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LBTO's Long March to Full Operation - Step 2

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ABSTRACT

Step 1 (Veillet et al.[1]), after a review of the development of the Large Binocular Telescope Observatory (LBTO from the early concepts of the early 80s to mid-2014, outlined a six-year plan (LBT2020) aimed at optimizing LBTO's scientific production while mitigating the consequences of the inevitable setbacks brought on by the considerable complexity of the telescope and the very diverse nature of the LBTO partnership. *Step 2* is now focusing on the first two years of implementation of this plan, presenting the encountered obstacles, technical, cultural and political, and how they were overcome. Weather and another incident with one of the Adaptive Secondaries slowed down commissioning activities. All the facility instruments should have been commissioned and offered in binocular mode in early or mid-2016. It will happen instead by the end of 2016. On a brighter side, the first scientific publications using the LBT as a 23-m telescope through interferometry were published in 2015 and the overall number of publications has been raising at a good pace. Three second generation instruments were selected, scheduled to come on the telescope in the next three to five years. They will all use the excellent performance of the LBT Adaptive Optics (AO), which will be even better thanks to an upgrade of the AO to be completed in 2018. Less progress than hoped was made to move the current observing mode of the telescope to a whole LBT-wide queue. In two years from now, we should have a fully operational telescope, including a laser-based Ground Layer AO (GLAO) system, hopefully fully running in queue, with new instruments in development, new services offered to the users, and a stronger scientific production.

Keywords: Large Binocular Telescope, operations, instrumentation, adaptive optics, interferometry, queue, service observing, seeing prediction

1. LBTO IN SHORT

1.1 The LBT partnership

The LBT is an international collaboration of the University of Arizona, Italy (INAF: Istituto Nazionale di Astrofisica), Germany (LBTB: LBT Beteiligungsgesellschaft), the Ohio State University, and the Tucson–based Research Corporation representing the University of Minnesota, the University of Virginia, and the University of Notre Dame.

1.2 The telescope

The Large Binocular Telescope Observatory is located in southeastern Arizona near Safford in the Pinaleño Mountains on Emerald Peak at an altitude of 3191 m, and its headquarters are on the Tucson campus of the University of Arizona. The binocular design of the Large Binocular Telescope (LBT) has two identical 8.4 m telescopes mounted side-by-side on a common altitude-azimuth mounting for a combined collecting area of a single 11.8 m telescope. The entire telescope and enclosure are very compact by virtue of the fast focal ratio (F/1.14) of the primary mirrors. The two primary mirrors are separated by 14.4 m center-to-center and provide an interferometric baseline of 22.8 m edge-to-edge. (Hill et al.[2])

The binocular design, combined with FLAO, the integrated Adaptive Optics (AO) utilizing adaptive Gregorian secondary mirrors (AdSec) to compensate for atmospheric phase errors (Esposito et al.[3]), provides a large effective aperture, high angular resolution, low thermal background, and exceptional sensitivity for the detection of faint objects.

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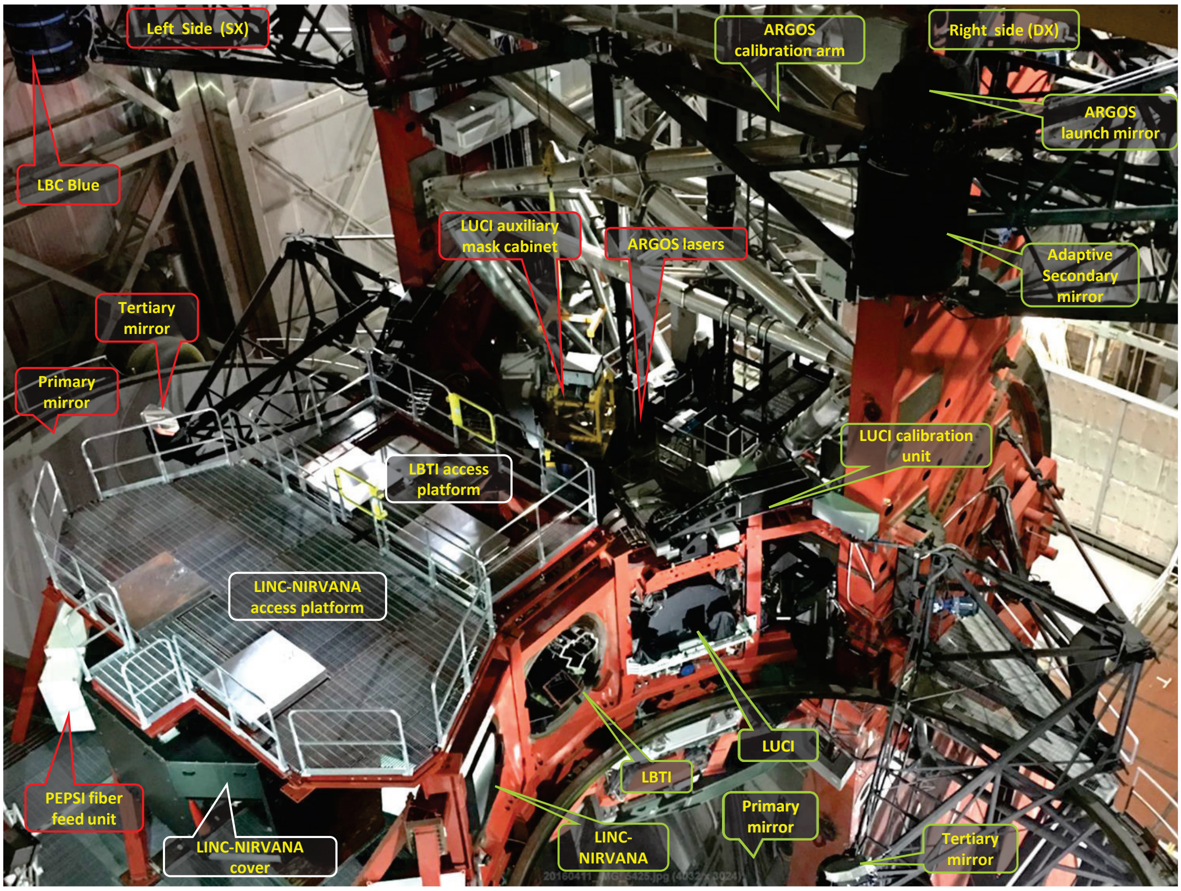

Figure 1. A look at the central instrument platform of the telescope at the time of a LUCI mask exchange using an auxiliary mask cabinet, seen hanging from the enclosure crane. Legend boxes are red for the left (DX) side of the telescope or instrument port for LBTI and LINC-NIRVANA. and green for the right (SX). White is for centered equipment.

