Design of a Steerable Two-beam System for Simultaneous On- and Off-axis Imaging with the NUI Galway L3-CCD Camera

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Abstract

The National University of Ireland at Galway photometric camera has been developed for confirming and improving existing detections of transiting exo-solar planets. Satisfactory differential photometry has been performed with this camera in challenging astronomical regimes such as near bright sources or within crowded fields. Its valuable results are partially due to the instrument’s use of a low light level charged coupled device for enhanced detector speed and sensitivity. The SNR benefits of this detector help reduce atmospheric effects such as seeing and scintillation but only within small fields of view. This presents limitations on possible science targets when suitable reference stars are not in the immediate vicinity of the target.

Conventional solutions for imaging larger portions of sky without sacrificing SNR include telescope focal reduction methods and large arrays of CCDs. An alternative solution offered by this thesis entails a two-path, ‘outrigger’ optical design to image target and reference stars separately. This design provides an effectively larger, yet sensitivity independent, field of view. By this new approach, it allows detection of variable targets that formerly were not reachable with smaller scale detectors.

The optical design was originally generated with AutoCAD® drafting software before being compiled in, and vetted with OSLO® optical design software. The optical model tested in OSLO® consists of two sets of two focal-reducing doublets. Its capability was analyzed in terms of wavefront, fractional energy and aberration performance. These tests were performed through Johnson passband filters B, V and I. Through each filter, the limiting design aberration was chromatic focal shift that appeared most severe in the B-filter’s bandpass range. However, the degree of image blurring caused by this aberration and others did not exceed the scale of that already produced by atmospheric turbulence. For each bandpass, the model’s imaging performance met, and exceeded expectations set by all design constraints.
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## Contents

1 **Introduction**  

2 **Introduction to Differential Photometry and Challenges With Detecting Stellar Variables**  
   2.1 Basic Differential Photometry  
   2.2 Causes of Variability in Stellar Light-Curves  
   2.3 Time frames for Variable Stars and Exo-Planet Transits  
   2.4 Problems for Detecting Variability through Differential Photometry  
   2.5 Solutions to These Differential Photometry Problems  

3 **Stellar Photometry and Differential Photometry**  
   3.1 Historical Context and Description of Photometry  
   3.2 CCD Noise Removal and Calibration  
   3.3 Principles of Differential Photometry  
   3.4 Photometry and Differential Photometry Observing Methods  
   3.5 Photometric Colour Correction and Filter Selection  
   3.6 All Sky Photometry and Differential Photometry Data Reduction  
   3.7 Post-Processing of Photometric Data  
   3.8 Limitations to DP and Transit Photometry: Scintillation & Seeing  
   3.9 Determination of Exoplanet Characteristics From Transit Photometry  

4 **CCD and L3CCD Detectors for Differential Photometry**  
   4.1 General CCD Details and Operation  
   4.2 Aspects of the L3CCD Used in the NUIG-PC  
   4.3 L3CCD Improvements: Gain Register with Frame Transfer  
   4.4 CCD Noise and Post Processing  
   4.5 Comparing Noise of Conventional CCDs to the L3CCD  
   4.6 Benefits of L3 High Cadence Imaging In Challenging Regimes  

5 **Optical Designs for Differential Photometry and Theory Used to Evaluate Them**  
   5.1 Increasing FOV for Greater Selection of Comparison Stars  
   5.2 Focal Reducer Designs  
   5.3 TRIFFID to NUIG-PC with Focal Reducer  

---

4
### 5.4 FOSC Camera Designs

5.5 ESO-VLT (FORS) Design

5.6 Design Requirements Based on Sampling Theory

5.7 Design Requirements Based on Stellar Density

5.8 Theory Used for Determining Performance of Optical Model

5.9 Wavefront and Fractional Energy Theory

5.10 Aberration Theory

5.11 Introduction to OSLO® Optical Design Software

5.12 Process for Checking Model Performance through B and I Filters

### 6 Design and Performance Analysis of the NUIG-PC Outrigger Model

6.1 Description of NUIG-PC Optical Design, Camera Box and Mounting Methods

6.2 Results and Limitations of Optimizing the Model with OSLO® Optical Design Software

6.3 Requirements and Constraints Met by the Optical Design

6.4 Procedure for Final Doublet Selection

6.5 Results of the Optical Models’ Wavefront and Fractional Energy Analysis

6.6 Results of the Optical Models’ Aberration Analysis

6.7 Performance Dependence on Operating Temperature

6.8 Analysis of Model Performance through B and I Filters

### 7 Conclusions
List of Figures

2.1 Light curves simulated by Cornell’s Java® based ‘Eclipsing Binaries’ application. Top – Light curves over 360 degrees of binary star rotation with star separations in varying multiples of stellar radii. Curves broaden with closer separation. Bottom - Light curves produced from binaries with rotation axes at various angles of inclination. Curve depth is proportional to angle (i) (Author). ................................................. 14

2.2 A crowded field centered on variable IO Aur. Circular labels denote identified variable star candidates (Richmond, 2006). .................. 16

2.3 Series of images taken during low seeing conditions of the Crab Nebula. Filmmstrip shows pulsar light on every fifth frame (Tulloch, 2004a). .... 17

3.1 Quantum efficiencies for several detectors are plotted over wavelength. CCD photon sensitivity is clearly dominant above 400nm (Sterken & Manfroid, 1992). .................................................. 19

3.2.A Example of aperture photometry showing inner signal circle and outer sky/reference annulus (Reference 1). ................................. 22

3.2.B Increasing aperture size plotted against SNR. SNR initially increases from better sampling then decreases due to cosmics and dim stars (noise) (Rockenfeller, 2005). ................................................. 22

3.3.A Light curve produced from a planet transiting HD 209458 derived from observations from the ground-based STARE Project Schmidt camera (Charbonneau et al. 2000, Brown et al. 2001). ................................. 27

3.3.B Light curve produced from a planet transiting HD 209458 derived from observations from Hubble’s STIS camera. Better sampled and more accurate Hubble data has provided a more clearly defined curve (Charbonneau et al. 2000, Brown et al. 2001). .................................................. 27

3.3.C Various parameters of a generic light curve used to determine independent variables R*, Rp, i and u (Brown et al. 2001). ................................. 27

4.1.A The Low Light Level (L3) camera with Andor iXon DV-887-BV CCD produced by E2V Technologies (Reference 2). ................................. 30

4.1.B Schematic and photo of L3CCD depicting frame transfer mechanism and extra gain/multiplication register used for high cadence, open shutter imaging (Sheehan et al. 2006a and Reference 2). ................................. 30

4.2 Avalanche gain due to impact ionisation. ‘Avalanche multiplication’ results from applying a large voltage across the L3 chip’s extra dc electrode (black) (Robbins & Hadwen, 2003). ................................. 31

4.3.A L3 noise vs. conventional CCD noise showing $\sqrt{2}$ noise factor for the L3 CCD (Tulloch, 2004a). ................................. 32

4.3.B Illustration of signal level where L3 SNR degrades to being worse than conventional CCD SNR due to L3 noise factor (Tulloch, 2006). ................................. 32
5.1.A The NUIG/DIAS high-resolution camera (TRIFFID) with focal reducing optics. A dichroic beamsplitter directs blue light to APD detector and red light to L3 camera (photo by Sheehan). ........................................ 37

5.1.B The NUIG-PC for differential photometry with filter wheel and simple focal reducing lens. Inset photo shows the off-the-shelf ‘Optec’ focal reducer (photos by Sheehan & Butler). ........................................ 37

5.2 Schematic of BFOSC’s optical design showing 110 degrees fold of light path, filter and grisms in the collimated beam and aperture wheel at the telescope focus (Reference 9). ........................................ 38

5.3 AFOSC’s 8 position grism and filter wheels with stepper motor in foreground (Reference 3). ........................................ 38

5.4 Optical design ray trace for the ESO-VLT (FORS) Spectrograph. Additional optics allow for minimizing aberrations at full-field (Nicklas, 2005). ... 39

5.5 An off-scale representation of the telescope secondary, focal reducing optics and CCD (all in red). For perfect Nyquist sampling, the system focal length is reduced from 12m to 8.25m as shown in black. The size H represents the scale of one pixel (Author). ........................................ 40

5.6 Left – Stellar density plotted as a function of magnitude and solid angle for North Pole stars in the V band (Bahcall, 1980). Right – Star counts per square deg in the I band for several star fields. North Pole fields (2-6) for magnitudes 12-25 are highlighted in red for further consideration (Bahcall, 1981). ... 41

5.7 Plot of required arcminute sky radius needed to locate two stars of the same magnitude through filters V, B, R and I. Results show high magnitude stars are more populous. To locate two like-magnitude stars in magnitude ranges of 10-25, a FOV of 12’ is required (Author). ......................... 42

5.8 Astigmatism causes tangential and sagittal rays to focus at separate distances. A single focal spot is aberrated into two separate ones called the tangential and sagittal lines. A best focus blur is left between the two lines (Author). 45

5.9 Longitudinal spherical aberration causing focal length to be dependent on aperture position. The above under-corrected LSA produces an image of a ring blur surrounding a central point (Author). ......................... 45

5.10 Chromatic focal shift is longitudinal focal displacement between blue and red foci. Under-corrected CFS produces an image in the focal plane that appears as a central red dot encircled by a blue ring (Author). ......................... 46

5.11 An image pictured with no distortion, with ‘barrel’ distortion and with ‘pincushion’ distortion (Author). ......................... 46

5.12 OSLO® software spreadsheet for a positive lens doublet (Author). ...... 47

5.13 Transmission plots for UBVRI filters from Custom Scientific for use by the NUIG-PC at Italy’s Loiano telescope (Reference 9). ......................... 48

6.1 AutoCAD® representation of NUIG-PC with ‘outrigger’ lens design. The top panel shows a close-up 3D rendering of both beam paths. Both red and blue incoming beams focus on different sections of the telescope’s focal plane. Beam separation is exaggerated for visibility purposes. The middle panel is a wire-frame representation of the camera box, instruments and optics. Both LL3 camera and filter wheel are labelled, as are three folds (F1-F3), three lenses (L1-L3), and one beamsplitter (B). Blue arrows indicate the direction that translation stages holding mounted optics must be permitted to travel. The lenses’ focal length-to-diameter ratios in mm are 60/10 for L1, 200/32 for L2 and 125/35 for L3. The two bottom panels show wire frame and 3D...
rendering of the top view of the design. Telescope field curvature is not taken into account for any of the above schematics (Author). 51

6.2 Top - Spreadsheet window for the V star’s light path. Lens focal ratios and light path magnification are listed in the top ‘Lens’ field. Bottom – Full view and close up of L2 and L3, or surfaces 3-5 and 6-8 (Author). 52

6.3 Top - Spreadsheet window for the C star’s light path. Lens focal ratios and light path magnification are listed in the top ‘Lens’ field. Bottom – close up of L1 and L3, or surfaces 3-5 and 6-8 (Author). 53

6.4 On-axis and off-axis spot sizes and fractional energy performance for the V star’s light path in the V-band. Top-left: on-axis RMS spot size, bottom-left: full-field RMS spot size, top-right: on-axis polychromatic encircled energy, bottom-right: through focus diagram (Author). 56

6.5 On-axis and off-axis spot sizes and fractional energy performance for the C star’s light path in the V-band. Top-left: on-axis RMS spot size, bottom-left: full-field RMS spot size, top-right: on-axis polychromatic encircled energy, bottom-right: through focus diagram (Author). 57

6.6 Ray-analysis output windows for the V star’s light path in the V-band. Two-axis plots describe longitudinal foci displacement vs. aperture/wavelength resulting from astigmatism, spherical aberration and chromatic aberration. 3D wire frame ray trace graphic included; distortion plot included (Author). 58

6.7 Ray-analysis output windows for the C star’s light path in the V-band. Two-axis plots describe longitudinal foci displacement vs. aperture/wavelength resulting from astigmatism, spherical aberration and chromatic aberration. 3D wire frame ray trace graphic and distortion plot included (Author). 59

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**List of Tables**

6.1 I-band results for both V and C starlight paths. RMS, FWHM and 60% encircled energy spot sizes as well as longitudinal astigmatism, spherical and chromatic aberrations are presented for on-axis and full-field positions (Author). 60

6.2 B-band results for both V and C starlight paths. RMS, FWHM and 60% encircled energy spot sizes as well as longitudinal astigmatism, spherical and chromatic aberrations are presented for on-axis and full-field positions (Author). 60
Acronym List

AD – Airy Disk
AP – Aperture Photometry
APDs - Avalanche Photodiode Detectors
ASP – All Sky Photometry
(C) star – Comparison/Reference Star
CFS – Chromatic Focal Shift
DP – Differential Photometry
DR – Dynamic Range
FL – Focal Length
FORS – FOcal Reducing, low dispersion Spectrograph
FOSC – Faint Object Spectrographic Camera
FOV – Field Of View
FWHM – Full Width at Half Maximum
LSA – Longitudinal Spherical Aberration
L3CCD – Low Light Level Charge Coupled Device
NUIG-PC – National University Ireland at Galway Photometric Camera
OSLO\textsuperscript{®} – Optics Software for Layout and Optimization
PSF – Point Spread Function
PEIS – Post Exposure Image Sharpening
RMS – Root Mean Squared
RV – Radial Velocity
SNR – Signal to Noise Ratio
STARE - STEllar Astrophysics & Research on Exoplanets
STIS – Space Telescope Imaging Spectrograph
SD – Seeing Disk
TRIFFID – TRansputer Instrument for Fast Image Deconvolution
(V) star – Variable/Target star
Chapter 1

Introduction:

If any branch of astronomy could be considered as egalitarian, photometry is a strong example. There are not many other astronomical disciplines that require so little in terms of instrumentation or resolving power in order to make a meaningful contribution to science. If anything is garnered from the research presented in this thesis, it should be recognition that small-scale, yet novel approaches to instrumentation are capable of notable contributions.

