AUTONOMOUS LASER RANGING RESULTS FROM MOUNT STROMLO

by

John Luck [1], Christopher Moore [2] and Ben Greene [2]

1. AUSLIG, Canberra ACT, Australia
2. Electro Optic Systems Pty Limited (EOS), Queanbeyan NSW, Australia

1 Introduction

This paper describes the performance and implementation of the Mt Stromlo SLR station operating in autonomous tracking mode, i.e. when the station is effectively unmanned. The current station and its performance is the culmination of many years of SLR work and experience in Australia. The milestones leading to the current situation are presented in the following table.

- *Nov 1997: Contract signed between Auslig and EOS. Building foundations laid.*
- *Oct 1998: Stromlo operations commenced.*
- *Nov 1998: Orroral ceased operation.*
- *Jul 1999: First successful* ***fully unmanned*** *tracking.*
- *Mar 2000: Routine* ***weekend*** *unmanned tracking and processing.*
- *Jul 2000: Routine* ***unmanned data transmission*** *to EDC.*
- *Jul 2000: 24h tracking record of 32 unmanned passes (out of 40).*
- *Oct 2000: Trials of* ***unmanned 7-day*** *operations, 24^h/day.*
- **Planned: Routine unmanned 24^h/7 days operations in 2001**

2 Auto Tracking Performance

The results during autonomous ranging at Mt Stromlo are comparable in every way with those achieved during manned operations. Currently the station operates unattended for approximately 80 hours per week, compared to 88 hours with an operator in attendance.

2.1 Productivity

In terms of productivity, either in terms of passes acquired, or the number of normal points generated, Mt Stromlo has consistently been one of the best SLR stations in the world. The station routinely acquires 30 or more passes per (clear) 24 hours when operating in either manual or autonomous modes.

Pass productivity in autonomous mode has been typically 81% compared to 89% in manual mode, with weather conditions not being a significant factor. Tracking in autonomous mode of LEO satellites such as CHAMP and WESTPAC, and high satellites such as GPS has been satisfactory.

2.2 Precision

One performance criteria used in the contract between AUSLIG and EOS is the percentage of passes whose “normal point precision” resulting from the weekly orbital analyses of Lageos 1 and Lageos 2 is no worse than 2mm. The results from Center for Space Research (CSR) reports, shown in Figure 1, indicate that the differences between Lageos 2 results obtained from autonomous and manned operations are not really significant. The more significant differences for Lageos 1 results are attributed to discrepancies in the orbit analyses rather than to station performance. This interpretation is supported by the outcomes shown in Figure 2 for the four analysis centers - CSR (University of Texas),

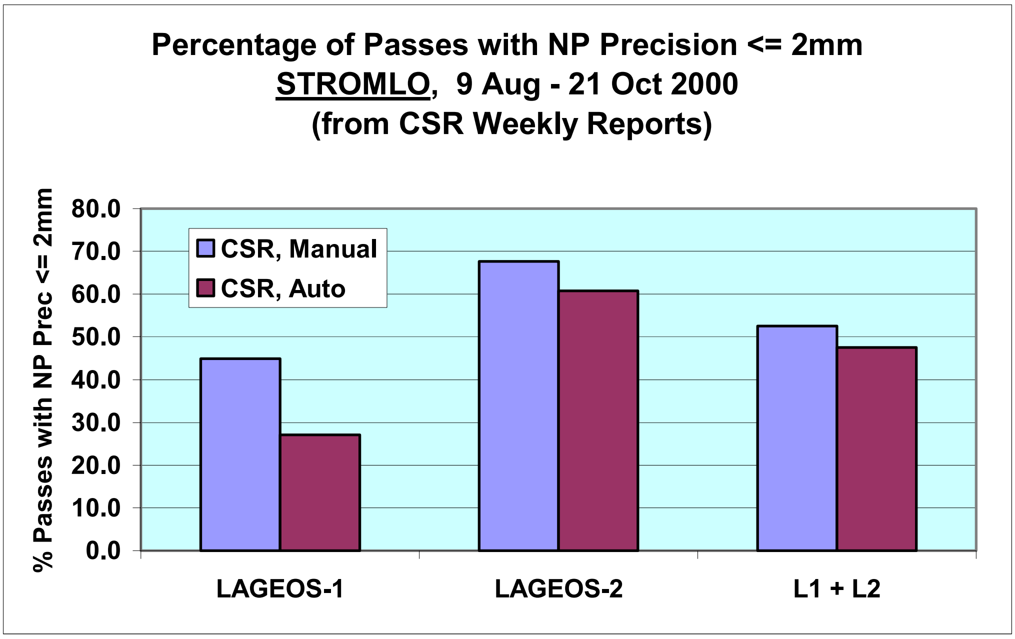

Figure 1:Precision of Manual vs Autonomous Operations

DUT (Delft), MCC (Moscow) and SHAO (Shanghai) that vary widely. A discussion on the consistently poorer results for Lageos 1 is outside the scope of this paper.

