13-0504

Challenges and progress with the development of a Lunar Laser Ranger for South Africa

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Abstract. *The development of a Lunar and Satellite Laser Ranger at the Hartebeesthoek Radio Astronomy Observatory, South Africa, in collaboration with the Observatoire de la Côte d'Azur (France) and NASA(GSFC) is progressing well. Complete refurbishment of the ex-French telescope is underway, this includes a complete strip-down of the telescope, re-aluminising and re-coating of the main and secondary mirrors, gearbox overhauls and new drive motors, encoders and servo system. We describe the development and algorithms of the telescope steer and tracking software system as well as the software approaches used to control and access various subsystems via micro-controllers. As far as possible, the Lunar Laser Ranger will be software operated. The focus of this approach is on efficiency, safety and optimal use of tracking time. Subsystems will be monitored continuously, flagging out of bound parameters for possible human intervention, or automatic system shutdown. An integrated but independent GNSS/electronic laser distance measuring system will provide continuous and automated inter-vector ties between the telescope's invariant reference point and pre-surveyed reference piers. The laser system being constructed in collaboration with NASA (GSFC) is described and some technical parameters are brought into context with expected system performance.*

Introduction

Lunar Laser Ranging (LLR) is a unique and currently the only method to obtain ranges to the Moon with centimetre accuracy. This allows use of the data for tests of the General Theory of Relativity, maintenance of a precise lunar ephemeris and evaluation of the time-rate-of-change of the gravitational constant *G*. For a recent review of LLR scientific applications refer to Williams et al., (2009) and Combrinck (2013). A status report[1] of the South African LLR project and short review of scientific objectives were given in Combrinck (2011), here we will report on issues relating to system hardware and software development. The International Laser Ranging Service (ILRS) (Pearlman et al., 2002), is a service of the International Association of Geodesy (IAG) and through the activities of its members, provide highly accurate global satellite and lunar laser ranging data. Satellite Laser Ranging (SLR) data are utilised in large number of scientific applications which range from geophysics, oceanographic research, precise orbit determination, the maintenance of the International Terrestrial Reference Frame (ITRF) through to fundamental physics.

The current ILRS network is shown in Figure 1, where it can clearly be seen that the network is more sparse in the Southern Hemisphere, this is especially true of the LLR stations, of which there are currently no operational LLR stations and far fewer SLR stations than located in the Northern Hemisphere. It is envisaged that the South African LLR station will rectify this situation to some extent by becoming operational within the next 3-4 years. This project is done in collaboration with

[1] Available from https://www.researchgate.net/profile/Ludwig_Combrinck/publications/

NASA (GSFC) and the Observatoire de la Côte d'Azur (OCA), which is located on the Plateau de Calern near Grasse (France). The OCA station utilises a 1.54-m Cassegrain telescope for LLR purposes and has been active in LLR observations for several decades. The 1 m Cassegrain telescope used in the South African LLR project was donated to South Africa by OCA. Locating an LLR system in South Africa improves the geometry of the LLR network and will add valuable data to a time series of data that is currently easily affected adversely if one of the existing stations experiences downtime. Recently Hofmann et al., (2014) (see paper in these proceedings) conducted a simulation illustrating the scientific advantages where an extended LLR network was evaluated by adding a station in South Africa or in Japan.

