ASTRONOMICAL TELESCOPES AT THE TURN OF THE CENTURY

JOSÉ M. RODRÍGUEZ ESPINOSA
Instituto de Astrofísica de Canarias, E-38200 La Laguna, SPAIN

Abstract: The final years of the XXth Century and the initial years of the XXIst Century are witnessing a revolution in the construction of large telescopes. This has been possible thanks to the availability of both thin mirror technologies and large computing power. Astronomy is thus benefiting from this. Indeed the turn of the century has been rich with new discoveries, from the detections of extrasolar planets to the discovery of the the farthest galaxies ever seen or the detection of acceleration in the expansion of the Universe.

Spain is leaving her imprint on the telescope making revolution and is promoting the construction of a 10.4 metre telescope in the "El Roque de Los Muchachos" observatory, on the Island of La Palma, Spain. The Gran Telescopio Canarias (GTC) is currently at an advanced stage of construction, with science operation expected to start early in 2006.

1 Introduction

Modern technology telescopes started to be made at the turn of the XIX century when precision mechanics and precision optics started to be common use. In the past, telescopes suffered from poor optics, as optical glasses were very difficult to manufacture, and aluminization techniques were far from perfect. Nonetheless Astronomy had continued its advance during the XIX century. This was the century of the stellar catalogues, the initial steps in stellar spectroscopy, with the generalized use of photographic plates.

The beginning of the XXth century brought us the HR diagram and the first attempts to study the stellar evolution. In the 20's, the Curtis-Shapley controversy on the size of the Milky Way was resolved and astronomers realised that the Universe was a few orders of magnitude larger than previously thought. At that time the recently built Mt. Wilson 2.5m telescope was used to observe galaxies and with it Hubble discovered the general expansion of the Universe. Extragalactic Astronomy was starting prompting the construction of a 5 metre telescope a top Palomar Mountain to put on a firmer basis the expansion claim by observing the farthest galaxies. The Palomar

5m telescope was finished in 1945, in the midst of the European War. The Hale 5m telescope, as the Palomar telescope was later known, has been one of the pillar of the development of astronomy during the XXth Century. Much of the theory of Stellar Nucleosynthesis was based on observation done with the Hale telescope. The discovery of the Quasars was also done with this telescope. The Hale telescope also set the standards for telescope making technology, later followed by many other telescopes built around the world.

2 Progress in Telescope Making

A key aspect that I would like to stress at this point is that the construction of new and better telescopes has been fundamental in the advancement of astronomy. New and better telescopes and instruments have always resulted in clear advances in most if not all branches of Astronomy.

It is interesting to note that as the XXth Century advanced new telescopes were getting built, however with no increase in the size of their primary mirrors. Several telescope built from the 50's to the 80's include the Shane 3m telescope at Lick, the Crimean 6 m telescope, the Kitt Peak 4m telescope, the ESO 3.6 m in La Silla, the German 3.6 m telescope in Calar Alto (Spain), the Anglo-Australian and the William Herschel 4m telescopes in Australia and at La Palma respectively, amongst others.

Except for the Crimean 6m telescope, it is interesting to note that most other telescope built during the XXth Century were of the so called 4m class. Astronomy was advancing though at quite a fast pace, with the discovery of AGNs and quasars, the most luminous objects known to date, or the many advances in the study of the chemical abundances in many different kinds of galaxies and environments. However as I say, all this progress was being made with 4m class telescopes.

The important aspect to notice is that the photon collecting power of these telescopes was being increased enormously. Not by making the telescopes bigger but by making the focal plane instruments more efficient and sensitive. This was so because in the early XXth century the most common detector used was the photographic plate. Around that time, advances in electronic devices resulted in a large improvement of the performance of detectors. First phototubes, and photonmultipliers, later semiconductor devices such as the Charge Coupled Devices, resulted in almost two orders of magnitude increase in detecting power, or quantum efficiency as it is generally known. Indeed the quantum efficiency of detectors was augmented from a few percent for photographic plates to almost 99% for modern CCD arrays. This was combined with the availability of panoramic arrays, allowing multi-object capabilities, or wide area surveys. The clear advantage for astronomy was that even if the size of telescopes did not increased, astronomers were having a bonus in the improvement of detector devices.

