Automated Control Software Checkout: the SLR2000 Experience
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Jan McGarry
NASA / Goddard Space Flight Center
Greenbelt, Maryland

John Cheek
Anthony Mallama
Raytheon Information Technology and Scientific Services
Lanham, Maryland

Anthony Mann
Michael Perry
Honeywell Technology Solutions Incorporated
Columbia, Maryland

Randall Ricklefs
University of Texas
Austin, Texas

Debugging automated software requires a somewhat different approach than testing conventional interactive software. Interacting with the software can change the results, and misrepresent a test of the automated decision process. On SLR2000 we are attempting to combine interactive testing with complete automated checkout using simulated hardware and conditions (weather, satellite, star) to control the flow of the experiment. Our testing approach and the current status of the SLR2000 software will be reported.

Introduction

NASA's next generation of Satellite Laser Ranging (SLR) systems will be totally automated, capable of making all of the decisions necessary to schedule, acquire and track the 20+ satellites carrying retro-reflectors, and capable of monitoring and, to some extent, maintaining its own health through external and internal monitors, dome control, and temperature controls. This system, called SLR2000, will communicate via the internet, and will download predicts and upload the tracking results along with system status to a parent facility daily. It will also have the capability of making emergency contacts should the need arise. This facility is expected to operate without the need for human intervention for periods of not less than four months at a time. For more detailed information on the SLR2000 system, please see the papers by John Degnan [1,2].

The software development effort for this system was built upon past SLR work, but the emphasis has clearly been on the automated aspects of this system. Testing this software requires some techniques new to conventional SLR systems. We have borrowed ideas from spaceflight systems in an effort to test all aspects of the automated SLR2000 processes.

Before we discuss our testing approach, we should begin with a brief overview of the SLR2000 software.

SLR2000 Software Overview

The SLR2000 system consists of multiple CPUs linked via an internal LAN and shared memory. The functions of each computer subsystem are:

Pseudo-OPerator (POP)
POP replaces the human operator and makes all of the real-time tracking and scheduling decisions. Dome control and star calibrations are also performed here. This software runs under LynxOS on an embedded VME Pentium.

Interface and Control Computer (ICC)
The ICC provides a DOS interface to do realtime data taking and control of the mount, ranging electronics, point-ahead and star camera systems. No decision making occurs here - this is strictly an I/O interface on a Pentium II computer.

Data ANalysis (DAN)
The Data Analysis computer does all of the post-processing analysis, performs all of the non-realtime hardware interface (including weather and transceiver), interfaces directly with the Health and Safety computer, and provides the external communication for the entire system. Part of this external communication is hosting the system's web site. DAN also hosts a server portion of the Remote Access Terminal software - giving the remote part of RAT complete access to the system. DAN operates on an embedded VME Pentium computer which is currently running LynxOS, although future plans are to move this computer to Linux.

Dome Control System (DCS)
The Dome Control System consists of two microchip controllers which control both the shutter open/close and also the movement of the dome. The dome moves only in azimuth, as the shutter opens from -5 degrees to 95 degrees in elevation relative to the telescope. The Dome Control System takes its direction from a 1Hz serial interface with POP, and returns its status and the dome slit location.

Health and Safety (HandS)
The Health and Safety system, as its name implies, monitors the system's health and security. It runs on a Compact PCI Pentium II computer under Windows NT, and communicates via sockets over the internal LAN with DAN.

Remote Access Terminal (RAT)
Not a part of the operational SLR2000 system, RAT nontheless plays an important role in the system. Since this is an automated system, there is no monitor or keyboard attached to the system. RAT provides the interface necessary for humans to interact with the system either locally or remotely. It give the SuperTech a means to communicate with the system when he makes his periodic maintenance visit, and it provides the tools for the software team to checkout the system.