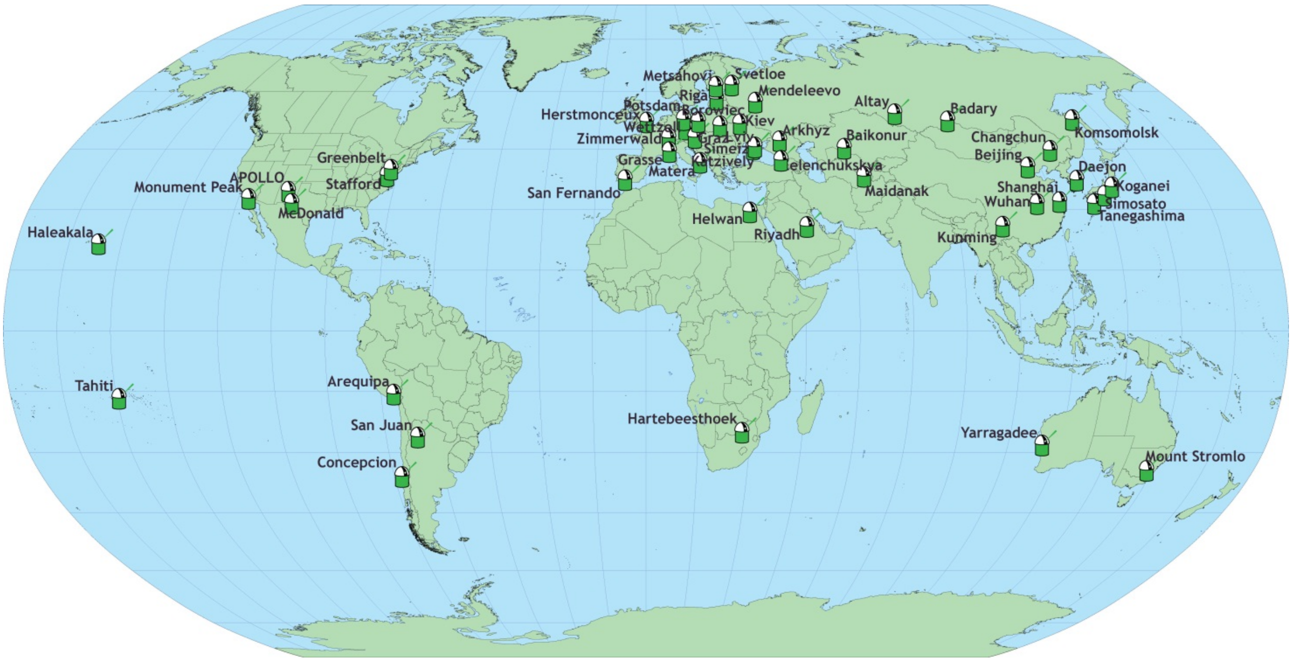

Figure 1. Current SLR and LLR network. The operational LLR stations are located at Apollo, McDonald (both USA), Grasse (France), Matera (Italy). Japan has indicated that they will be developing a system in the near future. The only future LLR station in the Southern Hemisphere is the one being constructed in South Africa at Hartebeesthoek (source http://ilrs.gsfc.nasa.gov).

Software development

Fundamental to the overall design concept of the LLR system is the software-centric model (see Figure 2) adopted for all telescope and peripheral hardware control functions. The interaction with all mechanical and electronic devices will therefore as far as is practical, be from a software interface. The programs are written in C/C++. Currently three main programs are being developed, these communicate via Dynamic Data Exchange (DDE). Smaller sub-programs are loaded into microprocessors.

- **LLRSteer:** This is a graphical interface to objects being tracked, contains the astronomical routines and displays of relevant parameters such as an object's Right Ascension (RA), Hour Angle (HA), Declication (DEC) and topocentric coordinates (Azimuth and Elevation). LLRSteer will also make provision for status messages, visualisation of objects and their metadata. Typical objects that can be selected for tracking will be LLR reflector arrays on the Moon's surface, calibration stars, planets, as well as artificial satellites using Two Line Orbital Elements or the ILRS consolidated prediction format if available and appropriate. Any target can be set up in an observing file, for instance positions of the telescope for storing, maintenance positions or ranging to calibration targets. These object target files are standard Excel spreadsheets so are easily updated by manual means. Subroutines from the IAU International Astronomical Union Standards of Fundamental Astronomy (SOFA) (http://www.iausofa.org) collection are used in LLRSteer, as well as some ILRS provided routines which are available for download at http://ilrs.gsfc.nasa.gov/technology/software/index.html.