A challenging area of differential photometry is detecting transits of exoplanets. Transit detection can be particularly complex if involving bright sources or dim sources within crowded fields. It is our goal to improve the NUI Galway Photometric Camera (NUIG-PC) to maximize its productivity in these regimes. Improvements in the instrumentation are oriented towards speed, sensitivity and angular coverage. In differential photometry, angular coverage can become a limiting factor for finding suitable comparison stars in the same field of view (FOV), particularly if the target is a bright source. Since brighter sources are less spatially dense, their mean angular separation increases. Moreover, the CCD’s image cadence can be limited by a larger angular separation since obtaining a larger FOV, while retaining suitable resolution, necessitates larger CCDs and typically longer readout times. We attempt to address this problem with a unique two-path, ‘outrigger’ optical system imaging onto a high speed, low light level charged coupled device (L3CCD). The additional optical elements decouple the adverse association between FOV and detector speed allowing previously unavailable variable sources to be examined.

The L3 chip’s high cadence imaging permits great improvements in signal to noise ratio (SNR). Good photometry results are not exclusively from the largest telescope apertures, or instruments with the largest bandwidth. Superior SNR can allow similar or better results from much smaller apertures with high speed instrumentation. The benefits of increased speed and improved sensitivity causes data taken from the NUIG-PC mounted on the moderately sized Italian Loiano 1.5m telescope to be comparable to data taken from traditional instrumentation mounted on larger telescopes. The size of the L3 chip still limits NUIG-PC science from the sector of all sky photometric surveys. Focus will be on confirming possible exoplanets already detected with radial velocity (RV) measurements as well as improving existing transit measurements.

The following chapter provides an introduction to differential photometry, discusses possible causes of stellar variability and the challenges involved in detecting that variability. The third chapter presents a more technical discussion of photometry
including detector calibration, observing methods, data reduction and interpretation of results. The following chapter covers the performance and advantages of the NUIG-PCs L3 detector. Chapter five reviews optical designs for differential photometry and covers design requirements for the NUIG-PC as well as optical theory needed to evaluate the new design. Chapter six introduces the NUIG-PC ‘outrigger’ design and presents the results of the optical models’ aberration analysis through three separate filters. The final chapter reviews and interprets the results obtained and offers possible future improvements.
Chapter 2

Introduction to Differential Photometry and Challenges With Detecting Stellar Variables

This section will introduce photometric methods and variable star targets as well as cover the causes and time frames for their light variations. From there, it will expand to describe the various difficulties of observing these targets from ground-based instrumentation. It will conclude by describing methods used to overcome several of these difficulties.

2.1 Basic Differential Photometry

The applications of general, or ‘all-sky’, photometry (ASP) are focused on recording star magnitudes relative to known or pre-classified standard stars. Differential photometry (DP) focuses on a much narrower window of sky with the goal of determining the variation of a single source. By recording the light levels of a target star, the background and 1-2 reference stars simultaneously, atmospheric effects may be subtracted from target star variations. The target star is often referred to as the variable (V) star and the reference as the comparison (C) star. Differential intensity measurements are established from V – C. Simultaneous measurement of a target with one or more suitable reference stars is a main concern for DP measurements.

2.2 Causes of Variability in Stellar Light-Curves

Reductions in the light levels from stars arise from a variety of conditions. Plotting this reduction in intensity over time will result in a light curve. Once variations in our atmosphere are accounted for, different models may be developed to explain various aspects of the shape, duration and periodicity of a light curve. Models for light variation commonly describe one of two types of physical circumstances. Variation is caused either by mechanisms related to the internal physical processes of the star or by the geometrical effect of obscuration of the star’s light by another body.

A prime example for internally caused variation is light from pulsars. The periodicity of pulsar light variation is extremely short and regular. A planetary transit model for the variation may be ruled out by its frequency alone. Other examples are
asteroseismic changes, star spots and dust formation effects within cooling atmospheres (Rockenfeller, 2005). Asteroseismically caused light variations are from the interior of stars undergoing oscillation modes when thermal energy is converted into kinetic energy (Brown, 2000). A combination of oscillation modes causes periodic pulsations in the star’s light levels. Full study of these modes requires detailed spectrum data. The resulting light curves summed over all frequencies appear random and non-periodic. Fourier analysis may be used to separate out the various frequencies contributing to the curve shape. The resulting curves are periodic on a scale of seconds to minutes. The curve’s period length is inversely proportional to the size of the dwarf star (Sackett, 1999).

Star spots are magnetically induced cool regions on the surface of highly magnetic stars. A star spot will revolve with the star and cause flux reductions that match the star’s rotation period. The resulting light curve can appear very similar to that caused by a planetary transit (Sackett, 1999). In fact, many closely studied variable stars are still not clearly determined to feature either a transit or star spot. One solution is to make a thorough comparison of light curves to RV observations of the perturbations of a host star’s motion due to an orbiting planet. These observations are seen as a Doppler shift in the wavelengths of the spectroscopic lines (Brown et al. 2001). Reductions due to dust formation are more typical of stars with high carbon levels. During periodic cooler cycles of the atmosphere, carbon condenses and reduces the intensity of emitted light by obscuration.

Examples of externally caused light variation are eclipsing or contact binary systems as well as transits of exo-planets. The light curves of binary systems are dependent on the flux contributions from two stars rotating around each other. System variables include the difference in stellar radii ($\Delta R$), the separation of stars (S) and the angle of inclination of system’s rotation axis to the line of sight (i). Comparing the light curve’s period and shape to various models permits estimation of these variables. Most binary curves are not viewed on axis (i<90), causing periodic curve depth disparity. If S is reduced to the point where an eclipsing binary becomes a contact binary, the bottom portion of the curve will flatten to a degree dependent on S. Figure 2.1 shows a binary system with different values of S and i. In most cases, binary system light curves will look very different from planetary transit curves. However, it is possible for them to mimic a transit shaped curve. A key difference is that a transiting star does not behave like a blackbody and light curves will remain wavelength dependent. Before confirming an exo-planet, it is important to either check data for wavelength dependency through filters or with any possible RV measurements (Sackett, 1999).

Exo-planet transits are not the leading cause of variable stars but they may be the foremost reason for intensified research in the field of DP. Exo-planet detection has become a thriving industry since Charbonneau’s accomplished photometric detection of an exo-planet in August, 1999. He theorized that tiny periodic reductions in star HD 209458’s light levels were due to a gas giant orbiting closely to the star (Charbonneau et al. 2000). Light curves were plotted from the intensity variations. These curves were the first indication of an exo-planet transiting the disk of a star. Like most first attempts, the modelling has its flaws, notably that scintillation and low SNR artificially broadens the base of the curve. Brown’s follow up with Hubble Space Telescope Imaging Spectrograph (STIS) data shows how atmosphere free imaging creates a light curve with higher definition (Brown et al. 2001). Figure 3.3 in section 3.9 shows both curves. The shape and period of transit curves are dependent on several factors in the same manner as curves from binary systems. Since detection
of exo-planet transits is one of the objectives of our instrumentation, more detailed study of transits is necessary. A review of transit photometry light curves is included in section 3.9.

![Light Curves simulated by Cornell’s Java® based ‘Eclipsing Binaries’ application. Top – Light curves over 360 degrees of binary star rotation with star separations in varying multiples of stellar radii. Curves broaden with less separation. Bottom - Light curves produced from binaries with rotation axes at various angles of inclination. Curve depth is proportional to angle (i) (Author).](image)

**Figure 2.1:** Light Curves simulated by Cornell’s Java® based ‘Eclipsing Binaries’ application. Top – Light curves over 360 degrees of binary star rotation with star separations in varying multiples of stellar radii. Curves broaden with less separation. Bottom - Light curves produced from binaries with rotation axes at various angles of inclination. Curve depth is proportional to angle (i) (Author).

2.3 Time frames for Variable Stars and Exo-Planet Transits

The flux from variable stars oscillates over a wide range of periods. The duration of periodicity and frequency of the light curves are examples of features that constrain possible causes of variation. For specifically determining transit candidates, causes of variation with periods outside a range of a few hours may be omitted. Pulsar light levels vary at small fractions of seconds, and cannot be confused with transits. Asteroseismic pulsations come closer at a range of periods of about five minutes for sun-like stars to twenty minutes for similar, older stars (Bedding et al. 2001). Periodicity from dust formation may be excluded as well since it occurs on much longer timescales.

Two origins of variability that may match the timeframes of transits are binary systems and star spots. Relying on additional observations is the best option for distinguishing one from another. Specifically, comparison of photometric to RV data often establishes which variable sources are due to transits. Only star spots produce photometric and RV data that both modulate in phase with the rotation period of the star. Transit RV modulation data is typically only periodically consistent with photometric modulation data. In addition, the phase of RV data from star spots is not well defined over longer time periods. Only actual transits will produce long-term consistency of RV data phase (Santos et al. 2003). Binary systems can be identified and discarded with spectral data as previously described.
The transit time for an exo-planet across HD 209458 is 184 minutes (Brown et al. 2001). The shape of the resulting light curve is examined in section 3.9. The duration of the transit depends on the orbital speed as well as the position where the body crosses the stellar disk. Orbital speed is determined by a planet’s proximity to its host star. Faster, more frequent transits contribute to why hot Jupiters are detected more often than more distant objects. Maximum transit duration also always occurs across the widest chord length of the disk. Since chord length is dependent on R* and i, transits take longer across larger stars viewed on-axis (i=90deg). Determining the length of the ingress and egress of a transiting planet is slightly more complex and covered in section 3.9. The duration of these periods is roughly 20 minutes with the start and stop being on the order of a few minutes. It is this timescale that measurements of an exo-planet’s density, size and atmosphere are dependent on (Charbonneau et al. 2002). Photometric instrumentation must be capable of capturing a maximum number of exposures within this period.

2.4 Problems for Detecting Variability through Differential Photometry

The previous three sections helped define areas of difficulty relating to detecting variability, specifically with transit photometry. Improved photometric instrumentation and observing methods must accommodate for and overcome these issues. Limited time frames for transits and limited fields of view may be resolved by improved instrumentation speed and sensitivity. In addition, better scientific methods are needed to identify false transit candidates as well as to improve measurements on verified transits.

Identifying new candidates may require observing in more challenging areas of sky. Examples of such areas include searching near particularly bright sources as well as within crowded fields. Figure 2.2 shows Mark IV data from the STARE project that is centred on variable IO Aur (Richmond, 2006). It should be apparent how dense the area is around the labelled V stars. Crowded field photometry requires particularly sensitive instrumentation to measure faint sources with small 1-2% light modulations because crowded fields tend to harbour a larger dynamic range of star magnitudes than uncrowded fields. In order to avoid saturation near bright sources, exposure times must be shortened. This typically results in a worsened duty cycle (ratio of exposure time to exposure time plus readout time). This may be alleviated by using smaller detectors with faster readout times. However, for DP, this poses the problem of severely limiting the number of available C stars needed for referencing to V stars. Thus, retaining a field of view large enough to include practical C stars may become a challenge within such dense regions. Even with smaller detector providing faster imaging and higher SNR, the instrumentation may not be sensitive enough to measure variations of the dimmest sources. It is a challenge to develop and control instruments sensitive enough to detect particularly weak signals concealed in the noise from bright backgrounds. It is essential to use detectors with the best possible SNR.

The problems associated with observing within crowded fields are compounded if particularly bright sources are close by. If the V star is in the close vicinity of a bright source, the target may be underexposed in order to avoid saturation in the area. This is still an issue for the instrumentation sensitivity. However, instrumentation speed becomes a factor now as well. Since brighter
sources saturate detectors more quickly, limited flux or exposure time per image is a problem. It becomes essential for SNR to be increased by capturing as many short exposure images as possible. The finite time to record transit ingresses further limits the amount of images that may be taken. For ground-based observations, the required imaging speed is also likely to be determined by the influence of atmospheric issues. Poor seeing conditions require a longer total exposure time to produce a desired SNR. With post processing techniques, this exposure time may be met by combining exposures that are short enough to avoid saturation. With a high duty cycle, the camera’s imaging speed, or cadence, may be fast enough to attain sufficient SNR and reduce the effects of seeing.

Figure 2.2: A crowded field centred on variable IO Aur. Circular labels denote identified variable star candidates (Richmond, 2006).

2.5 Solutions to These Differential Photometry Problems

Issues that limit the field of DP may be resolved with improved instrumentation sensitivity and speed. Using detectors with large dynamic ranges and improved frame rates allows instrumentation to image both dim and bright sources. The L3 chip’s novel design makes this possible for the NUIG-PC. SNR is further improved by several scientific methods including spatial binning and windowing, temporal binning and ‘lucky photometry’. Spatial binning and windowing is covered in section 4.2. Temporal binning may be performed during exposures or in post-image processing. During imaging, frames are added to improve SNR. Post-image temporal binning averages measurements to create smoother curves with less resolution. This option is best applied to data with high noise and high sampling. ‘Lucky photometry’ is useful for both fast variable sources and poor seeing. To illustrate by example, the L3 chip in frame transfer mode allows the Crab Nebula Pulsar to periodically be viewed only during low seeing conditions as shown in Figure 2.3. Selecting data only from these periods is referred to as ‘lucky photometry’ (Tulloch, 2004a).
In fields sparse of available C stars, increasing the FOV by alternative methods becomes more attractive. Simply increasing the detector size will result in more pixels, longer readout rates and poor duty cycles. For a square detector, including two stars on opposite corners minimizes the FOV size. Selecting a C star further out of field requires increasing the FOV by the added distance raised to a power of two. Increasing FOV to add light from C stars as far as 18 arcminutes from the V star degrades the pixel scale, increases sky background per pixel and limits the L3 detector’s dynamic range. The optical design covered in chapter six describes our method to introduce the C star’s light on the detector without increasing field and detector size. Both the FOV and detector size may then be minimized for faster imaging, a finer pixel scale and lower sky background per pixel around a target, regardless the location of the C star(s).

Figure 2.3: Series of images taken during good seeing conditions of the Crab Nebula. Filmstrip shows pulsar light on every fifth frame (Tulloch, 2004a).
Chapter 3

Stellar Photometry and Differential Photometry

Chapter three describes the technical aspects and methods of photometry and DP including colour correction, filter selection and data reduction. It will then describe in further detail some applications for reduced DP data from variable sources. Specifically, it will focus on how DP transit observations and subsequent data reduction can define light curves. It will conclude by further describing atmospheric limitations for transit photometry.

