

Chapter 1

The Nordic Optical Telescope

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Abstract An overview of the Nordic Optical Telescope (NOT) is presented. Emphasis is on current capabilities of direct interest to the scientific user community, including instruments. Educational services and prospects and strategies for the future are discussed briefly as well.

1.1 Introduction

The Nordic Optical Telescope (NOT) is a modern 2.6m alt-azimuth telescope, operating at Roque de los Muchachos Observatory, La Palma, since 1989 as the main northern-hemisphere optical facility for Nordic astronomers. Its f/11 Ritchey-Chretien optical system, the telescope, and the enclosure were carefully designed to deliver the best image quality at the site (Ardeberg, 1990).

Structure. The Nordic Optical Telescope Scientific Association (NOTSA) was formed in 1984 to construct and operate the NOT on behalf of the Research Councils of Denmark, Finland, Norway, and Sweden; the University of Iceland joined in 1997. The budget is shared roughly in the ratios 20:30:20:30:1%.

A Director has overall legal, financial, and scientific responsibility for operations and strategic planning, under the authority of the NOTSA Council, which represents the owners. On-site operations are ensured by a team of 13 staff members headed by an Astronomer-in-Charge; 5 research students complement the team.

User Community. 75% of the science time on the telescope are at the disposal of the Nordic community through competitive proposals peer-reviewed by the NOT Observing Programmes Committee. 20% of the time are allocated to Spanish astronomers through the Comisión de Asignación de Tiempo (CAT), while 5% go to international teams through the CCI International Time Programme (ITP).

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Fig. 1.1 The NOT at sunset with the dome lights on while turning (Photo: Jacob Clasen, NOT).

Not only Nordic astronomers, but *anybody* regardless of nationality or affiliation can apply for the Nordic time, and proposals are ranked solely on the basis of scientific merit. Thus, over the past 5 years, over 20% of the Nordic time has been allocated by the OPC to non-Nordic PIs. About half of these projects have been part of the OPTICON Trans-National Access Programme, which supports access for European researchers to all modern European 2-4m class telescopes. Thus, despite its name, the NOT already serves a broad European user community.

1.2 NOT User Services

A systematic upgrade programme has been conducted over the last five years to improve the scheduling, operation, instrumentation, and reliability of the NOT.

Scheduling. The NOT offers both visitor and service mode observations. The emphasis is increasingly on the latter because of the flexibility offered, and the fraction of service observing nights has increased steadily to $\sim 40\%$ in 2005 – 2007.

Part of the service time is allocated through a “Fast-track” procedure with a short lead time from proposal to execution, offered since 2005. Proposals for short observing programmes (max. 4 hours) can be submitted at any time (see <http://www.not.iac.es/observing/service/>) and are reviewed promptly by the OPC. The successful programs are then executed by the staff in queue scheduled service mode. Available instruments are ALFOSC, NOTCam, FIES and StanCam.

The pressure factor from proposals for the Nordic time has increased gradually in recent years, to about 2.5 over the last decade. Technical downtime is typically $\sim 1\%$, weather down time $\sim 10\%$ in summer (April-September) and $\sim 35\%$ in winter (October-March). However, actual usable hours vary by only $\sim 10\%$ over the year.

Operations. Major effort has been put into making the telescope control system fast, flexible, safe and easy to use. Telescope operators are not needed, but there is always a support astronomer to provide a thorough introduction on the first night of a visitor run, and technical support is at hand throughout.

For safety, the telescope is linked to our weather station, and the dome closes automatically if limits of humidity or wind are exceeded. Autoguiding starts fully automatically in most observing modes, and focusing is fast and reliable.

The entire observing system (detector + instrument + telescope) can be fully controlled by the new integrated data acquisition system, the *Sequencer*, implemented for the core instruments in 2006-2008. This permits in principle to automate the entire observation, although these features are currently under development.

Only one instrument at a time can be mounted at the main focus, but 45-degree folding mirrors in the adaptor allow the standby CCD camera (StanCam) and the high-resolution fiber spectrograph (FIES) to be available at all times, greatly increasing flexibility on time-critical programmes.

