A NEW TELESCOPE ARRAY FOR NEO DETECTION AND CHARACTERIZATION

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ABSTRACT

A new array of commercial-off-the-shelf (COTS) optical telescopes has been investigated to provide additional assets for performing near-earth objects (NEO) surveys, follow-up and characterization, thus complementing existing or planned facilities. After an extensive market survey, we have defined two architectures that optimally match the main goals of this new telescope array. The first solution is based on 10 wide field, 1-m aperture, telescopes, equipped with the largest monolithic charge-coupled devices (CCD) cameras. The second solution is based on 36 wide field, 0.6-m aperture, telescopes coupled to large complementary metal-oxide semiconductor (CMOS) sensor cameras. In both cases, telescopes will be installed in three different sites, two in the southern hemisphere and one in the North. By stacking images from different telescopes pointing the same field, similar detection sensitivities are achieved by both solutions, aiming to faint objects with a visual magnitude V=21.5 at peak signal-to-noise ratio (SNR) better than 5, under typical seeing conditions with median full-with-half-maximum (FWHM) of 1.5 arcsec. Also two or three larger telescopes for follow-up and characterization have been conceived. This study covers the preliminary architectural designs, the expected performances and costs, and organizational, operational and commercial approaches, to assess which models will be best suited to deliver final data.

1 INTRODUCTION

Under ESA's Discovery and Preparation elements of the Discovery Preparation and Technology Development activities, a study has started during 2022 to investigate potential designs for an array of COTS optical telescopes that will be devoted to perform a dedicated survey to detect NEO, execute their follow-up, and possibly characterize their physical parameters. The array-based solution should target to survey an area as large as possible on the sky for a given time, while being able to detect objects down to magnitude 21.5 in the visible. A set of commercial telescopes will be placed in a small number of sites. The study addresses also which is the optimal balance between distributed and centralized functions, within sites and between sites.

The study started by exploring the current state of the art in commercially available optical telescopes, instrumentations (camera sensors, enclosures, auxiliary items), and associated technologies to form a pool of building blocks to setup such an array. Then, an architectural design phase provided some possible solutions, based on previously identified building blocks, as result of a trade-off analysis of many key performance metrics, from sky coverage, sensitivity, number of sites, survey strategies, and operational aspects. A preliminary performance and cost analysis was performed to compare the different architectures, identifying main cost drivers, manufacturing issues, risks and their potential mitigations. Some of these activities are still ongoing and we aim to finalize this study in the next few months, including the analysis of different business models (e.g., private/public partnership) to run the telescope array and enable ESA to procure NEO survey data.

2 HIGH-LEVEL REQUIREMENTS

Starting from ESA requirements, we have derived some system and subsystem requirements that enable a selection of COTS products to setup this telescope array.

2.1 Telescopes

Telescope entrance aperture, field of view, focal length, pixel scale, optical efficiency, central obstruction, image quality and its uniformity and stability, and geometrical distortion are the main key parameters. Two main classes of telescopes can be identified: (a) wide field telescopes, mostly with a prime focus configuration, and (b) two-mirror telescopes, based on different optical configurations: Ritchey-Chrétien (RC), corrected Dall-Kirkham (DK). Two-mirror telescopes are generally equipped with field flatteners or field correctors to improve image quality over a larger native field of view.

Telescope apertures from 0.6 to 1 m have been

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considered in this market survey. While meter-class telescopes provide already large photon-fluxes, they are quite expensive and only few vendors offer very fast optics to increase sky coverage. As an alternative, smaller telescopes can be grouped together, by stacking images acquired with different identical telescopes, to compensate for their smaller photon collecting area.

Telescope field of views larger than 3 degrees have been pre-selected to enable NEO surveys. This requirement restricted a lot the number of available COTS telescopes. Similarly, focal length has been defined for two main pixel size ranges: 8-12 um, for longer focal length telescopes, and 5-7 um for the shorter ones. This two ranges closely match a typical pixel scale of 1 arcsec/pixel. This value is already the result of a trade-off to maximize the number of NEO detections: indeed, while smaller pixel scales will be limited by trailing losses for fast moving objects, larger pixel scales will be limited by high background photons coming from sky brightness.

Optical transmission has an impact on overall sensitivity and must be maximized. Prime focus configurations are generally offering better performances, due to the smaller number of optical elements with large efficiency losses. An average throughput of >60% is required, to guarantee enough collected photons. The typical wavelength range is covering the 450-800 nm range, to match also typical detector quantum efficiency response.

Another key optical parameter is the geometrical distortion that affect astrometric accuracy. Distortion must be smaller than 1% over the full field of view, but the smaller, the better.

Other parameters have been considered, like a back focal length large enough to accommodate for some filters and existing camera sensors, a focusing mechanism with at least three degrees of freedom (piston, tip, tilt) to have uniform point-spread functions (PSF) over the whole field of view, a small cumulated ghost relative intensity of <1E-4 to avoid contamination from bright stars within the large field of view.

2.2 Detectors

Two different sensor technologies are available: CCD and CMOS. The former one is very well known for astronomical applications, due to its properties, like very high quantum efficiency, linearity, and noise. Typical CCD costs are quite high for large area sensors. CMOS is an emerging new technology, at least on large areas, but they have largely improved performances, comparing very well with CCD. Moreover, they offer much faster readouts, thus decreasing overheads on typical applications where multiple short exposures are required, like in the synthetic tracking method.

