing tool. A minimum of three people is required to dismount / mount the camera on telescope and two people to manoeuvre safely at ground level. The weight of the camera is 50 kg and the operation can be performed in well under half a day. When not on telescope the camera will be stored in a dedicated container (see RfI Response Fig 20) for transport to the on-site workshop and potential storage whilst awaiting re-mounting. Maintenance of the full camera in the workshop will require a handling tool to support and manipulate the camera. Such a tool is being developed for camera AIV and will be supplied.

Azimuth motors. In case of failure, one or both the azimuth motors could be replaced. Failure occurrence rate could be considered moderate (> 15 years). A small crane, two operators are needed. Operation can be performed in half a day. Functional tests are need before the use of the telescope.

Elevation motor. In case of failure the drive has to be replaced. Failure occurrence rate could be considered moderate (> 15 years). A crane and two operators are needed. Operation can be performed in half a day. Functional tests are need before the use of the telescope.

Azimuth and Elevation locking pin motor. In case of failure, the drive has to be replaced. Failure occurrence rate could be considered moderate (> 15 years). A small crane and two operators are needed. Operation can be performed in half a day. Functional tests are needed before the use of the telescope.

Pointing Monitoring Camera. In case of failure, the camera has to be replaced. Failure occurrence rate could be considered moderate (> 15 years). A cherry picker and two operators are needed. Operation can be performed in half a day. Functional tests and night time alignment are need before the use of the telescope.

Camera Auxiliary Equipment. The camera chiller, pipes, PSU, power cables and data cables are all accessible and maintainable whilst on-telescope. Pipes and cables are all deliberately routed on the outside of telescope arms to aid in access for visual inspection and replacement.

Camera Components. The camera contains several LRU, divided mainly by accessibility. The major ones are listed below and can be seen in Figure 11 of the RfI Response.

- Lid system
- Entrance window
- Desiccator
- Fans and thermal exchange unit
- 32 x SiPM tiles
- 32 FEE modules
- Backplane
- Internal rack-mounted electronics: XDACQ, timing board and slow control system

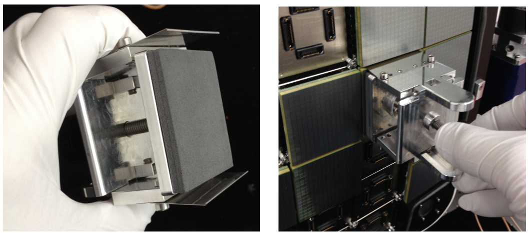

Figure 14: Prototype SiPM handling tool

Access to replace the lid, desiccator and fans / thermal exchange unit are possible whilst the camera is mounted on the telescope. To replace all other LRUs requires the camera to be unmounted and moved to a workshop (for further details see 4.B). It is anticipated that diagnostics established from normal camera operation will indicate clearly which LRU must be replaced. To replace the entrance window or SiPMs requires a relatively clean, low-dust, environment. To replace a FEE module the entrance window and corresponding SiPM tile must first be removed. Access to the LED flashers is possible without removing the entrance window. The Backplane can be accessed via the panel of the camera. To replace any internal-rack-mount electronics does not require the SiPMs of FEE to be removed as the entire focal plane assembly whilst attached to the internal rack may be removed as a single piece from the mechanical enclosure. To replace any camera components requires an ESD-safe environment and the proper tools. A custom tool for SiPM handling is required (see Figure 14 for a prototype).

Camera Auxiliary Equipment. The camera chiller, pipes, PSU, power cables and data cables are all accessible and maintainable whilst on-telescope. Pipes and cables are all deliberately routed on the outside of telescope arms to aid in access for visual inspection and replacement.

4.B Strategy: Provide details of the maintenance plan during operations. Include the foreseen preventive maintenance activities; the approximate frequency and costs; an estimate of the necessary time and manpower; and a list of the equipment needed for the main maintenance tasks. Information should be given at the level of the main sub-systems of the PBS (structure, camera etc.).

Table 1 shows the total maintenance for the main sub-systems. This is broken down further (in case the panel are curious) in Appendix A.

Mechanical Assembly. For the majority of the preventive maintenance issues 2 persons are needed, both of them licensed to the use of the cherry picker. Except for it, only ordinary tools (grease, screwdrivers, etc) are necessary for the operations. In Appendix A - Table 4 a breakdown of the maintenance plan is presented. Frequency is expressed in time/year, manpower in men-hours. The total is expressed in men-hours/year. Numbers in the table are based on the prototype experience in the field (ASTRI-MAN-GEC-3100-002b).

Table 1: Summary maintenance plan for the structure, mirror system and camera of each telescope.

Item	Man hour/week
Structure Maintenance	0.743
Mirror Maintenance	0.115
(Reflectivity measurements)	(0.067)
Total Structure & Mirror	0.858*
Total with reflectance monitoring	0.925
Camera Maintenance	0.26
Total	1.12

Optical Assembly. Also in this case operations can be carried out by 2 persons trained to the use of cherry picker. In the case of M2 changing also a crane is necessary for the operation. For reflectance measurements, an ad-hoc instrument has to be used. In the following table (Appendix A - Table 5) the schematic of the proposed plan is reported. It should be noted that the local reflectivity monitoring has not to be done on the total set of 18 panels forming M1 but it is acceptable a sampling (6 panels per telescope, randomly chosen each time).

Auxiliary assembly. In this case only functional test are foreseen. Normal night-time operations superseded these tests.

Camera Assembly. The strategy for camera maintenance is to perform only preventative maintenance and minimal repair work whilst the camera is mounted on telescope. The majority of camera repair will take place in a central CTA workshop. Once removed a camera may be immediately replaced with a spare (feasible due to the low cost and compact nature of the camera). Details for estimates of corrective maintenance (i.e. camera repair) are available on request. Whilst on-telescope visual inspection of the camera, chiller, PSU and all interfaces are expected. Chiller refilling will also be required (and can be performed at the same time as one of the regular inspections when required). The camera entrance window can be cleaned whilst on telescope, but should not be replaced. The camera lid or motors may be serviced whilst on telescope. The camera fans are accessible via an external panel that allows replacement whilst on telescope. The desiccator responsible for maintaining a controlled level of humidity inside the camera is also replaceable whilst on telescope. Appendix A – Table 6 summarises the camera preventative maintenance tasks, frequency, cost, time, manpower and required equipment.

4.C Provide some indication of the maintenance activities that may proceed in adverse environmental conditions, such as high wind. Note that manlifts typically cannot be operated with wind speeds above 10 m/s.