3 Implementation of Automation at Mt Stromlo

The implementation of automation at Mt Stromlo has involved the development and

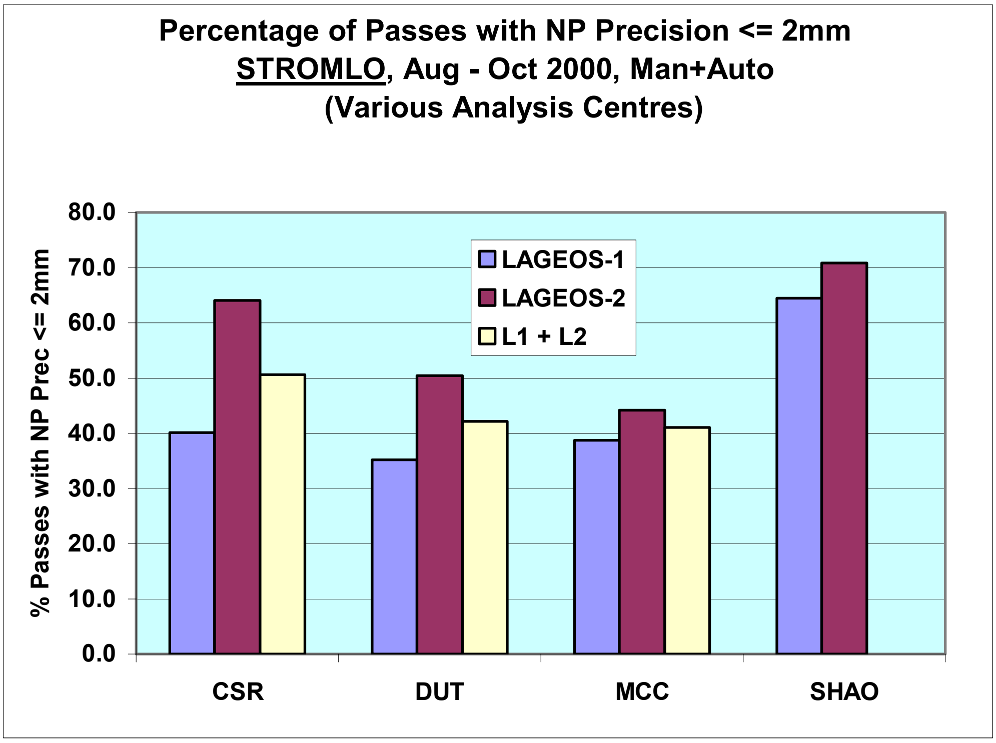

Figure 2: Comparison of Results from Analysis Centres

evolution of many aspects of the SLR ranging system. The idea that the automation processes must be built on top of solid and reliable physical infrastructure, hardware subsystems and operational software applications is key to a successful implementation. This idea is represent in the system architecture diagram in Figure 3.