In parallel, telescopes were being made better. Telescope mechanics was greatly improved with the use of Horizontal Mounts. These provided better mechanical stability for pointing and tracking, offering at the same time large Nasmyth platforms for the location of both heavy and sturdy high resolution spectrographs that allowed the study of lines profiles with unprecedented resolution. Horizontal mounts were known from several centuries back. Their astronomical use was however not widespread due to the complexity of the motion involved in tracking objects in the sky, necessary to correct for the motion of the Earth. Not until the advent of powerful enough computers was it possible to perform real time computations of the positions of the telescope axes required to follow a given object on the sky.

Summarizing, from the mid 40's to the mid 80's, Astronomy advanced at a great pace while the size of the telescopes remained rather constant at a canonical size of about 4 meter for the primary mirror. During this time the great development was in detector technology that evolved from photographic plates with quantum efficiencies of a few percent, to electronic devices bringing the quantum efficiency to almost 100%. Detectors also were enlarged in size from single unit detectors to arrays reaching several millions detectors per device. Science instruments benefited also from the availability of new detectors. New and much better instruments were therefore built for the 4m class telescopes. These allowed the fast advancement of astronomy that was made during the XXth century.

Telescope making also progressed. Mechanical precision was substantially improved. Optical fabrication and finishing, as well as metrology were also greatly improved in the interim. Finally, electronics, software and control did really come of age, thus setting up the stage for the revolution that was about to come in the last years of the XXth century.

3 Thin Mirrors

In the mid 80's it was clear that further advances in Astronomy required further increases in light gathering power. QSO research demonstrated that these were the nuclei of very faint galaxies that were very difficult to detect. QSO's were also the objects with the highest redshift known. QSO's were nonetheless pathological objects. If the high-z Universe was made of QSOs only it would have been difficult to reconcile the present day Universe with the high-z Universe. Therefore, it was clear that larger and more powerful telescopes were needed to, amongst other things, detect faint "normal" galaxies at high-z.

The road to higher quantum efficiency detector had already been explored. Further improvements in detector would come from either larger panoramic formats, better cosmetic or less electronic noise. However, even if these improvements were indeed welcome, the gain in actual photon collecting power would not be of order of magnitude, as would be required for the kind of Astronomy that people were trying to do.

Astronomy thus demanded larger telescopes. Telescope making technology had been largely improved in the past 50 years or so. Perhaps, the only stumbling block was the fact that increasing the size of primary mirrors had to be done not at the expense of heavier mirrors, as this would have resulted in much heavier mechanical structures that would have been poised to wild flexure problems.

The solution to this impasse came from the great creativity and insight of people like Jerry Nelson in California who proposed the use of thin mirrors. Thin mirrors had the great advantage of being much lighter and the disadvantage of being fairly deformable, requiring some active mechanisms for maintaining the optical figure as required, both when the mirror is static and against deformation by gravity as the mirror is changed in position.

Fortunately, the technology was ready to take up the challenge of actively controlling the shape of thin mirrors. Realising this was Nelson's greatest achievement. The road was therefore open to new increases in telescope sizes.

The late 80's were full of enthusiasm for the design of larger telescopes both in the US and in Europe. Thin mirror technology was indeed the default, although a large spree of technological developments were necessary before these ideas could be put into practice. These included polishing large thin mirrors, or in the case of segmented mirror, polishing off-axis powered mirrors. The segmented approach was developed by Jerry Nelson during the conceptual design of the Keck telescope. In Europe the prefered approach was to produce large monolithic thin meniscus mirrors. The support strategy was common to both. The mirror production strategy was very different though.

By the early 90's both in the US engineers were advancing in the construction of the Keck telescope, a 10 metre segmented primary telescope, and in Europe the canonical project was the VLT, an array of 4 eight meter telescopes to be located in Chile. Soon there was also the GEMINI partnership (UK, US, Argentina, Brazil and Chile), two eight metre meniscus type telescopes to be placed both in Hawaii and Chile, as well as the SUBARU telescope, a Japanese 8 metre meniscus telescope that was also to be located in Hawaii. Quite an impressive number of eight to ten metre telescopes at once!

The first of these telescopes to enter in operation was the Keck telescope. It was also the first large telescope to install a segmented primary mirror, and therefore to have solved all the difficulties related with the alignment and phasing of the 36 segments making up the full primary mirror. The success of this first large telescope was such that it prompted the Keck Foundation to fund a second one with the goal of making optical and infrared interferometry. Yet a step forwards towards increasing the spatial resolution of the observations.

