Roque de los Muchachos Observatory

William Herschel Telescope

TAURUS USERS' MANUAL

Version 1.2

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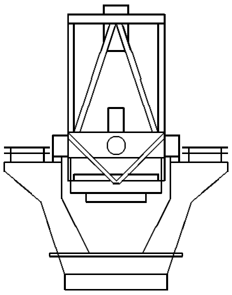
Steve Unger



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Part I

GENERAL

1 Introduction: scope of the manual and documentation

1.1 Scope of the manual

This manual describes the operation and performance of the TAURUS instrument as used both for CCD imaging and for Fabry-Perot interferometry.

The manual is divided into seven parts. Part I covers sources of information and help (remainder of Section 1).

Part II provides a scientific and technical overview of the instrument. The scientific overview covers both CCD imaging and Fabry-Perot spectroscopy.

The technical overview describes the optical and mechanical design of TAURUS itself (Section 3.1), its A&G unit (Section 3.2) , and its detectors (Section 3.3). Note that the telescope is not described here, since a detailed description is given in the WHT Users Guide. Section 3.4 describes in general terms how these components fit together to produce an observing system. Most of the above is relevant both to imaging observations and Fabry-Perot spectroscopy. Section 4 gives a technical overview of aspects of the system relevant specifically to Fabry-Perot spectroscopy.

Part III discusses how the instrument is set up when first mounted on the telescope. Observers should not normally have to read this part of the manual, but support astronomers should.

Parts IV and V describe the operation of TAURUS for imaging and Fabry-Perot observations respectively.

Part VI summarises the performance of the instrument.

Part VII is a reference section describing in detail the commands used to operate the TAURUS subsystem. Note that the commands for the other subsystems are not listed in this manual, since they (should) be listed elsewhere.

1.2 Obtaining copies of this manual

This manual has been prepared using LaTeX. A copy of the current source is held on the La Palma VAX 8300 in directory `[MANUALS.WHT_TAURUS]`, along with its associated rasterized file, `.DVI-CAN`. New copies of the manual may be printed out using:

- `WHT_GLASE [MANUALS.WHT_TAURUS]TAURUS_USER.DVI-CAN` or
- `INT_GLASE [MANUALS.WHT_TAURUS]TAURUS_USER.DVI-CAN`,

(to give output on the laser-printers in the WHT and INT buildings, respectively). A copy is also held on the STARLINK VAXcluster at RGO Cambridge, in the directory `CAVAD::DISK$USER1:[MANUALS.WHT_TAURUS]`.

1.3 Getting help

The present manual is designed to be the main reference for the operation of TAURUS. Additional background information may be found in the *Observers' Guide* (1988 edition). The FIGARO software for reducing TAURUS Fabry-Perot data is described in the manual *TAURUS data and how to reduce it.* In case of difficulty, consult your Support Astronomer or Duty Technician. More specialist advice may be obtained from Steve Unger (RGO project scientist).

1.4 Notation

The following conventions for computerese have been used more-or-less consistently throughout this manual:

- Examples of commands entered at the terminal are in typewriter font: `TFFILTER 5`, as are messages from the computer;
- Angle brackets denote parameter values or character strings: `<angle>`;
- Square brackets denote optional input *e.g.* `[x,y]`; all other parameters are obligatory;

Part II

OVERVIEW

2 Scientific overview

2.1 CCD imaging

Although TAURUS–2 was originally constructed primarily for use as a Fabry–Perot interferometer, it can also be used as a focal reducer for imaging observations.

The advantage of using TAURUS for imaging observations over using a CCD direct (e.g. at the auxiliary port of the A&G) is that it provides a plate scale better matched to the image size. When an EEV CCD with a pixel size of 22 μm is used direct at f/11, the scale is 0.1 arcsec/mm, oversampling the image and providing only a limited field. TAURUS with the f/4 camera provides a scale of 0.27 arcsec/mm, whilst TAURUS with the f/2.1 camera provides a scale of 0.51 arcsec/mm.

The disadvantage of using TAURUS over using a CCD direct is the extra optical elements. These have a throughput of about 60 per cent (see section 17), and increase the risk of ghosting (see section 19) and stray light.

2.2 Fabry-Perot spectroscopy

TAURUS is a wide-field imaging Fabry-Perot interferometer designed to obtain spectra over a field of up to 9 arcmin with a resolving power anywhere between 2,000 and 100,000. Its main use is in measuring velocity fields of extended emission line objects — HII regions, planetary nebulae, supernova remnants and galaxies.

The principles behind the operation of TAURUS are described in some detail by Taylor & Atherton *(Monthly Notices of the Royal Astronomical Society, vol 191, p675, 1980)*, Atherton et al. *(Monthly Notices of the Royal Astronomical Society, vol 201, p661, 1982)* and Taylor et al. *(Indirect imaging, ed. J Roberts, publ. CUP, p379, 1984)*. Briefly, the beam from the telescope is first collimated and then passed through a Fabry-Perot etalon. The field modulated by the Fabry-Perot interference rings is re-imaged by a camera onto a two-dimensional detector. The observing wavelength, and hence the order of interference at which the interferometer works, is determined by an order sorting filter, which can be placed either in the focal plane of the telescope, or in the collimated beam.

A TAURUS spectral scan normally consists of a large number (typically 100) of separate 2-dimensional images taken sequentially at different gap settings of the Fabry-Perot etalon, each giving a two-dimensional image in a different wavelength bin. By stacking these together it is possible to build up a 3-dimensional spectral line datacube.

3 Technical overview: imaging and spectroscopy

3.1 TAURUS–2

The major optical components of TAURUS–2 are shown schematically in Figure 1. The components are as follows:

3.1.1 Focal plane filter wheel

This has 8 positions, each of which can hold a circular filter up to 125 mm in diameter. The filters available for use with TAURUS-2 are listed in VIII. The filters can be tilted by up to 10 degrees; this has the effect of shifting the central wavelength of interference filters to the blue (see section VIII).

3.1.2 Focal plane aperture wheel

This has 8 positions, each of which can hold an aperture mask. Table 1 lists the aperture masks normally mounted.

Table 1: TAURUS-2 aperture masks

Position	Aperture
1	Clear, diameter 120 mm (9 arcmin)
2	Diffuser
3	Central pinhole, diameter 300 μm (1.35 arcsec)
4	Central hole, diameter 2 mm (9 arcsec)
5	Central pinhole, diameter 20um (0.09 arcsec)
6	Clear, diameter 120 mm (9 arcmin)
7	Clear, diameter 120 mm (9 arcmin)
8	Pinhole matrix, grid spacing 10 mm (45 arcsec), pinhole diameter 200 μm (0.9 arcsec)

3.1.3 Iris

The field diameter is defined by a variable iris placed at the f/11 Cassegrain focal plane. The maximum diameter of the iris is 150 mm, though the collimator cutoff is at 120 mm (9 arcmin).

3.1.4 Collimator

The collimator has a focal length of 660.3 mm. The diameter of the collimated beam is 60.3 mm. The position of the collimated beam does however change as a function of field angle and wavelength, giving an effective total diameter for broadband wide-field observations of about 68 mm.

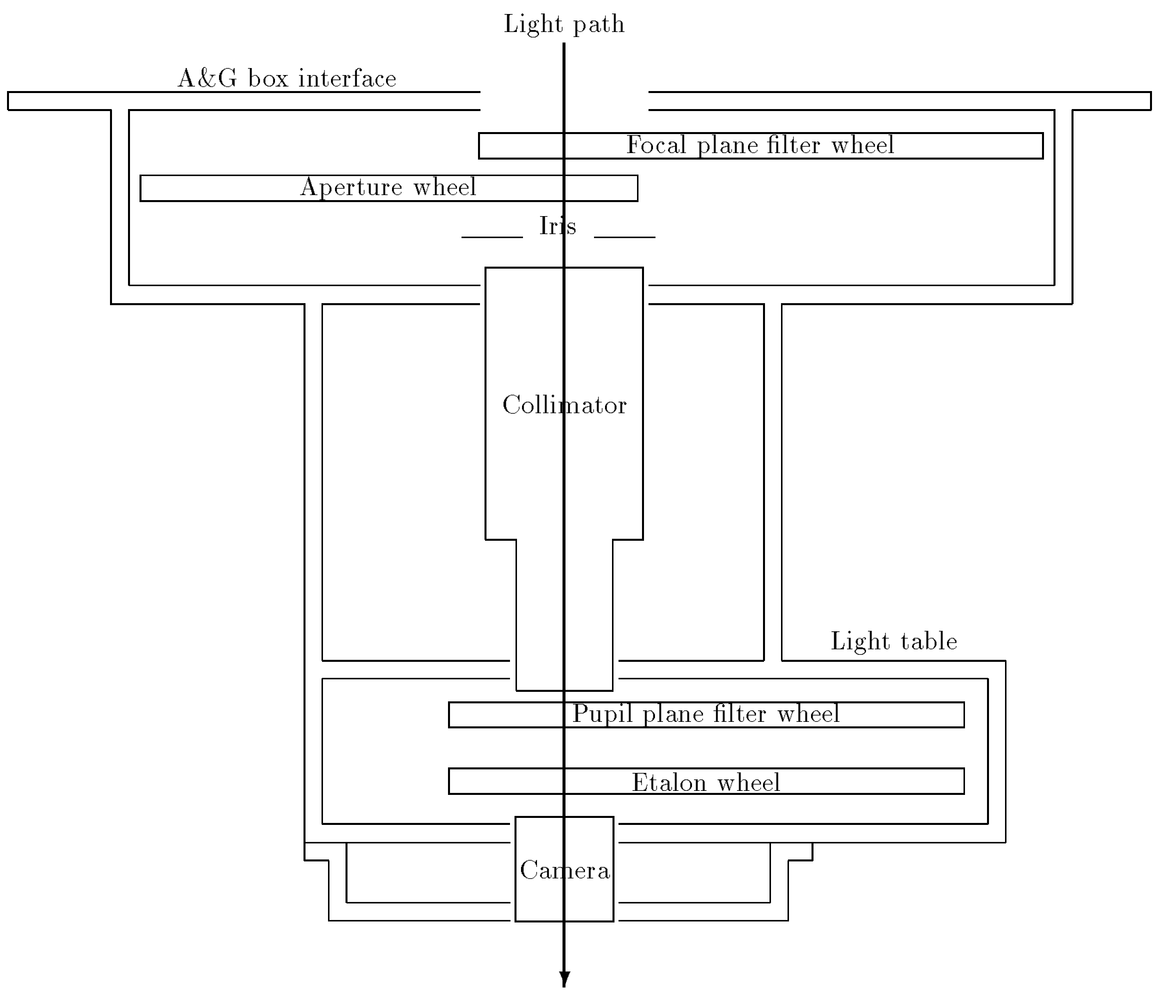

Figure 1: Schematic drawing of TAURUS

3.1.5 Pupil plane filter wheel

This has 8 positions, each of which can hold a circular filter up to 76 mm in diameter. Filters with a smaller diameter than the collimated beam (about 68 mm) will cause vignetting. The filters available for use with TAURUS-2 are listed in VIII.

Position 1 of the pupil plane filter wheel is a large hole, used to gain access to the etalon wheel when changing etalons; this position cannot be used for filters,

3.1.6 Etalon wheel

This has 6 positions, 2 of which are always clear for imaging observations. The remaining 4 positions can be used for Fabry-Perot etalons. The etalons available for use in TAURUS-2 are described in Section 4

The etalon wheel is contained within a sealed cavity. This cavity can be continuously flushed with dry nitrogen in order to maintain low humidity.

A light table is provided for alignment of etalons. The etalon to be aligned is positioned within the light table, and is illuminated with a comparison lamp mounted underneath the table. It is then possible to view the interference fringes through a transparent hatch in the top of the light table.

3.1.7 Camera

There is a choice of either an f/2.11 camera or an f/3.96 camera, with focal lengths of 128.1 mm and 240.1 mm respectively. These cameras provide scales at the detector of 23.25 arcsec mm^{-1} and 12.40 arcsec mm^{-1} respectively.

Note that in order to change cameras it is necessary to remove the detector; thus any change must be scheduled well in advance.

3.2 The Cassegrain A&G Unit

The WHT Cassegrain A&G unit is described in some detail in La Palma Technical Note 56. The users manual describes its operation in some detail. Briefly, the unit provides the following facilities:

3.2.1 Object acquisition

Object acquisition is carried out via an extendable probe carrying a mirror feeding a Westinghouse ISEC TV camera. When used direct, this provides a 1.5 arcmin field at the telescope scale of 4.51 arcsec mm^{-1}. It is possible to interpose a focal reducing system, which provides a larger field of 4 arcmin at a scale of 12 arcsec mm^{-1}. The TV camera is provided with a filter wheel with six filter positions. The available filters are CLEAR (UBK7), B (BG 28), V (BG 38), R (RG 630) and EMPTY (no filter). Note that the empty position will give a different focus position for the TV. These filters do not give a standard photometric system and the Johnson letters are given for guidance only. The TV can be focussed independently to compensate for different filter thicknesses.

3.2.2 Autoguider

The autoguider consists of a CCD detector head fed by a right-angled prism and focal reducing optical system, with a field diameter of 1.8 arcmin. The centre of the autoguider field rotates about the centre of the main field at a radius of 110 to 150 mm (8.2 to 11.2 arcmin) and the entire probe assembly has a radial displacement of 40 mm. The extreme edge of the autoguider field is partially vignetted, but only by about 5%. The autoguider has an azimuthal scan of 180 degrees, so the total area scanned at a field scale of 4.51 arcsec mm^{-1} equals 152 square arcmin or 0.04 square degrees. This gives a good chance of finding a star brighter than 11th magnitude at the galactic equator or 13th magnitude at the galactic pole *(C.W.Allen, Astrophysical Quantities, publ. Athlone Press, 1976).*

The limiting magnitude of the autoguider, for guiding at 1 Hz, is about V=17.5 in good conditions (that is, 1-arcsec seeing and a dark sky. When the telescope is being servoed on the tracking errors being sent from the autoguider, these are reduced to the 0.1 arcsec level.

The autoguider is provided with a filter wheel with six filter positions. The available filters are CLEAR (UBK7), EMPTY (no filter; different focus), OPAQUE (blanking disk), B (BG 28), V (BG 38), and I (RG 630). These filters do not give a standard photometric system and the Johnson letters are given for guidance only.