The main parameters to take into account in the selection process are:

- Detector area: the larger, the better, because it is directly related to final sky coverage of the array
- Pixel size: too small pixels offer reduced performances, like smaller dynamic range. CMOS sensors overcome this issue by using multiple readouts (HDR). However, an indirect side effect of smaller pixels is to require faster telescope optics (smaller focal ratios), with increasing complexity/costs and higher sensitivity to misalignments, operating and environmental effects. So, very small pixel should not be considered.
- Quantum efficiency: the higher, the better. Current back illuminated CCDs and CMOS offer peak efficiency >90%, generally around 600 nm. Of course, also broadband performances are important.
- Readout noise (RON): most of the observations will be limited by sky background shot noise, with readout noise being smaller. However, RON must be minimized to maximize dynamic range.
- Readout time: this adds an overhead on exposure time. When exposure are short (<60 sec), this factor may reduce observing efficiency. CCD are generally much slower to be read, even when multiple channels (up to 16) are available, especially to keep RON small. For example, a 80 Mpixel sensor with 16 channels read at 1 MHz will take 5 seconds to be read, typical within the slewing and settling time between two consecutive telescope pointings. At faster readouts, RON may increases to unacceptable levels. CMOS, on the contrary, offer much faster readouts (<1 sec.), still guaranteeing RON levels comparable, or even smaller, than CCD.
- Shutter: typical CCD requires physical shutter to prevent light reaching the sensitive area during the readout operation. Frame transfer CCD are only available on smaller area. Some camera sensors are already equipped with integrated shutter on the camera body. However, on very large detectors, this is not generally the case, and an external shutter must be provided. CMOS sensors do not require a physical shutter, due to their readout approach. However, two different approaches exist: rolling shutter, and global shutter. Rolling shutter introduces time delays across the sensor area, so that accurate timing can be compromised. Global shutter offers better performances.
- Cooling: in order to reduce dark current noise and to stabilize detector performances, detectors are cooled. The required temperature depends

on the maximum dark current value. On short exposures, this is less important, and simpler cooling technologies can be adopted, like thermoelectric (Peltier), multi-stage, cooling. Air or water are used to extract heat from the warm side of the cooling stage. On very large detectors, like CCDs, some cameras are equipped with cryogenic gases. This adds more complexity to the systems, especially to route cryo-lines from the cryocooling compressor to the sensor head. Moreover, it adds periodic maintenance operations, like gas refilling.

- Size, weight, and waste heat: also size and weight are important factors, due to limiting constraints on the telescope camera interface. On prime focus telescopes, moreover, the waste heat generated by the camera body, sitting in front of the telescope aperture, must be taken into account, to avoid introducing local seeing effects. Proper heat management should be designed into the system.

2.3 Mount

Meter class telescopes are generally integrated and delivered with telescope mounts. Some suppliers offer both equatorial and alt-azimuth mounts on the same optical tube assembly. There are some suppliers that offer mounts as separate items, but this approach is effective only on smaller telescopes (e.g., 50-70 cm aperture), and it is discouraged on larger ones.

Some mount characteristics have been identified to match overall system performances, mainly including pointing and tracking accuracy. Mount performances are linked to some mount components, like motor technology, axis encoders, safety brakes, and their telescope control system, both at HW and SW levels. It is mandatory to have some custom-oriented control system interfaces, to enable integration into the Telescope Array system and its specialized control software.

Key parameters are:

- Slewing speed and acceleration: typical observations will require slewing to adjacent FoV (about 2.5 deg) within few seconds. Speeds and accelerations of both axes must be enough to guarantee such a possibility.
- Pointing accuracy: this is related to the capability to centre the FoV. However, due to the very large FoV, high accuracy is unnecessary. Typical telescope mounts, after pointing model calibration, are capable to achieve <30 arcsec RMS pointing accuracy over the full sky (above 15 deg elevation).
- Settling time: this is quite important, adding overhead between two observations. The smaller, the better. Current requirement of <15 sec after 2.5 degree slewing command (two adjacent FoVs) seems quite reasonable for all existing COTS telescope mounts.
- Tracking speed: both sidereal and non-sidereal tracking speeds must be available to enable different NEO observation strategies.
- Tracking accuracy: blind (no guiding camera) tracking accuracy over short exposure (<few minutes) of <0.5 arcsec RMS are mandatory on any telescope mount. This must hold true at both sidereal and non-sidereal tracking speeds. This is also related to the control system architecture. Real-time controllers offer improved capabilities when observing at non-sidereal speed.
- Absolute encoders: in case of system failure, absolute encoders enable to recover accurate telescope positioning without a pointing recalibration procedure.
- Safety breaks: direct drive motors are a common standard feature on most of current telescope mounts, because they are offering high performances at a reduced cost. However, they fail to keep the position of the telescope in case of power failure or of their control system, especially if unbalanced or under unexpected events (earthquakes, very high wind gusts). In this case, safety breaks are necessary to prevent unwanted motions of telescope axes.

2.4 Domes

Different dome configurations are available on the market: classical domes, clamshells, and sliding roofs. Each of these solutions offers pros and cons, and cover a wide range of installation and operational costs. All of them needs to be fully motorized and must be operated remotely, with some level of autonomous operations, like automatic closure of the dome opening in case of bad weather conditions.

Main common characteristics for all type of domes are summarized here:

- Size: Classical domes and clamshells generally host a single telescope, so to minimize dome size accordingly. Sliding roofs, instead, are well suited to host many telescopes together. Size of dome or roof must be properly selected to host the given number of telescopes. In both cases, the minimum elevation angle and the potential vignetting due to closely packed telescopes/domes, put a constraint onto the minimum telescope/dome separation, and, then, on the telescope array distribution.
- Opening: it must be selected to enable minimum elevation angle observations for all, or most, of the telescope array configurations. It must be

motorized, remotely operated, with autonomous closure in case of bad weather (rain, high wind), cloudy coverage, and light levels (day/night).

- Slewing speed/acceleration: in case of classical domes, with an azimuthal axis of rotation, this axis characteristics must cope with minimum telescope mount performances, to avoid making the dome the limiting factor, adding additional overheads onto observation efficiency.
- Insulation & ventilation: domes should be designed to minimize the heat load inside the dome in daytime, under sunlight, and promote fast cooling to outdoor temperature during night time. This is aiming to reduce degradation of local seeing, especially at the start of the night, where some critical observations are run. Active ventilation, to start in advance of the observing night, may help to improve performances. Air conditioning may be prohibitive, mostly due to high operational costs, but it should be considered in site locations with high temperature excursion between day and night. In this case, inner temperature should be kept constant during daytime to the expected temperature at the beginning of the following night. The clamshell domes and the sliding roofs provide different performances with respect to classical domes. The former one easily provide a lot of ventilation while fully open, thus helping to remove waste heat. The latter one, instead, may be equipped with high insulation from the sun. Air conditioning is not generally easy, because sealing between indoor and outdoor is quite poor. However, after opening, fast cooling can be achieved as in the case of clamshells.