Soon thereafter the European VLT, the Japanese SUBARU and the international

GEMINI projects commissioned its first telescopes. In a few years, the total collecting area had increased several times the total collecting area ever built in the past. Results from these telescopes appeared immediately after their commissioning. High redshift galaxies, extrasolar planets, brown dwarfs, high-z supernovae, etc. Results that have put Astronomy in the first pages of mass media. Results, like the accelerated expansion of the Universe, obtained through the observation of high redshift supernovae, that have been considered by the US scientific journal "Science" one of the major physics discoveries of the decade.

4 The Spanish 10 metre telescope

In this scenario of excitement for new discoveries, Spain, through the pro-active promotion of the Instituto de Astrofsica de Canarias, started what will be the first European large segmented telescope. By the time of the Spanish decision to embark on the construction of a large telescope both approaches, the segmented and monolithic meniscus ones, had been demonstrated although only the Keck had recently started operation.

Prior to this, Spain, or rather the IAC had worked in a monolithic meniscus type eight metre telescope project together with the UK. This project, which was carried out till the production of a conceptual design document, was however abandoned when the UK joined forces with the US to constitute the GEMINI consortium. The IAC nonetheless insisted in pursuing the idea of having a large telescope in its observatory and continued its development work for controlling thin mirrors. Equally importantly though was the formation at the IAC of a group of scientists and engineers whose aim was the promotion and initial design of a Spanish large telescope.

This group produced a first design of a eight metre meniscus type mirror and called on a group of international experts to review the concept and make recommendations to pursue the idea of building a large telescope in Spain. It is interesting to note that the review panel consisted of the top leaders of the large telescopes projects then in the making. The panel was chaired by Paul Murdin, who had been in charge of the commissioning and first years of operation of the Williams Herschel telescope in La Palma. Jerry Nelson, from the Keck telescope, was also in the committee, and he represented the only large telescope that had started operation by then. Other members in the panel included Matt Mountain from GEMINI, Massimo Tarenghi, from VLT, Masanori Iye from SUBARU, John Hill, from LBT, and Arne Ardeberg from the NOT telescope. Soon after this meeting the idea of changing the project to a segmented telescope instead was taking shape.

The final decision to promote a segmented 10 metre telescope was taken after the visit of a group of scientists and engineers to the US to visit the Keck facilities, as well as some of the contractors that had participated in the production of the Keck mirror segments.

Reason for the change of concept were diverse. Certainly the success of the Keck telescope was taken into a account. However other considerations were also important. For instance, the difficulty in bringing a monolithic meniscus through the narrow and winding road to the observatory weithed heavily on the decission. The thought that a 10 metre segmented primary mirror telescope could be done for about the same price tag as an eight metre monolithic thin meniscus one was also important. Finally, although not considered at that time, it was soon realised that any future larger telescope would have to be segmented, thus Spain would be in a very good position for contributing actively to future large telescopes.

5 THE GTC

The Gran Telescopio Canarias (GTC) will be an advanced telescope when it enters operation at the Observatorio del Roque de los Muchachos (ORM) in the island of La Palma. It will carry a segmented primary mirror, consisting of 36 hexagonal segments. The secondary mirror will be a light weighted hexagonal mirror made of beryllium. The GTC will carry a third mirror, the tertiary mirror to fold the light beam to any of the Nasmyth or the folded Cassegrain foci. The optical desigh of the GTC is a Ritchey-Chretien with an effective focal ratio of f/17. This results in a focal plane scale of 1.21 arcsecond per millimetre.

6 The GTC: Status and perspectives

The Gran Telescopio Canarias (GTC) is currently being assembled at the ORM in La Palma. First light is expected for mid 2005 with the first science observations expected by mid 2006. As of this writing the enclosure, building and dome, are finished, with minor problems pending. These are related to the shutter motion and the ventilation windows. Solutions for fixing the problems exist already to be implemented by the summer 2004.

By the time the telescope is turned to the operation team, the two Nasmyth platforms will have been commissioned together with two science instruments (CANARICAM and OSIRIS/ELMER).