A rare feature of the NOT is its ability to go as low as 6.4° from the horizon, which is a unique capability in studies of objects in the inner Solar System, such as the planet Mercury to (see e.g. Warell & Karlsson, 2007).

Documentation and Data flow. A comprehensive set of documentation on the telescope, instruments, detectors, and operations is available at <http://www.not.iac.es>. This includes on-line tools for preparing proposals and/or observations, such as an Exposure Time Calculator and Script Generators for the core instruments. Quality control data on detectors etc. are also available.

All data from the core instruments (ALFOSC, FIES, MOSCA, NOTCam and StanCam) are stored in standard Multi-Extension Fits (MEF) format with primary WCS information in the headers. The data are delivered on DVD, or available by ftp for “Fast-Track” or time-critical Target-of-Opportunity observations. Technical details of the core instruments are summarised in the following sections. The optical zero-point magnitudes are summarized in Table 1.1.

Table 1.1 UBVRI zero-point magnitudes (for $1e^-/s$).

	<i>U</i>	<i>B</i>	<i>V</i>	<i>R</i>	<i>I</i>
ALFOSC	24.0	25.7	25.6	25.4	24.6
MOSCA	24.6	26.2	26.0	25.7	25.2
StanCam	23.8	25.7	25.4	25.3	24.5

1.3 ALFOSC

The Andalucia Faint Object Spectrograph and Camera (ALFOSC), owned by the Instituto de Astrofísica de Andalucía (IAA), has been used at the NOT by mutual agreement since 1996. ALFOSC was upgraded with a new CCD detector (e2v CCD42-40, $13.5\mu\text{m} \times 2048 \times 2048$) and new camera optics in 2003. The plate scale is $0.19''/\text{pix}$. The new CCD provides excellent resolution at all wavelengths, but

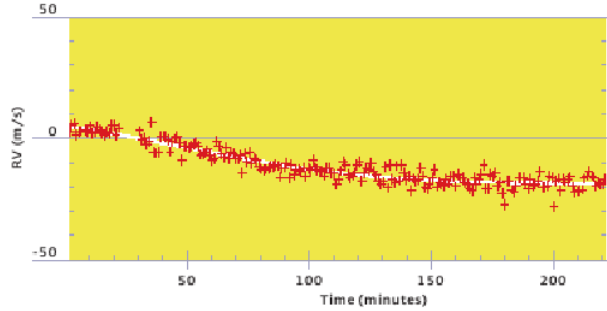


Fig. 1.2 A series of daytime sky spectra (reflected sunlight). The mean trend is likely due to winds in the upper atmosphere; the dispersion around the mean is < 3 m/s.

higher fringe levels than the previous CCD. Fast photometry with windowed read-out and on-line reduction with comparison star subtraction is offered.

With 16 grisms, ALFOSC offers spectroscopy in the resolution range $200 < R < 10000$. A VPH grism with spectral resolution $R=10000$ in the $6350\text{--}6850 \text{ \AA}$ range offers a total system efficiency of 30%. A set of vertical slits allow fast horizontal readout in a small window for time-resolved spectroscopy, and quick-look reduction tools are available for both long-slit and echelle spectra. Multi Object Spectroscopy (MOS) with pre-fabricated slit plates is available.

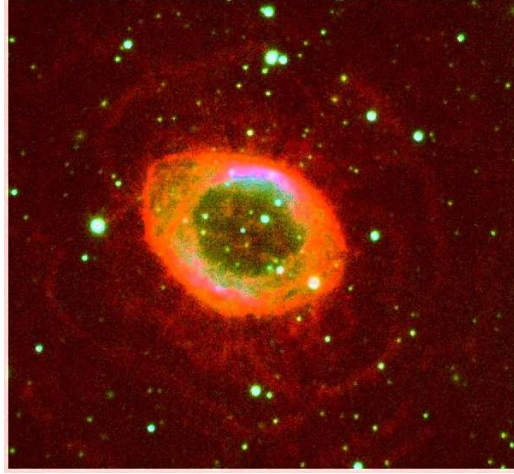
Dual-beam linear and circular imaging- and spectro-polarimetry is also offered with ALFOSC. A quick-look reduction tool for linear imaging polarimetry was added in 2007 (see <http://www.not.iac.es/instruments/alfosc/>).