1.3 The instrumentation

The instrumentation of the LBT is divided in three categories: – *Facility*, i.e. instruments to be proposed to users at first light (or soon after); – *Strategic*, in which LBT invested early on to prove the concepts chosen and provide unique scientific results; – *PI*, for which development and subsequent support for operation once on the telescope is completely handled by the PI and his/her team.

- Facility instruments, coming in pairs, are devoted to (1) wide field imaging (LBC), (2) visible- (MODS), and (3) near infrared- (LUCI) imaging and spectroscopy. They are described in detail by Rothberg et al.[4] and references therein. The LUCIs are complemented with ARGOS, a laser ground layer AO system, currently in commissioning.
- LBTI and LINC-NIRVANA are the strategic instruments. LBTI provides phased array imaging in Fizeau mode from 2 to 20 microns, as well as nulling interferometry at thermal infrared wavelengths. The two science cameras for LBTI, LMIRcam (2-5μm) and NOMIC (8-12μm), used for AO imaging since spring 2011 on, allow for single or dual aperture science (Hinz et al.[5]). LINC-NIRVANA is designed to be capable of phased array imaging and multiconjugate adaptive optics (MCAO), imaging in Fizeau mode at near-infrared wavelengths (Herbst et al.[6 7]).
- PEPSI, a fiber-fed high resolution (R= 43,000 - 120,000 - 270,000) high stability spectrometer and spectro-polarimeter (Strassmeier et al.[8]), is the only PI instrument currently on the telescope.

One should note that only LBTI is currently routinely using the excellent performance of FLAO, which will change very soon with the completion of commissioning of the LUCIs in AO mode. Over the past two years, all instruments went through significant steps, which will be described later in this article.

2. THE LONG MARCH - STEP 1... TWO YEARS LATER

LBTO's Long March to Full Operation - Step 1 (Veillet et al.[1]) outlined LBT2020, a six-year plan aimed at optimizing LBTO's scientific production while mitigating the consequences of the inevitable setbacks brought on by the considerable complexity of the telescope and the diversity of the LBT partnership.

2.1 LBT2020 under review (December 2014)

An important early goal of LBT2020 was to organize an external review of the observatory and of the LBT2020 plan itself. A Visiting Committee (VC) was formed, which brought a wealth of experience in large scientific facility operations and astronomical instrumentation, as well as a wide breadth of knowledge of the scientific field. The VC members were R. Bernstein (Project Scientist, The Giant Magellan Telescope), R. James (Senior Scientist, Brookhaven National Laboratory), N. Levenson (Deputy Director, Gemini Observatory), M. Phillips (Director, Las Campanas Observatory and the Magellan Telescopes), F. Rigaut (Associate Professor, The Australian National University), and B. Schmidt (Distinguished Professor, The Australian National University, Chair).

The VC report was extremely valuable to the observatory management and to the LBT Board. The overall strategy and capabilities for LBTO outlined in the LBT2020 were recognized as fundamentally sound. The statement "*the LBTO should prioritize commissioning of the facility instruments and ARGOS system to ensure these instruments are operating regularly and efficiently in binocular mode*" clearly stressed the importance of moving to full operation.

The VC was concerned by the development of new instrument projects, especially at a time when facility or strategic instruments were still to be commissioned and resources are limited. LBT should build on truly unique capabilities such as Fizeau interferometry or high strehl AO enabled by FLAO.

The observatory was encouraged to continue its development of a queue system and provide more tools to users as a way to enhance scientific output, allowing the highest priority programs to be completed and matching scientific needs to the weather conditions, while working to minimize the risk of users becoming detached from the facility.

The LBTO was seen by the VC as a lean operation, however adequately resourced to undertake the observatory's high priority items. Overall, the structure and management of LBTO seemed appropriate, especially given the relatively lean operations budget given the scale and complexity of the observatory.

2.2 LBT2020 and the challenges of the real world

Quite a few goals were set with both optimism and excitement. Unusually (hopefully!) bad weather for two consecutive years made the telescope less productive for its users as less observing time was available to science. An incident on one of the Adaptive Secondary mirrors (AdSec)in late August 2015 prevented any Adaptive Optics (AO) based observations for most of the second semester of 2015 and delayed even more the commissioning, already severely hit by the weather, of the AO-mode of the LUCIs.

3. OPERATIONS

3.1 Weather

On Mt Graham, weather is significantly worse than experienced by the other 8- to 10-m class telescopes, located in Northern Chile (Gemini South or ESO-VLTs), on Mauna Kea (Keck, Subaru, Gemini North), or La Palma (Grantecan). Over the past seven years (2009-2015), we lost an average of 35% of the science observing time to weather. However, the weather losses averaged 45% over the last two years (2014-2015), to be compared to only 31 % over 2012-2013. A plot of the time lost to weather is shown on Figure 2 together with a comparison between Mt Graham and Mt Hopkins.

It is something we have to live with. It makes every night even more precious and raises the pressure for decreasing as much as possible the time lost to other sources than weather. It also makes scheduled commissioning runs more vulnerable than usual and the completion of high priority science scheduled in classical visitor mode or even mini-queue runs even more unlikely.

