OSIRIS: Final Characterization and Scientific Capabilities

Jordi Cepa

Abstract OSIRIS, the optical Day One instrument for the GTC, will shortly be shipped to La Palma to start the commissioning at the telescope. Some results of the final laboratory characterization of the instrument are shown, together with the upgrades that are planned to be operational after Day One. Several large programs using the OSIRIS Tunable Filters are presented as well, to demonstrate the scientific capabilities of this characteristic OSIRIS observing mode.

1 Introduction

1.1 Brief History

OSIRIS (Optical System for Imaging and low Resolution Integrated Spectroscopy), was supported by the GTC Scientific Advisory Committee as the optical Day One instrument, in March 1999, after an international Announcement of Opportunity (AoO). The final concept of the instrument was fixed in July 2000, while the manpower required was available in Autumn 2000, and the total budget needed was secured in November 2001. After a Preliminary Design Review (PDR) held in April 2001 by a pannel of international experts, who issued a report where only minor technical amendments were suggested, OSIRIS entered the final design and fabrication phases.

The instrument was installed at the Nasmyth rotator of the Assembly, Integration, and Verification (AIV) laboratory of the Instituto de Astrofísica de Canarias (IAC) in May 2007 (Fig. 1), to start laboratory tests. After Factory acceptance in October 2008, OSIRIS will be shipped to La Palma in November 2008 for the on–site

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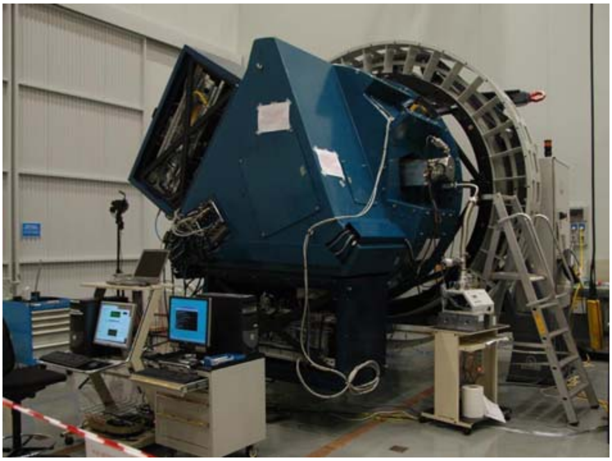

Fig. 1 OSIRIS instrument mounted at the Nasmyth rotator of the AIV room at the IAC for laboratory tests

Commissioning at the GTC, in preparation for the scheduled Day One operation in March 2009.

1.2 Institutions and Budget

OSIRIS has been designed and builded by the IAC and by the Instituto de Astronomía of the Universidad Nacional Autónoma de México (IA–UNAM). The IA–UNAM was responsible for the optical design and the fabrication of some camera lenses.

The project was funded by the Spanish Ministry of Science and Technology, by GRANTECAN S.A., and by the IAC.

1.3 The Challenge

OSIRIS is the first instrument designed and builded in Spain for a telescope larger than 4 m. This represented in itself a challenge both from a technological and a managerial points of view, specially when the following main general requirements were imposed by the OSIRIS Instrument Definition Team:

- Field of view of at least 8 arcmin in diameter (goal $8' \times 8'$).
- Excellent image quality ($\sim$ 1 pixel) to fully exploit the excellent site and GTC optics.
- Red optimized but blue sensitive (down to 365 nm) optics.

- Small pupil (80 mm ⊘) to accommodate sensible sized Tunable Filters (TF).
- For installation either at the Nasmyth or Cassegrain foci to ease GTC operation.
- Overheads due to instrument configuration changes limited by detector readout time.
- Able to accommodate the number of masks, grisms and filters required to operate in service mode without the need of changing these dispersive elements during the night.
- Maximum spectral resolution $\lambda/\Delta\lambda$ of 5,000 (goal 8,000).

Since its initial concept, maximum priority was given to the use of Tunable Filters for narrow band imaging from 365 to 1,000 nm. This is the main driver of the instrument, and its main distinctive characteristic, amongst similar optical camera–spectrographs for large telescopes.

2 OSIRIS Characteristics

The main general characteristics of OSIRIS, their observing modes, and the dispersive elements that can be accommodated in the instrument are summarized in Tables 1, 2, and 3, respectively.