2.5 Filters

Filters are needed to reject unwanted light: (a) short wavelengths: during bright time (full Moon), sky brightness increases especially at shorter wavelengths due to atmospheric scattering; (b) long wavelengths: above 700 nm air glow starts to become an important factor.

Standard Johnson-Cousin or Sloan/SDSS photometric filters can help to mitigate this effects. Many vendors offer off-the-shelf photometric filters, up to 100x100 mm size (e.g., from Baader Planetarium). Larger size are generally provided as custom products. While their cost is higher than COTS filters, due to the moderate large quantity needed to build the NEO TA, reasonable moderately prices per units are achievable.

There is a side effect to adopt standard photometric filters: they have a relatively narrow bandwidth. To increase the number of collected photons and the related SNR, a broader bandwith is advisable, as given by the "V+R" filter, thus covering from approximately 480 nm to 760 nm. Such a filter maximizes the number of photons in almost any observing condition. Such a filter is not COTS, but different vendors are available to provide it.

2.6 Site infrastructures

Together with the dome, auxiliary functions need to be provided, to operate a remote network of telescopes. Here we provide a list of the main components, not including the IT infrastructures, like computer hardware, to acquire, process, and transfer observing data.

Below a list of main site characteristics to deal with:

- Weather station: real-time data are mandatory to monitor environmental conditions, both indoor and outdoor. Typical dataset include temperatures (air temperature, dome temperature, telescope temperature, mirror temperature, …), relative humidity (both indoor and outdoor), dew point, wind (average and gusts speed and direction), rain, cloud coverage. Additional data may include: lightning (distance and approaching speed), earthquake detectors, sky quality meter (sky brightness), and atmospheric seeing. A lightning detector may be quite useful to shutdown delicate electronic systems, like computers and camera sensors, to actively protect them against EMI. Atmospheric seeing may help to correlate observed data with sky conditions.
- All-sky camera: this may prove quite useful to remotely verify sky coverage conditions, when standard cloud monitors are not well calibrated. Moreover, it can provide additional cloud detection functionality.
- Surveillance cameras: real-time video surveillance may help while remotely operating the system. Cameras should be available both inside the dome, equipped with IR lamps that can be remotely switched on/off, to check all equipment, and outside the dome, for general safety. Zoom cameras may help to detect issues on systems/subsystems.
- Lightning protection system: this is mandatory to protect operators and systems under bad weather conditions. Proper grounding must be developed: two separate groundings are required, one for all internal electrical devices, and one for the lightning path. This must be put in place at the time of the site infrastructure preparation. Typical observing site, on top of mountains, have quite bad ground resistivity, especially on rocky surfaces. In this case, deep rock drilling and other special devices to increase ground resistivity during dry weather, may help to keep the LPS efficient in all conditions.
- Flat-field screen: for daytime calibration, a

properly illuminated screen inside the dome can be used to run flat-field observation to routinely monitor system performances and execute flat-fielding. Typical white scattering surfaces are used to provide good uniformity patterns, places in front of the telescope aperture. For meter-class telescopes, the easiest solution is to install a white screen, properly illuminated, on the dome wall or under the roof, one for each telescope (Fig. 10). Halogen lamps can provide an ideal spectral distribution.

- Internet connection: this is mandatory to provide remote operations. High speed connections are required to transfer all the data, including pre-processed data, generated each night, and all/part of the raw data, during daytime, for off-line analysis. Backup, secondary, connections, like via 4G/5G mobile connection or radio links, even for slower connections, may prove very useful when high-speed connection does not work.
- Observatory auxiliary functions: all other active systems, like fans, air conditioning, emergency closure, rack cooling, power management, must be remotely monitored and actively controlled. UPS systems are mandatory to operate emergency operations. UPS power must be properly sized to keep up with all the devices to be run during the emergency procedures. Autonomous procedures must be put in place, even in case of no Internet connection.

2.7 Network geographical distribution

The NEO discovery capability is maximized by covering the whole sky with 24h continuous coverage. This cannot be achieved by a single observing site, but from a multiple number of different sites properly distributed around different longitudinal coordinates, and on both hemispheres. Many existing or planned networks work on the same principle. Many astronomical observatories exist around the world with good observing conditions. The most successful, however, are located at low latitudes, like Chile in South, or Canary Island and Hawaii in the North, where good seeing and a very large number of clear nights are generally available. Some complementarity to existing networks is highly recommended to maximize the overall number of new detections of NEO.

Here we summarize some general requirements for the observing sites that will host one or more telescopes of the ESA NEO Telescope Array:

- Clear nights: to maximize the number of useful nights, weather monitoring campaigns, extended at least over few years, are generally recommended. Very good sites offer up to 80% (yearly average) or more, including both photometric and spectroscopic nights. There are very few sites with such good conditions, and more common values are between 50% and 60%. Also seasonal variation is another main factor, because at larger latitude there are stronger variations from summer to winter. Again, the smaller, the better.
- Weather conditions: another important factor is the typical weather conditions. High winds are detrimental to good observations. Bad seeing is also related to local climatic conditions, linked to topographical characteristics, main wind directions, and other disturbing effects.
- Sky brightness: this is, very likely, one of the most important selection factors, because NEO observations will be sky background limited. Very dark skies are preferred, that are generally available quite far from large cities or human activities.
- Existing infrastructures: to minimize the installation costs, it is advisable to identify already existing civil infrastructures nearby that can provide access to power line, high-speed data connections, easy access roads for installation and regular maintenance, even during bad weather events.
- Night-time coverage: an ideal network will be always able to observe any point on sky all the time. This can be accomplished only by a large network of telescope widespread across the globe. However, when a limited number of sites exist, night-time coverage will decrease, thus reducing the detection rates. It is important to maximize this parameter while selecting a restricted number of sites.