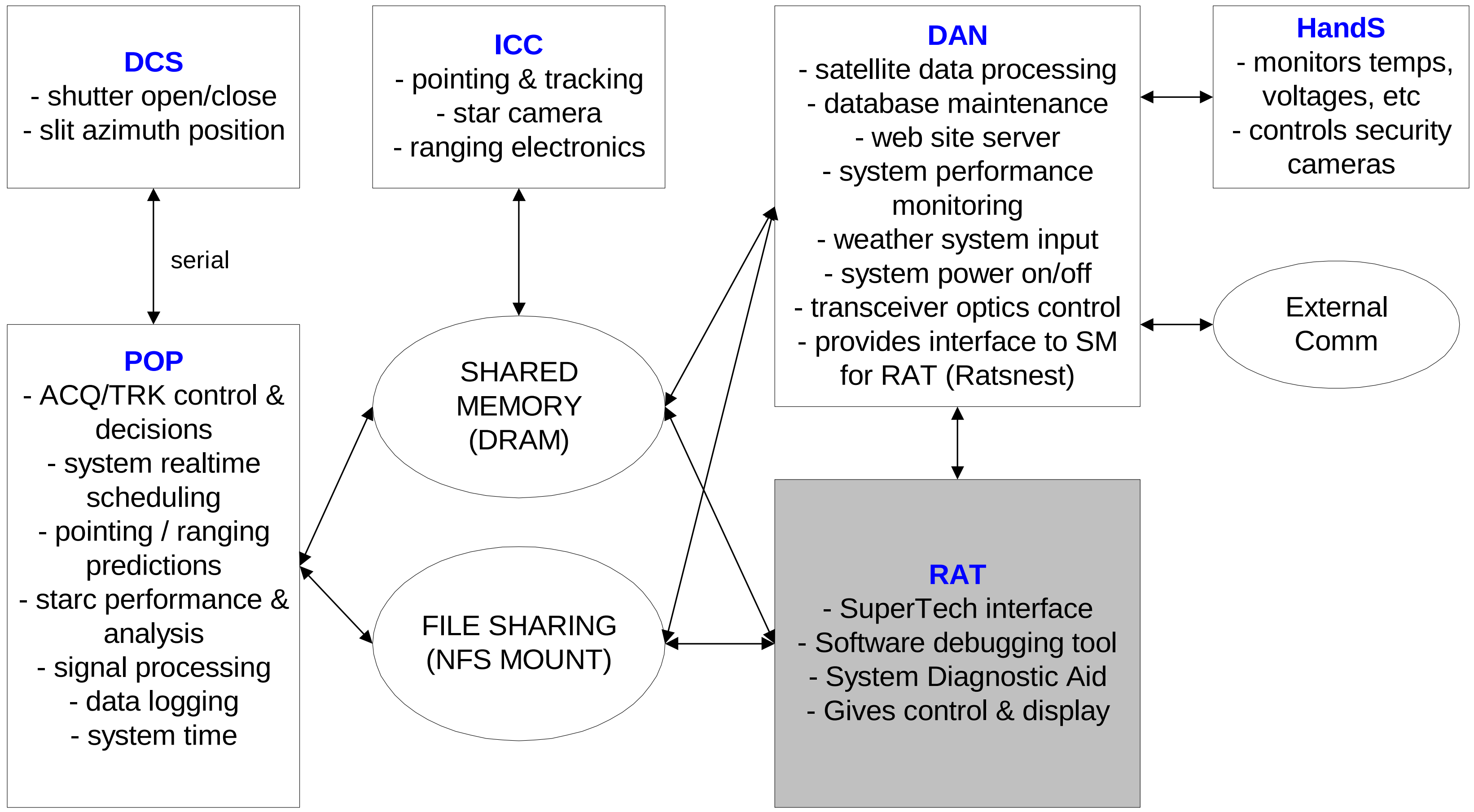
Figure 1 shows the connections between these computer subsystems. The ICC communicates directly with POP at 2khz (the laser fire rate) via shared memory (RAM located on the card that interfaces the ICC ISA bus to the VME bus). DAN also has access to the shared memory, as does the portion of RAT that resides on DAN.

POP, DAN and RAT also share file information by direct file copy and via NFS mount.   For instance, the log file is written by POP to its hard disk and then DAN mounts the log file directly from POP's disk. However, predicts are copied directly from DAN's disk to POP's before being used. The size of the file and the amount of access required determines whether a file will be copied or NFS mounted.

Rounding out the communication interfaces, as mentioned earlier, POP communicates via serial interface with the DCS, and HandS communicates directly with DAN via sockets.

A more detailed description of the SLR2000 software is given in [3,4,5,6].

SLR2000 SOFTWARE BLOCK DIAGRAM



DCS
- shutter open/close
- slit azimuth position

ICC
- pointing & tracking
- star camera
- ranging electronics

DAN
- satellite data processing
- database maintenance
- web site server
- system performance monitoring
- weather system input
- system power on/off
- transceiver optics control
- provides interface to SM for RAT (Ratsnest)

HandS
- monitors temps, voltages, etc
- controls security cameras

POP
- ACQ/TRK control & decisions
- system realtime scheduling
- pointing / ranging predictions
- starc performance & analysis
- signal processing
- data logging
- system time

SHARED MEMORY (DRAM)

FILE SHARING (NFS MOUNT)

External Comm

RAT
- SuperTech interface
- Software debugging tool
- System Diagnostic Aid
- Gives control & display

Figure 1: SLR2000 Software Block Diagram (RAT is not part of operational system).

SLR2000 Approach to Testing

Testing an automated system presents different problems than those traditionally faced on a conventional interactive SLR system. Operators often shared in the process of debugging the software. Here, in effect, we must debug even the operators! Interactive testing can accomplish only so much, and we must be careful to test all aspects of the the software prior to system deployment.