3 User Information and Pipelines

More information about the instrument, including exposure time calculators for broad band, tunable imaging and spectroscopy, and mask designer tools, can be found at www.iac.es/project/OSIRIS. More details on the mask designer software can be found in [3]. To train future GTC observers in the use of the tunable filters and specific MOS features, several workshops have been organized in La Palma, Granada and Mérida (México).

Table 1 Summary of the main characteristics of OSIRIS

Parameter	Value
FOV	$8.5' \times 8.7'$
Plate scale	$0.125''$/pix
Detector	2 MAT 4 k×2 k ($8''$ gap)
Broad band	ugriz & TF order sorters
Narrow band	2 Tunable Filters covering from 365 to 1,000 nm, with FWHM tunable from 1.2 to $\sim$ 4 nm depending on λ
Spectral resolutions	$\lambda/\Delta\lambda = 300, 500, 1,000, 2,000, 2,500$, and $5,000$ ($0.6''$ slit width)
MOS (masks)	$\sim$ 40 targets using classical slits or several hundreds of targets using multiplexing modes

Table 2 OSIRIS observing modes. Tunable imaging allows synchronizing the wavelength tuned with charge shuffling on detector for better continuum subtraction, while MOS mode allows Nod & Shuffle for excellent sky subtraction. Fast modes are achieved by combining charge shuffling or frame–transfer with windows on detector

Mode	Submodes
Imaging	Broad band
	Narrow band using TF (8′ ⊘)
Spectroscopy	Long slit (8.7′)
	Multiple Object (MOS)
Fast modes	Photometry
	Spectroscopy

Table 3 OSIRIS elements that the instrument can accommodate

Type	Number
Optical elements	2 TF
	24 filters
	6 grisms
Masks	13 masks

There will be two pipelines available for observers. One fully automated that work only on site using GTC specific image formats and recipes, and another interactive, standalone, based on Pyraf and running on Linux-based computers. The users will be provided with FITS format raw and reduced date using the on site pipeline.

4 Characterization Tests

The laboratory tests have demonstrated that the stringent general requirements described in Sect. 1.3 are fulfilled. For example, 80% of the polichromatic encircled energy is confined within ∼1 pixel, which is equivalent to a resolution of 0.15 arcsec. Also, the optical distortion is lower than 2%, as required.

The image movement, due to the combination of gravitational flexures and instrument rotation, is controlled by moving the collimator in two axis via an open loop. The residuals are ∼ 1 pix in the spatial direction and ∼ 0.15 pix in the spectral direction, within the specs of 1.0 and 0.5 pixels, respectively. However, work is still ongoing to reduce the image movement in the spatial direction to 0.5 pix.

4.1 Instrument Transmission

The instrument transmission versus wavelength is shown in Fig. 2, and includes the collimator and the camera, but does not include the telescope, filters or detector. It is excellent in the red, and very competitive in the blue, below 400 nm. In spite

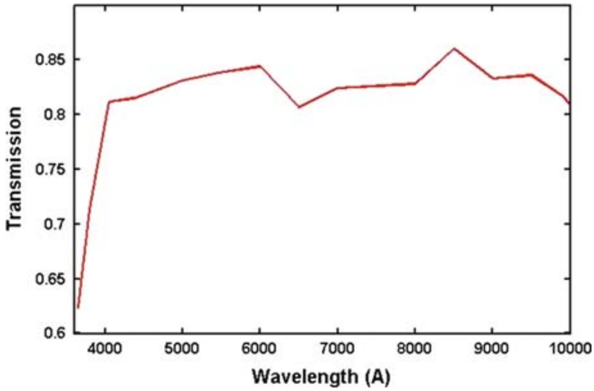

Fig. 2 OSIRIS transmission versus wavelength. Includes all OSIRIS optics but does not include telescope, detector or filters/grisms

Table 4 Mean times, in seconds, for changing instrument configuration of different instruments for 8–10 m–class telescopes. The information has been retrieved from on–line manuals available in the www of the different instruments. It is important to note that all elements (filters, grisms, TF and masks) can be changed simultaneously to save time

Telescope	Instrument	Mask	Grism	Filter
GTC	OSIRIS	20	6	3
VLT	VIMOS	210	90	180
GEMINI	GMOS	120	90	20
SUBARU	FOCAS	120	90	90

of being a blue sensitive instrument, the transmission in the red is comparable of higher than that of instruments such as DEIMOS (Table 6), specifically optimized in the red at the price of low blue performance. See [2] for details.

