Visible & Infrared Survey Telescope for Astronomy

Data Flow System

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1 Introduction

The Vista Infrared Camera (VIRCAM) is a wide-field near-infrared imaging instrument for the Cassegrain focus of the 4-metre Visible and Infrared Survey Telescope for Astronomy (VISTA). The pawprint of VIRCAM covers 0.59 square degrees in the Y, J, H, K_S (and possibly Z_{IR}) passbands using a 4×4 array of 2k×2k non-buttable chips with 0.34 arcsecond pixels.

1.1 Purpose

This document describes an Exposure-Time Calculator (ETC) for VISTA with VIRCAM. The general requirements for an ESO ETC are described in [AD1]. The ETC programmes allow the user a large amount of control over the simulator. The main task of the ETC is to evaluate the exposure time required to reach a given signal-to-noise for a given set of source characteristics, atmospheric conditions and instrument configuration. The ETC also allows the equivalent signal-to-noise to be computed for an input exposure time. VISTA is required to survey efficiently (i.e. to have high survey speed). The ETC therefore includes an extra layer of functionality to provide the actual elapsed time (including overheads) needed to complete a (filled) tile to the depths and signal-to-noise specified. This enables the user to examine different observing strategies and examine/minimize the overheads.

1.2 Scope

The ETC document and software is part of the design of VIRCAM/VISTA operations, which also includes a Survey Definition Tool [AD2]. The interaction with camera templates and observation strategy is briefly discussed in Section 3.

1.3 Applicable Documents

[AD1] VLT–SPE–ESO–19000–1618, *Data Flow for VLT/VLTI Instruments: Deliverables Specification*, Issue 2.0, Date 2004–05–22

[AD2] VIS-SPE-ATC-20000-0010, *Survey Definition Tool and Survey Progress Tool: Functional Specification,* Issue 0.9, Date 2004-10-07

[AD3] VIS-SPE-IOA-20000-0001, *VISTA Infra Red Camera DFS User Requirements*, Issue 0.5, Date 2004-04-08

1.4 Reference Documents

[RD1] *A Theoretical Investigation of Focal Stellar Images in the Photographic Emulsion and Application to Photographic Photometry*, Moffat A.F.J., 1969, A&A, **3**, 455.

[RD2] IRTRANS4: http://www.jach.hawaii.edu/JACpublic/UKIRT/astronomy/calib/atmos-index.html

[RD3] Infrared Exposure Time Calculator for ISAAC: http://www.eso.org/observing/etc/doc/ut1/isaac/helpisaac.html

1.5 Acronyms and Abbreviations

DICB	Data Interface Control Board
DIT	Detector Integration Time
ETC	Exposure-Time Calculator
FWHM	Full-Width at Half Maximum
IDF	Instrument Definition File
IR	Infrared
Mag	Magnitude
NDIT	Number of Detector InTegrations
PAF	Parameter Format File
QE	Quantum Efficiency
VIRCAM	VISTA InfraRed CAMera
VISTA	Visible and Infrared Telescope for Astronomy
VOTABLE	Virtual-Observatory Table format
WWW	World-Wide Web

2 Instrument Configurations

2.1 Overview

VISTA is an alt-azimuth 2-mirror telescope with a single focal station (Cassegrain), which can accommodate one of two possible cameras: an IR Camera or (if funded later) a visible camera. The telescope has a fast focal ratio (f/1 primary, f/3.25 at Cass) hence a compact structure. The telescope uses active optics, with 81 axial force actuators controlling the shape of the primary mirror (M1), and a 5-axis hexapod controlling the position of the secondary mirror (M2). The infrared camera (details in [AD3]) is a novel design with no cold stop, but instead a long cold baffle extending ~ 2.1m above the focal plane to minimize the detectors' view of warm surfaces. There is a large entrance window (95cm diameter) and 3 corrector lenses, all IR-grade fused silica. There is only one moving part (the filter wheel). The camera also contains fixed autoguiders and wavefront sensors (2 each, using CCDs operating at approximately 800nm wavelength) to control the tracking and active optics.

The filter wheel has space for 8 main filters, one of which is dark and the remaining seven are for science and include Y, J, H, K_S and any other filters that may become available.