For the time being, the main milestones are the completion of the telescope mount inside the dome, the reception of the first batch of segments, the acceptance of both the Acquisition and Guiding boxes and the Commissioning Camera. Further tasks for the immediate future are the start of the Astronomy operation group and the integration of the first science instruments. These first two instruments will provide the GTC with capabilities for low resolution multi-object spectroscopy, imaging in both lines and continuum in the optical and mid infrared, as well as polarimetry and, for the first time ever, coronagraphy in the mid infrared.

6.1 Enclosure

Work inside the enclosure is progressing. Offices are being furnished and labs are being supplied with their necessary equipment. The air conditioning system is working normally.

The GTC enclosure has been provided with 32 ample independently operated ventilation windows, allowing for 432 squared metre of clear opening spaces, to help maintain a laminar flow of air during the night. This is important to keep the inside temperature equal to the outside temperature, thus reducing temperature gradients that may degrade the quality of the images produced by the telescope.

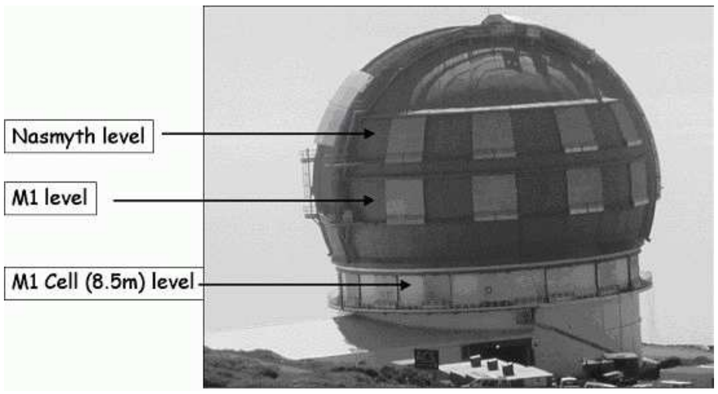

Figure 1: GTC enclosure showing the ventilation windows in three rows.

The azimuth pier is ready to take up the azimuth ring. As of this writing the azimuth ring is being mounted and adjusted. Figure 2 shows the interior of the dome with the azimuth pier in the centre. Figure 3 shows the azimuth ring already set over the pier.

6.2 Telescope Mount

Once all homogeneity, roughness, eccentricity, etc. tests are finished for the azimuth ring, the rest of the telescope will continue being mounted. Most major pieces of the telescope structure are at the site waiting to be installed. Those not needed in the

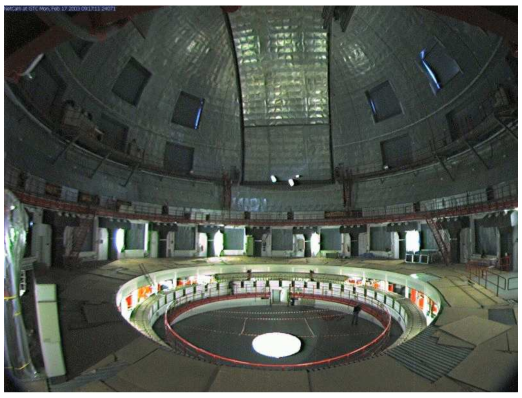

Figure 2: Interior of the dome showing the azimuth pier.

immediate future are still undergoing tests in their respective factories. That is the case for instance of the instrument rotator bearings (Figure 4).

Next steps in the mounting process will consist of the installation of the hydrostatic bearings and the rotating floor, allowing to test the azimuth rotation. Once this is achieved the azimuth encoder tape will be installed, and in parallel the yoke of the telescope will be erected, to continue with the elevation ring and mirror cell, the elevation trunnions and Nasmyth platforms, the tertiary tower, upper tube, spider ring and secondary support structure. This will take the rest of 2004 and some time in 2005.

By then, and once the necessary performance tests are satisfactorily passed, the telescope will be ready to take up the optics.

6.3 Telescope Optics

All 36 (+6 spare) segment blanks are fabricated. Made of Zerodur by SCHOTT, their measured properties comply with the specifications in all respects, in particular in term of low thermal coefficient of expansion and homogeneity of this coefficient.

The segment blanks are now at SAGEM, near Paris, where they are being polished. The polishing process is a lengthy and complicated one due to the extreme accuracy required to meet the strict image quality requirements of the GTC.