1.4 FIES

The Fiber Echelle Spectrograph (FIES) is permanently ready for use. For mechanical and thermal stability it is located in a separate building with thermal control. The detector is an e2v CCD42-40 ($13.5\mu\text{m} \times 2048 \times 2048$), which covers the wavelength range $370\text{--}730 \text{ nm}$ without gaps. The fiber diameters are 2.5" in low-resolution mode ($R = 25000$), 1.3" for medium ($R = 45000$) and high resolution mode ($R = 65000$; slit added). The FIEStool package provides on-line quick-look spectra and is also suitable for final reductions.

A main goal for FIES is high-precision radial-velocity work. The zero-point stability is currently $< 150 \text{ m/s}$ for a stellar spectrum followed by a separate Th-Ar lamp exposure, $< 15 \text{ m/s}$ for a stellar spectrum with *simultaneous* Th-Ar calibration. As an example, the $3 M_{\text{Jup}}$ transiting planet WASP-10b was confirmed i.a with radial velocities from FIES (Christian et al. 2008). Tests with series of daytime blue-sky spectra using simultaneous Th-Ar are also giving promising results (see Fig. 1.2; Frandsen et al. 2007). An iodine absorption cell is being added.

Fig. 1.3 NOTCam image of M57 in J (blue), H (green), and a narrow-band filter centred on the H_2 line at $2.121\mu\text{m}$ (red). FOV is $3.5' \times 3.2'$, north up, east left. Beam-switch observations with a total on-source integration time of 360 seconds per filter. Reduced with the NOTCam quick-look reduction package.



FIES is rapidly attracting interest and became the most-demanded instrument at the NOT among the applications for the semester 2008B. For more details, see <http://www.not.iac.es/instruments/fies/>.

1.5 NOTCam

The Nordic Optical Telescope near-infrared Camera and spectrograph (NOTCam) is a versatile instrument for the $0.8 - 2.5 \mu\text{m}$ wavelength range, using a recent Rockwell Hawaii-I HgCdTe detector ($18\mu\text{m} \times 1024 \times 1024$).

The image scale can be toggled in a matter of seconds between the wide-field (WF) camera ($0.234''/\text{pix}$, $\text{FOV} = 4'$) and the high-resolution (HR) camera ($0.078''/\text{pix}$, $\text{FOV} = 80''$). The WF camera suffers from some optical distortion in the corners, but the HR camera has a high optical quality all over the FOV. With proper telescope tracking, the HR camera regularly delivers perfectly round, deep stellar images with FWHM of $0.3-0.4''$.

Standard broad band filters JHK plus Y_n and 17 narrow-band filters are permanently installed. A cold shutter permits short integrations, and small cold stops are available for flux reduction of very bright targets. The zero-point magnitudes (for $1 \text{ e}^-/\text{s}$) are: 24.1, 24.1, and 23.5 mag, in J , H and K_s , respectively (Vega magnitudes). An example image is shown in Fig. 1.3.

Spectroscopy with the WF camera and a $0.6''$ slit gives a resolution of $R = 2500$ and covers the Y_n , J , H and K bands. The HR camera yields $R = 5500$ with a $0.2''$ slit and covers wavelength ranges from $1.26-1.34 \mu\text{m}$ ($\text{Pa } \beta$), $1.57-1.67 \mu\text{m}$, to $2.07-2.20 \mu\text{m}$ ($\text{Br } \gamma$). Wollaston prisms for polarimetry, low resolution grisms (Telting, 2004), and broad-band ZY-filters are being considered for the future. For more detail see <http://www.not.iac.es/instruments/notcam/>.

