1 Title: Completing the legacy of UltraVISTA

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1.1 Abstract:

We propose to complete the legacy of UltraVISTA by delivering the deepest degree-scale near-IR imaging of the sky, within the unparalleled COSMOS survey field. Our 3-year programme will bring the J, H, K_s imaging across the full 1.5-deg^2 footprint of VIRCAM to the same depths as will be achieved within the 'ultra-deep' strips of the current UltraVISTA programme at DR4; i.e. $J = 26.0$, $H = 25.7$, $K_s = 25.3$ (AB mag, 5-σ, 1.8-arcsec apertures). This will be well matched to the depths of the optical imaging from the new Subaru HyperSuprimeCam deep survey, and to the depths of the *Spitzer* IRAC imaging from SPLASH. This 756 hr programme will deliver new results on the galaxy UV luminosity function out to $z \simeq 8$ and the galaxy stellar mass function out to $z \simeq 6$. It will also be a key resource for the study of dust-enshrouded star-forming galaxies, and for identifying spectroscopic targets for *JWST*. This project maximises the value of the VISTA time already invested in the COSMOS field, and will secure the long-term legacy of VISTA for studies of the distant Universe.

2 Survey Observing Strategy

Because deep Subaru HyperSuprimeCam imaging of the COSMOS field is now planned to $Y = 26.4$ (with a Y-band filter fairly similar to the VISTA Y-band filter – see Fig. 1), we choose to focus on VISTA's unique strengths and concentrate on J, H, and K_s. Starting in Period 99 we will therefore commence bringing the 'deep' strips of the J, H and K_s image up to the depths achieved by summer (July) 2016 in the 'ultra-deep' strips (i.e. in UltraVISTA DR4, scheduled for summer 2017).

We will adopt the same observing approach as has been successfully utilised in UltraVISTA to date, observing in pawprints 4, 5, and 6, which are stepped vertically with respect to each other by the standard 0.475 of the detector size. The observations will be split up in Observing Blocks (OBs) of 1 hour of exposure time, exposing a single pawprint, although we will also continue to supply a substantial fraction of the time in the form of some 0.5 hour OBs to facilitate efficient use of the time, including morning twilight. Jitters in a box of ±60 arcsec will be used to allow for the correction of bad pixels, structure in the dark, and reliable sky subtraction. Three OBs offset vertically by 0.475 of a detector height will be grouped together, ensuring that the depth builds up evenly on the three pawprints that make up the deep strips in the given filter. Other than that, the OBs are independent, allowing the scheduling algorithm to, for example, change between filters to make optimal use of the conditions.

The required deep observations of course require clear (including photometric) conditions as utilised by Ultra-

VISTA to date. For consistency with the existing image stacks we also again request good seeing conditions, with FWHM < 0.8 arcsec, although we will continue to have around 20% of the OBs have a seeing constraint of 1.0 arcsec to balance image quality and survey progress.

We note that the brightness of the near-infrared sky depends on the time of night and filter band. In the K_s and H bands, observations can be started by the time the sky is dark enough for the telescope to operate, but it is known that the J-band sky continues to decrease strongly well after astronomical twilight, so, for an optimal survey, these exposures are reserved for the middle of the night. We note and welcome the progress that ESO has made in utilising twilight observations with VISTA. This, coupled with the fact that we are no longer requesting Y-band observations from P99 onwards, means that we can expect the survey to progress at least as efficiently as before.