Telescope The need to operate maintenance in adverse conditions is NOT foreseen. Due to the low frequencies of high wind conditions in the Southern site, it is then easy to plan a reliable schedule for maintenance. On the other hand, it should be noted that most of the preventive maintenance operations for the mechanical assembly do not need the use of a cherry picker. Therefore, many maintenance operations can be also performed with wind speeds moderately above 10 m/s

A particular case is represented by the operations close to the hot spots due to solar concentrations close to M2 focal position (and then to the focal plane). In this case, the operations are allowed only after having applied a shield on the secondary mirror as a protective screen, in order to avoid injuries to the operators.

Operations involving the direct contact with the M2 surface (e.g. cleaning of its surface) are allowed just at early morning or late afternoon in order to avoid any risk due to solar light hot spots.

Camera The possible maintenance activities that may take place under adverse weather conditions are outlined below. It should be noted that the maintenance activities covered refer to those taking place outside at the telescope. A fundamental feature of the proposed design is that the camera may be easily removed and replaced with a spare whilst the camera requiring corrective maintenance is transported to a central workshop. As the majority of corrective maintenance is not taking place in-situ, adverse weather will therefore have a limited effect.

- **Extreme temperatures:** All preventative maintenance procedures are expected to be possible across the full CTA survival temperature range (-15°C to +35°C). The chiller is rated for operation from -20°C to +45°C. The camera lid can be closed manually in the event of a power failure during window cleaning operations. Whilst camera unmounting may take place across the survival range, camera mounting should be avoided outside the CTA observing conditions (-5°C to 25°C) to allow the camera to be brought-online safely.
- **Mild Rain or Snow:** In the case of mild rain visual inspection of the camera, cables, pipework, chiller and PSU is possible. Filling of the chiller is possible. Opening the camera lid should be avoided and therefore camera window cleaning is not possible. Similarly, any activities that require the detaching of power cables or servicing / repair of the PSU or chiller should be avoided. Camera mounting / unmounting should not be undertaken.
- **Heavy Rain, heavy snow, hail, thunder / lightning:** No maintenance activities should take place under these conditions.
- **Wind (below 10 m/s):** The camera lid can open and close under wind from any direction at 10 m/s (and has been tested in a wind tunnel). All maintenance procedures are therefore possible.
- **Wind (above 10 m/s):** The maximum recommended wind speed for working ‘at height’ is 10 m/s, therefore only visual inspection of the camera from the ground should take place. Chiller and PSU maintenance should be possible with the correct safety procedures.

5 Optical Systems

5.A Mirror reflectivity: It is expected that the Chilean environment is significantly harsher than sites of current generation IACTs with respect to mirror reflectivity degradation.

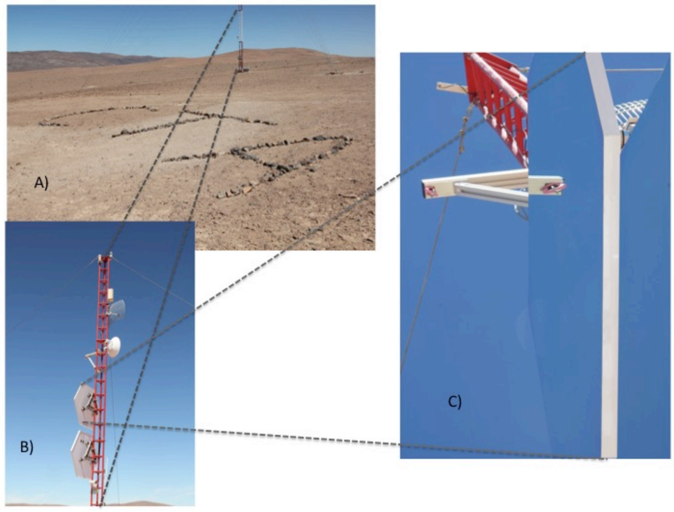

Figure 15: Field tests on mirrors at the CTA site in Paranal, Chile. A): The meteorological tower at the center of the site used for mounting the mirror panels for environmental aging tests. B) Picture of the mirrors mounted on the tower at a Height of 10 m. C)

The reflective coatings used for Cherenkov optics are different from the classical astronomical mirrors. In particular, for Cherenkov telescopes the aluminium reflecting film is overcoated by a quartz layer about 100 nm thick, in order to protect the metal film from oxidation and against other environmental hazards. The comparison between the usual deterioration time for the mirrors used in Cherenkov telescopes and in optical telescopes seems not very meaningful. In this respect, for optical telescopes it is indeed well known that a lowering in the reflectivity of up 3% of a simple aluminium layer can arise within the first few months after coating. On the contrary for Cherenkov telescopes, in spite of a lower initial reflectivity due to the quartz protection, this overcoating assures a good stability in the reflective properties of the optical surface. Therefore, the reduction of reflectivity for Cherenkov mirrors is not due to oxidation but, instead, it is mainly due to dust deposition and the surface deterioration due to the sandblasting effect of the dust. Other effects, like acid corrosion due to smog, sulphur, acids are not very probable in Paranal (it should be noted that the sulphur concentration is lower than in the Milano environment!).

ASTRI mirrors before shipping are heavily characterized against coating damage. In particular on prototypes tests on coating adhesion, thermal cycling, damp heat cycling, and solar radiation have been performed (CTA-RP-ML-435) and previously, the salt fog test was also performed on the MST mirror prototypes produced with the same technology by INAF/Media Lario (see document CTAM-RP-M-001).

On the other hand, mirrors of the same kind have been already mounted on the MAGIC I and II in La Palma, in real and harsh environment. In a systematic reflectivity measurements campaign carried out on the glass mirrors produced by INAF and Media Lario for the MAGIC II telescope, after 4 years of operations the loss in reflectivity was << 1 %/year (see e.g. M. Garczarczyk, 2011). After 10 years mirror reflectivity is still inside specification and there is not need of re-coating the mirrors.

Field aging tests are being carried out in Paranal, just in the valley that will host the CTA southern array on mirror prototypes of the same kind produced by INAF/Media Lario that will be used for the ASTRI telescope (see Figure 15). After more than year, at the visual inspection the reflectivity seems still extremely good.

5.B Provide details of the strategy for cleaning of optical components, in particular whether in-situ cleaning of mirrors is possible and cleaning of the camera entrance window

Mirrors: In the case of the prototype we have cleaned the mirrors once per year using 15-20 litres of water in total. To have the best result one has to a detergent and use distilled water, using natural sea sponges for cleaning. Other methods water-less, like using adhesive tapes or peel-able coatings that are specifically produced for that purpose have been investigated but not tested 8and the cost could be larger than water). In any case, these operations require the cherry picker and two men for at most one hour for both primary and secondary mirrors. Frequency of the cleaning procedure is once per year.