The autoguider can be focussed independently to compensate for different filter thicknesses.

3.2.3 Comparison lamps

A calibration system is provided consisting of an integrating sphere into which light is fed directly from two hollow cathode lamps (normally Cu-Ar and Cu-Ne) and a Tungsten lamp for a red continuum source. Light from a further 6 lamps (Fe-Ar, Fe-Ne, Th-Ar, Al/Ca/Mg-Ne, Na/K-Ne, and Deuterium) is imaged via fused silica lenses onto 3 mm diameter fused silica light guides.

It should be noted that the transmission of the fused silica light guides is poor (a few per cent at best) and in general only the directly fed lamps are used. It is possible to exchange lamps, in order to feed light from any of the lamps listed above directly.

Table 2: Comparison lamp filters

Filter wheel A	Filter wheel B
CLEAR	CLEAR
ND0.2	ND0.3
ND0.6	ND0.5
ND0.8	ND0.9
ND1.8	ND1.2
ND3.0	ND2.0
GG375	BG24
GG495	CLEAR

Any combination of lamps may be used simultaneously. The exit pupil of the integrating sphere is fitted with an obscuring disk to simulate the telescope entrance aperture obscuration, i.e. the secondary mirror structure. The reverse side of the acquisition mirror is used to feed the calibration light to the instrument. This enables (in principle !) simultaneous object acquisition and spectral calibration.

Two eight-position filter wheels are provided for the comparison system. The filters available are summarised in Table 2

3.2.4 Filters

Two filter slides, situated below the autoguider assembly, provide colour and ND filtering. Each slide carries five filters in cells, and the cells all carry discrete bar coding for filter identification. The filter cell carrier may be removed and alternative cells fitted. The filters have a maximum diameter of 85 mm. The name of the filter mounted in each position may be determined using a barcode reader. The filters available are listed in Table 3, together with their barcodes.

Table 3: Main A&G filters

Filter Name	Barcode
ND0.3	1
ND0.6	2
ND0.9	3
ND1.0	4
ND1.2	5
ND1.5	6
ND1.8	7
ND2.0	8
ND3.0	9
UG1	70
BG28	71
BG38	72
GG385	73
GG395	74
GG495	75
RG630	76
RG695	77
RG830	78
WG320	79

3.3 Detectors

TAURUS can be used with one of a number of different CCD detectors, or with the IPCS–2 photon counting detector.

A number of factors need to be considered when deciding which detector is to be used, and these are discussed in detail elsewhere (e.g. La Palma Observers Guide). Basically, the CCD has a much greater efficiency than the IPCS, but also has a higher level of detector noise. For imaging observations, where the dominant source of noise is sky background rather than detector noise, the CCD will always be the detector of choice

The choice is more difficult for Fabry-Perot observations. The much narrower bandwidth of such observations means that detector noise will normally be an important factor. A major advantage of Fabry-Perot observations with the IPCS is also that it is possible to scan through a spectral line datacube very rapidly, averaging out variations in atmospheric transparency (see section ?). Thus the choice of detector depends both on the brightness of the source being observed, and on atmospheric conditions (difficult to predict in advance !).

3.3.1 CCD

A number of different CCDs are available for use with TAURUS–2. Some of the CCDs are coated to give sensitivity in the blue. Table 4 summarises the formats and pixel sizes of the various chips, and whether or not they are blue coated. Note that the formats quoted are for the image area only, not including overscan. The properties of these CCDs are described in more detail in La Palma Technical Note 79.

Table 4: CCD detectors for TAURUS

Name	Format	Pixel size			Blue–coated ?
		microns	arcsec		
			f/2.1 camera	f/4 camera	
GEC5	385x578	22	0.51	0.27	Yes
EEV2	770x1152	22.5	0.52	0.28	No
EEV3	1241x1142	22.5	0.52	0.28	Yes

Table 5: IPCS pixel sizes

Resolution	IPCS pixel size		
	micron	arcsec	
		f/2.1 camera	f/4 camera
$\times 1$	84	1.95	1.04
$\times 2$	42	0.98	0.52
$\times 4$	21	0.49	0.26
$\times 8$	10.5	0.24	0.13

3.3.2 IPCS

The IPCS–2 was developed at UCL, and is described in more detail in ?. The IPCS–2 users manual describes how the detector is controlled. The IPCS–2 is a complex instrument to operate, and observers should read the users guide before using it.

The IPCS–2 consists of an EMI image intensifier with S20 photocathode, coupled to a GEC CCD camera. Each photon event can be centroided to an accuracy of 1, 1/2, 1/4 or 1/8 of a CCD pixel. The largest possible detector format is $320\times$r in X and $256\times$r in Y, where r is the resolution factor (1, 2, 4 or 8). The pixel sizes with each of these resolution factors are summarised in Table 5.

3.3.3 Data acquisition system

In addition to the detectors themselves, the data acquisition system on the WHT includes a Detector Memory System (DMS). This is an image processing system based on the VME bus architecture and using a 68020 microprocessor. Once data has been acquired using a detector, it is transferred into the DMS. In the case of a CCD this transfer occurs when the CCD is read out. In the case of the IPCS the coordinates of each photon event are transferred into the DMS as it is detected, and the data accumulated in the DMS to produce an image.

Once the image data is in the DMS, it can be displayed on a local colour image display for immediate assessment. Finally, it can then be transferred over a high speed link to the VAX computers for archiving and further assessment.

3.4 System control

This is an outline description of the parts of the control and data acquisition system on the William Herschel Telescope (WHT) relevant to TAURUS. It is not intended as a precise technical document nor as a reference, but simply as a high level description for the unfamiliar. If more information is required then you are advised to refer to the detailed documentation for the sub-system concerned.

3.4.1 Overview

The WHT control system differs substantially from the earlier INT and JKT systems. Whereas the INT and JKT systems have very little 'intelligence' in the instrument controllers, for the WHT system all the instrument controllers are microprocessor based.

A block diagram of the WHT computer and microprocessor system is shown in Figure 2. The system is arranged as a distributed control system with a VAX 3600 computer providing overall supervisory control over the local control microprocessor systems located in the control room and on the telescope. Low-level instrumentation control uses 6809 (known locally as 4MS), 68008 or 68020 microprocessors. For example, the Detector Memory System, which is a generic detector image acquisition, storage and manipulation subsystem, is based on a 68020 processor in a VME chassis. Communication between the systems is provided across an Ethernet based Utility Network, whilst transfer of image data occurs across dedicated links. In addition, a dedicated hardware link is provided between TAURUS and the IPCS to synchronise data acquisition with scanning of the Fabry-Perot etalon.

The VAX 3600 is also linked via DECnet to the telescope control computer (MicroVAX II), a VAXstation 2000 running the user interface, and a data reduction computer (VAX 8300).

3.4.2 User interface

The User Interface is provided by a VAXstation 2000 which provides a means of entering commands to the system and provides feedback to the user via a multi-page status display (the mimic). The observer will normally interact with two windows on this VAXstation, one providing the control interface and one providing the mimic.

3.4.3 Instrument control

Instruments are controlled from the VAX 3600, which runs the DEC standard VMS operating system together with VAX-ADAM. Each of the sub-systems (TAURUS, Cass A&G, the autoguider, the detectors, the DMS, and the telescope) sub-system has an associated ADAM 'd-task' in the 3600 which is responsible for controlling that sub-system.

A control interface is provided through the Interactive Command Language (ICL). Individual commands can be sent to the sub-systems via the d-tasks, or alternatively a sequence of commands can be bundled into ICL procedures to allow more complex, multi sub-system operations to be carried out.

The All d-tasks communicate with the outside world using a common communications task resident in the VAX 3600 known as Utilnet. This handles all the low level communications functions such as packaging the commands, transmitting and receiving datagrams (each command is usually contained within a single datagram) and handling timeouts and retries.

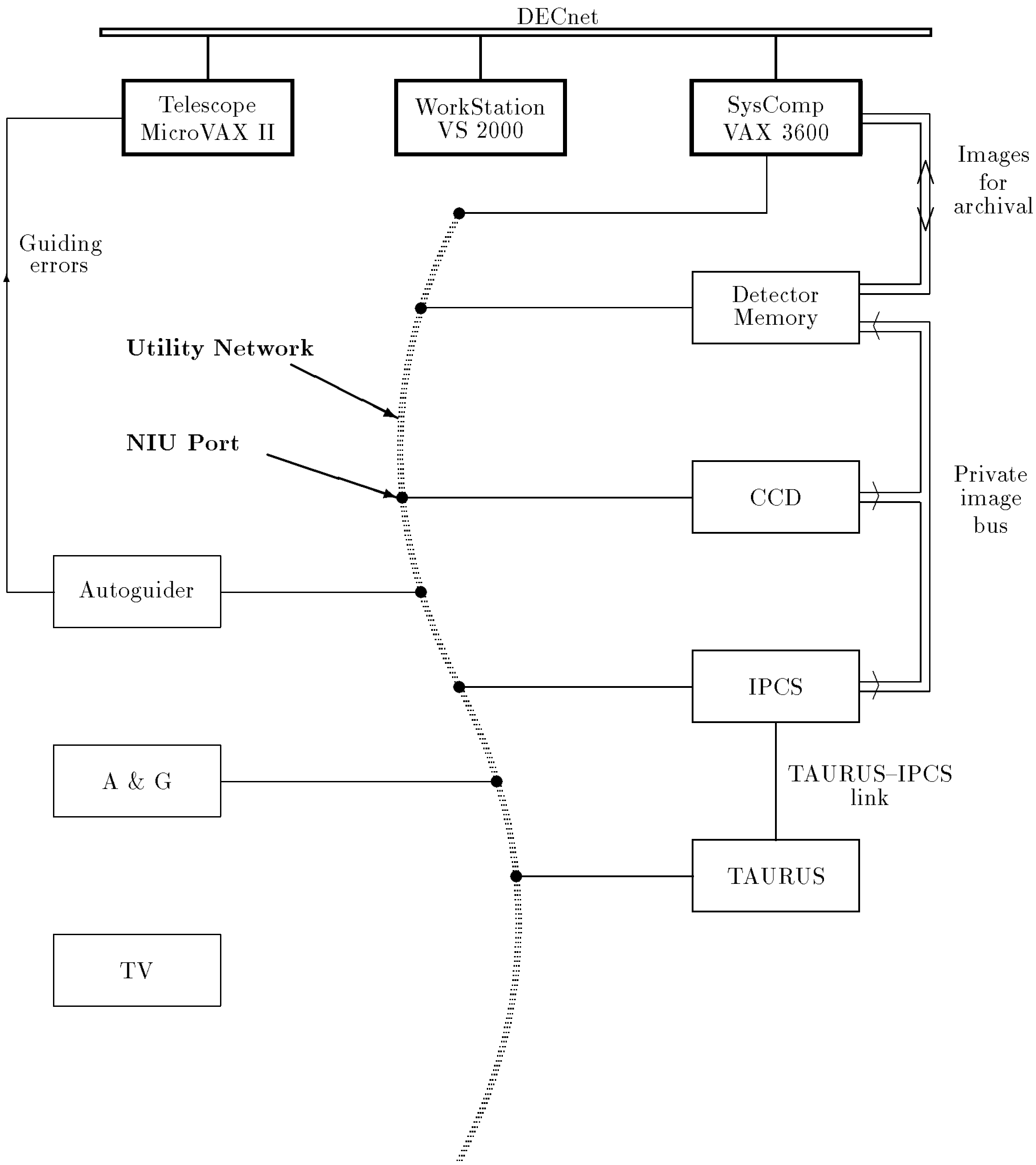

Figure 2: WHT System Configuration for TAURUS

Each instrument is controlled by a 4MS, a microprocessor system which is responsible for executing commands and returning status information for that instrument. Commands are sent from the 3600 to the 4MS systems over a Ethernet-based 'utility network'. The utility network uses an RGO-defined protocol which conforms to the requirements of the IEEE 802.2 and IEEE 802.3 standards. The physical, data–link, network and transport layers of the ISO Seven Layer Reference Model for Open Systems Interconnection are separately implemented in hardware data concentrators, the Sension Network Interface Units (NIU), each of which is able to connect up to 4 instruments to Ethernet. The remaining layers (session, presentation and application) are implemented in software in each of the attached instrument processors.

All instruments on the network have unique 4-letter identifiers which are transmitted on initialisation to the relevant NIU, allowing any instrument to communicate with any other by name. The protocol involves an attached processor announcing its presence by a broadcast message and then being able to communicate on a one–to–one basis with any other processor on the network. Note that, at present, only commands and status are interchanged in this fashion, image data transfer occurs over a private, parallel link.

3.4.4 Status information

Status information is returned from the 4MS systems to the 3600 control computer using the same procedure as is described above for instrument control. Status information received by the d-tasks is posted on a 'notice-board' maintained in memory by the ADAM system. Error messages are reported to the observer (usually).

A mimic task is responsible for picking up information from the notice-board and displaying it on the mimic screen. This is a multi-page status display, providing one or more pages of status information for each sub-system. The user determines which page is to be displayed using a mouse and menu.

3.4.5 Data acquisition

Data from both CCDs and from the IPCS is collected by the Detector Memory System. This is a VME system based around a 68020 high performance microprocessor system with 16 MByte of memory and a fast large capacity disk. The acquired data can be displayed on a local colour image display for immediate assessment. Transfer of data from the detectors to the DMS is over a private image bus.

A high speed parallel interface is also provided to allow transfer of data from the DMS to the VAX computers for further assessment and archiving. The data is collected from the Detector Memory System into a Figaro file on the VAX by the Data Collection Task (DCT), which also collects the header information from the internal ADAM noticeboards maintained by the d-tasks.

Thus the normal flow of image data is from the detectors to the DMS, and thence onto the 3600. On the 3600, the image data is merged with header information collected from the ADAM noticeboards , and a FIGARO file is produced. Finally, this is written to FITS tape.

3.4.6 The Autoguider and TV systems

The autoguider system consists of 2 parts. A dedicated CCD controller is located on the telescope. This differs from other CCDs in that the CCD chip is cooled by a Peltier Cell, and the application software is different. The second part of the autoguider consists of a VME system located in the control room.

