UBC-NASA Multi-Narrowband Survey. I. Description and Photometric Properties of the Survey

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ABSTRACT

Observations, analysis techniques and photometric properties of a multi-narrowband survey of a 20-deg\(^2\) area of sky at +33 deg declination are described. The survey is conducted with the 3-meter liquid-mirror telescope of the NASA Orbital Debris Observatory using intermediate-bandwidth filters. These filters have central wavelengths ranging from 455 to 948 nm, at intervals of 0.01 in log \(\lambda\), and give a spectral resolving power of \(\Delta\lambda/\lambda \sim 44\). In two spring observing seasons we have completed observations in 16 bands. Our preliminary object catalog contains over \(10^5\) detections to a typical 50% completeness limit of \(m_{AB} \sim 20.4\). This paper describes the observational techniques, data analysis methods, and photometric properties of the survey. The survey is expected to provide object classifications, spectral energy distributions and multi-narrowband redshifts for \(\sim 10^4\) galaxies and QSOs, for use in studies of galaxy and QSO distributions, evolution and large-scale structure. It will also provide photometry and spectral classifications for over \(10^4\) stars.

Subject headings: surveys, galaxies: photometry, galaxies: general, galaxies: stellar content, galaxies: structure, quasars: general

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1. Introduction

In recent years much progress has been made in understanding the distribution and evolution of galaxies. Much of this has been driven by the advent of redshift surveys. The CFA surveys (e.g., de Lapparent et al. 1986, Geller & Huchra 1989) provided the first extensive wide-angle view of the galaxy distribution. The combined CFA2 and Southern Sky Redshift Survey (SSRS2: da Costa et al. 1994a, 1994b) covers one third of the sky and contains 14,383 galaxy redshifts with a mean of \( < \frac{z}{z} > \sim 0.025 \). These surveys reveal a galaxy distribution dominated by filaments, sheets, and voids, with features comparable in size to the depth of the surveys.

Fiber-optic surveys, such as the Las Campanas Redshift Survey (LCRS: Shectman et al. 1996) and ESO Slice Project (ESP: Vettolani et al. 1997), have reached greater depth at the cost of reduced sky coverage and sampling completeness. The LCRS extends over 700 deg\(^2\) and contains 26,418 galaxy redshifts. Within the survey region, approximately 70% of galaxies having magnitudes in the range 15.0 < \( m_r \) < 17.7 were measured spectroscopically. The ESP covers 23.3 deg\(^2\) and contains 3342 redshifts to a comparable depth. These surveys reach depths of \( < \frac{z}{z} > \sim 0.1 \) and reveal structures with sizes of order 50 – 100 \( h^{-1} \) Mpc (the Hubble constant \( H = 100h \) km s\(^{-1}\) Mpc\(^{-1}\)).

Multi-slit studies, such as the ESO-Sculptor survey (Bellanger et al. 1995, Bellanger & de Lapparent 1993, Arnouts et al. 1997) and the CNOC surveys (e.g., Yee, Ellingson & Carlberg 1996), sample galaxies to \( < \frac{z}{z} > \sim 0.3 \) over angular areas of a few deg\(^2\). They reach a magnitude limit \( m \sim 21 \) with completeness exceeding 50%, and provide on the order of 10\(^3\) redshifts with \( < \frac{z}{z} > \sim 0.3 \). These are complemented by narrow-field spectroscopic surveys (e.g., Broadhurst et al. 1998, Colless et al. 1990, Lilly, Cowie & Gardiner 1991, Cowie, Songaila & Hu 1991, Lilly 1993, Colless et al. 1993, Lilly et al. 1995a, Koo et al. 1996, Munn et al. 1997) which cover areas of less than 1 deg\(^2\), but reach to faint magnitudes. For example, the Canada-France Redshift Survey (CFRS: Lilly et al. 1995a, Le Fèvre et al. 1995, Lilly et al. 1995a, Hammer et al. 1995, Crampton et al. 1993) contains redshifts for 591 galaxies having magnitudes in the range 17.5 ≤ \( I_{\text{AB}} \) ≤ 22.5 and has a median redshift of \( < \frac{z}{z} > \sim 0.56 \).