On the other hand, as reported in the previous paragraph, the exposition of the mirror to the environment will give valuable information on the coating degradation but also on the severity of the dust deposition process. Reflectivity tests after two years of exposure are going to be done, together with a measure of the contamination. The visual inspection done one year ago seems to exclude important problems of dust deposition or other contaminants on the mirrors.

Camera entrance window: The camera entrance window may be cleaned whilst in-situ. Details of access, manpower and frequency are given in section 4. Procedure:

- Park the telescope (i.e. camera horizontal with the window vertical).
- Open the lid (preferably via the control interface, but also possible manually).
- Use an airgun to blow off loose large particles that could scratch if caught in a brush.
- Douse the window with a sprayed mixture of neutral detergent and deionised water to loosen particles and dissolve grease.
- Douse again with plain deionised water to rinse off soaps and released materials.
- Allow to dry and inspect.
- If any area appears to still be dirty, repeat
- If any area is still dirty, repeat but agitate gently with a very fine bristled brush, rinse and allow to dry.

5.C Provide details of the plan for optical system alignment following exchange of mirrors or cameras (recoating or replacement).

As addressed in the proposal, alignment of the mirrors, differently by single dish telescopes, is not part of daily operations but instead can be considered a procedure of preventive/predictive maintenance. For this reason the Optical Alignment system is an AIV/maintenance tool to be mounted and used only when necessary and it is not permanently mounted on the structure. Plan of the alignment follow recoating or replacement and foresees the activities are already taken into account in the table regarding optics maintenance plan (that we consider very conservative, taking into account that in the reality we expect a coating reflectance degradation much lower than 4 % per year, see above) but are explicated here:

Item	Type	Frequency yr	Man hour	Man hour/yr	Man hour/week
Optical alignment system mounting	Mounting	0,10	4,00	0,40	0,008
Optical camera mounting	Change	0,10	4,00	0,40	0,008
Mirror alignment	Measurement	0,10	6,00	0,60	0,012
Optical camera dismounting	Change	0,10	4,00	0,40	0,008
Optical alignment system dismounting	Dismounting	0,10	4,00	0,40	0,008
Total					**0,035**

The mirror alignment procedure performed at night time typically needs two operators, applying an automatized procedure. This procedure, using an optical camera, scans the field of view for the PSF of the single panels, recognized them and optimize their positions with respect to the PSF of the telescope. Eventually check for the PSF optimization in the full field of view.

Upon exchanging the camera the PSF may also be measured across the FoV using the camera continuous pointing system (see sections 2.B, 3.A.i, 3.A.ii). As described in section 2.B, M2 may be adjusted via actuators to minimise the PSF.

6 Quality Assurance

6.A Please provide a high level summary of the Quality Assurance program including RAMS.

Telescope: The Quality Assurance (QA) program is described in the ASTRI Quality Assurance Plan (ASTRI-QA-PD-3000-004) and covers all the project phases, from the design to the decommissioning. In this answer we focalize on the manufacturing, AIV and operations.
The following items are part of the QA program:

1. Documentation control;
2. Design Control;
3. Critical Items identification and control (RAMS analysis);
4. Contract Review;
5. Procurement Control and Supplier Surveillance;
6. Assembly, Integration, Tests (AIT);
7. Handling, packaging, storage, transportation, delivery and acceptance;
8. Installation, maintenance and decommissioning;
9. Non-Conformance control.

The selection of manufacturers and suppliers is driven by proven ability in procurement of materials, parts and components needed to the project. They must guarantee their capability with regards to quality control and traceability. A detailed Statement of Work (SoW) specifies the characteristics of the subject of the procurement. The traceability system is based on log sheets, which describe the manufacturing, tests, inspection, integration, and non-conformance (if any).

- All incoming materials are inspected on arrival and it is verified that all the needed documentation is present, as foreseen by the QA plan.
- The AIV/AIT operations are described in a logbook containing the most important data, and a test report describes the test results.
- Package items shall be protected against shock, dust, water, and temperature gradients. Transportation boxes shall be equipped with shocks and temperature indicators. Maintenance operations shall be properly analysed and documented.
- The acceptance of the deliverable ASTRI products shall be completed according to the Acceptance Readiness Review (ARR).
- The RAMS activities are identified in a specific RAMS plan, and both a RAMS analysis and a Failure Mode Element Criticality Analysis (FMECA) are implemented for each subsystem.
- The maintenance plan, considering the requirements on the operation lifetime, is derived from the hardware reliability configuration and the MTBFs of the subcomponents. As by-product, a spare list and a maintenance manual complete this analysis.
- A safety assurance program is performed in parallel to the other activities, in order to identify hazards and eliminate them or mitigate them to an acceptable level.

Camera: QA for the camera will follow a similar framework to the telescope structure and optics. As many institutions are involved and many items are produced in-house, the focus will be somewhat different. As stated in the RfI Response, no formal QA or RAMS analysis has been completed for the camera. This will take place following in the next 12 months.

6.B Provide a high-level failure mode analysis.

A FMECA analysis has been carried out for the ASTRI telescope and the prototype CHEC camera.

Telescope: Failure modes have been identified for the following subsystems: power supply, azimuth gear/bearing, azimuth drive, azimuth encoder, elevation gear/bearing, elevation drive, elevation encoder, secondary mirror drive/encoder, motor brakes, door base interlocks, PLC TCU/THCU, cabinet thermal control system, auxiliaries and mirrors. A high-level FMECA analysis and discussion for the telescope prototype is contained in the document ASTRI-SPEC-INAF-1000-033 [9] where all the problems are well identified and under control. A specific document for the updated structure is under preparation.

Camera: Approximately 50 failure modes have been identified for the camera. Most were found to have a low probability of occurrence, but several had a high level of severity. In most cases failures can be identified using existing sensors, which then naturally provides a method of mitigating the risk. The highest priority (critical) failure modes for the camera are shown below together with risk-mitigation strategy implemented to lower the criticality.

- **The lid is open during rain/hail/high-winds.** To minimise the risk of significant damage the entrance window forms a hermetic seal to the camera. To avoid the lid failing in the open position it must be extremely reliable and on power-up defaults to the closed position. Accelerated ageing tests have been performed on the prototypes to assess the motors and hinges.