4.2 Overheads

The instrument overheads due to configuration changes are summarized in Table 4. The performance is far better than that of similar instruments in 8–10 m–class telescopes. Also, the 4 wheels holding TF, grisms and filters can be moved simultaneously and together with the mask loader. Hence the slowest element drives the final time for configuration changes: either the mask loader or the detector readout (that takes from 10 to 40 sec depending on the speed and the binning). Specially in service mode, when different observing programs requiring different configurations are scheduled during the night, it can save a substantial amount of observing time.

4.3 Optical Elements

The different broad band and order sorter filters have been characterized in the laboratory by measuring the transmission profile versus wavelength in different parts of the filter optical area, and at different tilt angles. The behavior is excellent and within specs (Figs. 3 and 4).

4.4 Tunable Filters

Tunable filters are etalons of very low resolution, with typical gap spacings of $\sim 2\,\mu$m, whose plate parallelism and distance between plates are controlled with an accuracy of $\sim$ 1 nm. They allow tuning any wavelength within their corresponding wavelength range (365–670 nm for the blue TF, 650–1,000 nm for the red TF) with a variety of FWHM available (Fig. 5). The tuning accuracy both in wavelength and FWHM is better than 0.1 nm. The tuning time range between 1 ms and 0.1 s depending on the gap change required. This fast tuning speed allows fast photometry with frequency switching between exposures.

The TF calibration involves checking plate parallelism, and establishing wavelength calibration, i.e. the equivalence between gap spacing in 16-bit counts and wavelength/order. Checking parallelism is a procedure that can be done in day time, although it is not expected to vary with time or even after switching off and on again the TF controller. Wavelength calibration is a procedure that takes about 90 s, and that can be done in day time using the A&G GTC unit or during the night. This procedure should be done every night, and checking it during the night might be required, depending on temperature changes.

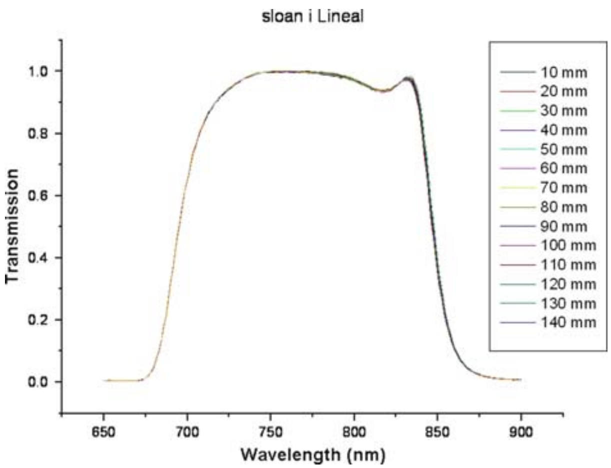

Fig. 3 Transmission of the i′ filter versus wavelength for different areas of the filter showing the excellent uniformity of the response

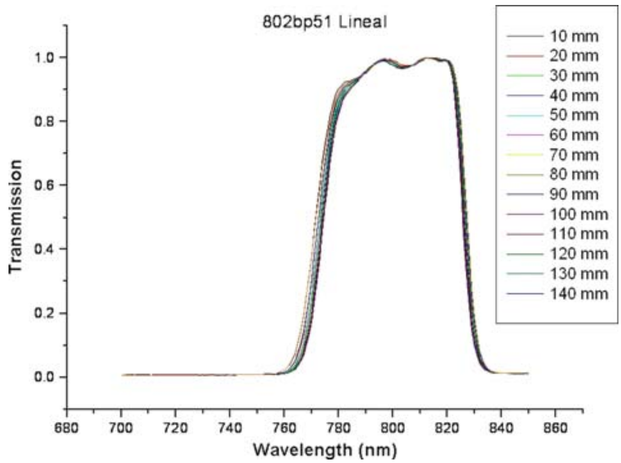

Fig. 4 Transmission of one of the order sorter filters versus wavelength for different areas of the filter showing the excellent uniformity of the response

