VISTA
OPERATIONAL CONCEPT DEFINITION DOCUMENT
VIS-SPE-VSC-00000-0002
v1.0

APPROVAL STATUS:
Under Change Control

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Written by	Signature	Date
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Contents

0 Change Procedure & History

0.1 Change Authorisation Procedure

The procedure for changes in this document is as follows: requests for change should initially be sent to the Project Scientist (PS), who will discuss the request with the originator and the Project Manager (PM).

If the originator, PS and PM can reach a mutually agreed form for the change, approval will be sought from the Principal Investigator, the VSC Chairman and the VEB Chairman. Subject to this approval the change will be implemented, and recorded in the change history below.

If the PS and PM are agreed that the proposed change is unnecessary or undesirable, it will be rejected, and this decision communicated to the originator and the Chairs of VSC and VEB.

In the unlikely event that the PS and PM are unable to reach agreement between themselves after discussion with the PI, their respective proposals will be put to the VEB for a decision.

0.2 Approved Changes - Most recent first

None at present so the present Table is merely a placeholder.

Change #	*version - running number - e.g. v2.0-1*
Location	*i.e. page/section/paragraph/line of part affected*
Originator	*i.e. his/her name and, in brackets, position/role*
Change	*i.e. a full description of the change, continued on as many subsequent lines as necessary*
Reason	*i.e. full reason for the change, continued on as many subsequent lines as necessary*
Approved by	*VEB Chairman or PI on day/month/year*

1 Introduction

This document is intended to provide a summary of how VISTA (Visible and Infrared Survey Telescope for Astronomy) will be operated to provide the required scientific data. It is **not** intended to provide top-level science specifications; those are contained in the Science Requirements Document (hereafter SRD). Rather, it is intended to provide an overview of the typical pattern of operations on various timescales from minutes to years, as an aid to the designers for optimising practical details such as camera changes, filter changes, slewing, guide star acquisition, detector readouts, dither patterns, calibration data, data storage, etc. (Commissioning procedures are not dealt with here, though will probably share some features of science & calibration data-taking).

In the event of any conflict arising, the SRD takes precedence.

Section 2 provides a brief description of the anticipated components of the system, specifying those assumptions which are necessary to detail the operations in later sections. Section 3 describes the operations on long timescales, including queueing of observations, camera changes, etc. Section 4 describes a "typical" day & night for each of the visible and IR cameras; some typical observing procedures used here are placed in § 5. Section 6 gives an overview of procedures for acquiring calibration data. Section 7 specifies the parameters of the Design Reference Programmes, which are to be used in evaluating the 'Survey Speed' figure-of-merit described in the SRD. Appendix A describes the outline concepts for the focal planes, filter wheels, guiders and controllers, which are currently less clearly defined.

2 Telescope Design (Assumptions)

This section provides an overview of the current design assumptions for the telescope enclosure, optics, baffles and instrument layout, in order to specify the assumptions necessary in the operational scenarios in following Sections.

Since at the time of writing (Mar 2001) the design of the two cameras has not yet been developed to the same level of detail as the telescope, only a short summary of relevant assumptions is provided here in § 2.6, with more details of some possibilities given in Appendix A.

References to relevant numerical specifications in the Science Requirements Document are given for convenience only, and are not an exhaustive list – of course, SRD Requirements & Goals not specifically cited here (e.g. because they affect mainly the 'overall system' rather than one specific item) also apply. In the event of any conflict arising, the SRD takes precedence.

The following Table gives approximate values for the main system parameters.

Table 1: **VISTA: baseline system parameters**

Primary mirror diameter	4 metres
Entrance pupil diameter	3.7 metres
Camera changeover time	$\leq$ 12 hours (Goal: 30 min)
System focal length	12.072 metres
Visible camera	
Wavelength range	0.33 (0.35 ?) — 1.05 μm
FoV (available)	2.13^o diameter
FoV (detectors)	1.6^o $\times$ 1.4^o
Detectors	5 $\times$ 10 mosaic of 2048$\times$4608 Marconi/EEV 42-90
Pixel scale	0.232 arcsec / 13.5 μm
System image quality	$\leq$ 0.4 arcsec at B-z' bands. (Goal: 0.3$''$ in r').
Readouts	1 per detector
Filters (mounted)	$\geq$ 10 (Goal: 20)
Infrared camera	
Wavelength range	1.1 — 2.3 μm (Goals: 0.95 - 2.45 μm)
FoV (available)	1.2^o diameter (Goal: 1.65^o)
FoV (detectors)	1^o $\times$ 1^o after 4 pointings
Detectors	3 $\times$ 3 mosaic of 2048 $\times$ 2048 Rockwell Hawaii-2
Pixel scale (IR)	0.307$''$ / 18 μm
System image quality	$\leq$ 0.5 arcsec (Goal: 0.4 arcsec).
Readouts	4 (32?) per detector
Filters (mounted)	$\geq$ 6 (Goal: 8)

2.1 Enclosure

The purpose is twofold: while the telescope is not observing, the enclosure must protect the telescope from high wind, rain/snow and heating by direct sunlight; while observing, the enclosure should (if necessary) reduce the effect of windshake on the telescope structure & optics, while giving smooth airflow to not degrade the seeing, and not obstructing the telescope's view of the target field. (Also, the enclosure's aperture should be wide enough that thermal emission from the dome does not directly reach the IR detectors when observing at K_s passband.) A fully-retractable enclosure may be considered; if so, careful consideration of windshake and scattered sky light/moonlight (especially in visible bands) will be necessary.

The enclosure will contain lifting mechanisms for mounting/unmounting instruments on/off the telescope, and access platform(s) for accessing electronics boxes etc. on the telescope and instruments. While the enclosure is closed, it must at least allow sufficient telescope motion & space to install, uninstall, and perform maintenance on the instruments, and to perform any necessary calibrations (e.g. dome flats). It must provide an opening for the primary mirror to be taken out to the coating plant. It should contain an uninterruptable power supply for the detector & telescope control systems (i.e. a power failure may stop the telescope drives, but should not require a full restart of the control systems). It must contain a tunnel or similar route for waste heat to be vented (e.g. downwind) such that it does not degrade the seeing for VISTA or any other nearby telescopes during normal weather patterns.

Desirable features include: light-tightness for ability to turn lights on at night without affecting nearby telescopes (and for taking dome-flat and dark calibration exposures during daytime); low vibrations so that dome rotation does not shake the telescope during tracking of science exposures (and/or a wide slit so that the dome does not need to be rotated as the telescope tracks the sky during a typical science exposure); and avoidance of oil or water drips onto the telescope during opening/closing of the slit.

2.2 Telescope Structure

The purpose of the telescope structure is to allow the optics (primary + secondary mirrors, corrector lenses, baffles, cameras) to be pointed at any desired area of sky within the accessible area (**SRD R 4.5.2/8, G 4.5.2/9**), and then to track sidereal (or nearly sidereal) motion of the target field, while maintaining the optics accurately at the correct relative positions, and compensating for their distortions under gravity to maintain image quality requirements (**SRD § 4.4.1, § 4.4.2**).

An altazimuth mount will be used; this gives a greatly reduced mass of the telescope, pier and enclosure, at the cost of needing to drive 3 axes (i.e. including field rotation) instead of 2 to track the sky.

It is likely that a relatively thin primary mirror (a meniscus $\approx$ 180mm thick) will be used to reduce mass, with a closed-loop active support system to maintain its shape to the required accuracy as the telescope elevation changes.

2.3 Telescope Optics

The telescope optics will consist of a concave primary mirror of ≈ 4m diameter and ≈ $f/1$ focal ratio, and a convex secondary of ≈ 1.25m diameter delivering a final beam of ≈ $f/3.1$ to a Cassegrain focus located ≈ 1.2m behind the pole of the primary. Both visible & IR instruments will use the same on-axis focal station, hence only **one instrument** will be mounted at any given time (see Figure 1). The conic constants are of 'quasi-Ritchey-Chretien' type, but the M1/M2 pair alone contain substantial spherical aberration (compensated by the corrector lenses); this must be taken into account in defining initial alignment procedures.

The mirrors will be coated with aluminium or silver. If silver coating is available, it will probably be the **'default'** coating, used for $\gtrsim 2/3$ of the total time for optimal performance in the red and IR bands. It may ideally be desirable to change between silver and aluminium coating on a cycle (e.g. a 4-year cycle with silver for 3 years followed by aluminium for 1 year) for optimisation of IR and blue/UV passbands respectively; as dictated by cost and science priorities.

Both for optimisation of K_s performance and to maximise the interval between re-coating of the optics, it is highly desirable to reduce dust accumulation on the primary mirror: therefore a cover system may be implemented and closed when the telescope is idle, and periodic CO_2 cleaning should be considered.

2.4 Baffles (Assumptions)

Baffles are essential to prevent stray light (e.g. direct-path radiation from off-axis sky, or moonlight scattered off the telescope structure, dome floor etc) from reaching the detectors (**SRD R 5.2/2**); while not significantly vignetting the light from the science field. In the K_s band, ambient-temperature surfaces are 'luminous' therefore additional considerations (e.g. cold baffles and/or reflective baffles, or a cold stop) are essential to meet **SRD R 5.2/3**.

Different baffling systems for visible & IR operations will be required, due to the different fields of view in addition to the K_s considerations above (though the secondary baffle may be common, see below).

The development of the baffle designs is still ongoing, so some details of § 2.4.1 and § 2.4.2 will change.

2.4.1 IR Cold Baffle layout

The baseline design uses a direct-imaging IR camera with a set of **cold baffles**. All IR passbands (J,H,K_s and others) share a common path, so the camera optics are fixed. In this design, the IR camera has a long cryostat, with a large front window ≈ 900mm in diameter located ≈ 2.3m above the focal plane. A series of annular baffles are located within the cryostat to absorb the thermal radiation entering the window from off-axis sky and from

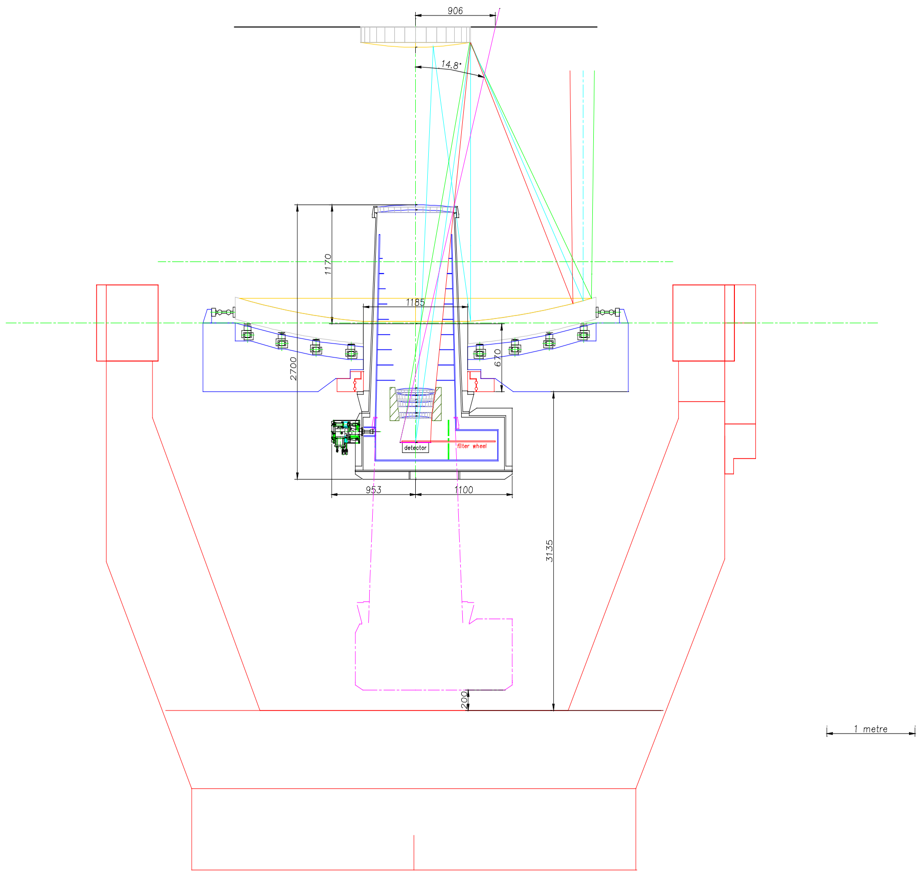

Figure 1: The approximate layout of the VISTA optics, with cold-baffled IR camera, in the 'post-DVR' f/1 design. Baffles are schematic not optimised: a warm reflective baffle will be added around the secondary. The closed cycle cooler and filter wheel are shown, respectively left and right of the focal plane. Dashed outline shows the path for unmounting the camera.

the dome. In the baseline design these baffles are black to optimise rejection of scattered light. Ideally they would be reflective at wavelengths $\gtrsim 3\mu$m to minimise thermal load on the cryostat and cooling of the window.

The uppermost cold baffle (near the window) subtends a half-angle $\approx 10.8^o$ as seen from the centre of the focal plane, compared to the half-angle $\approx 9.2^o$ subtended by the secondary. Therefore the central pixel of the focal plane sees an "annulus" between the front baffle and the secondary, while the corner pixels see "crescents" due to the relative parallax between the front baffle and the secondary. These crescents contribute extra 'unfocussed' background at the detector, so the long cryostat is necessary to minimise their solid angle. If these crescents consist of unimaged sky, there will be smooth but airmass-dependent variations in the intensity of un-imaged OH lines across the detector: this would be undesirable for flat-fielding reasons, so a **concave reflective baffle** around the secondary will be used.

This reflective baffle will have outer diameter ≈ 1.6m (to block all direct rays from detector to sky), and radius of curvature ≈ 2.8m so that the detector 'sees' the rear of the cryostat reflected in the baffle. The baffle must have high reflectivity, especially in the K_s band (e.g. gold coating) and good surface polish to minimise scattering, but its optical figure accuracy is relatively unimportant. It should have a reasonably small thermal time constant so it quickly reaches thermal equilibrium with the air.

(This reflective baffle also serves to block extraneous direct-path sky when operating at J,H bands; if the secondary were un-baffled at K_s, a *deployable* black baffle for use at J/H bands would be required instead).

It may be advantageous to slightly under-size the front cold baffle relative to the baseline unvignetted case; this gives modest vignetting at the corners of the focal plane but will significantly reduce the solid angle of reflective baffle seen from each point in the focal plane; hence increasing efficiency at K_s band. (E.g., undersizing the baffle by 6% gives $\approx 3\%$ vignetting in the corners, but reduces the solid angle of reflective baffle seen from the focal plane from 0.38 to 0.23 $\times$ the solid angle of the secondary.) This can be optimised at a later date without affecting subsequent sections.

Note: If different baffling schemes were needed for K_s as opposed to J,H bands, then it should be possible to switch between these schemes fairly quickly, though not necessarily every time the telescope is repointed (since the observing sequence can be adjusted to reduce these switches). To ensure that each field can be observed in each of J, H and K_s within well under 1 night, it must be feasible to switch baffles (either way) at least 6 times per night (e.g 1 hour J and/or H, then 1 hour K_s on first set of N fields; 1 hour K_s on second set of fields, followed by 1 hour J and/or H; etc). At 6 changes per 600-minute night, requiring less than 3% dead-time implies ≤ 3 minutes per change, and reducing this to ≤ 1 minute would be highly desirable. [Movable baffles are not essential in the baseline design, though they may be an option if it is chosen to vignette at K_s (as above) while not vignetting at J,H.] .

2.4.2 Baffles: Visible Camera

The baseline concept for baffling the visible camera is to leave the secondary reflective baffle in place, and in addition use a conical black baffle extending upwards from the primary, to be mounted whenever the visible camera is in use.

Given the 1.6m outer diameter of the secondary baffle (which is set by the IR design above), the visible baffle can extend sufficiently far above the primary to block all direct-path rays from the sky to the focal plane, with minimal additional vignetting.

Assuming that the secondary baffle is reflective at visible wavelengths as well as IR, careful consideration is necessary of possible multiple reflections (e.g. from off axis sources notably the Moon – see § 3.7 for details). If this proves a problem it would be possible to replace (or cover) the reflective baffle by a black one of equal dimensions, concurrently with the change from IR to visible camera.

