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THuCIDIDES: a high-efficiency multimode spectrograph design for the Hale Telescope

Bradford B. Behr

Department of Astronomy, California Institute of Technology
Pasadena CA 91125, USA

ABSTRACT

This paper describes the operating parameters and initial design of a new spectrograph proposed for the 200-inch Hale Telescope at Palomar Observatory. The instrument, whose working name is THuCIDIDES (**T**wo **Hu**ndred-inch **C**assegrain **I**mage-**D**eblurred **I**nterchangable-**D**isperser/**E**chelle **S**pectrograph), will feature high system efficiency and multiple modes of operation, including low- and intermediate-resolution long slit and multi-slit capability over 12.5×3 arcmin fields, and a cross-dispersed echelle mode covering 3800–8500 Å at $R = 20000$ (with a 1.2 arcsecond slit) up to $R = 60000$ (with an image slicer). A 4096×4096 pixel CCD will serve as the detector. The quasi-Littrow echelle configuration and use of a prism cross-disperser will result in high system efficiency, estimated at $\simeq 14\%$. The compact design will permit mounting in the Cassegrain ring plane, to reduce susceptibility to flexure. An optional fast-guiding tilt mirror provides modest improvement to seeing FWHM and slit throughput.

Keywords: optical instrumentation – echelle spectrograph – lens design – fast tip-tilt guiding

1. INTRODUCTION

The facilities for high-resolution spectroscopy at the Palomar 200-inch telescope are presently rather limited. The only instrument capable of spectral resolutions around $R = 20000$ over a wide wavelength range is the East Arm Echelle Spectrograph[1], which utilizes a fiber-optic conduit running from prime focus to a fixed-orientation optical bench, in order to eliminate flexure issues and maximize the wavelength stability of the spectrograph. Consequently, due to lossy fiber coupling, it suffers from poor overall efficiency ($\eta < 2\%$), and the single fiber does not permit a sky background channel. Low order grating and slit devices like the Double Spectrograph[2], although efficient, are limited to $R < 5000$. Many of the scientific pursuits of Palomar observers — stellar abundance work, quasar absorption lines, and globular cluster dynamics — would therefore benefit greatly from the availability of a high-efficiency, high-resolution Cassegrain echelle spectrograph, similar to those currently in operation on the LCO 100-inch[3], Palomar 60-inch[4], and the McDonald 2.1-meter[5] telescopes.

The underlying design philosophy for the THuCIDIDES echelle configuration emphasizes simplicity and maximum throughput. Specific design choices stemming from these priorities include use of a single lens system in double-pass as both collimator and camera, a prism (instead of grating) as the cross-disperser, and an optional fast tip-tilt guider. Details of these subsystems will be discussed below.

Although this proposed instrument was originally conceived solely as a cross-dispersed echelle, it became apparent that other modes of operation could be incorporated into the design at no penalty to the echelle performance. The large format of the CCD detector and the $f/16 \rightarrow f/3.3$ reimaging configuration will permit fields as large as 12.5×3 arcminutes (300×75 mm at Cassegrain focus) with either a single long slit or multi-slit mask. In order to accomodate the low-resolution requirements of most long/multi-slit work, the spectrograph follows a modular design, with interchangable 'bolt-on' disperser, slit, and reimaging packages, which are selected according to the spectral and spatial coverage desired for a given observing run.

This paper focuses on the optical layout of the spectrograph. The mechanical structure, CCD electronics, control systems, and other such facets of the design are still under development, and will be discussed in a later publication.

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2. PERFORMANCE SPECIFICATIONS

2.1. Basic Optical Parameters

Collimator EFL:	2180 mm
Camera EFL:	455 mm
Collimated beam diameter:	136 mm
Estimated efficiency:	$\eta = 14\%$ at 6000 Å

2.2. Echelle Mode

Grating:	12×6 inch 79.1 gr/mm R2 grating
Cross-disperser:	LF5 prism, 45° apex angle
Spectral range:	3800–8500 Å, continuous coverage to 7500 Å, 33 orders
Resolution:	$R\phi = 22400$, 5.4 pixels/arcsec
	nominal $R = 18700$ ($16\,\mathrm{km\,s^{-1}}$) with 1.2 arcsec slit (6.5 pixel res element)
	maximum $R = 60790$ ($4.9\,\mathrm{km\,s^{-1}}$) with 0.37 arcsec slit (2 pixel res element)
Slit length:	8.4 arcsec (45 pixels) nominal
Order spacing:	6 pixels minimum interorder gap

