Science Verification Plan

Responsible Editor:

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For discussion - and incorporation into Observatory TDR

Applicable Documents:

MAN-PO/121011 The CTA Observatory

History:

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1.1	2014-07-21	Some refinements
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1.3	2014-08-05	Input from J. Knödlseder

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Contents

1 PURPOSE

This document presents the plan for the verification of the scientific capabilities of CTA as an observatory, in the phase during and shortly after instrument construction. The list of capabilities to verify is inherited from the discussion document [1]. After discussion within the SUG, PHYS, DATA and MC groups the material in this document will be incorporated into the Observatory TDR.

2 OVERVIEW OF VERIFICATION PROCESS

Science verification (SV) is envisaged as an iterative process based primarily on observations of known gamma-ray emitting celestial sources. Science verification observations (SVOs) will begin when at least two telescopes of a given type have been commissioned. All commissioned telescopes will participate in a given SVO. It is anticipated that telescope commissioning will involve collection and analysis of air-shower data, but not the observations of gamma-ray sources. Science verification is part of the process of commissioning the Observatory as a whole, once CTAO elements are commissioned.

SVOs provide data that will be used to test key scientific capabilities of the instrument (see section 3). An annual cycle of repeated observation of the same target objects (see section 4) is planned. Demonstration of satisfactory performance based on SVO data will qualify that part of the array that passes for use in observatory science operations (including the Guest Observer programme). At the stage where SV of parts of the array is still ongoing, SV continues to have higher priority than any science operations, to allow for particular SVOs that require the full array (then comprising already qualified and non-qualified sub-arrays). It is envisaged that the SV processes will uncover technical problems with individual telescopes and other CTA Products that were not identified during commissioning. Such Products will then be returned to the commissioning state.

During times when SVO targets are not visible, other targets, aimed at providing early scientific impact for CTA, rather than towards Observatory commissioning, will take place. Such early science observations will be conducted at the discretion of CTA, until the arrays are sufficiently complete to start the Guest Observer programme. Early science observations will have lower priority than SV observations.

SVOs should continue, at a much reduced level, once the array is complete, to monitor the long term stability of the system.

In general, compliance with CTA level B requirements must be demonstrated during commissioning (as well as at the design stage). Design validation against Level A performance requirements is done using MC simulations. Final compliance demonstration of these high level (gamma-ray) performance requirements is done via SVOs.

The overall approach to early observations and SVOs is described in the Systems Engineering TDR [3].

The SV process requires considerable effort from skilled personnel. Providers of **all** in-kind contributions to the arrays will be expected to commit person-power to the SV process, commensurate with the scale of the contribution. The SV process will be led by CTAO.

3 CAPABILITIES TO BE VERIFIED

Gamma-ray source observations will be used for verification of:

1.1 The full software system, from DAQ to end user (SOFT)
1.2 Scheduling procedures (SCHED)
1.3 Calibration procedures (CALIB)
1.4 Background determination schemes (BACK)
2.1 Gamma-ray point-spread function (PSF)
2.2 Relative flux and spectral determination (SPEC)
2.3 Absolute flux determination (by comparison to other observatories) (ABS)
2.4 Light curve generation and periodicity determination (LC)
2.5 Absolute timing and barycentering (TIME)
2.6 Source localisation (LOC)
2.7 Reconstructing the morphology of extended sources contained with the FoV (EXT)
3.1 Surveying, mapping of regions larger than the field of view (SURVEY)
3.2 Sub-system and sub-array response (SUB)
3.3 Operation and data analysis under moonlight (MOON)
3.4 Operation and data correction/recovery under non-ideal weather conditions (COR)
3.5 Real time analysis and alert generation (RTA)
3.6 Reaction to external alerts (ALERT)
3.7 Divergent pointing / super-wide field of view mode (DIV)

Items 2.* must be verified as function of position in the system field of view (FoV), zenith and azimuth angle and also gamma-ray energy.

Item 2.3 ABS is applicable to the energy range with overlap to existing observatories. The absolute flux measurement in the non-overlapping energy range will be assessed by extrapolations from the overlap region.

Note that several of these items should already have been verified at the individual Product level (for example ACTL verification of scheduling). The SVOs will provide an independent verification of these elements, functioning as part of the full observatory apparatus.

4 VERIFICATION TARGET CLASSES

Five target classes are required to verify the capabilities listed in section 3:

1. **Bright point-like sources**, selected on the basis of flux and the level of confidence in their point-like nature, as well as absence of any know diffuse emission in the immediate vicinity. In practise these criteria point to the selection of variable extragalactic objects and in particular blazars.