VISTA is survey instrument, designed to cover large areas of sky as efficiently as possible. A typical multiband survey would cover a certain area (which may or may not be contiguous), would be observed to a uniform depth in several filters and would possibly be done with some repetition to pick up variability or proper motions. Such a survey will normally be the result of the combination of many observations made over many nights and several such surveys will probably be running concurrently. The ETC includes an extra layer of functionality to enable the user to examine different observing strategies and examine/minimize the overheads. Therefore the ETC also needs to cover the main observing modes:

- **Tile:** A filled and fully sampled area of sky formed by combining multiple pawprints. Because of the detector spacing, the minimum number of pointed observations (with fixed offsets) required for reasonably uniform coverage is 6, which would expose each piece of sky, away from the edges of the tile, to at least 2 camera pixels.

- **Microstep (pattern):** A pattern of exposures at positions each shifted by a very small movement (≤ 3 arcsec) from the reference position. Unlike a jitter the nonintegral part of the shifts are specified as 0.5 of a pixel, which allows the pixels in the series to be interleaved in an effort to increase resolution. A microstep pattern can be contained within each position of a jitter pattern.

- **Jitter (pattern):** A pattern of exposures at positions each shifted by a small movement (30 arcsec) from the reference position. Unlike a microstep the non-integral part of the shifts is any fractional number of pixels. Each position of a jitter pattern can contain a microstep pattern. The primary purpose of a jitter pattern is to remove bad pixels.

These observing modes are discussed in more detail elsewhere ([AD3]).

3 Observing Strategies

VISTA+VIRCAM has predefined observing templates from which the user may choose. These are described in detail in [AD3] and summarized briefly here. The component observations of a survey (filters F, tiles T, pawprints P, jitters J, microsteps M, and exposures E) can in principle be nested in various orders, subject to some restrictions, such as the innermost loop always being E. Different nestings require different observing templates and have different overheads.

Using shorthand (based on the order of nesting of the loops for the 6 components F, T, P, J, M, E with the order of the letters indicating increasing nesting of the loop read to right) the three allowable nestings would be:

- **FTPJME** — Complete all tiles in one filter, change filters and repeat the tile sequence.
- **TFPJME** — Complete each tile in all filters before starting on the next tile in the sequence.
- **TPFJME** — Complete each pawprint of the tile in all filters before starting on the next pawprint of the tile.

It is beyond the scope of the ETC to fully calculate the total time (with overheads) required to survey arbitrary areas with these different observing strategies. However the ETC can calculate the total elapsed time (with overheads) for one tile in one filter, and will indicate the overheads for each step of the calculation. In such a situation (1 tile, 1 filter) all of the three observing modes become identical.

A tool for calculating overheads where filter changes are also involved will be included in the P2PP [or SDT - TBD] module for VISTA.

4 Architecture

VIRCAM only has an imaging mode and consequently a single instrumental model. This is combined with the source model, a sky emission model, and an atmospheric transmission model. This section describes the component models of the ETC.

4.1 Instrument and Atmosphere Models

This model describes the sequence of instrument components that a light ray has to pass through during an observation. It consists of fixed components (e.g. primary and secondary mirrors, external baffles, cryostat window, internal baffles, 3 lenses) and a single user-selected component (filter). The instrument model also includes the model atmosphere and describes the effect of atmospheric absorption and extinction as a function of source airmass and humidity. The dominant source of opacity in the near infrared is absorption by water molecules. The ETC is provided with atmospheric transmission models that span a suitable range of user-selected airmass and humidity (e.g. [RD2]) assuming nominal extinction values for the VISTA site.

The numerical information for all these components will be supplied to ESO in order to define the Instrument Definition File. Once the user has selected the desired instrument setup, the ETC builds this model from the Instrument Definition File (IDF).

4.2 Sky background Model

This model describes the sky brightness as a function of wavelength. The dominant source of sky emission is in the form of narrow emission lines from O and OH. The 0.8-2.5 μm sky brightness is consequently highly variable and essentially independent of lunar phase, but is weakly dependent on airmass. The ISAAC ETC [RD3] assumes a default average sky (J=16.5, H=14.4, K_S=13.0 magnitude/arcsec^2), but also simulates bright and dark cases (delta sky = ±0.5 magnitude). The VIRCAM will follow the same practice. The sky model undergoes the same instrumental transformations as the source model, except airmass correction.

4.3 Source Model

Each simulated source is described by a spectral energy distribution and a geometry.