2.3. Long Slit Mode

Gratings:	300 gr/mm, 600 gr/mm, 1200 gr/mm from Norris Spectrograph
Spectral resolution and range:	$\Delta\lambda = 7.1$ Å over 4490 Å with 300 gr/mm and 1.2 arcsec slit
	$\Delta\lambda = 1.7$ Å over 1070 Å with 1200 gr/mm
Maximum slit length:	12.5 arcmin (300 mm at $f/16$)
Spatial scale:	0.19 arcsec/pixel

2.4. Multi-slit Mode

Spectral resolution and range:	same as long slit above
Field size:	12.5×3 arcmin, 300×75 mm masks at $f/16$
Slit width:	1.5 arcsec = 0.6 mm on mask

3. BASIC LAYOUT

Figures 1(a) and 1(b) show top-view and side-view plans of Thucidides, depicting the system in its short-slit echelle mode. Light at $f/16$ enters through the Cassegrain aperture and is reflected by feed mirror *FM* (optionally tip-tilt guided) into the Cassegrain ring plane and brought to a focus at the slit focal plane *SP*. Reflective slitjaws feed a video guider camera *GC* via a fold mirror (not shown), providing feedback to the tip-tilt system or indigenous telescope guiding. The $f/16$ beam is then collimated by a 240 mm Nikon lens *CL*, bent by *M1* and then reimaged at $f/3.3$ onto an intermediate focal plane *IP* by a 50 mm Nikon lens *RL*. Additional masking of stray light can take place at *IP*. After passing through *IP*, the light is reflected by a small fold mirror *M3* to the main collimator/camera lens *CCL* and is collimated for entry into the disperser unit, which contains the 79.1 gr/mm R2 grating *EG* and double-pass cross-dispersing prism *DP* (45° apex angle of LF5 glass). Exiting the disperser, the light is refocused by *CCL* on to the detector plane, where the spectral image is formed on the detector *CCD*.

Using the collimator/camera in double pass in this fashion (a technique shared by many other echelles) affords a number of advantages. Most notably, the small size of the reimaged field at the intermediate focus permits the angle between disperser input and output beams (2γ in echelle nomenclature) to be very small, for smaller prism size and improved efficiency, and the camera can be placed immediately following the disperser exit, before the highly-dispersed output beam has grown to enormous proportions. The design is also relatively compact, since the 2-meter EFL of the collimator does not have to be physically realized, and will mount on the uppermost Cassegrain ring plane, simplifying the mechanical structure of the device and keeping flexure to a minimum.

For long-slit or multi-slit mode, new reimaging and disperser packages, represented by the broken-line boxes, are inserted into the system in place of the echelle reimager and grating/cross-disperser units. A larger feed mirror *FM2* illuminates a long slit or slit mask at *SP*. The beam is reflected by *M2* immediately after the slit plane and sent to a large off-axis spherical collimating mirror *CM* of focal length 510 mm. Collimated beams from *CM* converge

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towards a pupil, where the lens system *RL2* reimages them at $f/3.3$ onto *IP*. *RL2* will have to be a custom optical system (not yet designed) to handle the wide field requirements, and a field lens *FL* at *IP* will be necessary to maintain telecentricity downstream of *IP*. The echelle disperser package will be exchanged for a low-order grating *G*, including a flip-in mirror *FIM* for slit alignment imaging. We may borrow gratings from Palomar's multifiber Norris spectrograph, mounted in one of the spare motorized grating mounts originally intended for the Double Spectrograph.

Other mode variations are possible. An image slicer can be placed immediately after the slit plane for increased spectral resolution, since the pixel sampling permits effective slit widths as small as 0.4 arcsec. A coronagraphic mode might be implemented by placing an occulting disk at *SP*, a Lyot stop at the pupil position in the small collimated beam between *CL* and *RL*, and a slit at *IP*. With an interference filter just before *RL2* and an alternative echelle disperser package without the prism, a single-order long-slit echelle mode could also prove useful.

4. SUBSYSTEMS

4.1. Fast Tip-tilt Guiding on Slit

The Palomar telescopes are equipped with a standardized video guider system which will keep stars or other targets centered on the slit against slow secular changes and pointing drift, but some advantage might be gained by also including a separate fast-guiding subsystem just upstream of the spectrograph slit. As part of a separate project, a team under J. K. McCarthy has placed a CCD device on a piezo-driven x-y stage, translating the chip in the focal plane under closed-loop feedback from a guide star on a photodiode quad cell. Tests of this system at the 200-inch Cassegrain station indicate that fast guiding at 20 Hz will remove a significant amount of the global tip-tilt component of the atmospheric seeing and wind shake, thereby improving the seeing disk FWHM by $\simeq 20\%$ under typical conditions. If such a system were to be implemented by driving mirror *FM* via feedback from the slitjaw image, the slit throughput could be improved by a significant amount, and the extent of the target image along the slit length (the spatial axis) would be reduced as well, minimizing contamination of the sky background channels and pixel readout noise. Such a system could be easily added after the instrument is first commisioned with a fixed mirror at *FM*.