The deep surveys have provided a wealth of information on galaxy evolution. The excess counts of faint blue galaxies detected in early photographic surveys (Peterson et al. 1979, Tyson & Jarvis 1979, Kron 1980) were shown not to arise from a new population of high-redshift objects, but rather from moderate redshift (\( z \sim 0.5 \)) galaxies undergoing frequent bursts of star formation (for a review see Koo & Kron 1992). The nature of these galaxies, and what becomes of them, is not yet clear. Two possibilities are that they disappear from low-redshift samples by merging (Lacey & Silk 1991, Broadhurst, Ellis &...
Glazebrook 1992, Cavaliere & Menci 1997), or by fading (Babul & Rees 1992, Babul & Ferguson 1996). If merging dominates, it may be revealed by studies of the frequency of close pairs of galaxies (Zepf & Koo 1989). Recent studies (e.g. Woods et al. 1995, Patton et al. 1997) have reached opposing conclusions; larger samples are needed to resolve this. If fading is the dominant effect, then the progeny of these dwarfs should be detected as an upturn in the local luminosity function at faint luminosities. The luminosity function found by the blue-selected ESP shows evidence for such an upturn (Zucca et al. 1997), primarily due to contributions from blue emission-line galaxies. The LCRS luminosity function (Lin et al. 1996) does not show the effect, although this may be due to the fact that the galaxies were selected in the R band. Driver & Phillipps 1996 have argued that neither current wide-angle surveys nor deep surveys sufficiently constrain the local luminosity function. Larger samples of faint galaxy redshifts will be key in resolving these issues.

In order to investigate further the nature of the galaxy population at moderate redshifts, we have undertaken a survey of \( \sim 10^4 \) galaxies over a strip of sky comprising 20 deg\(^2\). The survey is unique both in extent, and in the nature of the observations. It provides spectral energy distributions (SEDs) for all objects, from which are derived morphological classifications and redshifts. This paper introduces the survey and discusses its photometric properties, selection effects and completeness. The data provide a base for studies ranging from galactic structure to cosmology. The main scientific results will be presented in future papers in the series. The Object Catalog will be made available to the community via the World-Wide Web (http://www.astro.ubc.ca/lmt).

\section{Observations}

The survey observations are conducted using the 3-meter telescope of the NASA Orbital Debris Observatory (NODO: Potter & Mulrooney 1997), located in the Sacramento mountains of New Mexico, near the town of Cloudcroft. The site, at an elevation of 2756 m, is dry and has typically \( \sim 120 \) photometric nights per year. The observatory is located within a 30-minute drive of Sunspot, home of the National Solar Observatory (NSO), the Apache Point Observatory, and the Sloan Digital Sky Survey Telescope.

The NODO telescope is a zenith-pointing instrument employing a rotating liquid-mercury mirror. Recent technological developments at Laval University and the University of British Columbia (UBC) have made liquid-mirrors a viable low-cost alternative to glass mirrors for large zenith-pointing telescopes (e.g. Borra et al. 1992, Hickson, Gibson & Hogg 1993). The telescope is discussed in detail by Mulrooney (1998) and Mulrooney & Hickson (1998). The liquid mirror is similar in design to that of the UBC-Laval 2.7-meter telescope.
and consists of a rotating parabolic dish covered by a 1.8-mm layer of liquid mercury. It is supported by an air bearing coupled to a DC synchronous motor. The motor is driven by a power supply whose frequency is stabilized to 0.01 ppm by a crystal oscillator. The mirror has a focal length of 4.5 meters and is parabolic to within a fraction of a wavelength. Off-axis aberrations are removed by a three-element optical corrector lens located near the prime-focus. The corrector and detector are supported by a tripod and top-end positioning system which facilitates mechanical alignment and provides remote control of focus and detector rotation.

The detector used for survey observations is a 2048 × 2048 pixel Loral CCD. It is a thick, front-illuminated device, with reasonable response at red and near-infrared wavelengths but limited blue response. The pixel size is 15 um square, which gives an image scale of 0.598 arcsec pixel⁻¹ in both right ascension and declination. The CCD is housed in a thermoelectrically-cooled dewar. Heat is removed from the dewar by closed-circuit circulation of a water-glycol liquid to a cooling unit located on the observatory floor. The normal operating temperature of the CCD is -30°C, which keeps dark current at a low level when the CCD is operated in multi-pinned phase (MPP) mode. During observations the CCD is scanned continuously in time-delay integrate (TDI) mode (McGraw, Angel, & Sargent 1980, Hall & Mackay 1984). The scan rate is synchronized to the sidereal rate at the telescope latitude. The effective integration time is 97.0 s – the transit time of images moving across the CCD due to the Earth’s rotation. This results in a continuous data stream of 90 KB/s, about 0.3 GB/hr. The CCD is driven by a Photometrics controller interfaced to a SUN SparcStation-20 computer. Because the controller is designed for high-speed operation to support space-debris observations, the read noise is relatively high (28 electrons), and only a 12-bit analog-to-digital converter is provided. This has limited the performance of the detector, particularly at short wavelengths where the sky is less bright. We plan to upgrade the system with a low-noise 16-bit controller before the spring 1998 observing season.

Data acquisition is accomplished by Hickson’s Tditool software running under the Solaris operating system. It provides interactive control of data-acquisition parameters and a continuous display of image data. Each CCD line is written directly to an 8-mm data tape and to the computer display. A 32-MB buffer memory prevents any data loss due to interrupt-response delays by the operating system. The display is provided with zoom and contrast controls which facilitate monitoring of focus and image-quality during the observations. One 8-mm tape has sufficient capacity for a single night of data.