We have incorporated lessons learned from testing spaceflight software which include using simulations to allow testing of all expected events and determining the boundaries of the algorithms and software used, so we know what conditions the system can handle and what it can't. While we do not have the money or the manpower to duplicate the software testing efforts of the spaceflight missions, we can still perform some of the same kinds of tests, and work out many of the bugs long before we see the whole system put together. To this end we have approached the testing on four major fronts:

1) Develop a GUI interface that can be used locally or remotely (RAT)
RAT allows us to monitor the system and to control many aspects of the system. All of the important subsystem information is placed in shared memory and updated at least once per second so that RAT has access to this in realtime, and can display the details of SLR2000's current status during operation. RAT also has a set of tools that allow for analysis and display of automated tests, including Star Calibrations and Satellite Tracking. RAT also plays an important role in simulations, providing the interface for the tester to setup and monitor the testing. Figures 2 and 3 show an example of an operator input control panel in RAT, and the main RAT realtime display screen.

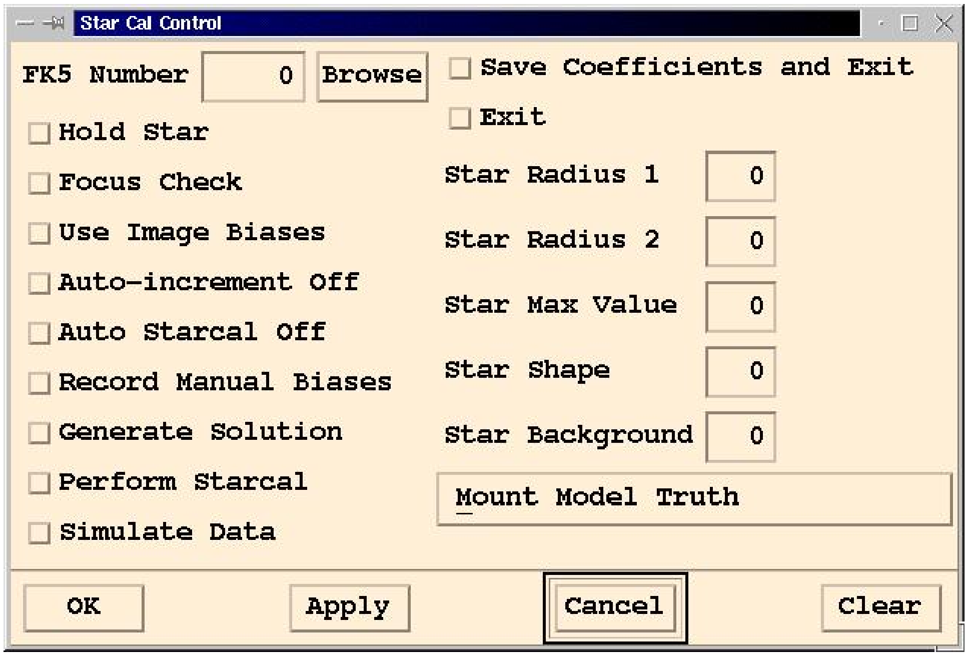
2) Test each major subsystem independently
Each major piece of hardware and software has been (or will be) tested independently. This includes the dome, the mount, the ranging electronics, the star camera, the weather instrumentation, and the various software pieces themselves. Testing includes not only the ability to control the hardware and get data from it, but also the associated decision making processes.

3) Simulate the external world (via a separate software package)
We have developed software simulators to allow us to test subsystems, as well as the complete system. These software routines simulate the weather, the satellite response, the star image, the mount movement, the ranging electronics, and the dome reaction, to:
(i) simplify the tests so we can better understand the results, (ii) allow the automated process to be tested without direct human interaction, and (iii) enable us to test all possible scenarios. Via RAT the human operator sets up the parameters of the experiment, and then RAT turns on the simulation routines. These routines run independently from the operational software as separate threads, and without the operational software's knowledge. Only the simulation threads and RAT have knowledge of the “Truth”. Recorded events can then be analyzed after the test using RAT's analysis tools.

4) Test the algorithms on other systems (NASA's 1.2 meter telescope)
Subroutines from the SLR2000 package have been ported to NASA's 1.2 meter telescope for use in testing the acquisition and tracking algorithms. The SLR2000 quadrant detector was also incorporated into the 1.2 m telescope. This gives us access to a working SLR system

prior to the SLR2000 mount being delivered, and allows us to test the acquisition and tracking algorithms in a more operator friendly environment, independently from the rest of the automated processes.

The rest of this paper describes the last two of these testing approaches in detail.