Figure 3 also illustrates the four major automation processes,

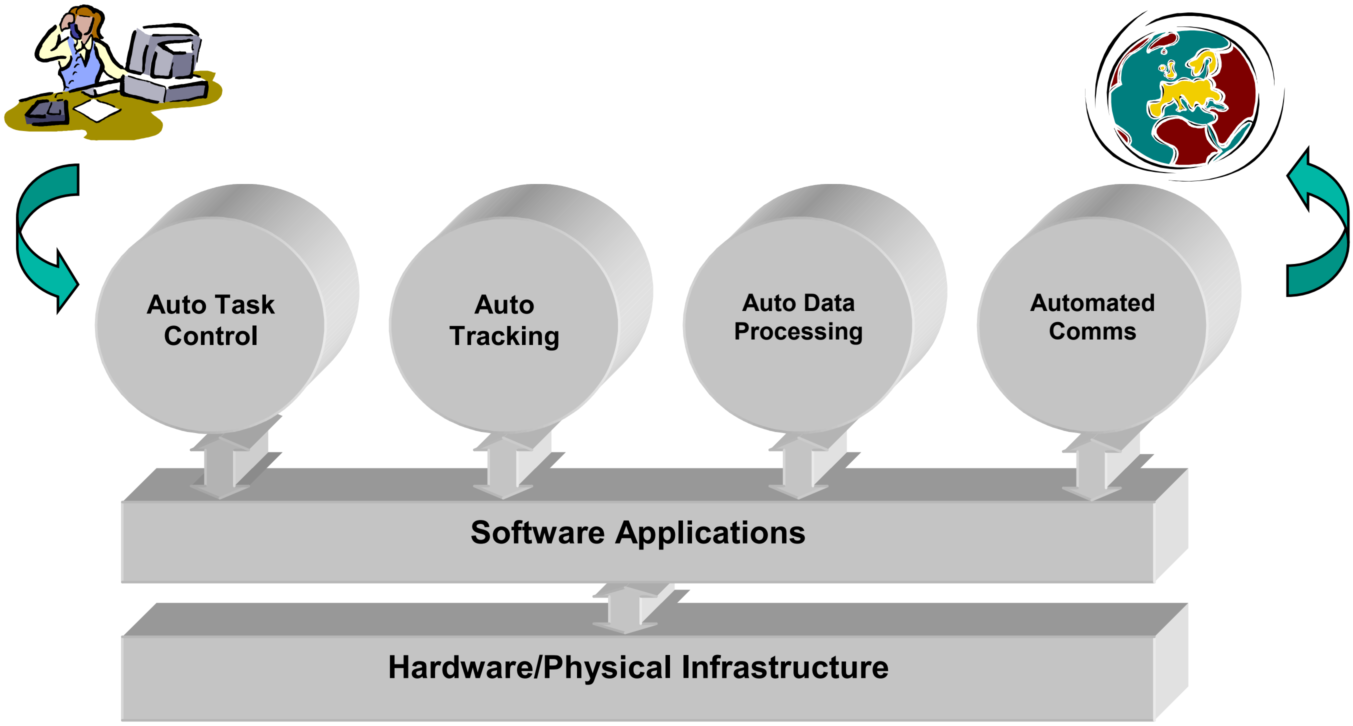

Figure 3: System architecture

- Automated task management
- Auto tracking
- Automatic data processing, and
- Automated communications.

that overlay the system foundations and provide a framework for the implementation and description of an automated SLR station.

These processes are equally important if automation is to be successful implemented. To rephrase a common aphorism, an automated system really is as strong or as capable as its weakest component. The secret is of course not to have any weak components.

Figure 3 also shows that the system must have an input and output. The output is of course the data products that are sent to the global data centres and the input is the planning and scheduling of tasks that is required for station operation.

4 Automatic Tasking

The approach taken to automated task management at Mt Stromlo, has been to develop pre-planned, static schedules that the system will follow come what may. It is a relatively straightforward approach, but from experience with tracking satellites over the last couple of years and the level of productivity that the station has achieved, it is an approach that works reasonably effective.

4.1 Mission Planning System

Operating schedules are prepared using the Mission Planning System (MPS) application. The MPS has been described before (Greene et al, 1998), but it is useful to include Figure