- **The window seal fails.** Water enters the camera resulting in potential damage to camera pixels and electronics. Accelerated ageing tests to mimic the lifetime of the window seal are required to assess the sealing method and preventative maintenance routine.
- **A cooling system failure resulting in potential damage to the camera.** A monitoring/control loop and fail-safe power-down of the camera is used to ensure no damage to the electronics occurs following a cooling failure. This has been tested with CHEC-S in the lab. Hexid fluids will be used in the chiller system to prevent freezing, and the chiller is specified to operate down to the camera survival temperature if required.
- **Loss of signal on all photosensors due to permanent damage to all photosensors**. The use of SiPMs (rather than MAMPS – c.f. CHEC-M) with appropriate current monitoring and preventative action minimise the chance and severity of this failure mode.
- **Damage to SiPMs through handling.** Previously this risk was minimised by using SiPMs with a coating (e.g. epoxy). The use of the latest, uncoated, SiPMs will require custom tools, a relatively dust-free environment and clear handling procedures.

6.C What is the remaining technical risks?

Telescope: the only risk that requires further reduction in criticality in the mirror coating. A reflectance loss less than 4% per year corresponds to a recoating of the mirror every 9 years to stay inside reflectance specification. Considering our experience in aggressive environmental situations (MAGIC at La Palma) we consider this a very prudential maintenance plan the recoating of the mirror every 10 years. With this maintenance plan we can mitigate the impact risk for coating failure and respect maintenance requirements in term of manpower and downtime operations.

Camera: There still exists a risk of damage to the camera from a leak in the cooling system and through handling of SiPMs. Pressurised air tests have been performed prior to installation in the camera to detect leaks, but further QA and potentially a design change is needed to minimise this risk. The CHEC-S prototype uses coated SiPMs, and even then, we have found damage may occur via incorrect handling. To take full advantage of the latest SiPM performance it is desirable to use un-coated SiPMs. The first samples of these devices have now been delivered and we are working with the manufacturer to identify removal tapes and tools suitable for handling.

6.D Comment on the production risks in the case of single-source suppliers. What is your mitigation strategy in case of problems?

Structure: the production scheme for the structure foresees a single prime contractor. Mitigation strategies in case of problems with subcontractors will be explicitly requested during the tender procedure. However, for sensible subsystems, like motors or PLC, we do not foresee particular problems, as they are all COTS and can be easily replaced without upsetting the design.

In case the prime contractor could not fulfil the contract there could be a serious drawback in the production. On the other hand, the design is already fixed, implying that the construction drawings are final. Those drawings and all the annexed documentation are or will be delivered to INAF by the company that has produced the current design. If necessary, these documents will allow us to place a new bid and so look for a new contractor with a likely delay of 6 to 12 months.

By the way, the mitigation of the single-source supplier risk of the structure can happen “naturally” because as stated in section 8 of RfI Response we are negotiating the participation in the project of the University of Sao Paulo/FAPESP in Brazil. The contribution would be in the production of the structures implying not just the supply of funds but also the direct involvement of a Brazilian company.

Primary mirror segments: as stated in section 1.3.2.1, the technique for the production of the primary mirror segments was developed jointly by INAF and the company that is currently producing the segments for the array of pathfinders, that is Media Lario Technologies (Bosisio Parini, Lecco, Italy). This means that INAF has the complete know-how of the production process and even produced the segments for the prototype. Then the mitigation strategy in case of problem will be to identify a new company to which transfer this expertise.

Secondary Mirror: we currently have a single supplier for the substrate of the secondary mirror, Flabeg Fe GmbH. However, the technology for the production of the substrate of the secondary mirror is very common in the production of glass e.g. for solar concentrators or even of glasses for automotive so we do not think that the replacing this supplier would be a problem.

Camera: The camera elements linked to single suppliers are SiPMs and FPGAs. All other components may be sourced from multiple suppliers. FPGAs will be supplied by Xilinx. A relatively small number of FPGAs are needed (~2k). Conversations with Xilinx began early in the design process to ensure product availability over the production phase of CTA, and following CHEC-M the FEE FPGA model was altered to one with a longer availability. It is likely that SiPMs will be supplied by Hamamatsu, who will also supply PMTs for the LST and MST. Products to date from Hamamatsu have been of high quality. It is more likely that a delivery schedule slip occurs than a sub-standard product is delivered. To mitigate against this, orders should be placed well in advance with a delivery schedule that proceeds at a rate exceeding the requirement for camera delivery. Discussions with the head of the solid-state division indicate that SiPMs can be delivered in 12 batches of 200 camera tiles each once per month starting 5 months from the purchase order. In this way all SiPMs should be in hand <50% the way through production phase.

6.E Provide a list of the few potential "catastrophic" failures and the plan for their mitigation and recovery.

Telescope: Catastrophic failures are only in case of damage to bear/bearing causing azimuth or elevation to be halted. Due to the very low probability of occurrence no mitigation is required.

Camera: The easiest catastrophic failures to imagine damage to camera either: in transit due to physical trauma, in operation due to water leakage or a serious electrical fault, or that extremely high illumination damages the photosensors or associated electronics.

- <u>Damage in transit:</u> To avoid damage a custom enclosure has been produced (see RfI Response section 5.2.3). Vibration tests (see 2.B) are planned for the prototype to assess limits on allowed accelerations during transit.
- <u>Water leakage:</u> The camera prototype has been environmentally tested against rain in accordance with the CTA requirements. As described above, risk mitigation for avoid leaks from the cooling system is ongoing.
- <u>Serious electrical fault:</u> Power to all internal electronics is supplied via a power-distribution PCB that also monitors currents and includes intelligence to shut down sub-systems if current limits are exceeded.
- <u>High illumination:</u> The SiPM bias circuit contains a current limiting resistor to automatically reduce the SiPM gain under extreme illumination. The HV circuit is rated to withstand high currents. The only danger is that the SiPM becomes very hot due to increased current flow. To prevent this the FEE FPGA is capable of monitoring current draw and disabling pixels on the time scale of under 1 s.

We plan to provide several spare complete cameras to CTA. In all cases if a significant fraction of a camera is damaged then a spare camera may be used. The damaged camera should then be shipped back to a European AIV site for repair / replacement.

6.F What is your plan to avoid high solar concentration during the day? Clarify also the parking positions during the day and throughout the year.

A study of the solar concentration hazard in parking position was performed for the ASTRI telescope, (ASTRI-IR-INAF-3100-074). In the study we took into consideration the CTA proposed South site, Cerro Armazones and the proposed parking position pointing to South direction.
The Sun trajectory at the site was considered and the Sun reflected power calculated for different Sun positions along day and year times.
The ASTRI telescope, being a 2M telescope, suffers from illumination in parked position all the year long. The illumination moves from M1 to M2 depending on the season, so both cases have to be studied.
By the way, considering the mirror areas, the incoming rays direction and the mirror reflectivity we estimated a maximum possible reflected power value of ~1.5 kW. This value is well below the CTA forbidden and risk solar concentration levels (5kW, 2kW).