Star Cal Control

FK5 Number 0

□ Save Coefficients and Exit

□ Exit

□ Hold Star

□ Focus Check

□ Use Image Biases

□ Auto-increment Off

□ Auto Starcal Off

□ Record Manual Biases

□ Generate Solution

□ Perform Starcal

□ Simulate Data

Star Radius 1: 0

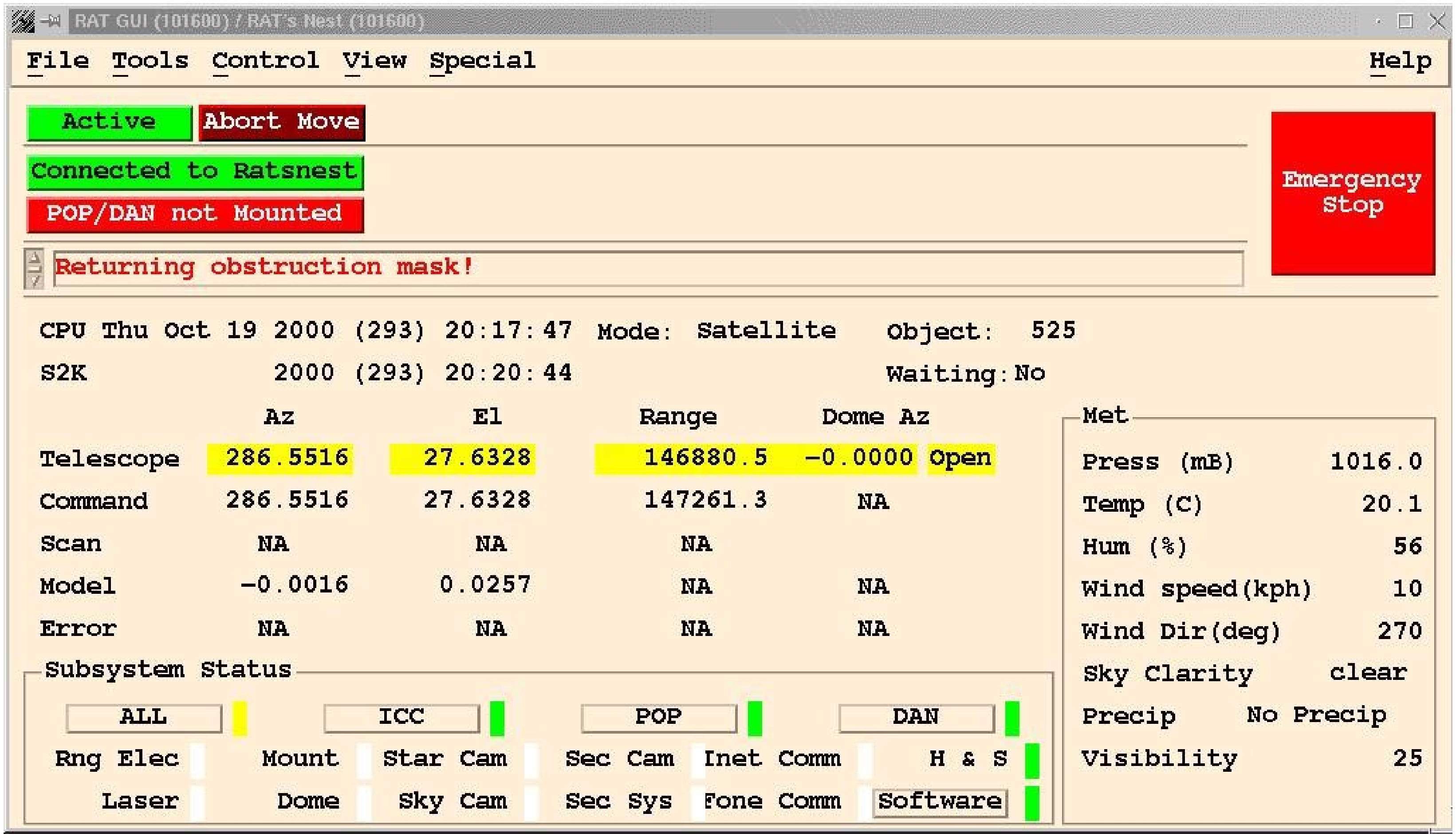
Star Radius 2: 0

Star Max Value: 0

Star Shape: 0

Star Background: 0

Figure 2: Operator Input Control Panel of RAT
Operator clicks desired functions and enters required data.



Returning obstruction mask!

```
CPU Thu Oct 19 2000 (293) 20:17:47  Mode:  Satellite   Object:   525
S2K             2000 (293) 20:20:44                    Waiting:No

                 Az          El        Range     Dome Az          Met
Telescope    286.5516     27.6328     146880.5   -0.0000  Open    Press (mB)         1016.0
Command      286.5516     27.6328     147261.3     NA             Temp (C)             20.1
Scan           NA           NA          NA                        Hum (%)                56
Model         -0.0016      0.0257       NA         NA             Wind speed(kph)        10
Error          NA           NA          NA         NA             Wind Dir(deg)         270
Subsystem Status                                                  Sky Clarity         clear
   ALL  🟨          ICC  🟩          POP  🟩          DAN  🟩       Precip        No Precip
 Rng Elec     Mount     Star Cam    Sec Cam   Inet Comm    H & S 🟩  Visibility            25
    Laser      Dome      Sky Cam    Sec Sys   Fone Comm Software 🟩
```