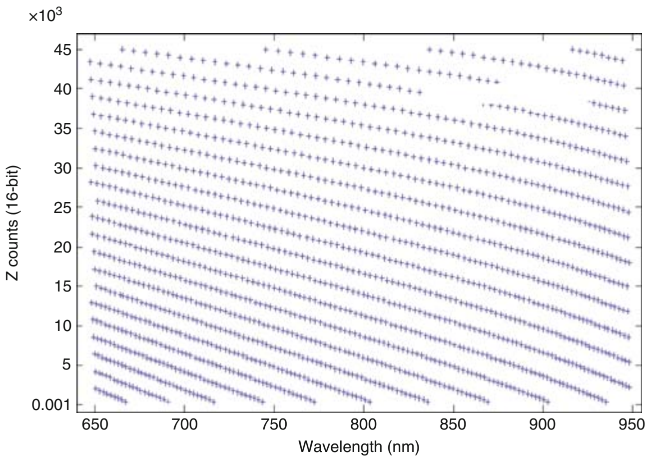

Fig. 5 Red TF calibration: Etalon gap in counts of 16-bit versus wavelength. Each set of points defining a straight line represent a different order. For each wavelength the different orders define the different FWHMs that can be tuned at this wavelength

5 OSIRIS Evolution and Context

5.1 Instrument Evolution

Sometimes the instrument capabilities, or even the basic instrument concept, face reality of budget, schedule or feasibility constraints, driving to a reduction of the instrument capabilities or its performance. This has not been the case of OSIRIS.

Table 5 Evolution of OSIRIS characteristics over time. They have not been reduced but increased

Feature	Letter of Intend	Announcement of Opportunity	Day One
Date	February 1998	December 1998	March 2009
Field of View	8′ ⊘	8′ ⊘	$8.5' \times 8.7'$
Maximum R	5,000	5,000 (goal 8,000)	5,000 (goal 10,000)
Observing modes	Broad band	Broad band	Broad band
	TF	TF	TF
	Long slit	Long slit	Long slit
	MOS	MOS	MOS
		Fast photometry	Fast photometry
			Fast spectroscopy
Image quality	–	$< 0.4''$	$< 0.2''$
Number of masks	–	> 6	13
Numer of filters	–	–	24
Number of grisms	–	–	6

On the contrary, OSIRIS capabilities and performance have been increased over time (Table 5), and the instrument to be delivered for Day One has more observing modes and capabilities than initially promised.

5.2 A Comparison

OSIRIS has been designed and optimized for imaging using Tunable Filters. However, its capabilities as spectrograph make it competitive with VIMOS at the VLT or DEIMOS at Keck (Table 6). OSIRIS has a MOS field and spectral resolution similar to DEIMOS, albeit with smaller spectral coverage. However, DEIMOS is not sensitive below 400 nm and its efficiency below 500 nm is smaller than that of OSIRIS. Also, although VIMOS field is quite large, its spectral resolution is limited to about 2,000, due to spectral stability limitations induced by instrument flexures. As a consequence, OSIRIS has advantage over DEIMOS for its blue sensitivity and over VIMOS for its higher resolution.

6 Future Upgrades

There are currently several OSIRIS upgrades under development or planned:

- *Integral Field Units*: This mode will be implemented by using 100 μm diameter OH doped fibers, thus with high UV and red transmissions, with microlenses of $0.6''$ diameter at both ends. Then, a square array of fibers in the sky is rearranged to form a linear array in the focal plane as input for the spectrograph. Two IFU are planned: a compact array of 12×12 arcsec^2, and a sparse array of 45×45 arcsec^2. These IFUs will be mounted in the mask loader and can use any of the grisms

Table 6 Comparison of optical imaging–spectrographs for 8–10 m–class telescopes. Data have been retrieved from the instrument www pages or reference publications. OSIRIS has higher resolution than VIMOS and higher UV-blue sensibility than DEIMOS

Feature	VIMOS	DEIMOS	OSIRIS	FORS	GMOS	FOCAS
FoV (arcmin^2)	$4 \times (7 \times 8)$	16.7×5.0	8.5×8.7	6.8×6.8	5.5×5.5	6 ⊘
Max. R	$\sim 2,200$	$\sim 5,000$	5,000	2,800	3,600	1,600
Blue transmission	Yes	No	Yes	Yes	Yes	Yes
Max. transmission		0.85	0.87	0.78	0.81	0.80
Masks	15	11	13	10	13	10
Filters	6	7	24	22	8	14
Grisms/gratings	6	2	6	6	3	5
IFU	Yes	No	Planned	No	Yes	No

available, thus yielding up to the maximum resolution that the instrument can achieve ($R = 5000$).