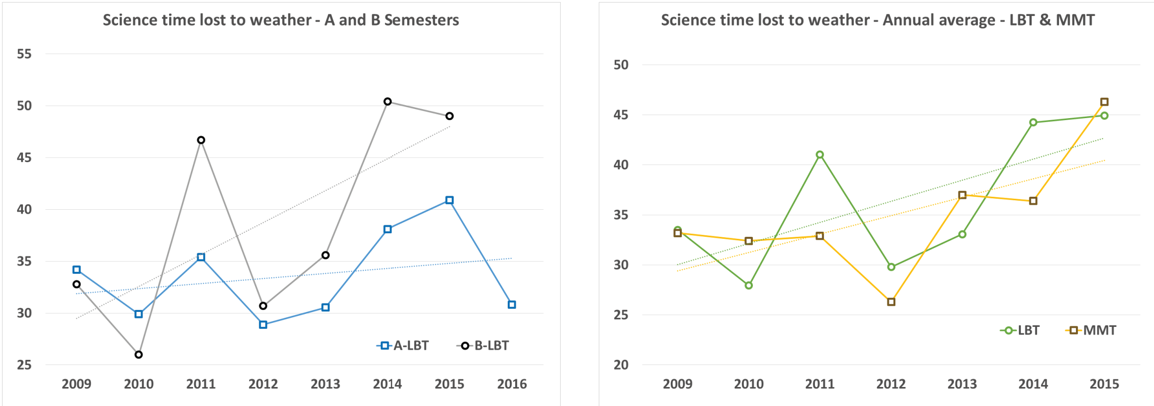

Figure 2. *Left*: The percentage of science time lost to weather at LBT (Mt Graham) is seen on the left per semester. "A" semesters go from Feb 1 to around July 10 and "B" semesters from mid-September to January 31. *Right*: The annual average loss of science time is shown over the past 7 years for LBT (Mt Graham - 3200m - 110km E-NE of Tucson) and MMT (Mt Hopkins - 2600m - 60km S of Tucson).

3.2 Observing time lost to technical problems and human errors

Figure 3 shows the losses to weather, technical issues and human errors over the past seven semesters, seen as a fraction of the whole time allocated to science, and as the fraction of clear science time. The latter will be used as our reference in the rest of the section.

Figure 3. *Left*: The fraction of science time scheduled for science for the past seven semesters divided in four sections: lost to weather, good for observing, lost to technical problems, and lost to human errors. *Right*: Same as on the left, but only looking at the clear weather scheduled time. Note that "human errors" started to be recorded systematically only since 2014B (see text for more details)

3.2.1 Human errors

Before looking more closely to the source of technical losses, let us comment briefly on human error losses. They come mostly from partner observers and are due to a combination of many factors: lack of experience, poorly prepared observing scripts, last minute preparation, lack of backup programs if the conditions encountered are not those required for the current program, or not enough observations to fill the night. They are relatively rare, but still cost nearly as much as the problems encountered on the facility instruments in 16A, as seen on Figure 4. We should note that the accounting is difficult and is likely underestimated as statistics show that the error logging depends on the Observing Support Assistant (telescope operator). As long as the observatory is not in an LBT-wide queue managed by LBTO, we can only mitigate this by offering better preparation tools. We will come back to this in the section on Queue.

3.2.2 Technical issues

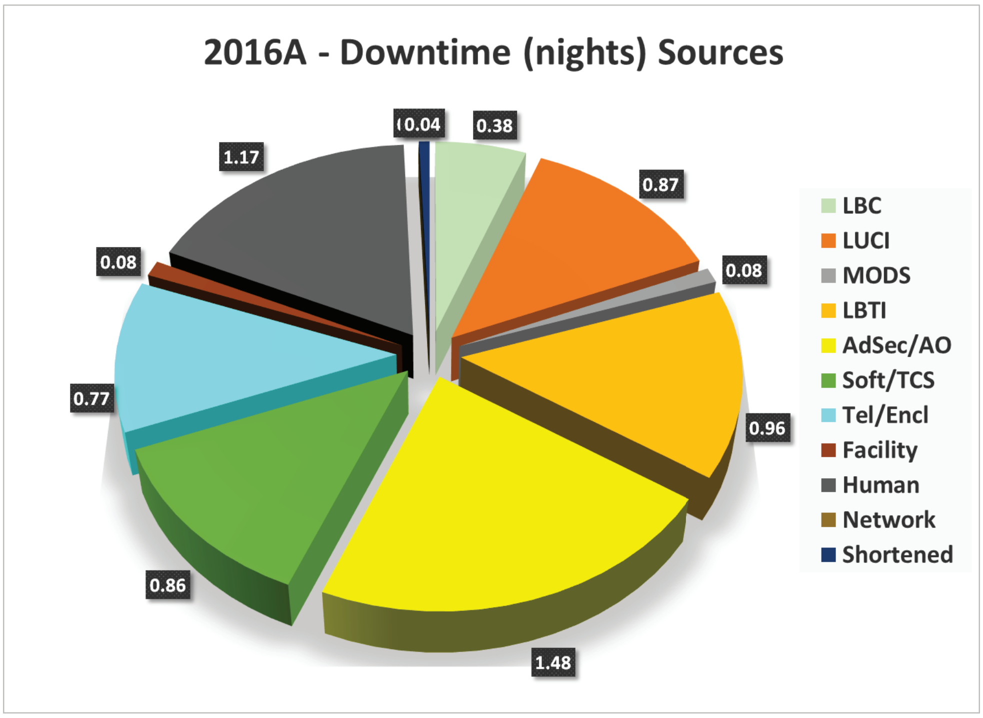

Figure 4. The various sources of time lost in 2016A. The issues with LBTI instrumentation were unusual and their source well-identified. The relatively high contribution of AO comes from the addition of small glitches with jumping actuators or seeing instabilities which makes the shell going to rest mode, something which will mostly disappear with the update of the AO software in June 2016.

As seen on Figure 4 for 2016A, the telescope and its control systems, including the active collimation of its primary mirrors and acquisition, guiding, and wave front sensing units installed at the various foci, continued to behave well, confirming the great improvements observed two years ago. The program of continuous preventive maintenance as well as the refurbishment of subsystems during the annual period of shutdown (∼July 10 – September 1) clearly show their impact on the reliability of the telescope. The telescope and associated control systems account for a loss of less than two percent of the clear observing time, a tribute to the hard work of LBTO staff to make the telescope as reliable as possible.