2. **Extended sources**, selected to be much larger than the CTA PSF at all energies and as bright as possible. Ideal candidates will have well defined boundaries rather then long tails/halos. An additional criterion would be to avoid objects in which time-variability of some spatial component is known or

Capability		Point Source	Extended	ToO	Pulsed	Empty
1.1	SOFT	✓✓	✓	✓	✓	✓
1.2	SCHED	✓	✓	✓✓	✓	✓
1.3	CALIB	✓	✓✓	✓	✓	✓
1.4	BACK	✓	✓✓	✓	✓	✓
2.1	PSF	✓✓		✓	✓	
2.2	SPEC	✓	✓✓	✓	✓	
2.3	ABS	✓	✓		✓✓	
2.4	LC	✓		✓	✓✓	
2.5	TIME				✓✓	
2.6	LOC	✓✓			✓	
2.7	EXT		✓✓			
3.1	SURVEY		✓✓			
3.2	SUB	✓✓	✓	✓	✓	
3.3	MOON	✓	✓✓	✓	✓	✓
3.4	COR	✓	✓✓	✓	✓	✓
3.5	RTA	✓				
3.6	ALERT			✓✓		
3.7	DIV	✓✓			✓	

Table 1: Mapping of capabilities to be verified to target classes.

likely.

3. **External alerts** or target-of-opportunity (ToO) observations. A ToO programme is described in the Key Science Project documentation, and serves a dual purpose of testing response to alerts and delivering early science.

4. **Pulsed sources**, selected on the basis of flux and with the widest possible energy range for the emission. In practice, the two pulsars detected so far from the ground represent the only suitable targets.

5. **Empty fields**, selected to avoid known or candidate sources and likely regions of diffuse emission.

An additional criterion for the selection of targets in all classes is observability from both hemispheres, or, if this is not possible, the presence of two suitable objects with appropriate declinations. Finally, sources should be selected with a spread of Right Ascensions to allow observations throughout the year at the sites in both hemispheres.

In all cases above, charged cosmic rays (CRs), as well as photons, can be used in the SVO process. CR electrons form part of the calibration process and protons and nuclei can be used to verify spectral reconstruction to 300 TeV (something that is not possible with known gamma-ray sources).

Table 1 provides the mapping between capabilities to be verified and target classes. In section 5 below we provide a baseline list of specific targets.

Object	**N/S**	**RA**	**Dec.**	**Notes**
		Pulsed		
Crab Pulsar	Both	5h34m	+22.0	Very bright, wide energy range
Vela Pulsar	S	8h35m	-45.3	Steady and bright low-E source
		Point source		
Mrk 421	N	11h04m	+38.2	Very bright, wide energy range
1ES 1959+650	N	19h59m	+65.0	Bight, wide energy range
PKS 2155-304	S	21h58m	-30.2	Brightest in south
PG 1553+113	Both	15h55m	11.1	Brightest accessible N+S
		Extended		
Vela Region	S	8h35m	-45.3	Bright, extended, dual purpose
RX J1713.7-3946	S	17h13m	-39.7	Brightest ext. source in south
MGRO J1908+06	Both	19h08m	+6.2	Brightest ext. source accessible N+S
Boomerang	N	22h28m	+61.1	Brightest ext. source in north
VER J2019+407	N	20h19m	+40.7	Very extended, bright northern source
		Empty		
Empty 1	Both	~1h	~0	Accessible N+S, RA slot free
Empty 2	Both	~9h	~0	Accessible N+S, RA slot free

Table 2: Baseline choice of objects for science verification observations with CTA. Those in italics represent possible alternatives (or additions).

5 SPECIFIC OBJECTS

Table 2 makes specific proposals for target objects in each class.

For most of these sources, highly statistically significant detections will be possible with the partial complete CTA in only a few hours. Longer observations are necessary to subdivide the data into a wide range of different pointing directions and environmental conditions and still have a significant signal in all subsets.

The motivation to share empty fields in the north and south, and to repeatedly observe the same fields, is that weak new sources will inevitably appear eventually, and these observations also constitute scientifically useful deep fields.

6 OBSERVING STRATEGY

Scheduling should be performed using the tools developed for this purpose, with additional constraints where necessary. Various observation modes will be required (wobble, mini-survey, divergent), with wobble mode as default, with four offset positions. The offset distance will need to be optimised after early background measurements, but 0.9° is considered to be a reasonable default.

Data should be taken in marginal as well as clearly acceptable conditions. Sources should be followed from culmination to 30° elevation. Point-source observations should be synchronised between hemispheres if possible. For the point-source, pulsed and extended cases, a range of offsets should be used, from 0 to 5° for bright sources.

It is anticipated that SVOs will take up roughly half of the available observation time in the middle of the construction phase, reducing to a few % of the time post array completion.