The telescope is equipped with a holder for a single 4-inch-diameter glass filter, located between the corrector lens and the detector window. The filter is inserted at the beginning
of the night, and is used for the entire night’s observations. The filters are selected from UBC’s set of 40 intermediate-bandwidth interference filters designed by Hickson specifically for multi-narrowband imaging. They have central wavelengths at a uniform logarithmic spacing of 0.01 and constant bandwidth of 0.02 in log λ. Because of the declining sensitivity of the CCD at long and short wavelengths, only 33 filters are used in the survey. These have central wavelengths in the range 455 – 948 nm, with corresponding bandwidths ranging from 17.6 to 39.1 nm. The logarithmic sampling interval of the filter set provides equal redshift resolution at all wavelengths. The individual filter bandwidths naturally increase in proportion to the central wavelength, and are set at twice the sampling interval in order to prevent aliasing effects when observing emission-line objects. The characteristics of the filters are described in Table 1. Their transmission curves are shown in Figure 1.

Observations were conducted during the months of April-June in 1996 and 1997. In 60 nights of observing we obtained data in 16 wavelength bands spanning the entire range of sensitivity of our detector. Almost all nights were photometric. We obtained a minimum of three nights of observations with each filter. This was done in order to allow the rejection of spurious events such as cosmic-ray hits, to provide an independent estimate of the photometric accuracy, and to improve the signal-to-noise ratio of the detections. In some bands additional nights were obtained because of poor seeing or clouds. Table 2 provides a summary of the bands observed, the number of nights, and the ranges of right ascension for which we have data.

3. Data analysis

The large quantity of data generated by the survey observations requires a dedicated data analysis facility and considerable software development. The data tapes obtained in the survey were analyzed at UBC using a software package Lmtphot, written explicitly for the analysis of liquid-mirror telescope observations. The package consists of interrelated programs which provide an automated path from the raw data tapes to the final catalog of object photometry. This section gives a brief description of these steps; more details can be found in [Hickson (1997)].

3.1. Preprocessing

Preprocessing steps consist of dark/bias subtraction, flat-field correction, and sky subtraction. With TDI operation, each image pixel results from integration over the entire
length of a CCD column. Because of this, variations in CCD pixel response are greatly diminished. The corrections for both dark current and flat-field are one-dimensional. The dark correction is determined by averaging many lines of TDI data taken with the CCD covered. Flat-field exposures are obtained on cloudy moonlit nights. By median filtering several hours of observations, any star images and cosmic rays are removed. After dark and flat-field correction, consecutive CCD lines are grouped into overlapping 2048-line blocks. Sky subtraction is then performed by subtracting the mode of each row and column. Because of the high degree of uniformity in TDI images, this technique works very well. Systematic variations in the background after sky subtraction are typically less than 0.02%.

3.2. Object detection and photometry

Object detection and photometry is performed on the individual data blocks described above. In order to reduce noise, object detection is done on a smoothed copy of the image. The smoothing is normally accomplished by means of a $5 \times 5$ pixel ($3 \times 3$ arcsec) boxcar filter, which provides a 5-fold reduction in background noise. Other filter sizes may be selected for special programs. In each block, the mean and standard deviation of the background is determined using iterative outlyer rejection to eliminate star images. All pixels having values more than 2.5 standard deviations above the mean are noted and all connected sets of such pixels are found. The boundary of each such set is taken to be the detection isophote of an object. For each object the first three moments of the intensity distribution within the detection isophote are determined. The zero-order moment gives the isophotal flux; the first-order moments give the centroid of the image, from which coordinates are computed. The second-order moments determine the moment-of-inertia tensor. From its eigenvalues the major and minor axis diameters and position angle of the equivalent Gaussian ellipsoidal intensity distribution are found. All photometric measurements are done on the original unsmoothed image, within the boundary determined from the smoothed image. The smoothed image is used only for object detection and the delineation of the detection isophote.

It is well-known that raw isophotal magnitudes become seriously biased for faint objects because an increasing fraction of the light from the object falls outside the detection isophote. On the other hand, adding flux from outside the isophote increases the noise of the measurement because the signal-to-noise ratio of exterior pixels is low. We choose instead to apply a correction to the isophotal magnitudes based on the flux and mean intensity within the detection isophote. This correction is computed by assuming that the relationship between the intensity of any isophote and the flux within that isophote
is the same as for a Gaussian intensity profile. Although disk galaxies might be better represented by an exponential profile, a Gaussian provides a good approximation to the seeing-degraded profiles of the faintest galaxies in our images, for which the magnitude correction is significant. The method was tested by applying it to realistic simulations of artificial images having scale, resolution and noise comparable to the actual data. The corrected-isophotal technique was found to provide an unbiased estimate of the true total magnitude and to have lower noise than alternative estimators. Details of the correction procedure and the simulations are described by Hickson (1997).