On the LBT, it is easy to move to another instrument if one fails. The switch will take only 10 to 30 minutes. Therefore, failures which could make an instrument unavailable for a long time do not translate to much time lost on the sky as other observations will be conducted as soon as the problem is deemed too complicated to be solved quickly: we have a theoretical limit of an hour maximum to be spent on repairing the issue at night before moving on to another instrument. Unfortunately, severe problems on a given instrument (such as LUCI) for months will actually impact the science, an impact which will not show up on the daily log of instrument problems. We will come back to this later in the Publications section.

The LBCs continue to be robust and do not contribute much anymore to the time losses. LBTO has taken ownership of the cameras, both of the software and the hardware side, a long process well supported by the original LBC team. An upgrade of the camera control is ongoing and should be concluded by the end of the 2016 shutdown. An upgrade of the software collimating the telescope is nearly completed and should drastically decrease the amount of time to be spent collimating at the beginning of a night where there is a significant temperature difference between the temperature of the main mirrors and the ambient temperature.

The pair of MODS has been very reliable, rarely generating a significant time loss. With the commissioning of MODS2 likely to be completed by the end of the year, LBTO will take ownership of the two MODS, likely before the end of the year. The development of an easy user-interface to prepare MODS1 and MODS2 binocular observations is still work in progress.

The LUCIs are currently one of LBT operations´ weak spots. Their multi-object spectrograph unit (MOS), the robot changing masks inside the cryostat, has been in particular the source of significant down time.

3.2.3 2015 DX-AdSec incident

We mentioned already a few times the excellent performance of adaptive optics at LBT, thanks to the adaptive secondaries, the FLAO systems and their pyramid sensors.

In *Step 1* of our Long March, we commented on a freezing incident and issues with the contacts between the back of the shell and the distribution board (see Christou et al.[9] for more details). We added that, as the first heavy user of these complicated systems, the observatory is learning, as time goes on, about their weaknesses and ways of addressing them. It is a painful process, which will eventually lead to a much better reliability of the AdSec's. Learn we did again indeed! It was this time a glycol leak, which fortunately had no consequences on the telescope and its subsystems beyond the AdSec unit on the right side (DX). Figure 5 gives some details on the event.

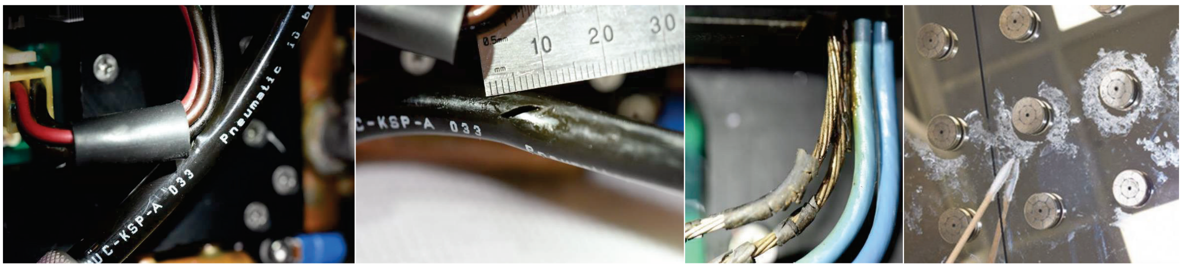

Figure 5. *From left to right –a* A glycol hose was in contact with wires, which could get very hot in special circumstances. *–b* This hose was weakened by excessive heating of the wires and burst when re-pressurized after the 2015 shutdown. The cm fracture is clearly seen on the picture. *–c* The insulation of other wires was found charred, but none were in close contact with a hose. *–d* A small area on the back of the shell was contaminated by the glycol leak, though not enough to warrant a stripping and recoating (local cleaning was enough).

The leak happened due to many factors, all conspiring to a catastrophic conclusion: incomplete shutdown procedure, miscommunication within staff, electronics design flaw in the Thin Shell Safety power supply circuit board, implementation design flaw, lack of leak detection mechanism. As a consequence, both AdSec's were grounded and the rigid secondary was back in service to ensure a continuous use of the telescope in seeing limited mode. One AdSec went back on sky by December 2015 and the second one by February 2016. Much was learned on the way, but the lesson was hard!

LBTI, especially in interferometric mode, lost nearly a full semester of science. The impact was high on the commissioning of the LUCIs in AO mode, already crippled by bad weather in previous semesters.

4. COMMISSIONING ACTIVITIES

4.1 Facility instruments and PEPSI

MODS2 was successfully commissioned and both MODS are now offered for science. PIs can use both of them simultaneously in "twinning" mode, i.e. with the same strategy on both sides (exposure times and offset patterns). An example of such an observation is seen on Figure 6.

LUCI2 was commissioned in seeing-limited mode and used for science while LUCI1 was retrofit with a new detector (H2RG) similar to the one in LUCI2, and an additional camera for AO imaging (a glass mirror version of the metal mirror camera already in LUCI2) was installed as well. Commissioning in AO mode is nearly completed in imaging mode for LUCI2 (see Figure 6) and ongoing for LUCI1. LUCI2 has still to be commissioned in diffraction-limited spectroscopic mode. Binocular mode has been already tested with the new software which came with LUCI2 and is now running both LUCIs .