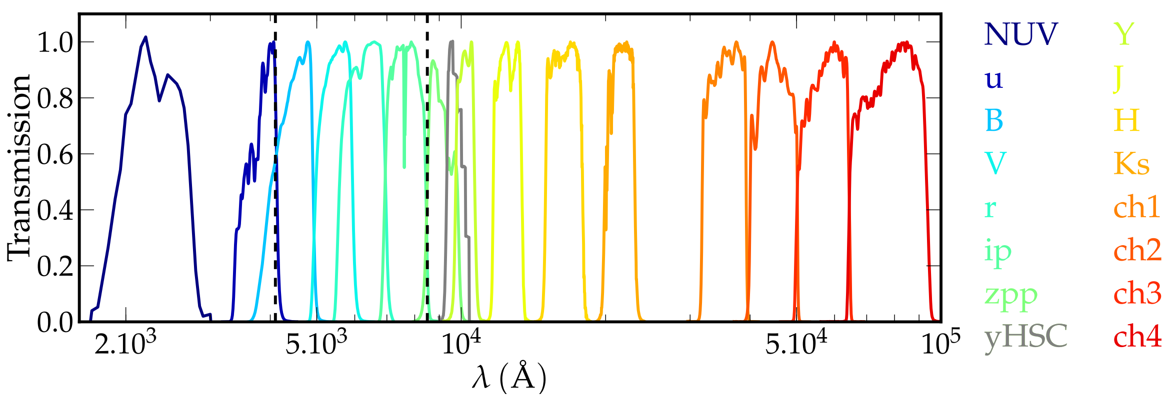

Figure 1: The filter coverage provided in the COSMOS field, highlighting the overlap between the Subaru HSC Y-band filter and the VISTA Y-band filter (from Laigle et al. 2016, ApJS, 224, 24). While interesting science (and helpful data checks) can undoubtedly be undertaken by combining/comparing the HSC and the existing UltraVISTA Y-band data, the efficiency of HSC at Y, and the depth of the planned deep HSC imaging survey in COSMOS, has motivated us to focus on obtaining complete imaging to a comparable depth in J, H and K_s (where VISTA+VIRCAM remains the most efficient camera in the world).

2.1 Scheduling & Observing requirements

As described above, our aim is to bring the entire J, H and K_s images up to the depths that will be achieved in the 'ultra-deep' strips in DR4 (i.e. including all data taken up until July 2016). Based on DR3, and the known observations from seasons 6 and 7 (see Fig. 2), we expect that the final depths achieved in the 'ultra-deep' strips in DR4 will be $Y = 26.3$, $J = 26.0$, $H = 25.7$, $K_s = 25.3$. For the reasons explained above, our plan is to consolidate and complete the images at these depths (rather than push still deeper in the strips) both because future science gains and legacy value are maximised by bringing the complete VIRCAM footprint to the same depth, and because these depths are both internally well-matched to galaxy colours and to the depths now achieved by complementary facilities at both shorter ($Y = 26.4$ from Subaru HSC) and longer ($m_{3.6\mu\mathrm{m}} \simeq 25.0$ from *Spitzer* SPLASH) wavelengths.

Given the anticipated impact of the HSC Y-band imaging, we choose to focus only on the J, H, and K_s imaging, and it is straightforward to calculate both the required integration and execution time based on our extensive experience of using VISTA to observe the COSMOS field over the past 7 years.

Thus, the imaging required to bring the 'deep' strips to the DR4 depth of the 'ultra-deep' strips requires:
i) 192 hrs of integration in the J-band;
ii) 264 hrs of integration in the H-band;
iii) 90 hrs of integration in the K_s-band.

Table 1: Scheduling plan and observing requirements

Period	Target name	RA	DEC	Filter setup	Tot. exp. time [hrs]	Tot. exec. time [hrs]	Seeing/FLI Transparency
P99	COSMOS	10 00 28.60	+02 12 21.0	J,H,Ks	45	62	$< 0.8''$ CLR
P100	COSMOS	10 00 28.60	+02 12 21.0	J,H,Ks	137	190	$< 0.8''$, Bright, CLR
P101	COSMOS	10 00 28.60	+02 12 21.0	J,H,Ks	44	62	$< 0.8''$, Bright, CLR
P102	COSMOS	10 00 28.60	+02 12 21.0	J,H,Ks	137	190	$< 0.8''$, Bright, CLR
P103	COSMOS	10 00 28.60	+02 12 21.0	J,H,Ks	44	62	$< 0.8''$, Bright, CLR
P104	COSMOS	10 00 28.60	+02 12 21.0	J,H,Ks	137	190	$< 0.8''$, Bright, CLR

The required integration time in K_s is significantly smaller than in J and H partly because we have already made significant strides towards deepening the 'deep' strips in K_s in seasons 6 and 7. In total, therefore, we require 544 hours of integration (192 hr in J, 262 hr in H, and 90 hr in K_s), spread evenly between paws 4,5,6 of the six-point VISTA mosaic pattern.