This sends commands to its CCD controller via a private RS232c serial link. Image data is returned to the VME system along a fibre optic cable. Whilst guiding, the autoguider calculates the tracking errors and transmits them across a second private serial link to the telescope control computer.

The integrating TV system is currently a stand alone system, not controllable across the Utility Network. It is based around a standard VME 68020 micro- processor system together with special cards to interface to the TV cameras and to provide a display.

4 Technical overview: Fabry-Perot spectroscopy

4.1 General principles

4.2 Servo control of etalons

To achieve optimal performance from a Fabry-Perot interferometer its plates must be held parallel and the distance between them must be controlled to a high degree of accuracy. Departures from parallelism and required spacing should be much less than the surface irregularities of the plates themselves. Modern interferometer plates can be polished so that surface irregularities are less then about 2.5 nm ($\lambda/200$ at a wavelength of 5000 Å), thus mechanical errors should be less than about 1 nm

It is difficult to achieve stabilities of this order for any length of time in a system that must allow the plate-spacing to be varied by accurately controlled amounts, unless some form of active feedback is employed to sense the actual plate position. This is particularly true for an instrument such as TAURUS, whose gravity vector varies as the telescope changes position.

The TAURUS etalons are stabilized in parallelism and gap by means of a Queensgate Instruments CS100 servo-stabilization system. This uses capacitance micrometers to sense variations in parallelism and departures from required spacing, and piezo-electric transducers to correct these errors. Capacitance micrometry makes it possible to sense pico-metre displacements.

The way this works in practice is as follows. The two coated plates which make up the Fabry-Perot etalon are held apart by three piezo-electric transducers(A, B and C). Five capacitors (CX1, CX2, CY1, CY2, CZ) are formed by evaporating gold pads onto the interferometer plates. The vector between CX1 and CX2 defines the 'X-axis' of the etalon, and the vector between CY1 and CY2 defines the 'Y axis'. The X-axis and Y-axis are perpendicular to each other, and the Y-axis is aligned with the vector joining the centre of the etalon plates to the connector block.

Parallism information is obtained by comparing CX1 with CX2 (the X-channel) and CY1 with CY2 (the Y channel). To monitor the spacing, CZ is compared with a further air-spaced reference capacitor CREF built onto one of the plates (the Z channel).

It is important to note that the measured capacitance depends not just on the optical spacing, but also on the dielectric constant. Changes in temperature, pressure and humidity will cause changes in the dielectric constant. Therefore in normal operation the TAURUS–2 etalon cavity is continually flushed with dry nitrogen.

The CS100 derives an error signal for each of the channels (x, y and z) from the capacitators, and applies a correction via the piezo transducers. The way in which it does this is shown in Figure 3, a schematic circuit diagram for the X channel.

In operation, the three capacitance bridges are excited by four AC bridge drive voltages of amplitude V_x, V_y, V_z, and V_{com}. These all have nominally equal amplitudes, but V_{com} has opposite phase to the others. Thus, taking the X channel as an example, if CX1 is equal to CX2, no current flow into the amplifier. If the etalon were to go out of parallel, so that CX1 is not equal to CX2, then a current would flow into the amplifier. This would be 90 degrees phase advanced on V_{com} if CX2>CX1 and 90 degrees retarded if CX2<CX1. The phase sensitive detector PSD, which uses V_{com} phase shifted by 90 degrees as a reference, will thus generate a voltage proportional to the error in magnitude and sense. This voltage is amplified and applied to the piezo–electric transducer B, in the correct sense to reduce the error, i.e. a closed loop servo is formed.

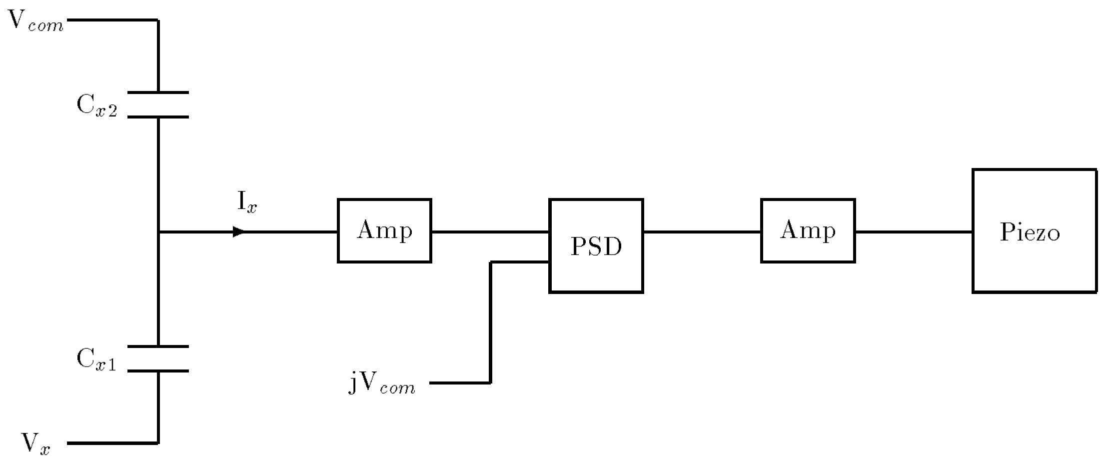

Figure 3: Schematic circuit diagram for CS100

Note that the X, Y and Z channels are not entirely independent. Moving the B transducer in response to an X channel error will actually generate an error in the Y channel, but this will be corrected by the Y channel servo. The Y servo-channel acts via transducer A, which does not generate an error in the X channel. The Z channel works by applying the same error signal to all three transducers.

In practice, when the interferometer plates are parallel CX1 will not be exactly equal to CX2. Also CZ will not equal CREF at the required optical spacing. Thus in order to be able to align the etalon, and set the gap, it is necessary to be able to apply an offset to the error signals in each channel. This is usually done using the front panel controls on the CS100 during instrument setup (see section ?), and using the control computer during an observation (see section ?).

Losses in the cables and non-ideal behaviour of the bridge drive circuitry produce a component of current into the amplifiers that is in phase with the bridge drive signal, instead of 90 degrees out of phase. This 'resistive' component is not detected by the PSD, so does little harm, but it is best to null it out to avoid the possibility of overloading the amplifiers. To enable this, the front panel controls of the CS100 include a resistive balance offset for each channel.

The way in which the etalon performs whilst being servo'd depends primarily on two parameters, the gain and time constant. The gain and time constant are set so that the response of the etalon to a change in gap is critically damped. This issue is analysed in detail in the CS100 manual.

The response time of the etalon to a $\lambda/2$ (one order) step input is about 300 microseconds. Typical performance of the system is such that a 'mechanical' finesse $N_mech > 50$ can be maintained almost indefinitely. Thus the spectral resolving power of the system is limited by the effective finesse of the etalons themselves, which typically has a value of $N_eff = 20$ –30 (see section ?).

4.3 Etalon scanning

A TAURUS scan normally consists of a large number (typically 60) of separate 2D images taken sequentially, each with a different setting for the etalon gap. Before each image is taken, the etalon gap is altered by changing the offset applied to the Z channel of the CS100 servo-controller. The set of 2D images are built into a 3D datacube in the Detector Memory System.

Acquiring a spectral line datacube therefore requires the process of data acquisition to be synchronised with the stepping of the etalon gap. There are two different ways of doing this, depending on whether the detector being used is a CCD or IPCS.

Data acquisition with a CCD is relatively straightforward, and is carried out under control of the system computer. The procedure is as follows:

Syscomp tells DMS to set up and clear 3D data buffer
LOOP for all etalon steps
Syscomp tells TAURUS 4MS to step etalon
Syscomp tells DMS which plane of datacube to expect next
Syscomp tells CCD to take image
CCD image read out into one plane of 3D data buffer
END LOOP
Keep datacube

Given the overheads involved in clearing and reading out the CCD, it can easily take 1–2 hours to scan through a complete datacube. During this time it is possible that the atmospheric transparency will vary, possibly producing spurious structure in the spectra. This problem can be minimised by, instead of scanning the datacube sequentially starting at plane number 1, scanning the planes in the datacube in a random order.

When the IPCS is used as the detector, the effects of changes in atmospheric transparency are minimised by using the 'rapid-scanning' technique. During a scan, the integration time at each step is kept to a minimum so as to complete a scan through the wavelength range as quickly as possible. The required signal-to-noise ratio of the data is then achieved by co-adding the results of a large number of successive scans in the DMS.

A typical rapid-scan might involve stepping the etalon every 100 milliseconds, in order to scan through the entire cube in less than 10 seconds. Thus synchronisation between the etalon stepping and data acquisition becomes time-critical, and can no longer be carried out over the utility network under control of the system computer. This synchronisation is therefore carried out via a dedicated link between the TAURUS and IPCS 4MS systems (see Figure ??). Whilst the data is being taken the TAURUS 4MS is slaved to the IPCS 4MS, stepping the etalon when requested to do so. The procedure is as follows:

Syscomp tells DMS to set up and clear 3D data buffer
Syscomp tells TAURUS to slave itself to IPCS
Syscomp tells DMS to start IPCS data acquisition
LOOP for number of scans
LOOP for all etalon steps
IPCS tells TAURUS 4MS to step etalon
TAURUS 4MS steps etalon, notifies IPCS when succesful
DMS takes exposure with IPCS, coadded into DMS
END LOOP
END LOOP
Keep datacube

4.4 Etalons available

The Fabry-Perot etalons available are listed in Table 6 . Note that the set of etalons previously advertised as being available for observations with TAURUS-1 *cannot* be used in TAURUS-2. The free spectral range and resolution of each etalon is given at sample wavelengths. The resolution has been calculated assuming an effective finesse of 20.

Table 6: TAURUS-2 etalons

Gap (μm)	Wavelength Range (Å)	Wavelength (Å)	Free Spectral Range (Å)	Free Spectral Range (km s^{-1})	Resolution (Å)	Resolution (km s^{-1})
125	4500-7000	5000	10	600	0.50	30
		6500	17	785	0.85	39
500	4500-7000	5000	2.5	150	0.125	7.5
		6500	4.2	195	0.21	9.8

4.5 Use of interference filters

An important point when observing with TAURUS is that since the interferometer operates at a high order of interference (typically a few hundred), it is necessary to isolate the wavelength region of interest using an order sorting filter. For observations of objects at high redshift, or of unusual emission lines, it is important to check that a filter with a suitable central wavelength is available. Also, the bandwidth of the filter should match the free spectral range of the etalon being used. If the bandwidth of the filter is less than the free spectral range of the etalon, this will restrict the wavelength range covered, whereas if the bandwidth of the filter is much larger than the free spectral range of the etalon, there is a risk of order confusion.

Part III

TAURUS INSTALLATION AND ALIGNMENT

5 Change checklist

This is a list of items to check after TAURUS has been put on the telescope. It is not intended to be a detailed description of the change, but to act as a checklist after the change is completed. The checks are divided into those that apply to all observations, and those that only apply when TAURUS is used in Fabry-Perot mode.

5.1 All observations

1. The schedule should specify whether the f/2 or f/4 camera is required. The f/4 camera requires the black spacer box between TAURUS and the detector, the f/2 camera doesn't.
2. When the CCD is mounted with the f/4 camera, a 9mm spacer is required.
3. The main wiring loom from TAURUS to 4MS has 10 cables at the 4MS end which must be connected.
4. The shutter controller. The cable for the A&G interlock goes to socket SK171 on the A&G 4MS. A cable is required either to the IPCS 4MS or CCD controller depending on the detector used. The appropriate detector should be selected using the 2-position knob. When the IPCS is used, a connection is required to the IPCS panic button.
5. An RS232 cable is required from socket J107 on TAURUS 4MS to the engineering terminal, and from socket J108 to the NIU.

5.2 Fabry-Perot mode only

1. A nitrogen flush to the etalon cavity is required, with the flow rate independently controllable via a flow meter.
2. The CS100 and the switchbox are mounted on the side of TAURUS itself. There are 6 cables between the CS100 and the switchbox, plus a mains supply for each.
3. If the IPCS is being used, then in order to implement the handshake between TAURUS and IPCS, a connection is required from the TAURUS 4MS socket J110 to the socket on the IPCS CCD controller labelled 'TAURUS SKCC'

6 Installation of Cameras

TAURUS can be used with two different cameras. This section describes the process for changing the camera. Note that this is a daytime job, since it involves removing the detector.

Both the f/2.1 and f/4 cameras are mounted on kinematic seats and tilt adjuster screws which allow them to be initially aligned and then repositioned accurately. The original intention was to have a seperate set of screws for each camera, however these proved difficult to install and it was found that the two cameras were sufficently aligned if they used the same screw settings. This alignment was checked using the f/2.1 camera alignment as a reference since it had previously been accurately set with respect to the collimator and instrument body axes. A HeNe laser was mounted on a tilting stand on the on the Al alignment T–piece. The laser was first roughly aligned in translation with the centre of the lens cover. The reflected spots from the optical components of the f/2.1 camera were observed on a small white screen in front of the laser. By subsequent iterations of translation and tilt all the reflected spots could be made coincident and the laser was now aligned with the optical axis. The f/4 camera was swapped for the f/2.1, the reflected spots were now within 3mm in the 800mm distance to the laser. This is equivalent to a maximum tilt of 0.1 degrees which has no significant effect on the optical quality, especially if the CCD tilt is adjusted. It is thus possible to swap between f/2.1 and f/4 cameras without the need for adjustment.

To install the camera, the lower section camera box is lowered from the back of TAURUS and the cameras inserted from the top after first removing the 3 screws from the underside of the box which clamp the camera to its kinematic seat (be careful not to move the smaller tilt adjuster screws by mistake). The easiest way to lower the camera box is to use the rising floor and trolley whilst TAURUS is on the telescope.

7 Installation and alignment of Fabry-Perot etalons

This section is not relevant for CCD imaging observations.

7.1 General description of the etalon cell

Each etalon appears physically as a circular black cell containing a pair of coated glass plates. Towards the top of the cell is a flange, in which the following sets of holes are drilled:

1. Two small holes (diameter approx 5mm) on opposite sides of the flange. These are used to attach the etalon handling tool to the etalon.
2. Three slightly larger holes (diameter approx 9mm) equally spaced (i.e. 120 degrees apart) around the flange. These are used to bolt the etalon to the etalon wheel.
3. Three more holes (diameter approx 10mm) equally spaced (i.e. 120 degrees apart) around the flange. These contain adjusting screws, used to align the etalon. The adjusting screws locate in kinematic mounts in the etalon wheel.