3.1 Historical Context and Description of Photometry

Photometric instrumentation is designed to record flux from stars. Flux may be described as photons per second striking a type of detector. The motive for recording photons has varied greatly over years as have the type of detectors. The first choice of detectors for recording flux was certainly the naked eye. A notable application of photometry is classifying stars into separate magnitudes (originally 1-6). Hipparchus first attempted this in 130 BC with a system of six different magnitudes (Sterken & Manfroid, 1992). Although the human eye is notably adaptable to varying light levels, it is non-linear compared to later detection methods. A perfectly linear detector registers each incident photon with an event. Emulsion photography combined with telescopes bettered photometry by improving detector linearity and the ability to discern magnitudes. The unaided eye can discern a brightness difference of 0.2 Magnitudes. Photography improved this by a factor of ten (Henden & Kaitchuck, 1982). Magnitude scales were changed accordingly, as well as colour classification due to differences in colour interpretation between the eye and photographic chemicals. Since the 1940s, photoelectric equipment like photoelectric cells offered even greater linearity but with low sensitivity due to a poor quantum efficiency. Photomultiplier tubes offered some signal amplification while retaining linearity until CCD arrays marked a further improvement with slightly less linearity but greatly improved quantum efficiency and spatial resolution. Figure 3.1 shows quantum efficiencies for several detectors. More information on detectors is presented in chapter four. (Sterken & Manfroid, 1992)

Usually, photometry seeks to record some degree of spectral information in addition to the radiation flux. Most photometers include different filter settings for
rudimentary temperature information of the source. If a detailed picture of the source’s spectrum is recorded in addition to photometric data, the instrumentation is suited for spectrophotometry. RV and light curve data produced in the same observation would be very practical for transit surveys. The majority of differential photometry instrumentation includes one to four different filters. Minimal spectral information is necessary to produce light curves of variable sources. Exo-planet and other variable source detections are principally occupied with recording the magnitude and characteristics of flux variation over time.

![Figure 3.1: Quantum efficiencies for several detectors are plotted over wavelength. CCD photon sensitivity is clearly dominant above 400nm (Sterken & Manfroid, 1992).](image)

3.2 CCD Noise Removal and Calibration

Before calculating magnitude differences or showing intensity variations with a light curve, we must perform a calibration/reduction step to remove some noise sources and instrumental effects from the science signal. Some types of noise are caused by imperfections in the detector. These contributions are added to the signal at different stages of detection and must be removed sequentially in the order that they contaminated the signal. The first source to contribute noise to the signal is bias, which is intentionally added to ensure noise levels do not produce a negative signal. The average level of bias is called overscan, a deliberate reading of extra pixel lines after the image is readout. This manifests in a small grey strip atop each image. Once the mean value of the overscan region is determined, it is subtracted from the pixels in each frame. Removing any residual bias requires exposing and averaging several short exposure bias frames. Residual bias is found by subtracting the mean of these frames from the overscan region. Any remaining bias must also be subtracted from each science frame.

After bias is removed, dark levels, from thermally generated electrons and damaged pixels, must be subtracted. Dark noise is measured by taking multiple long exposures with a closed shutter that records levels that are proportional to the exposure time. It is subtracted by scaling the mean exposure to each science frame’s
exposure time then subtracting from each science frame individually. Exposures are then divided by a map of the pixel sensitivity called a flatfield in order to compensate for dark pixels, bad columns and other pixel to pixel gain variations across the CCD (Stetson, 1987 and Gilliland, 1992). Shadowing from instrument optics and rings from dust may also cause variations. Flatfields are taken by exposing on both a white screen and the twilight sky through each filter. Dividing each science frame by a calibrated flat-field for that filter allows for a uniform chip response where star magnitudes are not dependent on what area of the chip is exposed (Gilliland, 1992). Noise removal should simultaneously clean both signal and sky levels. Isolating the star’s signal with the preceding noise removal steps may be illustrated with the expression:

\[
\text{Science} = \frac{(\text{Star} - \text{overscan} - \text{bias} - \text{dark})/\text{flatfield}}{(\text{sky} - \text{overscan} - \text{bias} - \text{dark})/\text{flatfield}}
\]

As may be expected, the signal processing steps covered do not remove all sources of noise. Readout noise is unavoidable and only minimized by using fewer pixels or fewer exposures. For X counts on N pixels, readout noise (RO) degrades the SNR by

\[
\frac{\text{S/N}}{\sqrt{\text{qX} + N \cdot \text{RO}^2}}
\]

with q signifying a factor from converting photon counts to electrons (Gilliland, 1992). Other sources of noise include deferred charge and poor charge transfer efficiency. Finally, multiple processed exposures are “median combined” (summed together to exclude outliers) to improve the SNR. A ‘cleaned’ signal with a high SNR may be used to accurately plot light curves for showing star variability or to determine a star’s magnitude. SNR influence on error in magnitude can be calculated by

\[
\text{magnitude error} = 2.5\log\left(\frac{\text{flux} + \text{error}}{\text{flux}}\right)
\]

For example, a SNR of 100 (flux of 1 and 1% error) would have a magnitude deviation of 2.5log(1.01/1) or 0.01mag.

### 3.3 Principles of Differential Photometry

Differential photometry records the light levels of a target star (V), the background and 1-2 reference stars (C) simultaneously in order to subtract atmospheric effects from target star variations. This is based on the assumption that light from two nearby stars passes through the same amount of atmospheric turbulence and is modified in an identical manner. Often, one or more additional C stars are recorded to ensure neither of the C stars vary relative to one another. Section 2.2 covered several of many causes of variations in sources. The principle of differential photometry requires the relative angular position of V and C stars to remain within the scale of smaller atmospheric turbulence. Assuming a ~one degree patch of sky fills the detector, C stars are required to be within the same FOV as V stars. Benefits from averaging data from additional outlying C stars need to be balanced with any uncertainty over their legitimacy as suitable comparisons. Simultaneous measurement of a target with one
or more suitable reference stars enables atmosphere-free V-C measurements. Further aspects of atmospheric effects and observing methods will be reviewed later.

### 3.4 Photometry and Differential Photometry Observing Methods

The observing methods for ASP and DP are notably different. It has been reviewed that DP measurements are based on relative measurements V - C with an additional check star C2 (Reference 1). Rather than constant reference to one or two comparison stars, ASP makes singular references to a catalogue of standard stars typically far out of the FOV. These stars provide predefined colour and magnitude information as related to a standardized system. Referencing them maps instrumental magnitudes to standard magnitudes. This is accomplished by photometrically calibrating out instrumental effects as well as varying degrees of extinction from different air masses. Instrumental effects are due to slight differences in the filter bandpass and detector response as compared to standard parameters. A simplified expression for a B-filter instrument magnitude is:

\[
B_{\text{instrument}} = B_{\text{catalogue standard}} + B_1 \text{ constant offset} + B_2 (B-V) + B_3 \text{ air mass extinction}
\]

Observing different coloured stars through the same air mass varies coefficient B2 only and observing identically coloured stars through different air masses varies only B3. By varying one coefficient while holding the other constant, both instrument coefficients may be estimated (Sterken & Manfroid, 1992).

Prior to CCD detectors, DP required recording the V and C stars sequentially. An example observation sequence could be: C1, V, C2, V, C2, V, C1. Variable star observations were bounded between reference stars for optimum interpolation of atmospheric changes (Henden & Kaitchuck, 1982). CCDs ended the obligation for separate V and C star measurements and interpolation techniques. However, well developed conventions are still applicable to new forms of DP. In order to avoid atmospheric errors, C stars should still be within 1 degree of the V star and have similar colour and brightness (Henden & Kaitchuck, 1982). To further reduce error, V and C stars should also be measured on different detector areas and through different air masses. C stars should also be in the range of -0.5 to 1.5 magnitudes brighter than the target so as not to limit the dynamic range. Generally 1.5mag brighter is preferred for increased SNR (Bailer-Jones & Mundt, 2001). Some general rules for selecting C stars are:

- Must be point-like (non-extended)
- Must have no close neighbours
- Must be in same FOV as V star
- Must be -0.5 to 1.5 magnitudes brighter than V star
- Must be non-variable to 95% confidence
- Must have no systematic trends in its light curves
- Must exhibit similar spectra to V star (Henden & Kaitchuck, 1982)

The process of slewing the telescope between each observation was both complicated and time consuming. The development of aperture photometry (AP) using large CCD chips permits the light levels of the V and C stars and background to be recorded
simultaneously. Imaging onto CCD detectors greatly improves the exposure rate available to astronomers.

AP is a common and simple method of differential photometry. AP places three rings or annuli around the V star as shown in Figure 3.2.A. The radius of the inner ring \((r_1)\) is adjusted such that the aperture includes as little as 80\% of the full width at half maximum (FWHM) of the star’s point spread function (PSF) for perfect seeing. It may be increased to 1.5 FWHM for normal seeing (Reference 1). Accurate data requires at least one hundred pixels to be included inside the sky aperture (Rockenfeller, 2005). The outer rings’ radii \((r_2 \text{ and } r_3)\) are set to include as much sky as possible without including light from the target star or any neighbouring stars. Best SNR is achieved with the smallest signal circle and largest sky annulus. Larger sky annuli beat down errors inherent in the detector. This is because pixels on the sky have both Poisson noise and readout noise that are in Gaussian distributions that improve with more averaging. Sky annulus noise decreases by a factor of \(\sqrt{N}\) by number of N pixels while signal circle noise increases by the same factor. The SNR may be calculated by the square root of the signal difference of the two annuli (Reference 1). The signal difference is the mean of sky pixel values subtracted from the value of each star aperture pixel value. Figure 3.2.B shows the effect of increasing aperture size on SNR (Rockenfeller, 2005). SNR eventually decreases due to cosmic rays and dim stars (noise). Once an annulus radius is chosen, the background measurements should ideally remain similar for other stars observed. This should be balanced with an aim to have the annulus include as many similar features as its associated signal circle.

Figure 3.2.A: Example of aperture photometry showing inner signal circle and outer sky/reference annulus (Reference 1).
Figure 3.2.B: Increasing aperture size plotted against SNR. SNR initially increases from higher star flux then decreases due to cosmics and dim stars (noise) (Rockenfeller, 2005).
3.5 Photometric Colour Correction and Filter Selection

All sky photometry includes use of standard stars out of the field of view of the instrument’s CCD and likely observed through different air masses. Viewing through different air masses results in separate rates of extinction for the two stars (Reference 1). Since extinction is wavelength dependent, the apparent magnitude of the target star is affected. This necessitates a process of colour correction that DP measurements do not require. The absolute magnitude of the target star may be determined by calculating the instrument’s colour coefficients and ensuring the reference star is a standard star with pre-defined colour information (Reference 1). Defining actual magnitudes instead of observed magnitudes requires “certain stars be defined to have certain magnitudes, so that magnitudes of other stars can be determined from observed fluxes that are corrected only for atmospheric absorption” (Henden & Kaitchuck, 1982). These requirements make photometric observations that seek to catalogue variations across the entire sky very complicated.

DP intending to observe variability within a small system such as during transit detection is simpler. DP entails recording only brightness variability and colour index (temperature) without determining actual magnitudes. Wavelength dependent second order extinction is still an issue, but not for determining magnitudes. It is still important to ensure that V and C stars to not diverge widely in magnitude from extinction effects. V and C stars should be selected with similar spectra, i.e. either both red or both blue. Since, for example, the I-band filter is fairly wide, dissimilar stars could cause undue magnitude differences. If such a selection were obligatory, a smaller band-pass filter would reduce the effect but in exchange for light loss.

Multiple filters for all-sky photometry are required for colour correction to determine magnitudes. In the case of DP, typically one to three filters are required to obtain adequate spectral information. The amount of spectral data needed depends on the DP application. In the case of observing pulsating stars, very minute light variations may occur only within a certain band-pass. For example, roAp stars pulsate <1% in the red only, necessitating the use of a J-band filter (Belmonte et al. 1991). For transit photometry, it is useful to plot the intensity variation over wavelength. An actual transit involves a blackbody blocking the source radiation and causing a uniform 1-2% drop across all wavelengths. Transit photometry is considered ‘grey’ in that it produces equal light curve shapes for all wavelengths. Only the planets’ atmospheres have a very slight affect on colour. By comparison, star spots cause periodic intensity drops over only some wavelengths. It is sufficient to switch between two filters to determine if a variable star has a transiting exo-planet instead of one or more star spots. In the case of hot blue stars, the colour index B-V should be used. For cooler red stars, V-I is preferred. If light curves are identical through both filters, the variability is likely caused by a transit.

3.6 All Sky Photometry and Differential Photometry Data Reduction

Data reduction for all-sky photometry (ASP) and DP have similar initial steps. For both, it is necessary to subtract the sky background and calculate the magnitude differences between the C and V stars through various filters (Henden & Kaitchuck, 1982). ASP requires periodically checking the reproducibility of C star measurement after sets of V star measurements. C star measurements at either side of measurement
‘blocks’ are averaged. Each target star is measured through one filter after the other before moving back to a reference star. The number of variable star measurements in a block would depend on whether their combination reaches a SNR of 100, the speed that the V star changes and the zenith distance of the target (Henden & Kaitchuck, 1982). Changes in magnitude thorough each filter must be calculated by a complex series of averages. The use of AP absolves this practice. Changes in magnitude (M) through filter B (for example) may be calculated directly by

$$\Delta B = -2.5 \log \left( \frac{F_{bV}}{F_{bc}} \right)$$  \hspace{1cm} (3.3)$$

where $F_{bV}$ and $F_{bc}$ are the fluxes from the V and C stars minus background (Henden & Kaitchuck, 1982). Calculations of $\Delta V$ and $\Delta I$ would be similar. A star’s magnitude is determined by the total flux ($F$) measured over an exposure time ($T$), or

$$M = -2.5 \log \left( \frac{F}{T} \right)$$  \hspace{1cm} (3.4)$$

where

$$F = \sum (F_{\text{inside r1}}) - [p * r1^2 * \text{mean}(\text{flux per pixel inside } (p * r3^2 - p * r2^2))]$$  \hspace{1cm} (3.5)$$

Further reduction and conversion to the standard photometric system is not needed for transit detecting DP (Stetson, 1987).

### 3.7 Post-Processing of Photometric Data

Further reduction before plotting light curves includes checking if variations in magnitude are real or just scatter due to noise. This can be checked by fitting “a second order polynomial to the plot of standard deviation ($\sigma_{RMS}$) of the relative light curves versus average instrumental magnitude of the stars in the target field” (Martin et al. 2001). Only stars well above the curve will indicate true variable stars.