Note: *This will be known when detailed visible-camera design has been completed.*

2.5 Correctors

In order to minimise optical aberrations over the wide field of view desired by VISTA, corrector lenses are clearly essential. Separate visible and IR correctors will be used, with AR coatings to optimise transmission at the relevant wavelengths. These will have maximum diameter of ≈ 800mm (visible) and 600mm (IR), and consist of around 5 elements (visible) and 3 elements (IR).
(Note: If the IR camera uses visible CCDs for guiding/wavefront sensing, the visible transmission of the IR corrector must not be too low, e.g. it should be $\gtrsim 50\%$).

The corrector mountings must maintain them aligned with the telescope optical axis to high precision as the telescope moves and/or the temperature changes, but they are otherwise static (except for the visible ADC, see Appendix A below).

Assuming the cold-baffle design, the IR corrector lenses will be inside the cryostat, therefore care will be needed to allow for thermal expansion effects on their mountings.

2.6 Cameras (Assumptions)

The details of the visible and infrared cameras remain to be finalised: here we summarise the main assumptions necessary for specifing operational details in later Sections. Additional considerations are outlined in Appendix A.

1. Separately mounted cameras.
2. Each camera has its own guiding and wavefront sensor(s).
3. Visible camera has an atmospheric dispersion compensator. (Not necessary in IR camera).

4. Visible camera: sweeping shutter, guide sensors possibly behind shutter.
5. Visible camera: assumed that filters can be changed in filter wheel/cartridge while camera remains mounted on telescope.
6. Visible focal plane: science arrays occupy 64% by area of circular field of diameter 444mm = 2.12 degrees.
7. IR corrector lenses inside cryostat.
8. IR camera filter wheel: 8 positions (7 filters + dark), located close to focal plane. Note that **SRD R 4.3.2/5** requires ≥ 6 + dark; see § 3.8 for notes on frequency of changing contents of the filter wheel.
9. IR focal plane: sized to accommodate 4×4 Hawaii-2 arrays on square grid at '90% spacing', i.e. centre-to-centre spacing is $1.9\times$ active detector width. Field diameter (diagonal of square enclosing all live pixels) is then 349mm = 1.67 degrees.
   SRD 6.3/2 requires 3×3 arrays; operational scenarios later do not change substantially with number of arrays.

2.7 Controllers (Assumptions)

Some relevant parameters as a guideline for specifying the detector controllers are:

1. Visible: mean interval between readouts typically ~ 5 mins (see § 7 for details for each DRP).
2. Visible: Minimising readout speed is very important; readout noise relatively unimportant.
3. Visible: Option to do 2×2 on-chip binning is highly desirable.
4. IR: arrays reset & read-out every ~ 10 sec.
5. IR: option to co-add multiple readouts in real-time before saving to permanent storage is highly desirable. However, it is highly desirable that the data acquisition system should be able to cope with saving each readout separately, to test for detector anomalies.
6. IR: ability to reset and read 'line by line' to perform multiple exposures with only one readout 'overhead' is highly desirable (see § A.2.6) .
7. IR: consideration required on minimising 'remnants' from bright objects – affects choice of detectors e.g. MBE preferred over PACE.
8. IR: typical interval between dither movements (hence length of a co-add sequence) ~ 1 minute ; (see § 7 for details for each DRP) .

2.8 Data Acquisition System

The data acquisition system should read out the data onto disk in standard format, probably FITS or whatever has replaced it as the world standard by then. For ease of operation of the automated reduction pipeline, and to ensure an "audit trail" of where every datafile has come from, it is **essential** that the FITS headers should contain all necessary information for automated archiving and processing of the data; including (but not limited to) the following:

1. A label indicating VISTA as source of the data.
2. A label for the instrument (visible or IR camera).
3. Observatory latitude and longitude.
4. A flag (TBD) indicating proprietary data rights if any.
5. Whether it is science, calibration or engineering data.
6. A unique identification string (defined by the appropriate Observing Programme Committee) for the science programme.
7. A scientist-defined identifying string for the field.
8. An 'externally-defined' identifying string: this should be a grid number if the field is centred on a standard grid, or a CDS-resolvable name if targeted on a named object (e.g. an NGC object etc).
9. Type of data: e.g. test, bias, dark, dome flat, sky flat, standard field, science field etc.
10. Identifiers for filter(s) in the beam. This should comprise (a) a keyword for the photometric system (Johnson,SDSS,etc); (b) letter(s) for the filter within the system; (c) a unique number for the physical filter; and (d) the location of the filter within the wheel/cartridge.
11. The local calendar date at the "beginning" of that night (i.e. unique flag for each distinct night). The local date at the previous 12:00 noon would be good; UT date at previous sunset is not suitable, because it may be non-unique given seasonal changes.
12. The nightly run number.
13. A unique run number, strictly increasing with time.
14. UTs of start, end, mid-exposure.
15. Length of exposure (requested and measured shutter-open time on a given pixel).
16. RA, Dec and equinox of nominal field centre.
17. RA, Dec etc of telescope pointing.
18. Offsets from 'central' dither position, in arcsec in both RA, Dec and camera x, y axes.

19. Non-sidereal tracking rate (if any).
20. A keyword to group together multiple runs at a set of dither positions.
21. Cassegrain rotator angle - both relative to telescope and sky, at start, middle and end of exposure.
22. Zenith distance, azimuth and hour angle of field centre at start, middle & end of exposure.
23. Lunar phase and angular distance of Moon from telescope axis.
24. Guide star(s) information - RA, Dec and pixel coords on guide chip.
25. Guider information - seeing and rms centroid errors (averaged over exposure) on each axis.
26. Temperatures of telescope tube, mirrors, air inside & outside dome.
27. Temperatures of instrument & detectors.
28. Weather info: wind speed & direction, barometric pressure, humidity.
29. The seeing measurement from the Paranal site monitor, concurrent with the exposure.
30. Versions of telescope software, controller software etc. This may be a single keyword which points to a database entry updated at each software update.
31. CCD readout info: speed, binning etc.
32. For each individual detector there should also be the following: (it is assumed that if there are multiple readouts per detector, these will be stitched together into a single raster by the DAS).
    - A sub-header so that each detector can have its own World Coordinate System.
    - Physical detector number (in case detectors fail and are replaced), number of pixels, overscans, etc...
    - Logical detector number (position in focal plane).

<u>Reminder:</u> This section consisted of assumptions needed for subsequent sections of this OCDD, and does not mention all or supersede any of the Requirements and Goals in the SRD.

3 Operations and Scheduling

This section provides an overview of the observing time on long timescales, in terms of operator requirements, long-term scheduling, camera changes, etc.

3.1 Lifetime

The lifetime of the VISTA telescope is expected to be at least 15 years. Therefore the systems will be designed to last at least this time without major upgrade. A major overhaul of any system should not be necessary before 10 years from the start of the operation. No additional instruments are expected or planned, with the exception of possibly adding or upgrading detectors in the focal plane(s) of either or both cameras.

3.2 Observing Mode

VISTA is designed to be simple, and thus to minimise operational costs. Therefore, it is intended that there will only be a single observing mode: **queue-scheduled observing**. Traditional 'visiting observer' or 'fully remote' operations will not be available, except in the following special cases:

a) For scheduled programmes which require real-time data processing (e.g. supernovae, Kuiper belt objects, etc), suitably authorised scientists should be able to perform real-time processing on the incoming datastream, e.g. at Paranal, or (if a fast link is available) at an appropriate data centre. (Details in **SRD R 7.7/1**) These scientists may be expected to provide their own software and travel funding, and will not control the detailed telescope observing schedule – though the time window (during which their observations will be attempted) will be known in advance.

b) Any other exceptional circumstances which will require prior approval by VEB and ESO, and availability of any necessary additional funds.

Briefly, a large set of desired observations (e.g. 3 months' worth) will be entered into a queue using ESO tools. Each desired observation will include information such as telescope pointing, exposure time, filter, absolute timing, ranges of allowable seeing, airmass & sky brightness, priority etc – see § 3.6 below. (After the observations have been entered in the queue, these priorities should be adjustable by an external science panel, e.g. to speed up completion of certain projects if necessary). In Garching, a "Medium Term Schedule" (MTS) consisting of a few weeks' worth of observations will be selected. This is then sent to Paranal, where each day a "Short Term Schedule" (STS) is selected from the MTS consisting of sufficient observations for the following night, plus an excess. The STS should take account of the prevailing weather, lunar phase & seeing conditions at the time, and should be sufficiently flexible to permit changes if the conditions change during a night. The telescope pointing, tracking, guiding, offsetting, filter selection, exposure and data inspection must all be controllable from the VISTA console in the Paranal Observatory central control room. The actual commands at the console to move the telescope etc will be issued by a dedicated VISTA telescope operator. It is expected that only a single operator will be present on a typical night.

(If camera changes during a night are possible, these will be relatively infrequent, will be scheduled in advance and may require additional staff. 'Flexible' camera changes may be accommodated by scheduling 'optional' camera changes and then cancelling them if desired, but ad-hoc requests for a night-time change will not be allowed under the anticipated running cost model.)

3.3 Overrides

There is one "exception" to the above queue mode, the case of override observations: these are defined as observations which are both time-critical and occur unpredictably with very short notice, e.g. gamma-ray bursts, near-earth asteroid alerts etc. The SRD contains a Requirement (**SRD R 7.3/3**) that these can be acted upon within 60 minutes, (Goal: 10 minutes), where the time is measured between the approved alert reaching Garching, and the shutter opening). They are expected to take a fairly small fraction of VISTA observing time, perhaps in the region of 1 hour on one night per month. It is anticipated that these overrides may be accommodated by an authorised scientist telephoning the appropriate person in charge, quoting an appropriate password and giving the override request to be forwarded to Paranal. The operator at Paranal can then either manually override the queue, or insert the override observation(s) into the 'queue' at the highest possible priority.

Nighttime camera changes will **not** be expected in response to an override. **If** unscheduled next-day camera changes are available, and a very strong science case can be made, these may be permissible, but for 'standard' overrides this is unlikely to be the case, (for operational cost and scheduling reasons).

3.4 Camera Change Schedules

As specified in § 2, only one camera will actually be mounted on the telescope at any given time, and thus simultaneous visible & IR observations will not be possible using VISTA alone.

The large majority of camera changes will take place in daytime. It is scientifically desirable to retain the option of attended night-time camera changes. It is appreciated that as these will imply an extra operations cost, such changes could only be implemented occasionally.

It is anticipated that to minimise disturbance to the focal planes, both visible and IR cameras will be permanently kept at close to operating temperature even when not mounted on the telescope (except when occasional maintenance is performed on the camera not in use).

The breakdown of usage is expected to be roughly **70% for the IR camera and 30% for the visible camera** (though this is somewhat preliminary, it is almost certain that the IR fraction will be between 60% and 80%). The visible fraction quite nicely (and fortuitously) matches the fraction of 'dark' time, defined as within roughly ±5 days of a

New Moon. Obviously, visible observations especially in the blue are severely compromised by moonlight scattered in the atmosphere, while IR observations are almost unaffected by the Moon. Therefore, the **"default" mode of operations** will probably be to change cameras **twice per month**: from the IR to the visible camera around New Moon – 5 days, and from the visible to the IR camera around New Moon + 5 days. These camera changes should take place in daytime to avoid loss of observing time, and can be scheduled well in advance. The timings of camera changes relative to New Moon can usually be adjusted by ± 1 or 2 days to allow for holidays or similar logistic constraints. [If the fraction of visible time is significantly below 30%, a cost-saving alternative might be to use the visible camera for 12–14 days every second New Moon.]

(Rarely, it might be desirable for monitoring purposes to schedule "flexibly timed" camera changes, e.g. specify a period of ~ 3 days during which exactly one camera change will be made, with the precise day to be specified ~ 12 hours in advance. This may be the case e.g. to get a 'second bite' at time-critical observations which had been clouded out.)

However, there are some time-dependent observations e.g. monitoring projects for which the simple "two change per month" strategy is not appropriate. Most monitoring projects require the visible camera (due to the larger field and greater sensitivity for objects of 'normal' colour), and for monitoring on timescales of weeks/months it is unacceptable to be limited to a 10 out of 29 day duty cycle.

Also, many projects require multicolour visible and IR coverage of the same fields. For this purpose it is desirable to minimise the time-lag between observing the field in different filters, otherwise variable objects get erroneous colours. The fraction of variables is small, so this is a minor problem for statistical projects; but it may be a more severe problem for selecting very rare objects (e.g. high redshift quasars) by colour, since the variables (if of large amplitude) may outnumber the genuine rare objects.

However, it is impractical to demand that most or all fields are observed with both cameras (visible & IR) within a single night, since this can only be done in dark/grey time. Therefore, for most fields there will be unavoidable time delays of $\gtrsim 1$ week between optical & IR observations. An alternative way to minimise contamination of unusual-colour samples may be to observe each field in e.g. 5 visible filters on a single dark night, then observe it in 3 IR filters at a different time, and repeat *one* visible passband (e.g. r' or i') as close as possible in time to the IR observations. Objects showing significant variation between the two r' images can then be discarded from the colour-selected sample. (Another possibility is to use a filter in the IR camera approximating the visible z' passband; though depending on the QE of the IR detectors this may be inefficient.)

Thus, it is likely that for some moderate fraction (perhaps 10%) of the total time, it might be desirable to exchange cameras more frequently than twice per month. Assuming (as appears likely with the on-axis instrument design) that camera changes within a night are allowed only rarely, a cycle e.g. (1 night visible, 2 nights IR) might be adopted for perhaps a 6-month baseline.

Also, rather than scheduling numerous camera changes as above, it may well be more suitable to arrange corresponding observations with the nearby "VLT Survey Telescope" (VST), for the subset of VISTA science programmes requiring either visible observations at times when VISTA has the IR camera mounted, or near-simultaneous visible-IR coverage. It is anticipated that VST will have a single instrument (the visible camera OmegaCam) in full-time use for its first 5 years of operations, so this appears a natural possibility without requiring VST instrument changes. While the VST's collecting area and visible field of view are significantly smaller than VISTA, in principle it can collect suitable data to satisfy the majority of VISTA's time-variability projects given sufficient observing time. (Among the exceptions would be high-z supernovae and the Kuiper belt, for which the depth/time ratio of VISTA are required; but these two programmes can both be scheduled satisfactorily within VISTA's dark time).

If not enough VST time is available to satisfy all of the above, it may well be worth scheduling longer periods when VISTA has the visible camera mounted continuously, e.g. for 1 or 2 continuous periods of 6 months each: these periods to be dedicated predominantly to monitoring projects such as exoplanets, microlensing, QSO variability etc. This means it is highly desirable that the visible camera should be able to run continuously on the telescope for 6 months without substantial maintenance.

3.5 Checks following a Camera Change

SRD R 4.3.3/1 specifies that it must be possible to change cameras between the end of one observing night and the start of the next.

It is recognised that immediately following a camera change, it may also be necessary to consume some **nighttime** observing time: both for instrument alignment to reach optimum performance, and/or to take calibration observations to calibrate out any systematic changes (e.g. astrometric or gain changes) which may have taken place since the camera was last in use. A future version of this document will refer to the following Requirement, which will be submitted as a Change to the SRD:

1. **Requirement:** Following a camera change, it should be possible to reach standard operating performance **and** take sufficient calibration data to calibrate out any systematic changes, using not more than 1–2 hours of of clear nighttime and 5 hours of additional daytime following the camera change.

Here we suppose that the physical camera change, basic alignments and liveness tests should consume most of daytime on e.g. Monday. By 2 hours after sunset on Monday, the system should be ready for normal observing. Then Tuesday morning twilight and daytime 07:00-12:00 can be used in running through a standard set of daytime calibration measurements (see § 6). This should allow a diagnosis of any problems in time to fix them if possible, or otherwise to adjust the observing schedule for Tuesday night so as to minimise their impact and then fix them on Wednesday daytime.

3.6 Observation Specification

It is anticipated that the basic unit of observing will be an "Observation Block" (OB); these are constructed off-line via ESO's P2PP (Phase-2 Proposal Preparation) software package.