On the side of the etalon cell is a connector block to which various electrical connections are made. A schematic diagram of the connector block, showing the function of the various connectors, is shown in Figure 4.

7.2 Loading etalons

Etalons can be loaded into positions 1, 2, 4 or 5 of the etalon wheel. Positions 3 and 6 are intended as clear positions, and have no cabling for etalons. Note that each position in the etalon wheel which has cabling for an etalon must *always* contain either a real or dummy etalon, properly cabled up. Otherwise loose cables can be snagged when the wheel is moved.

In order to access a particular position in the etalon wheel, it is necessary to move it into the light-table, by moving the opposite position into the beam.

Etalons are loaded into the etalon wheel through the access hatch for the pupil-plane filter wheel, which is located in the top of the TAURUS–2 light-table. In order to cable up the etalon it will also be necessary to open the access hatch for the etalon wheel, which is located in the bottom of the TAURUS–2 light-table. Both hatches are opened using a special two-pronged tool, which is usually attached to the side of the instrument with a piece of string.

In order to access the etalon wheel from the top of the light-table, it is necessary to move the pupil-plane filter wheel so that the large hole in this wheel is located in the light table position. Do this by putting position 5 of the pupil plane filter wheel into the beam.

When changing an etalon it is convenient to disengage the detent pins for the etalon and pupil plane filter wheels, so that they are not clamped. This will make accessing the etalon in order to connect wiring more straightforward. To do this, the parameters used when requesting the wheels to move should be negative. For example, in order to change the etalon in position 1 of the etalon wheel, issue the following commands from the instrument control computer:

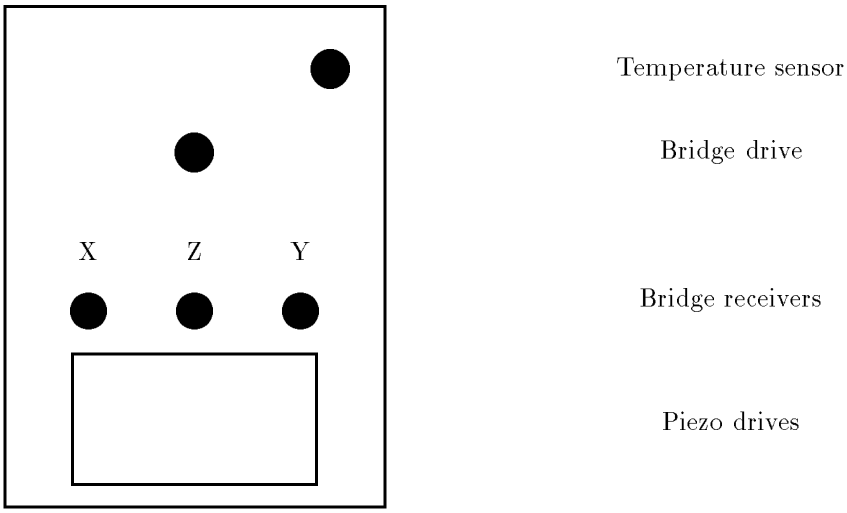

Figure 4: Electrical connections to TAURUS etalons

ICL>	TPFILTER -5	Select large hole in pupil filter wheel
ICL>	ETALON -4	Move etalon position 1 to light table

The procedure to change the etalon is as follows:

1. Disconnect the cabling to the etalon currently in the wheel. Access to the connectors is rather cramped. The simplest approach is first to disconnect the piezo drives (multiway connector with locking screw), accessing the connector block from underneath. Then disconnect the temperature sensor and bridge drive from above. Finally disconnect the 3 bridge receivers. Put the cables to one side.
2. Use an Allen key to unscrew the three bolts attaching the etalon to the etalon wheel. Don't unscrew the kinematic mounts by mistake !
3. Attach the etalon handling tool to the etalon in the wheel. To do this, locate the two screw threads at the bottom of the tool in the corresponding holes in the etalon flange, then tighten the black knobs on the top of the tool.
4. Lift the etalon out of the etalon wheel, and through the access hatch in the top of the light table. Detach the handling tool.
5. If the etalon removed is a real rather than a dummy one, attach its protective covers and put it away.
6. Attach the handling tool to the etalon to be used.
7. Lower the etalon through the access hatch in the top of the light table, into the etalon wheel. The etalon should locate in the kinematic mounts on the wheel. Detach the handling tool.
8. Fix the etalon to the wheel using the three Allen screws.
9. Cable the etalon up. The simplest approach is first to connect the 3 bridge receivers. Make sure these are connected the right way around; note that the Z bridge receiver is between the other two. Then connect the temperature sensor and bridge drive from above. Finally connect the piezo drives (multiway connector with locking screw), accessing the connector block from underneath. Take care when doing this, since it is easy to misalign and bend the connection pins if the connector is carelessly inserted.

7.3 Servoing etalons

First make sure that the CS100 and its switchbox are switched on. These electronics units are both mounted on the side of TAURUS.

Now select which etalon is to be servo'd. The cabling from the etalons is routed to the switchbox, which selects which etalon is currently being controlled by the CS100. The CS100 itself can be controlled either locally, using the switches on the front panel, or from the system computer. Setting up the etalon it most straightforward when the CS100 is under local control. In order to servo the etalon in position number 1, and set the CS100 to local control, type the following commands:

ICL>	ETALON_VOLTAGE 1	Servo etalon 1
ICL>	CS100_LOC	Select local control

The procedure for servoing an etalon is first to open the servo loop using the two-position switch on the CS100 panel. Then for each of the channels set the coarse, fine and resistive offsets, servo gain and time constant. Then close the servo loop again, and check that the etalon servo's without overloading.

A log of the offsets, time constant and gain for each etalon is kept on the VAX 8300 in the directory [TAURUS.INSTR.CS100]. These parameters do not change greatly with time, and so at the start of an observing run it should be possible to servo the etalon using the same values for these parameters as were used in the previous run.

If the values of these parameters are not known, the etalon should be servo'd using the following procedure:

1. Set the servo gain for each channel to 8, and time constant to 1.6 ms.
2. Ensure that the CLOSE LOOP and INTEGRATE switches are down, and the METER DISPLAY switch is up.
3. Turn on power
4. Null the X, Y and Z meters using the X, Y and Z COARSE and FINE PARALLELISM controls. There is some interaction between the channels, so it will be necessary to iterate. Do not aim to achieve an exact null.
5. Switch the METER DISPLAY switch to RESISTIVE COMPONENT and null the readings using the R BALANCE control.
6. Switch the METER DISPLAY back to ERROR SIGNAL and repeat step (4). Iterate between (4) and (5) until the meters read zero when switched to RESISTIVE COMPONENT and are on scale when switched to ERROR SIGNAL
7. Set the gains to 32 and time constants to 250 s, and switch the CLOSE LOOP switch up. After a delay of about 1s, the LOOP CLOSED LED should light, indicating correct closed–loop operation.

The etalon is now under servo control, but the offsets, gain and time constamnt will not be optimised. The CS100 manual describes the process by which the optimum time constant and gain are determined. The normal values for TAURUS–2 etalons are a time constant of 250 seconds and a gain of 16. The process of optimising the offsets is described in Section 7.5. Note that the offsets should be re-optimised at least every few days, and preferably before each night's observing.

When the etalon cannot be servo'd, the problem is almost always the electrical connections to the etalon. Disconnect and reconnect all the cables.

7.4 Mechanical alignment of etalons

The orientation of the etalon can be altered by adjusting the 3 Allen screws which locate the etalon in its kinematic mount. You will first need to gain access to the etalon from above, by moving both it and the large hole of the pupil-plane filter wheel into the light table. Then follow the following procedure to change the etalon orientation:

1. Loosen the bolts holding the etalon to the etalon wheel, and slacken off the lock-nut on one of the adjusting screws.
2. Use an Allen key to turn the adjusting screw by a well-defined amount (e.g. a quarter of a turn)
3. Tighten the lock nut and bolts

The reason for changing the mechanical alignment of the etalon is normally to deal with the problem of ghost images (section 19). The aim is usually either to throw the ghost image well away from the real image, or to align it with the real image. Which approach to take depends on circumstances. The former approach is much easier, but may cause problems when the object being observed has emission over the whole field. In general, the latter approach is to be preferred, except perhaps when the scientific aims of the project require the detection of faint structure close to a bright point source.

It is not easy to tilt the etalon by a precisely repeatable amount, thus the process of aligning the etalon is rather iterative. You will have to take a series of images of the pinhole mask, illuminating it with the tungsten calibration lamp, with the etalon in the beam. Each of the pinhole images will have an associated ghost image, offset from the real image by the same amount. The procedure is then to remove the etalon from the beam, adjust one of the alignment screws as described above, return the etalon to the beam and take another image. Changing the tilt of the etalon should shift the ghost images with respect to the real images. It normally takes a few iterations to establish how much of an adjustment, of which alignmnent screws, should in principle produce the required shift. Then a few more iterations to get it right.

7.5 Optical alignment of etalons

The final process in setting up an etalon is the optical alignment of the etalon plates (i.e. setting the plates parallel). This should be carried out when the etalon is first loaded, and then checked during the observing run, preferably every day.

Note that before the etalon can be accurately aligned, the etalon compartment should have been flushed with dry nitrogen for at least an hour.

The etalon is aligned by moving it into the light-table position, illuminating it with an arc lamp mounted below the light-table, and viewing the Fabry-Perot ring pattern from above. The access hatches should not be opened during this process, as this will disturb the controlled environment of the etalon compartment. Instead, there are two slides above and below the light table. The slide below the light table covers a diffusing screen. Remove this slide, and bolt the calibration lamp unit to the underside of the light table. Then remove the slide above the light table, which covers a viewport. Note that in order to move the top slide, it will be necessary to use an electric screwdriver (or similar) to depress a catch in the top left hand corner of the slide.

If you switch the calibration lamp on, and the etalon is servoing correctly, you should now be able to see the Fabry-Perot ring pattern through the top viewport. As you move your head from side to side across the etalon, the ring pattern will appear to contract or expand if the etalon plates are not parallel. The basic aim of the alignment process is to minimise this variation in ring radius, by adjusting the offsets applied to the CS100 servo channels. The CS100 should be set to local control during the alignment process, as for the initial servoing of the etalon.

First move your head from side to side along the X axis of the etalon, and adjust the COARSE X PARALLELISM control on the CS100 to minimise the expansion or contraction of the rings as the head is moved. Then move along the Y axis, and adjust the COARSE Y PARALLELISM. The orientation of the X and Y axes is marked on the top of the light-table. The FINE Z control should now be used to make a ring just appear in the centre of the field and the alignment process should be repeated observing this ring and adjusting the X and Y FINE PARALLELISM controls. This small central ring is very sensitive to departures from parallelism, so provides an accurate indication of alignment. Some

Part IV

IMAGING OPERATION

8 Starting up

8.1 Acquisition/slitviewing TV

Starting up the TV microprocessor is described in the telescope manual.

8.2 Autoguider

The autoguider is a Peltier-cooled CCD, operated at -35 degrees C. It should always be left at room temperature when not in use. It is flushed with nitrogen in order to prevent condensation on the chip surface. In order to make sure there is a supply of nitrogen to the CCD, check that there is nitrogen gas at pressure connected to the flushing box inlet, and check that the 24V supply to the flushing box is connected and on.

The autoguider's microprocessor is started simply by turning it on; it lives in the same blue cupboards as the TV micro, behind the door labelled NASMYTH (of course!). If the red light labelled G.O.A.T. (on the top rack) is on, the CCD controller at the telescope will have to be switched on as well. The light should then go off. After starting the micro, type `START-UP`. The cooling system will start to cool the chip and will not let you do anything else until it has. Check the flowmeter on the input to the flushing box, and adjust the flow if it is not adequate. This should not normally be necessary as the flow is under automatic control. After 5–10 minutes, the system will respond with `READY TO GO`. During observing, watch out for ice forming on the surface of the chip. If this occurs, shutdown the system by typing `SHUT-DOWN` at the autoguider keyboard. If persistent icing occurs, increase the nitrogen flushing rate.

8.3 Instrument control computer

The microVax 3600 and the VAXstation should both be running. If this is not the case, ask for help. If there is not already a window on the VAXstation, it is now necessary to create one. Do this by using the mouse to move the cursor to the position on the screen where you want the window to be created, then click on the leftmost button of the mouse. A menu will be displayed. Use the mouse to move the cursor so that the option 'create new VT200 window' is highlighted, and once again click on the leftmost button of the mouse. A window will be created on the VAXstation screen and you will be prompted to log onto the VAXstation. Log on as user OBSERVER (password WHT_OBSERVER). You should then set host onto the microVAX 3600 by issuing the command LPVC, and login again as OBSERVER (password WHT_OBSERVER)

Once logged onto the microVAX 3600 you can then start up the control system by simply typing ICL. You will be asked if you wish to load the system tasks, to which you should reply YES. You will then be asked if you wish to run the mimic display on the (V)axstation or (I)kon, to which you should normally reply V. You will probably have to adjust the size and location of the mimic window. To change the size, move the cursor to the top left hand corner of the window and click on the leftmost button of the mouse. You will be presented with a menu, from which you should select the option 'change the size'. The window frame will change colour. You can then change the size of the window by using the mouse to move the cursor to part of the window frame, clicking on the leftmost button of the mouse, and then moving the cursor whilst holding the leftmost button of the mouse down. It is possible to move the window by simply by using the mouse to move the cursor to part of the window frame, clicking on the leftmost button of the mouse, and then moving the cursor whilst holding the leftmost button of the mouse down. There is a different mimic page for each system. The required page can be selected using a menu displayed in the mimic window.

8.4 Liquid nitrogen

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When TAURUS is used with a CCD, remember that the CCD cryostat has a hold time for liquied nitrogen of about 12 hours. It is advisable therefore for it to be refilled in the evening before the start of observing and in the morning after observing.

9 Setting up

9.1 Loading filters

When TAURUS is used for imaging observations, the etalon wheel is empty and filters are mounted in either the focal plane filter wheel or the pupil plane filter wheel.