The advisability of using total magnitudes to estimate spectral energy distributions is debatable because the flux in different bands is not determined from exactly the same areas. (See Koo & Kron 1992 for a discussion of the difficulties of measuring colors of faint galaxies). On the other hand the use of a common fixed aperture has its own problems. Unless the aperture is much larger than the seeing disk, seeing variations will cause significant changes in the fraction of flux within the aperture. However, such large apertures generally result in unacceptably-high levels of sky noise. In addition, noise fluctuations affect the alignment of the apertures, so the areas of measurement are in fact never exactly the same.

In order to identify and separate objects whose images overlap, the object detection algorithm is run repeatedly using increasingly-bright thresholds. At each stage the object list is examined for multiple detections within the isophotal boundary of every object found in the previous iteration. In such cases the isophotal and total fluxes of the “parent” object, determined from the original \((2.5\sigma)\) isophote, is divided amongst the “children” in proportion to their isophotal fluxes at the time that their images separate. This recursive technique is similar to that used by other photometric packages and is very successful at separating blended images. For our data, the fraction of objects affected by blending is typically of order 1%.

The photometry program produces a list of all objects detected in a night’s observations, with instrumental magnitudes and positions, estimated errors, image parameters and the seeing FWHM, determined from star images. Initial (instrumental) coordinates are determined by applying corrections for aberration, nutation to the Cartesian coordinates of the image centroids, then precessing these values to a standard epoch. The preprocessing, object detection and photometry is the most time-consuming part of the analysis, requiring about 4 hours of CPU time on a Sun Ultra-I computer to process a 3-GB data tape. The process produces a photometry file, with typical size \(\sim 10\) MB, for each night of observations.
3.3. Astrometric and photometric calibration

An astrometric and approximate photometric calibration is obtained from data in the Hubble Space Telescope Guide-Star Catalog (GSC: Lasker et al. 1990, Russell et al. 1990, Jenkner et al. 1990). The calibration process consists of matching stars in the GSC with those in the photometry file, then applying appropriate corrections to the instrumental positions and magnitudes. The matching is done iteratively, beginning with the brightest stars to obtain a rough fit, then improving the fit by using the more numerous fainter stars, one magnitude interval at a time. At each level, five free parameters are fit. These are the coefficients of a linear regression in right ascension and declination and a fixed magnitude correction. The fitting error is minimized in 5-dimensional parameter space by means of the simplex algorithm. The technique is robust and converges to the correct solution in a relatively short time. It typically takes about 5 min to calibrate an entire photometry file. The resulting coordinates have typical RMS errors of $\lesssim 1.0$ arcsec in both right ascension and declination. We believe that the technique is capable of greater accuracy, but we are presently limited by distortion in the telescope’s optics. The magnitude fitting is necessary to correctly match the target and GSC stars. A constant is added to the instrumental magnitudes of the target stars so that their mean magnitude matches that of the listed V-band magnitudes of the corresponding GSC stars.

After astrometric calibration, a more-accurate photometric calibration is made using spectrophotometric standard stars in the survey field. As only two stars in our survey area have published spectrophotometry (HZ 21 and BD+332642) a program to establish secondary spectrophotometric standards in the LMT survey area was undertaken at Kitt Peak national Observatory (KPNO). Using the 2.1-meter telescope and Goldcam spectrograph, 22 stars were observed in the region of sky observed by the NODO telescope. The resulting spectrophotometry is reported in a separate paper (Hickson & Mulrooney 1998). These stars pass through the NODO telescope field at approximately 30 min intervals, providing an accurate calibration for all our wavelength bands. For each band, the product of the filter transmission curve and standard star specific flux is integrated to provide the magnitude zero point for the band. In order to correct for any slow variations in transparency during the night, a second-order polynomial is fit to the zero points obtained from the standard stars and applied to the instrumental magnitudes to give the calibrated magnitudes for all objects.

We use the AB magnitude scale (Oke 1974) defined by

$$m_\nu = 56.10 - 2.5 \log f_\nu$$

where $f_\nu$ is the specific flux, in W m$^{-2}$ Hz$^{-1}$, averaged over the filter bandpass. As our filters
have relatively narrow bandwidths, this is a good approximation to the monochromatic flux at the central wavelengths of the filters (Table 1).