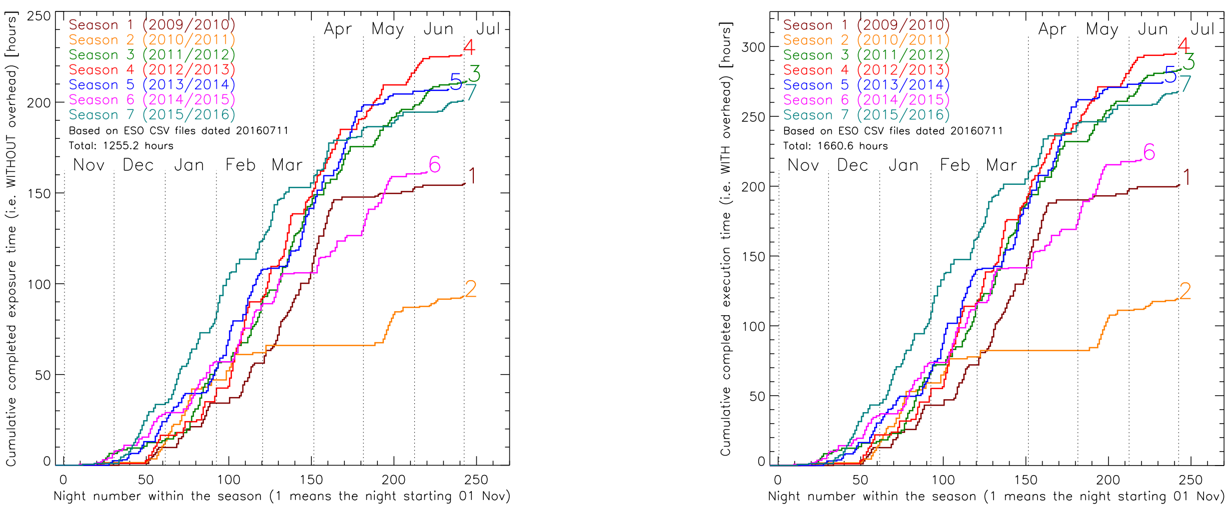

Figure 2: Season-by-season observing progress to date in the UltraVISTA programme. The left-hand panel shows integration time, while the right-hand panel shows execution time. Experience therefore shows the observing overhead is 1.32 (including Y-band, but 1.39 for the required mix of J, H and K_s proposed here), and that despite the constraints of observing at a single RA, a $\simeq 750$ hour programme can certainly be executed in $\simeq 3$ typical observing seasons. We note that season 1 fell short just because it was the first year of VISTA survey operations, while M1 was realuminized in the season 2. The second half of season 6 simply seems to have been a period of unusually poor weather at Paranal.

Based on our experience, as documented in Fig. 2, the observing overhead for UltraVISTA is both well measured and highly repeatable. Specifically, the observing overheads are 1.22 in J, and 1.48 in both H and K_s (the larger figure at longer wavelengths arising from a combination of the required shorter individual exposures, and some use of shorter OBs to help exploit twighlight). The requested *observing* time in each waveband is therefore 234 hours in J, 388 hours in H, and 133 hours in K_s, yielding a total of 755 hours, which for simplicity we round up to: **Total required time = 756 hours**.

Spread across 3 years, we therefore require 252 hours of observing time each year, and experience suggests that this should be split 1:2 between the two semesters each year (due to the RA of the target field lying at $\simeq 10h$). Excluding season 1 (start of survey) and season 2 (VISTA offline for 2 months), the median completed execution time is about 275 hours per season (i.e. per year; see Fig. 2, right-hand panel). There is therefore a bit of room to fit the required 252 hours. Given the proposed P99 start, we request a 6-semester schedule of: **62, 190, 62, 190, 62, 190 hours**, but if P104 is seriously at risk due to FOREMOST, then we could increase the allocation somewhat in the earlier periods to reduce the proposed allocation in P104 (this would also allow room for some carryover into P104 from any unanticipated bad weather season).