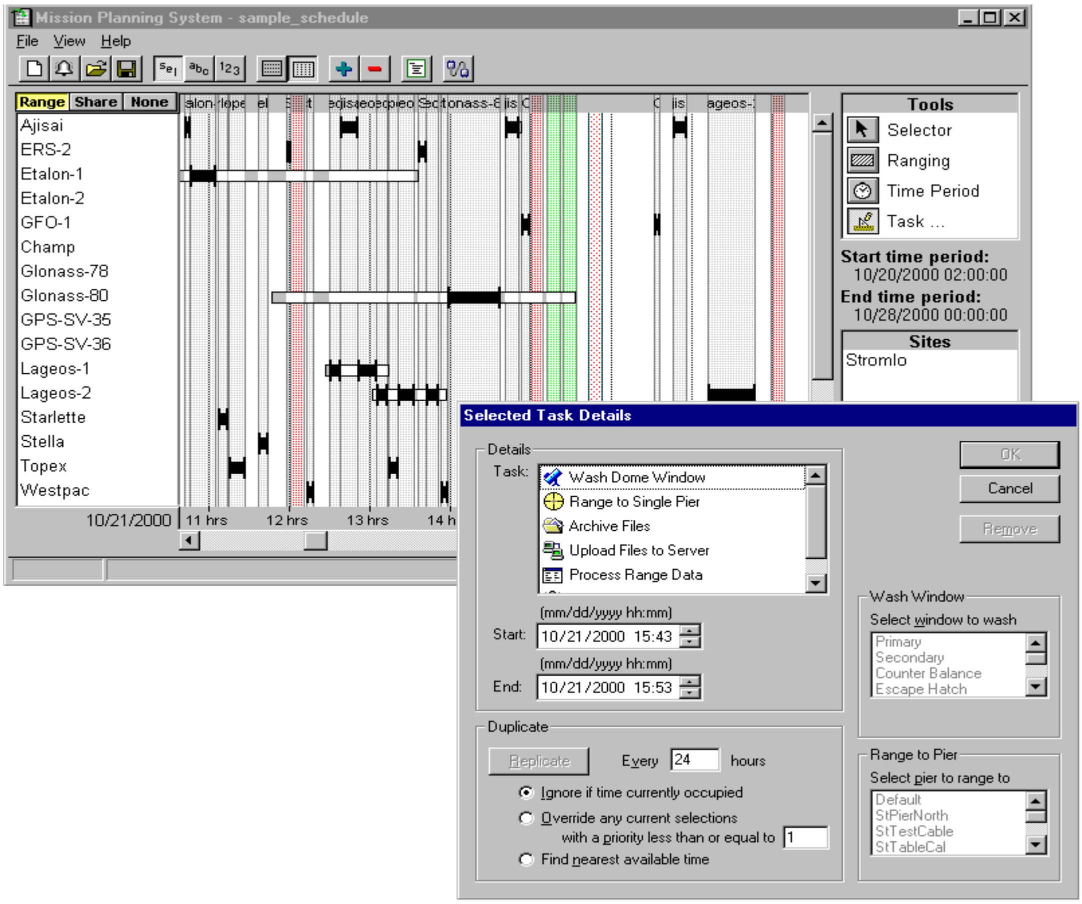

Figure 4: Mission Planning System

4 to graphically illustrate the types of tasks that the unmanned station will perform under control of an automatic schedule.

Figure 4 illustrates a 7–day schedule generated for actual use at Mt Stromlo. It shows the a typical variety of SLR tracking tasks that are created for whole and segmented satellite passes, and where the priority, timing and duration of tracking tasks are planned and applied. While higher priority low earth orbit satellites interrupt higher orbit passes, it is relatively unusual for LEO passes to overlap completely with other LEO passes hence loss of data due to priority conflicts is not a significant issue.

4.2 Calibration and Data Processing Tasks

As well as SLR tasks, we can add any number of other tasks to the schedule. The dialog shown in Figure 4 allows a planner to select a task from a menu of possible tasks and to define its start and end times. Selected tasks are inserted in the schedule as illustrated by the coloured stripes on the display.

For Mt Stromlo, such tasks usually include ranging to our primary calibration pier, or to our auxiliary piers when we require a Minico. They include tasks to perform data processing, to generate alerts file, to prepare data for publication and to archive files.

4.3 Automatic Task Management

If the automatic schedule is being run, when the time comes to start each scheduled task in turn, the system automatically

- checks the status of the hardware
- establishes the required hardware configuration
- checks safety interlocks
- generates any data required for that task
- logs events and errors
- manages all of the low-level functions required to complete the task, and
- stores any output data.

5 Autonomous Tracking

To automatically track a satellite requires that a system be capable of performing a wide variety of functions or tasks in a coherent and cooperative way. The following represents just some of the tasks undertaken by the Mt Stromlo system while ranging during a satellite pass.

- Aircraft detection
- Skyline identification
- Sun avoidance
- Collision band management
- Beam crossing avoidance
- Return rate calculations
- Control of telescope offsets (biasing)
- Control of ranging window widths and offsets
- Satellite acquisition and tracking optimization.

Some of these functions are best performed by the dedicated hardware, electronic and embedded software sub-systems, while some are better performed by more complex purpose built software applications.

In the Mt Stromlo system, functions such as control of laser firing in defined regions of the sky, aircraft detection, beam crossing avoidance, sun avoidance and protection, and minimization of collision zones are managed automatically at all times by dedicated low level facilities. Management of telescope and ranging window controls during target search, acquisition and tracking optimisation is provided by auto tracking software applications.

5.1 Collision Band

A "collision band" refers to the condition in which the range to a target would cause timing measurement of an outgoing laser pulse to coincide with a returning pulse from a previous event. Such collision zones are unavoidable, but the Mt Stromlo system continuously monitors this condition and minimizes its effect by automatically modifying the fire rate slightly.

5.2 Beam Crossing

Beam crossing avoidance is perhaps a less familiar facility. The station on Mt Stromlo has the benefit of being close to a number of astronomical observatories belonging to the Australian National University. Being a good neighbour, the station has the responsibility for disabling laser transmission when the beam would otherwise intersect the observatories line-of-sights.

Using a combination of software functions and internet communications between our station and the observatory's telescope control systems, the station automatically inhibits laser firing whenever a beam crossing is imminent.

5.3 Return Rate Measurement

One vital data item that is necessary for automatic tracking to function is a reasonably good measure of actual return rate in real-time. In the Mt Stromlo system this is obtained by a real time histogram analysis that takes into account signals that are trending. It is also important that such a measure of return rate is also subjected to an appropriate level of smoothing.