There are several factors to be considered when deciding which wheel to use for filters:

- Small filters used in the focal plane filter wheel may limit the field-size. The plate scale at the telescope focal plane is 4.51 arcsec/mm. Thus, for example, the 50 mm square filters used for imaging on the INT and JKT will provide a field when used with TAURUS of only 3.8 arcmin square.
- Small filters (diameter $<$ 68mm) used in the pupil plane filter wheel will cause vignetting
- Some filters used in the pupil plane filter wheel are known to produce ghost images at the level of a few per cent. There is no evidence of filters used in the focal plane filter wheel doing so.
- When interference filters are used in the focal plane filter wheel is it possible to fine–tune their wavelength by tilting them (see section VIII). This is not possible when filters are used in the pupil plane filter wheel.

In practice it is almost always preferable to use the focal plane filter wheel.

Before loading a filter in either of the filter wheels it must be mounted in a suitable holder. This should normally be done by the support astronomer and should *not* under any circumstances be attempted by inexperienced observers !

The access hatch for the focal plane filter wheel is on the side of the instrument, towards the top, and is labelled as such. In order to gain access to a particular filter wheel position, it is necessary to use the **TFFILTER** command to move the filter in the opposite position into the beam. For example, since there are 8 positions in the filter wheel, it is necessary to move the filter wheel to position 1 in order to change the filter in position 5. The access hatch can then be opened and the filter changed. There is no software lock on the access hatch, but the computer will detect and display its current status. An interlock prevents any of the TAURUS mechanisms, including the filter wheel, from being moved whilst the access hatch is open. Once all the required filters are loaded, it is necessary to use the **TFNAME** command to tell the computer where they are loaded, so that this information can be displayed on the mimic screen.

The access hatch for the pupil plane filter wheel is on top of the light table. It is not labelled. In order to open it, a special two–pronged tool is required, which is usually attached to the side of the instrument by a piece of string. The rest is as for the focal plane filter wheel, except that the **TFFILTER** and **TFNAME** commands are replaced by **TPFILTER** and **TPNAME**.

9.2 Setting fieldsize

In order to minimise stray light and ghosting it is advisable to use the iris to limit the fieldsize (see section 19) An iris diameter of 106 mm just covers the field of the EEV3 CCD.

9.3 Instrument focus

TAURUS is focussed using one of two aperture masks mounted in the aperture wheel. One mask provides a matrix of large (200 μm) regularly spaced pinholes, whilst the other mask provides a single laser–drilled small (20 μm) pinhole. The former is useful for coarse focussing, whilst the latter is useful for fine focusssing and for assessing the on-axis image quality. With the f/4 camera, the 20 μm pinhole projects to 7 μm on the detector, whilst with the f/2.1 camera the pinhole projects to about 7 μm, both of which are much less than the CCD pixel size.

The procedure is first to check the coarse focus by selecting the matrix mask, and illuminating it using the tungsten lamp in the A&G unit. Take a series of exposures with different values of the camera focus, and measure the FWHM of the images. Then use pencil and graph paper to determine the optimum focus.

It should be possible to bracket the best focus; as the camera position is changed the image quality should first improve as the position of best focus is approached, and then start getting worse again once the position of best focus is passed.

For each exposure use the **TFOCUS** command to set the TAURUS focus. Then take an exposure using the **EXPOSE** command. Finally measure the FWHM of one of the pinhole images using the DMS. The DMS functions **X–FIND** and **Y–FIND** can be used for this purpose.

The camera can be moved through a total range of 6000 μm. With the f/4 camera, the values of camera focus with the B,V,R and I filters are 3150, 2950, 2850, 2800 respectively. An error in the camera focus of $\pm$ 200 changes the FWHM by less than about 5 per cent. So a typical focus run might involve taking a series of exposures covering the range 2250 to 3750 in steps of 250.

An example set of commands to carry out this procedure might be as follows. All the commands are issued from ICL, except for X–FIND which is issued from the DMS keyboard. Note that the actual procedure used will depend, for example, on the name of the detector being used.

ICL>	TAPERTURE 8	Select pinhole mask
ICL>	TFFILTER B	Select required filter
ICL>	AGMIRROR ACQCOMP	Select A&G comparison mirror
ICL>	COMPLAMPS W	Turn on tunsten lamp
ICL>	COMPFILTA ND3.0	Select appropriate ND
ICL>	TFOCUS 2250	Change TAURUS focus
ICL>	EB 10	Take CCD exposure
	X--FIND	Use DMS to measure FWHM of images
ICL>	TFOCUS 2500	Change TAURUS focus
ICL>	EB 10	Take CCD exposure
	X--FIND	Use DMS to measure FWHM of images
ICL>	TFOCUS 2750	Change TAURUS focus
ICL>	EB 10	Take CCD exposure
	X--FIND	Use DMS to measure FWHM of images
ICL>	TFOCUS 3000	Change TAURUS focus
ICL>	EB 10	Take CCD exposure
	X--FIND	Use DMS to measure FWHM of images
ICL>	TFOCUS 3250	Change TAURUS focus
ICL>	EB 10	Take CCD exposure
	X--FIND	Use DMS to measure FWHM of images
ICL>	TFOCUS 3500	Change TAURUS focus
ICL>	EB 10	Take CCD exposure
	X--FIND	Use DMS to measure FWHM of images
ICL>	TFOCUS 3750	Change TAURUS focus
ICL>	EB 10	Take CCD exposure
	X--FIND	Use DMS to measure FWHM of images
ICL>	TFOCUS 3150	Set TAURUS focus to optimum value

If it is not possible to go through focus within the allowed range of camera movement, it may be necessary to adjust the capstans on the CCD. Note that increasing the value of the camera focus has the effect of moving the camera down, out of the instrument; thus, if the position of best focus lies above the allowed range of camera movement, it will be necessary to raise the detector. If this still doesn't help, and the image quality is poor, check that the correct spacer box and spacer ring have been used between TAURUS and the CCD. The f/4 camera requires a black spacer box, the f/2.1 camera doesn't. The spacer ring should have a thickness of ? mm.

Once the approximate focus has been measured, fine-focussing can be carried out by selecting the laser-drilled pinhole and repeating the above procedure.

Finally, it is worth noting that the position of best focus is slightly wavelength-dependent (see section 18), Thus, if the best image quality is required, it will be necessary to measure the position of best focus at each observing wavelength.

9.4 Telescope focus

Once TAURUS itself has been focussed, the next stage is to focus the telescope onto the detector. The procedure is simply to take a series of CCD exposures with different values of the telescope focus, and measure the FWHM for each one. Then use pencil and graph paper to determine the optimum focus.

For each exposure use the **FOCUS** command to set the telescope focus. Then take an exposure using the **EXPOSE** command. Finally measure the FWHM of a star in the field using the DMS. The DMS functions **X–FIND** and **Y–FIND** can be used for this purpose.

The nominal telescope focus is at 97.45 mm. A typical focus run might involve taking a series of CCD exposures over a range of ±0.3mm (i.e. from 97.15 to 97.75 mm) stepping the focus by about 0.1 mm between exposures. A smaller stepsize of about 0.03mm might be appropriate in conditions of very good seeing.

An example set of commands to carry out this procedure might be as follows. All the commands are issued from ICL, except for FOCUS which is normally issued from the TCS and X–FIND which is issued from the DMS keyboard. Note that the actual procedure used will depend, for example, on the name of the detector being used.

`ICL>`	`TAPERTURE 1`	Select clear aperture
`ICL>`	`TFFILTER B`	Select required filter
`ICL>`	`COMPLAMPS OFF`	Turn off lamps
`ICL>`	`AGMIRROR OUT`	Remove A&G comparison mirror
`TCS>`	`FOCUS 97.15`	Change telescope focus
`ICL>`	`EB 10`	Take CCD exposure
	`X--FIND`	Use DMS to measure FWHM of images
`TCS>`	`FOCUS 97.25`	Change telescope focus
`ICL>`	`EB 10`	Take CCD exposure
	`X--FIND`	Use DMS to measure FWHM of images
`TCS>`	`FOCUS 97.35`	Change telescope focus
`ICL>`	`EB 10`	Take CCD exposure
	`X--FIND`	Use DMS to measure FWHM of images
`TCS>`	`FOCUS 97.45`	Change telescope focus
`ICL>`	`EB 10`	Take CCD exposure
	`X--FIND`	Use DMS to measure FWHM of images
`TCS>`	`FOCUS 97.55`	Change telescope focus
`ICL>`	`EB 10`	Take CCD exposure
	`X--FIND`	Use DMS to measure FWHM of images
`TCS>`	`FOCUS 97.65`	Change telescope focus
`ICL>`	`EB 10`	Take CCD exposure
	`X--FIND`	Use DMS to measure FWHM of images
`TCS>`	`FOCUS 97.75`	Change telescope focus
`ICL>`	`EB 10`	Take CCD exposure
	`X--FIND`	Use DMS to measure FWHM of images
`TCS>`	`FOCUS 97.45`	Set optimum telescope focus

Remember that the telescope focus will depend on which filter is being used in the focal plane filter wheel. Table 7 gives the offset in telescope focus required for different filter thicknesses for both interference (n=2.1) and glass (n=1.5) filters. The standard BVRI Harris glass filters used with TAURUS all have a thickness of 4mm, so should all provide the same focus. Table 12 lists the thicknesses of the interference filters normally used with TAURUS.

Once the telescope is focussed on the detector, it is necesary to check that the autoguider and field–viewing TV are also in focus. The procedure is as before to adjust the focus of these mechanisms, using the AUTOFOCUS and TVFOCUS commands, until the FWHM of images seen on the autoguider and on the TV system is minimised. The nominal values of AUTOFOCUS and TVFOCUS (as of 17/5/91) are 3000 AND 15000 respectively.

Table 7: Effect of filters on telescope focus

Filter type	Filter thickness (mm)	Offset to telescope focus (mm)
CLEAR	CLEAR	0.0
Interference	3.0	–0.08
Interference	5.0	–0.13
Interference	6.0	–0.16
Interference	7.0	–0.18
Interference	7.5	–0.19
Interference	8.0	–0.20
Interference	9.0	–0.23
Glass	4.0	–0.07
Glass	7.0	–0.12
Glass	7.5	–0.12

9.5 Rotator PA

It will make data reduction more straightforward if the rotator PA is adjusted so that the CCD chip is aligned with the cardinal points. Unfortunately, the rotator PA required is not the same each observing run, since it is possible to mount the detector in more than one orientation.

The simplest method of measuring the required rotator PA is to take a pair of exposures of a star, offsetting the telescope either in RA or dec between the two exposures. Use the DMS to measure the coordinates of the star in the two images, and hence determine the direction in which the star moved on the chip. Then adjust the rotator PA until this direction is aligned with one of the chip axes.

10 Observing

10.1 Acquisition

The telescope points sufficently well that object acquisition for TAURUS imaging observations is extremely straightforward. As long as the object coordinates have been typed in correctly, it is very unlikely that the object will be far from the field centre. Thus it is not worth wasting observing time using the TV to verify that the right field is being observed. If you disagree with this statement, or for some reason are unhappy with your coordinates, then it is possible to view the field using the acquisition TV in the A&G unti; type **AGMIRROR ACQCOMP** to select the acquisition mirror, and once you're happy, type **AGMIRROR OUT** to get rid of it again.

10.2 Guiding

Working the autoguider entails orchestrating the A&G, autoguider and telescope. There are three stages – search for a guide star, start the autoguider following a star, and start the telescope acting on the tracking errors being sent by the autoguider.

In order to find guide stars, the autoguider probe can be driven in an angular direction around a half-circle, and also has 40 mm of radial travel. The commands for setting the position of the autoguider probe are

`ICL>`	`AUTORADIAL r`	(r in μm : $0 < r < 40000$)
`ICL>`	`AUTOTHETA` θ	(θ in millidegrees : $0 < \theta < 180000$)

In general it is preferable to guide using an autoguider filter similar to that being used for the observations. Note however that this may make it more difficult to find an appropriate guide star. In order to see if a guide star is present, take an exposure. The autoguider will then search for a suitable guide star and mark it with a cursor. The commands to do all this are as follows:

`ICL>`	`AUTOFILT B`	Select autoguider filter
`ICL>`	`ACQINT t`	Set exposure time (t in millisecs)
`ICL>`	`FIELD`	Take exposure, search for guide star

If a suitable guide star is not found an error message will be returned, and it will be necessary to either change the filter, the integration time or the position of the guide probe. Note that bright guide stars ($m < 12$ or so) are unsuitable as they saturate the CCD in one second. In general it will be necessary to search a few guide probe positions to find a suitable guide star. In this case it will be useful to know that the chip subtends 13500 r-units, and 7500 θ-units. The most effective procedure is to drive the probe to its furthest radial extent (r = 40000), see if an appropriate guide star is present, and if not, offset in θ by 7500 units and try again.

Once a suitable guide star has been located, it is necessary first to tell the autoguider to start generating guiding errors, and then to tell the telescope control system to start using the errors. It will also be necessary to tell the telescope control system the position of the guide probe. The commands to do this are:

`ICL>`	`GUIINT t`	Set guiding exposure time (t in millisecondss)
`ICL>`	`FOLLOW ON n`	Generate guiding errors (n is number of exposures to average per guiding error
`TCS>`	`PROBE r` θ	Tell TCS probe coordinates
`TCS>`	`AUTOGUIDE ON`	Start guiding

Finally, stop guiding using the following commands:

```
TCS>  AUTOGUIDE OFF
ICL>  FOLLOW OFF n
```

10.3 Taking data

11 Instrument calibration

11.1 Bias frames

Take a series of exposures with zero integration time. These can then be averaged to obtain adequate signal to noise.

Note that the bias level in each exposure can be estimated from the overscan region of the data frame.

Table 8: Areas of blank sky

Sourcename	RA	Dec
BLANK1	04 25 46.0	+54 09 03
BLANK2	13 04 33.0	+29 50 49
BLANK3	16 49 42.0	–15 21 00
BLANK4	19 19 09.0	+12 22 05
BLANK5	21 26 54.4	–08 51 41
BLANK6	23 54 08.9	+59 28 18

The location of the overscan region for various chips in use on La Palma is summarised in La Palma Technical Note 79.