The following list indicates the set of parameters to be specified by the scientist(s) to define an observation. Some are required and others are optional, as indicated.

1 **Required:** A scientist-defined string, e.g. labelling the Observation Block within the programme. (This should be stored in the headers to feed back to the scientist, but should not otherwise be relied on in the archiving or pipeline processing).

2 **Required:** A scientist-defined priority value *within* the science programme (so the scientist may specify the approximate order in which his programme is executed, subject to external constraints).

3 **Required:** The celestial coordinates (Right Ascension and Declination) of the field centre, with equinox (e.g. 1950, 2000 or Apparent).

4 **Required:** The desired position angle of the camera y axis (to be defined) on the sky (degrees East of North): default 0^o, range $0 - 360^o$ (**SRD R 4.5.2/3**).

5 **Required:** A filter (or set of several filters).

6 **Required:** A set of dither offsets (specified in Arcseconds either in RA, Dec or in the camera x,y axes). [Sets of "standard" dither patterns may be specified, from which the scientist picks one; or he/she may define his own preferred pattern, subject to acceptance by the VISTA Science Processing Data Centre. A typical pattern in the IR camera may be a 3×3 square grid with 15 arcsec spacing.]

7 **Required:** Exposure time at each dither offset & filter (possibly scalable with seeing).

7b **Alternatively** a required S/N, and dither frequency, may be specified for an object of specified magnitude and profile; then the system may compute the appropriate total exposure time based on prevailing observing conditions.

8 **Required: (?)** Celestial coordinates (RA, Dec) for some guide star(s), number TBD. (Methods for guide-star selection are dealt with in § 5.2 below).

9 **Required:** A range of acceptable seeing values.

10 **Required:** A range of acceptable airmass values.

11 **Required:** A range of acceptable atmospheric transparency.

12 **Optional:** A non-sidereal tracking rate up to 10 arcsec/minute (**SRD R 4.5.3/4**) ; or possibly 60 arcsec/minute (**SRD G 4.5.3/5**) (and, if so, also probably an absolute time zeropoint).

13 **Optional:** A specification of pixel coordinates for up to 2 guide stars. (This is in the case of repeat observations where it is desired to bring the same objects back close to the same pixels at each visit (**SRD R 4.5.2/7**); this will imply specifying similar airmass for observations after the first.)

14 **Optional:** A range of absolute times for the observation.

15 **Optional:** A range of relative times (e.g. between different filters, or for a monitoring programme).
Note: The method by which the scheduler links OBs for monitoring programmes etc (requiring multiple visits to a field at roughly specified intervals) is TBD.

Note: The method by which the scheduler chooses sufficient calibration observations is TBD. Clearly it is desirable for different programmes executed on the same night to "share" calibration data when possible, but certain programmes may require additional calibrations.

For the **Visible Camera only** the following additional items will be required:

16 **Required:** A maximum sky brightness.

17 **Required:** (Probably) A specification for ADC behaviour: either Nulled, or fixed at mid-exposure value, or (if available) Tracking.

18 **Optional:** (If available) Optional specification of 2×2 on-chip binning.

19 **Optional:** (If available) Readout speed (e.g. Normal or Slow). A single readout speed $\sim$ 400 kHz should be adequate for most observations, but for a few cases e.g. narrow-band filters a slower readout with reduced read-noise may be desirable.
Note: *(This will become clear after evaluation of ESO controllers).*

20 **Optional:** (If available) optional specification of a neutral density filter.

3.7 Moon Avoidance

In order to verify the acceptability of detailed baffle designs for VISTA, in combination with various possible enclosure designs, the scattered light from off-axis bright sources must be considered. The Full Moon is by far the brightest object in the nighttime sky, so for large off-axis angles if the baffling is adequate against the Moon it should automatically be so for all other sources.

However, at small off-axis angles it may be impractical to baffle adequately against the Moon, so it is necessary to have an estimate of the moon-avoidance strategy; i.e., the limiting angle away from a Full Moon at which the imaging sensitivity is unacceptably degraded relative to a hypothetical perfectly-baffled system.

It is desirable to specify three angular regimes, hence two divisions. In the large-angle regime (i.e. normal observations, which can be scheduled any time) the sensitivity should be essentially unaffected; in an intermediate regime a moderate degradation is acceptable (e.g. for time-sensitive observations, where we want to minimise the 'coverage gaps' as the Moon moves at 13^o per day relative to the the target fields); finally in a small-angle regime observations may be ruled out. These angles should clearly be different in the visible and IR cameras, since the IR camera will usually be used during bright of moon. For the IR camera, clearly since the Full Moon will regularly pass near the zenith it would be undesirable to enforce Moon avoidance angles much greater than 30^o, otherwise the survey efficiency would be reduced by increased airmass and poorer seeing.

Note: A future version of this document will refer to the following two Requirements which will be submitted as Changes to the SRD.
The large-angle values (5% IR, 20% visible) below are the same as those specified in **SRD R 5.2/2** ; however that did not specify any angular distance ranges, so these two Requirements constitute a 'clarification' of **SRD R 5.2/2** .

1. **Requirement:** For the IR camera, the contribution to detector background from 'locally scattered' moonlight, in any IR filter, should not exceed 5% of the 'natural sky' background at any angle $\geq 25^o$ from Full Moon; and it should not exceed 50% of the natural sky value at angles $15^o - 25^o$ from the Full Moon.

   For the visible camera, the angles can be relaxed because it will mostly be used during dark time; however, occasional visible observations during bright time are essential for monitoring programmes, so some requirements are still necessary:

2. **Requirement:** For the visible camera, in any filter, the contribution to detector background from 'locally scattered' moonlight should not exceed 20% of the natural sky background (including moonlight scattered in the atmosphere) at angles $\geq 45^o$ from the Full Moon; and should not exceed 50% at angles $25^o - 45^o$ from the Full Moon.
   Note: Since the brightness of the Moon relative to the sky is very much greater in the visible, the baffling requirements might turn out to be harder to meet in the visible.

3.8 Filterset Changes

It will sometimes be necessary to change the set of filters mounted in the filter mechanism (wheel, jukebox etc) for each camera.

The allowable timescales for these operations are specified as "between the end of one night and the start of the next" for the visible camera (**SRD R 4.3.2/4**); and within 20 days for the IR camera (**SRD R 4.3.2/7**). Night-time changes of filterset for either camera will not be permitted.

Though not required by the above, it is clearly highly desirable for reasons of operational cost, flexibility and stability that visible filters can be changed while the visible camera remains mounted, without needing to dismount & remount the camera. If this is not the case, the visible filterset changes should as far as possible be done when the visible camera is off the telescope.

For the IR camera, the situation is very different. It is highly desirable to minimise IR filterset changes since they will require a thermal cycle and opening of the cryostat, which is undesirable for reasons of detector stability.

It is assumed that approximately 4 'key' filters e.g. Z_{IR},J,H,K_s will be permanently installed.
Note: Z_{IR} denotes a passband, details TBD, from $\sim 0.97 - 1.1\mu$m. This will be optimised with respect to the IR array QE's, and is distinct from the visible-camera z' passband $\approx 0.85 - 1.0\mu$m.
Other filters (e.g. narrowbands, K_{long}) will be 'rotated' among the remaining slots in the filterset. It is assumed that these other filters will only be installed or removed when the IR camera is warmed up for other purposes (e.g. $\sim$ annually).

An estimate for the number of 'non-key' filters to be used over the 15-year period would be ≈ 10, e.g. a few 'line' filters such as Paβ, Brγ, H_2, a few alternative broadband filters such as K_{long} and an SDSS-like z', and approximately 5 narrowband filters e.g. 1 or 2 in each of the 3 main windows, for picking features at specific redshift intervals.

If an SDSS-like z' (matching the visible-camera passband) is used very regularly in addition to Z_{IR}, this may lead to 5 'Key Filters' in which case it would be extremely desirable to meet the Goal in **SRD G 4.3.2/10(a)** .

4 A Typical Day & Night

In this section we summarise a typical 24-hour period for VISTA, to illustrate the detailed operations such as slewing, exposing, filter changes and dither offsets which take place many times per day/night. There are two subsections, one each for the visible and IR cameras; though there is a considerable amount of duplication between these two subsections, they are written as "standalone" subsections to avoid excessive cross-referencing. We have put the visible camera section first since it is slightly simpler.

To keep this section concise, for a number of detailed observing procedures such as guide star selection & acquisition, dither offsets etc, we refer forward to § 5, and for some calibration procedures we refer to § 6.

4.1 Typical Day and Night: Visible Camera

4.1.1 Visible Camera: Daytime

During the day the main tasks are to check the health of the system, take a modest amount of calibration data, and check that the previous night's data has been archived and that ample disk space is available for the following night's data.

In more detail, these are:

1. During the day, routine maintenance of telescope, enclosure and cameras may be carried out as necessary: including e.g. mirror cleaning, electrical maintenance (batteries), mechanical maintenance (oil) etc.
2. The previous night's data should be written to permanent storage medium (e.g. tape or DVD). (This may happen automatically during the night, if so it should be checked this has happened correctly). This corresponds essentially to 'Quality Control Level 0' (QC0); this is just a quick-look check that data exists and has been archived correctly.
3. Set the mirror cooler (or enclosure air-cooling system, if applicable) to bring the primary mirror to the forecast nighttime temperature.
4. Run a daily "disk-space maintenance" task. All data on the 'raw data' disks should have an associated 'expiry time'; this should default to a standard value e.g. 20 days, but this should be extendable e.g. for real-time monitoring programmes. The disk-space task should locate any expired data, check that it has been archived to permanent storage, and then delete it. It should then report the amount of free space on the 'raw data' disks; if this is less than a specified value, e.g. 5 nights' worth, it should report a warning. (This should be set so that any single disk failure will not reduce the free space below 2 nights).
5. If necessary, place in the filter wheel/cartridge any "non-standard" filters anticipated for use in the following night.

6. Take a set of bias frames, i.e. turn all dome lamps off and take a sequence of ~ 6 zero-second exposures (see § 6.1.1.).

7. Take a sequence of dome flats, as in § 6.1.3. Then turn off illumination and close mirror covers.

8. The dome flats should be briefly checked (e.g., compared with a similar set certified as "normal"), by a procedure & criteria to be specified later. Similarly the bias frames should be checked e.g. for pickup and to check the readout noise is within tolerances TBD. This is to ensure all detectors and electronics are functioning normally. If not, diagnose and schedule a fix.

4.1.2 Visible Camera: Evening Twilight

1. Just after sunset, the dome slit and mirror covers should be opened.

2. The telescope should slew in turn to a set of e.g. ~ 3 moderately bright pointing stars, place each on the autoguider, and measure the offset between its predicted position based on the pointing model and the observed position. (This can start very soon after sunset using bright stars, assuming that the guide sensor can be windowed down to enable very short exposures – this is helpful to get pointing checks done before twilight flats, leaving more time for standard fields later in twilight).

   The pointing model should be updated based on these offsets.

   The absolute accuracy or zero-points on the Altitude, Azimuth & instrument rotator encoders should be sufficiently accurate to guarantee putting the pointing star(s) on the guide chip(s).
   Enough pointing stars should be observed to check that the standard pointing model is working adequately. Hopefully this can usually be a few stars for simplicity. Occasionally (e.g. especially after maintenance periods / mirror re-coating / minor earthquakes etc), a full pointing re-calibration may be necessary, requiring e.g. $\gtrsim 50$ stars; this can preferably be done during a night of poor transparency or seeing.

3. Approximately 30 minutes after sunset (i.e. when the sky has reached an appropriate surface brightness TBD), the telescope should point to a suitable field with as few bright stars as practical (one of e.g. 12 pre-defined fields equally spaced in RA), at e.g. 70^o elevation and roughly East in azimuth; it should then track open-loop. Then a series of twilight flats should be taken (with telescope offsets ~ 30 arcsec open-loop between each frame) in each of the filters planned for that night (details in § 6.1.4.) There may be insufficient time to complete all filters, in which case the remaining filters should be done in morning twilight.

4. Focus and alignment: After the flatfielding, the telescope should place a suitable star on the wavefront sensor (e.g. near one of the standard fields to follow to reduce slewing), and perform any necessary adjustments e.g. focus, secondary tilt & decentre, primary-mirror supports etc; see § 5.6.

   This should take place *after* the pointing and flat-fielding so the temperatures have had time to settle after dome opening, but before the end of twilight so that standard-star observations can be done without loss of science observing time.

5. Towards the end of twilight, the telescope should slew in turn to ~ 3 photometric standard fields at varying airmass. For each field a single short ~ 5 sec exposure should be taken, in each of the filters planned to be used that night – typically u', g', r', i', z'.

6. Carry out "Quality Control Level −1" (QC–1), which is the nightly check that all systems are ready for science observations. This will consist of a series of checks on e.g. image quality, throughput etc, the details to be specified later. (Some of these checks may already be included in the above).

4.1.3 Visible Camera: Night

At this point we are ready to take science data. A suitable field will be chosen either automatically from the queue, or semi-automatically (e.g. the computer produces a short list of suitable fields from which the telescope operator picks one). This choice should be made on the basis of sidereal time, UT, seeing, photometric conditions, science priority, 'within-programme' priority, etc; based on the parameters specified in § 3.6 above. The field will typically be less than 30^o from the zenith (i.e. fairly close to the meridian and Southerly declination).
Note: The future use of laser guide stars at the VLTs is obviously a strong possibility. If so, the VISTA scheduling tool will need to take account of pointing information from the lasers, such that VISTA can be adaptively scheduled to avoid regions of sky affected by scattered light from the lasers.

In this example night we give an observing sequence appropriate for the **Wide Survey** (DRP-1A) of § 7, since this is probably the most demanding in terms of overheads (except for the Atlas which is only a Goal). Deeper surveys involve less frequent slewing and filter changes, but similar frequencies of readout and dithering.

To execute the observation sequence, the telescope should slew to the desired location. Simultaneously while slewing, the instrument rotator should set the desired PA of the camera, and the dome should slew to the appropriate azimuth. (If the dome then stops, it should stop 'ahead' of the telescope so the longest possible time elapses before vignetting).

Also simultaneously, the first desired filter in the observing sequence should be inserted in the beam.

While slewing (or before), suitable guide star(s) should be selected as in § 5.2. When the slew is complete and the telescope has settled, it should start tracking open-loop, the field should be acquired using method (A) of § 5.3 and the guide loop closed.

Then the following sequence of exposures should be taken: (exposure times are illustrative from DRP-1A).

1. A 180-sec exposure should be taken with the g' filter

2. While reading out, the telescope should offset (+20,+20) arcsec in the camera x, y axes, and guide on the new position.

3. Another 180-sec exposure should be taken with g' filter.

4. A 10-sec exposure should be taken with the g' filter.

5. The z' filter should be inserted and a 540-sec exposure taken, then the telescope should return to the (0,0) dither position. and another 540-sec exposure taken.

6. The i' filter should be inserted, and a 260-sec exposure taken at each of the (0,0) and (+20,+20) dither positions.

7. The u' filter should be inserted, and a 450-sec exposure taken at each of the (+20,+20) and (0,0) dither positions.

8. The r' filter should be inserted, and a 200-sec exposure taken at each of the (0,0) and (+20,+20) dither positions, followed by a 10-sec exposure at one dither position.

In the above, the dither positions are taken in 'alternating' order to reduce the number of offsets. It is desirable to take the g', r' exposures first and last (or vice versa) to maximise time-lag for detection of moving (solar system) objects; the order of the other filters is usually flexible. It is preferable to take exposure pairs in the same filter consecutively to minimise PSF variations between pairs. (Therefore, though some programmes may prefer it, in this example it is **not** allowable to reduce dither moves by cycling through the 5 filters at the (0,0) dither position then repeating the 5 filters in reverse order at the (+20,+20) dither position).

The above would give 54 minutes science exposure per pointing, plus the following overheads: 5 telescope offsets of ≈ 30 arcsec; 12 readouts (two per filter plus the added short g', r' exposures). and 4 filter changes.

4.1.4 Visible Camera: Morning Twilight

Additional standard field exposures (≈ 3 fields).

Additional twilight sky flats (cf evening twilight).