3 BUILDING BLOCKS

This section provides a summary of the market survey of all potential system components to build a telescope array based on commercial-off-the-shelf products. Previous sections identified which characteristics each device or product must satisfy to match the NEO telescope array (TA) system.

3.1 Telescopes

We have inquired many companies around the world that design and manufacture meter-class telescopes. Some of these companies advertise their products on their websites and dedicated astronomical magazines. Few others have been involved in delivering many telescopes on custom basis and do not have, strictly speaking, COTS products, even if most of these telescopes are based on shared designs, identical subsystem components, and common design and manufacturing supply chain.

Almost all of these telescopes are two-mirror designs, with Ritchey-Chrétien and modified Dall-Kirkham designs being the most common ones. Some companies have designed and built also prime-focus systems, with wide field of views. Here we have collected information on both configurations, because while the latter ones will be dedicated to the survey telescope array, the former one may be adopted for follow-up telescope to complement the survey telescopes. The list of suppliers we have contacted so far include: AstroSysteme Austria (ASA), APM Telescopes, ASTELCO, DFM Engineering, Officina Stellare, PlaneWave.

Only few telescopes offer a close match with the telescope array requirements and they will be considered for a further technical investigation. We have compared performances, based on the currently available information. It is important to notice that quite often image quality, for example given by spot diagrams or spot size vs. wavelength and field position, are nominal values, for the ideal telescope with perfect optics, perfectly aligned, and without any environmental effect, like gravity, temperature changes, thermal gradients, or vibrations. As-built performances may differ quite a bit, especially on very fast optics, because they are generally more sensitive to manufacturing errors, misalignments and environmental effects.

Some examples of prime focus telescopes are shown in Fig. 1 to Fig. 4, for reference only, covering the 0.5-1 m entrance aperture.

Figure 1. ASA UWF1000 F/1.3 telescope (credits: ASA website).

Figure 2. Officina Stellare 1-m F/2 Wide-field Mufara Telescope during factory acceptance tests (credits: Officina Stellare).

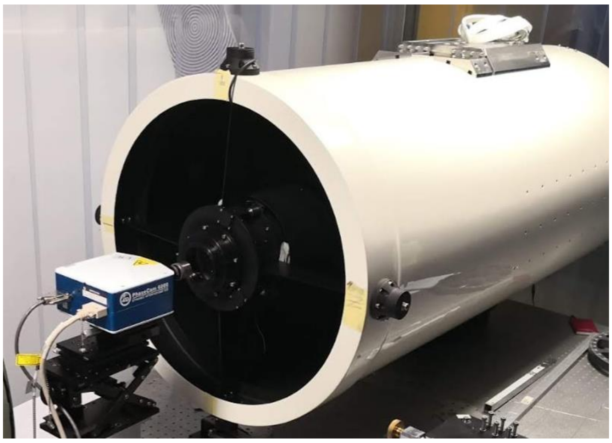

Figure 3. Officina Stellare 600-mm F/2 prime focus telescope under interferometric tests in the lab (credits: Officina Stellare).

Figure 4. ATLAS 0.5-m F/2 OTA in its test stand at DFM Engineering (courtesy: DFM Eng.).

3.2 Camera sensors

Many different vendors have been inquired and cover both CCD and CMOS sensors. An incomplete list of cameras is given in Tab. 1, while a quick comparison chart for some of those sensors is shown in Fig. 5.

The two largest detectors are CCD290-99 from Teledyne e2v, and the COSMOS-66 from Teledyne Princeton. The former is offered, fully integrated, by Spectral Instruments, packaged inside a cryocooled compact camera housing, installed, for example on the WMT (Fig. 2). The latter is a quite recent product fully designed and manufactured by Teledyne Princeton. It is thermo-electrical cooled inside a relatively bulky housing (Fig. 6). Fig. 6 to Fig. 8 show some examples of camera sensors, mounted inside their housing, where cooling systems and readout proximity electronics are hosted. Please note the quite different aspect ratio between the sensor area and their housing.

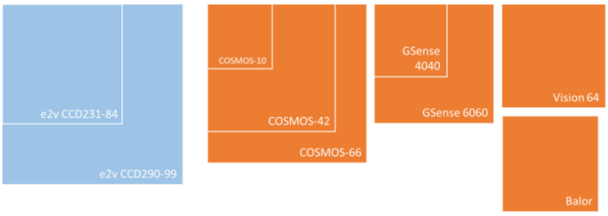

Figure 5. Comparison chart of CCDs (blue) and CMOS (orange) sensor areas, represented on the same scale.

Table 1. Large format camera sensors.

Supplier	Model	Sensor (mm)	Pixel (um)
Teledyne Princeton	COSMOS-66	81 x 81	10
	COSMOS-42	65 x 65	10
	COSMOS-10	33 x 33	10
Finger Lake Instruments	Kepler 6060 BI	61 x 61	10
	Kepler 4040 BI	37 x 37	9
	KL400	23 x 23	11
	DC23084	61 x 61	15
Spectral Instruments	1110S (290-99)	92 x 92	10
	1110S (231-84)	61 x 61	15
	Vision 64	53 x 53	6.5
Andor Oxford Instr.	iKon-XL 231	61 x 61	15
	iKon-L 230	61 x 61	15
	Balor	49 x 49	12
Moravian	C4	37 x 37	9
SBIG	Aluma AC4040	37 x 37	9
XIMEA	MX377MR-GP-B	61 x 61	10
QHYCCD	QHY6060	61 x 61	10
	QHY411	54 x 40	3.76
	QHY4040/Pro	37 x 37	9

Finger Lake Instruments and Spectral Instruments cameras offer much more compact housing than the Teledyne Princeton COSMOS-66.

Figure 6. COSMOS-66 prototype model.

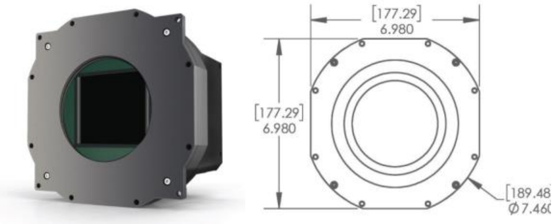

Figure 7. Finger Lake Instruments Kepler 6060 (credits: FLI Camera website).