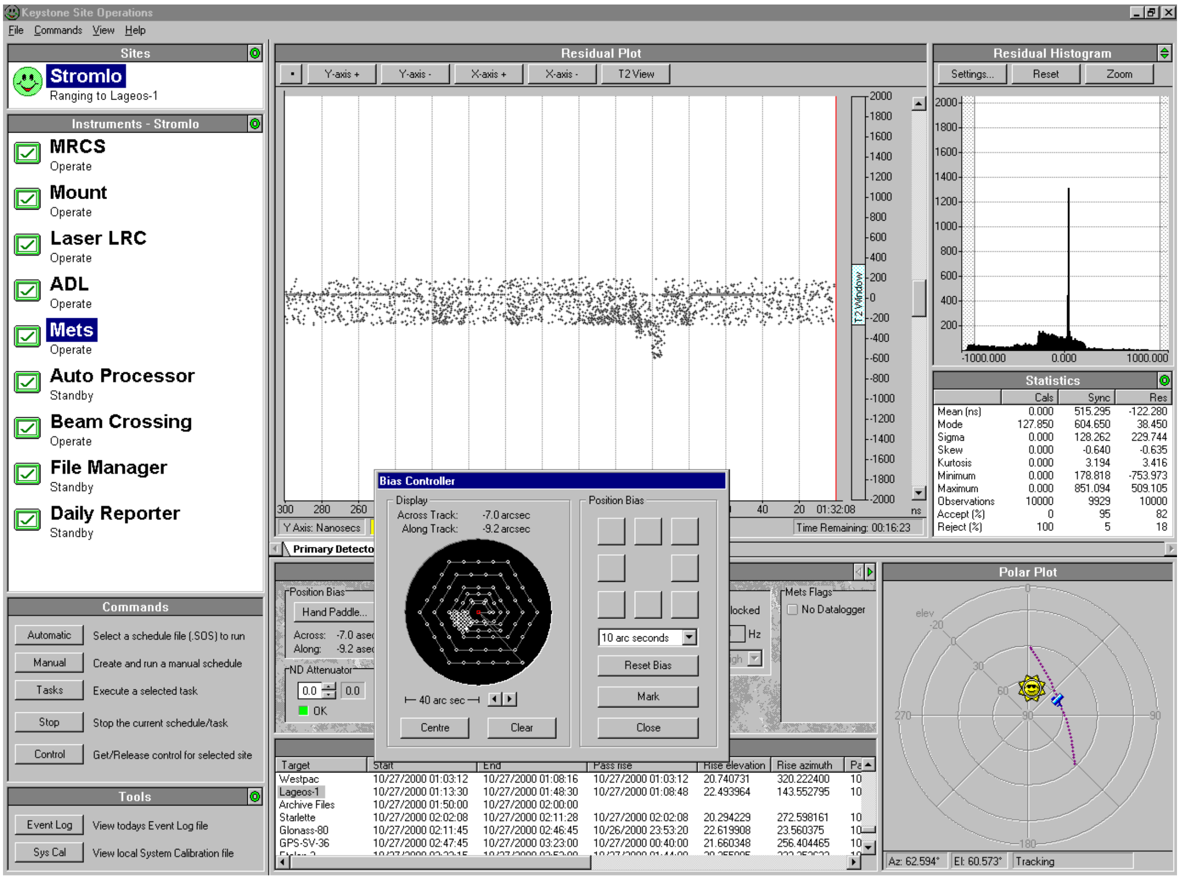

Figure 5: Displays showing auto tracking in progress

5.4 Automated Acquisition and Tracking

Accomplishment of actual automatic, i.e. unaided, satellite acquisition and tracking in the Mt Stromlo system is controlled by purpose built Auto Tracking Scripts that takes as input, the current measurement of return rate, and outputs commands that control the telescope along-track and across-track offset and the ranging timing window width and position.

5.4.1 Auto Tracking Language

To implement such a script, a specially developed Auto Tracking Language (ATL) was developed which is interpreted by the underlying system management software applications and which provides a powerful syntax. This ATL has been described in more detail in Greene et al (1998).**Auto Tracking Scripts**

Development of the auto track script approach was based on the following advantages.

- Scripts could evolve without requiring software rebuilds whenever a change was required.
- Development of the scripts could be handed off to people other than the software engineers.
- Unique scripts could be developed that were optimised for each satellite or class of satellite.
- It would be easy to add new scripts whenever new satellites are added to the ranging schedule.
- Scripts could be quickly modified to reflect the quality of available predictions, as has happened with the advent of daily IRVs.

The scripts that have been developed to date use spiral search patterns for acquisition, using parameters optimised for different satellites. Such a search pattern is illustrated in the bias controller dialog in Figure 5. This figure shows the Mt Stromlo system control display while automatically tracking during a Lageos 1 pass.

Once a satellite is acquired, the script continues to control the telescope in a way that attempts to optimise the return rate and which also responds to logic that tries to *infer* and *account* for intermittent loss due to, say, cloud.

If the satellite is really lost, after a time the script returns to a spiral re-acquisition pattern.

The auto track pass illustrated in Figure 5 shows that two spiral patterns occurring before satellite acquisition and fine control during acquisition. There was loss of signal at times due to patches of cloud, and change of range window at one point after a significant period of signal loss.