### 3.8 Limitations to DP and Transit Photometry: Scintillation & Seeing

In order to distinguish the advantages available from the NUIG-PC, it is important to consider the typical limitations of ground based transit photometry. Ground based observations are unstable compared to those taken above the atmosphere. This instability is due to clouds and shifting air layers of dissimilar indices of refraction. It manifests itself in constantly changing levels of flux across detector pixels. The amount of flux on a pixel depends on the irradiance of a particular point source and the direction of the light.

Irradiance is determined by the local extinction through the atmosphere above the observatory modified by scintillation. Atmospheric extinction is defined as loss of star flux by scattering, absorption, refraction and dispersion of energy through the Earth’s atmosphere. Scattering off small particles is worse for shorter wavelengths as it is “inversely proportional to the fourth power of lambda” (Rayleigh Scattering)
Total extinction in the blue occurs at close to 290nm. Scintillation is worse near the horizon, with smaller aperture scopes, shorter exposures, and with fewer exposures. Scintillation is viewed as flying shadows across the aperture causing random variations in brightness or simply as star flicker. It is proportional to the square of the air mass size and inversely proportional to 2/3 power of the aperture size. It is only a concern if the atmosphere modulation is larger than the telescope aperture. Scintillation may be limited by increasing aperture or by increasing exposure time. Section 4.3 on detectors explains the benefits of high cadence imaging in this case.

The second variable influencing the amount of flux on a pixel is the direction of light. Direction is determined by refraction through the atmosphere modulated by seeing conditions. Small temperature changes in the atmosphere affect the local index of refraction, bending starlight as would a thin lens. The resulting effect of seeing causes the Airy-disk size ($\theta = 1.22* \frac{\lambda}{D}$) image to rapidly move about on the order of a few arc seconds causing a speckle pattern on the telescope focus. Fast exposures will capture the speckle pattern but longer exposures will capture the FWHM of the seeing disc. The disc is created when the speckle pattern averages over time to become a much larger “fuzzy blob”, or more specifically as a point spread function with its diameter defined by the angular resolution of the telescope.

Without the aid of adaptive optics, limiting the telescope diameter with an aperture mask to ~4x the Fried Parameter ($R_0$) is important for image sharpening techniques (Fried, 1966). Limiting aperture size is not desirable for DP. However, I-band measurements using a full aperture on the scale of ~10 $R_0$ still permits slight benefits from image sharpening. $R_0$ is typically defined either in terms of aperture size or the seeing quality. Defined by aperture size, it is the point at which the telescope diameter is large enough to no longer influence resolution. Defined by seeing quality, it is the length scale where turbulence becomes a problem (typically 20cm to 5cm). A common PSF of 1” corresponds to $R_0=12cm$ by the Raleigh definition for resolution $R= \frac{\lambda}{D} = 0.1386/D$ (meters). If the aperture size is exactly set at $R_0$, the scale of the atmosphere is on the same scale as the Airy disk and only diffraction still limits the final resolution. The RMS variation of the turbulence is $= \frac{\lambda}{14}$ and may still be improved by post-exposure tip/tilt removal. This can be accomplished using a simple shift-and-add image sharpening technique called post exposure image processing (PEIS) as described by Redfern (1991). A larger aperture would cause multiple star images to form (speckles) in the focal plane. Although some speckling may occur, PEIS is optimum at ~4$R_0$ because the speckles are still tightly bunched (Butler et al. 1998). For Butler, PEIS resulted in a reduction in seeing by a factor of 2 (O Tuairrisg et al. 2003).

A similar parameter to $R_0$ is $T_0$. $T_0$ is defined as the length of time before turbulence creates blurring. The benefits of PEIS show the importance of determining this exposure time and achieving it with high cadence imaging. For typical conditions, $T_0$ is ~10ms or 100Hz (Devaney, 1966). The L3CCD readout speed is ~30Hz at full frame and can reach 100Hz when windowed to ¼ frame. Imaging at this speed normally is hindered by the problem of high readout noise. Section 4.5 describes how the L3 chip alleviates this concern.

### 3.9 Determination of Exoplanet Characteristics From Transit Photometry
Case Study – HD209458 Light Curves with STARE and HST/STIS

The product of DP transit observations and subsequent data reduction should be a clearly defined light curve. This section will review light curves from transit photometry performed on HD 209458. It was previously mentioned that this source was the first to successfully produce a transit’s light curve. Figures 3.3.A-B show this curve set next to one produced later with improved SNR (Charbonneau et al. 2000 and Brown et al. 2001). The secondary observations from Hubble’s STIS spectrograph provided a much larger scale of spectral information. The STIS collected large amounts of photons ($2.5 \times 10^8$) per 80s exposure cycle. The exposure times were 60s with 20s readout time for a 75% duty cycle (Brown et al. 2001). A huge total exposure time was required for high SNR at each measurement for each wavelength. By summing photon counts over all wavelengths of 684 useful spectra accumulated, the STIS spectrograph utilizes spectra to provide a highly sampled photometric signal (Brown et al. 2001). The improved SNR clearly defines and unflattens the base of the curve. The STIS data also has the benefit of coming from observations above the atmosphere. Stable light, free from scintillation and the blurriness of ‘seeing’, results in a lower margin of error for each data point plotted.

Applying the STIS spectrograph data to a model of a dark circular planet transiting a stellar disk provides a planet-star radius ratio $R_p/R*$ and inclination angle $i$. Combining this information with pre-existing RV data is crucial. Radial Velocity measurements are typically available because the method is best for first step detection of possible exo-planets. The majority of exo-planet detections have been made with this method. RV provides orbital periods, $Mp\sin i$ values and the mass-radius ratios of exo-planets ($Mp/R_p$). By combining RV data with photometry measurements of $(i)$, the quantity $Mp$ may be isolated from $Mp\sin i$ measurements and the radius of the planet independently measured. Measuring $R_p$ independently is important because errors in photometrically measuring $R_p$ are caused by uncertainty in $R*$ and limb darkening (Brown et al. 2001). Another solution is using highly accurate spectra data to allow these uncertainties to be reduced. This may also allow for detection of planetary elements when light passes through the planet’s atmosphere. The STIS data was taken over the spectral range 581 to 638 nm to specifically detect Na D lines in HD 209458’s atmosphere (Brown et al. 2001).

The light curve in Figure 3.3.B is the result of a 184.25 minute transit creating less than a 2% drop in apparent star brightness (Brown et al. 2001). Each plotted point is a full spectrum exposure averaged into a photometric measurement. The accompanying schematic in Figure 3.3.C describes how Brown’s planet-disk model is used to determine independent variables $R*$, $R_p$, $i$ and $u$. $U$ is the limb darkening parameter that describes the degree that a planet removes less light when crossing the dimmer (1-2% darker) edges of a star. The shape and depth of the light curve provides a great deal of information. Four curve parameters ($w$, $l$, $d$, and $c$) are dependent on the variables mentioned and may be measured accurately. The ingress duration ($w$) depends on $R_p$ and the angle between the stellar limb normal and the planet’s trajectory. This angle tends to zero at $i=90$ (viewed on axis), thus $w$ is proportional to both $i$ and $R*$. The transit length ($l$) depends on $R*$ and $i$ and the transit depth ($d$) depends on the variable ratio $R_p/R*$ (Sackett, 1999). Curvature ($c$) depends on the limb darkening parameter ($u$), $i$ and $R*$. Reviewing these curve parameters shows each one is dependent on the stellar radius $R*$. For this reason, $R*$ must be determined independently of curve parameters. It may be provided interferometrically or from observations of spectra that classify the star on the HR
diagram. If lacking two or more confirmed transits, the orbital period $P$ may be determined from

$$P = \sqrt{\frac{4\Pi^2 a^3}{GM^*}}$$

where $a$ is orbital radius (Sackett, 1999). Since $R^*$, $R_p$, $i$ and the degree of limb darkening depend on measurable quantities $l$, $d$, $w$, $c$ and $P$, all of these “system parameters” may be estimated (Brown et al. 2001). Brown claims the precision of photometric modelling will be good enough to detect earth size planets around solar size stars (Brown et al. 2001). Although STIS data is well sampled and free from atmospheric effects, the observations are restricted to a 75% duty cycle. Higher speed instrumentation and larger apertures from ground based photometric measurements may aim to approach the quality of space observations. The NUIG-PC is designed for that approach.

Figure 3.3.A: Light curve produced from a planet transiting HD 209458 derived from observations from the ground-based STARE Project Schmidt camera (Charbonneau et al. 2000, Brown et al. 2001).
Figure 3.3.B: Light curve produced from a planet transiting HD 209458 derived from observations from Hubble’s STIS camera. High SNR Hubble data has provided a more clearly defined curve (Charbonneau et al. 2000, Brown et al. 2001).
Figure 3.3.C: Various parameters of a generic light curve used to determine independent variables $R^*$, $R_p$, $i$ and $u$ (Brown et al. 2001).
Chapter 4

CCD and L3CCD Detectors for Differential Photometry

Chapters two and three described effective photometric instrumentation as being both sensitive and fast. The L3 detector within the NUIG-PC advances both aspects for DP. It does this by simultaneously producing images at a fast rate while limiting noise to relatively low levels. The L3 detector chip’s high SNR reduces the effects of seeing and scintillation. This section covers the operational characteristics of the L3CCD, improvements and comparisons to conventional CCDs as well as how its high cadence imaging reduces atmospheric effects.

4.1 General CCD Details and Operation

Before explaining the operational characteristics of the L3CCD, a brief summary of general CCD features and functions is beneficial. Charged Couple Devices (CCDs) are the product of etching light sensitive silicon wafers with a grid of electrodes to form a pixel array on a solid state circuit. The advantages of CCDs include high dynamic range, high quantum efficiency, a linear response and an extended field of view. As was previously mentioned, CCDs measure photons linearly by use of the photoelectric effect. Once illuminated, photons absorbed by the silicon layer raise electrons from the silicon’s valence band to its conduction band across an energy gap of 1.14eV (Sheehan, 2005). The number of electrons raised is proportional to the number of photons striking the silicon layer. Applying voltage separates the elevated electrons from the positive holes they leave behind. Manipulating the voltage across the pixel array allows for charge packets collected in each pixel to be moved. The array of silicon photodiodes are arranged in channels where a process of charge coupling allows the charge packets to be moved to an output register by adjusting the potential difference between pixel elements. Charges trapped in these potential wells are moved to the register by “lowering the level of the next collector toward the output register to the same level as the original well, after which the level of the original well is raised, building a barrier” (Sterken & Manfroid, 1992). This process is repeated three times to perform one clock cycle of moving a charge from one pixel to another or from the register to the amplifier. Since the register clocking rate is faster than the channel clocking rate, the timing of electron packets leaving the register allows for determination of the quantity and the location of where photons
struck. Once the number of photons incident on each pixel can be determined, a grey-scale image of the incident intensity may be created. A total of 3072 transfers are required to clear all charges on the L3s 512x512 chip (Sheehan, 2005).

Since the poli-silicon gate structure on CCDs does not transmit shorter wavelengths efficiently, most Cameras like the L3 have a thinned, back-illuminated CCD. The CCD is flipped upside down with the electrode structure now attached to the substrate and the silicon facing upwards. The light sensitive silicon layer is then thinned down to ~10µm and an anti-reflection coating is applied (Sheehan, 2005). By exposing the chip’s thinned backside, its quantum efficiency improves for blue light. Near saturation of the potential wells must be avoided to ensure good quantum efficiency. This allows QE to approach 90% but has a trade-off between readout noise and readout speed (Reference 2). The L3 chip attempts to resolve this issue.

4.2 Aspects of the L3CCD Used in the NUIG-PC

E2V Technologies produced the Low Light Level (L3) CCD in 2001. The chip used by the NUIG-PC is specifically the Andor iXon DV-887-BV. This product is pictured in Figure 4.1. The chip features a MHz readout range that facilitates high cadence imaging which is beneficial for rapidly varying sources, imaging faint sources in a crowded field (high dynamic ranges) and retaining high SNR for bright objects. One trade-off for this extraordinary speed is a relatively small size preventing large-sky applications such as surveys. This fact limits the NUIG-PC to confirming RV variables and improving past measurements.

For detectors within cameras, the term image cadence is a derivative of bandwidth. Bandwidth is defined as events/sec or frames/sec in the case of the L3 camera. The L3 has a bandwidth of 10MgZ or 10 million pixels/sec. 10Mill pixels/(area of detector) = 10Mill/(512x512) = Max frame rate of approximately 32 frames/sec (Reference 2). If an event occurs faster than 1/32 second, the L3 camera would not register the variation without windowing or binning. Windowing entails reducing the frame size used on the CCD to increase frame rate (i.e., using only a 200x200 grid instead of the available 512x512). Binning averages sections of pixels together to lump them as a single pixel. This process sacrifices spatial resolution for increased readout speed. In the case of less than perfect seeing, binning may also be used to improve SNR for detecting faint signals. An atmosphere-broadened PSF may be binned to the Nyquest limit of two pixels per FWHM thereby improving the SNR by ~ $\sqrt{N}$ (Sheehan et al. 2006a). As an example, a signal of 10,000 +/- 5 counts/pixel across a 8x8 array has a signal of 64x10,000e, a readout noise of $\sqrt{64 \times 5}=40$ and a SNR equal to 16,000. Binning 16x16 reduces 64 pixels to 4 with reduced readout noise of 2*5 and a SNR = 64,000.

Besides high quantum efficiency, science grade CCDs should have either low noise or high pixel readout rates. Unfortunately, noise and readout rates are coupled for most detectors. The novel benefits of the Low Light Level CCD (L3) are “low readout noise, high readout rates, and 100% duty cycle” (Sheehan et al. 2006a). The L3 achieves high readout rates while retaining low readout noise by amplifying the signal above the noise level with a built-in gain register pictured in Figure 4.1.B. During long exposures, this solves the problem of spending nearly half of observing time waiting for the camera to readout data. Operating close to 100% duty cycle (ratio of exposure time to exposure time plus readout time) allows the shutter to
remain open continuously. When more frames per unit time may be co-added, a net improvement in the SNR is the result. An additional benefit of higher duty cycle percentages is a reduction in the effect of scintillation.

Figure 4.1.A: The Low Light Level (L3) camera with Andor iXon DV-887-BV CCD produced by E2V Technologies (Reference 2).
Figure 4.1.B: Schematic and photo of L3CCD depicting frame transfer mechanism and extra gain/multiplication register used for high cadence, open shutter imaging (Sheehan et al. 2006a and Reference 2).