The secondary mirror is also being polished after a complicated blank production process in which several blanks were broken. The secondary mirror is made out of Beryllium as it needs to be very light while being fairly rigid. The GTC secondary mirror (Figure 5) is an important part of the telescope as it defines the entrance aper-

Figure 3: The azimuth ring on top of the pier.

Figure 4: Instrument rotators bearings being tested.

ture of the telescope. This is to maintain low thermal emissivity for better infrared performance of the telescope. The secondary mirror has five degrees of freedom, to maintain the correct alignment between the primary and secondary mirrors when the telescope changes elevation, to perform fast guiding and to correct for wind buffeting on the telescope structure, and finally to perform chopping for infrared observations.

Other important optical systems include the Tertiary mirror that is being polished in Moscow and it is expected to be finished by mid 2004, the Commissioning Camera, that is being made in Mexico and is about to be completed, and the Acquisition and Guiding (A&G) boxes. Both the Commissioning Camera and the A&G boxes are complicated subsystems, employing several cameras (Figure 6) as well as several wavefront sensing devices. The Commissioning Camera is meant to help during the initial alignment and phasing of the primary mirror segments. The A&G boxes will be in charge not only of acquiring the object to be observed and keeping it within

Figure 5: Secondary mirror.

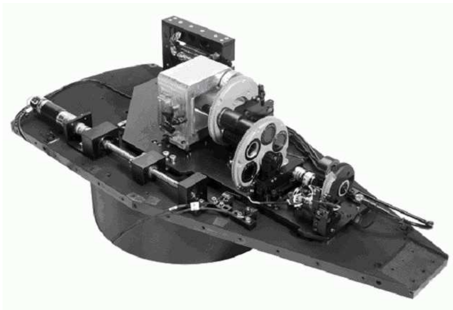

Figure 6: One of the arms of the Acquisition and Guiding boxes. The picture shows the optics inside this arm.

the aperture of the instrument, which is the classical use of the A&G boxes, but also will perform wavefront sensing to regularly monitor the status of the telescope optics. This is an advantage with regards to the Keck telescopes. These can not perform wavefront sensing on real time except when their Alignment Camera is installed, which is not always the case.

6.4 Software and Control

The GTC will be controlled by an overall software system that sees the GTC as a single unit. Every subsystem will be included in this software, from the dome and the different equipment in the dome to the telescope, optics, instruments, and including the data acquisition and processing pipelines from the moment a proposal is submitted by an astronomer to the moment the data are sent to the astronomer and archived in the GTC archive. The control system is therefore key to the successful operation of the GTC.

Of great interest for astronomers is every thing that is related with the science instruments and the scientific data. The software for generating the observing proposals is quite advanced, with test versions already available. This software will use a scheme of two phases. Phase II will be used by those astronomers granted time by the different allocation committees, to introduce enough details of their observations to produce the observing blocks that will be used by the observatory staff to perform the observations.

The control system includes data reduction pipelines, consisting of a basic reduction pipeline and a more advanced data reduction. The basic reduction is meant to correct those effects that are originated in the detector arrays, i.e. bias, dark current, flats, cosmetic, etc. Then, depending on the observing mode, there may be a more advanced pipeline that might perform wavelength calibration and a spectral extraction. This software may be of valuable use for the astronomer, at least to make an assessment of the data present in the archive. The software is also of good use for the observatory crew to ascertain the quality of the observation being done during the night, and indeed for monitoring the performance of the instruments.

7 The Science Instruments

The GTC will be equipped with a suite of facility instruments presently under construction. The first generation instruments will be OSIRIS and CANARICAM. A third instrument under construction, ELMER, is a backup instrument meant to be used if the main instruments are not on time when they are required at the telescope.

A instrument belonging to the second generation of facility instruemns, EMIR, has been started, so that there is not a big gap between the arrival of the first instruments, and that of the second generation. To complete the picture, some visiting instruments that have been proposed will be mentioned. These are CIRCE and UES.

In what follows there is a brief description of these instruments.

7.1 OSIRIS

OSIRIS is instrument whose primary design goal is to perform wide field (8' x 8) optical imaging with tuneable filters, therefore being specially suited for performing surveys and detailed studies of emission line objects. OSIRIS will also be capable of performing low resolution spectroscopy (R= 500 to 2500), both multi-object and long slit, as well as fast photometry and spectrophotometry.