4.3.1 Source Spectrum

The spectral energy distribution is calculated from a list driven menu. Computed spectra are scaled in flux to match the required magnitude in the specified filter. AB magnitudes and fluxes will also be supported. The following spectral energy distributions are available:

- Power Law Continuum ($F(\lambda)=constant \times \lambda^{\alpha}$, $F(\nu)$ or $\nu F(\nu)=constant \times \nu^{\alpha}$, scaled to the object magnitude, (with appropriate units e.g. W/m^2/µm, Jansky, W/m^2)
- Blackbody (defined by the user-selected temperature in Kelvin, scaled to the object magnitude)
- Emission line (a Gaussian with user-selected flux, λ_{cen} and *FWHM*)
- Object Magnitude (system AB/Vega)

4.3.2 Source Geometry

The ETC can simulate either point sources or extended sources.

- A point source has spatial extent on the sky significantly less than the seeing diameter. The signal-to-noise is computed over a circular aperture with user-selected radius (default radius is equal to the seeing). The point spread function is modelled by a Moffat function [RD1].
- For extended sources, all calculations are in terms of surface brightness, and magnitudes are in magnitudes per square arcsecond.

4.4 Software Environment

The ETC software will make use of an HTML/Java based interface and modules written in C in line with standard ESO practice.

5 ETC Characteristic Data

The VIRCAM ETC requires access to an ETC database containing the following:

1. **Calibration files:**
   - sky background emission
   - telescope emission (primary and secondary mirrors, and baffle)
   - camera window emission
   - cryostat emission (baffles, lenses, filters)
   - atmospheric transmission (including extinction and absorption)
   - optical reflection and transmission (primary and secondary mirrors, cryostat window, lenses within cryostat)
   - filter transmission curves
   - detector characteristics, including: quantum efficiency (10%, 90% values), gain, read-noise.

2. **VIRCAM Instrument Definition File**

Additionally, The ETC will make use of the following data which are not stored beyond the duration of a simulation.

- Observation related: e.g. user-defined instrument configuration, observing characteristics. These data are stored in a temporary file and summarized in the output.
- Run-time files: these contain intermediate results from the simulation.
- Simulation results: the output is stored in a single temporary file that can be retrieved by the user.

5.1 ETC Database

The file formats and reference units are defined as follows:

5.1.1 Units

The VIRCAM ETC database will follow standard ESO practice and will use nm for wavelength and ergs/s/cm^2/nm for monochromatic flux. The user interface will allow a range of commonly used units; results will be communicated in a range of units. Transmission, reflectivity and quantum efficiency values range from 0 to 1. Sky brightness is given in magnitudes/square arcsecond. Extinction values are in magnitudes per unit airmass.

5.1.2 File Format

- Calibration files are stored as ASCII files to minimize external dependencies. Two comment lines indicate the file contents; a third gives the number of rows that follow. Sampling in wavelength will be set to x.x nm. These files will be kept up-to-date (by the ESO operations team) and will take into account changes in instrument performance over time.

- The IDF is written using DICB keywords in a PAF according to [AD1].

6 ETC User Interface

The ETC will reside in Garching and the user interface will be via HTML-based web pages. The look and feel will follow extant ESO instrument ETC interfaces, with one important enhancement. VIRCAM is a survey instrument and the ETC includes functionality to enable the user to examine different observing strategies and examine/minimize the overheads. The GUI interface will have the following layout:

- **Heading:** Links to ETC help, FAQ, useful numbers (gain, zeropoints etc)
- **Sections 1-5:** Input parameters
- **Output Page:** summary of the input parameters and the results of the simulation in form of both numbers and graphs/files that can be retrieved via the web (see below) including overheads.

The required functionality, and look-and-feel, was arrived at by considering a number of use-cases (see Section 10). The interface should be accessible by a remote command-line call (or uploadable parameter files) so that is simple to repeat calculations. Similarly, the results should be downloadable in simple ASCII so that the ETC can be accessed by external software, e.g. the Survey Definition Tool [AD2].

6.1 Input Parameters

This section describes the layout and instrument specific parameters of the input HTML form taking into account the instrument configuration, and to a limited extent, the possible observing strategies. From a user's point of view, the VIRCAM ETC GUI should appear very similar to the ISAAC ETC GUI (see Section 11 for a mock-up for VIRCAM).