4.3 L3CCD Improvements: Gain register with Frame Transfer

The L3s special gain register is included between the normal register and the amp. Conventional CCDs have readout registers of the same width and row number as the image area. The L3 chip has 520 additional pixels in its register by including an extra dc electrode in each stage that has a large (~40V) voltage difference from the DC level (Tulloch, 2006). This large difference deepens the quantum well to the point where impact ionisation or avalanche multiplication occurs. This is the process where electrons striking atoms dislodge additional electrons thus causing an ‘avalanche gain’. This event is pictured in Figure 4.2. The gain per stage is a statistically small 1.5% (α) but across a total of 536 stages (N), the total gain reaches 2900 by EM-Gain = (1 + α)^N. (Sheehan, 2005 and 2006b) This on-chip gain increases the average signal above the noise level of the amplifier. Since readout noise is kept at a relatively low level and the gain is effectively independent of the readout rate, the L3CCD can operate as high as 35MHz for high light levels. A major benefit of the L3 chip is that for low light levels, the on-chip gain allows for weak signals to be distinguished from noise. Section 2.4 covered such detector sensitivity issues within crowded fields.

The L3s frame transfer mechanism is comprised of both exposed and masked-off portions of the CCD pixel array. Figure 4.1.B shows the mechanism is simply a large CCD with half of its area masked off by aluminium. When set to EMCCD mode, the gain register and frame transfer are turned on. Instead of pausing to
readout after exposure, it allows continuous packet clocking towards the high speed gain register. The frame transfer is completed in 2ms. If the exposure time is longer than the cycle time set by the readout rate, the maximum dead time will only be 2ms. A normal CCD without frame transfer has a dead time of ~30 seconds. The resulting duty cycle would be under 40% compared to 99%.

![Diagram of avalanche gain due to impact ionization](image)

**Figure 4.2:** Avalanche gain due to impact ionization. ‘Avalanche multiplication’ results from applying a large voltage across the L3 chip’s extra dc electrode (black) (Robbins & Hadwen, 2003).

4.4 CCD Noise and Post Processing

Improving the SNR in problematic regimes (bright sources and high dynamic range scenarios) is achievable by identifying and limiting sources of noise. Four main sources of noise are recognizable from the L3CCD. Readout noise is dependent on readout rate and becomes problematic when conventional CCDs take frames above ~90 KHz. Shot noise is independent of readout rate but dependent on the signal level. It is equal to the square root of the signal in electrons and therefore is a problem at higher signal values (bright sources). Dark current is caused by thermal electrons and is temperature dependent by $I \propto e^{(-1/T)}$ (Janesick, 2001). The L3 chip is actively cooled to -75°C in order to reduce thermal noise. A bias level must be applied in order to avoid negative signal values caused by fluctuations in weaker signals by readout noise. As discussed, the subtraction of this bias level is the first to be done in image processing.

4.5 Comparing Noise of Conventional CCDs to the L3CCD

Noise from the L3 chip initially appears worse than from conventional chips. Additional amplification from the gain register means the standard deviation of the
signal no longer follows Poisson statistics but rather increases as $\sqrt{2}$ times the signal mean (Tulloch, 2004b). This additional multiplication noise of $\sqrt{2}$ is called the L3 noise factor ($F$). Fig 4.3.A shows L3 noise vs. conventional CCD noise (Tulloch, 2004a). At a 10K signal, RMS variation (noise) is equal to $\sqrt{10K} = 100$ for Poissonian noise, but $\sqrt{2} \times \sqrt{10K} = 140$ for the L3CCD. The noise factor’s impact on the system is halving the quantum efficiency (Tulloch, 2006). If taking a single exposure of brighter objects, the EMCCD SNR will always be $\sqrt{2}$ worse than a normal CCD and require a longer exposure time. The noise factor is not a problem at low light levels but it degrades the signal otherwise. The L3 SNR is higher than the conventional CCD’s until the ~25e signal level. Figure 4.3.B shows this crossover level (Tulloch, 2006). The following equation shows total noise contributions for both conventional and L3 chips (Robbins & Hadwen, 2003).

Conventional CCD = $\sqrt{\text{shot noise} + \text{dark noise} + (\text{RO noise})^2}$ \hspace{1cm} (4.1)

EMCCD = $\sqrt{F^2 \times \text{shot noise} + F^2 \times \text{dark noise} + (\text{RO noise})^2}$ \hspace{1cm} (4.2)

![Figure 4.3.A: L3 noise vs. conventional CCD noise showing $\sqrt{2}$ noise factor for the L3 CCD (Tulloch, 2004a).](image)

![Figure 4.3.B: Illustration of signal level where L3 SNR degrades to being worse than conventional CCD SNR due to L3 noise factor (Tulloch, 2006).](image)

The L3 noise factor degrades the chip performance at single exposures. However, the gain register permits readout rates in the MHz range. The resulting cycle time on the L3 is far superior. With a conventional 1024x1024 array, the readout rate would be 20kHz without a frame transfer mechanism. The cycle time would be 15 seconds for exposure plus 29 seconds for readout. With the L3’s 512x512 array, the readout rate would be 1 MHz owing to the frame transfer mechanism. The cycle time would be 262 ms including 2ms for readout. The
resulting 99% duty cycle of the L3CCD is markedly larger than the 34% duty cycle of the conventional chip. A $\sqrt{X}$ improvement in SNR is the benefit of every X increase in frame rate that the L3 allows. Although the L3 requires a longer exposure for a specific SNR, improved duty cycle at low readout noise allows for more exposures and a higher SNR over time. For brighter objects, better relative performance comes from the L3 chip.

The L3CCD outperforms conventional CCDs for many regimes. A novel gain register combined with a frame transfer mechanism permits fast readout rates with near zero dead time. Detecting bright star transits and achieving high dynamic ranges for crowded fields (by amplifying the dim signal above the noise level) are possible.

4.6 Benefits of L3 High Cadence Imaging In Challenging Regimes

The L3CCD reduces atmospheric problems in particularly difficult regimes by increasing SNR. Atmospheric problems are mainly comprised of seeing and scintillation effects whereas challenging regimes include bright sources and high dynamic range scenarios (crowded fields). Noise reduction in these regimes is essential to overcome atmosphere.

Most transits detected are of large gas planets orbiting closely to their host stars. Consequently, these transits are short, on an order of 3 hours with ingress/egresses of ~30 minutes. A source varying on a time scale of 30 minutes cannot be considered as a rapidly varying. However, in most cases, the planet is orbiting a bright star. Since bright sources quickly saturate CCDs, more exposures are required for a suitable SNR. More exposures increase the total readout time from any CCD but conventional CCD data particularly suffers due to poor duty cycles. More observation time is spent reading out conventional detector data for this type of observation. The L3CCD becomes particularly useful in the context of transit photometry. A benefit of the L3CCD’s improved duty cycle is limiting the influence of scintillation. Reducing scintillation is typically achieved by increasing aperture or by increasing exposure time. A longer exposure time averages out modulations in the atmosphere and removes any darkening caused by scintillation. For most cameras, the exposure time is limited by the duty cycle. By exposing nearly continuously, the L3CCD alleviates the effect of scintillation for brighter sources. Compared to conventional CCDs, the L3CCD’s performance advantage is proportional to increased source brightness.

L3CCD imaging speed also directly influences the effects of seeing on camera exposures. Section 3.8 defined $T_0$ as the length of time before turbulence creates blurring. The NUIG-PC L3CCD can image faster than $T_0$ (~100 Hz) when windowed to ¼ frame, yet not exclusively (Reference 2). Both L3 CCDs and conventional types can avoid seeing or blurring effects by imaging faster than $T_0$. However, for conventional CCDs, this cadence produces images full of noise. The L3CCD can defeat the effects of seeing while simultaneously maintaining high SNR. The effects of the gain register as well as improved image stacking from a high duty cycle improve SNR. L3CCDs are of the most use in any observing scheme that is restricted by detector noise. Imaging faint sources within crowded fields is one such regime.

An important application of the L3 chip is in crowded field photometry. Retaining low noise with high speed is not the sole benefit of the L3CCD. Increased sensitivity is also attained when using its gain register to reduce effective noise levels. Increased sensitivity is essential for challenging regimes like crowded fields. For this
type of target, amplifying signal above noise allows for weak signals or faint sources to be picked out of densely populated areas. Imaging these sources within crowded fields places several brighter objects within the FOV, thus increasing background light levels around the target star. The capacity of the L3CCD to image in crowded fields depends on its dynamic range (DR). DR is most broadly defined as the ratio of brightest object to dimmest object. For a CCD, the DR = (Sensor Well Depth) / (Readout Noise). Since applying gain to the L3 chip decreases effective readout noise, its DR can be increased. However, there is a limit in applying gain across gate 2 and the DC level to increase DR (Figure 4.2). DR will increase with applied gain only as long as sensor well depth is not limited. Gain may be increased only until the multiplication register is saturated. At this point the number of counts read (or effective well depth) reaches its capacity of 800,000e (Sheehan, et al. 2006a). Further increases in gain will still reduce effective readout noise but effective well depth reduction will balance out any net changes in DR. This situation may be illustrated with an example of two gain settings on a theoretical chip with a saturation signal level at 1000.

100 counts x gain of 10 = 1000 (just saturated), effective well depth = 1000/10=100
100 counts x gain of 20 = 2000 (oversaturated), effective well depth = 1000/20=50

The L3 gain should ideally be set at maximum gain but before this balance breaks down and the dynamic range starts decreasing. In addition, the divergence of the possible gain or output counts should be taken into account to ensure that the output signal plus the EM noise factor of $\sqrt{2}$ do not exceed the size of the output register. Other methods to improve SNR in crowded fields include combining images, binning, and improving detector duty cycles. The benefits of high image cadence are not exclusive to limiting atmospheric effects. The L3CCD’s duty cycle also improves sensitivity for crowded field observations.
Chapter 5

Optical Designs for Differential Photometry and Theory Used to Evaluate Them

Before presenting the modelling and analysis results of this project, this chapter will examine some theory behind both the design and the analysis of its optical performance. It will include discussions of what benefits are earned from the design as well as design requirements based on sampling theory and stellar density. Performance analysis will be explained in terms of wavefront, fractional energy and aberration theory. The chapter will conclude with a brief introduction to OSLO® optical design software and a description of methods used to inspect the design at the B and I filter bands.

5.1 Increasing FOV for Greater Selection of Comparison Stars

Previous sections covered various limitations to DP including limited sensitivity in crowded fields around bright sources. Most instruments’ FOV are limited by detector size with proper PSF sampling as well as detector sensitivity. However, increased FOV is desirable to obtain a greater number of transit candidates with C stars suitably in range. When imaging within crowded fields, this creates an impasse. Increased FOV in crowded fields results in more sources on the detector, quicker saturation and a limited ability to obtain light from faint sources. In other words, too much light may exceed the detector’s dynamic range. Combined with the likelihood of PSF undersampling, increasing FOV is notably deleterious for the images from most instrument designs. Applying an optical model with an ‘outrigger’ design is a suitable solution to overcome these issues. An additional optical path permits an effectively larger, yet sensitivity independent, FOV while retaining proper PSF sampling. This approach will allow previously unavailable variable sources in fields sparse of needed C stars to be examined without increasing field size. The new design for the NUIG-PC allows for selecting targets with minimal background light regardless of the location of the C star(s). The following sections will elaborate on the details of other focal reducer designs. The limited merits and notable shortfalls of these designs should justify the need for an alternative ‘outrigger’ design.
5.2 Focal Reducer Designs

Increasing FOV by telescope focal length reduction is typically accomplished with transmissive optics. Several lenses that collimate then refocus the light can perform this. These designs may increase the FOV ~4 fold and place more C stars on the detector. Unfortunately, such a moderate increase rarely images brighter C stars where possible variables have not been previously measured (see section 5.7). RV measurements show many V stars without nearby C stars remain to be confirmed photometrically.

Combining focal reducer designs with particularly large CCDs has often been the best solution for challenging star fields. The preceding section on detectors describes the penalty for large CCDs. Increasing detector size results in higher readout noise, notably longer readout times and overall inferior SNR. There is also the issue of cost. Doubling the detector size typically results in twice the price. Without breaking the budget, possible modifications to improve the NUIG-PC FOV are limited. The simplest (and worst) optical design modification considered was adding a single large doublet before the telescope focus. Proper Nyquest sampling of a target’s PSF should be across ~2 pixels. A lens strong enough to increase FOV by ~3X change in scale (or x9 Area) can create notable undersampling.

5.3 TRIFFID to NUIG-PC with Focal Reducer

Various types of collimating focal reducers to increase the FOV were also considered. Prior to any modifications, the NUIG/DIAS high resolution camera (TRIFFID) was constructed as this type of simple focal reducing camera. Its collimated beam permitted a dichroic fold to bend blue light towards avalanche photodiode detectors (APDs) for studying pulsars. The TRansputer Instrument for Fast Image Deconvolution (TRIFFID) instrument box, pictured in Figure 5.1.A, shows both the diodes and L3 camera. In this configuration, the L3 camera was used only for alignment purposes. Once the focus of the instrumentation was reoriented towards crowded-field photometry, the NUIG-PC was assembled. The shutter, dichroic and APDs were removed, a filter wheel was installed in the converging beam and the camera was moved forward. An off-the-shelf ‘Optec’ focal reducer was introduced to reduce the Loiano 1.5m, Ritchey-Chretien Telescope’s F/8 beam to F/5. This focal reducer moderately increased the telescope’s 2.4 minute FOV to four arcminutes. Although cost effective, four arcminutes is only suitable for capturing V and C stars of magnitude 20 and dimmer. Figure 5.1.B shows the top view of the NUIG-PC with inset of the focal reducer.
5.4 FOSC Camera Designs

The TRIFFID camera’s original design was very similar to faint object spectrographic camera (FOSC) designs. FOSC designs have been widely used since 1992 (Reference 19). They are all focal reducers consisting of a collimator with the same F-number as the telescope, three instrument wheels and a camera to refocus the beam onto the detector. The design’s primary benefits include reducing the effective focal length of telescope to obtain a larger FOV and the ability to quickly switch from direct imaging to spectroscopy with a simple configuration change.