OSIRIS will be equipped with two modern 2Kx4K CCD arrays, with frame transfer

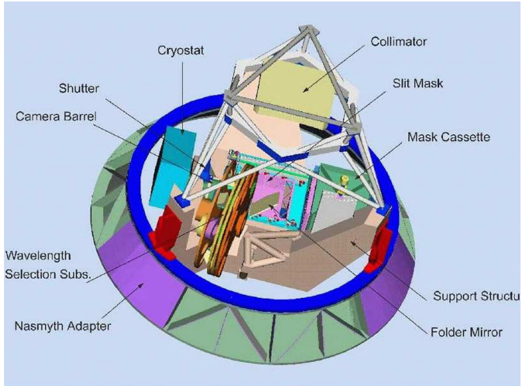

Figure 7: A drawing of OSIRIS showing its main parts.

capabilities, allowing observations of the line and continuum, followed by on chip subtraction before reading out the array, therefore substantially reducing the noise.

OSIRIS is a project led by Jordi Cepa, from the IAC, with strong collaborations from the Institute of Astronomy at the UNAM (Mexico) and the University of Cantabria (Spain). OSIRIS will be an excellent instrument to study the evolution of galaxies both in clusters and in the field, as well as detailed observations of nearby galaxies. Figure 7 shows a drawing with the main parts of OSIRIS marked. OSIRIS is in a fairly advanced state of construction. Integration is expected to start in the second half of 2004, with completion expected by June 2005, well in time of being installed at the telescope for tests and commissioning.

OSIRIS should be able to reach 26 magnitude objects in the r (SDSS) band with a signal to noise ratio of 5 in 1000 seconds. In spectroscopy, OSIRIS should be able to observe objects of magnitude between 20.5 and 22 depending upon the wavelength and the dispersion employed.

7.2 CANARICAM

CANARICAM is a thermal infrared instrument being built at the University of Florida, Gainsville. Charlie Telesco is the Principal Investigator. Charlie Telesco is very well known for the constructions of several first class thermal IR instruments both for space and the ground. CANARICAM will be capable of performing imaging, spectroscopy, polarimetry and coronagraphy in the mid IR bands from 8 to 25 micron. CANARICAM will be specially suited for observing brown dwarfs and extrasolar planets, as well as dust enshrouded objects like protostars, regions of star formation, and high redshift star forming galaxies.

CANARICAM is fairly advanced with most optical components already fabricated. The cryostat (Figure 8) is undergoing tests, and will be ready to start integrating all components soon. CANARICAM is expected to be delivered in June 2005.

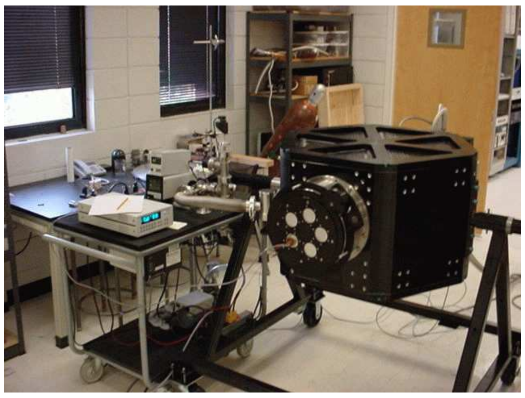

Figure 8: The CANARICAM dewar undergoing tests in the laboratory.

CANARICAM will be able to observe point sources as faint as 30 μJy (S/N= 1 in 1 hour) in the 10 μ band or perform line spectroscopy of objects with 0.7 x 10^{-18} W m^{-2} with the high resolution grating (R $\sim$ 1300).

7.3 ELMER

ELMER is an instrument for performing imaging and low to intermediate resolution spectroscopy in the optical range. With a field of view of over 3 x 3 arcminutes squared ELMER is optimised for maximum throughput. The design of ELMER (Figure 9) has been made in such a way as to minimise risks maintaining a tight budget.

ELMER is advancing quite satisfactorily under the leadership of Marisa García Vargas, from the GTC Project Office. ELMER will perform imaging with conventional narrow and broad band filters, and low resolution (R= 500) spectroscopy with prisms, medium resolution (R=1500) spectroscopy with grisms, and relatively high (R= 5000) resolution with Volume Holographic Prisms.

ELMER is also capable of performing fast photometry as well as fast spectrophotometry. This is achieved, as in OSIRIS, by using the charge transfer capability of the array detectors combined with adequate masks and a clocking strategy for fast shifting of the charge up in the array.