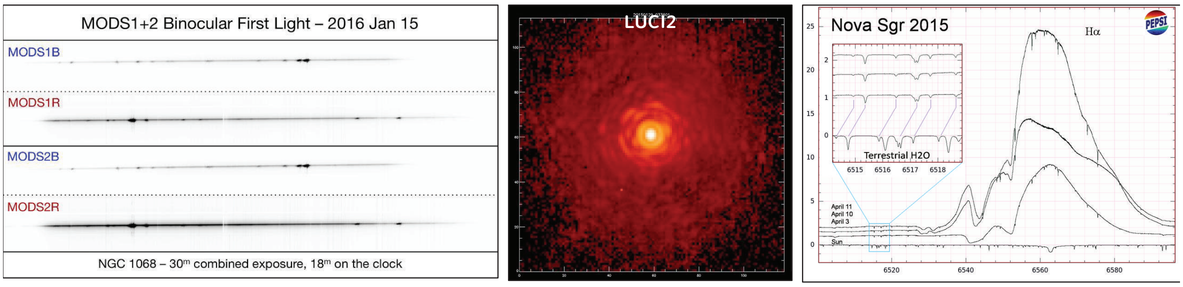

Figure 6. *From left to right –a* First light observation with MODS1 and MODS2 in binocular mode. Many of the observing programs with MODS entail long exposure times. For such observations, using the two MODS to do the same thing in parallel on each side of the telescope improve the efficiency of the telescope by a factor two! *–b* First AO light on the N30 camera of LUCI2: Strehl Ratio of 75*–c* Observation of Nova Sgr 2015 by PEPSI. An excerpt of the spectrum around Hα, showing in exquisite details a very dynamic nova, thanks to the 270,000 resolution of the instrument.

PEPSI saw first LBT light, was commissioned, and started science in 2015. Results were spectacular, as seen in Figure 6. There are no other spectrographs yet on 8-m class telescopes able to deliver a full visible spectrum in three exposures at a resolution of 270,000. After the commissioning of its polarimetric modes in the fall of 2016 and a period of refurbishment to ensure a better efficiency and stability, PEPSI should be available for science to the LBT partnership in 2017.

4.2 ARGOS

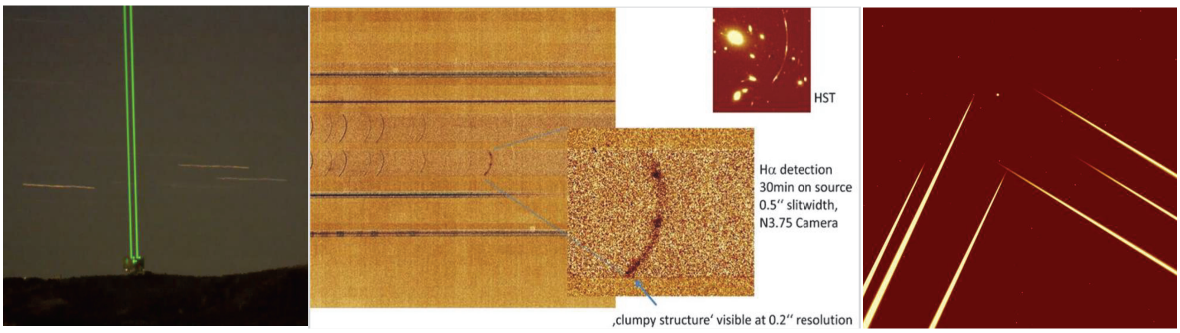

Figure 7. *From left to right –a* ARGOS propagating its laser, as seen from 20 miles away (*Photo courtesy of Dean Ketelsen*). *–b* ARGOS spectroscopy of the SDSSJ1110+6459 (z 2.48) lensed galaxy arc. *–c* The ARGOS asterism: three beams for each side of the telescope. Each of the six lasers delivers consistently between 15W and 18W.

ARGOS, the ground-layer AO system to be used with the LUCIs, had its first laser propagation at the end of 2013. In November 2014, the LBTO adaptive optics was locked on the three laser guide stars of the ARGOS constellation on the right side of the telescope, achieving an impressively good correction on the whole field of LUCI2.

In March 2016, the first observations in spectroscopic mode were made on the left side with LUCI1. While there is still much work to be done to bring ARGOS to full operations, the coming commissioning runs will allow us to start science programs in shared risk while improving the operability of the system and its efficiency, and learning its weaknesses by logging as much flight time as possible in "science operation" mode.

The observations made so far show an improvement of a factor of at least 2 in image quality over the whole field of the LUCIs (4' x 4').

4.3 Lean-MCAO

After a successful primary acceptance in Heidelberg (Germany) in May 2015, LINC-NIRVANA (LN) in its Lean-MCAO inception arrived on Mt Graham in October 2015. The LN bench was installed on the telescope in November for a dry run without any optics. The installation and removal went well (Figure 8). The LN team worked through the first semester of 2016 reassembling the whole instrument in the mountain clean room. This effort was successfully concluded before the shutdown of the facility for the summer of 2016. LN is scheduled to come on the telescope, fully assembled this time, in September, with final alignment and first light later in the semester, and the first commissioning nights in January 2017.

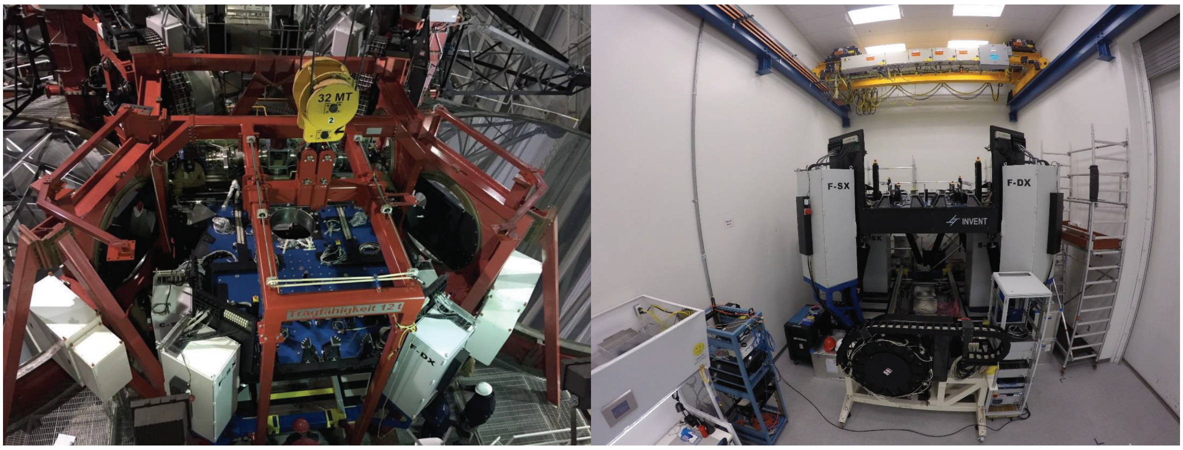

Figure 8. LN in November 2015. *Left:* The LN bench landing on the LBT instrument platform for a fitting test. *Right:* The LN bench in the mountain clean room ready for a full reassembly of the Lean-MCAO instrumentation.