6 Auto Processing

The implementation of auto processing was a challenge. This was developed in parallel with the collection of many months of ranging data, sufficient to incorporate the extremely wide variety of data distributions that auto-processing would have to deal with. A number of data processing techniques were implemented and tried, but it became obvious that successful auto-processing was going to depend on finding the right combination of processing techniques that would remove noise points without significantly losing any signal.

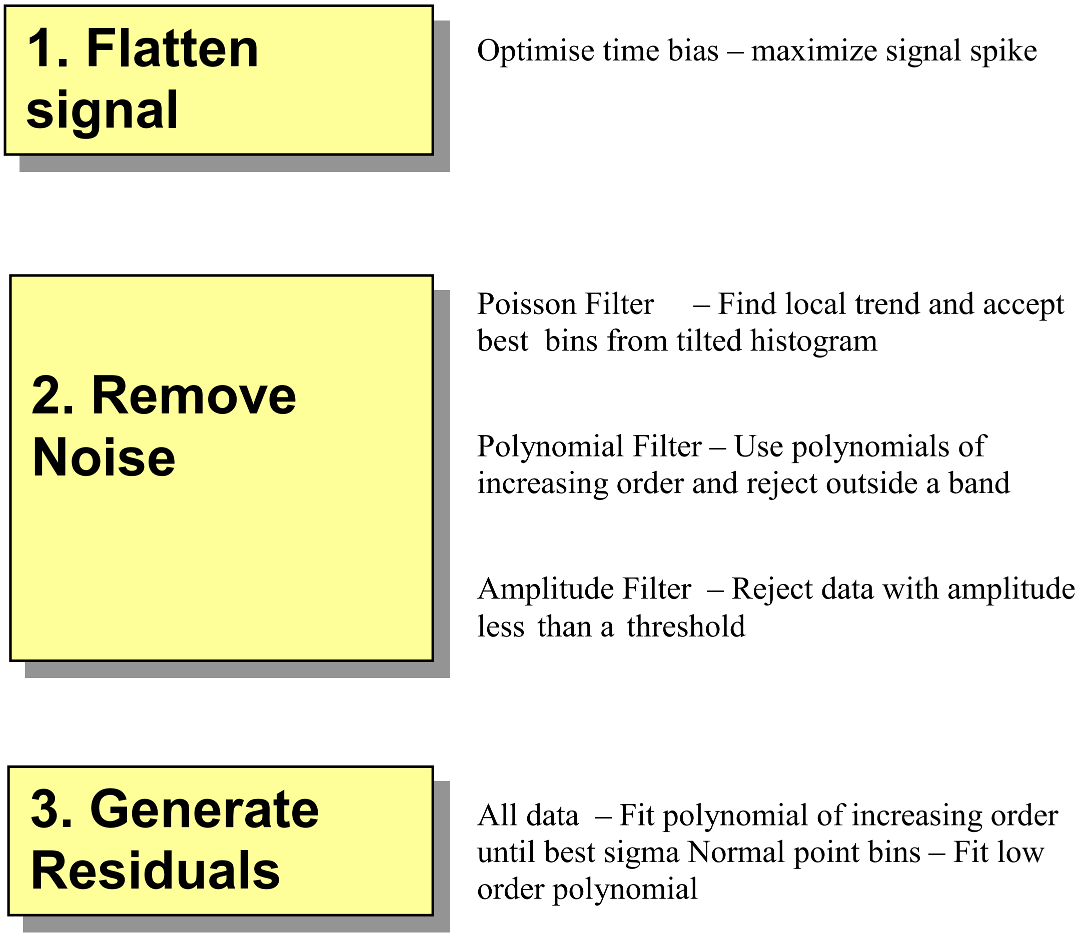

Figure 6: Main auto processing steps

While this approach required a significant amount of trial and error, the experience enabled the strengths and weaknesses of each method to be identified. The combination of techniques that has been adopted at Mt Stromlo has proved to be very robust and accurate as evidenced by the station's productivity and data quality results. Figure 6 illustrates the main steps performed by the auto processor.

6.1 Signal Flattening

Once all range data for a complete pass is accumulated, pre-processing the data to generate residuals with a minimal trend is performed. In other words, to flattening as far as possible any signal that may be in the data set. This pre-processing step reduces ambiguity between signal and noise and is essential for subsequent noise removal processing. The most successful technique found for flattening the signal is based on recursive optimisation of a time bias applied to prediction data.

6.2 Noise Removal

It was found that the successive application of two filtering techniques was very effective in removing noise without significantly losing real signal data. First, a "Poisson" filter, based on an existing technique (Ricklefs and Shelus, 1992), is applied. This technique scans data within short time intervals using tilted histogram analysis to identify locally trended signals and remove noise based on Poisson p.d.f. criteria. This technique is excellent at extracting real signal data, but it often will include spurious noise points that cannot be distinguished from a real signal, especially when analysing measurements with a large amount of noise.