- *Higher resolution*: Additional VPH–based grisms for $R = 5,000$ in the spectral range 400–500 nm, and $R = 10,000$ in the red are planned. It is important to point out that this resolution in the blue is not currently available in any of the spectrographs for 8–10 m–class telescopes.
- *3D spectroscopy*: This mode is implemented by changing one of the TF for a higher resolution etalon. The etalon, already purchased by IA–UNAM and currently under characterization, has $R = 10,000$, and a spectral range of operation from 650 to 900 nm.

7 OSIRIS Core Team Surveys

There are several surveys in which the OSIRIS Core Team is engaged, together with other collaborators. All of them are based in the spectral tomography either by using the TF or the order sorters. In what follows, several surveys using the TF tomography technique are briefly summarized.

7.1 TF Tomography

In the TF tomography technique, several images at the same pointing on the sky are taken using different TF tunings. Then, a data cube with the wavelength or redshift as the third dimension is obtained. For each emission line, a perfectly defined volume of the Universe in redshift range and limiting flux is scanned.

Using this technique, three different surveys will be tackled, funded by a coordinated project of the Spanish *Plan Nacional de Astronomía y Astrofísica*:

- *OTELO*: (OSIRIS Tunable Emission Line Object) survey using the red TF to detect low and high redshift emitters including Lyα up to redshift 7.

- *HORUS*: (Hydrogen and Oxygen Recombination line Unified Survey) using the blue TF to search for Lyα emitters from redshifts 2 up to 4.
- *GLACE*: (GaLAxy Cluster Emission line survey) using the TF for observing emitters in known galaxy clusters at redshifts 0.4 up to 0.9. The different optical lines to be scanned will allow deriving star formation rates and metallicities, and studying AGNs and optical cooling flows.

7.2 OTELO

In OTELO survey, the TF tomography will be applied to scan through two areas relatively free of OH sky lines, at 815, and 925 nm approximately. Table 7 summarizes the main survey characteristics comparing them with the most conspicuous and deep narrow band survey to date (SUBARU Deep Field). OTELO will be the deepest emission line survey, yielding redshifts with spectroscopic accuracy and deblending Hα from [NII] for low redshift emitters.

The scientific applications of OTELO include studying star formation rates, metallicity evolution [7], AGNs [10], distant QSO [4], Lyα emitters [5], the stellar component [9], and galaxy color evolution [1].

OTELO survey will provide a large database of about 40,000 emission line objects at different redshifts from 0.24 to 7.0 (Table 8).

It is very important to note that the minimum equivalent width (EW) of 15 Å stated in Table 7 corresponds to the minimum detectable flux. For brighter objects, such as emission line ellipticals or S0, the minimum detectable EW is of $\sim$ 0.3 Å.

Table 7 OTELO survey characteristics compared with SUBARU Deep Field narrow band surveys (from [8])

Characteristics	SUBARU	OTELO
Flux limit at 5σ	6×10^{-18} erg cm^{-2} s^{-1}	10^{-18} erg cm^{-2} s^{-1}
Minimum EW	15 Å	2 Å
Area	0.25 sq.deg.	0.10 sq.deg.
Redshift accuracy	10^{-1}–10^{-2}	10^{-3}–10^{-4}
Cosmic statistics	Single field	Different fields
Deblend Hα from [NII]	No	Yes

Table 8 Expected OTELO census of galaxies at different emission lines, including emission line ellipticals. Assuming no evolution and a concordance Cosmology $H_0 = 65$ km/s Mpc^{-1}, $\Omega_{m0} = 0.3$, and $\Omega_{\Lambda 0} = 0.7$

Morphology	Max. z	Number
E/S0	0.84	$\sim 10^3$
Sa–b–c–d–Im	1.50	3×10^4
Sy	1.50	7×10^3
BCD	0.84	10^3
Lyα	7.0	10^3