4.2. Collimator/Camera Lens

The lens system labelled *CCL* in Figure 1 is used in double-pass, as both the collimator and the spectrograph camera. This six-element all-spherical design was adapted from the Epps camera for the Palomar Double Spectrograph Red Camera upgrade, simplified and optimized for this application using the *Code V* raytracing package. The EFL of the composite lens is 455 mm. Lens element parameters are listed in Table 1. Glass types are from the O'Hara catalog. The calcium fluoride element (#3) is made the center element of a triplet in order to isolate it from atmospheric humidity. The field flattener (#6) doubles as the CCD dewar window.

Table 1. Lens element parameters for the collimator/camera system.

element	R_1 (mm)	R_2 (mm)	center thickness (mm)	glass
1	231.94	706.37	30.00	FPL 51
			107.73	air
2	307.61	135.49	10.00	LAL 7
3	135.49	−212.37	70.00	CaF_2
4	−212.37	−1651.08	10.00	LAL 12
			244.64	air
5	225.75	−491.02	30.00	FPL 51
			99.39	air
6	−179.48	186.05	5.00	SiO_2
			20.00	air

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This lens system produces good spot sizes from collimated light over the entire $(61\ \mathrm{mm})^2$ area of the CCD for most of the desired spectral range. Polychromatic spot sizes (down to $\lambda = 4000$ Å) are 9μ (RMS diameter) at chip center and 21μ at the corners. Raytraced spot diagrams for field center, edge, and corner are shown in Figure 2, and the variation of center spot size as a function of wavelength is plotted in Figure 3. Performance degrades sharply below 4000 Å, unfortunately, but an additional *CCL* lens element and/or more sophisticated design revisions may be able to remedy this weakness.

4.3. Grating and cross-disperser

A 79.1 gr/mm echelle grating, measuring 12×6 inches, is already in hand (currently in use with the East Arm Echelle), and will serve as THuCIDIDES' primary dispersing element. The collimated beam diameter will completely fill but not overfill the projected grating surface area, so as not to lose light of the edge off the grating. The echellogram image format is well-matched to the available detector size. Thirty-three orders, from $m = 27$ to $m = 59$, will fit on the chip along the cross-dispersion axis, for a spectral coverage from 3800 Å to 8500Å. The redmost part of the spectrum ($\lambda > 7500\mathring{A}$) will suffer from some wavelength coverage gaps, as the length of the free spectral range for orders $m \leq 29$ exceeds the chip width, but key spectral lines such as the O 7770 triplet will still be observable. By tilting the grating, orders further to the red or to the blue can be selected, but the camera's chromatic performance will deteriorate rapidly outside of the design range.

A Schott LF5 prism with apex angle 45° cross-disperses the echelle orders. We chose a prism rather than a grating for this task in order to achieve greater system efficiency, and to have more regular spacing of echelle orders on the detector. LF5 is an excellent glass for this purpose, as it combines low index, high dispersion, and good throughput even in the blue. The cross-dispersion has been chosen to fit the entire wavelength range of interest on to the detector, while still providing sufficient inter-order separation in the blue to prevent order overlap.

4.4. Detector

A 4096×4096 CCD with 15μ pixels, manufactured by Lockheed-Martin Fairchild, will be used as the THuCIDIDES detector. The device will be thinned and backside-illuminated for maximum quantum efficiency in the blue. The small pixel size will oversample the normal slit width (1.2 arcseconds) by a factor of three, so for work at $R \simeq 20000$, on-chip binning may be desired for lower read noise and faster readout. (Alternatively, for higher-resolution tasks where some efficiency hit is acceptable, a narrow slit or image slicer may be employed.) A standard Palomar dewar will probably house the detector, and as mentioned in the introduction, readout electronics and control systems are yet to be decided upon.

5. ACKNOWLEDGEMENTS

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Figure 1(a). THuCIDIDES Cassegrain ring layout (top).