The solution is to then apply a "Polynomial" filter. On the basis that the output of the previous step is primarily signal, fitting of a polynomial to the results will not be heavily biased by remaining noise. Data outside a band around the fitted curve can therefore be eliminated as being noise. This technique works well provided the filtering is started with a zero order polynomial and then higher order polynomials are applied iteratively.

Finally, an "Amplitude" filter can be selectively applied to remove data with an amplitude less than a threshold value obtained from the calibrated characteristics of the compensated SPAD detector.

6.3 Residual Generation

Once noise has been effectively removed, subsequent polynomials of increasing order are fitted to the remaining data is performed until variance is minimized. Residuals and thence normal points are determined using the Herstmonceux, (1984) protocol.

It should be noted that routine ranging to calibration targets and subsequent data analyses and calculation of system delays are also performed automatically. These processes are relatively straightforward, except to say that during normal operations, we ensure that a calibration target range task is performed immediately prior to an automatic processing task and when the processing is performed, calibration target data are always processed first. These rules simplify the generation of pre- and post cal data that will be used in subsequent processing of satellite ranging data.

Having generated normal point data, the next aspect of automation is the process of transferring the results to global data centres.

6.4 Communication Infrastructure

Successful automated communications depend very much on the reliability of the communication infrastructure. This infrastructure must cover all aspects of the communications pathway and include the local physical infrastructure, the provision of internet services and the performance of remote servers.

The local physical infra-structure, including the station's local area network, modem devices and local phone lines must be reliable and fault tolerant. Fortunately these factors are largely under the control of the SLR station, and the experience at Mt Stromlo has been that once a few initial problems were resolved, problems of any significance have been rare. Damaged phone lines would has caused approximately 1 day of lost communications in 3 years.

With the expansion of the internet and proliferation of internet services providers (ISPs), this factor is largely under the control of the SLR station although the quantity and quality of ISPs could hinder the development of automation in some regions of the world. It is fortunate that the location of Mt Stromlo near Canberra means that the quality of its internet service is high and lost communication due to the ISP or international connections has been extremely rare, perhaps 1 day per year.

As far as the performance of the remote servers is concerned, there have been a number of occasions when communications were lost due to problems at the data centres - possibly as much as one week per year as far as the station at Mt Stromlo is concerned. However, the SLR community is progressing work to improve reliability of communications to the data centres.

6.5 Use of File Transfer Protocol

Automated communications at Mt Stromlo is based on the use of File Transfer Protocol (FTP) client/server processes, rather than say, e-mail.

This approach was adopted since the use of FTP allowed the (local) station control of the timing and frequency of data transfers, ensuring that transferred data was consistent and transmissions could be synchronized with local processes by the use of automated FTP scripts. It was felt that this also allowed for the development of one technique that could then be used for all data transfers, regardless of remote server.

A very capable third party FTP client application has been adopted that includes a powerful FTP scripting language integrated with automatic scheduling functions. Figure 7