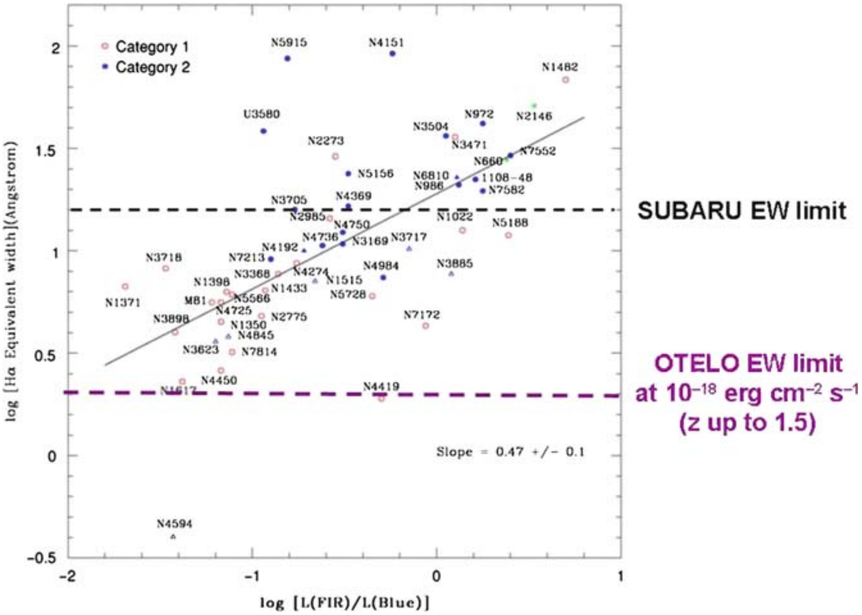

Fig. 6 OTELO EW limit will allow observing for first time in emission line surveys, all spirals up to redshift 1.5, and emission line ellipticals and S0 up to a redshift 0.84. Figure adapted from [6]

This implies that, *for first time in this kind of surveys*, all spirals up to $z = 1.5$, and most emission line ellipticals and S0 up to $z = 0.84$ can be detected (Fig. 6).

7.3 Lyα Emitters

The combination of HORUS and OTELO will render an important view on Lyα emitters (LAEs). HORUS is expected to gather LAEs, and Lyα blobs (LABs) at redshifts ranging from 2 to 4, while OTELO would provide LAEs at redshift 6, and 7, the latter representing the most distant LAEs known to date (Table 9). Also, some of the most conspicuous optical lines will be observed with NIR spectrographs to determine SFR and metallicites for the lowest redshift LAEs and LABs (Table 9). This database will allow studying the evolution of the LAEs luminosity function, and constraining the reionization epoch.

8 Summary

OSIRIS is an instrument of a wide field of view, with high red transmission and UV–blue sensitivity, very small overheads for changes of instrument configuration, and optimized for the use of Tunable Filters.

Table 9 Lyα emitters that will be collected by HORUS and OTELO TF tomography surveys. The rest frame optical emission lines that can be observed in the NIR are indicated

z	Lyα (nm)	[OII] (μm)	Hβ,[OIII] (μm)	Hα (μm)	Age (Gyr)	Project
2.1	377	1.2	1.6	2.0	3.2	HORUS
2.5	426	1.3	1.8	2.3	2.8	HORUS
3.1	499	1.5	2.0	–	2.2	HORUS
3.8	584	1.8	2.4	–	1.7	HORUS
5.7	815	–	–	–	1.1	OTELO
6.6	925	–	–	–	0.9	OTELO
7.0	980	–	–	–	0.8	OTELO

Although narrow band imaging using the TF in the blue and red is a unique mode in 8–10 m–class telescopes, OSIRIS has other special modes such as MOS Nod & Shuffle, fast photometry (with frequency switching using the TF), and fast spectroscopy. Its field of view and spectral resolution place OSIRIS in a competitive place with respect to VIMOS and DEIMOS.

Several large format surveys using the TF tomography technique will allow obtaining the deepest emission line surveys to date, that will allow studying galaxy formation and evolution including the farthest known LAEs (up to $z = 7$) and normal spirals and emission line ellipticals (up to $z = 1.5$).

OSIRIS will be shipped to La Palma in November 2008 to start on–the–sky tests at the GTC, in preparation for starting Day One operation in March 2009.

8.1 More Information

More information about the instrument including exposure time calculators can be found at www.iac.es/project/OSIRIS.

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