To check any possible hazard situation, we studied both the solstices cases searching for small hot spots (1 cm^2 scale) with power density equivalent to the forbidden and risk ones (0,5 W, 0,2 W). Given the specific small hot spots study we can conclude that, even being a 2M telescope, ASTRI telescope design presents the following advantages:

- No one of the mirrors is a focusing surface, they are both polynomial optics. The focusing is obtained when the double reflection is operating; this means that a single reflection never generates a point like spots.
- The Schwarzchild-Couder polynomial design allows having a very short focal length; this means that the pseudo focusing areas will always be found quite close to the mirrors. For what concern the reflection on M2 the generated small hot spots are always in the cavity between the two mirrors; in the case of M1 the concentration areas are just behind M2 but never lower than 2 m.
- ASTRI structure is elevated, this means that even the small hot spots created by the reflection on M1 never reaches the ground.

7 Production

7.A Provide which major parts of the production will be contracted to industrial partners and which will take place primarily in house. Note that this is just for understanding; there is no right or wrong answer.

Pathfinder: For the array of pathfinders mirrors and structures are already contracted to industry while the ASTRI cameras will be soon.

Telescope: For the production, telescope mechanical structure and mirrors will be contracted to industrial partners.

Camera: The production, population and electrical testing of all PCBs will be contracted to industrial partners. Camera electrical component (e.g. FEE module) assembly and quality control will then take place in-house. The production of SiPMs also be contracted to industrial partners. SiPMs will delivered attached to PCBs with basic test data (breakdown voltage, dark current). In house SiPMs will go through further quality control. Mechanics will largely be produced in-house using the facilities at MPIK. Some elements such as anodising and laser welding will be contracted to industrial partners. The production and quality control of custom cables (specified for e.g. length) will be contracted to industrial partners. Camera assembly and verification will take place entirely in house. The camera chiller and PSU will be purchased as off-the-shelf items from industrial partners.

7.B Clarify the extent to which telescope assembly proceeds on-site or prior to shipping.

Process validation for the assembly will be obtained with a full assembly in workshop prior shipping. The process validation permits to minimize risks and costs. When validated assembly will follow this plan:

1. Full pre-assembly of the mount (lower part of the telescope) with cabinets
2. Observing Support structure assembled at the site, only M2 shipped with populated support structure
3. Not assembled subsystem are: the dish in two parts, counterweights (masses and 6 trusses), 3 mast, top ring and central tube

7.C Clarify the extent to which the final design exists, is in construction, or a further design iteration is needed.

Telescope: As written in section 1.6.1 and 1.6.2 of RfI the design of mechanical structure and mirrors is final and no further iterations are needed. Furthermore, mirrors and structures for the array of pathfinders are in construction or built (M2 mirrors).

Camera: As explained in section 1.6.3 of the RfI Response a further camera design iteration is needed. Table 1 of the RfI Response clarifies in detail the work needed for each major component of the camera.

8 Operation

8.A Provide details of the amount of on-site training and knowledge transfer needed, including whether maintenance contracts for proprietary designs are needed.

Telescope: The use of the telescope is easy in its basic operations (operating the telescope, alignment, focusing) and on-site training of about one month assures the know-how transfer to crews at the observatory. Also maintenance operations are standard. Only the exchanging of the mirrors (M1 panels and M2) is an operation of major maintenance, requiring devoted training.

Camera: Onsite training and knowledge transfer will be required for:

- **Camera handling, storage, transportation:** this can be covered at a central location with a hands-on demonstration and supporting documentation. A half-day course would be sufficient.
- **Camera installation / removal:** this would require detailed documentation and a presentation to cover the procedure prior to a demonstration on-telescope. Training would include knowledge transfer on chiller and PSU connection and basic operation. Such training could be covered in a 1-day course. In addition, personnel would first require manlift training and working-at-height training.
- **Commissioning:** training will take place via shadowing experts from the camera team, a commissioning guide and dedicated briefings. It is likely that detailed tests and debugging are done by the camera team.
- **Operation:** camera operation will be outlined in a manual and operator training will take place in conjunction with the central telescope control. Detailed documentation will be provided for diagnostic / engineering work on the camera with training courses run for on-site staff when required. A 3-day training course would be sufficient to operate the camera in engineering mode and diagnose problems.
- **In-situ maintenance:** can be covered by detailed documentation and a presentation to cover the procedure prior to a demonstration on-telescope. Such training could be covered in a half-day course. Some personnel would first require manlift training and working-at-height training. Chiller maintenance and repair will require training in conjunction with the manufacturer. Although a maintenance contract with the chiller manufacturer is not required, it may be efficient if the same manufacturer is used for all CTA chillers.
- **Off-telescope maintenance:** the knowledge transfer here is the most challenging. It should be expected that a full week is required be properly trained in the replacement of LRUs. An additional week would be required for verification / debugging test training. In all likelihood on-site staff tasked with repairing cameras would be shadowed by a camera expert for 4 – 8 weeks to ensure full knowledge transfer.

8.B Provide an estimate of the power consumption including the following (for the structure, camera and telescope total):

a. Mean and peak power consumption during operations

b. Mean power consumption during daytime

Table 2 shows the requested power information. During operation the camera uses 0.7 kW, and additional 0.1 kW is included for the efficiency of the camera PSU. The camera chiller consumes on average 0.8 kW. During operation the total camera power is then 1.6 kW. The peak power occurs when the camera lid is moving, but this only add an additional 17 W. During the day most camera functions are disabled. A minimum of 11 W is needed in favourable conditions. Enabling internal fans increases the mean power to 90 W. The peak power comes during day light if the chiller is then additionally required (0.9 kW).

Table 2: Mean and peak power consumption for telescope and camera during daylight and operation.

	Daylight		Operation	
	Mean Power (kW)	Peak Power (kW)	Mean Power (kW)	Peak Power (kW)
Telescope	1.3	2.3	2.8	7.5
Camera	0.1	0.9	1.6	1.6
Total	1.4	3.1	4.4	9.1

9 Upgradability

9.A Provide more details on the upgradability, in particular the ease and science impact of different upgrade options.