The first goal of LN on LBT is to commission the Lean-MCAO (Multi Conjugate AO on a 10"x10" field of view) on both sides of the telescope, before going to a science program fully dedicated to this mode over 2017 and 2018.

5. OPTIMIZING OPERATIONS

5.1 Scheduling and observing modes

The observatory is currently offering the three pairs of facility instruments, LBTI, and PEPSI for general use by the LBTO community.

Around 200 nights a year (or around 60% of the time) are devoted to science, with the rest being shared between shutdown (10 to 11 weeks around monsoon season), commissioning and in-house engineering time. Scheduling of the telescope is done on a semester basis, A-semester running from February 1 to shutdown (around July 8), and B semester from the end of shutdown and observatory restart (around September 18) to January 31.

The allocation of time to partners is done according to their share in the LBT Corporation. Each partner has its own process to allocate time, from executive decision or consensus to time allocation committees following a proposal submission process.

For scheduling purposes, LBTO has four partners (LBTB-Germany, INAF-Italy, OSU/RC, and AZ-UofA). Their observing time is scheduled in "partner runs" of 5 to 8 nights each. The scheduling of these runs is optimized to allow high priority observations of each partner to have a better chance to be completed, such as transit observations or a particularly heavy observing load at a given time of the year.

LBTI is used for science more and more by the the whole partnership, peaking at more than 35% of the available observing time in 2016A. Observations are mostly performed by the UA-based LBTI team. LBTI is therefore scheduled for four to five dedicated runs every semester interleaved with the partner runs described above.

To optimize the scheduling of some of the commissioning activities, which are more efficiently done for a few hours every night over many nights, or need specific conditions which are somewhat rare, partner runs are sharing time with such commissioning activities. Last but not least, ARGOS commissioning runs are scheduled in long blocks and it is anticipated that ARGOS-enabled runs will be scheduled when ARGOS is fully operational.

The observing schedule is available on the home page of the LBTO web site at http://www.lbto.org/

5.2 Binocular all the time

The LBCs have been in binocular mode for nearly a decade. The move to binocular mode with pairs of MODS or LUCIs is very high priority for the observatory. It will be essential to the scientific productivity of the observatory in the years to come.

All facility instruments should be fully functional by the end of 2016. Binocular capabilities will evolve from the current "twinning" modes to "mixed modes", such as spectrosocopy on one side and imaging on the other, on the pairs of LUCIs and MODS. The binocular development will culminate with the offering of any combination of facility instruments by mid-2017. One should note that the telescope and its control system are ready for this. The development of preparation tools and the training of the PIs to the binocular capabilities of the telescope will be essential to the success of the high versatility, which will be offered to the users. *Step 3*, in 2018, will give us a chance to comment on the success of the whole-binocular LBT!

5.3 Q or no Q?

Step 1 presented a plan to move to an LBT-wide queue mode (hereafter **Q**) at a rather swift pace . The reasons for such a move have already been mentioned earlier in this document. They were already outlined in an LBT Board-commissioned Operation Readiness Review back in 2011: the need for high priority science to be completed first was the most striking argument, especially at a site with sub-optimal weather conditions (at least compared to Chilean and Hawaiian observatory sites).

This move to **Q** was supported by the Visiting Committee and the observatory moved forward with the clear philosophy: no need to reinvent the wheel. After all, quite a few observatories successfully moved to **Q** with good results, even at sites where the weather is not much of an issue. LBTO decided to use the developments made by the Gemini observatory for their own queue program, which they kindly made available to the observatory.

The initial desire was to move fast, but the LBT membership actually felt that moving too fast was not the best option. The desire to keep control of the observing time at the partner's level, the fear to move to a system which would cut users from the observatory, or the concerns about the ability of the observatory to actually deliver a viable system made the partner-based Queue Advisory and Review Committee (QuARC) reorient the priorities of the **Q** project at the end of 2015. The QuARC stressed the high interest in all the tools developed for observing preparation but at the same time highlighted the need to move slowly and let the users and observers get used to these tools and gain confidence in the capabilities of LBTO to observe for the partners before committing to a move to an LBT-wide queue instead of the mini-queues handled by some partners, or the classical mode still used by the UA partner for their non-LBTI observing programs. See Edwards et al.[10] for an exhaustive account of the past two years progress of the **Q** project.

In spite of some disagreements between the LBT partners, which only reflect their diversity, one should note that every one agrees that ensuring the completion of the high priority programs is very important. ARGOS-enabled runs will eventually be done in queue mode with a good dose of service observing and an LBT-wide queue is likely to be adopted for a good fraction of the observing time as it will be the best way to mitigate the impact of weather and to give the extreme-AO or interferometric programs their best chance of being completed in the appropriate conditions.

5.4 ALTA: An LBT-centric weather and seeing forecast service

For a classical visitor coming for a night or two for a given program, the priority is clear and only the weather can actually derail the plans for the night. If that program needs a very good seeing, and the seeing is not good, a backup program is the only choice left to the observer while waiting for better conditions.

For the partner mini-queues, and even more for **Q**, the situation is very different. With all instruments available at any time and a few programs (or many with **Q**) to choose from, observers have more choices available. We can cite of few of the many applications of a good forecast model: If seeing is good, they can go for a LUCI-AO program. If it is not that good, perhaps a MODS program requiring only an average seeing will be well suited. If water vapor content is going to be high for the whole night, no need to plan for interferometry at 10μm. A good prediction of wind speed and direction will help the program or target selection as observing with a high head wind is not a good idea due to wind-induced telescope shakes.