3 Survey data calibration needs

Tests we have made with UltraVISTA data products have demonstrated that the current VISTA calibration has been perfectly adequate for the UltraVISTA survey, and we expect this to be the case for the UltraVISTA extension described here. As previously, we request our observations to be taken in `CLEAR` conditions as we will be able to photometrically rescale all data to current observations.

4 Data reduction process

We will use image processing techniques and tools which have been proven in previous UltraVISTA releases; for more details see McCracken et al. (2012) and the DR2 and DR3 survey release documents. Our survey processing software is built around the "astromatic" software suite developed at the IAP by E. Bertin.

We note that, since the UltraVISTA ultra-deep stripes have already reached the depths of the survey extension proposed here, we anticipate no particular algorithmic or technical difficulties in processing the survey extension. In addition, extensive tests on the DR2 and DR3 UltraVISTA data products have shown that, to the best of our current knowledge, our stacked images are free from residual systematic effects (e.g. background subtraction problems or photometric astrometric calibrations). Our relative photometric calibration in DR3 is now at the few percent level, and our internal astrometric calibration is much better than one resampled COSMOS pixel (i.e. less than 100mas, more than adequate for the precise computation of photometric redshifts). The volume of data represented by the survey extension is easily manageable with current computer hardware.

As in our past UlraVISTA data releases, the key to producing the highest quality data products is a two-step data reduction process.

To briefly summarise: CASU will carry out basic processing (dark correction, nonlinearity correction, flat-field correction, sky-background correction at the OB level, destriping and astrometric calibration). Then, at TERAPIX, we will generate catalogues and weight maps from this initial CASU sky-subtracted data and generate first-pass stacks.

These first-pass stacks are used to generate object masks which are then used to compute sky frames for each of the individual images (the important point is that this is done for `all` the images taken in the old and new UltraVISTA programme from its start in 2009 until the current time). These sky frames are subtracted from the individual images (after the sky-frames generated by CASU are first added back, as CASU do not deliver images without sky-subtraction). The images are then "de-striped" (in both $x-$ and $y-$ directions) and large scale gradients are removed. These steps ensure than all residual instrumental background are perfectly removed. Next, weight-maps and catalogues are re-generated once more for each individual image. From these catalogues, for each individual image, we compute a global astrometric solution combining all data and all bands. This technique has worked successfully for the DR2 and DR3 releases. We will use an external astrometric catalogue based on the Pann-STARRS Medium-deep survey data which has been successfully used for processing UltraVISTA DR3 survey data. This astrometric catalogue has also been carefully chosen so that the new UltraVISTA survey data will align perfectly with up-coming HyperSurprimeCam data in the COSMOS field. Once astrometric solutions are computed, the images are coadded to the final COSMOS astrometric grid using a pre-defined tangent point. In the final processing step a few percent of the images will be rejected with seeing, ellipticity and transparency cuts, which helps remove bad images; in the past only a few percent or less of images are rejected. Images will be coadded using `SWarp` with optimally rejected pixels.

At the end of processing we will have pixel-matched multi-band images in each of the UltraVISTA bands aligned to the pixel grid of the COSMOS project (and the Hyper-SuprimeCam legacy survey). Note that at IAP we have all previous UltraVISTA data stored on disk, so that we will be able to optimally co-add all previous data to each years' new data set. For instance, it will be probably be necessary to compute new object masks for the new UltraVISTA survey data by including both old and new data. Thus, each new UltraVISTA release will contain all previous data from all previous releases, from both the original survey and from the survey extension. We note that it will not be necessary to reprocess *all* previous data, just data from the "deep" stripes which will be observed during the survey extension. This process, while it is quite costly in computer resources, produces perfectly flat images with no sky residuals and enables the optimal extraction of faint sources and limits the amount of spurious detections.

At present, we intend to use the same techniques adopted in the UltraVISTA survey to compute multi-band matched catalogues (dual-image mode `SExtractor` based on a multi-band detection image), but we are following closely recent developments optimal source extraction methods for multi-band photometry (e.g., future generations of the `SExtractor` tool and will adapt our techniques if they have proven benefits. It is worth noting that, thanks to queue-scheduled observations between UltraVISTA bands, point-spread function homogenisation is usually not necessary within the UltraVISTA bands. The data reduction process is summarised in Fig. 3.