Park telescope at zenith, close mirror covers, close dome, shut down telescope (e.g. stop oil pumps etc). Check progress of writing data to permanent storage media, fill LN2 dewar(s) if any, send fault report (filled out during nighttime) to daytime maintenance team, Email nightly report to Garching, END.

4.2 A Typical Day & Night: IR Camera

4.2.1 IR Camera: Daytime

During the day the main tasks are to check the health of the system, take a modest amount of calibration data, and do data archiving.

In more detail, these are:

1. The previous night's data should be written to permanent storage medium (e.g. tape or DVD). (This may happen automatically during the night, if so it should be checked this has happened correctly). This corresponds essentially to 'Quality Control Level 0' (QC0) in the ESO definition; this is just a quick-look check that data is not obviously defective and has been archived correctly.

2. Set the mirror cooler (or enclosure air-cooling system, if applicable) to bring the primary mirror to the forecast nighttime temperature.

3. Run a daily "disk-space maintenance" task. All data on the 'raw data' disks should have an associated 'expiry time'; this should default to a standard value e.g. 20 days, but this should be extendable e.g. for real-time monitoring programmes. The disk-space task should locate any expired data, check that it has been archived to permanent storage, and then delete it. It should then report the amount of free space on the 'raw data' disks; if this is less than a specified value, e.g. 5 nights' worth, it should report a warning. (This should be set such that any single disk failure should not reduce the free space below 2 nights).

4. Take a sequence of dark frames, i.e. place the dark slide in the IR camera and take a pre-defined sequence of exposures (see § 6.2.2).

5. Take a sequence of dome flats, i.e. point the telescope at a white panel on the dome, illuminate it, and take a set of frames with lamp-on and lamp-off as detailed in § 6.2.3. (It is probable (dependent on details of controllers/readout modes) that dome flats will not be possible at K_s due to the high count rate; if so, differences between sky frames taken at start & end of twilight are a likely replacement). The remainder of the dome lights should stay off during this sequence. Then turn off illumination and close mirror covers, and replace the the dark slide.

6. The dome flats should be briefly checked (e.g., compared with a similar set certified as "normal"), by a procedure & criteria to be specified later. This is to ensure all detectors and electronics are functioning normally. If not, diagnose and schedule a fix.

4.2.2 IR Camera: Evening Twilight

1. At around sunset, the dome slit should be opened, then the mirror cover(s) opened.

2. The telescope should slew in turn to a set of ~ 3 moderately bright pointing stars, place each on the autoguider, and measure the offset between its predicted position

based on the pointing model and the observed position. (This can start very soon after sunset using bright stars, assuming that the detector can be windowed down to enable very short exposures).

The pointing model should be updated based on these offsets.

The absolute accuracy or zero-points on the Altitude, Azimuth & instrument rotator encoders should be sufficiently accurate to guarantee putting the pointing star(s) on the guide chip.
Enough pointing stars should be observed to check that the standard pointing model is working adequately. Hopefully this can usually be a few stars for simplicity. Occasionally (e.g. especially after maintenance periods / mirror re-coating / minor earthquakes etc), a full pointing re-calibration may be necessary, requiring e.g. $\gtrsim 50$ stars; this can preferably be done during a night of poor transparency or seeing.

3. Approximately 30 minutes after sunset, (i.e. when the sky has reached an appropriate surface brightness TBD), the telescope should point to a suitable field with as few bright stars as practical (one of e.g. 12 pre-defined fields equally spaced in RA), at e.g. 70^o elevation and roughly East in azimuth; it should then track open-loop. Then a series of sky flats should be taken in each of J, H and K_s filters. For each filter, e.g. 5x10 sec exposures should be taken; with small telescope offsets e.g. 30 arcsec open-loop between each (e.g. at the centre and corners of a square of side 1 arcmin).

4. Focus and alignment: After the flatfielding, the telescope should place a suitable star on the wavefront sensor (e.g. near one of the standard fields to follow to reduce slewing), and perform any necessary adjustments e.g. focus, secondary tilt & decentre, primary-mirror supports etc).

   This should take place *after* the pointing and flat-fielding so the temperatures have had time to settle after dome opening, but before the end of twilight so that standard-star observations can be done without loss of science observing time.

5. Towards the end of twilight, the telescope should slew in turn to ≈ 2 photometric standard fields at different airmasses, and for each field take a single short ~ 5 sec exposure in each of J,H,K_s filters.

6. Carry out "Quality Control Level -1" (QC–1), which is the nightly check that all systems are ready for science observations. This will consist of a series of checks on e.g. image quality, throughput etc, the details to be specified later. (Some of these checks may already be included in the above).

4.2.3 IR Camera: Night

At this point we are ready to take science data. A suitable field will be chosen either automatically from the queue, or semi-automatically (e.g. the computer produces a short list of suitable fields from which the telescope operator picks one). This choice should be made on the basis of sidereal time, UT, seeing, photometric conditions, science priority, 'within-programme' priority, etc; based on the parameters specified in § 3.6 above. The field will typically be less than 30^o from the zenith (i.e. fairly close to the meridian and

Southerly declination).
Note: The future use of laser guide stars at the VLTs is obviously a strong possibility. If so, the VISTA scheduling tool will need to take account of pointing information from the lasers, such that VISTA can be adaptively scheduled to avoid regions of sky affected by scattered light from the lasers.

In this example night we give an observing sequence appropriate for the **Wide Survey** (DRP-1A) of § 7, since this is probably the most demanding in terms of overheads (except for the Atlas which is only a Goal). Deeper surveys involve less frequent slewing and filter changes, but similar frequencies of readout and dithering.

To execute the observation sequence, the telescope should slew to the desired location, and when settled should start tracking open-loop at the sidereal rate. Simultaneously while slewing, the instrument rotator should set the desired PA of the camera, and the dome should slew to the appropriate azimuth. (If the dome then stops, it should stop 'ahead' of the telescope so the longest possible time elapses before vignetting).

Also simultaneously, the first desired filter in the observing sequence should be inserted in the beam.

While slewing (or before), suitable guide star(s) should be selected as in § 5.2, and the field should be acquired using method (A) of § 5.3.

Science Integrations:

Now the science field is ready to observe: we typically want a set of e.g. ~ 3 exposures $\times$ 9 dither positions $\times$ 3 filters $\times$ 4 telescope pointings, to give a filled 1 square degree field in the J,H,K_s filters.

Note: The following sequence assumes that the overhead for a filter change is smaller than for an offset of 10 arcmin plus acquisition of new guide star(s); this may not be the case. If so, it may be more efficient to do the 4 pointings in the K_s filter, then 4 pointings in H filter, 4 pointings in J filter. This is allowable, as long as it is possible when desired to observe the 4 pointings in each of J,H & K_s within an elapsed time of 2 hours (due to zenith distance constraints). Thus ability to change filter roughly hourly would be the minimum tolerable, implying an overhead for IR filter change ≤ 1 minute.

Note: The order in which the filters are observed is not normally important, and, if filter change time is a significant overhead, the order could be optimised to minimise filter changing overheads (e.g. J,H,K_s; K_s,H,J; J,H,K_s etc).

Now the field has been acquired, the following sequence of exposures are taken:

1. The J filter should be inserted, the dark slide removed, and a set of e.g. 2 x 20-sec exposures taken. (See § A.2.6 for discussion of readout modes.)

2. The telescope should offset ≈ 15 arcsec closed-loop to the next dither position (or, if quicker, apply an open-loop offset and then 'tweak up' the pointing at the new position using the guider).

3. Repeat step 1 .

4. Repeat steps 2 and 3 for the remaining 7 dither positions.

5. Change to H filter (refocussing if necessary) and repeat steps 1-4 for the same 9 dither positions, but using 4 x 10-sec exposures at each position.

6. Change to K_s filter, (refocussing and changing baffles if necessary), and repeat steps 1-4 as above, using 4 x 10-sec exposures at each position.

Now move to next pointing (e.g. 10 arcmin East, 0 arcmin South), acquire new guide stars, and repeat steps 1–6 above.

Move to 3rd pointing (e.g. 0 arcmin East, 10 arcmin South) and repeat steps 1–6 above

Move to 4th pointing (e.g. 10 arcmin East, 10 arcmin South), and repeat steps 1–6 above.

This completes one science field, with a total of 72 minutes exposure time (6 minutes per pointing per filter x 3 filters x 4 pointings). To this are added the overheads, comprising $\sim$ 300 readouts, $8 \times 3 \times 4 = 96$ 15-arcsec dither offsets, 12 filter changes and 4 10-arcmin offsets & guide-star acquisition (or 2 filter changes and 12 10-arcmin offsets for the alternative sequence above).

Now the dark slide should be inserted, the telescope should slew to a standard field (e.g. a slew $\sim$ 45 degrees), the dark slide removed, and a set of short (possibly unguided) exposures taken with each of J, H, K_s filters. (The precise number of standard fields per night is TBD; a 'high' estimate is 3 fields at different airmasses at each of evening twilight, midnight and morning twilight; plus one field at low airmass at 4 other times e.g. near 20:30, 22:00, 02:00 and 03:30.)

Now a new science field is selected (typically 1.5 hours East of the previous one), the telescope should slew there, and the same observing procedure as above should be followed.

4.2.4 IR Camera: Morning Twilight

Additional standard field exposures ($\approx$ 2 fields).

Additional twilight sky flats (cf evening twilight).

Park telescope at zenith, close mirror covers, close dome, shut down telescope (e.g. stop oil pumps etc). Check progress of writing data to permanent storage media, fill LN2 dewar(s) if any, send fault report (filled out during nighttime) to daytime maintenance team, Email nightly report to Garching, END.

5 Basic Observing Procedures

In this Section we specify some details of basic "low-level" nighttime observing procedures such as guide star selection, acquisition of target fields, dither motions ; these are performed numerous times per night, so minimising of overheads is important. Guide star selection and acquisition is effectively the same for both cameras (though each camera will have its own sensors); for dither motions the strategies are different so there are separate subsections for each camera.

5.1 Focusing

Due to the fast f/ratio of the primary, very accurate control of focus is required. It is assumed that this will be done by piston movements of the secondary mirror, under closed-loop control using dedicated focus sensors within each of the cameras. It is probably desirable, at least for the visible camera, that the focus sensors use the same or similar filter as the science detectors.

5.2 Guide Star Selection

There are three possible modes for guide star selection: one of (A) or (B) below should be available as the default, with (C) as a back-up.

A) Guide star(s) are selected at the time of defining an OB; this requires a suitable software package and catalogue to be distributed.
(Note: this mode will not work for Solar System targets, where the pointing will depend on the exact UT of observation which is not known in advance.)

B) Guide star(s) are selected "just in time" by the TCS: i.e. either when the "next" OB is entered into the system, or at the time a slew is actually commanded, the TCS automatically searches for guide stars in the appropriate windows from an on-line catalogue. This has the disadvantage that it requires extra code for the TCS, but the advantage of simplifying OB preparation, and the guide star selection code only needs to run at the telescope. This should not add overhead since it can take place during the 'previous' science exposure, or during the slew.

C) Guide stars are selected by 'blind search', i.e. the guider reads out a random sub-window of the guide chip(s); if no suitable guide star(s) are found, it tries a different window, and so on until guide star(s) are found. This mode is wasteful of time but should probably be available as a 'back-up' in case the pre-selection fails for some reason (or, if method (A) is the default and rapid override observations or Solar System observations are being attempted).

Whichever of (A), (B) or (C) above is used, the system should avoid selecting guide stars close to the edges of the guide sensor(s), so that the same guide star(s) can be used for the range of dither positions to follow.

Preferably for (A) or (B) above, the selection of guide stars should provide an element of 'redundancy' e.g. select two suitable guide stars per sensor or many sorted by magnitude), so that alternates can be used in the rare event that some of the first-choice guide stars turn out to be unsuitable (e.g. double stars, spurious objects such as plate defects, asteroids etc).

Assuming that guide-star coordinates have been provided by one of (A) or (B) above, the guider should then read out a window around the anticipated guide star position(s), large enough to ensure that the guide star(s) are contained in the window given the 3σ pointing errors (and probably, also large enough to encompass the range of dither positions to follow - otherwise a different window on the guide chip will need to be defined after each telescope dither movement).

5.3 Field Acquisition

Once suitable guide star(s) are located on the guide sensor(s), there are two options for acquiring the target field:

A) Since the field of view of VISTA is very large compared to the typical pointing errors, the simplest option will be to accept the telescope's blind pointing: i.e. guide-star pixel coordinates have not been specified. In this case the TCS should then close the loop on the telescope tracking wherever the guide star(s) initially land, and should log the difference between measured and expected positions (for use in later checking/updating of the pointing model), and should report a warning if this difference exceeds a specified threshold e.g. 3σ. .

B) Occasionally, more accurate pointing will be required, (**SRD R 4.5.2/7**), e.g. to "repeat" a previously visited field, or to ensure that a bright star falls down the 'gap' between 2 CCDs, to ensure that specific object(s) avoid bad columns on the detectors, etc. It is assumed that this will be done by knowing the geometry of the guide sensors relative to the science detectors, and specifying the pixel coordinates on which the guide star(s) should fall. If there is only one guide sensor this requires accurate **absolute** encoding of the rotator angle. In this case the TCS should tweak the telescope in RA, Dec and (if multiple stars) rotator angle to bring the guide star(s) as close as possible to their desired pixel locations.

It may be preferable to make method (B) the default since this improves the accuracy of the RA,Dec in the data headers.

It is clearly necessary to check periodically (though not every exposure) that the pointing is not grossly in error. It is assumed that the surface density of guide stars is much less than 1 per 3σ pointing error circle of the telescope, so if more than 1 guide star is found on different guide sensors, each within the 3σ error circle, this is sufficient confirmation. (The periodic wavefront sensing operations should also provide a pointing check).

If the guide star(s) do not appear as expected, the guiding system should look for any alternates as provided above; if these still do not appear then either the presence of clouds or a serious pointing error is likely, and a pointing test should be considered.

5.4 Guiding

The default for all science exposures should be closed-loop guiding, using the guide stars selected by one of the methods above. [If non-sidereal telescope tracking has been specified, the TCS should compute the desired motion of the guide star(s) across the guide sensor(s), and guide on this moving position - up to a maximum of 1 arcmin relative movement (**SRD 4.5.3/4**).] The guider should provide periodic estimates of the atmospheric transparency to flag the presence of passing clouds. If the transparency drops below a threshold value [TBD] then a warning should be issued to the telescope operator, who may consider suspending or terminating the exposure. In this case the telescope should continue to track open-loop.

Depending on the time overhead for guide-star acquisition, and the accuracy of open-loop tracking over short timescales, it may be allowable for very short exposures (e.g. standard star fields) to be performed with open-loop tracking, but this should not be assumed in computing survey speed.

5.5 Dither Motions

For both visible and IR cameras, regular 'dither' movements are required. The purpose is to take multiple exposures, for each of which the sky is shifted by a small amount relative to the detectors. This is mainly for optimal flat-fielding and fringe removal, and also for 'painting over' detector defects and CCD gaps, etc. The frequency of dither movements is much greater in the IR camera, but their size is usually greater in the visible camera.

5.5.1 IR Camera: Dithering and Tiling

One telescope **"pointing"** consists of a set of exposures with small **"dither"** offsets ~ 15 arcsec between each: the dithering enables construction of median sky-flats (in later software processing) by moving the objects relative to the detectors, so that each pixel sees 'blank sky' most of the time. These offsets should be reasonably accurate (i.e. probably closed loop , **SRD R 4.5.2/5**) to enable repeatable dither patterns to be constructed, (and possibly (**SRD G 4.5.2/6**) to enable fractional-pixel substepping to be done in the best seeing). However, the 'demanded' offset values will **not** be used to finally combine the images - detected stars at each pointing will be used to measure the 'true' offsets and register the images prior to software image stacking; thus any errors in the (actual — requested) offsets **do not** contribute to the error budget for image quality.