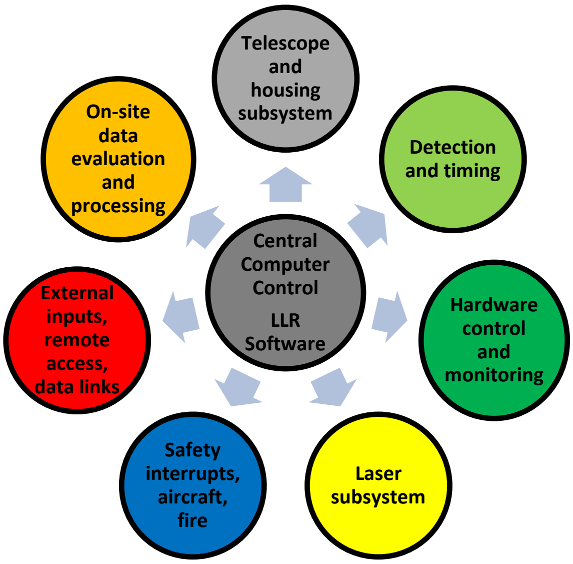

Figure 2. The complete system design is software-centric, where a central computer allows commands and commuication to all subsystems via a graphical user interface.

Some graphical routines were obtained from open source software (Home Planet, by John Walker, available at http://www.fourmilab.ch/homeplanet/). Provision will be made at some stage to analyse SLR and LLR data in near real-time, which will facilitate data quality checking, this software will adhere to International Earth Rotation Service (IERS) (Petit and Luzum, 2010) standards, available from (http://tai.bipm.org/iers/conv2010/).

- **LLRServoControl:** This program runs in a console type window and its main function is to communicate with the servo controllers. Table 1 contains some of the electrical and other specifications of the servo drives. LLRServoControl communicates with four servo

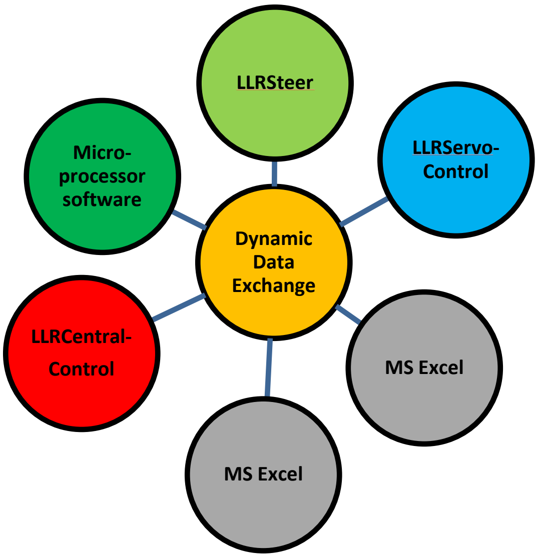

Figure 3. Sub-programs communicate via Dynamic Data Exchange, some writing to MS Excel to facilitate plotting and simple statistics as well continuous data exchange.

Table 1. Electrical specifications of the servo drives as configured for the LLR

Parameter	Units	Value
Power supply voltage	Volts	48
Maximum continuous current	Amps (RMS)	15
Maximum continuous phase current delivered to motor	Amps (RMS)	15
Overload phase current (1 second)	Amps	30
Maximum overload current (1 second)	Amps	50
Maximum continuous output power at full temperature range	Watts	1000
Efficiency at rated power		>98.5%
Pulse width modulated switching rate	KHz	40(±1)
Encoder (differential quadrature line driver signal interface (RS422) signal frequency	MHz Volts	2 (max) 0 to 5

controllers set up in a daisy chain configuration. Each servo controller reads positional data from an encoder; there are four encoders, one attached to each of the drive motors and one attached to each of the telescope axes. This configuration allows accurate speed control of the motors, accurate axes position determination and calculation of mechanical backlash in the gear subsystem. It also provides for redundancy, as in the case of either a servo controller or encoder failure, LLRServoControl can be switched to steer the telescope using either the servocontrol/encoder combination located on the axes or on the motors, with full functionality retained. The servocontrollers are based on an Embedded Motion Control library (EMCL), which is a firmware managing the control and communications functions of the motion controller system.