The VIRCAM form, like the ISAAC form, is divided into five main sections. The most obvious difference is in Section 5 of the form where the user can select the calculation mode. The default option (1. S/N ratio) will calculate the total exposure time required to reach the user specified signal-to-noise ratio. The second option effectively allows the user to select the total exposure time to determine the resultant signal-to-noise. VIRCAM has an additional option (3. Observing strategy) to specify more details of the planned observations, up to the number of pawprints covering the same piece of sky in one tile (at this stage we do not allow for multiple tiles nor for filter changes within or outwith a tile).

The table below shows the input parameters in each section of the form, default options or values are in **bold**. The input method is either via a drop down menu where a limited number of values is allowed, or via a box in which the user types. Additional parameters which have not been included at this point, but may need to be considered are: ambient temperature, state of cleanliness of optical surfaces and distance of pointing from moon.

§1	Flux Distribution Object Brightness Brightness Units Spatial Distribution	Menu: **Power Law** (Menu: $F(\lambda)$, $F(\nu)$, $\nu F(\nu)$, α) Blackbody (temperature, K) Line (wavelength, flux, width) Box: **15.0** (only used for options 1-3 above) Menu: **Vega Mag**, AB Mag, Jy, $ergs/cm^2/s$, W/m^2 Menu: **Point Source**, Extended
§2	Airmass Seeing Humidity	Box: **1.60** Box: **0.80** Box: **50%**
§3	Filter	Menu: Y **J** H K_S etc
§4	Detector integration time (*DIT secs*)	Box: **20.0** (defaults to background limited value)

§5	Mode: 1. **Required S/N ratio**, or 2. Total object on-chip exposure time ($T_{exp}(obj) = N_{INT} \times N_{DIT} \times DIT$ *secs)* or 3. Observing strategy • N_{DIT} - the number of snapshot integrations (each of *DIT* sec) coadded in data acqusition system (DAS) before a frame is saved • $N \times M$ - the number of microsteps in X&Y in the microstepping pattern • N_{jitter} - the number of jitters in the jitter pattern • N_{paw} - the number pawprints that make up each tile • N_{pco} the number of pawprints covering the same piece of sky in one tile	Box: **20** Box: **120** Box: **3** Menu: **1×1** (no movement) or 2×2 only Box: **2** (any integer allowed) Box: **6** (any integer allowed) Box: **2** (any integer allowed)

The first two options simply calculate the on-chip exposure time per object ($T_{exp}(obj)=N_{INT} \times N_{DIT} \times DIT$) for a required signal-to-noise(option 1), or the achieved signal-to-noise for a given on-chip exposure time per object, $T_{exp}(obj)$ (option 2).

The third option (Observing strategy) enables an observer to select each step in an observing stratgey, that involves a single tile in one filter only. There are certain constraints, for example $N_{DIT} \times DIT$ needs to be greater than about 30 seconds in order for the wavefront sensor to integrate on a star. The N_{INT} frames that go into the calculation of total on-chip exposure time per object per tile are $N_{INT} = (N \times M) \times N_{jitter} \times N_{pco}$ (where N_{pco}=2 in the default scheme to complete one tile with 6 pawprints filling a tile with every sky pixel observed twice). Note that the total exposure time *per tile* is $T_{exp}(tile)=T_{exp}(obj) \times N_{paw}/N_{ppo}$ (or 3 times $T_{exp}(obj)$ in the default tile filling scheme, i.e only 1/3 of the tile time is spent on each particular piece of sky, the rest of the time being spent filling in the gaps between the chips)

For the Observing strategy option, the ETC will report back three times

- $T_{exp}(obj)$ the total on-chip exposure time per object
- $T_{exp}(tile)$ the total exposure time per tile
- $T_{elapsed}(tile)$ the elapsed time per tile, allowing for instrument and telescope overheads (e.g. time to microstep, jitter, movement to the pawprint positions making up a tile, time to write data to disk etc).

A more detailed discussion of this is given in Section 7.2.

Guidance on overheads incurred in doing another tile at the same position, with or without a filter change, is given in the help.

The output page will include warnings if users selected non-optimal or high overhead observing strategies. In addition the ETC will include extensive help pages with worked examples suggesting a number of observing strategies for common requirements.