1.6 MOSCA

The MOSaic CAmera (MOSCA) is a direct imager featuring 4 Loral CCDs of $15\mu\text{m} \times 2048 \times 2048$ corresponding to $0.11''/\text{pix}$ and a FOV of $7.7'$. The gaps between the four CCDs are $9-12''$. The advantages of MOSCA are the uniformly good PSF over the entire FOV and the high throughput (see Tab. 1.1), especially in the U band. For more detail see <http://www.not.iac.es/instruments/mosca/>.

1.7 StanCam

The Stand-by Camera (StanCam) has a TEK 24 thinned CCD ($\mu\text{m} \times 1024 \times 1024$; $0.176''/\text{pix}$, FOV = $3'$). It is permanently available at a folded Cassegrain focus. Together with NOTCam it offers near-simultaneous UBVR_IJHK coverage. For more detail see <http://www.not.iac.es/instruments/stancam/>.

1.8 Visitor instruments

The Turku photo-polarimeter Turpol provides linear and circular simultaneous UBVR_I polarimetry of single sources (diaphragms) with high precision through a double image chopping technique. Polarization levels below 0.01% can be detected at the NOT, and systematic errors for brighter stars are $\sim 0.005\%$ (Piirola, 1999). On-line reduction is available. See <http://www.not.iac.es/instruments/turpol/>.

SOFIN, a high resolution echelle spectrograph, is supported by the University of Helsinki and Astrophysikalisches Institut Potsdam. It covers the spectral range 3500 - 9000 Å with resolutions $R = 27,000 - 170,000$, and is also capable of spectropolarimetry (Ilyin, 2000). Observations are performed in service mode and reduction software is available. See <http://www.not.iac.es/instruments/sofin/>.

The PolCor “Lucky” polarimeter/coronagraph, equipped with an EMCCD ($16\mu\text{m} \times 512 \times 512$, $0.12''/\text{pix}$, FOV = $1'$) with up to 33 Hz readout rate, has a rapidly turning polarizer and three coronagraphic disks. A computer controlled Lyot stop masks the M2 support vanes. The fwhm improves from initially $0.7''$ to $0.4''$ applying only shift and add techniques, but improves further to $0.2-0.3''$ using frame selection and deconvolution (Olofsson & Florén, 2008).

Among other visitor instruments, *LuckyCam* was used at the NOT in 2002-2004 to obtain near diffraction-limited imaging in the I band using reference stars as faint as 16.5 mag. Keeping the 1% best frames improved the image quality from $0.7''$ to $0.1''$ (Mackay et al. 2003). Recently, also FastCam (Oscos & Rebolo et al. 2007) also obtained diffraction-limited I band imaging using 1-5% of the frames.

1.9 The educational role of the NOT

In a world of 8-m telescopes it makes sense to spend a modest amount of time on a 2m-class facility to train the next generation of astronomers - at least those who will be involved in designing and building the next generation of telescopes and their instrumentation. At the NOT, we are taking a systematic approach to this challenge and are developing a varied set of offers of educational services to universities, covering the whole educational “food chain”.

The traditional use of the NOT in education has been for on-site courses, where groups of typically 12 PhD or MSc students spend 1-2 weeks on La Palma learning how to observe with the NOT, reduce and analyse their data, and formulate their next observing time applications effectively. Such courses are highly educational, motivating, and popular with the students, giving them real hands-on observing experience. The NOT supports these courses by providing a small “class room” at ORM, with the control room screens projected on the wall and with 12 standard laptops available for data reduction and analysis.

These courses have become very popular, but cannot handle large volumes of students. We are therefore also developing remote observing as a means to involve hands-on observing in university courses without actually taking the students to La Palma. The observing courses at Molėtai Observatory in Lithuania have pioneered this technique, most recently in 2008.

Finally, the NOT currently hosts 5 PhD or MSc students, who typically spend a year at on La Palma, devoting 75% of their time to their thesis projects and 25% on support duties, service observing, or various developments. Experience shows that this experience is a significant asset for their future careers, whether in or outside astronomy.