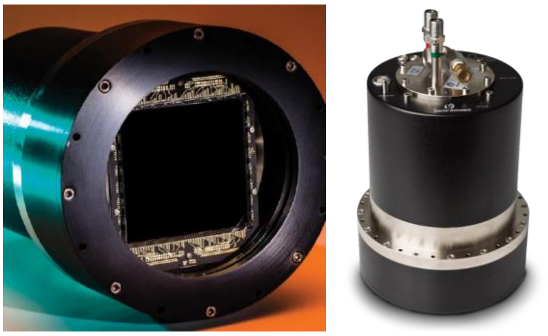

Figure 8. Spectral Instruments 1110S CCD camera (credits: Spectral Instruments).

3.3 Enclosures

Some companies design and distribute rotating classical domes and clamshell ones. The classical domes have been very common from small to very large sizes since many decades. They are generally custom designed, made out of steel or aluminium, and they take longer installation time. More recently, by using glass reinforced polymers technology, clamshell domes have gained widespread use to host smaller telescopes. But the improved quality of clamshell has increased and is now covering larger sizes, up to 6.5-m.

Sliding roofs have been designed and built by many different companies and they are used for industrial applications, too. Other solutions include retractable tents, but they are considered less attractive due to their typical shorter lifetime.

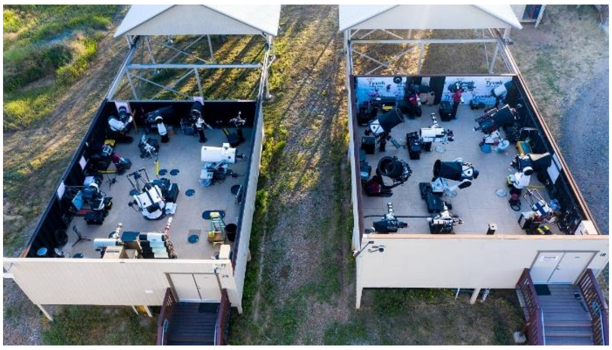

Figure 9. Sliding roof used to host multiple outreach telescopes (credits: Sierra Remote Observatory).

3.4 Auxiliary items

Flat field screen: proper flat fielding is performed on sky after sunset or before dawn. However, to help functional checks and monitoring, like detector non linearity, shutter uniformity, or telescope mirror reflectivity, daytime flat fielding is useful. To implement such a possibility, different solutions exist, mainly based on pointing the telescope aperture towards a uniformly illuminated screen, as large as the telescope pupil.

For small scopes, some companies sell flat-field screens. However, for larger aperture, no commercial device exist with such a specific purpose. However, such a system is relatively simple to implement, based on a white-painted matte (scattering) surface, to be illuminated by one or more halogen lamps with regulated intensity. Such white screens can be attached to the dome.

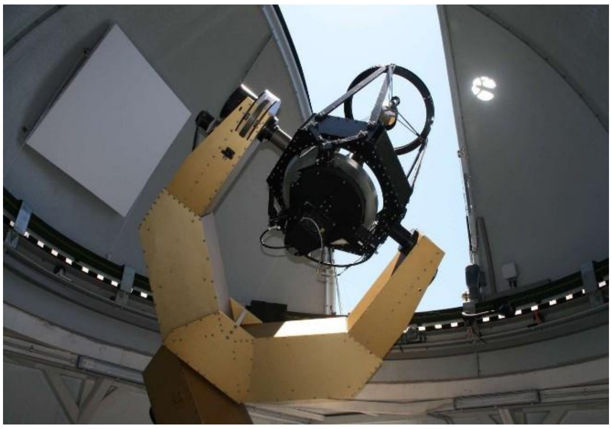

Figure 10. Flat field screen inside a dome (credits: ESA CESAR Observatory).

Field derotator: on Alt-Azimuth telescope mounts the field will rotate during each exposure. To compensate for that, a third motorized axis is added. This applies to all AltAz foci: prime focus, Cassegrain, Nasmyth. On smaller telescope, especially for the prime focus systems, this motorized system may add complexity and weight, sometimes reducing the space available between the telescope mechanical flange and the detector.

Prime focus telescopes from Officina Stellare and ASA offer an integrated field derotator. Also other vendors, like PlaneWave offer derotators at Nasmyth foci only.

Focuser: a focusing system is mandatory on any telescope to compensate for focus changes introduced, for example, by temperature changes. Most commercial telescopes provide such a system already fully integrated into the optical tube assembly, either by moving the mechanical interface flange where the focal plane instrument is attached, or by moving an optical element (e.g., secondary mirror). This is not further addressed here, as all the pre-selected telescopes have this as a built-in feature.

However, it must be noticed that on wide field telescopes with very short focal ratio (<F/3), focus may change across the field of view, as result of small tip/tilt errors between the focal plane and the detector plane. This effect can be compensated for by a tip/tilt mechanism between the telescope interface and the detector assembly. Few telescopes offer this feature (e.g. Officina Stellare WMT).

GPS systems: for accurate astrometry, especially of fastest targets, accurate exposure timing is required. This can be provided by a GPS synchronization system. A trigger signal can be sent directly to camera sensors (where this feature is available) to add an accurate timestamp to the exposure, down to <1msec UTC accuracy (e.g., Shelyak Instruments TimeBox). Some cameras (e.g., Finger Lake Instrument Kepler) offer an auxiliary device with very high accuracy, down to few microseconds. On a distributed network of telescopes, equipped with their own cameras, synchronization between different cameras is quite important, especially when stacking multiple observations together. Also accurate time-stamping is required. A time distribution system is likely to be required. Moreover, some sync-input is required on cameras, to enable synchronous observations.

Filter wheels: COTS filter wheels exist only for sizes smaller than ≈65 mm (square), so that they are not applicable on NEOTA, where much larger filters are needed. Specially designed filter mechanisms have been produced by different companies (e.g., Officina Stellare WMT with 150x150 mm filters), based on custom-designs.