User-selectable results will include:

- summary of input parameters
- counts/e$^-$ from object (within specified aperture)
  - *vs* seeing
  - *vs* exposure time
- counts/e$^-$ from sky (within specified aperture)
  - *vs* exposure time
- signal-to-noise ratio
  - *vs* seeing (in specified time)
  - *vs* time (elapsed/exposed)
  - *vs* sky brightness (in specified time)
  - *vs* magnitude (in specified time)
- time to reach specified signal-to-noise
- input spectrum
- spectrum seen by detector
- detected electrons *vs* wavelength
- tile observing efficiency (= $T_{exp}(tile)/T_{elapsed}(tile)$)
- saturation/non-linearity warnings for sky and target

7 Mathematical Model

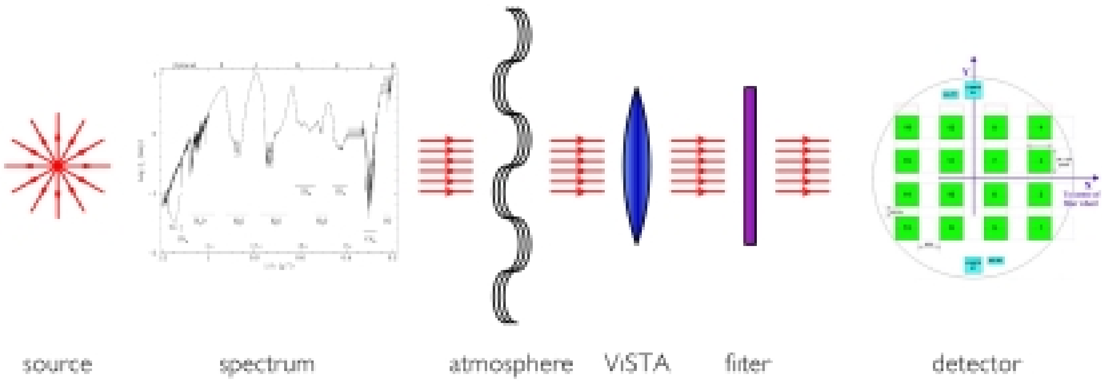

Figure 7-1: The Propagation of the Signal

7.1 Basic Signal to Noise Calculation

We start with a (template) spectrum in photons against wavelength and normalized to match the magnitude in the chosen filter. Then, the number of electrons/nm detected is given by the following equation relating the input spectrum to the output spectrum as shown in Figure 1.

$$P_{\det}(\lambda) = T_{\exp}(obj)P_{in}(\lambda)T(\lambda,\chi)F(\lambda)AR(\lambda)Q(\lambda)$$

where

- $P_{\det}(\lambda)$ is the detected spectrum in electrons/s/nm/m^2
- $T_{\exp}(obj)$ is the total object on-chip exposure time in seconds
- $P_{in}(\lambda)$ is the input spectrum in photons/s/nm/m^2
- $T(\lambda,\chi)$ is the transmission of the atmosphere at the given airmass
- $F(\lambda)$ is the throughput of the filter
- A is the unobstructed area of the main mirror in m^2
- $R(\lambda)$ is the throughput of the telescope/instrument
- $Q(\lambda)$ is the QE of the assumed detector

The total number of source electrons (per square arcsecond for an extended source) collected in bandpass λ_1 to λ_2 is then

$$N_{src} = \int_{\lambda_1}^{\lambda_2} T_{\exp}(obj)P_{in}(\lambda)T(\lambda,\chi)AR(\lambda)Q(\lambda)F(\lambda)d\lambda$$

and for the background

$$N_{sky} = \int_{\lambda_1}^{\lambda_2} T_{\exp}(obj)P_{sky}(\lambda)T(\lambda,\chi)AR(\lambda)Q(\lambda)F(\lambda)d\lambda$$

where $P_{sky}(\lambda)$ is the spectrum of the sky in photons/s/nm/m^2/arcsec^2 taking into account lunar phase and time of night.

For a point source, we calculate the source and sky photons within a user-defined aperture. For an extended source, the calculation is per square arcsecond. We assume that the point spread function can be approximately described by a Moffat function [RD1],

$$I(r) = I_O\left[1+\left(\frac{r}{\alpha}\right)^2\right]^{-\beta}$$

such that the number of electrons detected within a circular aperture, out to radius r (arcseconds), is:

$$N_{src}(r) = N_{src}\{1-[1+(r/\alpha)^2]^{1-\beta}\}$$

where

- β is the atmospheric scattering coefficient and
- α is related to the full-width half-maximum (i.e. the seeing) of the profile by the equation:

$$\alpha = \frac{FWHM}{2(2^{1/\beta}-1)^{1/2}}$$

The number of sky background electrons enclosed in the same aperture is simply:

$$N_{sky}(r) = N_{sky}\pi r^2$$

From which we can calculate the signal-to-noise ratio

$$SNR = \frac{N_{src}(r)}{[N_{sky}(r)+N_{src}(r)+\pi r^2(RN)^2]^{1/2}}$$

where RN is the detector read noise per pixel (e^-). The number of detected counts is calculated from the gain of the A/D converter.