3.4. Merging and cataloging of object data

The next step is the merging of calibrated photometry files from all nights in which observations were made with the same filter. The program identifies all objects which are detected with position errors of less than 3.5 arcsec and magnitude differences of 1.0 or less. In order to reject cosmic rays and spurious detections of noise, we require that an object be detected on more than one night. 3.5 arcsec corresponds to $2.5\sqrt{2}$ times the typical astrometry error. The chance of an object having a position error larger than this is about 0.01. At the lowest galactic latitudes reached by the survey, the density of objects, most of which are stars, is of order $10^{-3}$ arcsec$^{-2}$. The probability of finding a second object within 3.5 arcsec of a given object is therefore of order $1 - \exp(-0.006\pi) \approx 0.02$. Thus the 3.5-arcsec criterion leads to roughly comparable rates of dropouts and contamination in the most crowded area of the survey.

For each night, the random error in the magnitude is estimated from the object counts, isophote area and background variance. The mean magnitude is then determined, weighting the magnitudes for each night by the reciprocal variances. The same weights are used when computing the mean values of the other photometric and astrometric parameters for each object. The final photometric errors are computed as follows: For each object, the variance of the mean is computed from the individual magnitude variances. This provides an estimate of the random noise. However, systematic errors can occur due to imperfect correction of extinction variations. The total error (random plus systematic) is estimated by computing directly the variance of the magnitudes obtained on different nights. The larger of these two error estimates is adopted.

This procedure produces a single photometry file for each wavelength band. These files are then merged to form a single file of SEDs for each object. Objects whose positions agree to within 3.5 arcsec are assumed to be the same, and the individual magnitudes, in the different bands, are entered in the corresponding fields of the object data in the output file. The result is a set of magnitudes, in as many as 33 bands, for each object.
4. Performance of the telescope

The image quality of the liquid-mirror telescope is primarily limited by the seeing at the site. The median FWHM of our star images is 1.4 arcsec, although images as small as 0.9 arcsec were occasionally recorded. While the present corrector does provide good image quality over the entire 0.33-deg field, it does not remove distortion. This is a problem for TDI observations because the images do not track in straight lines at a constant rate. The field distortion is in fact more serious than the usual star-trail curvature effects which are present due to the non-zero observatory latitude (Gibson & Hickson 1992, Zaritsky, Shectman & Bredthauer 1996). As a result, the images suffer from a varying degree of image smear which, while small at the field center becomes \( \sim 2 \) arcsec near the north and south edges. Because of this, the survey area was restricted to the central 75\% (16 arcmin) of the CCD field of view. We plan to upgrade the corrector with one designed for TDI observations before the spring 1998 observing season.

The combined throughput of the atmosphere, telescope, corrector and CCD was determined from the observed flux of the standard stars, and is shown in Figure 2 as a function of wavelength. The throughput is \( \sim 18\% \) between 650 and 800 nm and declines rapidly at wavelengths shorter than 500 nm and longer than 900 nm due to the falling CCD response. The overall efficiency and shape is consistent with expectations. The useful wavelength range with this CCD is approximately 450 – 950 nm.

One area of concern with liquid mirrors is the effect of wind. Under calm observing conditions, fluctuations in the rotation period of the mirror are 10ppm, due primarily to thermal gradients in the dome area. Larger fluctuations are observed on windy nights, due to wind gusts affecting the mirror. Although the telescope is well shielded inside the observatory’s 50’ diameter dome, useful observations are not possible when exterior winds exceed 12 m s\(^{-1}\). With such high wind speed, variations in mirror rotation speed of order 30 ppm are seen. The image quality is degraded (star images have FWHM \( \sim 2.4 \) arcsec), but at least part of this may result from poor atmospheric seeing associated with high wind speed.

5. Properties of the survey

The coordinates and area of the survey region are indicated in Table 3. Since the NODO telescope is a zenith-pointing instrument, the region of sky surveyed is determined by the observatory latitude and the time of observations. Our spring observing season, characterized by good weather at the site, typically extends from early April until late June.
Although some observations were made with right ascension as early as 9 hrs, the region of overlapping coverage extends approximately from 12-19 hrs. In order to avoid the high stellar density near the galactic plane, which would make accurate photometry difficult, we chose to end the survey region at 18:00 hrs right ascension. The total area is 20.13 sq deg.

The survey region extends over a wide range of galactic latitude, $10 \deg > b > 85 \deg$, and contains over $10^5$ stars and galaxies. Because of image distortion introduced by the telescope corrector, we do not attempt to distinguish stars from galaxies on the basis of image structure, although it should be possible to do this using images obtained with the new corrector. However, unlike conventional photometric surveys, stars and galaxies can be distinguished by their different spectral signatures. In their study of the multi-narrowband imaging technique, Hickson, Gibson and Callaghan (1994) simulated both stars and galaxies and included 81 stellar templates, as well as galaxy templates, in the analysis program. For signal-to-noise ratios of 5 or more, galaxies were rarely confused with stars. Similar results have been found by Peri, Iovino and Hickson (1997) in simulations of QSO spectra. In the spectral analysis of the catalog, objects will be compared with both galaxy and stellar templates, in order to separate stars and galaxies, provide spectral classifications for both and estimate galaxy redshifts. The resulting stellar data set will be useful for studies of stellar populations and galactic structure.