3.5 Candidate sites

Different selection criteria have been defined to pre-select potential sites to host one of the nodes of the NEO telescope array. These criteria are briefly described below.

- **Sky brightness**: this is one of the most important parameter to optimize performances, because it directly affects the detection sensitivity to NEO discovery. SNR will depend mostly on sky brightness background photon noise. Then, by selecting dark sky will improve SNR. Few sites have been characterized for sky brightness. Most of the existing data are only available from other astronomical observatories.
- **Seeing:** together with sky brightness, it directly control the detectability of new NEOs. Smaller seeing will concentrate target photons on fewer pixels, thus increasing SNR. Statistics distributions have been measured on existing major astronomical observatories (like La Silla or Canary Islands), where many observatory are located. Also different seeing measurements have been defined: the simplest measurements are based on seeing monitors that look at the Polaris (northern hemisphere), while more sophisticated instruments are the DIMM (differential image motion monitor).
- **Clear nights:** the number of nights with full or partial clear sky conditions is quite important. These numbers typically vary during the year, with some seasonal variation. The NEO TA observing efficiency depends on this number. When multiple nodes are adopted, the likelihood of bad weather on all sites decrease, especially if different nodes belong to different hemispheres.
- **Logistics and infrastructures:** it is quite important to identify sites that are easily operated along the year in terms of accessibility and other infrastructures (roads, power line, high-speed data connections, water supply, …). Bad logistics can be detrimental to continuous operations throughout the whole year. Sites must be accessible for regular operation, planned and unexpected maintenance, especially during the first years of operation, when extended commissioning runs are expected. Existing infrastructure are preferred.
- **Manpower cost:** also the cost of local personnel is important to enable affordable local manpower. Some sites are generally very expensive (like Australia).

A preliminary list of potential sites to host one node of the telescope array has been identified. Fig. 11 shows the geographical distribution of these sites. Sparse data are available about their weather statistics, median seeing, sky brightness, and number of clear nights. Moreover, when available, data are not homogeneous, sometimes covering many years of observations, more often few days only, being not representative of yearly average conditions.

Figure 11. World map of candidate site to host the ESA

NEO telescope array.

4 ARRAY ARCHITECTURE

4.1 Array configurations

We have explored many different combinations of telescopes and cameras. We have then preselected two quite different HW cases, that offer however, similar sensitivities, due to their similar cumulative entrance aperture (stacking of multiple telescopes). Tab. 2 gives a summary of their parameters. The two configurations proposed are quite different from the HW point of view, but, by making use of low-detector noise and stacking of simultaneous exposures from different telescopes pointing on the same field position, can achieve similar performances at a comparable overall cost.

Table 2. Large format camera sensors.

Array Architecture	A	B
Telescope mount	Alt-Az	EQ
Entrance aperture (m)	1	0.6
Focal ratio	2.1	2.1
Sensor	CCD	CMOS
Sensor area	9k x 9k	8k x 8k
Pixel size (um)	10	6.5
Pixel sampling (arcsec/pixel)	0.98	1.03
Field area (sqdeg) per tel.	6.0	5.5
Readout time (sec)	5 - 15	0.025
Slew time, adjacent FoVs (sec)	10	8
Number of telescopes	10	36
Stacked observations	2	4
Array simultaneous sky coverage (sqdeg)	30	50

4.2 Architecture A

The architecture of option A reaches V_{lim} of 21.5 at least with a SNR of 5 as a minimum. This architecture uses 1 m telescopes with a FoV of 6 square degrees each. The assumption is that two telescopes are operating in pair (looking the same part of sky) and the images are stacked to reach the required limiting magnitude of 21.5. The total number of telescopes is 10, but working as 5 couples.

- **Telescope sites:** 3. One in northern hemisphere, such as Canary Islands, two in southern hemisphere, i.e. La Silla in Chile, and South Africa/Namibia or Western Australia
- **N. of telescopes per site:** 4 in two sites (Canary Island and La Silla), 2 in the third site
- **Telescope**: 1-m, FoV 6 sq.deg
- **Pixel sampling**: 1.0 arcsec
- **Exposure time single image**: 42 sec.
- **Tot. integration time (2 tel.):** 84 sec
- **Idle time:** 17 sec.
- **N. of revisits:** 4

4.3 Architecture B

The major difference for this option compared to the option A are the number of telescopes and the size of primary mirror. The assumed size of the telescope aperture is 600 mm, while the total number of telescopes is 36 and will work in group of 4, in stacking mode, to be able to reach the required magnitude of 21.5.

- **Telescope sites:** 3. One in northern hemisphere, such as Canary Islands, two in southern hemisphere, i.e. La Silla in Chile, and South Africa/Namibia or Western Australia
- **N. of telescopes per site:** 12
- **Telescope**: 0.6-m, FoV 5.5 sq.deg
- **Pixel sampling**: 1.0 arcsec
- **Exposure time single image**: 55 sec.
- **Tot. integration time (4 tel.):** 220 sec
- **Idle time:** 8 sec.
- **N. of revisits:** 4

Architecture B, being based on smaller aperture telescopes, requires to stack more simultaneous images to obtain the same SNR, acquired with different telescopes. However, the higher number of telescopes (36 instead of 10) enables a larger sky coverage, thus improving overall performances (see next section for more details).

5 PERFORMANCES

5.1 Simulation approach

The approach for preparing the simulation starts from preparing the synthetic NEO population. We used the synthetic population generator of the ESA NEOPOP tool developed by SpaceDys. In particular, we generated 10,000 synthetic NEOs (orbits) in the range of absolute magnitudes between 22 and 28. For increasing the simulation statistics, we oversampled smaller objects. In other words, the population size distribution does not represent the real one, and the number of smaller objects increases with the decrease of the size.

The first analysis step includes the generation of ephemerides for all 10,000 virtual asteroids for a timeframe of 15 years in steps of one hour for all sites involved in the simulations. This is the most intensive work in terms of computational load. It usually takes several hours to complete, also using parallel computing with up to 64 cores. The second step needs to define the telescope array architecture and efficiency profile.

Observing sites: for example, two or three sites distributed around the globe.