5 Manpower and hardware capabilities devoted to data reduction and quality assessment

We will adopt the same overall strategy for the UltraVISTA extension which has proved so successful for the UltraVISTA survey to date.

Preparation of OBs for each of the observing periods as well as monitoring of progress and interaction with the ESO Survey Support Scientist will be carried out in Copenhagen using our existing tools and expertise. Pre-reductions of the observations will done in CASU at Cambridge. Sky-subtraction, calibration and stacking of the images will be done at the IAP using computer resources of the TERAPIX data centre. Qualitity control will be undertaken at all nodes. Phase 3 will be completed in collaboration between Copenhagen and TERAPIX. Overall survey management will be carried out in Edinburgh and through bi-weekly teleconferences. The allocation of resources within the team is summarised in Table 2.

The TERAPIX cluster at IAP has been upgraded recently. Currently the centre has around 800Tb of fast redundant disks and around 200 CPU cores. This is more than sufficient to process all data from the UltraVISTA extension, which we estimate will need around 100Tb/year (this figure comes from our experience of dealing with previous data releases; typically a large amount of temporary space is required to handle intermediate data products during the processing.) We expect to have sufficient resources to maintain the cluster (disk replacements) during the lifetime of the survey. The TERAPIX cluster will also handle production of the stacks from the sky-subtracted calibration data, together with preliminary catalogues.

As in the past, all institutes will participate in the validation of the final data products.

6 Data quality assessment process

We will use the techniques developed within the UltraVISTA survey to identify issues during data reduction and processing. This is centered around a set of tools that have been developed at the IAP to monitor data processing and data reductions. These tools have proved very effective at identifying problems in very large data sets.

Table 2: Allocation of resources within the team

Name	Function	Affiliation	Country	FTE/year
J. Dunlop	PI, Survey Strategy + OPC Reporting	University of Edinburgh	UK	0.5
F. Cullen	PDRA			
T. Kemp	PhD student			
M. Franx	Co-PI, Data Quality Control 3 + Catalogue Production	Leiden Observatory	NL	0.5
New Hire	PhD student			
O. Le Fèvre	Co-PI, Data Quality Control 3 + Catalogue Production	Laboratoire d'Astrophysique de Marseille	FR	0.5
Y. Khusanova	PhD student			
J. Fynbo	Co-PI, OB prep, Survey Monitoring	Dark Cosmology Centre,	DK	0.5
B. Milvang-Jensen	Phase 3 Survey Manager + OB submission			
H. J. McCracken	Terapixprocessing + Data Quality Control 2 & Phase 3	Institut d'Astrophysique de Paris	FR	0.7
New Hire	Software Engineer			
M.Irwin	VDFS Pipeline processing + Data Quality Control 1	University of Cambridge	UK	0.2