As an illustration of the photometric accuracy of the survey, we plot in Figure 3 the magnitude differentials from two different nights, at 752 nm, as a function of magnitude. The curve shows the RMS magnitude difference which rises from $\sim 0.04$ for $m < 16$ to 0.52 at $m = 21$. From this we can estimate the standard error in our magnitudes, which are based on the mean of typically three measurements (from three nights of observations). The mean of three magnitude measurements is smaller than the RMS difference between any two individual measurements by a factor of $\sqrt{6} \simeq 2.45$. Thus, we expect our mean magnitudes to have typical errors ranging from 0.02 to 0.2 mag. The absence of magnitude differentials greater than 1.0 is a result of the 1-magnitude limit imposed by the object pairing algorithm. From the figure it is evident that the number of objects missed because of this becomes significant only at magnitudes comparable to the 50% completeness limit.

6. Selection Effects and Completeness

Before the survey data can be used for statistical analysis, a complete characterization of the selection effects is needed. Our photometry algorithm finds all light distributions which exceed a surface-brightness threshold over a minimum number of contiguous pixels. The detected objects will therefore be limited by surface brightness as well as by apparent
magnitude. In addition, there will be an angular separation limit below which objects are not individually distinguished.

In order for an object to be detected, the smoothed surface brightness in its image must exceed the detection threshold for a minimum of 5 contiguous pixels. This corresponds to a minimum area $A_m = 1.788 \text{ arcsec}^2$. Thus, if $f$ is the flux within the detection isophote and $\bar{i}$ is the mean intensity within this isophote, the first selection criterion is

$$f/\bar{i} \geq A_m$$  \hspace{1cm} (2)

Clearly, for the object to be detected at all, we require

$$\bar{i} > i_m$$  \hspace{1cm} (3)

where $i_m$ is the detection threshold intensity. Because object detection is done on a smoothed version of the image, these selection effects refer to the average surface brightness of the object over the smoothing area (normally $3 \times 3 \text{ arcsec}$).

A third selection effect occurs because we require a minimum signal-to-noise ratio $\zeta$. The noise has contributions from the Poisson noise in the image and the background, hence,

$$f > \zeta^2 (g + \sigma^2/\bar{i})$$  \hspace{1cm} (4)

where $\sigma^2$ is the background noise variance and $g$ is the system gain (the signal produced by a single photoelectron). Equations (2 - 4) represent the three photometric selection criteria of the survey.

In order to maximize both the number of objects detected, and the accuracy with which they are measured, the surface brightness of the detection isophote is set at as low a level as the background noise will permit. Thus, $i_m = \epsilon n^{1/2} \sigma$ where $n$ is the number of pixels in the smoothing kernel and, typically, $\epsilon = 2.5$. The background noise is generally dominated by light from the sky, which varies substantially with lunar phase. Thus, the selection criteria (2) and (3) are local rather than global. The values of $\sigma$, for each object, are recorded in the individual photometry files, along with $n$, $\epsilon$, $\zeta$, and $g$. From these the selection criteria can be determined for each object.

Although the selection criteria are local, global averages can be made for any subset of data. This is illustrated in Figure 4, in which the mean surface brightness

$$\mu = m - 2.5 \log A$$  \hspace{1cm} (5)

where $A$ is the area of the detection isophote, is plotted vs $m$ for objects in the range 12.0 - 12.1 hrs in the 752 nm band. The three solid lines indicate the respective selection
criteria, Equations (2 - 4). There is good agreement between the shape of the region delineated by the lines and the boundaries of the data points.

The magnitude limit for any portion of the survey data can be estimated from the surface brightness of the detection isophote, the minimum area required for detection, and the seeing FWHM. This is a function of sky brightness and atmospheric conditions, and so can change on short timescales. Since all necessary data are recorded in the catalog, it is possible to compute the limiting magnitude for any time and wavelength band.

The completeness limit can be estimated by examining the counts $N(m)$ of objects whose magnitude is less than or equal to $m$. At high galactic latitude, the counts at the faintest magnitudes are dominated by galaxies, which have a linear log $N$ vs $m$ relation. We calculate the 50% completeness limit $m_{1/2}$ as the magnitude at which the observed counts fall below a linear extrapolation of the $N(m)$ relation by a factor of two. Figure 5 shows the $N(m)$ plot for the 752 nm band. The 50% completeness limits for the various wavelength bands range from 19.0 to 21.1; the median value is 20.4.