Figure 3: Main RAT Realtime Display

Simulate the external world via a separate software package

SLR2000 can simulate the following external conditions:

1) The weather, including clouds: either by a separate thread on DAN, or from a separate computer simulating both the weather parameters and the actual serial interface. This includes the pressure, temperature, humidity, sky cloud cover, precipitation and visibility. We have verified that 2 of our 3 serial instruments are being simulated accurately by temporarily relocating them inside the computer lab and connecting them to DAN in place of the simulators. The third serial instrument was impractical to move. Our wind sensor, which is an analog device, is simulated by a simple battery / rheostat circuit connected to DAN's A/D board. Most of the weather processing code on DAN has been thoroughly debugged with the aid of these simulators. The simulators are highly useful for tests where we change the weather conditions. For example, we can cause simulated precipitation to begin falling, and then verify that other parts of the system are responding correctly. For more information on the SLR2000 weather instrumentation, see the paper by Anthony Mallama [7].

2) Star images: a separate simulation thread on POP gets data from RAT, including the "True" mount model. This information is passed to a routine on the ICC which simulates the star images at the correct location in the CCD star camera. The star's location and size is based on the star selected by the operational part of POP and the corresponding pointing commands. POP operates normally and is unaware whether the images are simulated or real. The entire automated star calibration process from scheduling through selection of stars, image collection and centroiding, bias calculation, and the final mount model calculation, was successfully tested with the full SLR2000 software system in October 2000 using this simulation technique. Reaction of the system to clouds was not tested at that time, however, and remains to be done. Figure 4 shows the data flow in a simulated versus operational star calibration, and figure 5 shows simulated CCD images as seen by POP in its process of centering the star.

3) Satellite response: similar in concept to simulating star images, the satellite simulation will be a separate thread on POP that will get its information from RAT, including the orbital "Truth" (timebias, rangebias, and crosstrack bias). The POP thread will calculate the satellite response based on satellite information from a POP file, the orbital information obtained from RAT, the atmospheric characteristics from DAN, and the pointing angles calculated by the operational part of POP. The satellite response will be passed to the ICC in the form of a signal probability, a noise probability, and an expected range return time. The ICC simulates the actual returns. The operational part of POP will be unaware of whether the range returns are simulated or real. This function is not yet completed on POP. Figure 6 shows how the simulated satellite testing fits into the SLR2000 software.

4) System health: simulated by a random number generator that selects various system status levels based on a set of probabilities. The reaction of the software to error conditions can be tested using this code.

5) Dome control: the DCS interface can be simulated by a separate computer emulating the DCS and the dome hardware (to allow testing outside of the SLR2000 facility).