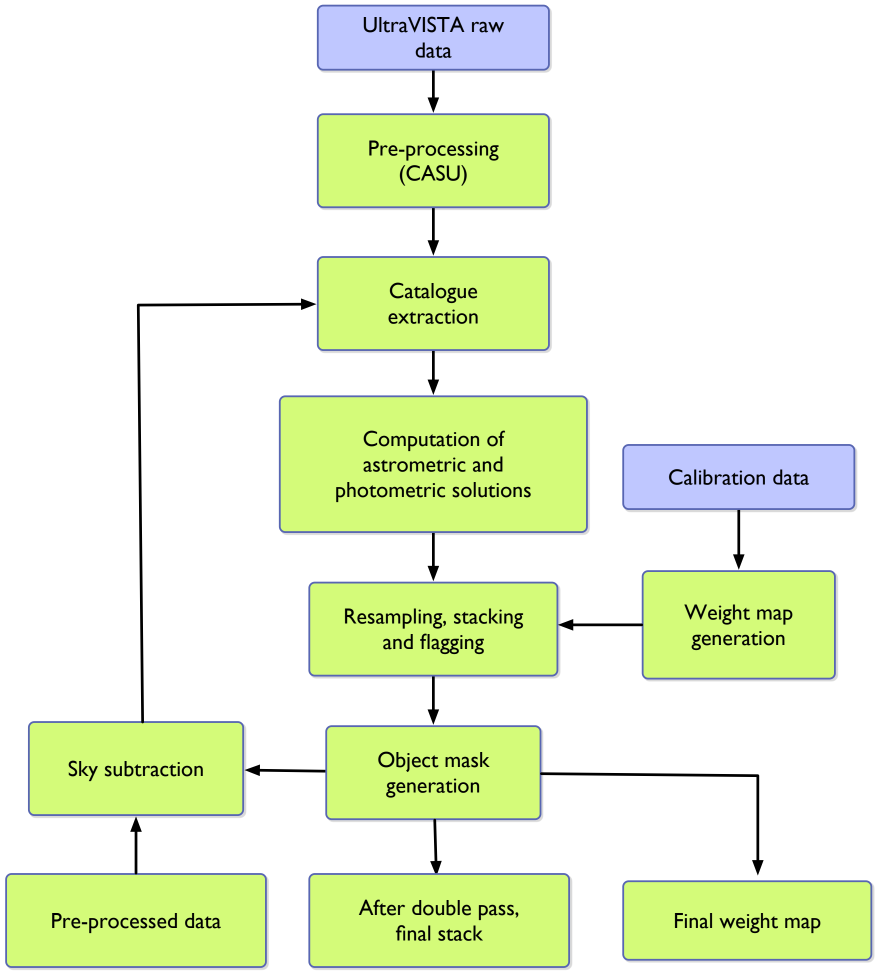

Figure 3: Block diagram of the UltraVISTA extension data processing. Note the double loop in the processing necessary to sky-subtract the images. In addition, in the actual survey data processing, astrometric and photometric computations are made using all available data in all bands. A threshold in seeing, ellipticity and photometric conditions is also normally applied before the final stack.

Concerning the individual images:

- Verification of background noise and photometric properties of each individual image based on distributions derived from previous UltraVISTA survey data;
- Verification and monitoring of individual point-spread functions on each image using the point-spread extraction tool `PSFex` and the `SPREAD_MODEL` object parameter;
- Verification of internal astrometric solutions using `Scamp` check-plots and external astrometric solutions using Pann-STARRS reference catalogues.

Concerning the stacked images:

- Positional comparisons with external astrometric catalogues (2MASS, FIRST) with sources extracted from the stacks;

- Verification of achieved depths using aperture-based noise estimates;
- Comparison with existing photometric catalogues including, but not limited to, both previous UltraVISTA data releases and external photometric catalogues.

7 External Data products and Phase 3 compliance

For each of the data releases, we intend to provide stacked images as well as their corresponding weight maps. These weight-maps correspond to the `MAP_WEIGHT` images produced by `Swarp` and have pixel values proportional to the inverse variance. The stacks provided will be based on all UltraVISTA data taken to that data, combining data from the original UltraVISTA survey and from the new survey.

Concurrent with each ESO data release of the stacked images, we will release the individual "1-hour OB" images through the Wide Field Astronomy Centre at Edinburgh (to enable interested members of the astronomical community to undertake variability studies etc). The first of these releases (in summer 2017 - see below) will release all the individual OB images taken since the start of the original UltraVISTA programme.

We will provide two sets of source lists: "dual-mode" ones, in which the K_s image is used as the detection image and each of the other images in turn is used as the measurement image; and "single-band" source lists in which each individual image is used in turn as both the measurement and the detection image. Dual-mode source lists have the advantage that, as the same number of entries is present for each source, colours can be easily computed for each object. The second type of source list contains, in principle, all sources to a given detection threshold (1.8σ). Source lists will be extracted using `SExtractor` and delivered in FITS format. From these source lists we will construct and deliver a multi-band catalogue in compliance with the Phase-3 standard document.

All data-products will be Phase-3 compliant. Phase-3 compliance will be assured by a set of tools we have developed for the UltraVISTA ESO data releases to date.

8 Delivery timeline of data products to the ESO archive

We plan three data releases, following our now established pattern of updating the UltraVISTA public dataset every second year.

- DR4 (Summer 2017, containing all data to Summer 2016, and part of the "UltraVISTA classic" dataset)
- DR5 (Summer 2019, containing all data taken to Summer 2018, new plus "classic")
- DR6 (Summer 2021, final data release containing all UltraVISTA and UltraVISTA extension data).