- **LLRCentralControl:** This program is a graphical user interface which allows control and access to microprocessors which reads voltage and current levels, enables relays to switch power supplies and peripheral equipment on or off. It can trigger certain events and make appropriate decisions depending on the status of hardware. It effectively replaces the ‘control console’ and acts as the operator interface to all hardware. A feature is available that can display JPEG images of instruments, for instance a picture of the telescope parked at zenith if that is the case to facilitate rapid instrumentation status information.

- **Program inter-connectivity:** LLRSteer and LLRServoControl shares data via Dynamic Data Exchange (DDE) (see Figure 3) utilising raw DDE as well as the Dynamic Data Exchange Management Library (DDEML). The DDEML is a dynamic-link library (DLL) that LLRSteer and LLRServoControl uses to manage the interaction between client and server. In this way, continuous exchanges are possible in which both programmes send updates to one another as new data becomes available. Both programs (acting as servers) write parameters directly into Excel worksheets (acting as clients) and this creates an efficient way to create plots of changing parameters as well as a means to perform simple statistical operations on the parameters.

- **Microprocessor software:** This code is uploaded into microprocessors via a USB interface, LLRCentralControl communicates with this code and allows access to the functions of the microprocessor. A subset of the C programming code is used to program the microprocessors. LLRCentralControl communicates with the microprocessors via a USB port.

Telescope refurbishment

The mount and tube assembly were both completely dissasembled in order to inspect and evaluate the mechanical condition of components such as gears, seals, panels, insulation, fasteners and optical assemblies. Special protective boxes were constructed for the main and secondary mirrors, these will be re-aluminized and re-coated early 2014 before being reinstalled. Figure 4 illustrates various stages of the telescope refurbishment. A special cradle was built to enable the tube to be moved via a chain and gearbox arrangement to allow easy access to its various parts. The secondary mirror spider was completely refurbished; the spider retains the secondary mirror holder in place and allows adjustments in three dimensions to be made to center and focus the secondary mirror in the light path.

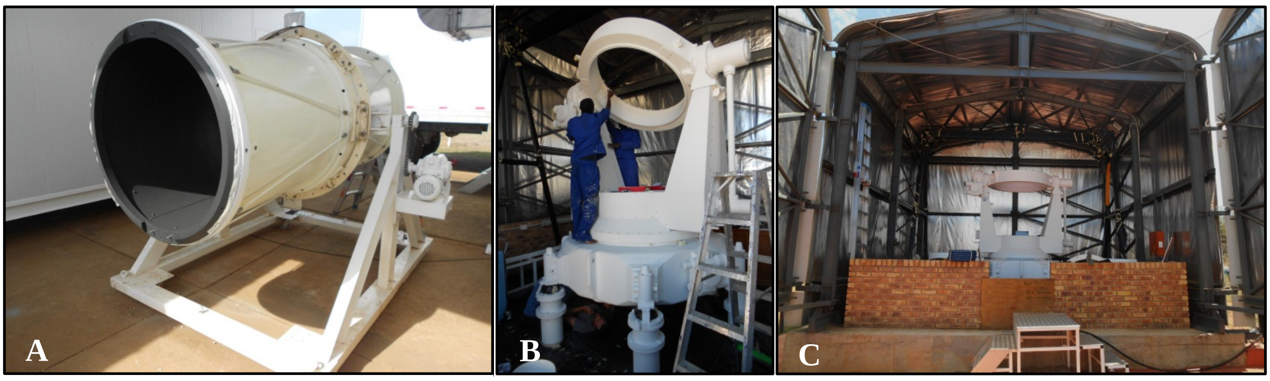

Figure 4. (A) Restored main tube with secondary reflector and spider removed (without covers), (B) the azimuth-elevation mount was painted with a heat reflecting paint containing microscopic glass globules and sealed with a tough oil resistant paint, (C) a run-off enclosure instead of a dome is used which will allow the telescope to acclimatize to the ambient environment and so improve structural and optical stability.