7. Discussion

This paper introduces the UBC-NASA Multi-Narrowband Survey, which began in 1996 and is now $\sim 50\%$ complete. Observations have been made in 16 wavelength bands and are continuing in order to enlarge the data set to 33 bands. Our preliminary catalog is reasonably complete to a magnitude of $m_{AB} \sim 20.4$ a surface-brightness of $\mu_{AB} \sim 23.5$. In addition to the narrowband data, we also obtained 15 nights of observations using broad-band B, V, R and I filters, which are currently being reduced. These data will compliment the narrowband data and allow us to reach fainter magnitude limits with lower spectral resolution.

These data provide a base for studies of the galaxy space density and luminosity function to $z \sim 0.5$, galaxy spectral evolution and large-scale structure. Simulations (Hickson, Gibson & Callaghan 1994, Cabanac & Borra 1995, Chapman & Hickson 1997) indicate that galaxy redshifts can be obtained with an accuracy of $\Delta z \sim 0.03$ with the full set of 33 bands. This should suffice to detect the presence of structures on scales reported by Broadhurst et al. (1990) if they exist. Also, simulations indicate that, by means of topological measures, such data can also serve to distinguish competing models of galaxy formation by means of topological measures (Brandenberger, priv. comm.).

With the data already in hand, redshifts with accuracy $\Delta z \sim 0.05$ are achievable. The object catalog will be refined as additional observations are obtained. The image database
will also allow targeted programs not possible from the catalog alone. For example, by increasing the degree of smoothing, the surface-brightness limit can be extended to $\mu \sim 26$ in order to detect and study low-surface-brightness galaxies. The very high degree of background uniformity provided by the TDI imaging technique make this data set particularly valuable for the study of such objects, and a study is presently underway (Mulrooney 1998).

The catalog is expected to contain $\sim 10^3$ QSOs (Zitelli et al. 1992). Simulations (Peri, Iovino, & Hickson 1997) indicate that QSO’s can be reliably detected, and distinguished from stars, at signal-to-noise ratios $\gtrsim 7$ from the survey data. While our survey area is less than a factor of two larger than that of the Durham-AAT survey (Boyle et al. 1990), which reaches a comparable magnitude limit, our multi-narrowband technique is relatively free from selection biases and should be sensitive to quasars over a wide range of redshifts.

The several hundred thousand stars contained in the catalog will be of value for studies of stellar populations and galactic structure. The multi-narrowband photometry will provide accurate spectral classifications as well as magnitudes and colors for most of these stars. In addition, the geometry of the survey area probes a relatively large range of galactic latitude.

This survey will compliment, and provide experience for a similar survey to be conducted at +49 deg declination using a 6-m liquid-mirror telescope (the LZT project: Hickson et al. 1997). This instrument, the successor to the UBC-Laval 2.7m, is currently under construction and is expected to see first light in 1998. It will use the UBC filter set and should reach $m_{AB} \sim 23$ and measure over $10^5$ galaxies.

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Table 1. Filter Specifications.

| ID | $\lambda_0^a$ | $\Delta \lambda^b$ | log($\nu_0$)$^c$ | $\Delta \log(\nu)^d$ | $t_0^e$ | $W^f$ |
|----|---------------|------------------|-----------------|------------------|--------|--------|
| 948| 947.7         | 39.08            | 14.5003         | 0.019            | 0.933  | 36.43  |
| 925| 924.5         | 40.04            | 14.5111         | 0.019            | 0.928  | 36.96  |
| 906| 906.3         | 35.32            | 14.5198         | 0.018            | 0.900  | 31.71  |
| 883| 883.1         | 41.28            | 14.5311         | 0.021            | 0.924  | 38.10  |
| 868| 867.9         | 35.10            | 14.5388         | 0.018            | 0.952  | 33.38  |
| 844| 843.8         | 35.58            | 14.5509         | 0.019            | 0.932  | 33.09  |
| 825| 824.8         | 33.67            | 14.5608         | 0.018            | 0.950  | 31.96  |
| 806| 805.9         | 34.62            | 14.5709         | 0.019            | 0.936  | 32.27  |
| 788| 787.5         | 33.31            | 14.5809         | 0.019            | 0.927  | 30.85  |
| 770| 769.6         | 31.86            | 14.5910         | 0.018            | 0.937  | 29.79  |
| 752| 752.4         | 33.25            | 14.6008         | 0.019            | 0.955  | 31.72  |
| 735| 734.7         | 32.17            | 14.6111         | 0.019            | 0.940  | 30.17  |
| 719| 718.7         | 30.54            | 14.6208         | 0.019            | 0.954  | 29.13  |
| 704| 704.4         | 29.88            | 14.6293         | 0.019            | 0.930  | 27.78  |
| 688| 688.0         | 29.20            | 14.6397         | 0.019            | 0.936  | 27.30  |
| 671| 671.3         | 29.08            | 14.6503         | 0.019            | 0.933  | 27.10  |
| 655| 654.6         | 27.99            | 14.6612         | 0.019            | 0.930  | 26.03  |
| 641| 641.1         | 23.98            | 14.6705         | 0.016            | 0.919  | 21.99  |
| 629| 628.7         | 26.39            | 14.6789         | 0.018            | 0.952  | 25.10  |
| 614| 613.7         | 23.62            | 14.6893         | 0.018            | 0.910  | 21.45  |
| 598| 597.6         | 24.31            | 14.7010         | 0.018            | 0.717  | 17.41  |
| 586| 585.6         | 23.10            | 14.7099         | 0.018            | 0.720  | 16.63  |
| 571| 571.1         | 21.71            | 14.7207         | 0.017            | 0.750  | 16.26  |
| 557| 557.0         | 21.35            | 14.7314         | 0.017            | 0.707  | 15.05  |
| 545| 545.1         | 21.00            | 14.7409         | 0.017            | 0.726  | 15.22  |
| 533| 532.7         | 22.76            | 14.7505         | 0.019            | 0.730  | 16.59  |
| 519| 519.0         | 22.72            | 14.7609         | 0.022            | 0.679  | 15.38  |
| 510| 510.2         | 22.36            | 14.7698         | 0.019            | 0.689  | 15.39  |
| 498| 498.1         | 21.91            | 14.7798         | 0.019            | 0.670  | 14.66  |
| 486| 486.0         | 20.22            | 14.7904         | 0.019            | 0.752  | 15.18  |
| 476| 475.6         | 19.30            | 14.7998         | 0.018            | 0.690  | 13.31  |
| 466| 465.9         | 18.48            | 14.8090         | 0.018            | 0.673  | 12.42  |
| 455| 454.5         | 17.67            | 14.8196         | 0.018            | 0.632  | 11.17  |