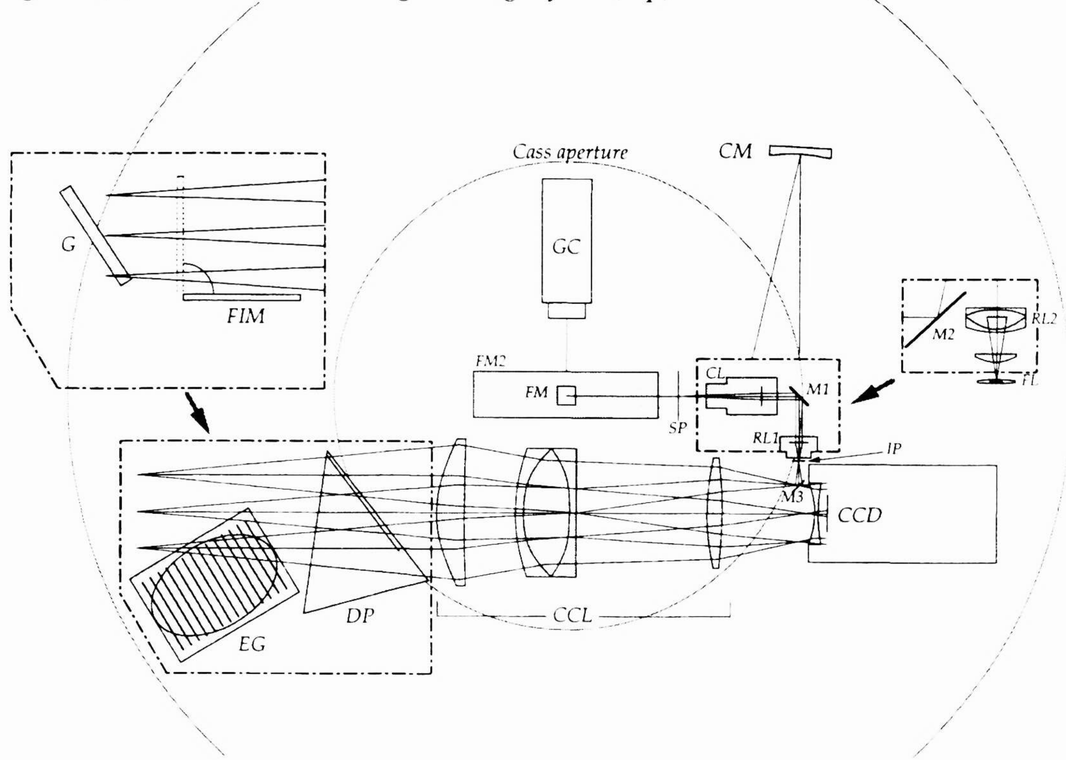

Figure 1(b). THuCIDIDES Cassegrain ring layout (side).

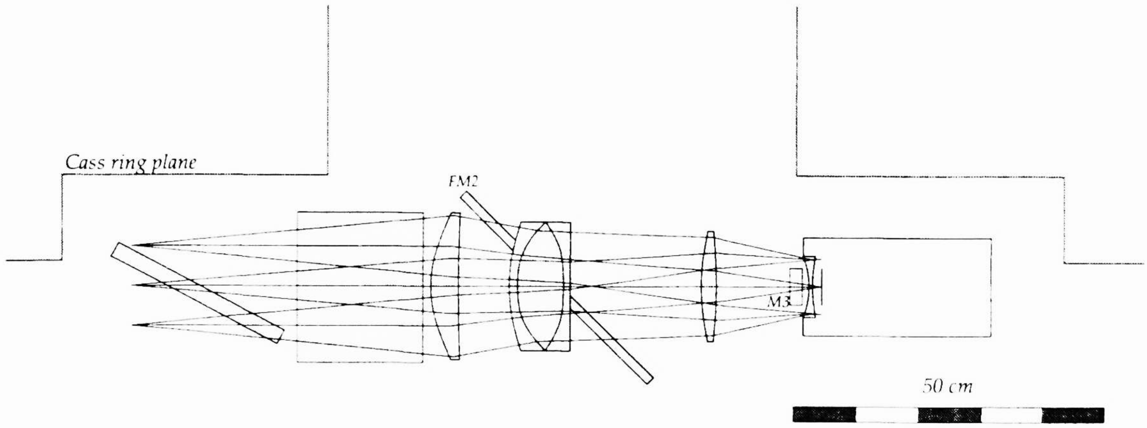

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Figure 2. Polychromatic spot sizes for *CCL* single pass.