At the highest-energies the SSTs offer a unique science case for the efficient and precise study of extended sources and of diffuse emission regions. As previously stated many high-energy sources are extended and will be observed for longer than 50 hours – so will not be background free. The areas in which the SST performance might be then best be improved are: angular resolution, background rejection power and gamma-ray field of view. Angular resolution and background rejection power depend on telescope multiplicity and image quality, and therefore physical FoV, trigger threshold, pixel size and pixel signal-to-noise. The gamma-ray field of view depends on ability to capture images and reject background at increasing off-axis angles is therefore dominated by the physical FoV, with all aspects that improve background rejection power also coming into play. We regard an increased FoV as the main upgrade path. Other upgrades are discussed in Appendix B.

Increasing the FoV. As stated in section 2.E.iii the proposed optical design would support a FoV up to 12° in diameter. This would be most desirable if the current angular pixel size could be retained. To implement this would then require new cameras with ~double the number of pixels. Such an upgrade would likely then require advances in technology to facilitate a feasible per-pixel cost. Whilst it may be possible to reuse existing SiPMs and FEE modules, it may also be desirable to upgrade these at the same time (see Appendix B). In this way the improvements in signal-to-noise offered by new SiPMs could be taken advantage of. Increasing the FoV is highly desirable, allowing:

- the detection of high-energy showers at large impact distances and increased off-axis angles without image truncation, leading to the capture of other-wise missed off-axis events, increased telescope multiplicity and background rejection power;
- the efficient study of extended sources and of diffuse emission regions; and
- large-scale surveys of the sky and the parallel study of multiple sources in the FoV, e.g. in the band of the Milky Way.

10 Cost Estimates

Costs according to the requested standard WBS are addressed below. It should be noted that it is not straight forward in all cases to follow the requested standardisation or labour categorisation.

Telescope Structure and Optics: Table 4 of the RfI Response details all capital and manpower costs associated with the production and onsite AIV of the telescope structure and optics. All explicit FTE costs outlined in Table 4 of the RfI Response under "Telescope Structure" and "On-site AIV / Telescope" are for INAF engineers at 70k€ per year. Due to the manufacture, provision and large fraction of AIV in industry it is difficult to separate costs beyond what has already been done in Table 4 of the RfI Response. This is further complicated by the necessity to outsource some fraction of AIV work for the installation of structures in Paranal (e.g. to local staff). Capital costs also include 'hidden' technical and engineering labour that is outsourced to industry. Note, it is therefore not easy (and perhaps not useful) to explicitly discuss the separation of the capital costs from labour or to sub-categorise labour costs by the requested roles for activities that will be outsourced.

Camera: Camera costs are presented in Table 3. Caveats:

- Labour costs are included as FTE and at the standard CTA rate of 70k€ per FTE. This may be an overestimate in the case of technicians.
- All scientists are included as "Engineer".
- Camera AIV off-site (i.e. building and testing the camera from the qualified pieces) was not included in the requested WBS and therefore is added as an additional sub-item under "Camera".
- As requested shipment and onsite AIV are no longer broken into camera and telescope. However, these are distinct items with exceptionally different shipping and onsite AIV requirements and costs and are delivered by separate groups. Table 4 in the original RfI Response shows these differences.

Table 3: Camera costs itemised by standard WBS

	Production Costs								
	Capital Cost per Unit	FTE (Team) (Months)			FTE Cost	Cost per Unit	Contingency	Total Cost per unit	Additional Chile local FTE months
	(k€)	Engineer	Designer	Technician	(k€)	(k€)	(k€)	(k€)	
3. Camera	156	2.3		3.4	33	189	45	234	
Sensor System	46.5	0.15		0.10	1.5	48.0	12.0	59.9	
Electronics	72.5	1.00		1.40	14.0	86.5	21.6	108.1	
Camera Mechanical	21.0	0.10		0.40	2.9	23.9	4.8	28.7	
Auxiliary Systems	12.5			0.20	1.2	13.7	2.7	16.4	
AIV	3.9	1.00		1.30	13.4	17.3	3.5	20.7	
4. Camera Shipment	4.0			0.1	0.6	4.6	0.9	5.5	0.05
5. Camera AIV On-site	1.6	0.5		0.6	6.4	8	2.0	10	0.9
Total	**162**	**2.8**		**4.1**	**40**	**202**	**47**	**249**	**1**

Shipment: The total cost of shipment is evident from Table 4 of the RfI Response. Categorisation of staff is likely 'technician'.

AIV: Please see the above statement on "Telescope Structure and Optics" and Table 3 for the camera.

Management: The management manpower counted as IKC is not entirely clear (for example in the case of senior project staff) and needs to be discussed in a wider framework within CTA before any solid costs are estimated as part of IKC costs.

Remaining research and development: For Structure and mirrors, no further R&D is required. Entirely subjective numbers can be provided for the camera. As has been made clear, the submitted proposal is to develop a camera based on the CHEC prototype. It has been stated that a further camera iteration is required. Beyond this any cost estimates involve complete guess work as to which additional groups would be involved and to their manpower efficiency. Capital costs may be more accurate / representative than manpower costs at perhaps ~0.5 – 0.8 ME. In many funding cases there is also a clear division in requested funding between the R&D stage and the Production phase. No further funding requests are required to complete R&D. In the case of both camera and telescope large R&D costs have already been incurred. However, it is our understanding the R&D will not be included as an IKC to CTA and therefore highly irrelevant to the final product cost

11 Questions to the 2M SST proposal (ASTRI, CHEC)

Please provide all your responses to the requirements for a single combination of structure, camera and pixel size.

This has now been addressed in Q2. We present a baseline design of CHEC with 6 mm pixels on the ASTRI structure.

Clarify how the large field-of-view improves the angular resolution.

As also discussed in 2.F, an increased FoV results in images being captured by more telescopes and in fewer images being truncated by the FoV. An increased FoV therefore increases telescope multiplicity and improves the quality of images in each event. Both of these factors help to identify an event as a gamma ray and improve the event reconstruction, thereby improving the angular resolution. At the highest energies, and for the fixed telescope spacing of the CTA South layout an increase in FoV beyond the 8° requirement largely improves the angular resolution for off-axis events.

Elaborate on your strategy to increase the production rate to 30-33 cameras per year.