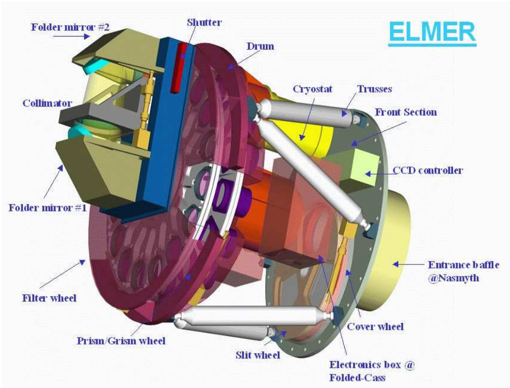

Figure 9: Drawing of ELMER showing the main parts and the compact design.

It is expected that ELMER will attain very high sensitivities. Current estimations provide figures like 26.8 magnitude in the r band (S/N: 5 in 1 hour with 1 arcsecond seeing). For spectroscopy the expected sensitivity is 20-22 magnitude (depending on wavelength) for a S/N= 20 under 0.6 arcsecond seeing in 1 hour.

ELMER is designed to be eventually installed at one of the GTC Folded Cassegrain foci, providing therefore an excellent standby instrument for imaging and spectroscopy even when the primary instrument may be any other of the GTC facility instruments.

7.4 EMIR

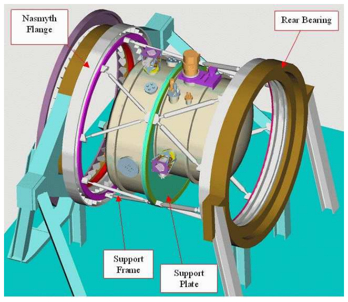

Figure 10: Drawing of EMIR showing the main parts and the compact design. The outer shield is a cryostat

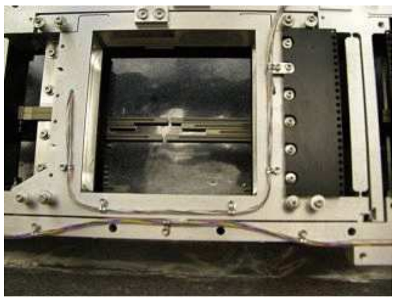

Figure 11: Prototype of the EMIR slit mask unit. Note the sliding blades that make up the slit of the desired size.

EMIR is a wide field multi-object cryogenically cooled near IR spectrograph (Figure 10). EMIR is being designed and fabricated at the IAC under the leadership of Francisco Garzón, with strong collaborations from the Universidad Complutense de Madrid and the Observatoire de Midi-Pyrenees. The design of EMIR is driven by COSMOS, a scientific project which aim is to make a census of the star forming galaxian population out to redshift 2.5, in order to set quantitative limits to the star formation density when the Universe was much younger than it is now.

EMIR will perform imaging and spectroscopy from 1 to 2.5 μm. Key features in EMIR are the very wide field of vision, 6 x 6 arcminutes squared, and the relatively high resolution required to perform an adequate subtraction of the OH telluric lines. EMIR will perform multi-object spectroscopy with masks that will be cryogenically cooled. One of the challenges of EMIR is to produce a mask changing mechanism that does not involve warming up and cooling down the instrument every time that the masks need to be changed. The current baseline for EMIR is to implement a robot (Figure 11) that will be in charge of producing the masks whenever needed. This robot will use a set of cryogenically cooled sliding blades that can be software controlled. EMIR is expected to be completed by the end of 2006.

7.5 Visiting Instruments

The GTC is adopting a policy for visiting instruments in order to fill some niches not covered by the initial facility instruments. There are several instruments that have been proposed as visiting instruments. Perhaps the two more interesting ones are CIRCE and UES.

CIRCE is a near IR camera that will fit into one of the Folded Cassegrain foci. CIRCE will be provided by the University of Florida and will add near IR capabilities to the GTC before the arrival of EMIR.

UES is a high resolution echelle spectrographs that has been in use at the Williams Herschel telescope fore more than ten years. UES has been recently decommissioned. Ramón García López from the IAC is leading the conversion of UES to the GTC, through a fibre plus micro lenses link. UES will be upgraded with new coatings, new detectors and new software. UES will provide high resolution (R 50000) to the GTC.