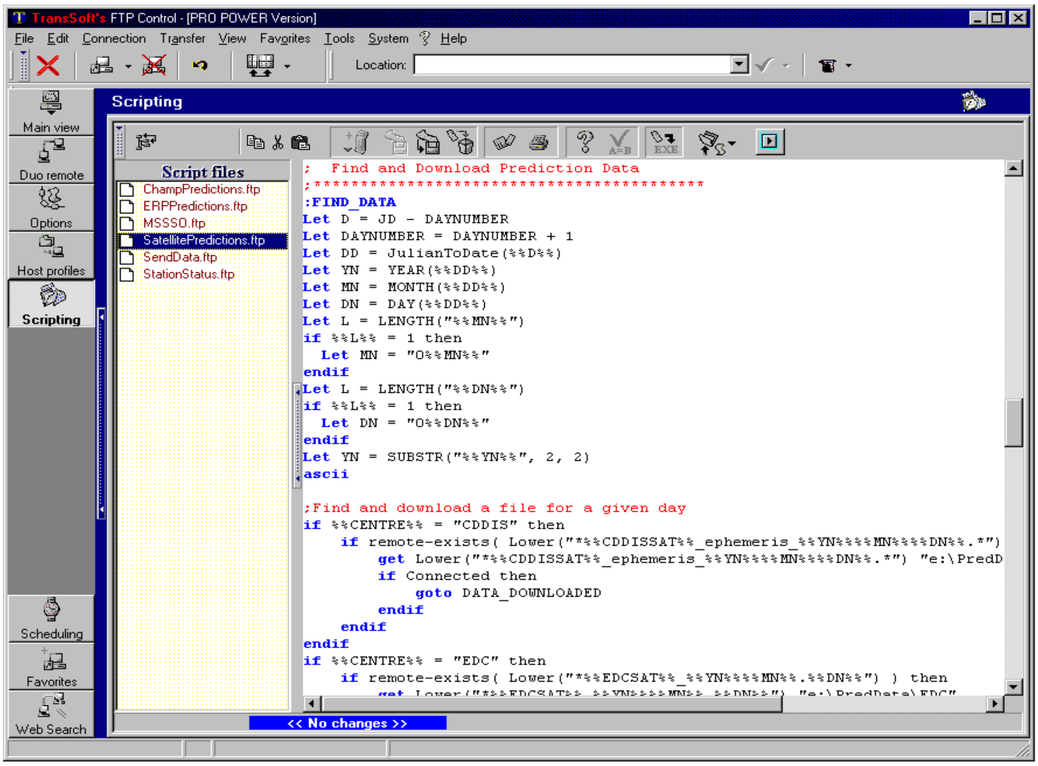

Figure 7: Sample FTP Script

illustrates the use of this application for script development.

This has allowed us to develop quite robust scripts for managing FTP communications including;

- connecting to remote servers,
- managing responses to non-availability of servers or to communication loss/interruption,
- controlling file selection and upload or download processes, and
- initiating local processes associated with data transfers.

All file transfers are managed using these FTP scripts, including the downloading of various prediction files, the uploading of normal point data and status files, and connecting to the local astronomical observatory for telescope status information.

6.6 Data Preparation and Validation

Automation requires that received data undergoes appropriate validation before it is can be used by the operational system When an automated FTP script downloads prediction data, it also initiates processes that perform quite involved data consistency checking, file storage and preparation of prediction files for use by the SLR system.

Similarly, the automatic communication system ensures that data being sent is correctly prepared and acceptable for publication. This system is synchronised with the process that collects, formats and aggregates processed range data into files ready for transmission.

The processing of range data and preparation for transmission is under the control of the automated task schedule.

7 Future Development

It is clear that station automation must continue to be developed, to increase functionality and reliability, and to reduce reliance on human intervention. In the following sections, a brief description is given of some of the planned developments at Mt Stromlo that have the potential to improve the station's automated operations.

7.1 Cloud Monitor

One of the most significant items for improving the performance of station automation will be the ability to detect and monitor cloud cover. Such a device is currently being tested.

A reliable measure of cloud cover will allow the station to operate more selectively and not waste expensive resources by ranging into overcast cloud when unattended.

If the auto-tracking system knows explicitly that tracking has been affected by cloud, then it may be able to make better decisions on how to respond, and perhaps lead to improved productivity in patchy cloud conditions.

At least, a measure of cloud cover in real time will allow us to log weather based data that will allow us to automatically produce performance statistics that can more accurately factor in the effects of weather, and which will support the automatic generation of performance reports.

7.2 High Energy Laser

Research and development of laser ranging technologies are continuing, including a high-energy laser system that may be used in an automated system to quickly acquire high orbit satellites and perhaps other satellites in marginal weather conditions.

7.3 Advanced T/R Box

In association with the development of a high energy laser system is the development of an advanced T/R box which is being designed to integrate both a high precision SLR laser system and the high energy laser, and which will be able to support multiple wavelength operations.

This design of this T/R box should also enable us to successfully implement real-time symmetric calibrations.

7.4 Continuing Software Development

Finally, continuing development of the software systems should see applications in at least three key areas of development.

The first may come from a spin-off from some other work EOS is currently doing which should allow us to develop a more capable scheduling system, perhaps one that will allow more dynamic scheduling which may take into account current system performance and conditions.

EOS is also in the process of introducing a new generation of software architecture to make it much more flexible in terms of interfacing with hardware and platform independence, and at the same time continuing to improve the reliability of software applications and the sub-systems to which they interface. Reliability is one of the most important factors achieving sustained automatic operations.

8 Conclusion

In conclusion, the work so far completed in developing automated processes and results that Mt Stromlo SLR station as achieved allows a great deal of confidence in saying that

"a fully automated SLR station is now a reality"

9 References

Reference 1 – Greene, B., J. Cotter, C. Moore, A. Loeff, I. Fras, P. Burns, H. Kunimori, T. Gotoh. "Keystone (KSP) Class Autonomous Satellite Laser Ranging (SLR) Systems." Proceedings of the 11th International Workshop on Laser Ranging Instrumentation, Deggendorf, Germany, 1998.

Reference 2 – Ricklefs. R. and P. Shelus, "Poisson Filtering of Laser Ranging Data". Proceedings of the 8th International Workshop on Laser Ranging Instrumentation, Annapolis, Maryland, USA, 1992.

Reference 3 – Herstmonceux, 1984."On the generation of normal points and the exchange of SLR data", Resolution 3, Proceedings of the 5th International Workshop on Laser Ranging Instrumentation, 1984.