11.2 Dark frames

Dark exposures are obtained using the **DARK** command. This has exactly the same syntax as the **EXPOSE** command. It takes an exposure of a specified length, but without opening the shutter.

11.3 Flatfielding

Flat fields can be obtained using either the twilight sky or the calibration system in the Cassegrain A&G.

Table 8 lists several areas of sky containing relatively few stars, well-suited for twilight sky flat-field observations. These are observed in exactly the same way as any other object.

For flatfield observations using the comparison lamps in the Cassegrain A&G, the first step is to put the acquisition and comparison mirror must be in, since the calibrating light is reflected from its bottom surface. Then switch the tungsten lamp on, select the required filter and take the exposure. The commands to do all this are as follows:

`ICL>`	`AGMIRROR ACQCOMP`	Select comparison mirror
`ICL>`	`COMPLAMPS W`	Turn tungsten lamp on
`ICL>`	`TFFILTER B`	Select required filter
`ICL>`	`EXPOSE BLUE 5`	Take exposure
`ICL>`	`KEEP BLUE`	Keep data

Exposure count-rates for flatfields using the tungsten lamp, the standard Harris broadband filters, and the f/4 camera are summarised in Table 9. This data can easily be scaled to observations with the f/2.1 camera, by multiplying the count rates by a factor of 4.

11.4 Photometric standards

Photometric standards, and their WHT names, are listed in the appendices to the WHT Users Manual. The positions of these stars are stored online by the WHT Telescope Control System, and can be selected using the WHT names.

Table 9: Flatfield count rates

Filter	ND	Counts/sec
B	2.7	3000
V	3.9	2100
R	5.0	2000
I	5.0	8000

The original source for the Landolt standards is:

'UBVRI photometric standard stars around the celestial equator', A.U.Landolt, 1983, *Astron.J.*, **88**, 439.

Photometric sequences for CCD observations are given in:

C.A. Christian *et al*, 1985, *PASP*, **97**, 363
R.E. Schild, 1983, *PASP*, **95**, 1021
R.S. Stobie *et al*, 1985, *A&A Suppl.*, **60**, 503.

Note that many of the Landolt standards are too bright for a 4–m telescope with a reasonable integration time. Integration times should be kept above about 5 seconds in order to avoid errors due to shutter timing (See section 21). In order to do this without saturating the detector, it may be necessary to defocus the telescope.

Part V

FABRY-PEROT OPERATION

This section describes the operation of TAURUS–2 in Fabry-Perot mode. There are a number of aspects of TAURUS operation that are almost identical for imaging and Fabry-Perot observations; instead of repeating this information, this part of the manual simply refers back to the relevant sections in Part IV.

12 Starting up

12.1 Acquisition/slitviewing TV

See section 8.1

12.2 Autoguider

See section 8.2

12.3 Instrument control computer

See section 8.3

12.4 Liquid nitrogen

See section 8.4. This section is not relevant for TAURUS when used in Fabry-Perot mode with the IPCS.

13 Setting up

13.1 Loading filters

See section 9.1

13.2 Loading etalons

The procedure for loading etalons is described in section 7.2, and should normally have been carried out by the support astronomer when the instrument was first mounted on the telescope. The optical alignment of the etalons should be checked before each night, and the procedure to do this is described in section 7.5.

13.3 Setting fieldsize

See section 9.2

13.4 Instrument focus

See section 9.3 for how to focus TAURUS in Fabry-Perot mode with the CCD.

The IPCS is a more complex detector to operate than the CCD, and can easily be damaged by overillumination. Its operation is not described in detail here, since it is described in the the IPCS users manual; please read this before using the IPCS.

The focus procedure for TAURUS with IPCS differs in two ways from the focus procedure for TAURUS with CCD. Firstly, it is necessary to open the IPCS shutter explicitly using the **IPO** command, before an EXPOSE command is issued. After an exposure is completed, the shutter is closed using the **IPC** command.

Secondly, and most importantly, remember that *The IPCS can be severely damaged by over-illumination.* Therefore, when observing a calibration lamp whose intensity is not known, the following procedure should be followed.

1. Switch IPCS to overscan mode by typing **OVERSCAN**.
2. Select the maximum possible neutral density filtering for the calibration lamp, using either the **COMPFILTA nd** or the COMPFILTB nd command. The allowed values of **nd** for the two commands are summarised in Table 2.
3. Open the shutter using the **IPO** command, viewing the IPCS realtime display, and keeping your finger on the IPCS panic button. Hit the panic button if the illumination level is too high.
4. Gradually reduce the level of neutral density until the illumination level is acceptable.

13.5 Telescope focus

See section 9.4 for how to focus the telescope when using TAURUS in Fabry-Perot mode with the CCD.

The process of focussing the telescope onto the IPCS is as follows:

1. Find a suitable star for focussing. This should produce an acceptable level of illumination on the detector without the need to use a neutral density filter in the A&G unit, since use of these neutral density filters will result in a shift of the telescope focus.
2. Set the telescope focus to the lowest value to be covered in the focus run. Use the **FOCUS** command on the TCS to do this.
3. Start an exposure using the **EXPOSE IPCS** command.
4. Once you have adequate signal-to-noise, close the IPCS shutter using the **IPC** command, increment the telescope focus, and offset the telescope using the TCS handset by about 5 arcsec.
5. Repeat until the telescope has clearly gone through focus.

Table 10: Free spectral range of TAURUS etalons

Etalon	Wavelength (Å)	FSR (mpu)	Stepsize (mpu)	Range-scanned (mpu)
125μm	6600	615	11	660
	5000	466	9	540
500μm	6600	660	12	720
	5000	500	9	540

6. Finish the IPCS exposure. Measure the FWHM of each image as described in section 9.4, and determine the position of best focus

Remember that the telescope focus will depend on which filter is being used in the focal plane filter wheel. Table 7 gives the offset in telescope focus required for different filter thicknesses for both interference (n=2.1) and glass (n=1.5) filters. Table 12 lists the thicknesses of the interference filters normally used as order-sorting filters with TAURUS.

13.6 Rotator PA

See section 9.5

13.7 Setting datacube parameters

In order to set up the datacube parameters it is necesssary to specify the detector format (i.e. the x and y dimensions and pixel size for the datacube) and the parameters for the etalon scanning (i.e. the z axis and pixel size for the datacube). The detector format used depends as usual on the required fieldsize and spatial resolution. The etalon scanning parameters depend on the free spectral range, finesse and zero point. In order to determine these parameters it is normally necessary to take a few trial exposures.

Since setting up TAURUS for observing is rather complex, ICL procedures have been produced to guide the observer through the process. These are described in section 15. Briefly, the **FP_MODE** procedure is used to specify the detector being used, and the **FP_SETUP** procedure is used to specify all the observing parameters. Subsets of the parameters can be altered using **FP_SETUP_2D** and **CS100_TABLE**. Finally, datacubes are acquired using **FP_EXP_3D** and images are acquired using **FP_EXP_2D**.

In order to specify the etalon scanning parameters, you will first need to determine the free spectral range (FSR) of the etalon at the wavelength of the observations. Note that the FSR is linearly proportional to the wavelength of the observations, so given an estimate at one wavelength it is straightforward to obtain an estimate at a different wavelength. The nominal FSR for the standard etalons at standard wavelengths are is given in Table ??. A log of actual measurements is stored on-line on the 8300 in the directory [TAURUS.INSTR.CS100]. The FSR is normally specified in microprocessor units (mpu).

If you wish to measure the FSR yourself, this is done as follows using observations of an arc line. See section 16.1 for a summary of useful arc lines. First set up for data-acquisition using the **FP_MODE** and **FP_SETUP** commands. Then take a series of 2D exposures using **FP_EXP_2D**, altering the etalon gap each time using **FP_SETUP_2D**, until you can see a nice ring. Note the Z offset from the mimic. Keep increasing the gap, until the same ring reappears with the same radius. Note the Z offset again.

The difference between the two values of the Z offset is the FSR. In order to be able to reduce the data, it is normally necessary to scan the etalon over slightly more than the FSR. For example, if the FSR is 600 microprocessor units, scan the etalon over 660 units.

The number of planes in the datacube is determined by the etalon finesse. The TAURUS etalons have a finesse of between 20 and 30, implying that about 60 planes are required in the datacube. Note that the instrumental profile of a Fabry-Perot interferometer is not Gaussian, but has rather more power in the wings. It is therefore advisable to oversample slightly. Thus in the example above, where the FSR is equal to 600, it would be normal to step the etalon 60 times, incrementing the gap by 11 microprocessor units each time.

Table **??** summarises suggested etalon stepsizes and scan ranges, assuming that the datacube has 60 planes.

The zero point of the etalon scan is determined primarily by the properties of the phase calibration cube (see section 16.1). It is usually preferable to set the zero-point such that the calibration line appears both at the start and end of the scan i.e. good data is obtained on the calibration line in two adjacent orders of interference.

14 Observing

14.1 Acquisition

See section 10.1

14.2 Guiding

See section 10.2

14.3 Taking data

Assuming that the instrument has been set up correctly, taking data is relatively straightforward. Use the procedure **FP_EXP_2D** to take 2D images and the procedure **FP_EXP_3D** to take datacubes. These procedures are described in section 15

15 ICL procedures

TAURUS Fabry-Perot spectroscopy is somewhat complex, and a number of ICL procedures are available to guide the observer through the process of setting up and acquiring datacubes. These are described in this section. Operation with the IPCS and CCD are described separately.

15.1 IPCS

15.1.1 FP_MODE

The observer will be asked whether the detector being used is the IPCS or CCD. This command must always be specified before any of the other procedures are used.

15.1.2 FP_SETUP

This ICL procedure prompts for all the parameters required for the data acquisition process. These are:

- The IPCS resolution factor. This determines the spatial resolution, and is equal to 1, 2, 4 or 8 (see section ?).
- The central row and column of the image on the CCD camera. In other words, these are the cordinates that the centre of the image would have if the resolution factor were 1.
- The dimensions of the image in centroided pixels.
- The number of IPCS frames per etalon step. When using the IPCS it is normal to scan through a datacube very rapidly many times. At each position the detector is exposed for a specified number of ICPS frame times. An IPCS frame time is typically 10–20 millisecs. Each time the etalon is stepped one IPCS frame is lost, hence in order to keep overheads down, whilst still scanning rapidly, this parameter is normally set to about 10.
- The number of etalon steps (i.e. the z dimension of the datacube) This must be less than 255 if a single-sided ramp, 128 for a double-sided ramp (see below).
- The start position for the etalon scan. The etalon gap is altered during an observation by applying an offset to the Z servo channel. The start position specified here is the Z offset to be used for the first plane of the datacube. It is not specified in physical units, but in 'microprocessor units'
- The size of the etalon step. This is the amount by which the Z offset (i.e. the etalon gap) is incremented between successive planes of the datacube. It is not specified in physical units, but in 'microprocessor units'
- The type of ramp function used. It is possible to scan the datacube in two different ways. If a single-sided ramp is used then the datacube will be repeatedly scanned from 1 to n, where n is the number of planes. If a double-sided ramp is used then the datacube will be repeatedly scanned from 1 to n, and then back down from n to 1.
- The frame number to be used for 2D images. During the night it will be necessary to take 2D calibration frames such as ring frames (see section 16.2). The parameter specified here determines the Z offset (i.e. etalon gap) to be used for 2D images. For example, if this parameter equals 10, then 2D images will be taken with the same etalon gap as plane number 10 in the datacubes.

15.1.3 CS100_TABLE

This command is used to redefine the etalon scan parameters (number of etalon steps, start position, increment, type of ramp), without the observer having to reset all the other parameters defined by the FP_SETUP procedure.

15.1.4 FP_SETUP_2D

This command is used to reset the frame number to be used for 2D images, without the observer having to reset all the other parameters defined by the FP_SETUP procedure.

15.1.5 FP_EXP_3D

This procedure acquires a 3D datacube, using parameters defined by FP_SETUP.

In the case of the IPCS, the procedure first sets up TAURUS, the detector and the DMS for the exposure. TAURUS is slaved to the IPCS. The observer is asked to specify the total integration time. The observer is then asked whether the shutter should be opened, then asked to check that the intensity level is OK, and then asked if the exposure should be started.

At the end of an exposure, type **SLAVEOFF** to release TAURUS from the IPCS, the **IPC** to close the shutter and **KEEP IPCS** to keep the data. It may take several minutes to keep the data.

15.1.6 FP_EXP_2D

This procedure acquires a 2D image, using parameters defined by FP_SETUP.

The etalon is first stepped to the previously specified position. The observer is asked to specify the exposure time. The observer is then asked whether the shutter should be opened, then asked to check that the intensity level is OK, and then asked if the exposure should be started.

At the end of an exposure, type **IPC** to close the shutter and **KEEP IPCS** to keep the data.

15.2 CCD

15.2.1 FP_MODE

The observer will be asked whether the detector being used is the IPCS or CCD. This command must always be specified before any of the other procedures are used.

If a CCD is being used, the observer will be prompted for the values of the following logical names. The observer is unlikely to know the values of all these logical names, but the support astronomer should.

- The name of the D-task (e.g. CCD1)
- The name of the DMS buffer (e.g. ISIS_CCD1)
- The number of the DMS buffer (e.g. 2)
- The name of the DCT buffer (e.g. ISISCCD1)
- The head number of the CCD.

15.2.2 FP_SETUP

This ICL procedure prompts for all the parameters required for the data acquisition process.