A set of 4 pointings with offsets of (0,0), (0, +10) arcmin, (+10, 0) arcmin and (+10, +10) arcmin in the camera x, y directions fills in the detector gaps (here assumed $0.9\times$ detector active width), and gives coverage of a filled 1 degree square on the sky, a **tile**, with a uniform exposure time. These ~ 10 arcmin offsets require a lower accuracy of ~ 2 arcsec (**SRD R 4.5.2/4**); i.e. to ensure uniform sky coverage the offset errors must be substantially smaller than the widths of the resulting on-sky detector overlap regions ~ 30 arcsec, but pixel-level accuracy is not required. Thus it is anticipated that these 10 arcmin offsets may be done open-loop, and different guide stars used at each different pointing.

5.5.2 Dither Movements: Visible Camera

For the visible camera the frequency of dithers is lower, since the readout overhead is greater and the flat-fielding is not so difficult as in the IR. Usually (though not always), one dither movement will be performed per detector readout, preferably in parallel with the readout.

For short exposures $\lesssim 10$ minutes, typically only 2 dither positions per pointing will be used to cover the 'small' CCD gaps and defects, and also for cosmic-ray rejection. Therefore, for short exposures typically the two dither positions will be at (0,0) and (30,30) arcsec in the camera x, y axes.

For long exposures $\gtrsim 30$ mins, it is preferable to readout every $\sim 300-600$ sec for improved dynamic range, reduced cosmic rays etc, so a larger set of dither positions may be used, e.g. a 3×3 square grid of unit spacing 30 arcsec, rotated by 20^o relative to the camera x, y axes so as to minimise the effects of bad columns etc which run along detector axes.

In detail, there are various possible dither strategies: small dithers are optimal for reducing pixel-scale variations from field distortions, and for ensuring that all data on a single sky position originates from a single physical CCD; while larger dithers are preferred for filling in detector gaps, at the cost of some non-uniformity of exposure near the gaps.

A) No dithering: Here the pointing is not changed between readouts.

B) Small dithers: To remove bad columns etc, while minimising PSF variations and field distortions between adjacent dither positions, dithers $\sim 5-10$ arcsec may be used.

C) Medium dithers: This mode also enables 'filling in' the smaller ~ 20 arcsec gaps between CCDs; thus the dither size will be typically 20-30 arcsec.

D) Large dithers: To fill the 'large' gaps between CCDs, larger dithers will be required $\gtrsim 5$ arcmin. These may require separate guide star acquisitions at each dither position.

It is assumed that method (C) will be the default since it can fill in the small detector gaps while still giving minimal non-uniformities.

Depending on detector layout, method (D) may be 'replaced' by using two separate telescope pointings displaced by ~ 0.7 degree or around one field radius; each pointing will comprise a set of dither positions using (C). Together the two pointings can give a filled rectangle with complete coverage of the wide detector gaps, at the cost of some redundancy.

5.6 Wavefront Sensing

It is assumed that periodic wavefront-sensing operations will be performed at intervals of $\sim 1-2$ hours during the night, to optimise the M1 figure and M1-M2 relative alignment (apart from focus for which closed-loop control is assumed).

In between wavefront sensing operations, the M1 and M2 supports should account for changes in telescope elevation and temperature using open-loop control via suitable look-up tables.

It is likely that the wavefront sensor will be fixed relative to the focal plane (possibly via a pickoff mirror), so a telescope slew of ~ 1 degree will be required to bring a suitably bright star onto the wavefront sensor. The star should be selected so as to minimise the change in elevation between the star and the following science field (possibly using the predicted mid-exposure elevation of the science field ?). Then an integration of ~ 1 minute will be peformed on the wavefront sensor to average over atmospheric variations, and the appropriate updates computed and sent to the primary and secondary mirror supports; then the telescope can slew to the following science field.

To minimise the required frequency of wavefront sensing, it is desirable to adopt an observing strategy so as to reduce changes in $\sin(ZD)$. For sidereal motions, the maximum such change occurs for fields passing through the zenith for which $\sin(ZD)$ changes by 0.23/hour; however typical values may be around half of this.

6 Calibration Data

This section describes the various calibration data-taking procedures necessary: the calibration data then feeds into the software pipeline along with the science data, to remove the instrumental signatures and provide science-quality data products. (The required software processing is set out in the separate VISTA Science Processing Requirements Document, but this section describes how the necessary calibrating data is actually taken).

Again there are two subsections, one for each camera, with a significant amount of (intentional) duplication to minimise cross-references. The visible camera subsection is placed first since it is probably more familiar to the average user.

6.1 Calibrations: Visible Camera

6.1.1 Bias Frames

Purpose: These are zero second exposures, to be subtracted from all other frames.
Also test for mains pickup & cross-chip uniformity, and serious light leaks.
Frequency: Twice daily (evening & morning) .
Procedure: During daytime, with dome lights off, a sequence of $\approx$ 10 zero-second exposures should be taken. These will then be suitably combined (e.g. medianed) in software to remove cosmic-ray events and produce a 'master bias' frame.
Special requirements: None.

6.1.2 Dark Frames

Purpose: These are exposures of non-zero duration with zero detector illumination to measure CCD dark current, possible amplifier LED effects, etc. (For modern CCDs these are probably negligible, but it is necessary to check this occasionally).
Also check charge-transfer-efficiency by searching for 'trailing' of cosmic rays.
Frequency: After camera change, or if new filter has been inserted in wheel/cartridge.
Procedure: During daytime (or during cloudy nights if dome/shutter combination is not sufficiently light-tight), a series of exposures of e.g. 10, 60, 600 sec should be taken with the shutter closed (and possibly a blocking filter also inserted).
Special requirements: If possible, dome should be light-tight enough that light level in-dome during daytime is low, e.g. comparable to that at night outside.

6.1.3 Dome flats

Purpose: Measure pixel-to-pixel QE variations; verify liveness of all detectors; check for any additional dead or hot pixels since previous flats.
Frequency: Daily for one filter (to check camera liveness). Full set (all filters) weekly.
Procedure: Point telescope at (stationary) illuminated white spot on dome, and take a set of e.g. 6 exposures of suitable duration to give e.g. 30,000 electrons per pixel or $\sim 1/3$

of full-well. Repeat for each science filter in use previous/next interval.
Special requirements: Lamps illuminating spot should be 'white' enough to keep required exposure times in the range ~ 3 sec – 100 sec. (Shorter exposures are sensitive to shutter non-uniformity; longer ones accumulate more cosmic rays). Can use different lamps from the linearity test below, if necessary.

Note: it is not necessary for the dome-spot illumination to be accurately flat (large-scale variations can be calibrated using sky flats). However the white spot should fill the beam, and the illumination should be accurately stable in time, and smoothly varying across the spot. Colour-balance filters may be desirable to make the colour of the lamps roughly similar to the sky.

Note: For some purposes sky flats alone may be sufficient, however for optimal removal of fringing etc it is highly desirable to have both dome and sky flats.

6.1.4 Twilight flats

Purpose: Measure pixel-to-pixel QE variations. Flag any additional hot pixels/dead columns etc.
Frequency: Nightly (evening & morning twilight).
Procedure: Typically 30 minutes after sunset / before sunrise, point telescope to a patch of sky devoid of bright stars, and approx. 20^o from zenith in anti-sun direction. Take a series of e.g. 3 exposures in each of 4 filters, with telescope offsets $\sim 45''$ along a 'diagonal' of the detectors between each. Exposure times should be adjusted so as to obtain $\sim 40,000$ electrons per pixel.
Special requirements: Fast readout (e.g. ≤ 30 sec) is very desirable to enable getting enough frames in the available twilight period.
It is helpful to have a script to monitor sky brightness using the autoguider and automatically adjust exposure times.

6.1.5 Astrometric calibrations

The ultimate purpose is to translate 'raw' position measurements as (x, y, n) where x, y are in (fractional) pixels and n is CCD number, into equatorial RA and Dec (α, δ).

Assuming that the focal plane is sufficiently stable (i.e. all the chips are fixed relative to each other, apart from low-order distortions e.g. a global thermal expansion & flexure), this is probably best done via a two-stage procedure.

The first stage is to (occasionally, e.g. once per month or once per thermal cycle of the camera) map the transformation from pixel coordinates (x, y, n) to physical (x', y') in microns in the focal plane (i.e., essentially map the positions and orientations of all CCDs). This first transformation is measured by taking a series of exposures of (in principle any) stellar field, with offsets by approximately (0, 0.5, 1.0, 1.5) detector widths in each of camera x, y axes, and some camera rotations by e.g. $0^o, 90^o, 180^o$. For each offset frame a list of high S/N stars will be produced in software, and an 'initial guess' solution will match up these lists.

This provides a large but highly over-constrained set of equations which can be solved for the transformation to x', y' (apart from an overall scale factor), and also for the geometrical distortions (e.g. barrel distortion etc.) from the telescope optics.

Then for any individual science frame, solving for a relatively simple transformation based on e.g. a few dozen or more astrometric standard stars in that frame will map x', y' to (α, δ), e.g. using low-order polynomial mapping from x', y' to the tangent plane. (One point to note here is that the available astrometric standards should be faint enough to not saturate; otherwise a separate short ~ 5 sec exposure (in one filter) will be required for every science field.)

The above two-step procedure avoids the need to separately solve for every chip on every field; this would be undesirable because it requires a minimum of 2 astrometric standards per chip (which may not be realisable), and would not be robust against outliers.

As noted by the VST team, it may be desirable to define an astrometric standard field very near the South Celestial Pole; then taking a short exposure of this field e.g. once per night during twilight can check the stability of the first transformation on a nightly basis. The required frequency is nightly, or less often if so determined during commissioning or early operations.

6.1.6 Photometric Calibrations

The purpose is to transform counts in ADU's into magnitudes on a standard system. Assuming that the flat-fielding has been performed accurately, conversion to magnitudes on the 'VISTA system' can be done by a single equation per passband i of the form

$$m_i' = -2.5 \log_{10}(ADU) - c_i - d_i X - e_i(m_j' - m_i')X \quad .$$

Here c_i is the overall zero point (i.e. total telescope & detector throughput), d_i is the atmospheric extinction in mags per airmass, X is airmass and e_i is the 2nd-order colour term (e_i is generally negligible except in blue/UV bands, and can possibly be fixed to a standard value for simplicity – this will be determined during commissioning). Then a colour equation e.g.

$$m_i = m_i' + f_i(m_i' - m_j')$$

will be required to convert to magnitudes m_i on an external standard system, e.g. SDSS etc; the colour term f_i describes to first order the difference in effective wavelength between VISTA and SDSS response functions, i.e. should be small.

An additional second-order correction is likely to be necessary for chip-dependent colour terms. First order or 'grey' variations of gain and/or QE between chips will be removed by the flat-fielding procedure; however, if the shape of the QE curves varies between individual detectors, there will be small shifts in effective wavelength of the passband between chips. This will give an offset to the instrumental magnitude of an object, proportional to the colour difference between the object and the 'standard' SED defining the zeropoints of the magnitude system; i.e. a term of the form

$$\Delta m_i' = g_{ijk}(m_i' - m_j') \ ,$$

where subscript k labels the chip and j is a neighbouring passband to i. These terms are most likely to be important in u', z' bands where the QE is a strongly varying function of wavelength. They should be calibrated by observing a standard star field at many offsets e.g. 0,0.5,1,1.5,2 chip widths in each of the camera x, y axes; then an iterative procedure may be used to solve for g_{ijk}. (There is an arbitrary choice about the 'reference point' here, i.e. which chip actually defines the 'VISTA instrumental system'. Either one specific chip or a mean/median of all chips may be used).

It is reasonable to assume that c_i is constant at least over the course of a night (and hopefully considerably longer); thus if d_i is also constant over a single night, in principle two standard fields at different airmasses (e.g. near zenith and near ZD $\sim 60^o$ suffice to solve for c_i, d_i in a given filter. However, if no other sky monitoring data is available it is necessary to observe standards ~ 6 times during a night to check for variations of d_i due to non-photometric conditions, e.g. cirrus or possibly dust clouds.

Therefore the 'baseline' strategy will be to observe ~ 3 standard fields at respective airmasses $\sim 1.1, 1.5, 2.0$ at each of evening twilight, midnight and morning twilight; plus 1 standard field at intervals e.g. 20:30, 22:00, 02:00, 03:30 local time.

However there are several possible methods to reduce the required amount of calibration data:

i) It may be possible to use a standard colour-dependence of atmospheric extinction, i.e. just measure d_i in one passband e.g. g' and assume all other d_j's are fixed multiples of that; this should be accurate unless substantial amounts of 'grey' dust are present in the atmosphere, which is unlikely at Paranal.
Note: *This will be clarified either before operations (using data from other telescopes), or during commissioning/early operations.* This would mean that many standard-field observations could be cut down to a single filter.

ii) It would be highly desirable to have some form of independent sky monitor available (e.g. a $\sim$ 20cm telescope monitoring fairly bright stars), to measure the overall atmospheric extinction on a quasi-continuous basis, and thus flag non-photometric nights. If the independent monitor showed stable extinction through the night, standard fields with VISTA e.g. at evening twilight, midnight and morning twilight should be sufficient calibration, i.e. eliminating the need for 2-hourly standard fields.

iii) Another possibility is to use 'local' calibrators, i.e. if an external catalogue is available with a sufficiently high density of well-measured stars, there will be suitable calibrators in every science frame (possibly requiring added short exposures to avoid saturating these) and separate standard fields may be unnecessary. A promising possibility is the approved FAME satellite (Full-Sky Astrometric Mapping Explorer); this is mainly for astrometry but is also planning to deliver photometry to ~ 0.001 mag in Sloan $g'r'i'z'$ for ~ 40 million stars to $V \sim 15$. (NB: it will *not* deliver 0.01 mag on fainter stars since only selected data will be downlinked from the satellite). While this clearly cannot be relied on, if successful this could significantly increase VISTA's observing efficiency.

6.1.7 Cross-talk test

Purpose: These are exposures with a small fraction of pixels brightly illuminated (but below saturation), and most pixels dark - any cross-talk will show up as "ghosts" of the bright spots at matching pixel locations (corresponding to the same time of readout) in the other CCDs.
Frequency: During commissioning, and annually thereafter.
Procedure: Various possibilities - either use the dome lamps and a "filter" consisting of a set of small holes in a black mask; or point at a single very bright star with a neutral-density filter, and take a sequence of exposures moving the star around the focal plane (good image quality not required). Or do in laboratory off-telescope (not very satisfactory since characteristics are likely to be different at the telescope)

If significant cross talk shows up, it will be highly desirable to fix it by shielding (or, less good, to remove it in software).
Special requirements: Pinhole 'filter' or ND filter.

6.1.8 Gain Measurement

Purpose: Measure amplifier gain in electrons per ADU.
Frequency: Quarterly.
Procedure: As for dome flats, but take a set of dome flats with a single filter and several exposures of each of 10,30,100 sec exposure time. Each set is scaled to same mean (to remove lamp variations), then differenced. Plotting rms vs mean counts gives gain, assuming Poission statistics.
Special requirements: As for dome flats. Also requires pickup noise to be small.

6.1.9 Interference test

Purpose: Check for electrical interference with CCD readouts caused by e.g. dome motion, telescope slewing, etc.
Frequency: After camera change (preferably same day).
Procedure: Take a series of ~ 10 bias frames with dome and telescope stationary; then repeat with dome moving, repeat again with telescope slewing, repeat with dome & telescope static but filter wheel moving; and compare both mean values and rms noise.
Special requirements: (Desirable) ability to rotate dome while telescope parked, to distinguish interference from dome or telescope drives.

6.1.10 Amplifier Linearity Calibration

Purpose: Measure linearity of CCD readouts (i.e. linearity of conversion from detected electrons to output ADUs). A separate (e.g. quadratic or cubic polynomial) correction will then be calculated for each amplifier, to convert 'measured' ADUs into 'linear' ADU's.
Frequency: After camera change (following day?).

Procedure: Take a sequence of dome-flats (with a single science filter) of varying exposure times in a non-ordered series; e.g. 60, 5, 30, 10, 40, 5, 30, 10, 40, 60 sec (etc). The longest exposure time should give counts $\approx$ 100% of saturation. Plotting ADUs vs exposure time will measure the linearities.
Special requirements: Dome-flat lamps must be stable to $<$ 0.5% over timescales of minutes to hours. Post-hoc shutter timing must be accurately linear (see below), and/or lamp brightness should be adjusted so exposures are long enough that shutter timing errors are negligible. (Using pre-flash LEDs internal to the cryostat may be another possibility here).