To accommodate the production rate of 30 – 33 cameras at least three AIV sites will need to be operated in parallel (with potential additional sites acting in contingency). The rates of camera production per site are then:

- Y1 Q1 – Q2: 1 camera
- Y1 Q3 – Q4: 3 cameras
- Y2 Q1 – Q2: 5 cameras

- Y2 Q3 – Q4: 5 cameras
- Y3 Q1 – Q2: 6 cameras
- Y3 Q3 – Q4: 5 cameras

An overall AIV manager will begin work prior to the Production Phase in collaboration with the systems engineer and local site AIV leads to prepare AIV sites. Each site will be equipped to identical specifications. Procedures and training will take place prior to production with each site practicing the AIV procedure on a prototype / pre-production camera. During Y1 Q1-Q2 1 camera per AIV site will be produced and further technical staff will be fully trained in the AIV procedure. An AIV oversight meeting will take place in Y1 Q2 and plans will be refined if necessary. The second half of Y1 offers the final opportunity to demonstrate successful procedures and refine plans. The 3 cameras produced in Q3-Q4 of Y1 should therefore be attempted undergo AIV at a rate of 1 per month, with an equal amount of time thereafter to verify the quality control as sufficient and refine procedures.

Although this sounds daunting, it should be noted that this is largely a feasible plan due to the compact nature of the camera. Storage and handling is a much reduced prospect compared to a ~1 m, ~1 tonne camera. Two full prototypes have been produced. The team has learnt the value of an easy-to-assemble camera, and of custom tools to ensure each task can be performed quickly and correctly. The current CHEC-S prototype has many aspects that can and will be improved in the final design, but even then, it can be completely taken apart and rebuilt by a single person in a working week. At MPIK the camera prototype is undergoing tests in a full dark room with an illumination setup suitable for use in the final system. A second full camera AIV setup is under construction at MPIK with a walk-in dark box, illumination setup, chiller, electronics assembly rooms, mechanical assembly area and storage space for at least 30 cameras. ECAP, DESY and U. Leicester all have dark boxes and illumination setups capable of qualifying full cameras.

The most difficult aspect of mass production may not be the AIV of the cameras themselves however, but of the production and sustained delivery of camera sub-assemblies such as the photosensors, FEE modules and other electronics. A successful ramp up to the AIV of 30 – 33 cameras per year requires sub-assemblies be delivered to the AIV sites fully built, tested and calibrated. Several aspects of this have been considered:

- Photosensors will be attached to bias boards and basic tests will be performed by the manufacturer.
- The FEE modules each consist of multiple PCBs, and 32 modules are needed per camera. Once produced modules must be assembled, tested and calibrated in a temperature chamber. To aid in this several manufactures will be worked with prior to the Production Phase to establish good quality assurance and redundancy. Manufactures will provide basic PCB testing. At least 2 institutes will be required to keep up with delivery of FEE modules to the AIV sites. FEE PCBs will be produced as early as possible (lower lead time than photosensors for example) and module qualification will ramp up before the peak camera production rate is reached.
- The number of PCBs per camera other than the FEE is small (approximately 5 envisaged in the final design). The work of producing and qualifying these is currently spread across 3 institutes.
- Chiller, pipes and fibre cables are all COTS.
- All cables will be produced and tested in industry.
- Where possible camera sub-assembly will take place well in advance of camera AIV. For example all 70 PCBs of a given type will be procured and in hand in Y1 Q1.

The man-power suggested for commissioning is rather large - please clarify why the high number of personnel are needed.

Telescope: The manpower required to commissioning the camera In the RfI, we stated that the commissioning team will be made by six persons. A possible composition of the team would be:

1. Scientist responsible for the commissioning
2. Calibration/AIV manager
3. 2 Technicians/Engineers for operations (one for the Camera and one for the Telescope & mirrors).
4. SW engineer for control software issues

5. Data handling expert for quick look, pipeline and archiving issues

The pathfinder phase will allow us to fine-tune the composition of the commissioning team both in terms of necessary expertise and manpower.

Camera: The manpower required to commission a single camera is 6.8-person months per unit, costing around 40kE. We feel this is a reasonable fraction of the total camera cost. The amount of time represents the fact that many camera items are produced in-house and that many institutions are involved (leading to a certain level of inefficiency). The total cost per pixel of the camera, including this level of manpower is still under 100€ per channel.

For shipping, a large number of (potentially expensive) containers is projected. Clarify whether the container are bespoke or standard, whether a smaller number of containers could be used or containers re-used, and the potential benefits (e.g. assembly).

For shipping a large number of containers has to be taken into account. For the electromechanical structure the design foresees two standard 40 feet type containers (no bespoke boxes, etc.). This has changed respect to what reported in the RfI after an interaction with the supplier of the structures for the array of pathfinders.
Our suppliers shipping experience widely demonstrates there are no economic benefits on the re-use of the containers.

We assume here that the panel are interested in the containers for shipping the telescope parts. If we are mistaken and further clarification regarding the camera shipping container options described in RfI Response section 5.2.3 are required then we will be happy to provide these.

References

The telescope team have made available all applicable documents via: http://www.brera.inaf.it/SST-RfI2019/
(login: astri-chec, password: chec)

1. ASTRI-QA-PD-3000-004 – ASTRI quality plan
2. ASTRI-IR-INAF-3100-074 – ASTRI SST-2M: Safety of the parking position
3. CTA-RP-ML-435 – Validation and qualification report of the industrial production process
4. ASTRI-MAN-GEC-3100-002b – ASTRI - prototype telescope maintenance manual
5. ASTRI-DES-GEC-3100-030b – FEM report
6. Giro, E., et al., "First optical validation of a Schwarzschild-Couder telescope: the ASTRI SST-2M Cherenkov telescope", Astronomy & Astrophysics, Vol. 608, id. A86
7. M. Garczarczyk, "Reflectivity of the MAGIC-II reflector", MAGIC Internal, 11 October 2011 (in annex)
8. CTAM-RP-M-001, Cold Slumped Glass Panels for CTA MST – Full Scale Prototype test report, 26 March 2012
9. ASTRI-SPEC-INAF-1000-033, FMECA of the ASTRI Telescope Structure

Appendix A: Further Maintenance Breakdown

Table 4: Schematic of the maintenance plan for each telescope structure.