If the detector is the CCD, the observer will be prompted for the following parameters:

- The dimensions of the CCD in x and y
- The binning factor
- The size of the CCD window in unbinned pixels
- The origin of the CCD window
- The exposure time for each plane of the datacube
- The name of the file specifying the order in which the planes of the etalon are to be observed. This file is simply a text file, containing the same number of records as there are planes in the datacube. Each record contains a single integer, defining one plane of the datacube. Whilst the etalon is being scanned, this file is used to determine which plane of the datacube should be observed next. For example, if record number 5 contained the integer 10, then the 5th image obtained would be of plane number 10. Use of this file allows the datacube to be scanned in a pseudo-random order, defined by the observer. It is up to the observer to make sure that each plane of the datacube is specified in the file once and only once.
- The number of etalon steps (i.e. the z dimension of the datacube) This must be less than 255.
- The start position for the etalon scan. The etalon gap is altered during an observation by applying an offset to the Z servo channel. The start position specified here is the Z offset to be used for the first plane of the datacube. It is not specified in physical units, but in 'microprocessor units'
- The size of the etalon step. This is the amount by which the Z offset (i.e. the etalon gap) is incremented between successive planes of the datacube. It is not specified in physical units, but in 'microprocessor units'
- The type of ramp function used. This should always be set to 0 for observations with the CCD.
- The frame number to be used for 2D images. During the night it will be necessary to take 2D calibration frames such as ring frames (see section 16.2). The parameter specified here determines the Z offset (i.e. etalon gap) to be used for 2D images. For example, if this parameter equals 10, then 2D images will be taken with the same etalon gap as plane number 10 in the datacubes.

15.2.3 CS100_TABLE

This command is used to redefine the etalon scan parameters (number of etalon steps, start position, increment, type of ramp), without the observer having to reset all the other parameters defined by the FP_SETUP procedure.

15.2.4 FP_SETUP_2D

This command is used to reset the frame number to be used for 2D images, without the observer having to reset all the other parameters defined by the FP_SETUP procedure.

15.2.5 FP_EXP_3D

This procedure acquires a 3D datacube, using parameters defined by FP_SETUP.

The procedure will first set up TAUUS and the CCD for the observation.

It will then open the file specifiying the order in which the planes of the datacube are to be scanned and ask you whether you wish to scan the entire cube. Normally the answer will be yes, unless a previous exposure has been aborted. If a previous scan failed partway through, then answer no here, and you will be asked which records of the file should be scanned.

You will then be asked to input the integration time per step. In order to keep the total integration time for the cube below 2 hours, it is normally necessary to specify about 100 seconds here.

The procedure will create a DMS buffer and ask if you want to clear it. Answer yes, unless you are restarting a previously aborted exposure. The procedure will then scan through the datacube.

At the end of this procedure, type **FPKEEP** to keep the data.

If the procedure fails whilst the datacube is being scanned, it is possible to restart. First type **CLOSE TABFILE** to close the file specifying the order in which the etalon is being scanned. You may have to type **DELETE CLOSE** first, in order to remove an ICL procedure whose name conflicts with the ICL command to close a file. Then restart the system , answering no when asked if you want to scan the entire cube, specifying which planes to scan, and answering no when asked if the DMS should be cleared.

15.2.6 FP_EXP_2D

This procedure acquires a 2D image, using parameters defined by FP_SETUP.

The etalon is first stepped to the previously specified position. The observer is asked to specify the exposure time and then asked if the exposure should be started.

At the end of this procedure, type **FPKEEP** to keep the data.

16 Instrument calibration

16.1 Phasemap cubes

Raw TAURUS datacubes have the property that the surfaces of constant wavelength are parabaloids of revolution rather than planes. Before the data can be sensibly analysed it must be rebinned so that the surfaces of constant wavelength are datacube planes. This is the process of phase calibration. FIGARO software is available to carry out this process, and is described in some detail in the manual *TAURUS data and how to reduce it* by Jim Lewis and Steve Unger.

In order to use this software, a phasemap calibration cube will be required. This is a 3D observation of an arc line of known wavelength, using the same datacube parameters as the observation cubes, and is used to define the precise form of the parabaloid of revolution. The calibration cube should be taken at a wavelength close to that of the observation. Table 11 lists some useful calibration lines obtained using the CuNe lamp, and lists the filters required to isolate these lines. I usually use the 6598 Åline as the

Table 11: Useful arc lines for TAURUS calibration

Lamp	Filter wavelength (Å)	Line wavelength (Å)
CuNe	5033	5031.3504
		5035.989
		5037.7512
	5145	5144.9384
	6300	6304.7892
	6589	6598.9529
	6673	6678.2764
	6730	6717.043

principal calibration line for observations at Hα and the lines close to 5033 Åas the principal calibration lines for observations close to [OIII].

If time permits, try to observe more than one calibration line for each observation. This may not always be possible, since each cube will take about an hour to acquire. It is not so imnportant when a single filter transmits 2 or 3 well separated lines, as is the case for the 5033 filter.

Try to set up the etalon scanning so that the ring produced by the principal calibration line is just appearing at the first plane of the cube. As you scan through the cube, this ring will then appear to grow in size until it disappears off the edge of the field. Towards the end of the scan it will reappear. Having the same line twice in the same datacube, in adjacent orders, makes it possible accurately to determnine the free spectral range.

16.2 Ring images

Ring images are what they say, images of the ring pattern produced by the arc lamp. Use the same setup of the calibration system as is used for the phase-calibration cube, and select one plane which shows a nice ring pattern. Obtain a 2D image of this ring pattern every hour or two throughout the night.

By tracking variations in the radius of the ring through the night it is possible to monitor and correct for drifts in the etalon gap. By tracking variations in the coordinates of the centre of the ring pattern, it is possible to monitor and correct for flexure

16.3 Whitelight cubes

This is simply a 3D flatfield. Take a 3D exposure using the same setup and same filter as for the actual observations, but using the tungsten lamp in the A&G.

16.4 Matrix masks

This is a 2D image of the pinhole mask, illuminated by the tungsten lamp in the A&G. It is used to map the variation in detector pixel size across the field, particularly important for the IPCS.

it is important to know the pixel size accurately, as any error in this parameter produces an error in the estimate of the etalon gap, and hence an error in the wavelength scale.

Part VI

PERFORMANCE

17 Throughput

The theoretical and measured throughput of TAURUS–2 with the f/2.1 camera is shown in Fig ?. The throughput is between 55 and 70 per cent over the wavelength region from 4000 Åto 1 μm.

This figure excludes the filters and etalons used with TAURUS–2. Efficiency curves for the broadband BVRI filters used with TAURUS are given in La Palma Technical Note 73. Efficiency curves for the interference filters used with TAURUS are given in La Palma Technical Note 75. The peak transmission of each interference filter is summarised in Table 12. A typical value is 60 per cent.

When TAURUS is used in Fabry-Perot mode, an efficiency for the etalon of between 70 and 90 per cent can be assumed.

18 Image quality

Spot diagrams for TAURUS–2 are shown in figures ?.

19 Ghosting

There are two known sources of ghosting with TAURUS–2

19.1 f/4 camera pupil ghost

When TAURUS is used with the f/4 camera, a bright ghost image is visible of the telescope pupil. This is the result of a reflection between the back of the last element in the camera and the front of the CCD cryostat, imaging the telescope pupil onto the detector with the intensity reduced to a few tenths of one per cent. The ghost image is easily recognisable, since the shadow of the secondary mirror and its support structure are clearly visible. the ghost image can be flatfielded out, and it is hoped in the future that the f/4 camera will be modified to remove it entirely.

In the meantime, the intensity of the ghost can be reduced by using the iris to reduce the fieldsize to that required for a particular observation, rather than just letting the fieldsize be determined by the size of the chip.

Note that the f/2.1 camera does not suffer from this problem, and so this camera should be used if high spatial resolution is not important.

19.2 Filters and etalons in the collimated beam

When filters are placed in the pupil–plane filter wheel, ghost images can be produced with peak intensities of a few per cent of the real images. In general it is preferable to use filters in the focal–plane filter wheel.

When TAURUS is used in Fabry–Perot mode, the presence of an etalon in the collimated bveam can introduce ghosting at levels as high as 10 per cent. It is however possible to align the etalon either to throw the ghost image well away from the field centre, or to superimpose the ghost on the actual image (see section ?).

20 Flexure

During commissioning tests of TAURUS–2 with the f/2 camera, on both the AAT and WHT, flexure was measured to be at the level of 5–6 microns per hour.

21 Exposure timing

Shutter-timing tests suggest that exposure times of one second will have an accuracy of about one per cent. If the exposure time must be known very accurately, as when standard stars are observed, it is advisable to use exposure times greater than 5 seconds.

22 Field of view

When TAURUS is used in imaging mode, the field of view is limited by the following factors:

1. The field cutoff of the collimator, equal to 9 arcmin.
2. Filters placed in the focal plane may further limit the field of view. The scale at the input focal plane is 4.51 arcsec mm^{-1} for TAURUS-2. Thus, for example, a filter with a diameter of 75 mm would limit the field to 5.6 arcmin. This constraint can be avoided by using filters in the pupil plane. However, using filters in the collimated beam leads to an increased risk of ghost images, and in the case of the smaller filters may cause vignetting.
3. The size of the detector. The scale at the detector focal plane is 23.25 arcsec mm^{-1} for TAURUS-2 with the f/2.1 camera and 12.40 arcsec mm^{-1} for TAURUS-2 with the f/4 camera. Thus, for example, the EEV3 CCD, whose size is 27.9×25.7mm, will provide a field of 5.8×5.3 arcmin when used with the f/4 camera.
4. Optical quality. The f/4 camera is designed to give high spatial resolution at the expense of field. The quality of the images therefore degrades somewhat with field radius (see section ?). This may place a limit on the fieldsize useable for a particular project.

When TAURUS-2 is used as a Fabry-Perot interferometer, the field may be further limited by the following factors:

1. The field of view of TAURUS-2 is not limited in the conventional way by the Jacquinot criterion *(Journal of the Optical Society of America, vol 44, p761, 1954).* At high resolutions, the field will however be limited by the width of the interference fringes. The wavelength change across a detector pixel increase with both the distance from the field centre and with the resolution, so there exists an off-axis angle beyond which the wavelength change across a single pixel is greater than the spectral resolution. For a pixel size of p micron and a resolving power R, the off-axis angle in arcmin at which this results in a a degradation of resolution by a factor of $\sqrt{2}$ is given by:

$$\theta = k \times \frac{10^4}{R} \times \frac{50}{p} \tag{1}$$

k = 12.5 for TAURUS-2 with the f/2.1 camera
k = 23.5 for TAURUS-2 with the f/4 camera

2. The total size of a datacube must not exceed the amount of memory available in the Detector Memory System (48 Mbyte as of 17/5/91).

Part VII

TAURUS commands

23 Reference section

This section contains a detailed description of the commands available for controlling TAURUS from ICL.

Notation:

- Examples of commands entered at the terminal are in typewriter font: `TFFILTER 1`;
- Angle brackets denote parameter values or character strings: <`angle`>;
- Square brackets denote optional input: `[x,y]`; all other parameters are obligatory;

23.1 CS100_CLOSE

Close CS100 servo–loop

Format:	`CS100_CLOSE`
Examples :	`CS100_CLOSE`
Comments:	Issuing CS100_CLOSE will only result in a change of state of the etalon if the CS100 has been switched to the etalon (command ETALON_VOLTAGE) and external control has been enabled (command CS100_EXT).

23.2 CS100_EXT

Sets the CS100 to external control etalon cavity

Format:	`CS100_EXT`
Examples :	`CS100_EXT`
Comments:	This command is used to set the CS100 to external control, so that the etalon can be stepped under control of the system computer.

23.3 CS100_GAIN

Sets the gain for the CS100 servo–loop

Format:	`CS100_GAIN <parameter>`
Units:	none
Range:	0 < `<parameter>` < 9
Defaults:	Defaults to 5 on power–up
Examples :	`CS100_GAIN 5`
Comments:	Issuing CS100_GAIN will only result in a change of state of the CS100 once external control has been enabled (command CS100_EXT).

23.4 CS100_INT

Enable or disable integration on CS100 servo–loop

Format:	`CS100_INT <parameter>`
Units:	none
Range:	`<parameter>` = ON or OFF

Defaults: Defaults to OFF on power–up
Examples : `CS100_INT ON`
Comments: Issuing CS100_INT will only result in a change of state of the CS100 once external control has been enabled (command CS100_EXT). The CS100 is normally used with integration off.

23.5 CS100_LOC

Sets the CS100 to local control
Format: `CS100_LOC`
Examples : `CS100_LOC`
Comments: This command is used to disable control of the etalon from the system computer. This mode is selected while the etalon is being aligned.

23.6 CS100_OPEN

Open CS100 servo–loop
Format: `CS100_OPEN`
Examples : `CS100_OPEN`
Comments: Issuing CS100_OPEN will only result in a change of state of the CS100 once external control has been enabled (command CS100_EXT).

23.7 CS100_RESET

Reset CS100 servo–loop
Format: `CS100_RESET`
Examples : `CS100_RESET`
Comments: Issuing CS100_RESET will only result in a change of state of the etalon if the CS100 has been switched to the etalon (command ETALON_VOLTAGE), external control has been enabled (command CS100_EXT) and the servo loop closed (command CS100_CLOSE).

23.8 CS100_STEP

Steps the etalon to a specified position in the 4MS lookup table
Format: `CS100_STEP <offset>`
Units: none
Range: 1 < `<position>` < No. of positions in table
Examples : `CS100_STEP 10`
Comments: This command is used to step the etalon by applying an appropriate Z offset. The Z-offset to be applied is derived from a lookup table held in the 4MS, which must have been previously calculated using the CS100_TABLE command. Issuing CS100_STEP will only result in a change of state of the etalon if the CS100 has been switched to the etalon (command ETALON_VOLTAGE), external control has been enabled (command CS100_EXT) and the servo loop closed (command CS100_CLOSE).

23.9 CS100_TABLE

Set up lookup table in the TAURUS 4MS for etalon scanning.
Format: `CS100_TABLE`
Examples : `CS100_TABLE`
Comments: This is an ICL procedure used to set up the lookup table in the TAURUS 4MS used for etalon scanning. You will be prompted for the start, stepsize, and number of steps in

the lookup table. You will also be asked whether you want a single-sided or double-sided lookup table; a single-sided lookup table is normally used.

23.10 CS100_TICO

Sets the time constant for the CS100 servo–loop

Format:	CS100_TICO <parameter>
Units:	none
Range:	1 < <parameter> < 9
Defaults:	Defaults to 8 on power–up
Examples :	CS100_TICO 8
Comments:	Issuing CS100_TICO will only result in a change of state of the CS100 once external control has been enabled (command CS100_EXT).