Weather models: we can make use of up to 18 weather models, nine for northern hemisphere and nine for southern hemisphere, each one representing different seasonal effects. For each hemisphere, we can use three different typical modes or conditions (good weather, medium, bad) according to typical expected weather statistics (86%, 66% and 46% of good / clear nights). For each mode, we can use three different schemas with similar statistics but different distributions.

Limiting magnitude and exposure time: these two quantities are obviously related, while the first quantity depends also on the expected optics performance.

Pixel size is involved when dealing with the expected trailing loss for fast moving objects.

Efficiency dimming when close to limiting magnitude: a stochastic approach is involved to play a realistic efficiency in detecting objects when they are close to the detectability threshold.

Sky coverage in square degrees/hour: this depends upon the number of involved telescopes, the single telescope field of view, the exposure time together with the idle time (telescope slewing + chip read out) and the assumed number of frame per each sky pointing. To be more realistic, we assume that there is no overlap of sky coverage from other telescopes of the network. In other words, we assume that a smart scheduler coordinates all telescopes of the array. Moreover, we consider a prudent and somewhat conservative approach when determining a realistic sky coverage per hour.

Observability constraints, such as minimum distance to the Moon, minimum distance to the galactic plane, minimum elevation above horizon, and others, are involved in the ephemerides filtering.

The scripts running this analysis are quite fast and they usually take only few minutes. The results include a statistic of the asteroids detected, their absolute magnitude, their family, but, most importantly, they include also the time to or from the nearest close approach. This parameter, in particular, can give important clue on the efficiency in detecting NEOs with enough lead-time before impact. The simulation, of course, shows also NEOs discovered after close approach. This happens when the NEO is coming from the direction of the Sun, where we are obviously blind, and move away from our planet. Anyhow, for the purpose of these simulations, we consider the subset that has been discovered before close approach and with a lead-time less than 200 days. We do not consider those discovered too early in time for determining the expected lead-time, because, even if the early discovery is generally quite important for easily planning the mitigation actions, this is out of the scope of determining how efficient the telescope array for detecting the so-called imminent impactors is.

5.2 Weather influence

We studied how performances of a single site differ for different weather statistics. It is quite obvious that a good weather statistics site is performing much better, but sometimes it might limit the selection to few observing sites around the world (i.e. La Silla or Mauna Kea are top class sites, but this does not mean they are available for new installations) and the client might need to choose other sites with worse weather statistics, but which can still guarantee a good performance. In general, having a good geographical distribution can be an advantage even if the weather performance is not the top. This analysis gives some data to be considered.

Fig. 12 shows the discovery counts as function of absolute magnitude H and weather model. It is easily noticeable that under good weather, number of discoveries is larger than under bad weather. The net gain is between 10% and 20%. Anyhow, the weather conditions do not seem to affect heavily the array performance as we could argue. In other words, good weather is better, also considering other side effects such as seeing condition and light pollutions, but we can cope with less performing sites.

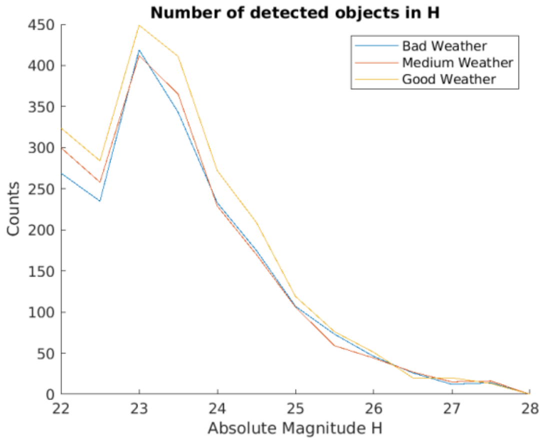

Figure 12. Number of discovered targets for each absolute magnitude H and for each weather model.

5.3 Array performances

The most important key performance metrics of the simulations are two:

- The efficiency in discovering new NEOs for the considered timeframe, which for this simulation is 30 years

- the lead time from discovery to close approach time. This quantity gives a metrics on the efficiency to discover possible imminent impactors with enough lead-time that allows the realization of prompt mitigation actions. The graph will show only the lead-time when the close encounter is within 60 days.

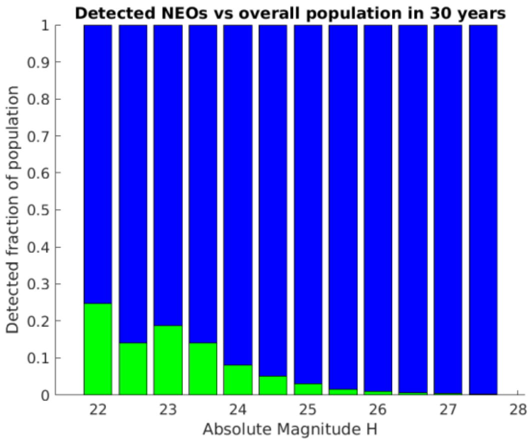

Figure 13. Number of discovered targets for each absolute magnitude H within 30 years.

Fig. 13 shows the efficiency distribution for different absolute magnitudes H (equivalent to sizes) against the overall simulation population. For example, a value of 0.25 means that the architecture is efficient in detecting the NEO at le level of 25% of the entire population within 30 years of operations. Almost identical results are obtained by the two different architectures.

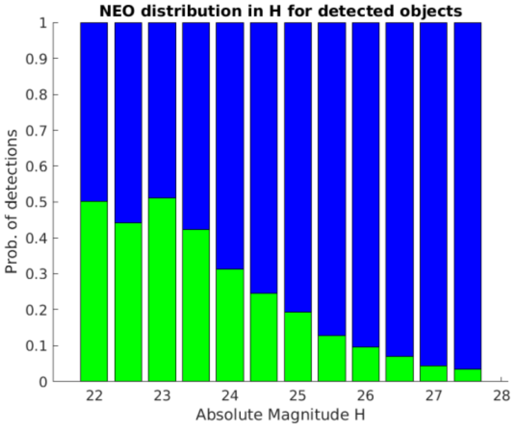

Figure 14. Survey efficiency in detecting observable targets for the overall NEO population.