8 Adaptive Optics

The quest for image quality can be taken beyond the optics of a given telescope. Once a telescope is built with precise requirements on the quality of the optics, reality tells that the atmosphere is then the limiting factor dictating the image quality obtained on the array detectors. This is commonly known by the term "seeing limited" images. Space telescopes on the contrary are limited by the quality of their optics, or in other words, they produce diffraction limited images.

Ground based telescopes are actively working on methods to circumvent the atmosphere in their quest for image quality. One method that is actively being developed is "Adaptive Optics". Adaptive Optics is a technique that tries to correct for turbulence in the atmosphere therefore producing nearly diffraction images. There are two main elements to an adaptive optics system, namely the characterization of the turbulence pattern in the atmosphere and the reconstruction of the corrected light beam. The first one requires the availability of a bright enough reference source. The second one is done with a deformable mirror that produces positive or negative phase shifts in the footprint of the beam in order to flatten it out.

The first part is achieved with a wavefront sensor that analyses that light from the reference source on almost real time, thereby determining the aberrations that the light beam carries after its passage through the atmosphere. The measurements need to be done relatively fast as the atmosphere is constantly changing. This requires a relatively bright source close to the object of interest. This is not always possible and in order to increase the fraction of sky over which the correction can be made artificial laser reference stars are produced. This is technique that has been tested satisfactorily, however the availability of sufficiently powerful lasers is still a problem.

Once the signal has been processed by the wavefront sensor and the aberrations have been determined the loop is closed with the deformable mirror, and this is programmed in such a way as to correct the beam. Deformable mirror technology is advancing quite rapidly.

The GTC has a Adaptive Optics programme, still in the design phase, that will allow for adaptive correction of the beam, delivering corrected images in the J, H and K bands. The baseline is to have an Adaptive Optics system by early 2007, to be used with natural reference stars. This initial system will be upgradeable to its use with a laser reference star system, and subsequently further upgraded with the utilization of a second deformable mirror. This produces better correction and a larger and more homogeneously corrected field.

9 The Future

The Kecks in the States and the GTC in Spain will be the only segmented telescopes with strict image quality requirements produced so far. Future large telescopes however will also be segmented. Thus the technology demonstrated by the Kecks and much improved by the GTC will be instrumental for the development of future larger telescopes.

The construction of larger telescopes is also very much dependent on the availability of adaptive optics. This is mostly because the size of the focal plane instruments grows with the size of the telescope except in the case of telescopes that are diffraction limited. Large telescopes will also be very much dependent on the active correction of its optics. This will be complicated due to the large number of segments required to fill a large aperture. Indeed large telescopes are truly challenging projects.

There are at present several very large telescope projects. Most of these projects are still at a very preliminary stage of development. Some do not even have funds to go beyond a more or less detailed design stage. However the name of the game is telescopes of sizes ranging from 30 to 100 metre that should be ready in the next decade.

The most advanced project is perhaps the California Extremely Large Telescope or CELT, which is led by Jerry Nelson from the University of California. CELT is a partnership of the University of California and Caltech. Also in the US there is the Giant Segmented Mirror Telescope (GSMT) concept, a 30m telescope project promoted by the AURA New Initiatives Office. In Europe there are two projects with a very differing approach. The EURO50 is a 50 metre aspheric primary telescope, very much along the design lines of the US projects CELT and GSMT. EURO50 is being promoted by the Lund telescope group with participation of groups from other European countries like Spain, Ireland and the UK. The second European project is the OverWhelmingly Large (OWL)telescope. The baseline is a 100 metre spherical primary telescope.

All these projects are expensive, with price tags ranging from 700 to 1000 M. Whether one or more of these very large telescopes is made is still to be seen. The odds favour the CELT, which with private funds is progressing quite fast in its design stage. Europe is lagging behind for lack of funding. Two outcomes are possible. Either the European Union come up with a fair fraction of the funds required, or there is a world wide effort to converge to a single project.

10 Summary

The GTC is a 10m telescope currently being built in La Palma, Spain. The GTC is a collaboration between Spain (90%), Mexico (5%) and the University of Florida (5%). The expected day for completion of the project is May 2006, after several difficulties have resulted in some delay. A set of facility instruments will be ready by then. I do expect that the GTC will be an outstanding telescope at the disposal of the Spanish, Mexican and Floridian astronomical communities.

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