There are several FOSC designs with similar optical components in use at sites including Asiago (AFOSC), Bologna (BFOSC), and the Danish DFOSC. Each of these has the same camera-to-collimator focal ratio of 146.3mm/252.1mm producing a 0.58 magnification. Their respective FOVs are 8.14’ x 8.14’, 13’ x 12.6’, and 13.7’ x 13.7’ with each bending the telescope light path 100-110 degrees after the telescope focus (References 3, 9 and 15). The schematic of BFOSC’s optical design in Figure 5.2 shows the filter and grism wheels are placed in the collimated light beam with the aperture wheel at the telescope focus (Reference 9). Selecting a grism (combination of grating and prism) disperses a spectrum centred on the location of the object in the camera field of view. AFOSC’s grism and filter wheels are pictured in Figure 5.3 (Reference 3). The wheels are controlled with stepper motors, have 7 positions for optics and 1 position free. Like the NUIG-PC, the camera may be moved back towards the rear flange as necessary.

The large FOVs from FOSCs are not obtained without nuisance. The full frame readout times for their detector sizes (~1200x1200pix) ranges from 18 seconds at 100KHZ for BFOSC to over a minute for DFOSC (References 9 and 17).
Compared to the NUIG-PC readout time of 262 ms, FOSC SNR for bright objects is limited. It should also be noted that although the NUIG-PC FOV is relatively small (4' vs. ~13'), 13' still isn’t broad enough for finding C stars for sources brighter than 13 MAG (see Figure 5.7). Since both the FOSC and NUIG-PC designs use transmissive optics, both are affected by sky concentration and are less suitable for high precision, all-sky photometry. Sky concentration describes transmissive optics’ propensity to concentrate light towards the field center. Once frames are divided by flat fields that are affected by sky concentration, the central field suffers from light loss. For DFOSC the loss has been measured at 2% (Reference 17). Since this is a systematic effect, consequences for DP with the NUIG-PC are minimal and may subsist only of slightly altered amplitudes in the flux change.

Figure 5.2: Schematic of BFOSC’s optical design showing 110 degrees fold of light path, filter and grisms in the collimated beam and aperture wheel at the telescope focus (Reference 9).

Figure 5.3: AFOSC’s 8 position grism and filter wheels with stepper motor in foreground (Reference 3).

5.5 ESO-VLT (FORS) Design

The FOcal Reducing, low dispersion Spectrograph (FORS) for the ESO-VLT is a similar collimated path, large detector design. Figure 5.4 shows considerable more
optical modelling has been included to correct for various telescope aberrations such as field curvature (Nicklas, 2005). Although the beam is never truly collimated, additional optical mechanisms such as interference filters and polarizers may be inserted in the pupil stop. The filters allow for narrow band observations and the polarizers permit adjustable phase retardation of linear or circular polarized light. FORS also has a top section containing slit masks for a MOS detection mode. The instrument features a large 2048 x 2048 pixel CCD and the optics’ 0.22 focal ratio creates a FOV of 6.83’ x 6.83’ (Nicklas, 2005). Even though the focal reduction is twice that of FOSC ratios, the FOV is smaller because of the difference in telescope sizes. The larger VLT telescope has a longer focal length and faster F/#. Before focal reduction, the VLT has a smaller FOV than FOSC equipped telescopes.

![Figure 5.4: Optical design ray trace for the ESO-VLT (FORS) Spectrograph. Additional optics allow for minimizing aberrations at full-field (Nicklas, 2005).](image)

Reviewing the preceding optical models shows they are more complexly designed than the simplest focal reducers. These models are more elaborate since they have been designed for focal length reduction, room for instrumentation and tight aberration control. They each achieve a larger field of view by two simple methods, increasing the number of pixels or decreasing the focal length of the optical design. A new ‘outrigger’ design for the NUIG-PC achieves a larger FOV by an alternate method. In our case, added design complexity is oriented solely towards achieving larger fields. Each new surface causes light loss via scattering and ghosting. Since each additional surface might produce reflective ghost images on the detector, a minimum of additional optics was introduced. A schematic for the NUIG-PC’s new optical design is shown in Figure 6.1.

### 5.6 Design Requirements Based On Sampling Theory

Fulfilling Nyquist sampling restricts the range of usable magnifications for each design. Recapping the necessity for a focal length reducing magnification (of less than 1) clarifies this restriction. Since atmospheric seeing typically results in a 0.5-1.0 arcsecond seeing blur from the telescope, the star’s image size is mismatched from the detector’s pixel size. Focal reducing optics are necessary to decrease the scale of the seeing disk size to the pixels’ scale. The number of pixels needed to record the blurred star image is established by Nyquist’s sampling theorem. The sampling theorem dictates that images should be recorded at a frequency of twice per image scale, or at the ‘Nyquist frequency’ (Nyquist, 2002). Thus, focal reducer magnifications should image the seeing disk across slightly less than two pixels. Slight undersampling in this manner reduces resolution but also provides a larger
FOV. Oversampling is to be strictly avoided. With proper (de)-magnification, the FOV of the telescope should increase by 8/5 fold.

The sizes of both the telescope’s seeing disk and the CCD’s pixel size are required to find the correct magnification of the focal reducers. The size of the pixels on the L3 CCD are 16µm. The seeing disk (SD) size is typically about nine times larger than the unaberrated Airy disk (AD) under the best conditions. The AD radius can be found from:

\[ R = \frac{1.22\lambda}{D} = \frac{1.22(500\text{nm})}{1.5\text{m}} = 4.06\times10^{-7} \text{ radians} = 0.08'' \]  

Thus, for Nyquist sampling, 0.8” must be spread over two pixels resulting in a pixel scale of 0.4”/pixel. Applying trigonometry to Figure 5.5 shows that the image size on the CCD is equal to the product of the combined optics’ new focal length (FL) and the tangent of the angle that subtends the telescope secondary to the image on the CCD. We express this as:

\[ H = FL \times \tan(u) \quad \text{FL} = \frac{0.4'' \text{(in radians)}}{16\mu \text{m}} = 8.25\text{m} \]

Finally, the magnification may be found by taking the ratio of the reduced FL to the original telescope FL, or \( M = \frac{8.25}{12} = 0.6875 \). Both focal reducers’ designs must have magnifications of 0.6875 or slightly less for a larger FOV.

Figure 5.5: An off-scale representation of the telescope secondary, focal reducing optics and CCD (all in red). For perfect Nyquist sampling, the system focal length is reduced from 12m to 8.25m as shown in black. The size H represents the scale of one pixel (Author).

5.7 Design Requirements Based On Stellar Density

DP requires a variable star and a reference star in the same FOV. It is important that they both be of similar magnitude so that the detector dynamic range can image both without saturation or low SNR. For this reason, it is necessary to identify the typical FOV, or circle radius in arcminutes, needed to find two stars of similar magnitude through various filters. The typical required FOV is important because it tells how far the ‘outrigger’ lens is required to extend in order to image a C star. Since stellar density is a function of star magnitude, the additional field size required is dependent
on the desired C star’s magnitude. It is necessary to determine the mean required field size based on stellar density per magnitude.

Bahcall provides star density distributions on the sky as a function of magnitude and solid angle (1980). Figure 5.6 (left) shows the results for high galactic latitude at 50 degrees (North Pole) in the V band (Bahcall, 1980). In a following paper, Bahcall presents star counts in 17 different directions, or star fields, on the sky as a function of filter bands: B, R and I (1981). The paper’s results are based on predictions of star counts per magnitude at the “north galactic pole (SA57)”. Tables are provided to indicate which star fields (2-7) are in the same 50-degree latitude position as well as to list the star counts in these fields for the B, R and I bands (Bahcall, 1981). Figure 5.6 (right) shows star counts for the I band. Stars per square degree (X) for these bands were averaged across fields 2-6 for magnitudes 10 through 26 and combined with the V-band data (Bahcall, 1980). \((3600/X)\) determines the number of square minutes per star for all four bands. The circle radius needed to cover the area occupied by a single star is then \(\sqrt{\frac{3600}{3.14X}}\). Finally, doubling that arcminute radius encircles two stars of like magnitude. The radii for two stars in each band are shown in Figure 5.7. As expected, lower magnitude (brighter) stars are less dense and require larger radii to encompass both variable and reference stars. By limiting the target range of our instrumentation to magnitudes of fainter than 10 in I or 12 in V, the mean radius for two like stars is 18 arcminutes. To allow placing both V and C stars on a square detector in any orientation, an extra minute of field angle is added at the edges. A star-to-star FOV of 20’x20’ is then required.

![Figure 5.6: Left – Stellar density plotted as a function of magnitude and solid angle for North Pole stars in the V band (Bahcall, 1980). Right – Star counts per square degree in the I band for several star fields. North Pole fields (2-6) for magnitudes 12-25 are highlighted in red for further consideration (Bahcall, 1981).](image)

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Figure 5.7: Plot of required arcminute sky radius needed to locate two stars of the same magnitude through filters V, B, R and I. Results show high magnitude stars are more populous. To locate two like-magnitude stars of magnitude 10 in B-I or 12 in V, a FOV of 18’ is required (Author).

5.8 Performance Analysis of the Optical Model

Rays from a point source passing through a perfect optical imaging system will focus to a point regardless of ray path or wavelength. Paraxial rays, i.e. rays propagating through the optics very close to the optical axis, approximate perfect propagation. For real lenses and mirrors, rays further away from the optical axis and off-axis will become aberrated, thus creating a blur in the focal plane. The degree of blurring caused by telescope and instrument optics compared to that caused by atmospheric seeing conditions determines the image quality of the optical system with respect to the atmospheric blur (seeing). Space instrumentation such as the Hubble telescope and Wide Field Camera can work at the diffraction limit because images are not affected by atmospheric turbulence. For ground-based telescopes, it is useful to aspire towards image quality that approaches the system’s diffraction limit. However, it is more practical to simply ensure blurring from lens aberration contributions do not exceed what is already caused by the most optimistic seeing conditions. To certify that the NUIG-PC optical model performs adequately, several analysis steps are needed. These steps are needed to confirm that the size of both the star’s image and the seeing disk blur remain as close as possible to the size of 1-2 pixels, or 16-32µm. This section describes the theory behind a complete geometrical analysis of the on-axis and off-axis spot sizes using spot diagrams and fractional energy throughput.
analysis. Aberration theory is also used to identify the causes of image degradation present in the optical system. The manner in which several aberrations contribute to the image blur is covered in depth.

5.9 Wavefront and Fractional Energy Theory

Full-field spot diagrams were produced from on-axis rays and off-axis rays. Each spot diagram is a result of ray tracing multiple paths from one object point through the entrance pupil of the system. The pattern that the rays form in the image plane permits analysis of the total transversal aberration for possible contributions like astigmatism and coma. OSLO® provides spot size outputs in the forms of ‘geometrical RMS radius size’ as well as full width at half maximum (FWHM) spot sizes. Root mean squared (RMS) spot size is calculated from averaging the magnitudes of each ray’s radial distance to the spot center, or

\[
\sqrt{\frac{\sum_{i=1}^{N} (ray - to - center)^2}{N}}.
\]  

(5.3)

The RMS averaging method diminishes the spot size contribution from outlier rays. The FWHM size is determined from measuring the width of the beam’s point spread function at half maximum size. OSLO® also features an ‘sdsa’ command to overlay a black annulus equivalent to the Airy disk size on spot diagram displays. For each light path, the Airy disk diameter is dependent on the focal length of the lens receiving light from the telescope, the wavelength viewed (filter selection) and the telescope diameter. The annulus size describes the diffraction limit of the system. Its diameter is equal to:

\[
D = \frac{2(FL)1.22\lambda}{D} = (FL)2.44(550\text{nm})/1.5\text{m}
\]  

(5.4)

For image spot sizes smaller than the diffraction limit, the RMS radius method may provide a meaningless result if the size is much smaller than the Airy disk. In this case, diffraction effects dominate the images. This is caused by the finite size of the aperture limiting the amount of light passing through. Central obscuration of the telescope might result in the image PSF redistributing light from its primary peak into secondary or tertiary diffraction rings. For diffraction-dominated images, a proper description of spot size should include not only the FWHM size, but also Strehl ratios. For spot sizes larger than the diffraction limit, defining spot size with the RMS method gives reliable results.

In addition to evaluating the full size of the image pattern, it is important to determine the energy distribution within that image. In many cases, a large percentage of the energy may be focused into a much smaller radial size. It is possible to have a poor/large RMS image size but excellent fractional energy and vice-versa. Fractional energy analysis was performed to determine if at least 60% of the fractional energy is imaged within the 32µm two pixel size. In the case of aberrations causing a poor energy distribution, it is necessary to establish how much additional image space is needed to receive 60% or more of the transmitted energy. In this manner, energy distribution effectively influences spot size.
‘WVF’ is a useful OSLO® command that prints the spot size’s Strehl ratio. The Strehl ratio is defined as

$$\text{SR} = \frac{-d^2}{4 \Pi^2 \lambda}$$

(5.5)

where $d$ is RMS wavefront aberration in $\lambda$ that causes spread outside the Airy disk ring. It provides the peak intensity normalized to the peak of the un-aberrated PSF. The ratio should be above 0.8 for diffraction limited systems. Since the NUIG-PC is a seeing-limited system, the Strehl ratio is used only as an indication of comparative doublet-to-doublet performance.

5.10 Aberration Theory

Although spot diagrams provide a good interpretation of image quality, that interpretation is an incomplete one. A comprehensive description of optical performance must include measuring the amount of several types of aberrations individually. This may not be an essential effort if spot size analysis results show that the image is notably smaller than model constraints. However, in the case that the image size is large or not well-behaved, aberration analysis is necessary. Spot size diagrams determine how large an image spread is but not where the spread comes from. Viewing the spot size contribution from each aberration identifies the limiting component i.e., which aberration is causing the most blurring. OSLO® describes the level of aberrations by measuring the difference between the behaviour of imaged paraxial rays and imaged off-axis rays. Any deviation from a perfect system would entail off-axis rays being imaged onto a different location. Aberration descriptions readily available from OSLO® include graphical depictions of astigmatism, longitudinal spherical aberration, chromatic focal shift and distortion. The manner in which these aberrations contribute to the image blur should be described in detail.