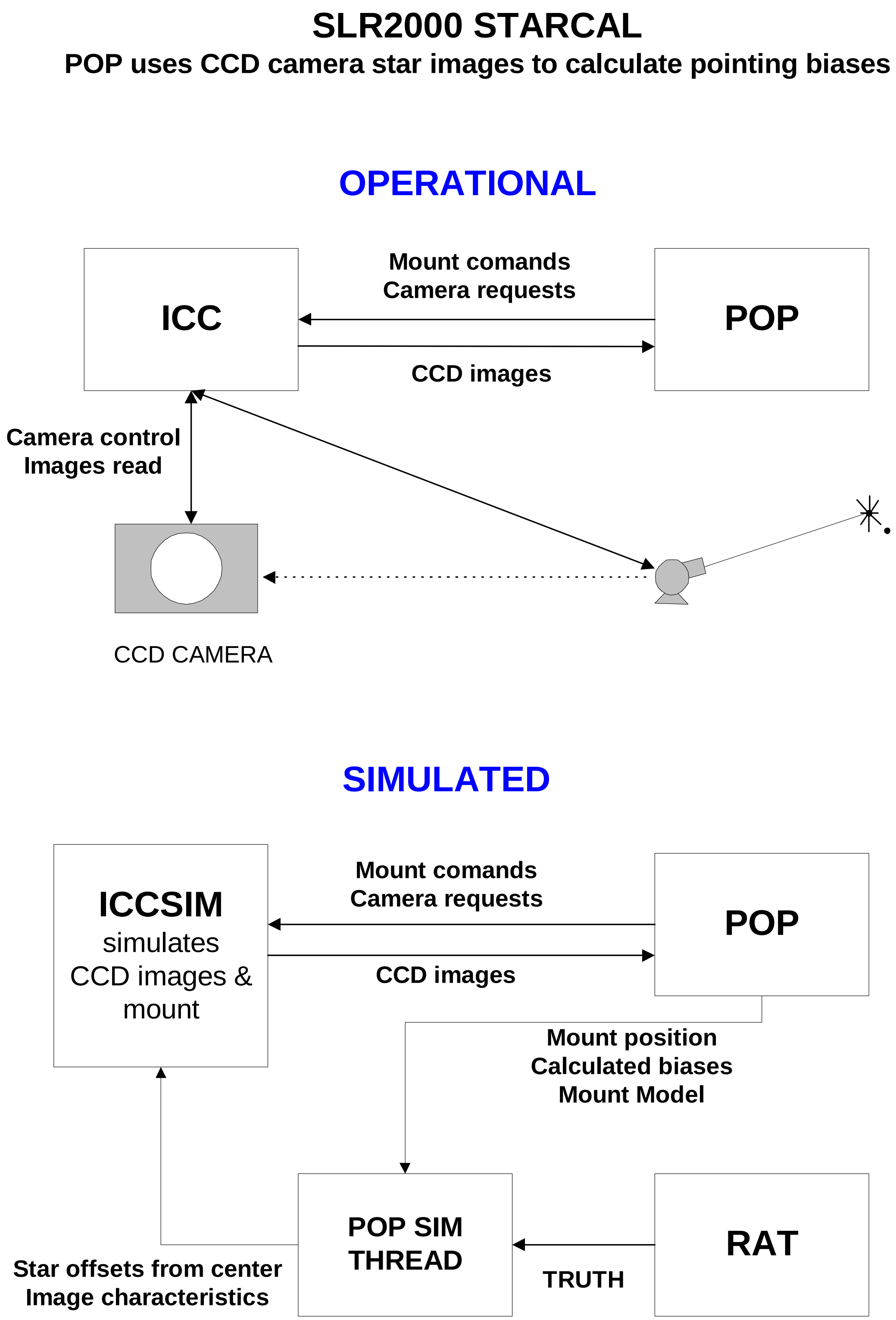
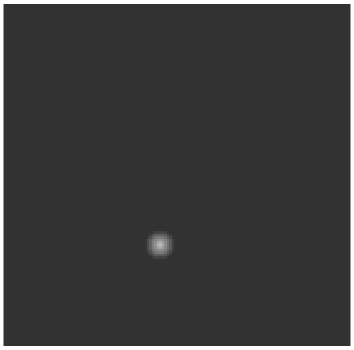


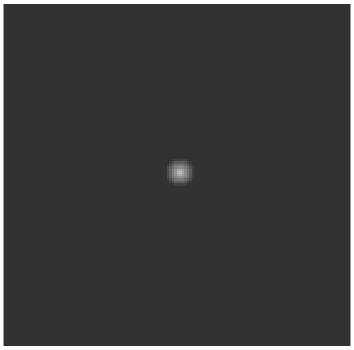
Figure 4: Data flow in a simulated versus operational star calibration

- The CCD star camera image size is 242 x 242 pixels with a 2 arcmin FOV. The pixel brightness range is 0-255.
- The simulated star characteristics shown here are: circular, nonrandom, with a diameter of 10 pixels, a maximum brightness (at the center) of 200, and background brightness of 20.

- Image #1: position in CCD camera is due to offset between mount model currently in use by operational software and the "True" mount model (as specified by RAT). No biases have yet been applied.



- Image #2: POP has calculated biases from previous image, and has applied them. Star is now closer to being centered, and would be completely centered if all scale factors hadn't been slightly changed from absolute "Truth".



- Image #3: Star is now centered. POP records biases and moves on to the next star.

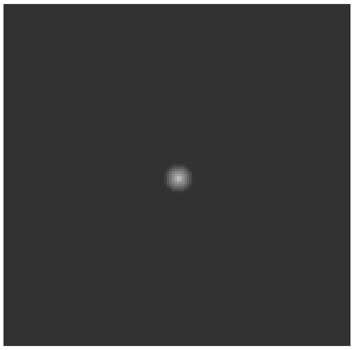


Figure 5: POP centers a star (unaware that the image is simulated) Images taken from October 16-19, 2000 Star Calibration Tests.