Control centre

A 12 m shipping container has been fitted with insulation layers on the inside as well as the outside of its sides. Three air-handlers have been installed to provide filtered air to the control centre. A positive pressure is maintaind in the laser room, to avoid dust contamination of optical components. The control centre and control room is shown in Figure 5. The layout of the control centre consists of the laser room, power supply room, control room and a small admin room. Some of the graphical user interfaces of LLRSteer can be seen on the screens.

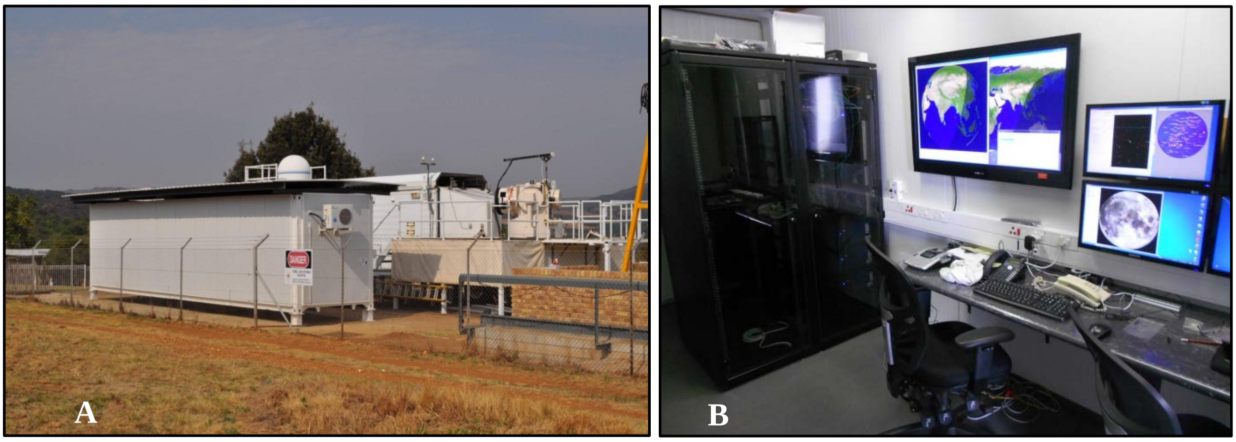

Figure 5. (A) The modified shipping container which is utilized for the control centre. It has been fitted with a shade providing roof. (B) Two standard 19” racks will contain all the electronics and the operator will track the Moon and satellites using only a mouse and keyboard.

Laser subsystem

The laser built by the NASA SLR contractor (Cybioms Corporation) will be dual functional, providing a 1 kHz, 0.5 mJ section for satellite laser ranging and a 10 Hz, 100 mJ (<80 pico-second pulse length) section for LLR. The main (1 m) mirror will be used for ranging to the Moon, whereas a beam expander mounted to the side of the main tube will be used for SLR purposes.

Other subsystems

Several other subsystems are in the process of being designed or evaluated. Power supplies for the telescope drive system, servo controllers, dc motor encoders and suitable housings for these have been purchased and integration into the LLR system will be in early 2014. We are investigating several suitable station time systems, single photon detection systems as well as event timers.

Expected accuracy

Users of LLR data normally ask what is the expected accuracy of the system; we expect that as the laser, photon detection package, event timer and internal calibrations will be state of the art, sub-cm accuracy will result. We do plan to increase the power of the laser to 200 mJ at a later stage and this has been made provision for in the laser table layout. Expected return rate is about 4 to 6 photons per minute, given astronomical seeing conditions of 1 to 2 arc-seconds.

Acknowledgements

The assistance and collaboration of OCA (France) is greatly appreciated, in particular the support of Pierre Exertier, Francis Pierron, Etienne Samain and Clément Courde. Constant support of NASA and Thomas Varghese of Cybioms Corporation for this new LLR development is appreciated. Andre van der Merwe of HartRAO was responsible for the tube and mount refurbishments. Funding received from the National Research Foundation (NRF) and the Department of Science and Technology, South Africa, towards this project is appreciated. This work is based on research supported by NRF grant IFR2011041500034.

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