1.10 Future perspectives

The world of today and tomorrow is scientifically, technically, financially, and politically very different from that of 1984 when NOTSA was founded. The great majority of our users have access to state-of-the-art 8m telescopes; European cooperation and coordination have developed enormously; and the stand-alone paradigm for NOT has become obsolete. An International Evaluation of the NOT in 2006 supported this view (see report at <http://www.not.iac.es/news/reports/>).

Given NOTSAs active participation in both the OPTICON and ASTRONET European networks (see <http://www-astro.opticon.org> and <http://www.astronet-eu.org>), it was natural to view the role of the NOT as part of a future pan-European facility of modern 2-4m telescopes. Through a series of discussions in the user community, this vision was turned into a specific long-term strategy (Andersen, 2006) and “Development Plan” (Augusteijn, 2007).

The overarching long-term goal is to optimise the performance of the NOT by specialising its performance in specific areas, in concert with similar moves at other

telescopes. This only works if an overall plan exists, and the ASTRONET Board is therefore appointing a European Telescope Strategy Review Committee with the charge to consider innovative ways to plan, equip, and operate a set of European 2-4m telescopes so as to achieve optimum scientific returns and cost-effectiveness, including better coordination with other disciplines such as space astronomy. The NOT is committed to becoming part of such a new, common European 2-4m facility.

Meanwhile, we continue to specialise and optimise the NOT for high-impact Nordic science. This includes a thorough review of the instrumentation, operating modes, and scheduling of projects, with emphasis on remaining competitive in studies of transient and variable sources. As part of this strategy, we are seeking to move to a single set of permanently mounted instruments, which would enable us to respond quickly and flexibly to new events and optimise scientific productivity in areas where the NOT can still be competitive if deployed intelligently. Detector and data acquisition systems are being upgraded in parallel.

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References

1. Andersen, J.: NOT Beyond 2009: Towards the Common Northern observatory. (2006). http://www.not.iac.es/news/reports/NOT_StrategyReport_Fin.pdf
2. Ardeberg, A.: Some properties of the Nordic Optical Telescope. (1990). <http://www.astro.lu.se/Resourcer/NOT/proptxt.html>
3. Augusteijn, T.: Development Plan 2008-2010. Astronomer in Charge's Report (2007). http://www.not.iac.es/news/reports/Dev2008_2010.pdf
4. Christian, D.J., Gibson, N.P., Simpson, E.K. et al.: WASP-10b: a $3M_J$, eccentric transiting gas-giant planet. Submitted to MNRAS. arXiv:0806.1482 (2008)
5. Frandsen, S., Telting, J., Buchhave, L.: FIES. NOT Annual Report 2007. http://www.not.iac.es/news/reports/annual/NOT_AnnRep07.pdf
6. Ilyin, I.: High resolution SOFIN CCD échelle spectroscopy. PhD thesis. Oulu 2000 University Press. ISBN 951-42-5724-3.
7. Mackay, C.D., Baldwin, J.E., Tubbs, R., Cox, G.: High-resolution "Lucky" imaging. NOT Annual Report 2003. http://www.not.iac.es/news/reports/annual/NOT_AnnRep03.pdf
8. Olofsson, G. & Florén, H.G.: The PolCor "Lucky" Polarimeter/coronagraph. (2008) <http://www.not.iac.es/instruments/polcor/PolCor-2.pdf>
9. Oscoz, A., Rebolo, R. & the FastCam Team: FastCam: Diffraction-limited optical imaging. NOT Annual Report 2007. http://www.not.iac.es/news/reports/annual/NOT_AnnRep07.pdf
10. Pirola, V.: Polarimetry at the NOT. In: Astrophysics with the NOT, eds. H. Karttunen, V. Pirola, University of Turku, p. 63
11. Telting, J.: Spectroscopy at the NOT. Current instrument status and possible efficiency/functionality upgrades. (2004) <http://www.not.iac.es/instruments/development/JHTspecUpgrades.pdf>
12. Warell, J. & Karlsson, O.: A search for natural satellites of Mercury. Planetary and Space Science **55**, 2037–2041 (2007)