A lens is affected by astigmatism when the tangential and sagittal foci no longer coincide. The edge-side perspective of Figure 5.4 shows tangential rays in the plane of the page. Rays perpendicular to this plane are referred to as sagittal rays. Imaging a point source with a perfect lens allows both sets of rays to be focused on the same point. The astigmatic lens in Figure 5.8 shows that the tangential and sagittal foci no longer coincide. Instead, a point source is imaged as two separate lines with a blur in the middle called the circle of least confusion. Note that the tangential and sagittal focal lines are perpendicular to each other. The combination of these lines makes astigmatic images appear as an ‘X’ shape in the focal plane. Since astigmatism is dependent on the square of the off-axis distance divided by the focal length, or $(h/f)^2$, it can be minimized by limiting the span of off-axis rays and the degree of lens curvature (Smith, 2000). Controlling astigmatism was accomplished by omitting high powered doublets from both designs.
Figure 5.8: Astigmatism causes tangential and sagittal rays to focus at separate distances. A single focal spot is aberrated into two separate ones called the tangential line and sagittal line. A best focus blur is left between the two lines (Author).

Longitudinal spherical aberration (LSA) results in the focal length being dependent on the ray height in the pupil. Undercorrected (negative) spherical aberration is pictured in Figure 5.9. Ideally, all rays should focus at the same position as paraxial rays, at a single spot in the paraxial focus. Object distance and lens power contribute to LSA producing images that instead appear as a ring blur with a central point (Smith, 2000).

Figure 5.9: Longitudinal spherical aberration causing focal length to be dependent on aperture position. The above undercorrected LSA produces an image of a ring blur surrounding a central point (Author).

Since the index of refraction is inversely proportional to wavelength, blue light bends more severely through transmissive optics. Longitudinal chromatic aberration is caused by short (blue) wavelengths focusing at shorter distances than longer (red) wavelengths. Figure 5.10 identifies the total distance from blue focus to red focus as the chromatic focal shift (CFS). In some cases, positive (overcorrected) CFS focuses red light to a shorter distance. In this case, the focal plane image will appear as a central blue dot encircled by a red ring (Smith, 2000). Selecting doublets composed
of half undercorrecting crown glass and half overcorrecting flint glass has partially corrected CFS effects.

![Chromatic Focal Shift Diagram]

Figure 5.10: Chromatic focal shift is longitudinal focal displacement between blue and red foci. Undercorrected CFS produces an image in the focal plane that appears as a central red dot encircled by a blue ring (Author).

Distortion causes images to either increase or decrease in scale, thus it is typically expressed as a percentage of original size. The percent distortion increases as the square of the axis to ray distance. This causes points farther from the axis to be spread out further and the sides of the image to curve. Figure 5.11 shows a representation of a normal image undergoing both ‘barrel’ and ‘pincushion’ distortion. ‘Barrel’ refers to negative/inward, or undercorrected distortion. ‘Pincushion’ refers to positive/outward, or overcorrected distortion.

![Distortion Diagram]

Figure 5.11: An image pictured with no distortion, with ‘barrel’ distortion and with ‘pincushion’ distortion (Author).

5.11 Introduction to OSLO® Optical Design Software

Analysis of the NUIG-PC design was performed with OSLO® LT/EDU optical design software. OSLO® is an acronym for ‘Optics Software for Layout and Optimization’. It is one of several programs used to design and optimize optical systems. In OSLO®, designs are created one surface at a time. Each optical element is a combination of two or more surfaces that bound a solid object. Light rays used to analyze the
design's performance travel through each surface from left to right. The surfaces are thus labelled 0 - 8 in the sequential order that the light rays intersect with them. The object surface is always designated as surface number 0 and the highest numbered surface is designated as ‘IMS’ for the image surface regardless if an image is formed there or not. The OSLO® surface data spreadsheet allows for entering data for each surface. The spreadsheet from a generic doublet design is shown in Figure 5.12. The data fields in this sheet include ‘thickness’ (the distance to the next surface), the ‘aperture radius’ (size of the surface), the ‘Glass’ (material to the right of the surface), and ‘Special’ (for setting conic or aspheric shape values). Sign conventions used in ray tracing can be confusing. For OSLO®, radius of curvature values are only positive for central points to the surface’s right. Similarly, thickness values are positive only for rays travelling left to right. Additional aspects and limitations of OSLO® software will be discussed in the chapter on results.

Figure 5.12: OSLO® software spreadsheet for a positive lens doublet (Author).

5.12 Process for Checking Model Performance through B and I Filters

Wavefront, fractional energy and aberration analysis were also performed for the wavelength ranges included in the B and I bands. The Loiano telescope filter bands are pictured in Figure 5.13. The filters’ percent transmission is plotted over filter bands U, B, V, R, and I from 300nm to 1200nm. NUIG-PC photometry will be performed with the B, V and I bands only. For each band, the software ‘wavelength’ field was set to include 25nm wavelength increments, each weighted to its transmission percentage.

47
Figure 5.13: Transmission plots for UBVRI filters from Custom Scientific for use by the NUIG-PC at Italy’s Loiano telescope (Reference 9).
Chapter 6

Design and Performance Analysis of the NUIG-PC Outrigger Model

This chapter presents the project’s design and results from the analysis of its optical performance. Design results include a to-scale 3D model of the new NUIG-PC box accompanied by its corresponding assembly in OSLO® optical design software. Design results also include explanations of what requirements and constraints were met as well as the process followed to select the most suitable optics. Analysis results are obtained exclusively from OSLO® software. They comprise results of the optical designs’ PSF, fractional energy and aberration performance. Additional analysis results include the designs’ performance dependence on operating temperature as well as their performance through B and I passbands. The chapter concludes with some general conclusions on performance of the total design.

6.1 Description of NUIG-PC Optical Design, Camera Box and Mounting Methods

AutoCAD® drafting software was used to create a to-scale 3D model of the NUIG-PC with its new optical components. The goal of this model was to ensure that the combined focal lengths of the design’s lenses permitted all components to fit within the pre-fabricated TRIFFID camera box. Figure 6.1 shows this light-tight box containing the L3 camera, filter wheel and NUIG-PC optics. All components (excluding the camera and filter wheel) are to scale.

The design shows two light paths from the F/8 telescope that focus on different sections of the telescope’s focal plane. The red light path shows variable starlight heading to the detector on-axis. The blue light path represents light from a C star coming from as far as 18 arcminutes off-axis (outside FOV). The separation of both paths is initially exaggerated for clarity purposes. Both ultimately come to focus on the detector with foci separated by ~4mm. The C star’s light is reflected off three fold mirrors before combining with the V star’s light after the beamsplitter. This combined light path approach avoids placing any adjustable optics too close to the detector. A beamsplitter is an optical device that splits a beam of light in two. In the case of this design, it is a glass plate with a metallic or dielectric coating. C star and V star light will both transmit and reflect off the beamsplitter. Although this allows beam paths to be combined, it also necessitates the use of optical baffles within the
NUIG-PC box. Light baffles are commonly black anodized metal structures placed in positions to absorb and trap the stray light paths. For this design, stray light includes paths transmitting through the beamsplitter from fold three, reflecting from lens two and ghost lens reflections. Baffles are not depicted in Figure 6.1 in order to retain picture clarity and simplicity.

The blue arrows in Figure 6.1 indicate the direction of motion that translation stages and their mounted optics may move. Three translation stages fitted with micrometers are required to focus both lens 1 (L1) and lens 2 (L2). Lateral adjustments are also required for L1 and fold 1 (F1). This lateral degree of freedom is necessary to select the off-axis C star’s light from different points in the field. Selection of stars in the near-field may be limited by clipping of the V star’s light path by F1’s mount. Focus adjustments are necessary to properly collimate the transmitted beams. This is achieved by positioning each lens one focal length distance back from the telescope focal plane. It is also imperative that the stacked translators under F1 and F2 travel exclusively in perpendicular directions. Otherwise, each lateral adjustment of F1 would cause an unwelcome focal shift. The motions of the two translators may be aligned interferometrically or by other methods.

Once attached to the Loiano 1.5m telescope mounting flange, the telescope mount permits the entire instrument box to be rotated about the main axis (red beam). A full 360-degree rotation allows the C star channel to sweep a full arc of the sky around the target including portions outside the central part of the FOV. Although ‘outrigger’ path imaging from outside the FOV does take images through possibly different air masses, the camera takes V and C star images simultaneously. Simultaneous imaging minimizes the possibility of false variability. The best argument for permitting far-field imaging in this case is the vastly different time scales of variation due to transits compared to variations from atmosphere effects. Comparatively, false variation due to clouds or air pockets occurs over a much shorter timeframe than transit variation. Atmosphere variations may be averaged out over the 2-3 hour time period of a transit. Other types of variables like pulsars oscillate on a much more regular interval than the effects caused by the atmosphere. The degree of clear periodicity also allows atmosphere variation to be isolated.
Figure 6.1: AutoCAD® representation of NUIG-PC with ‘outrigger’ lens design. The top panel shows a close-up 3D rendering of both beam paths. Both red and blue incoming beams focus on different sections of the telescope’s focal plane. Beam separation is exaggerated for visibility purposes. The middle panel is a wire-frame representation of the camera box, instruments and optics. Both LL3 camera and filter wheel are labelled, as are three folds (F1-F3), three lenses (L1-L3), and one beamsplitter (B). Blue arrows indicate the direction that translation stages holding mounted optics must be permitted to travel. The lenses’ focal length-to-diameter ratios in mm are 60/10 for L1, 200/32 for L2 and 125/35 for L3. The two bottom panels show wire frame and 3D rendering of the top view of the design. Telescope field curvature is not taken into account for any of the above schematics (Author).
6.2 Results and Limitations of Optimizing the Model with OSLO® Optical Design Software

The OSLO® spreadsheets for both NUIG-PC light paths are shown in Figures 6.2 and 6.3. Each spreadsheet describes light from the telescope entering two doublets and imaging onto the detector. While the OSLO® LT/EDU version is free to download, it does have some limitations. LT/EDU designs are restricted to a 10 surface limit. The LT/EDU package is also limited to race trace analysis through sequential surfaces only. These limitations presented a problem for analysing the NUIG-PC design. The design’s separate light paths cannot be modelled from sequential surfaces. In addition, Figure 6.2 shows ten surfaces are required for only one of two light paths. Due to these limitations, the NUIG-PC design was modelled and analyzed as two separate OSLO® files, one file for each light path. The first surface in each spreadsheet is set as a ‘perfect lens’ of zero thickness, 150mm diameter and 1200mm focal length. These lenses simulate the same F/8 cone of light as would be received by the NUIG-PC from Italy’s 1.5m Loiano telescope. The V star’s light path contains two achromatic doublets separated by 104.6mm. The first doublet has a 200mm focal length, 30mm optical diameter, and a 8.1mm thickness. The second has a 125mm focal length, 30mm optical diameter and a 9.1mm thickness. Both are composed of SF5 and BK7 glass. The C star’s light path contains two achromatic doublets separated by 350mm. The first doublet has a 60.1mm focal length, 9mm optical diameter, 4.9mm thickness and is composed of SF2 and BK7 glass elements. The second doublet is identical to the V star light path’s second doublet. Non-powered surfaces (folds) were not included in either spreadsheet.

Figure 6.2: Top - Spreadsheet window for V star’s light path. Lens focal ratios and light path magnification are listed in the top ‘Lens’ field. Bottom – Full view and close up of L2 and L3, or surfaces 3-5 and 6-8 (Author).
6.3 Requirements and Constraints met by the Optical Design

Many parameters of the doublets included in both light path models are restrained. Some restraints are very obvious while others take some effort to clarify. The most obvious limitation of the combined model may be the requirement that surfaces six through eight be identical for both light path designs. The combined model must acquiesce to the condition that lens three (L3) is a common element for both designs. Since both light paths use the same rear lens, rays must also be focused at the same distance (thickness of surface 8+IMS) from L3 to the CCD surface. Section 6.4 covers steps taken to meet this constraint.

To ensure the images of both V and C stars projected onto the CCD are of the same scale, the combined magnification of both light paths must be as similar as possible. The magnification of a two-lens focal reducer is equal to the ratio of the lenses’ F-numbers. This means lens one (L1) and lens two (L2) must have the same F/#. The f-numbers of both L1 and L2 are also limited to being less than F/8. A front lens with a larger F/# would cause portions of the F/8 telescope beam to be clipped by the lens’s aperture. Selecting lenses close to F/7 ensures that there is no vignetting and provides some margin so as not to lose light in case of misalignment. An effective lens F/# may be created by ‘stopping down’ (reduction with mask) a lenses aperture to the desired diameter. All lenses were intentionally oversized by 1-2mm to be then ‘stopped down’ to allow for easier alignment. The effective f-numbers of L1
and L2 are 6.66 and 6.67, respectively. Thus, the combined magnifications of both light path designs are identical.

The previous chapter described how magnification must also be limited to 0.6875 or less for proper Nyquist sampling. However, using doublets that produce that specific focal ratio would require custom made optics. Due to cost considerations, another design constraint is using lenses that are available to order from catalogues. OSLO® comes with a built-in lens component library featuring lenses from typical manufacturers such as Schott and Melles Griot. By selecting lenses available in the lens catalogue, two designs with magnifications of 0.666 and 0.625 were developed. The second was retained due to slightly better results. For a 0.625 magnification, the new system FL is 7.5m, the pixel scale is 0.44”/pixel and the linear size of the seeing disk is ~0.03mm to 0.05mm.

It may be the case that several magnitude choices for C stars are available. However, target stars may not be omitted solely by their magnitudes. Bearing this in mind, the beamsplitter’s pass/reflect ratio was chosen in order to maximize the amount of flux on the target star. The beamsplitter is chosen at 80% pass and 20% reflect. Other model requirements are based on the goal to provide the largest possible field for C star selection. Figure 6.1 shows that L1 is comparatively small to L2. L1 and the mounting hardware around it must be kept minimal in size to ensure closest possible placement to the V star’s light path. This minimizes what portions of the FOV are unavailable so that the V star’s light path is not vignetted. Finally, L1’s translation stage must provide enough lateral travel to guarantee that enough extra sky can be imaged to select a suitable C star. Since stellar density is a function of star magnitude, the additional field size required is dependent on the desired C star’s magnitude. In section 5.7, star counts provided a maximum required field size of 20’x20’. This field size applied to formula 5.2 shows that L1’s translation stage must translate at least 4.8cm. A solid 5cm adjustment range should comfortably permit C star selection for all bands.