7 DATA ANALYSIS

The following data analysis steps are required:

1. Application of low level calibration procedures, see [4]. Where appropriate, alternative calibration algorithms/approaches should be compared to test stability.
2. Production of key parameter distribution plots for each telescope, as a check of commissioning. The parameters to be compared (to simulations and to other telescopes) include Hillas parameters (image moments) up to 2^{nd} order.
3. Coincidence rates should be compared to expectations from Monte-Carlo (MC) simulations, and also participation rates for individual telescopes.
4. Shower analysis / event reconstruction should be performed for all subsystems independently and different reconstruction algorithms (including those used for pipelines A, B and C) compared. Subsystem cross calibration should be performed/applied.
5. Background modelling for all subsystems independently. Wherever possible three indepentant background estimates should be made, based on the *reflected*, *ring* and *template* approaches [5]. Measured source significance values should be compared to expectations. Significance distributions should be made for empty fields.
6. Atmospheric corrections should be applied and the cosmic ray electron spectrum derived and comparison to previous (i.e. archive and CTA reference) observations.
7. The spectra and morphology of sources in the FoV should be derived for each subsystem independently. Comparison to MC simulations should be made for point-like sources, and comparisons to measurements from other observatories made where appropriate (given the much improved sensitivity of CTA).
8. Barycentering should be performed and phasograms (phase-folded light-curves) generated for pulsed sources. Peak positions in phaseograms should be monitored as a function of time to test system timing stability.
9. Steps 5 to 8 should be repeated at the full system level.

The Data pipelines section of the CTA Data Project TDR provides details of the procedures to be followed.

8 ACCEPTANCE CRITERIA AND PROCEDURES

Two main criteria must be met for a sub-array to be qualified for observatory science:

1. Performance requirements are all satisfied.
2. The system can be modelled at the required level.

Only once these criteria are met can response matrices be generated for a set of telescopes and data from the sun-array used to perform science analysis with the required sensitivity and precision.

These two criteria are discussed in turn below.

We note that a two stage SV process may be appropriate, with readiness for point-like source observations in a more limited energy range preceeding full readiness.

8.1 Performance requirements

Compliance with scaled point-source sensitivity requirements will be tested using the measured collection area and background rate from SVOs of point-like sources. The scaling reflects the partially complete nature of the system or sub-system and the scaling factors will be derived using MC simulations. Compliance with angular resolution requirements will be tested in a similar way.

8.2 Systematic uncertainties

The analysis steps described above will result in a certain level of disagreement in reconstructed quantities between data and simulations, and between different data sets. The level of disagreement that is acceptable is discussed here, with reference to the CTA requirements [6].

The acceptable systematic errors on the absolute level of reconstructed flux are given in A-PERF-0260, A-PERF-0380 and A-PERF-0410. The requirements apply to variations in reconstructed flux of a known steady source (i.e. an extended source) in time, after all corrections, as well as comparisons of the averaged datasets to other instruments. These requirements apply to favourable weather conditions (class A). In class B weather conditions (high levels of aerosols, partial cloud cover), a factor two larger uncertainties can be accepted, post-correction.

For the gamma-ray PSF, the acceptable level of disagreement with MC simulations is 8% in the 50% and 80% containment radii and 12% in the 90% containment radius, for all energies at which sensitivity is required.

For low-level parameter distributions the same percentages apply, noting that these values may be adapted in specific cases based on pre-(mass)-production telescope data.

8.3 Acceptance Procedure

At least once per year available SVO data will be processessed by the SV team and a *Science Readiness Assessment* document produced including:

- summary of all tests of invidual telescopes including a statement on which telescopes must be recommissioned, and which are included in the further assessment.
- summary of sub-system level tests and evidence of qualification of individual sub-systems.
- summary of system level tests and evidence of qualification of the system.

Where sub-systems or the full system are judged not to have reached science readiness, a recommendation should be made in the assessment document on what action should be taken. Actions may include:

- hardware changes
- recharacterisation of elements
- calibration and reconstruction pipeline changes
- simulation updates/refinements

These recommendations and the whole Science Readiness Assessment document will be put forward to the observatory technical committee and actions will be agreed upon there.

Once hardware and procedural changes are no longer deemed necessary, these aspects will be frozen, to allow the collection of a coherent set of SV data and acceptance to take place. Post-acceptance all proposed hardware and procedural changes must be reviewed and approved by the technical committee.

An individual telescope can re-enter the SV process once re-commissioning has taken place.

REFERENCES

[1] **MAN-PO/221213** On Key Science Projects and the Science Verification Phase

[2] **MAN-PO/120130** Preliminary Technical Design Report

[3] **MAN-PO/XXXXXX** CTA Systems Engineering Technical Design Report

[4] **MAN-PO/XXXXXX** Central Calibration Facilities and Procedures TDR

[5] **A&A 466, 1219 (2007)** Background Modelling in VHE gamma-ray Astronomy

[6] CTA Requirements Database