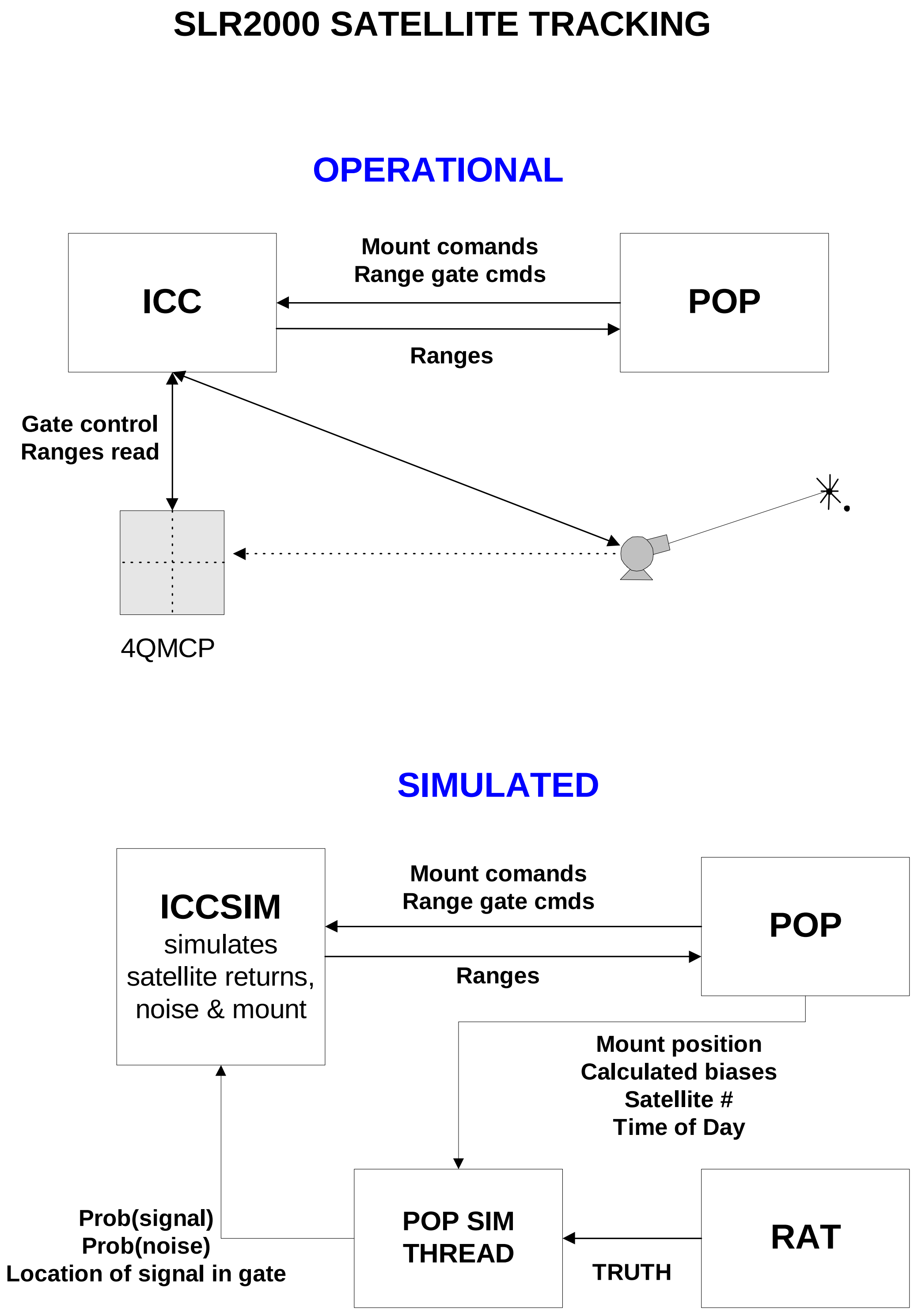


Figure 6: Data flow in simulated versus operational satellite tracking

Test the algorithms on other systems (NASA's 1.2 meter telescope)

Code was ported from SLR2000 to NASA's 1.2 meter telescope Satellite Laser Ranging system [8], and the SLR2000 quadrant MCP (QMCP) detector was integrated into the 1.2m Telescope's receiver system (see figure 7). Most of the satellite acquisition and tracking algorithm software was moved, including:

- Angular and range search routines required to find the satellite. These consist of a spiral scan in azimuth and elevation, moving outward from the expected satellite location, and steps in the range window location outward from the expected range time.

- Signal processing. As presented at this and earlier Workshops [9,10,11], the Poisson statistics of the noise can be used to distinguish it from the signal by binning the range returns in observed minus calculated (O-C) space. Satellite returns will fall within one to two bins, while the noise will be spread out evenly over the entire range window. The signal processing algorithm looks at a sequence of range returns and flags all returns that it determines are signal.

- Angular bias calculation. The number of signal returns in each of the four quadrants can be counted to periodically compute the azimuth and elevation biases (see below).

- Time and range bias calculation. The signal returns can be analyzed for a periodic calculation of time and range biases. This data is then applied to the system biases, and used in the next prediction cycle. Care must be taken after a time bias calculation, to remove the time bias contribution from the angular biases, to ensure these biases aren't effectively applied twice.

The 1.2m Telescope Facility setup allows us to test and debug the acqusition and tracking (ACQ/TRK) algorithms within the constraints of the 1.2m Telescope. These include a 10Hz laser with <30mJ output in green, and a receive energy attenuated to a few photoelectrons. It provides us with real hardware to work with, actual satellite responses, an interactive environment to test out the algorithms, and separates the testing from the rest of the automated SLR2000 software.