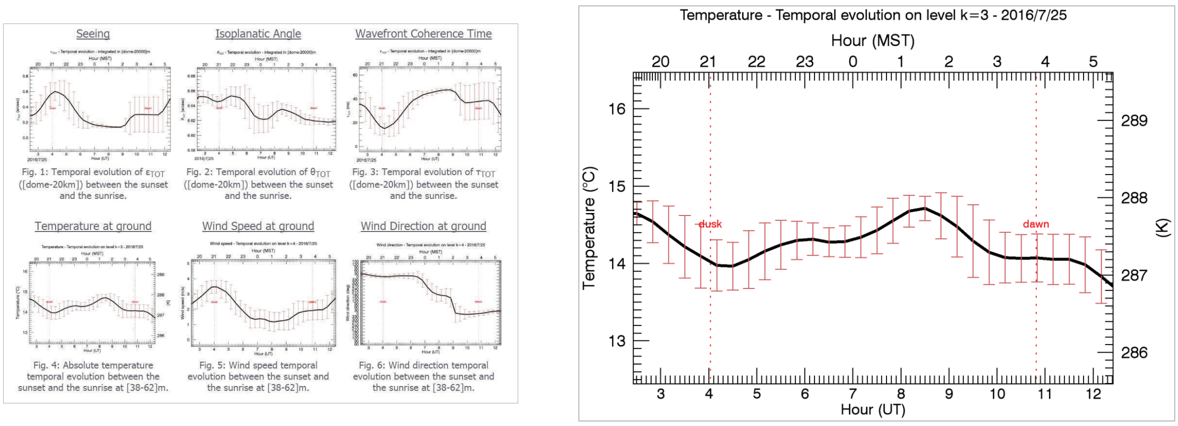

Figure 9. *Left:* A snapshot of part of the summary page of the ALTA forecast. It gives at a glance the main parameters of the night to come. *Right:* Forecast of the temperature for the night at the level of the telescope. Note that the turbulence parameters are displayed but not calibrated yet. They should be available by the end of 2016.

Therefore, a solid forecast fine-tuned to Mt Graham covering not only the usual meteorological parameters like temperature, wind, humidity, but also optical turbulence (seeing, isoplanetic angle, wavefront coherence time) would be a very helpful tool to prepare the observations of the night. As there is good experience in forecasting optical turbulence at the INAF Arcetri Astrophysical Observatory, where FLAO was born, LBTO decided to contract Arcetri for this forecast work, giving birth to the ALTA (Advanced LBT Turbulence and Atmosphere) Center, led by E. Masciadri.

The first milestone of the project was reached at the end of June 2016 with the release of the forecast of the weather parameter through a web portal (url: /http://alta.arcetri.astro.it/) where forecast for the coming night is proprietary but previous forecasts are public. Figure 9 shows a forecast summary page and a plot of the temperature forecast.

The next milestone is for the end 2016, with the release of the optical turbulence parameters. More information on ALTA and seeing predictions in Masciadri et al,[11] .[12]

6. PREPARING THE NEXT DECADE

6.1 Completing the ongoing projects

The highest priority of the observatory is to be fully operational with its suite of facility instruments, including ARGOS, in a fully binocular mode. It was planned for the end of 2016 but will now happen before mid-2017, except for ARGOS which will not be fully operational before the end of 2017. The delay of one semester is easily explained with the consequences of the AdSec glycol leak incident, which slowed down all AO-related activites, and the usually bad weather which slowed down considerably the commissioning of the LUCIs in AO mode.

Meanwhile, LBTI will continue to enhance its operational readiness and increase its capabilities and scientific productivity. The upgrade of LMIRcam, the main detector currently using AO for science at LBT, proposed two years ago, was finally funded by LBTO and is moving forward. Spectroscopic capabilities were added by the LBTI team as part of the ongoing ALES project (see Skemer et al.[13] for more information).

SOUL (Single conjugated adaptive Optics Upgrade for LBT, see Pinna et al.[14]), which intends to improve the current AO system (wave front sensor detector improvement and increase of the number of sub-apertures), went through a preliminary design phase, which was successfully reviewed at the end of 2015. It is now funded by LBTO and LBT partners and will move forward. It is considered as an important project which will improve the performances of the existing system on bright stars and enable AO observations on fainter targets, thus improving the sky coverage of AO at LBT. SOUL will be deployed in 2017 for LBTI and 2018 for the LUCIs, maintaining the high-resolution and extreme-AO capabilities of the observatory at their best possible level.

6.2 Investing for the longer term

As we explained in *Step 1*, many proposals were submitted in 2014 for next generation instruments and a few of them were selected at various levels for further studies. They are described in some details in Wagner et al.[15] and a presentation of each of them can be retrieved from the 2014 LBTO Users' Meeting web site (http://lbto2014um.weebly.com/).

Two years later, and after much discussion at the LBT Scientific Advisory Committee (SAC) and Board of Directors, two of the initial proposals were selected as "PI second generation instruments": SHARK, which morphed into two instruments, SHARK-NIR (Farinato et al.[16]) and V-SHARK (Pedichini et al.[17]), and iLocater (Crepps et al.[18]). The decision was difficult as there are no resources at the observatory to fund any development and the partnership is not ready at this time to bring additional funding not related to operations. At the same time, there is a clear need for small and fast-track new instruments able to use at their best the performance of the AO, especially upgraded with SOUL. A big instrument à la LUCI or MODS would not be manageable, as stressed by the Visiting Committee in early 2015.

- The SHARK concept is a pair of instruments taking advantage of the existing LBTI AO modules upgraded by the SOUL project described above. One channel covering the NIR (0.9–1.7 μm), SHARK-NIR, and a visible one (0.6–0.9 μm), V-SHARK, will provide both imaging and coronagraphic modes. SHARK-NIR and V-SHARK passed successfully their Preliminary Design Review in December 2015 and March 2016 respectively.

- iLocater (The World's First Diffraction–Limited Doppler Spectrometer) is a high-resolution spectrometer that will identify and characterize Earth–like planets orbiting the nearest stars.

These new instruments are given a "PI" status, which means that they are developed at no cost to the observatory. These instruments are scheduled to come after the completion of the ongoing projects and highest priority items we mentioned in the previous section, not impacting their progress. The conditions imposed on the development of these new instruments also ensure that the observatory will not divert its current resources from the high priority tasks while still enabling staff to follow them as they progress. Finally, they will not come to the telescope as long as the observatory is not ready for them. Completing the current projects is clearly LBTO's highest priority!