Fig. 14 shows the efficiency of detecting observable NEOs during the 30 years simulated period. In this case, the y-axis represents the probability to detect an NEO with that absolute magnitude H range: we obtained this by considering the simulation-detected targets compared with those NEOs that had a ephemerides V_{mag} less than the threshold (in this case 21.5). It is predictable that going to higher H values (smaller sizes) the chance of detecting the targets is dimming (shorter visibility time). The reasons why part of the targets are not detected may be multiple, such as the weather statistics, or when the target is not satisfying some observability constraints: too close to the galactic plane, too fast, too close to the Moon, visible for a very limited time of the night at dusk or dawn, or visible magnitude too close to detection threshold, where a stochastic detection approach is introduced in the simulation.

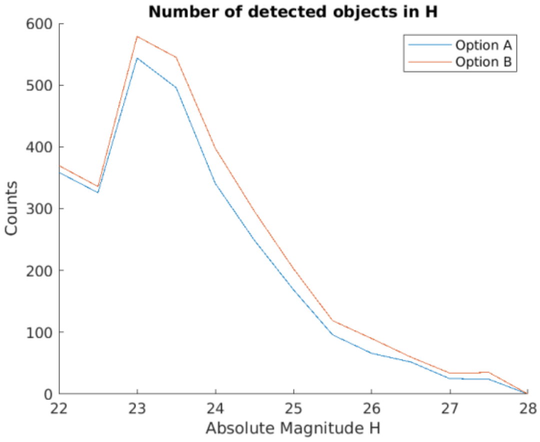

Figure 15. Number of detected objects for each absolute magnitude H.

Fig. 15 shows on the same graph both the performance of the two different architectures. It is clear that Architecture B is generally slightly better. The relative net gain is larger on smaller targets, thus making Architecture B even more attractive. The main reason is due to the wider sky coverage of the latter architecture, achieved by the high number of telescopes (36 instead of 10).

The other important metric is the time to close approach. This is shown in Fig. 16 and 17 for the two different array architectures. . Values less than 0 mean that the NEO has been discovered after close encounter. The colours represent different NEO populations.

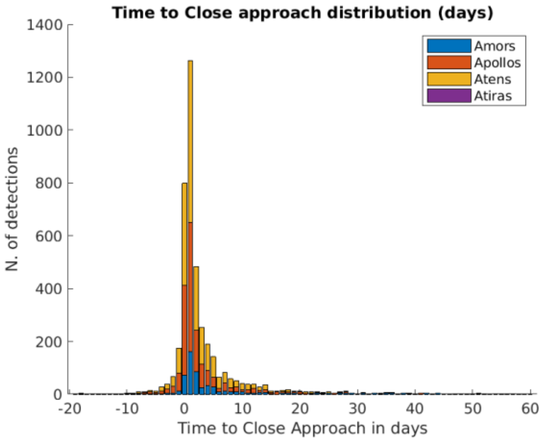

Figure 16. Lead time distribution of discovered NEOs of the simulation for Architecture A.

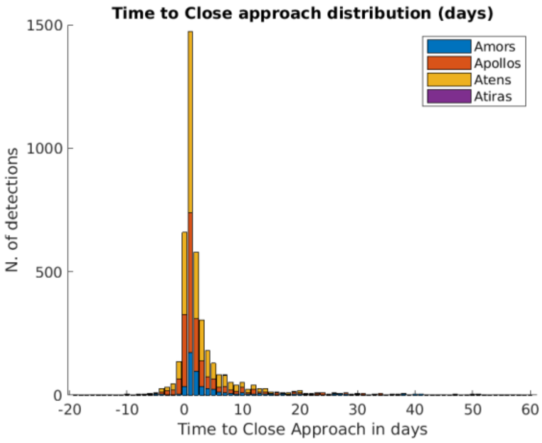

Figure 17. Lead time distribution of discovered NEOs of the simulation for Architecture B.

The lead-time is considered from the first detection time to the nearest close approach time: positive numbers mean that the discovery was performed before the close approach, while negative numbers represent cases when the target has been discovered after the close approach. The colour code represent the different NEO populations: Amors, Apollos, Atens and Atiras. In this case, the peak is at about 1 day of lead-time, which might be not sufficient. Anyhow, the median is at longer lead times (few days), which gives more time for mitigation actions. In other words, 50% or so of the discoveries might have enough time to alert for an imminent impact. This result is not unexpected, because the main driver is the limiting magnitude of this telescope setup. In fact, when we are focusing on objects smaller than H =22, the observability conditions at V=21.5 are reachable only at the very end of the path toward Earth. To improve the lead-time for such a class of targets, bigger (and more expensive) telescopes are needed.

6 PRELIMINARY CONCLUSIONS

The simulations with the two considered options show that both architectures are generally equivalent, but Architecture B is better performing in terms of number of detected objects. In particular, architecture B is better performing at smaller size targets. This is due to the wider sky coverage of this setup.

The weather is obviously influencing the detection capability and the lead-time to close approach. Anyhow, the benefits are not too extreme and we can cope with less performing sites, if it is not possible to access the best astronomical sites.

The choice between the two architectures depends also on other aspects:

- **Complexity:** a higher number of telescopes and cameras, which need to work in parallel, include a certain level of complexity, which may result on a higher level of failures (camera or telescope not working, need of higher number of spare parts…)
- **Scalability:** a larger number of telescopes of the network enables a more scalable system. The project can start with a small number of telescopes, and, later on, scale up the system according to the available budget
- **Cost per unit telescope:** a smaller telescope is more in line with a COTS approach, which may be a bit more difficult for bigger primary mirrors. This implies that smaller telescopes are considerably cheaper
- **Cost per unit cameras:** smaller cameras are generally much cheaper
- **Computational needs:** with more telescopes, the data production increases noticeably and this require a much more demanding computational power.

Considering all previous aspects, Architecture B seems still having more benefits than disadvantages. The fact that is easily scalable is very suitable for the purpose of this project and the budgetary perspectives.