6.4 Procedure for Final Doublet Selection

Once the requirements for the optical model were identified, building a design from catalogue lenses was possible. Achromatic doublets were selected to reduce chromatic aberration by balancing a positive crown glass lens with a negative flint glass lens. Any doublet combination selected must reduce the focal ratio of the system by a factor of 3/2 (from F/8 to F/5.5) as well as have the same back focal lengths. An iterative process of looking for well-performing doublet combinations that meet both requirements was necessary. Many attempted doublet combinations also produced unsuitable degrees of aberrations or had focal lengths that did not meet size constraints for the instrument box.

OSLO® software allows users to set one or more model parameters as variable fields in order to perfect the design with an optimization command. Both light path designs were optimized with a variable front doublet position and doublet separation. ‘GenII’ error functions were generated and run through 1000 iterations before applying a polychromatic focus command to the rear doublet position. This focusing procedure places the image plane at the position of smallest image spot size, so called the disk of least confusion, for all wavelengths examined. Unfortunately, producing identical distances between the rear doublet and focus position for both light path designs was not typical. On Figures 6.2 and 6.3, this would appear as different values
for the IMS thickness fields for both light paths. Once doublet combinations that produced similar focal plane distances were identified, further steps were needed to force identical distances for both paths.

Further optimization was performed with slider wheel adjustments. This OSLO® feature allows direct slider-wheel manipulation of any design parameter. Using slider wheels, further slight adjustments to L1’s position placed the C star light path’s rear focal plane in the same location as the V star focal plane. L1 adjustments were then repeated to optimise the focal plane positions of starlight passing through the remaining B and I band filters. The final design is composed of Ross Optics doublets AOC066, AOC210, and AOC216. The circumstance that each doublet selected is a Ross Optics product is purely coincidental.

6.5 Results of the Optical Models’ Wavefront and Fractional Energy Analysis

This section describes results from the complete geometrical analysis of the on-axis and off-axis spot sizes with spot diagrams and fractional energy throughput analysis. It describes analysis repeated for performance through each filter. Additional results include aberration analysis and performance dependence on operating temperature.

On-axis and full-field spot diagrams were produced from on-axis rays and off-axis rays. Figures 6.4 and 6.5 show on- and off-axis spot sizes and fractional energy performance for both V and C stars light paths in the V-band. The left side windows of both figures display the on-axis (top) and full-field (bottom) spot diagrams for both the C and V stars’ light paths. In the case of the main channel or V star path, the full-field spot was set to 2.32mm or 1’ off axis with OSLO®’s ‘sop’ command. This command moves the spot center laterally off-axis in the field of focus in x and y directions. Since the ‘outrigger’ path is designed for only small FOVs, the full-field spot’s wavefront was examined only at 0.04mm or ~10” off axis. Since the point spread function (PSF) varies dependent on the field of view position, spot size values were expected to increase for off-axis field points. The RMS spot sizes from the V star path were 4.522µm for on-axis and 5.504µm for 1’ off-axis. Spot sizes from the C star path were 1.6604µm for on-axis and 1.661µm for 10” off-axis.

The RMS spot size relative to the black Airy disk ring size initially makes the C star path’s wavefront seem particularly well behaved. However, comparing the size and scale of the V star and C star spot sizes shows they do not diverge notably in quality. Equation 5.1 shows that the ring sizes for both light paths are dependent on the focal lengths of either L1 or L2 (60mm and 200mm). Since the Airy ring size of the C star path is 200/60 times, or ~3 times, larger than the other path, the spot size only appears smaller by comparison.

L1’s short focal length is a product of its small size and this size is what produces such a large Airy disk. Its particularly small aperture causes diffraction effects to become dominant in only the C star’s light path. Since the spread of the spot size is below the diffraction limit given by the Airy disk, it is more suitable to provide the image’s FWHM size. The ‘ppss’ command prints out PSF information including the $e^{-2}$ diameter in X and Y (FWHM size). The C star path’s on-axis FWHM diameter is 7.911µm in both X and Y. Since the FWHM size is roughly twice the RMS size, the image quality is nearly diffraction limited and may be approximated by a Gaussian function. For V-band light, the optics alone produce spot sizes on the order of $1/8^{th}$ to $1/4$ of a single pixel size. Without considering fractional
energy distribution and specific aberration contributions, minimal image degradation is caused by the optics as compared to that caused by atmospheric blurring.

The relative spot size to Airy disk ring size shows the V star path’s wavefront is not dominated by diffraction. This is partially due to its larger size and focal length causing a magnification that forms a smaller Airy disk diameter. Although an image’s energy distribution should be examined in any case, it is particularly important to do so for the V star path. The top-right windows of Figures 6.4 and 6.5 display the polychromatic encircled energies of both light paths. For multiple wavelengths within the V-band, the graphs plot the averaged energy percentage vs. spot radius. 60% encircled energy is attained at spot sizes 6µm and 20µm. Both paths have suitable energy distributions imaged onto a two pixel (32µm) scale. Strehl ratios were also examined for both designs. For V and C star paths, Strehl ratios of 0.939731 and 0.996798 showed better than typical (0.5-0.8) performance for typical focal reducers. Positive results in the V band for both Strehl ratios and fractional energy analysis were encouraging. They show that a majority of energy from a point source is imaged well within the 32µm size limit.

The bottom right windows in Figures 6.4 and 6.5 are called through-focus diagrams. They are an extra method to quickly determine image quality both on- and off-axis as well as at various distances from the focal plane. An initial design requirement is setting the field angle size of the transmitted rays in degrees. Half of the NUIG-PC’s 4’x4’ FOV makes a 0.03x0.03 degree field. The through-focus diagram shows that the image size increases by a negligible amount both at the 0.03 full-field angle as well as at 100µm defocus.

Figure 6.4: On-axis and off-axis spot sizes and fractional energy performance for the V star’s light path in the V-band. Top-left: on-axis RMS spot size, bottom-left: full-field RMS spot size, top-right: on-axis polychromatic encircled energy, bottom-right: through focus diagram (Author).
6.6 Results of the Optical Models’ Aberration Analysis

By measuring the contribution of several types of aberrations individually, the aberration component causing the most blurring was identified. Figure 6.6 and 6.7 show the ray-analysis output windows for both light paths in the V passband. They include graphical representations of several aberrations as well as a ray trace graphic. These aberrations include astigmatism, longitudinal spherical aberration, chromatic focal shift and distortion. OSLO® results for each light path and through each filter show chromatic aberration to be the limiting component of this design.

The top-left window of each figure displays the contribution of astigmatism to the image blur. The astigmatism plots in Figures 6.6 and 6.7 show longitudinal displacement from the best focus (X-axis) vs. off-axis angular displacement (Y-axis). The V star path window indicates both sagital (S) and tangential (T) rays are initially displaced 75µm on-axis and do not diverge off-axis. The C star path window indicates both sagital (S) and tangential (T) rays are initially displaced -50µm on-axis and diverge to -100µm and -200µm at full-field for S and T, respectively. The on-axis displacement for both paths does not indicate any (actually impossible) existence of astigmatism on the paraxial plane. OSLO® minimizes the total spot size by balancing the relative displacements from the focal plane position to the focal positions of each aberration. For the V star path, this indicates a near lack of any astigmatism. For the C star path, the scale of astigmatism is only 1/10 the effect due to chromatic aberration.
The top-middle windows of Figures 6.6 and 6.7 display the contribution of longitudinal spherical aberration to the image blur. Each plotted line in these windows indicates a V-band wavelength contributing to the average polychromatic performance. The LSA plots in Figures 6.6 and 6.7 show longitudinal displacement from the best focus (X-axis) vs. ray height in the aperture (Y-axis). The V star path window shows the wavelengths positions’ range from 125µm to 250µm on-axis and ~25µm to 125µm at full field. The C star path window shows the wavelengths positions’ range from ~25µm to ~300µm on-axis and do not diverge off-axis. The scale of LSA is the same for each light path and slightly better behaved for the V star. Results indicate that there is no significant influence on the image spot size.

The bottom-left windows of Figures 6.6 and 6.7 display the contribution of distortion (%) to image displacement. The distortion plots in both figures show no distortion on axis. However, the levels increase to 0.01% and 0.05% at full-field for V and C star paths. The V star path features overcorrected distortion and the C star path features undercorrected distortion. Neither path shows a level of distortion large enough to appreciably displace stars on the detector.

The top-right windows of Figures 6.6 and 6.7 display the contribution of chromatic focal shift (CFS) to the image blur. The CFS plots in both figures show longitudinal displacement from the best focus (X-axis) vs. wavelength (Y-axis). The V star path window indicates CFS is insignificant from 500nm to 600nm but increases to 250µm towards 700nm, and 750µm towards 400nm. The C star path window indicates CFS is also negligible from 500nm to 600nm but increases at roughly twice the scale as the V star path CFS. The scale of this aberration shows that CFS is the limiting component for spot size reduction even through the limited passband of the Johnson V bandpass filter. The design performance’s results through additional filters prove to be even more limited. This is covered in section 6.8.

Figure 6.6: Ray-analysis output windows for the V star’s light path in the V-band. Two-axis plots describe longitudinal foci displacement vs. aperture/wavelength resulting from astigmatism, spherical aberration and chromatic aberration. 3D wire frame ray trace graphic included and distortion plot included (Author).
6.7 Performance Dependence on Operating Temperature

A final check for the two light path designs’ performance through each filter entailed checking for temperature dependence. The ‘tem’ command sets the design at the desired temperature in degrees Celsius. The instrument’s operating temperature is roughly –80 degrees C. Although this not an extreme temperature, caution betters indiscretion to ensure aberrations would not enlarge. In all instances, changing temperature had a negligible to non-existent affect on spot sizes, fractional energy and aberration levels.

6.8 Analysis of Model Performance through B and I Filters

Wavefront, fractional energy and aberration analyses were also performed for the wavelength ranges included in the Loiano telescope’s B and I filter bands pictured in Figure 5.13. In order to condense these results for simplicity, the analysis outcomes are organized and displayed in Tables 6.1 and 6.2 for both passbands. Several results are notable for each of the two light paths through both filters. CFS is again the dominant aberration now in the B and I passbands, causing a larger RMS spot size to slightly oversample the detector. In the B-band, its contribution is a factor of ten worse than from the I-band and a factor of 20 worse than from the V-band. The ratio of FWHM to RMS spot sizes show that neither red nor blue light will produce images with diffraction-limited quality on the detector. The V-path Strehl ratios and fractional energy sizes are particularly poor as well. These parameters indicate that a
large amount of light is being distributed outside the Airy disk diameter. However, the RMS spot size is still the deciding factor for design implementation. Regardless which filter or light path is considered, the spot sizes remain under the 32µm sampling limit.

<table>
<thead>
<tr>
<th>V Path, I-Band Analysis</th>
<th>RMS Spot Size</th>
<th>FWHM</th>
<th>60% F.E. Spot Size</th>
<th>Strehl Ratio</th>
<th>Astigmatism</th>
<th>LSA</th>
<th>CFS</th>
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<td>na</td>
<td>na</td>
<td>190um</td>
<td>0 to 1.5mm</td>
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<td>C Path, I-Band Analysis</td>
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<td>na</td>
<td>-750um</td>
<td>-1.3 to 4mm</td>
<td>Long λ</td>
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Table 6.1: I-band results for both V and C starlight paths. RMS, FWHM and 60% encircled energy spot sizes as well as longitudinal astigmatism, spherical and chromatic aberrations are presented for on-axis and full-field positions (Author).

<table>
<thead>
<tr>
<th>V Path, B-Band Analysis</th>
<th>RMS Spot Size</th>
<th>FWHM</th>
<th>60% F.E. Spot Size</th>
<th>Strehl Ratio</th>
<th>Astigmatism</th>
<th>LSA</th>
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<tr>
<td>C Path, B-Band Analysis</td>
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Table 6.2: B-band results for both V and C starlight paths. RMS, FWHM and 60% encircled energy spot sizes as well as longitudinal astigmatism, spherical and chromatic aberrations are presented for on-axis and full-field positions (Author).
Chapter 7

Conclusions

Using OSLO® to observe the optical model’s wavefront, fractional energy and aberration performance illustrates how the NUIG-PC behaves in bandpass ranges B, V and I. Both chromatic focal shift and energy distribution results show that diffraction limited performance at I and B passbands is difficult to obtain. However, since the NUIG-PC is to be commissioned for ground-based observations, the atmosphere driven SD size is what ultimately limits performance. Compared to aberration sizes in any of the three passbands, the 5-10X larger SD still determines the final image size on the CCD. For this reason, the wavefront and fractional energy analysis shows the design meets image requirements for each passband.

Additional aberration analysis shows that performance deteriorates most notably in the B-band. This is partially to be expected since most unspecialised optics are well behaved only for red to visible light. For ‘off-the-shelf’ catalogue lenses, chromatic effects are nearly negligible from 500-800nm. Problems arise in the bluer end of the spectrum because shorter wavelengths always cause higher chromatic aberrations. Designing and including additional optics for the B-band only may improve the implementation of the total optical model. Future efforts may include design modifications to ‘shore-up’ the effects of chromatic aberration in the B passband. This might be accomplished by switching to a triplet design or by using a re-imaging system produced exclusively with reflective optics.

Once the NUIG-PC is provided with this new optical design, its ability to detect variable sources in challenging astronomical regimes will be improved. Enlarging the instrument’s effective FOV while maintaining detector speed is the method described for increasing the number of variable sources obtainable for detection. The two-path, ‘outrigger’ optical system imaging onto an L3CCD is designed to accomplish this by decoupling the adverse association between FOV and detector speed as well as reducing the influence of atmospheric effects. Providing new variables in areas previously avoided will hopefully allow the NUIG-PC to detect transiting exo-solar planets. It is our goal that this camera may produce valuable science by focusing specifically within crowded fields or in the vicinity of bright sources. When large-scale and high-budget photometric surveys avoid these challenging areas, many opportunities still remain to identify new variable sources. The simplicity of this design shows valuable photometric data can be provided from minimal instrumentation mounted on sub-two meter telescopes. The ‘outrigger’ system was designed specifically to observe variables within overlooked stellar regions. Focusing on these regimes capitalizes on the availability of smaller scale
telescopes and detectors. The steerable, two-beam system for simultaneous on- and off-axis imaging is both small-scale and low-cost, yet still capable of notable differential photometry contributions.
Bibliography