6.1.11 Shutter Timing - Linearity

Purpose: Check linearity of reported vs actual exposure time.
Frequency: After camera change (following day).
Procedure: With dome lamps on, take a 'multi-exposure' consisting of **only one** reset & readout, between which the shutter opens/closes 30 times for 2 seconds each; while summing the 'reported' shutter-open times. Take a normal 60-second exposure and compare counts.
Special requirements: Ability to command shutter open-close for specified time and report back 'measured' shutter-open time, without doing anything to detectors. (Note: just summing up 30 separate 2-sec frames (separately read out) is not a sufficient test, as it cannot discriminate shutter vs amplifier non-linearity).

6.1.12 Shutter Timing - Repeatability

Purpose: Check repeatability of reported exposure time.
Frequency: After camera change (same day?).
Procedure: With dome lamps on, take a sequence of $\sim$ 10 separate short exposures $\sim$ 2 sec each. Comparing mean counts vs reported shutter timing will reveal random timing errors.
Special requirements: None.

6.1.13 Light-leak test

Purpose: Test for light leaking round filter and/or shutter.
Frequency: After camera change (same day).
Procedure: Take a set of exposures $\sim$ 300 sec with telescope pointing at illuminated dome spot; but with permutations of shutter open/closed and either blocking filter or (any) science filter. Comparing the results with dark frames of equal length will reveal any leaks (and whether they are past filter or shutter).
Special requirements: Black (opaque) "filter" insertable in the filter wheel.

6.1.14 Ghost test

Purpose: Measure ghost images arising from bright objects.
Frequency: Annually.
Procedure: Take a sequence of exposures containing a bright star, and move around by various relative offsets. The ghosts can be identified as they move in different directions to real stars.
Then a model of the most serious ghosts can be made, and they can be subtracted or clipped from science images.
Special requirements: None.

6.1.15 Remnant test

Purpose: Measure effects of 'memory' in detectors after illumination by bright objects.
Frequency: Annually.
Procedure: Take overexposed dome flat (or twilight flat, or bright star field) followed by a sequence of frames ~ 60 sec with shutter closed.
Special requirements: None.

6.1.16 Rotator Centring

This may be mainly a commissioning procedure but is noted here since it also impacts on astrometric calibration.

Purpose: Measure location of rotator centre in focal plane.
Frequency: After camera change ?
Procedure: Take short exposure with open-loop tracking and rotator moving rapidly. Stars trail into 'arcs' defining rotator centre.
Special requirements: Adequate open-loop tracking. Ability to drive rotator rapidly during exposure.

6.2 Calibrations: IR Camera

The general procedures are fairly similar to those in the visible camera below: however many of the details are significantly different, especially the flat-fielding procedures, since the flat-fielding is considerably more critical in the IR due to the very high background levels. Also there is a mixture of additive terms from variations in thermal background across the field of view, additive terms from variations in the OH lines from the sky, and multiplicative terms from variations in pixel response.

6.2.1 Bias frames

Not required assuming reset-read-read sampling or similar is used (see § A.2.6 for details).

6.2.2 Dark frames

These are more important in the IR camera than the visible; therefore are required probably daily. Dark current may possibly be non-linear with exposure time, therefore a range of exposures is required matching those in the science frames.

Purpose: To measure dark current from thermally excited electrons in the detectors.
Frequency: Twice daily (evening & morning).
Procedure: Dome lamps off, insert cold dark slide within cryostat, take a set of ~ 10 integrations matching lengths of each of the science exposures used during the adjacent night.
Special requirements: Cold blocker essential.

6.2.3 Dome flats

Purpose: To measure pixel-to-pixel variations of QE.
Frequency: Daily for one filter; weekly for all filters.
Procedure: Point telescope at dome spot. Take groups of frames with lamp-on and lamp-off respectively; difference these to remove thermal signature of telescope, dark current etc.

Note: it may be impossible to take these at K_s due to the high count rate from the dome thermal emission.

Note: though median sky flats may be constructed from data frames, it is highly desirable for optimal photometric accuracy to obtain **both** dome flats and sky flats since the former are not affected by "additive" contributions such as fringing. A suitable combination of the two may be used in later processing to make "superflats".

6.2.4 Twilight sky flats

Purpose: To measure pixel-to-pixel variations of QE.
Frequency: Twice daily, at evening and morning twilight.
Procedure: Approx. 20 minutes after sunset, point telescope at patch of sky devoid of bright stars, $\sim 20^o$ ZD and near anti-solar azimuth.
Take series of exposures of fixed length ~ 2 sec, with random telescope offsets ~ 15 arcsec, to give count levels spanning $\sim 50\%$ down to $\sim$ few% of full-well, (as the sky brightness changes). Differencing these frames will give detector response to "sky difference only", removing telescope thermal contribution.
Special requirements: Ability to take short exposures.

This may only be possible for 1 filter per twilight period – probably K_s. Differencing may be unnecessary for J,H filters.

6.2.5 Cross-talk test

Purpose: To test for cross-talk between readouts of different detectors.
Frequency: Annual (or after camera change?)
Procedure: Observe bright star field (e.g. open cluster) with either a narrow-band filter, or a neutral-density filter, or mirror covers partially closed: cross-talk will show up as 'ghosts' of bright objects at matching pixels on other detectors.
Special requirements: A means of reducing throughput (e.g. narrowband filter, ND filter or part-closed mirror cover) is desirable to enable observing bright star field(s), to minimise confusion from fainter 'background' stars.

6.2.6 Interference test

Purpose: To test for electrical interference on detectors/controllers from dome & telescope drives etc.
Frequency: After camera change (preferably same day).
Procedure: Take set of 'dark' frames with dome moving; repeat with dome static and telescope slewing; and again with dome & telescope parked & instrument rotator slewing. Comparing with 'normal' dark frames will reveal interference effects.
Special requirements: Ability to move dome and telescope separately is desirable to distinguish source of interference (if any).

6.2.7 Amplifier Linearity Calibration

Purpose: Measure linearity of measured counts vs. photons incident on detector.
Frequency: After camera change (probably next day).
Procedure: Take sequence of dome flats with both lamps-on and lamps-off, and range of exposure times in each case, so as to give range of counts e.g. few % to 80% of full-well in the lamp-on frames. Subtracting lamp-off from equal-time lamp-on frame, and then plotting counts vs exposure time, shows linearity of each pixel.
Special requirements: Lamps should be stable to $\lesssim 0.5\%$ over timescale of minutes to hours. Lamp-off frames should have low counts; (or use darks if not).

6.2.8 Light-leak test

Purpose: Test for light leaks in dark slide.
Frequency: After camera change (same day).
Procedure: Point at dome spot, insert dark slide. Take sets of longish exposures with lamps on and lamps off. Differencing will reveal light leaks.
Special requirements: None.

6.2.9 Ghost test

Purpose: Measure 'ghost' images arising from multiple reflections off corrector lenses etc.
Frequency: Annual.
Procedure: Point at bright star field (possibly with narrow-band filter). Take set of exposures with various telescope offsets. Ghosts can be identified since they move in different directions to real objects. Then a model of the main ghosts can be made, and they can be subtracted or clipped from science images.

6.2.10 Remnant test

Purpose: Measure 'remnant' effects in detector following illumination by bright sources.
Frequency: Monthly.
Procedure: Observe a bright star field, then insert the dark slide and take a series of exposures of equal duration. Remnants will appear as fading images at the locations of the bright stars.
Special requirements: None.

6.2.11 Astrometric Calibrations

The basic principle is very similar to that in § 6.1.5 above.

Here there is the additional step of 'tying' the 4 pointings into a contiguous $1^o \times 1^o$ tile, by matching of objects in the overlap regions. Each overlap region is $\approx 10 \times 0.5$ arcmin, so there may not be enough objects in any single overlap to do a separate solution. However, a full tile comprises 6×6 effective 'detector-pointings' and thus has 60 overlap stripes (30 each horizontal and vertical). This will give ample objects to define relative shift and rotation between the 4 pointings.

Stacking the residuals for a single detector for every tile observed on a single night can also be used as a cross-check that the relative positioning of the detectors in the focal plane is constant.

6.2.12 Photometric Calibrations

Again, the basic principles are very similar to those in § 6.1.6 above.

If the filter passbands are chosen to avoid the atmospheric water absorption bands (e.g. by using Mauna Kea '98' passbands, notably with a narrower J_{98}), variations in atmospheric extinction will be minimised, and will be similar for J,H,K_s bands. This will probably mean that the second-order colour $\times$ airmass term will be negligible.

The second-order colour-detector terms may be important particularly at Z_{IR}, J bands, depending on the (uncertain) rolloff of the detector QE at shorter wavelengths.

Here an important possibility for 'local' calibration will be the all-sky 2MASS survey, now completed with most of the data public. This gives a typical S/N of 20 for point sources at J $\sim$ 15.2, $\mathrm{K_s} \sim 14.0$. Near the Galactic poles there are $\sim$ 300 stars per square degree brighter than these limits (cf `http://www.ipac.caltech.edu/2mass/releases/second/doc/sec6_5.html`). Either of the above magnitude/filter pairs should give $\approx 10,000$ detected electrons/sec (summed over pixels) in VISTA, so saturation may occur about 1 mag brighter and leave $\sim$ 150 usable calibrator stars per square degree. In principle averaging these should be sufficient to calibrate to 0.01 mag (assuming the errors reduce like $1/\sqrt{N}$).

The 2MASS calibration is believed to be internally consistent at the 1% level based on multiply-observed stars. Residual errors would presumably be correlated on the scale of one 2MASS tile, which is 8.5 arcmin (RA) $\times$ 6 degrees (Dec). This is quite different to the geometry of VISTA tiles, so a cross-comparision should be able to pinpoint the source of any systematic errors.

6.3 Calibration Frequencies

Here in Table 2 we provide a summary of the frequencies for which each of the above calibration procedures are required.

Also, concerning the available times for twilight procedures: the end of nautical twilight (Sun 12^o below horizon) occurs ≥ 52 minutes after sunset; and the end of astronomical twilight (Sun 18^o below horizon) occurs ≥ 78 minutes after sunset. (The precise values vary seasonally; the above are minimum values, and the maxima are $\sim 15\%$ larger.)

Table 2: Frequency of calibration procedures.

Visible Camera:	
Evening & morning :	Twilight flats ; 2 standard fields.
Daily:	Bias frames ; Dome flats (1 filter)
Weekly:	Dome flats (all filters)
After camera change (same day):	Dark frames; Light leak test ; Interference test
After camera change (next day):	Amp. linearity calibration; shutter linearity test ; shutter repeatability test.
Quarterly:	Gain measurement.
Annual:	Cross-talk test; remnant test ; ghost test.
IR Camera:	
Evening & morning :	Twilight flats ; 2 standard fields; Dark frames.
Daily:	Dome flats (1 filter)
Weekly:	Dome flats (all filters)
After camera change (same day):	Light leak test ; Interference test
After camera change (next day):	Amp. linearity calibration ; remnant test.
Quarterly:	Gain measurement.
Annual:	Cross-talk test; ghost test.

7 The Design Reference Programme

This section specifies the "Design Reference Programme" (DRP), i.e. a set of nested 'Key Surveys' which should be used to optimise the "Survey Speed" quantity described in Section 7 of the Science Requirements Document.

Definition: The DRP is not intended to be frozen as VISTA's actual observing programme; this will be updated to take account of changing science priorities before first light. However, the DRP is intended to be a reasonable approximation to the actual observing programme, to allow suitable tradeoffs to be made and to allow realistic quantitative comparison of the merits of various possible design options.

The DRP is divided into 4 main parts, namely the Wide, Deep and Very Deep surveys and Monitoring projects, plus a 5th part (the Atlas) which is a Goal and thus not used in assessing survey speed. Some of these parts (the Wide Survey and the Monitoring) are further subdivided. Each of these surveys is primarily defined by a solid angle of sky, a set of passbands and a detection limit to be reached in each passband, and optionally the number of repeat observations of each field.

In the following Tables, 'Mag:' is the magnitude (Vega zeropoint) giving a 5σ detection of a point source, assuming a $1.6''$ diameter software aperture containing 90% of the flux. 'Mins:' is the estimated on-target exposure time per object in minutes scaled from Table 9 of the Science Requirements Document. 'Nights' is clear 10-hour nights without overheads, assuming $2.25\,\mathrm{deg}^2$ detector coverage in the visible, and $0.25\,\mathrm{deg}^2$ in J,H,K_s.
Note: the Mins and Nights values are just **illustrative** to show the approximate balance of the programme, and will vary according to design choices. The **primary definitions** of the DRP are the **areas** and **magnitude limits** specified for each survey.

DRP-1: The Wide Survey

Band	u'	B	g'	V	r'	i'	z'	J	H	K_s
(DRP-1A) Wide high-b survey (3000 deg^2)										
Mag:	24.3	-	25.5	-	25.5	24.0	23.0	21.2	20.0	19.5
Mins:	15.0	-	6.0	-	31.3	8.6	18.0	4.1	3.4	8.6
Nights:	33.	-	13.	-	70.	19.	40.	83.	69.	173.
(DRP-1B) Wide low-b survey (1500 deg^2)										
Mag:	23.5	-	25.0	-	24.0	23.5	22.0	20.5	19.5	19.0
Mins:	3.4	-	2.2	-	2.0	3.4	2.9	1.1	1.4	3.4
Nights:	4.	-	2.	-	2.	4.	3.	11.	14.	34.
(DRP-1C) Wide survey: +2 epochs r', 2 z' (3000 deg^2)										
Mag:	-	-	-	-	24.5	-	22.3	-	-	-
Mins:	-	-	-	-	5.0	-	5.0	-	-	-
Nights:	-	-	-	-	22.	-	22.	-	-	-

Total (Wide surveys) : **617 nights** + overheads.

Notes:

1. The wide high-b survey is likely to cover most of the two 2dF galaxy survey strips ($\sim 10^o \times 80^o$ in NGP and $15^o \times 100^o$ in SGP), plus various other smaller squarish regions.

2. It is desirable that for the Wide survey (at least most of it), the $u'g'r'i'z'$ bands are observed within a single night if possible, to minimise colour errors from variable objects and to minimise PSF variations between different passbands. The g', r' bands should be observed first & last (or vice versa) to maximise time-lapse for detecting asteroids. If the field is at ZD $\gtrsim 45^o$ it may be desirable to define this order so as to get u', g' closest to the meridian.

3. In § 4 we have assumed J,H,K_s taken within a single night. There are conflicting preferences here - using a single filter per night may be preferable for flat-fielding, while minimising time delays may be better for object colours and giving similar PSFs per band. We are 'pessimistically' assuming J,H,K_s on a single night since it leaves the other alternative open.

4. Note that the r' band is significantly deeper than the others to provide image morphologies for the weak-lensing project. (Possibly a short r' may be taken at the same time as $u'g'i'z'$, then a longer r' at a different time of good seeing for the weak lensing).

5. The additional 4 epochs (two each at r', z') in DRP-1C allows for e.g. +1 night, +1 week, +4 yrs and +8 yrs for outer solar system objects and stellar proper motions respectively. (Asteroid fields may require moving to lower ecliptic latitude).

6. For the low-latitude survey DRP-1B the depths are shallower since crowding, especially in the IR, is expected to set the limit.

The following table sets out the estimated frequencies of each of the various overheads, to be used in calculating estimates of survey speed:

Overheads: Wide Survey, 1A & 1B (Visible camera)	
Guide-star acquisition	1 per field
Detector readouts:	12 per field (2 per filter + short g', r')
Filter changes:	5 per field (*)
Dither moves:	5 per field (*,†)
(IR camera)	
Guide-star acquisitions:	4 per tile
Filter changes:	3 per tile
Detector readouts:	Every ~ 10 sec
Data save to disk:	1 per dither position
Dither move:	1 per minute.

(*) It is likely that these can proceed in parallel with readout, for the visible camera. (In the IR camera the telescope cannot be moved during readout of science exposures).