Item	Type	Frequency /yr	Man hour	Man hour/yr	Man hour/week
Base Structure	Inspection	0,300	1,850	0,555	0,011
Az Encoder	Inspection	1,000	0,650	0,650	0,013
AZ Bearing Spur	Greasing	4,000	3,000	12,00	0,231
AZ Bearing	Greasing	2,000	2,350	4,700	0,090
Az Bearing Seal	Inspection	2,000	1,850	3,700	0,071
Az Bearing Screw	Inspection	1,000	1,850	1,850	0,036
Az Motor	Inspection	2,000	0,650	1,300	0,025
Az Motor	Change Oil	0,200	8,000	1,600	0,031
AZ Stow Pins	Greasing	0,300	1,000	0,300	0,006
AZ Stow Pins	Inspection	1,000	1,000	1,000	0,019
AZ Stow Pin Gearmotor	Change Oil	0,125	4,000	0,500	0,010
El Stow Pin	Greasing	0,300	1,150	0,345	0,007
El Stow Pin	Inspection	1,000	1,350	1,350	0,026
EL Stow Pin Gearmotor	Change Oil	0,125	1,500	0,188	0,004
Az Fork Structure	Inspection	0,300	1,000	0,300	0,006
El Axis Bearing	Greasing	0,300	0,500	0,150	0,003
El Axis Bearing Screw	Inspection	1,000	0,850	0,850	0,016
EL actuator	Greasing	1,000	2,000	2,000	0,038
ELA Upper	Greasing	0,300	0,650	0,195	0,004
Optical Structure Steel	Inspection	0,300	3,000	0,900	0,017
Electrical Cabinet	Inspection	2,000	1,500	3,000	0,058
Electrical Cabinet Filters	Change	4,000	0,300	1,200	0,023
Total					**0,743**

Table 5: Schematic of the maintenance plan for the mirror system of each telescope.

Item	Type	Frequency/ yr	Man hour	Man hour/yr	Man hour/week
Mirror Recoating	Change	0.10	40.00	4.00	0.077
Mirror Reflectance	Measurement	0.00	2.00	0.00	0.00
Mirror	Inspection	2.00	1.00	2.00	0.038
Total					**0.115**

Table 6: Camera preventative maintenance breakdown. All activities at height are specified to require at least 2 people. Cost includes manpower at 70k€ per person per year and estimates of the consumables.

Item	Action	Time (hours)	Number of people required	Man-hours	Frequency / yr	Man-hours / yr	Approximate Cost / yr (€)	Equipment
Camera	Inspection	0.25	2	0.5	6.0	3.0	105.0	Ladder / manlift, local control laptop
Chiller	Inspection	0.25	1	0.3	6.0	1.5	52.5	Local control laptop
PSU	Inspection	0.25	1	0.3	6.0	1.5	52.5	Local control laptop
Camera	Clean window	0.50	2	1.0	4.0	4.0	180.0	Ladder / manlift, local control laptop, ESD protection, protective gloves, protective eye weat, air gun, detergent spray, deonised water spray, very fine bristled brush
Camera	Replace fans	0.75	2	1.5	0.5	0.8	66.3	Ladder / manlift, local control laptop, replacement fans, M4 hex-key, M3 hex-key, ESD protection, custom tool to support fan-entry panel during procedure
Camera	Replace dessicator	0.25	2	0.5	1.0	0.5	37.5	Ladder / manlift, ESD protection, replacement dessicator
Camera	Replace lid	1.00	2	2.0	0.2	0.4	214.0	Ladder / manlift, local control laptop, replacement lid, M4 hex-key, M2.5 hex-key, ESD protection, custom tool to support lid during procedure
Chiller	Refill	0.25	2	0.5	2.0	1.0	75.0	Cooling fluid, protective gloves, protective eye wear.
Chiller	Full service	1.00	1	1.0	1.0	1.0	55.0	Cooling fluid, tool kit, protective gloves, protective eye wear.
					Total per camera / week	**0.26 hours**	**16.1**	

Appendix B: Further Upgrade Paths

Below we present alternative / additional upgrade paths to that of increasing the camera FoV.

Mirror coating technology: There would be some overhead in deploying new mirror-coating technology. As mirror re-coating is expected every six years this could be implemented on the telescope mirrors without significant additional disruption. Scientific impact would mainly come from an improved reflectivity averaged over the mirror life time and potentially improved tuning to the Cherenkov spectrum. These factors would help to maintain the sensitivity of CTA over time and improve intensity resolution (signal-to-noise) in the camera, allowing a reduction in trigger threshold (increasing telescope multiplicity) and improving reconstructed image (leading to improved background rejection power). An improvement in signal-to-noise may be particularly helpful in high NSB regions of the sky, for example helping to improve sensitivity along the galactic plane. Sensitivity in moonlight would also be improved, which in addition can increase the effective duty cycle of the array.

Improved photosensors: The baseline camera design presented here features 6 x 6 mm^2 SiPMs. These are commercially available from several suppliers and are an extremely active area of development, e.g. for medical applications. It is an almost certainty that improved SiPMs will be available within a few years of CTA operation. To replace the SiPMs on a camera could be done for a cost of approximately 20% of the total camera cost. It is, in principle, possible to upgrade the the SiPMs on-site, though dedicated upgrade space and tools would be required. More likely cameras would need to be sent back to Europe for upgrade and performance verification. The total cost for all SST cameras would then likely be on the order of 4 - 8ME. The dominant effect would be equivalent to increasing the telescope reflector size – more photons are captured. Improved SiPMs could increase the Cherenkov light collected by each telescope by up to 50% whilst rejecting more NSB and exhibiting lower optical cross talk (ENF) thereby leading to significantly improved intensity resolution (signal-to-noise). Telescopes would then trigger on smaller Cherenkov images, and captured images would contain more detail. These effects increase the telescope multiplicity thereby improving angular resolution and improve the background rejection power. As above, improvements may be most valuable in NSB regions of the sky.

Finer pixelisation: Finer pixelisation would further improve the angular resolution and background rejection power, but reducing the pixel size is only possible down to the PSF of the telescope optics. In the RfI response we discuss the possibility of a using 3 x 3 mm^2 pixels. This is only feasible with a dual-mirror design optimised for a smaller PSF and would require significant work prior to the completion of the final design to make such an upgrade tangible.

Firmware upgrades: Upgrading the FW in the camera can be done remotely, and therefore this is the easiest upgrade to deploy, coming at effectively zero cost. It is likely that most upgrades would be targeted at reducing calibration time and frequency, lowering power consumption and reducing dead time. All of these indirectly provide a scientific return by increasing the duty-cycle of the cameras. A more dramatic upgrade to the trigger logic could improve the trigger efficiency of the telescope. This would lower the minimum image amplitude and increase the telescope multiplicity for events. In turn the angular resolution may improve.

Intensity interferometry (II): Dedicated hardware is needed to perform II. Adding additional hardware, e.g. to the lid of cameras, would be the easiest option. In this this upgrade could, in principle be performed at a fraction of the camera cost and without interruption to normal operation. Sub-milliarcsecond imaging of nearby main sequence stars and binary systems can provide critical information on stellar phenomena such as rotational deformation, accretion effects, and the universality of sunspot cycles. The science impact of implementing II in the SST array could therefore be significant, opening up an entire new field of study for CTA.