VIRCAM has 16 detectors and inevitably there will be some spread in sensitivity across and between the arrays (expected to be <20%). For the ETC calculations we will use two values of the QE:

1. for signal-to-noise calculations we will use the 90th percentile QE (that is 90% of VIRCAM pixels have a measured QE greater than or equal to this value).
2. for saturation calculations we will use the 10th percentile QE (that is 10% of VIRCAM pixels have a measured QE greater than or equal to this value).

7.2 *Calculation of object and tile exposure times, and elapsed time for a tile*

Although VIRCAM allows three observing modes (FTPJME, TFPJME, TPFJME) as explained above the ETC is limited to simple calculations involving a single tile in a single filter, for which all three modes are in practise identical. Consequently although the elapsed time to perform an observing sequence will in practise depend on the observing mode used this is cannot be taken in to account in the ETC. So for a given tile and filter we have:

$$T_{\exp}(obj) = DIT \times NDIT \times N \times M \times N_{jitter} \times N_{pco}$$

where $T_{\exp}(obj)$ is the total on-chip exposure per object arising from the product of DIT (detector integration time), $NDIT$ (the number of integrations at each microstep position), $N \times M$ (the number of microsteps at each jitter position), N_{jitter} (the number of jitters around each pawprint position) and N_{pco} (the number of pawprints covering a given sky position within the tile).

The on-chip exposure time for the whole tile is

$$T_{\exp}(tile) = T_{\exp}(obj) \times N_{paw} / N_{pco}$$

The elapsed time per tile is

$$T_{elapsed}(tile) = (((((((DIT + O_{DIT}) \times NDIT) + O_{micro}) \times N \times M) + O_{jitter}) \times N_{jitter}) + O_{paw}) \times N_{paw})$$

where the $O_{\text{subscript}}$ are the time overheads associated with each operation. Thus the ETC will calculate elapsed tile time as well as actual tile and object exposure times.

Calculation forms.

8 Calculation Functions

The ETC will include the following data files:

- sky background emission
- telescope emission (primary and secondary mirrors, and baffle)
- camera window emission
- cryostat emission (baffles, lenses, filters)
- atmospheric transmission (including extinction and absorption)
- optical reflection and transmission (primary and secondary mirrors, cryostat window, lenses within cryostat)
- filter transmission curves
- detector characteristics, including: quantum efficiency (10%, 90% values), gain, read-noise.

9 Validation Sets

A validation dataset of tables and input data parameters, together with intermediate and final results will be provided with the ETC.

10 Appendix A – Use-Cases

To help develop the functionality of the ETC, the following use-cases were considered.

UC1: What exposure time is required to reach J=24 at 5σ (i.e. how many background limited exposures would need to be stacked) at zenith, with seeing=0.9 arcsecs assuming no jittering and no microstepping

SED	Magnitude
mag	24
Geometry	point source
Airmass	1.0
Seeing	0.9
Humidity	50%
Filter	J
DIT	<default=20s>
Mode	Signal-to-noise
SNR	5

UC2: What signal-to-noise do I get for a galaxy with K_S=20 mag/arcsec^2 in a 5 minute exposure with airmass=1.5 and seeing=0.8 arcsec assuming no jittering/microstepping.

SED	Magnitude
Mag	20
geometry	Extended
Airmass	1.5
Seeing	0.8
Humidity	50%
Filter	K_S
DIT	<default=10s>
Mode	exposure time
Exposure	300

UC3: I want to image a tile with 2x2 microstepping and a 5-point jitter pattern using the default pointing and tiling mode with background limited exposures. How deep do I go and what are the overheads.

SED	Magnitude
Mag	22
geometry	point source
Airmass	1.0
Seeing	0.8
Humidity	50%
Filter	H
DIT	<default=10s>
Mode	observing strategy
NDIT	3
microstepping	2×2
Jitter	5
pointings	6

11 Appendix B – VIRCAM ETC WWW Interface Mock-up

This is a preliminary version of the expected ETC interface and will evolve. This section will also grow to include an output page.

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