23.11 CS100_XOFF

Applies an offset to the X channel of the CS100 servo–loop

Format:	CS100_XOFF <offset>
Units:	none
Range:	–2048 < <offset> < 2047
Defaults:	Defaults to 0 on power–up
Examples :	CS100_XOFF 100
Comments:	Issuing CS100_XOFF will only result in a change of state of the CS100 once external control has been enabled (command CS100_EXT). The etalon will only change state if the CS100 has been switched to the etalon (command ETALON_VOLTAGE) and the servo loop closed (command CS100_CLOSE).

23.12 CS100_YOFF

Applies an offset to the Y channel of the CS100 servo–loop

Format:	CS100_YOFF <offset>
Units:	none
Range:	–2048 < <offset> < 2047
Defaults:	Defaults to 0 on power–up
Examples :	CS100_YOFF 100
Comments:	Issuing CS100_YOFF will only result in a change of state of the CS100 once external control has been enabled (command CS100_EXT). The etalon will only change state if the CS100 has been switched to the etalon (command ETALON_VOLTAGE) and the servo loop closed (command CS100_CLOSE).

23.13 CS100_ZOFF

Applies an offset to the Z channel of the CS100 servo–loop

Format:	CS100_ZOFF <offset>
Units:	none
Range:	–2048 < <offset> < 2047
Defaults:	Defaults to 0 on power–up
Examples :	CS100_ZOFF 100
Comments:	Issuing CS100_ZOFF will only result in a change of state of the CS100 once external control has been enabled (command CS100_EXT). The etalon will only change state if the CS100 has been switched to the etalon (command ETALON_VOLTAGE) and the servo loop closed (command CS100_CLOSE).

23.14 ETALON_VOLTAGE

Select the etalon to be servoed

Format:	`ETALON_VOLTAGE <parameter>`
Units:	none
Range:	`<parameter>` = 1, 2, 4 or 6
Examples :	`ETALON_VOLTAGE 1`
Comments:	This command selects which etalon is to be servoed by the CS100. The signals between the etalon and CS100 are routed via a switch–box mounted on the side of TAURUS. Make sure the switchbox is switched on before issuing this command.

23.15 ETALON

Moves the TAURUS etalon wheel to the specified position.

Format:	`ETALON <position>`
Range:	`<position>` is an integer in the range –6 to 6 or the name of the etalon.
Defaults:	None
Examples :	`ETALON 3` or `ETALON 125UM`
Comments:	There are 6 positions in the etalon wheel. Positions 1, 2, 4 and 5 can be used to hold Fabry-Perot etalons, whilst positions 3 and 6 are always left empty for imaging observations. The position of the wheel can be selected either by specifying a number between –6 and 6, or by specifying the etalon name. In normal operation the parameter should be positive. If the parameter is negative, the wheel will not be clamped on completion of the move, and the position of the wheel will become undefined.

23.16 IRIS

Use the iris to set the field diameter.

Format:	`IRIS <diameter>`
Units:	mm
Range:	0 < `<diameter>` < 150
Defaults:	None
Examples :	`IRIS 100`
Comments:	The iris is used as a field stop. The iris diameter should be set to match the field of view of the detector, in order to reduce scattered light and the danger of ghost images. At a plate scale of 4.51 arcsec/mm, a field of view of 1 arcmin implies an iris diameter of 13.3 mm.

23.17 IVALVE

Sets the state of the N_2 inlet valve used for flushing the TAURUS etalon cavity

Format:	`IVALVE <state>`
Examples :	`IVALVE OPEN`
Defaults:	Defaults to CLOSED on power–up
Comments:	

23.18 OVALVE

Sets the state of the N_2 outlet valve used for flushing the TAURUS etalon cavity

Format:	`OVALVE <state>`
Examples :	`OVALVE OPEN`
Defaults:	Defaults to CLOSED on power–up
Comments:	

23.19 TANAME

Sets the names of the aperture masks in the focal plane aperture wheel

Format: `TANAME`

Examples : `TANAME`

Comments: TANAME is an ICL procedure which prompts the user for the position and name of each aperture in the focal plane aperture wheel. This results in the correct name for each aperture mask being displayed on the mimic. The procedure automatically loads the names of the standard set of aperture masks.

23.20 TAPERTURE

Moves the TAURUS aperture wheel to the specified position.

Format: `TAPERTURE <position>`

Range: `<position>` is an integer in the range –8 to 8, or the name of the aperture mask.

Defaults: None

Examples : `TAPERTURE 3`

Comments: There are 8 aperture wheel positions. These can be selected either by specifying a number between –8 and 8, or by specifying the aperture name. In normal operation the parameter should be positive. If the parameter is negative, the wheel will not be clamped on completion of the move, and the position of the wheel will become undefined.

23.21 TAURUS_INIT

Initialises the specified mechanism

Format: `TAURUS_INIT <mechanism>`

Parameters: Possiblle values of `<mechanism>` are ALL, TAPERTURE, ETALON, TFFILTER, TFTILT, IRIS, TPFILTER, TFOCUS

Defaults: None

Examples : `TAURUS_INIT TFFILTER` or `TAURUS_INIT ALL`

Comments: This command issues a request to the TAURUS local controller to initialise the specified mechanism. If 'ALL' is specified then all mechanisms will be initialised. Note that initialisation of IRIS and TFOCUS can be slow (up to 100 seconds). When the focal plane filter wheel is initialised you will be asked whether the tilt mechanism is already parked, and will have to check the tilt status on the mimic display.

23.22 TAURUS_UPDATE

Finds the status of the specified mechanism

Format: `TAURUS_UPDATE <mechanism>`

Parameters: Possible values of `<mechanism>` are ALL, TAPERTURE, CS100, ETALON, TFFILTER, TFTILT, IRIS, IVALVE, OVALVE, TPFILTER, PRESSURE, TFOCUS, TEMPERATURE

Defaults: None

Examples : `TAURUS_UPDATE CS100` or `TAURUS_UPDATE ALL`

Comments: This command issues a status request to the TAURUS local controller for the specified mechanism. If 'ALL' is specified then status is requested for all mechanisms. If 'CS100' is specified then status is requested for all CS100 parameters.

23.23 TENAME

Sets the names of etalons in the etalon wheel

Format: `TENAME`

Examples : `TENAME`
Comments: TENAME is an ICL procedure which prompts the user for the position and name of each etalon in the etalon wheel. This results in the correct name for each etalon being displayed on the mimic.

23.24 TFFILTER

Moves the TAURUS focal plane filter wheel to the specified position.
Format: `TFFILTER <position>`
Range: `<position>` is an integer in the range –8 to 8 or the name of the filter.
Defaults: None
Examples : `TFFILTER 3` or `TFFILTER HARRIS-V`
Comments: There are 8 filter wheel positions. These can be selected either by specifying a number between –8 and 8, or by specifying the filter name. In normal operation the parameter should be positive. If the parameter is negative, the wheel will not be clamped on completion of the move, and the position of the wheel will become undefined.
This command automatically disengages the tilt mechanism before the wheel is moved, and sets the tilt to zero on completion.

23.25 TFNAME

Sets the names of filters in the focal plane filter wheel
Format: `TFNAME`
Examples : `TFNAME`
Comments: TFNAME is an ICL procedure which prompts the user for the position and name of each filter in the focal plane filter wheel. This results in the correct name for each filter being displayed on the mimic.

23.26 TFOCUS

Set the camera focus
Format: `TFOCUS <position>`
Units: micron
Range: 0 < `<position>` < 6000
Defaults: None
Examples : `TFOCUS 4400`
Comments: Note that although the focus can be set very accurately, the image quality is not particularly sensitive to small changes (< ????) in the camera focus.

23.27 TFTILT

Tilts the filter in the TAURUS focal plane filter wheel.
Format: `TFTILT <angle>`
Units: Tenths of degrees (?)
Range: `<angle>` is a number in the range 1–10, or –1 to select the parked position.
Defaults: none
Examples : `TFTILT 0`
Comments: An interference filter in the focal plane can be tilted in order to shift its central wavelength to the blue (see section VIII).
The mechanism responsible for tilting the filter can be disengaged from the filter holder by parking it. This is necessary whilst the filter wheel is moving, and the TFFILTER command is responsible for parking the tilt mechanism before a wheel move and re-engaging it after the move. Note

that the tilt mechanism must NOT be set to the parked position during an observation, since position of the filter holder is then not defined; if you do not want to tilt the filter, the tilt angle should be set to 0.

23.28 TPFILTER

Moves the TAURUS pupil plane filter wheel to the specified position.

Format: `TPFILTER <position>`

Range: `<position>` is an integer in the range –8 to 8 or the name of the filter.

Defaults: None

Examples : `TPFILTER 3` or `TPFILTER HARRIS-V`

Comments: There are 8 filter wheel positions. These can be selected either by specifying a number between –8 and 8, or by specifying the filter name. In normal operation the parameter should be positive. If the parameter is negative, the wheel will not be clamped on completion of the move, and the position of the wheel will become undefined. Note that position 1 is a large hole, used for accessing the etalon wheel, and cannot be used for mounting filters.

23.29 TPNAME

Sets the names of filters in the pupil plane filter wheel

Format: `TPNAME`

Examples : `TPNAME`

Comments: TPNAME is an ICL procedure which prompts the user for the position and name of each filter in the pupil plane filter wheel. This results in the correct name for each filter being displayed on the mimic.

23.30 TSLAVE

Enable or disable slaving of TAURUS to the CCD-=IPCS.

Format: `TSLAVE <state>`

Examples : `TSLAVE ON`

Comments: TAURUS must be slaved to the CCD–IPCS for rapid scanning of the etalon to take place. This command is not relevant to observations with a CCD detector. Slaving can only be enabled if the CS100 has been switched to the etalon (command ETALON_VOLTAGE), external control has been enabled (command CS100_EXT) and the servo loop closed (command CS100_CLOSE). Do not disable slaving whilst an IPCS exposure is in progress; if you wish to finish an exposure prematurely first abort or finish the exposure, wait for the etalon to stop scanning, and then type TSLAVE OFF.

24 Command summary: imaging observations

This section summarises the TAURUS commands useful for imaging observations. An abbreviated form is available for many commands, and this is summarised here.

Command	Abbreviation	Meaning
ETALON x	ETA x	Move etalon wheel
IRIS x	IRIS x	Select iris diameter (x in mm)
TANAME	TAN	Set names of aperture masks
TAPERTURE x	TAP x	Move aperture wheel
TENAME	TEN	Set names of etalons
TFFILTER x	TFF x	Move focal-plane filter wheel
TFNAME	TFN	Set names of focal-plane filters
TFOCUS x	TFOC x	Set camera focus (x in μm)
TFTILT x	TFT x	Tilt focal-plane filter (x in degrees)
TPFILTER x	TPF x	Move pupil-plane filter wheel
TPNAME	TPN	Set names of pupil-plane filters
TAURUS_INIT name	TI name	Initialise mechanism
TAURUS_UPDATE name	TU name	Get status of mechanism

25 Command summary: FP observations

Part VIII
Filters available for use with TAURUS

A Broadband filters

A set of BVRI broadband filters is available specifically for use with TAURUS. The filters have a diameter of 125mm, so mount in the focal plane filter wheel without restricting the field of view. The design of the filters is identical to that of the KPNO Harris filters. Transmission curves are given in La Palma Technical Note 73.

Adapters are available to allow the 50mm square filters originally purchased for use on the INT and JKT to be used in the TAURUS focal plane filter wheel. However, these filters restrict the field of view to 3.8 arcmin square.

B Interference filters

The interference filters available for use with TAURUS–2 are listed in Table 12

When these filters are mounted in the focal plane filter wheel, it is possible to shift their central wavelength to the blue (*not* to the red) by tilting the filter (Lissberger & Wilcock *Journal of the Optical Society of America, vol 49, p126, 1959*). At a tilt angle θ degrees, the effective wavelength L_{eff} depends on the nominal wavelength L_{nom} as:

$$L_{eff} = L_{nom} \times (1 - \frac{\theta^2}{28984}) \tag{2}$$

This equation assumes a refractive index for the filter of 2.1. The maximum tilt possible is 10 degrees. This gives a fractional shift in the effective wavelength of about one third of one per cent, corresponding for example to a shift of 17 Åat a wavelength of 5000 Å. Note however that tilting the filter also results in a broadening of the bandpass and a reduction in the peak transmission.

Table 12: TAURUS-2 interference filters

Central wavelength (Å)	Bandpass (Å)	Diameter (mm)	Thickness of filter (mm)	Thickness of cell (mm)	Comments
3737	50	50	8.5		
3770	15	50	9.0		
4550	100	76.2	4.0		
4550	300	63.5	6.1	7.0	
4770	320	63.5	5.9	7.0	
4868	15	63.5	6.1		
4880	100	76.2	10.5		
4883	15	63.5	7.0		
4898	15	63.5	7.0		
4912	15	63.5	6.1		
4962	15	76.2	6.1	6.7	
4974	15	76.2	6.0	7.0	
5010	100	76.2	10.0		
5009	15	76.2	13.0		
5012	20	50.7	9.1	10.0	
5000	350	63.5	7.0		
5021	15	76.2	13.0		
5032	20	50.8	9.2	10.1	
5033	15	76.2	13.0		
5046	15	76.2	12.2		(Missing)
5052	20	50.8	9.2	10.1	
5065	15	76.2	7.0		
5072	20	50.7	10.0		
5092	20	50	10.6		(Missing)
5145	15	76.2	6.1	7.0	
5175	15	76.2	5.9	7.0	
5220	380	63.5	6.0	7.0	
5340	15	76.2	5.1	7.0	
5450	410	63.5	6.1	7.0	(Broken)
5700	450	63.5	6.0		
5905	10	76.2	7.0		
5960	490	63.5	6.1	7.0	
6240	540	63.5	5.9	7.0	
6303	15	63.5	10.0		
6345	18	50.7	6.0		
6565	15	76.2	13.0		
6568	17	50.7	6.0		
6577	15	76.2	13.0		
6589	15	76.2	14.0		
6589	16	50.8	5.1	6.0	
6590	130	76.2	10.3		
6601	15	76.2	13.0		
6610	16	50.7	6.0		
6613	15	76.2	13.0		
6631	17	50.8	7.0		
6652	17	50.8	7.0		
6673	17	50.8	7.0		
6689	15	63.5	6.1	7.0	
6730	50	50.8	6.1	7.0	
6770	50	50.8	6.1	7.0	