$^a$mean wavelength (nm), from transmission curve

$^b$bandwidth (nm): equivalent width/central transmission

$^c$log of central frequency (Hz): c/mean wavelength

$^d$log frequency bandwidth: $0.434 \times$ bandwidth/mean wavelength

$^e$central transmission

$^f$equivalent width (nm): integral of transmission curve
Table 2. Observations

| Filter | Nights | ra range       |
|--------|--------|----------------|
| 455    | 3      | 11:05 - 19:35 |
| 510    | 3      | 11:32 - 19:30 |
| 557    | 6      | 09:42 - 19:00 |
| 571    | 5      | 08:24 - 19:01 |
| 598    | 2      | 11:43 - 19:30 |
| 629    | 3      | 10:08 - 19:01 |
| 655    | 3      | 10:10 - 19:31 |
| 688    | 3      | 09:23 - 19:03 |
| 704    | 3      | 11:49 - 19:05 |
| 752    | 3      | 10:30 - 19:15 |
| 788    | 4      | 09:57 - 18:58 |
| 806    | 3      | 12:21 - 19:40 |
| 844    | 5      | 10:20 - 19:08 |
| 868    | 7      | 10:40 - 19:35 |
| 906    | 4      | 12:30 - 19:05 |
| 948    | 3      | 10:23 - 19:03 |
Table 3. Survey Parameters

| Parameter                          | Value                      |
|-----------------------------------|----------------------------|
| ra range (2000)                   | 12 00 00 - 18 00 00        |
| dec range (2000)                  | 32 52 00 - 33 08 00        |
| central dec (2000)                | 33 00 00                   |
| dec width (arcmin)                | 16.00                      |
| ra length (arcdeg)                | 75.48                      |
| area (sq deg)                     | 20.13                      |
| pixel size (arcsec)               | 0.598                      |
| wavelength range (nm)             | 455 - 948                  |
| spectral resolving power          | 44                         |
| magnitude limit (typical)         | 20.4                       |
Fig. 1.— Transmission curves of the filters.

Fig. 2.— System throughput. The product of atmospheric transmission, primary-mirror reflectivity, corrector transmission and CCD quantum efficiency is plotted vs. wavelength.

Fig. 3.— Photometric residuals. The difference between magnitudes measured on two successive nights, in the 752 nm band, is plotted vs. the mean magnitude. The curve shows the RMS magnitude difference, which rises from $\sim 0.04$ for \( m < 16 \) to 0.52 at \( m = 21 \). The standard error in our final magnitudes (which result from the mean of typically three measurements) is smaller than this RMS difference by a factor of \( 6^{1/2} \approx 2.45 \).

Fig. 4.— Selection effects. Mean surface brightness within the detection isophote is plotted vs. total magnitude, in the 752 nm band, for objects with right ascension in the range 12.0 – 12.1 hrs. The solid lines, labeled with numbers corresponding to equations in the text, indicate the three selection effects of surface area (2), surface brightness (3) and signal-to-noise ratio.

Fig. 5.— Differential object counts. The number of detected objects, per square degree per magnitude interval, in the right ascension range 12-15 hrs is plotted vs. magnitude in the 752 nm band.