(†) Here it is assumed that each of the 5 filters is observed at 2 dither positions, but the order goes $g'_1, g'_2, z'_2, z'_1, i'_1, i'_2 \ldots$ (where subscripts 1,2 indicate dither position); hence 5 offsets not 10 are required.

Overheads: Wide Survey, 1C (Visible camera)	
Guide-star acquisition	1 per field (‡)
Detector readouts:	10 per field (2 per filter)
Filter changes:	5 per field (‡)
Dither moves:	5 per field
(IR camera)	
Guide-star acquisitions:	4 per tile
Filter changes:	3 per tile
Detector readouts:	Every ~ 10 sec
Data save to disk:	1 per dither position
Dither move:	2 per minute.

(‡) Filter changes vs guide-star acquisitions may be traded off by observing several fields in sequence, then changing filter and repeating these fields etc.

DRP-2: The Deep Survey

The following Table specifies the parameters of the Deep Survey:

DRP-2: Deep survey (100 deg^2)										
Band	u'	B	g'	V	r'	i'	z'	J	H	K_s
Mag:	25.8	26.8	-	26.4	26.0	25.5	24.5	22.8	21.5	21.0
Mins:	237.7	54.5	-	78.7	78.7	136.8	285.8	78.7	54.5	136.8
Nights:	18.	4.	-	6.	6.	10.	21.	52.	36.	91.
Total (Deep) : **244 nights** +overheads										

Notes:

1. The Deep survey may comprise several $\sim 4^o \times 4^o$ blocks for large-scale clustering measurements, plus additional smaller regions distributed in RA. (The VIMOS survey regions are one possibility for the contiguous blocks).
2. B,V have replaced g' here for improved photometric redshifts.
3. Here the default strategy will be one filter per night for optimal flat-fielding.

Overheads: Deep Survey (Visible camera)	
Guide-star acquisition	1 per hour
Detector readouts:	1 per 10 minutes
Filter changes:	Rare
Dither moves:	1 per 10 minutes (*)
(IR camera)	
Guide-star acquisitions:	1 per hour
Filter changes:	Rare
Detector readouts:	Every $\sim$ 10 sec
Data save to disk:	1 per dither position
Dither move:	1 per minute.

(*) It is likely that these dithers can proceed in parallel with readout, for the visible camera. (In the IR camera the telescope cannot be moved during readout of science exposures).

DRP-3: The Very Deep Survey

The following table specifies the parameters of the Very Deep survey.

DRP-3: Very Deep survey (15 deg^2)										
Band	u'	B	g'	V	r'	i'	z'	J	H	K_s
Mag:	26.5	-	28.0	-	27.0	26.0	25.0	23.8	22.5	22.0
Mins:	863.2	-	597.2	-	496.7	343.6	717.9	496.7	343.6	863.2
Nights:	10.	-	7.	-	6.	4.	8.	50.	34.	86.
Total (Very Deep) : **204 nights** +overheads										

Notes:

1. The Very Deep survey will be primarily aimed at areas with extensive multi-wavelength coverage, e.g. XMM, SIRTF Legacy Fields, deep submillimetre fields etc; with the emphasis on the IR and fields that are too large to have useful coverage from 8-metre telescopes.

2. The exposures may be built up over multiple nights; typically each field will be observed in a single filter for $\sim$ 2 hours near the meridian, and multiple such 2-hour blocks co-added to give the final data.

Overheads: Very Deep Survey (Visible camera)	
Guide-star acquisition	1 per 2 hours
Detector readouts:	1 per 10 minutes
Filter changes:	Rare
Dither moves:	1 per 10 minutes (*)
(IR camera)	
Guide-star acquisitions:	1 per 2 hours
Filter changes:	Rare
Detector readouts:	Every $\sim$ 10 sec
Data save to disk:	1 per dither position
Dither move:	1 per minute.

(*) It is likely that these can proceed in parallel with readout, for the visible camera. (In the IR camera the telescope cannot be moved during readout of science exposures).

DRP-4: Monitoring Projects:

Unfortunately it is generally hard to merge these because of different directions, time patterns etc. The following are representative ones:

DRP-4A: High-z supernovae

- Each individual epoch should cover $7\,\mathrm{deg}^2$ to a 5σ point source detection limit of $i' = 26$.
- The above should be repeated at 3 epochs (respectively New Moon -21, -7, -3 days) once per 6-month semester.
- All the above should be repeated $\times 10$ semesters, i.e. 30 epochs in total.

For each semester, the actual required nights will be specified ~ 3 months in advance, when scheduling of follow-up on other telescopes is known; therefore if observations fail (e.g. due to cloud or poor seeing) they <u>must</u> be re-attempted on following night(s).

(Fields should be 'any' high galactic latitude field, and located East of the meridian at midnight to facilitate later followup for ~ 2 months with other telescopes.) Using fields also selected for the Very Deep survey may be helpful.

DRP-4B: Exoplanets

There are three parts to the programme.

i) Transits: Here moderate number of fields should be observed with ~ 1 minute exposures in the r' band at 300 epochs quasi-randomly distributed within an interval of 1 year. Very precise *relative* photometry is required for bright objects (**SRD R 4.6.3/1**), possibly requiring additional non-standard calibration data.

ii) Microlensing alerts: A total area of $40\,\mathrm{deg}^2$ in the Galactic bulge should be observed; to a S/N of 10 for a point source of $r' \approx 21.0$; $\approx$ once per 2 nights for one continuous 6-month period (approx March-September, i.e. one Galactic bulge 'season'). Near-real-time data processing is required, to provide alerts of ongoing events within a few days of observing for more frequent monitoring with other (narrow-field) telescopes to search for planetary anomalies.

iii) Microlensing anomalies: Here the aim is to both discover events and characterise planetary anomalies in a single programme, requiring much more frequent sampling and higher signal-to-noise. This requires $\approx 8\,\mathrm{deg}^2$ monitored with S/N ≈ 50 on stars of $r' \approx 21.0$, with a frequency of every 20 minutes (e.g. cycling round 4 fields every 20 minutes) for a full 6-month Bulge season. If the required number of Bulge fields are completed in < 20 minutes, the remainder of each 20-minute cycle is free to be used for other programmes (e.g. other monitoring).

DRP-4C: QSO Monitoring

- Area to be monitored: $5\,\mathrm{deg}^2$.
- Filters: u', g', r', i', z', J,K_s.
- Depth (each epoch): S/N = 100 for a point source of $u' = 19.0$, $g' = 20.0$, $r' = 20.0$, $i' = 19.5$, $z' = 19.0$. S/N = 50 for point source of J = 19, $K_s = 17.5$.
- Frequency: Roughly equally spaced sampling: once every ~ 3 nights (visible bands only) for 1 year; repeated for another 1 year after 5 years. Also once every month (visible and IR bands) for 10 years.

Notes: Near-circumpolar fields are required (i.e. observable with elevation $\gtrsim 20^o$ at some point during any night of the year).
Calibration will be relative to stars in same field, so only modest additional calibration data is required.

DRP-5: Southern Sky Atlas (Goal)

This survey intends to use the poor-seeing time (e.g. the worst-seeing 20% of the 'Surveys' time) to survey the entire Southern hemisphere ($\delta < 0$) in 4 optical and 2 infrared passbands. This requires 9,000 telescope pointings in the optical and $\approx 80,000$ pointings in the IR.

There is no specific depth requirement, as long as the depth scales as expected from the deeper surveys given the available integration times and seeing - though as a guideline, this Atlas would reach ≈ 1 mag deeper than the SDSS survey in the visible bands, and over 2.5 mag deeper than 2MASS in the infrared.

The Goal (**SRD G 6.3/5**) is that the VISTA system overheads are small enough that, given a fixed allowance of 4000 clock hours for the survey, it spends ≥ 2000 **hours** integrating on sky. <u>For this survey only</u>, given the poorer seeing and to help to reduce the overheads, it is permissible for the system image quality to be up to 50% larger than the standard SRD specifications, (e.g. to permit open-loop tracking or less frequent optics realignment), and 2x2 rebinning of pixels in the visible camera is permissible to reduce readout time.

This Atlas is an SRD **Goal** rather than a Requirement (and thus is not used in assessing survey speed) as the target level of overheads may potentially be non-trivial to meet; also it would provide mainly a general-purpose community resource (especially for identifications of sources from other wavebands) rather than specifically tailored science aims. However, a great deal of valuable science would also arise, e.g. for discovering bright examples of rare classes of object.

A Cameras and Detectors (Assumptions)

The designs for the two cameras have not yet been developed in the same level of detail as those for the telescope optics. This Appendix provides an outline of preliminary issues concerning the designs of the two cameras, guiders, detectors and controllers. As in Section §2, references to Requirements and Goals in the SRD are given for convenience, but are not exhaustive and do not modify the Requirements and Goals. If there is any conflict the SRD takes precedence.

A.1 Visible Camera (Assumptions)

A.1.1 Visible Camera: ADC

To minimise the effects of wavelength-dependent atmospheric dispersion away from the zenith, an Atmospheric Dispersion Corrector (ADC) is probably required in the visible range, but is not required in the IR.

It appears that to meet the PSF anisotropy limits of the weak-lensing project (**SRD 4.4.1/3(a-e)**), and also to meet the image-quality specifications at B, g' bands at ZD $\gtrsim 45^o$ (**SRD R 4.4.1/1**), the ADC is probably essential. Including an ADC will result in some reduction in UV throughput (due to the types of glass required), and a slight reduction of image quality near the zenith. To minimise these effects, the ADC does not necessarily have to give full correction for all wavelengths at ZD $> 50^o$; full correction for B through r' bands at $ZD \leq 50^o$ should be sufficient.

The ADC will consist of a pair of rotatable or movable prisms, probably integrated as two elements of the visible corrector; these must rotate/move as the telescope points at different elevations. However, since single exposures are unlikely to be longer than 30 minutes, it is probably not essential for the ADC to 'track' during an exposure – setting the prism positions to the appropriate mid-exposure value prior to opening the shutter, and then leaving them static for the duration of the exposure, would be acceptable.

Note: *The above details will be finalised during final design stages of the visible camera.*

A.1.2 Visible Camera: Shutter

The shutter prevents light from reaching the detectors. In the visible camera, a shutter is essential since the readout times are substantial ($\gtrsim$ 30 sec) and light must not fall on the detector during readout. The shutter should provide a uniform exposure duration across the focal plane, and accurate (post-hoc) timing of the duration of the exposure (**SRD § 4.6.1, 4.6.2, 4.6.3**). It should be able to deliver short exposures when required to avoid saturation on bright objects (**SRD § 4.6.6**).
Given the large size of the focal plane $\sim$ 444mm diagonal, this probably requires a 'sweeping' shutter e.g. two chasing blades or a rotating sector. Assuming such a 'sweeping' shutter is used, different locations in the focal plane get the same exposure duration but slightly 'offset'

in absolute time. It is desirable to keep this offset small to minimise seeing variations across the field of view. Also the absolute time (UT) of mid-exposure (at any location in the focal plane) should be reconstructable post-hoc to under 0.1 sec accuracy (**SRD R 4.6.6/2**)

A.1.3 Visible Camera: Filter Mechanism

The visible filter mechanism places a filter in the beam to accept only light of a specified wavelength range; most commonly a broad-band filter, e.g. one of $u'g'r'i'z'$, or sometimes a narrow-band filter e.g. width 1%. The filter should have very low 'out-of-band' leaks (especially red-leaks, since the night sky is very red); and negligible light should reach the science detectors without passing through the filter (**SRD R 4.3.1/4**). Filters will be changed many times during the night (sometimes as often as once every few minutes), so the mechanism must be fast & reliable. The mechanism should relocate the filters to high positional accuracy (**SRD R 4.3.2/9**), (to ensure repeatability of dust-specks etc so that they are calibrated out by the flat-fielding software). Each physical filter should have a unique machine-readable identifier to avoid human error as to which filter is where; and each glass filter should have its own filter-holder so glass is not swapped around between holders. (**SRD R 4.3.2/1**).

The total area of each filter is very large, so consideration of mosaiced filters is almost certainly necessary; in this case, it is desirable that the join structure does not shadow the detector array. It is also desirable that filters are close to the focal plane, to minimise optical errors from non-flatness of filters. If different filters are of different thicknesses, an automatic focus adjustment will be necessary on changing filter.

To meet the dynamic range requirements (**SRD R 4.6.6/1, G 4.6.6/3**) a Neutral Density filter might be employed, presumably requiring an extra slide in front of the filters to hold it. If this is used, probably a choice of 1 or 2 such filters, e.g. $\log_{10} D = 1$ or 2, would be sufficient, on a simple in/out slider. These would be used for increasing dynamic range i.e. for occasional calibration exposures of bright objects such as photometric or astrometric standard stars, and possibly for pointing checks very soon after sunset; so some degradation of image quality when ND filters were in use would be acceptable. Whenever ND filters are in use, a warning should be issued to the operator at the start of each exposure, to avoid accidentally leaving them in the beam.

A.1.4 Visible Camera: Detectors

The science focal plane will consist of a mosaic of ≈ 50 CCDs, possibly Marconi-EEV model 42-90, with a format of 2048×4608 pixels of 13.5μm. Operating temperature is approx. 180 K, so they must be maintained in a cryostat, cooled either by LN2 or a closed-cycle cooler.

They should probably be kept at operating temperature quasi-permanently except during maintenance periods, since random CCD failures (while rare) appear to preferentially occur during thermal cycles, and hot pixels sometimes change their behaviour after such cycles.

The chips must be aligned with the focal surface to high accuracy $\sim 10\,\mu$m; the Marconi packaging appears helpful in this respect. They should probably be mounted on a low thermal expansion base plate to minimise astrometric errors etc. arising from spatial or temporal temperature gradients.

It may be desirable to obtain (e.g. via metrology ?) a "contour map" of the deviations of the CCD surfaces from a plane (or from the idealised sphere with the curvature of the telescope focal surface). This could be useful in analysing image distortions, especially for the weak-lensing project (**SRD R 4.4.1/3(d)**).

The layout of the individual chips depends on considerations such as dither patterns, optical distortions, available optical field size, maximum size of filter elements etc. For the Marconi CCDs, the inactive packaging material around the edge of each individual detector is 5.0 mm on one short side, 0.15 mm on the other short side, and 0.26 mm on each of the long sides (these values are probably non-negotiable). The "baseline" layout will be three "blocks" of respectively 2×10, 2×10 and 1×10 chips (see Figure 2). Within each block the chips will be close-butted ($\approx$ 1mm gaps in both directions); there will be larger gaps $\sim$ 15mm between blocks (i.e. 2×5mm for connectors plus extra to avoid shadowing by filter joins etc). In this layout, with EEV42-90 detectors, the rectangle enclosing all live pixels is 341×285mm, i.e. diagonal of 444.4mm; this corresponds to 2.12^o at $0.232''$/pix.

An alternative suggestion (from the weak lensing group) is a layout of e.g. 44 chips with a 2×14 column in the centre and two columns of 8 chips, (one at each field edge), separated by a gap of $0.9\times$ the detector long axis. This fits within a similar field to the baseline 5×10 layout, and might be preferable in terms of gap-free tiling of sky.

Currently, the exact layout is to be decided: the focal plane should be large enough to accommodate the baseline 5×10 Marconi 42-90 chips, with zero vignetting out to at least 90% of the radius to the corners, and vignetting preferably not over $\sim$ 10% at the corners.
Note: *The detailed layout is to be decided by the PS with the advice of the appropriate VSC Working Group, in consultation with the MO.*

A.1.5 Visible Camera: Guider

The choice of guide setup is affected by filter layout etc. Guiding through the science filter has advantages re. differential refraction, aberrations etc, but has the drawback that for some filters (e.g. u', narrowband), it will limit the surface density of adequately bright guide stars. Ideally a separate filter (either selectable separately from the science filter, or mosaiced together with each science filter as separate 'window-pane(s)' on each filter mosaic) would be provided for the visible-camera guide chip(s). If so, no light passing through the guide filter may fall directly on the science array (**SRD R 4.3.1/4**), and any scattered light must be low enough not to significantly increase the background on the science array; whether these are feasible depends on the focal-plane layout.