Unlike the current facility instruments, these new instrument projects will be monitored by the observatory, which will be involved very early on in their development. Instead of being black boxes, they will arrive at the observatory as well-known entities fitting the operations of the telescope, with clear software and hardware requirements when appropriate. **Q**-compliance will be required for the new instruments which intend to be offered to all partners. The two SHARKs and iLocater will benefit highly from **Q** as they are designed primarily for diffraction limited mode, therefore requiring good seeing.

7. SCIENCE PRODUCTIVITY

7.1 Publications

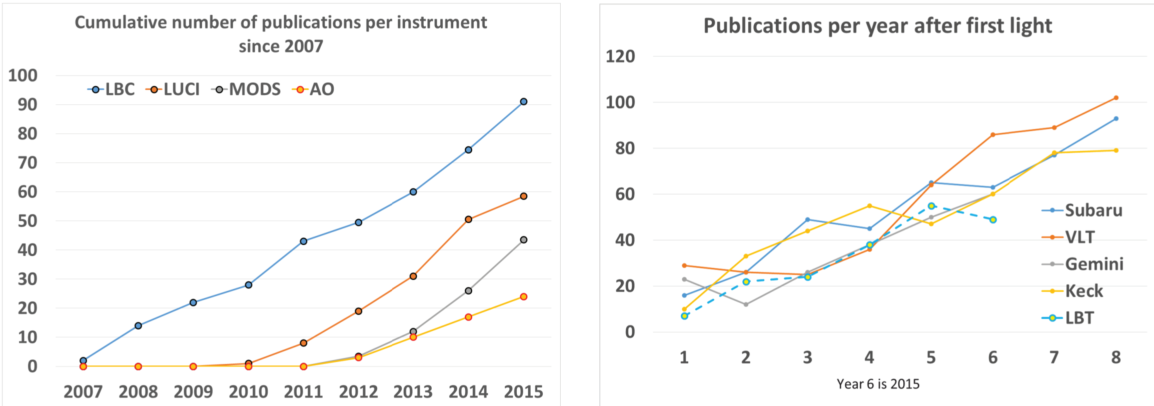

Figure 10. *Left*: The cumulative number of publications per year and per instrument. AO is a combination of FLAO imaging using PISCES, a simple NIR camera, in the early years with an increasing number of papers based on LBTI in imaging or interferometric mode in the past two years. *Right*: The progression of LBTO publications compared to the major 8-10m class telescopes. See text for more details.

The left graph on Figure 10 shows the cumulative number of papers per instrument over the years.

Wide-field imaging with the pair of LBCs is producing a steady flow of publications. With one side optimized for blue and the other for red, LBC is actually one of the few wide field cameras able to observe efficiently in the blue side of the visible spectrum. The pair of LBCs also allows simultaneous observation in two different wavelength, an asset when studying extrasolar planets atmosphere through their transit, or faint rotating bodies which require long exposure times like asteroids or Kuiper Belt objects: the field size provides a wealth of reference stars for accurate relative photometry and the simultaneity mitigates the effect of shape variations.

LUCI, after a regular acceleration in 2013 and 2014, shows a clear deceleration in 2015. It reflects the various issues encountered in 2013/2014 which led to many high priority programs not observed and only few data acquired. The curve is expected to grow again at its 2014 rate in the very near future.

MODS is on a steady climb, reflecting the reliability of the instrument and its amazing throughput. With the move to binocular mode, which will double its efficiency, one can expect that MODS will continue to significantly contribute to the scientific production of the observatory.

The progression of the number of publications follows the slope of other major observatories in their early years, as seen on the right of Figure 10. With two 8.4-m mirrors, we should eventually do better than single telescopes, including Keck or Grantecan, if publication rate and size are correlated (which is somewhat true). After all, the combined mirror area of LBT is equivalent to an 11.7-m telescope! However, the mix of poor weather statistics and summer monsoon shutdown will likely bring us back to the pack of the current large telescopes.

7.2 LBT as a forerunner of the ELTs

As we stated in *Step 1*, LBT is a pair of 8-m class telescopes working together as well as the first of the ELTs (Extremely Large Telescopes), able to provide the spatial resolution of a 22.7m telescope. Therefore, LBTO must offer to its users the efficiency and versatility of the current generation of 8- to 10-m telescopes while developing its interferometric capabilities to indeed become the first ELT. This dual mission is illustrated in the mission statement currently used as the basis for this development plan up to the end of the decade:

As the first of the ELTs and one of the leading 8-m class telescopes, LBTO must offer, as efficiently as possible, state-of-the art instruments delivering high-quality data to the users of the observatory, thus enabling excellent science at the forefront of astronomy.

It is therefore satisfying to see that the first two publications from the LBT in interferometric mode were published in 2015, one using LBTI as a nulling interferometer (Defrère et al.[19]) and the other as a Fizeau interferometer (Conrad et al.[20]), followed by a few more!

This is clearly only the beginning of an exciting era. With LBTI continuing to develop its interferometric capabilities, especially in Fizeau mode with integral field unit spectroscopy and with improved sensitivity in nulling mode, LBT will have a unique role while we wait for the first ELTs to come to operation in diffraction limited mode.

If LN current Lean-MCAO mode is successful, there will likely be a push to move to MCAO with a much larger field (40"x80" for example), which would be a unique capability in the Northern Hemisphere. Such a move could be done while protecting the use of LN as an interferometer, which would provide a 10"x10" field of view at the resolution of a 23m telescope. More on this in *Step 3*.

8. CONCLUSION

LBTO continues to move at a fast pace toward full operation, a move which will be its first priority. The optimization of the observing modes and the improvement of the services to users runs a close second.

The coming two years should see more efficient operations leading to better data and more science, with the full operation in binocular mode of the facility instruments, the development of exciting new projects which will eventually complement the current suite of instruments, and more ELT-like science thanks to LBTI using improved AO capabilities. *Rendez-vous* in two years with *Step 3*!

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