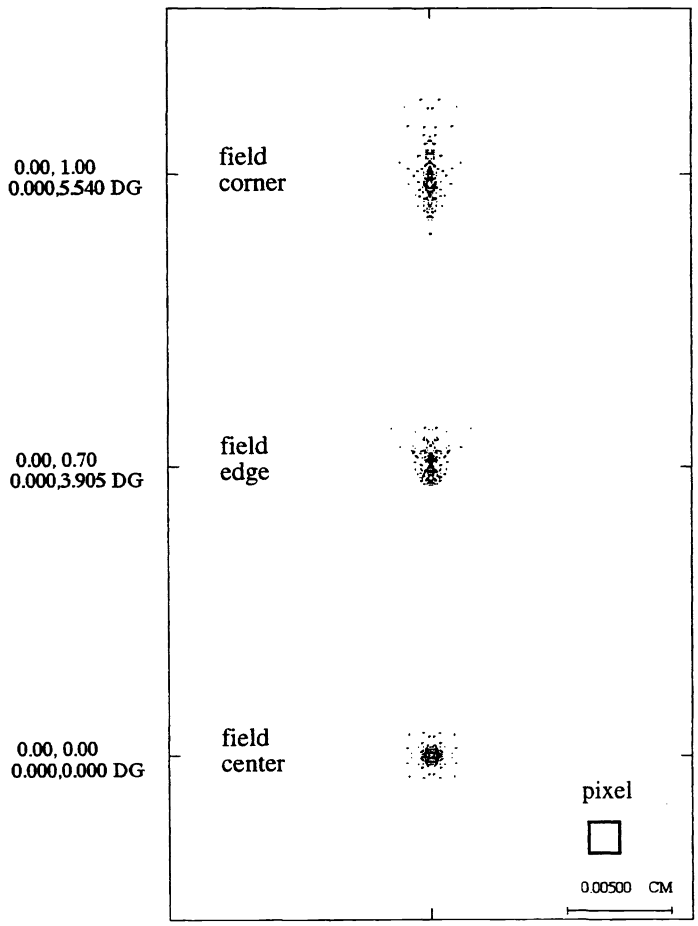

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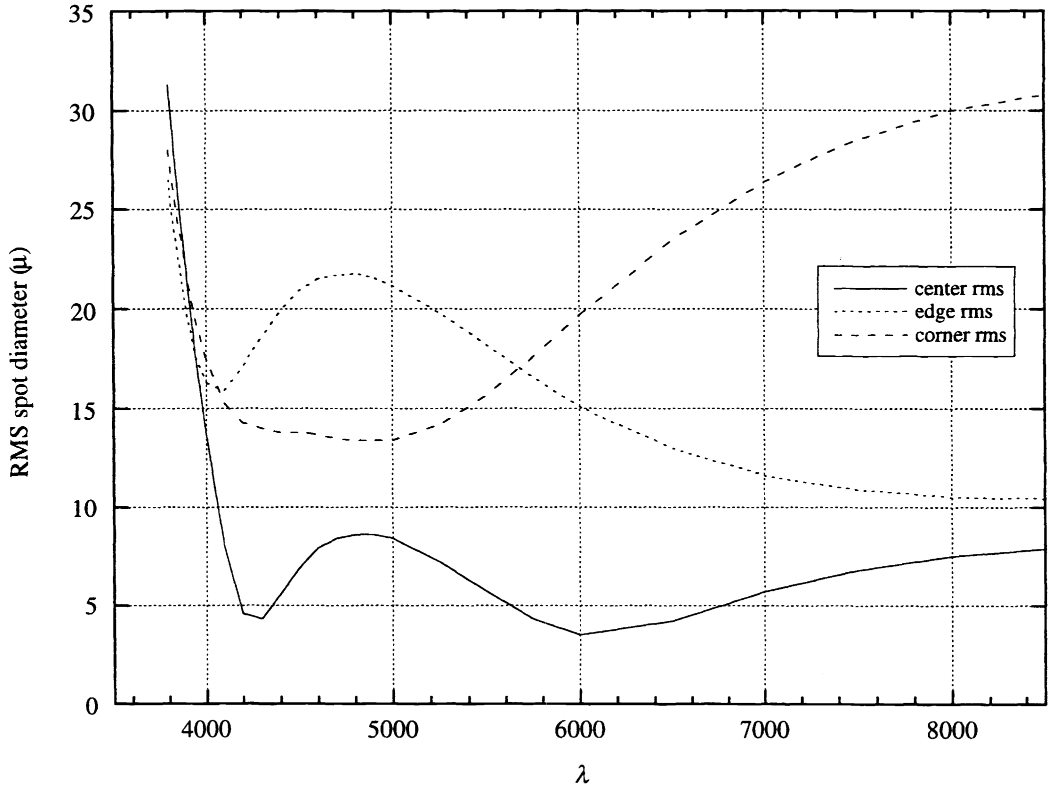
Figure 3. Chromatic performance of collimator/camera lens (CCL) system



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