Due to the large field of view, astigmatism is likely to be one of the main residual aberrations. Since this is sensitive to defocus, it is very likely that an auto-focus mechanism must be included to meet the image-quality requirements in the SRD. This may be done either by the guide chips (e.g. tilting or offsetting in the axial direction), or by separate focus chip(s)

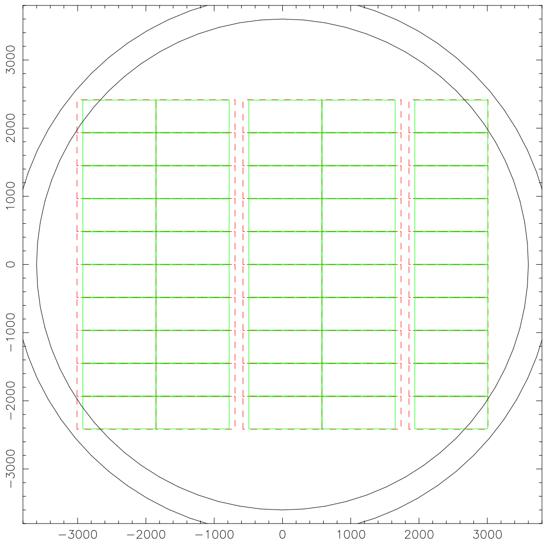

Figure 2: The 'JIF-like' layout of the CCDs in the focal plane. Solid-green lines denote 'active' pixels, dashed-red lines denote packaging. Axes are in arcsec, assuming 0.232″/pixel. The circles indicate diameters of 2.0 and 2.2 degrees. Note that the 'single' column may be moved to the centre for improved tesselation.

near the guide chip(s), or by a separate wavefront sensor.

It is also likely that two guide sensors on roughly opposite sides of the optical axis may be necessary to provide closed-loop control of instrument rotator axis. Given a circular focal plane with an inscribed square of detectors, there should be a reasonable amount of space to place these in the focal plane if desired.

If the guiders are close to the focal plane, they will probably be behind the shutter. If so, care is needed to avoid guiding errors accumulated while the shutter is closed causing trailing after the shutter opens. This is probably manageable via software. Alternatively, a multi-part shutter may be considered which enables the shutter to be simultaneously open on the guide stars and closed on the science field. As for the differing filters above, scattered light will need to be considered in this case, though the "open on guide stars, closed on science field" state need only last a few seconds before each exposure: during CCD readouts both would be closed.

A.1.6 Visible Camera: Wavefront Sensor

It is assumed that the wavefront sensor will be fixed relative to the science focal plane, either co-planar with it or using a pickoff mirror. It will probably occupy one of the 'segments' between the rectangular science array and the circular field of view.

A.1.7 Visible Camera: CCD Controllers

The controllers are required to reset the CCD detectors prior to each exposure, and readout the data at the end. (The initial reset step may be skipped to save time if the shutter has not been closed for long since the last readout, but is required to remove accumulated cosmic ray hits if $\gtrsim 1$ minute has elapsed since the last readout.)

Concerning readout, almost all science exposures will be sky-noise limited so the level of readout noise is not a critical issue; though it is desirable to keep it $\lesssim 10e^-$, for the case of e.g. narrow-band filters.

Minimising readout time is very important since for many programs the integration times will be only a few minutes and may ideally be split into 2 sub-exposures. It is highly desirable to have the capability of 2×2 on-chip binning and consequently $4\times$ faster readout (while preserving dynamic range if possible), especially for the Atlas section of § 7. (Other binning factors e.g. 2×1 or 3×3 are not of much interest.)
[As an example, the VST uses ESO FIERA controllers and can read out the entire focal plane in ≈ 20 sec, which appears very satisfactory. However, due to disk write speed, there is a separate limitation on short exposures **only** since it takes 60 sec to dump the data to disk following readout – this does not affect long exposures since the data-dump proceeds in parallel with the next integration, but for short exposures it means that the minimum 'cycle time' between two consecutive readouts is 60 sec. It would be desirable to reduce that, e.g. by having a memory buffer between controllers and disk.]

Another desirable feature is optional on-chip clocking during science exposure to reduce 'blooming' caused by charge from saturated bright stars bleeding along rows during the exposure.

Though the Marconi chips have two amplifiers per chip, using one output amplifier per chip is probably preferable; this is helpful in that it improves yield of usable chips (e.g. chips with only 1 functioning amp out of 2 are usable) and hence reduces cost, and also eases the calibration procedures.

A.2 IR Camera (Assumptions)

There are several options for the layout of this camera: the cold-baffle option (A) is currently the preferred solution.

A) A **cold-baffle** solution. This requires a long cylindrical cryostat, with a large front window ($\sim$ 900mm diameter) located well forward ≈ 2.3 metres above the focal plane. The cryostat contains a series of cold baffles around the beam so the detector sees no warm high-emissivity surfaces at angles outside the science beam.
To avoid excessive vignetting at the edge of the focal plane, the cold baffles must be slightly larger than the diameter of the on-axis beam, thus the detector will see an un-baffled 'annulus' outside the secondary but within the front cold baffle. This annulus may comprise either unfocussed sky, or probably a warm concave reflective baffle around the secondary reflecting back into the cryostat.

This design requires careful assessments of scattering of thermal radiation from the dome within the cryostat, and of temperature gradients across the window; both these effects have been studied in some detail, and the results appear very promising. Since no complex re-imaging optics are required, it has the major advantages both of simplicity and of excellent image quality (meeting the goal **SRD G 4.4.2/2** over a field of view encompassing 4×4 arrays). In comparision to a cold-stop solution, the modest $\sim 10\%$ increase in K_s background arising from the 'annulus' above is compensated by the increased throughput, so the sensitivity is very similar.

B) Cold-stop solutions for K_s only, with direct imaging for JH. (Cold-stop designs with a common path for J,H,K_s do not give the required image quality due to chromatic aberrations with available materials). There are several flavours:

- **B1)** A split focal plane whereby half the focal plane is filled with detectors operating at J/H; the other half of the focal plane is empty, and the beam passes through focus then through a cold-stop and reimaging optics to the K_s focal plane.
- **B2)** A dichroic solution where a dichroic is placed after the corrector lenses; the JH light is imaged directly onto the JH detectors, while the K_s passes through the cold-stop as above to separate K_s detectors. This has the drawback of additional aberrations from the dichroic, but the advantage that a smaller field diameter is required to accommodate a given number of detectors.
- **B3)** A movable mirror arrangement for separate JH/K_s paths to a common focal plane. This may have difficulties with packaging.

A.2.1 IR Camera: Corrector

Since a cold-baffle solution appears very probable, it is likely that the IR corrector will be inside the cryostat; therefore care is needed to allow for thermal expansion effects on the mountings. (Alternatively, if a cold-stop is used, one of the corrector elements may form the front window of the cryostat).

A.2.2 IR Camera: Filters

As for the visible camera, the filter mechanism places a filter in the beam to accept only light of a specified wavelength range; most commonly a broad-band filter i.e. one of J,H,K_s and possibly K_{long}; or occasionally an intermediate or narrow-band (e.g. 1%) filter. The numbers of available filters are specified in **SRD R 4.3.2/5** .

Many of the same considerations apply as in the visible: i.e. minimising out-of-band filter leaks, especially red leaks; minimising light reaching the detectors 'around' the filter; and locating the filters close to the focal plane to minimise image degradation from optical non-flatness of filters.

The IR filters must be maintained at cryogenic temperatures to avoid thermal emission from the filters themselves adding to the background reaching the detectors. (Warm filters combined with a cold 1.9μm short-pass filter might have been a possibility for obtaining some 'extra' daytime-changeable filter slots, cf **SRD G 4.3.2/10(b)** but given the cold-baffle design there is no available location for warm filters).

With the cold-baffle design, off-axis thermal radiation is kept to low levels. However were we to return to a cold stop § A.2(B), it may be important to minimise red-leaks for J, H filters at large off-axis angles at wavelengths $\gtrsim 1.9\mu$m, to avoid increased background from thermal radiation outside the science beam.

Mosaiced filters will almost certainly be required, due to limitations on available sizes of monolithic filters in the IR. These should be straightforward to design with a separate piece of filter material per detector, assuming the spacing between detector centres will be $\approx 1.9\times$ the live detector width (i.e. gaps of $0.9\times$ live width). Avoiding 'shadowing' of the focal plane by the joins in mosaiced filters again requires filters to be located fairly close to the focal plane.

Another consideration specific to the IR camera is that filter changes should not result in a large increase in the level of radiation reaching the detectors (**SRD R 4.3.2/8**). This is automatically satisfied assuming a filter 'wheel' is used; though if a juke-box or 'lollipop' filters are used, a dark-slide at a separate location may be required.

A.2.3 IR Camera: Cold blocker

For the IR camera, a cold blocker is essential (**SRD R 4.3.2/6**), i.e. a cold opaque surface which may be inserted into the beam so that effectively zero radiation of the wavelengths of interest falls on the detectors, in order to measure detector dark current. This may most simply be an opaque sheet occupying one position of the filter wheel; alternatively, if spaces in the filter wheel are very limited, or a non-wheel solution is used, it may be located elsewhere in the beam. There is a certain advantage to having a separate cold blocker since it enables night-time dark current measurements without moving the science filter.
Note: *The location of the blocker will be determined during final IR camera design – the current optical layout uses an 8-position wheel solution, so the blocker in the wheel looks simplest.*

The cold blocker must be available for use at any time that the camera is operational (**SRD R 4.3.2/6**). Most commonly these dark-current measurements will be made in the daytime, so insertion/removal time is not critical (though should probably be ≤ 30 sec).

A.2.4 IR Camera: Detectors

These will comprise a 3×3 mosaic (possibly upgraded to 4×4 if external funds are available) of Rockwell 2048×2048 pixel Hawaii-2 arrays; preferably MBE type for improved quantum efficiency and reduced 'remnant' effects; or possibly PACE type for schedule or cost reasons. Operating temperature is ≈ 77K.

Some freedom of choice may be possible in the long-wavelength cutoff of the detector response; if so, it is essential for the detectors to have good response out to $\geq 2.30\mu$m and preferably 2.45μm (to permit use of a $K_{\rm long}$ filter, **SRD G 4.3/2**). It is preferable to have the detector QE as **low** as possible longward of 2.5μm to avoid increased background from (possibly scattered) radiation red-leaking through the filters.

Good detector QE down to 1.0μm is highly desirable to optimise use of the $1.0 - 1.1\mu$m "Z_{IR}" band; response down to 0.9μm is also desirable to allow a filter giving similar response to Sloan z' band.

Note: *All the above are to be discussed with Rockwell prior to placing the detector contract.*

Due to the detector packaging of the Hawaii-2 devices, it is not possible to close-butt the individual detectors. Therefore a '90% spacing' layout will probably be adopted, where the detector centres are placed on a square grid of spacing 1.9× the active detector width. This layout allows efficient gap-free coverage of sky using 4 telescope pointings each offset by 0 or +0.95 detector widths in each of the detector x, y directions.

A.2.5 IR Camera: Guider

It is quite likely that guiding in the IR camera will be done with a visible-wavelength CCD (and probably a reddish filter); in this case the beam to the guider clearly must not pass through the IR science filter, and any relative chromatic terms must be allowed for e.g. in software.

Assuming a circular field of view with science detectors occupying a roughly inscribed square, there should be suitable space for guide detectors around the outer segments of the field; though additional lenses might be required to correct for chromatic aberrations since the guide beam will have passed through the IR corrector lenses.

Note: *The above will be clarified during final design of the IR camera.*

A.2.6 IR Detector Controllers

The controllers are required to control the detectors, i.e. to reset them prior to an exposure and read out the data into e.g. memory or to disk following the exposure.

It is very desirable that the next exposure can begin soon after a readout is completed, i.e. not have to wait for data to be exported from memory to disk etc.

Maximising readout speeds will be very important, due to the high sky background especially with H,K_s filters: the estimated background rates are $\sim 500, 2100, 2700 e^-$/sec/pixel at J,H,K_s respectively.

Thus it is expected that individual exposures will be only $\approx$ 10sec duration to give a count level from sky $\approx 1/3$ of saturation. For a 2-sec readout overhead, this would require pixel readout rates of $\sim$ 500kHz for 4 readouts, so it would be highly desirable to use 32 readouts per array to both reduce readout rates and improve observing efficiency (or alternatively mode (E) below).

There are a number of possible modes for readout of the IR arrays: the strategy actually used will depend on experiments with real Rockwell 2k arrays. The primary considerations will be speed and stability (i.e. avoiding time-variable detector artefacts); minimising readout noise is relatively unimportant. Some possible modes are as follows:

(A) Reset-read-read. This is the 'default' mode for modern arrays, and should be available for VISTA. Here one or more fast resets are performed, then the array is read line-by-line, and starting e.g. 10 sec after the first read, a second read is performed. Subtracting the first read from the second gives the 'data' frame. The exposure time is set by the interval between reads, hence there is a minimum exposure equal to the time for 1 complete read. The overhead for each exposure is the time for 1 reset + 1 read.

(B) Multiple sampling This is similar to (A) except that multiple ($n > 1$) non-destructive reads are performed at the beginning and end, and averaged to reduce read noise. This mode can reduce read-noise but may be of limited use for VISTA science observing since saturation may occur too quickly. (However it may be useful for doing linearity checks).

(C) Up-the-ramp: Here the array is reset and then a number of non-destructive reads performed at fixed intervals until the total integration time is reached. Fitting a straight line to counts vs time for each pixel, (optionally with a cosmic-ray rejection algorithm applied), gives the 'data' frame. As for (B), this mode reduces read-noise but may be of limited use for VISTA since saturation may occur too quickly.

(D) 'Hodapp' mode: This is a variant of (B) where the first read of the beginning set and the first read of the end set are discarded before averaging; this is intended to reduce instabilities caused by the varying elapsed time since the last readout.

(E) 'CIRSI' or 'MPIA' or 'RRR' mode: Here the array is reset and read 'line by line': After an initial full reset, a pass across the array is performed as follows: `foreach N {read line N; reset line N; read line N}` . Then 2nd, 3rd, 4th passes are done, and the second read of the 1st pass subtracted from the first read of the 2nd pass etc. (The first read of the 1st pass is 'unnecessary' but is done so that the array is treated the same way at all passes). This reduces the overhead for a sequence of integrations at a common pointing to the time for a *single* detector readout. This mode may be highly desirable for VISTA to improve observing efficiency, but the effect on detector stability would need careful checking.

Whichever mode is used, to reduce the data volume, it is **highly desirable** to have the ability to co-add a set of e.g. 6×10 sec integrations in temporary storage before writing to permanent storage medium. (It is not necessary to perform 'on the fly' cosmic-ray rejection on the individual readouts before co-adding, since the fraction of affected pixels will be very small, ($\sim$ 14 hits per detector per minute) and multiple dither positions can be used to perform cosmic-ray rejection in later processing).

For improved dynamic range on bright objects, it is desirable to have the ability to non-destructively readout the arrays e.g. after 1 sec within a 10-sec integration. This data could be either stored separately, or a 'pixel replacement' could be performed whereby pixels saturated in the 10-sec integration are replaced by 10$\times$ their value in the 1-sec integration, before storage.

A.3 Data Volumes

For assessing requirements of the data-handling and pipeline-processing system, it is useful to have an estimate of the typical and maximum data volumes.

The baseline visible camera has 472 million pixels, i.e. produces 943 MB of data per readout. For DRP 1-A there will be approximately 12 science readouts per hour, plus 40 standard-field frames, 20 twilight flats, and approximately 20 daytime calibration frames; this gives a total of 200 frames or 188 GB per day. Deeper surveys may give 1/2 to 2/3 of the above rate, while a few monitoring programmes (e.g. exoplanets) may give a higher rate e.g. double the above.

The baseline IR camera (3$\times$3 arrays) has 37.7 million pixels, i.e. produces 75.5 MB per save as 2-byte integers. If all individual detector reads are saved, we assume 10-sec integrations and 20% overhead, giving one readout per $\sim$ 12 sec. This is 3000 readouts i.e. 225 GB per 10-hour night (daytime calibrations are only a modest overhead to this). This can be reduced by a factor $\sim$ 3 assuming 1-minute co-add sequences converted to `real*4` format before saving.