Figure 8 demonstrates the type of testing possible using the 1.2m Telescope Facility. This is a STARLETTE pass taken on 02/09/2000 at 23:58 GMT. The automated ACQ/TRK algorithms were not turned on at this time, however, the information from the QMCP was recorded. The system records the primary roundtrip range time from the HP5370. The delays from that time to each of the quadrant events is measured by a Phillip's Scientific Time to Digital Converter (TDC), one channel for each quadrant. After a sufficient amount of signal data has been extracted from the returns, angular biases can be determined by counting the number of signal returns in each quadrant and computing the location of the center of the returned laser image in the detector field of view:

$$dx = ((nQ1+nQ3)-(nQ2+nQ4))/(nQ1+nQ2+nQ3+nQ4)$$
$$dy = ((nQ3+nQ4)-(nQ1+nQ2))/(nQ1+nQ2+nQ3+nQ4)$$

where nQi is the number of signal returns in quadrant "i", and (dx,dy) is the normalized offset from the center of the FOV.

For the results shown in figure 8, 50 seconds worth of signal data (around 100 counts) was used to determine the angular biases.

The Coude path rotation must then be removed from the image location and it must be scaled (for SLR2000 as well). For the 1.2m telescope this rotation is:

$$\theta = AZ + EL + 45 \text{ (in degrees).}$$

After performing a negative rotation through θ to get the unrotated (dx′,dy′), the biases can then be computed from:

$$\text{Azbias} = -dx' \cdot \text{scale}/\cos(\text{elevation})$$
$$\text{Elbias} = -dy' \cdot \text{scale}$$

where scale ≈0.004 degrees (for 1.2m telescope setup).

In the O-C plot of figure 8 biases have been added to quadrants 2,3, and 4 to visually separate the returns. Without biasing the returns quadrants 2,3, and 4 would directly overlay the returns from quadrant 1 (and each other) and would be indistinguishable. Jumps in the range O-C data are timebias corrections applied by the operator. The gray boxes represent the quadrant detector's field of view with the triangles indicating the image location as calculated from the signal data.

The operator was using an O-C plot displayed on the 1.2m telescope console to optimize the tracking returns by entering time and angular biases, and thereby centering the satellite in the receiver field of view. The success of the operator's efforts can be seen in the quadrant information. At the acquisition of the STARLETTE pass the image was located in the lower right of the quadrant detector. Later as the operator applied biases, the angular error decreased and the image was basically centered in the field of view.

Testing has been limited to date due in part to mount problems at the facility. We hope to complete this work in the coming year before we have to test on the integrated SLR2000 system, where algorithm debugging will be much harder!

SLR2K QUADRANT PMT TRACKING

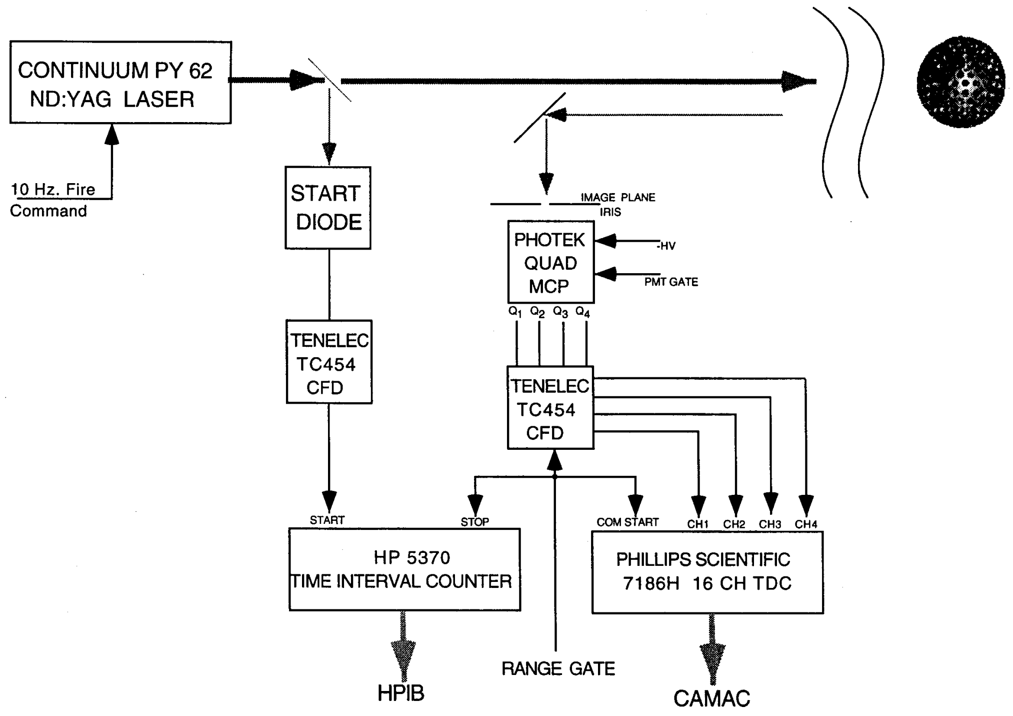
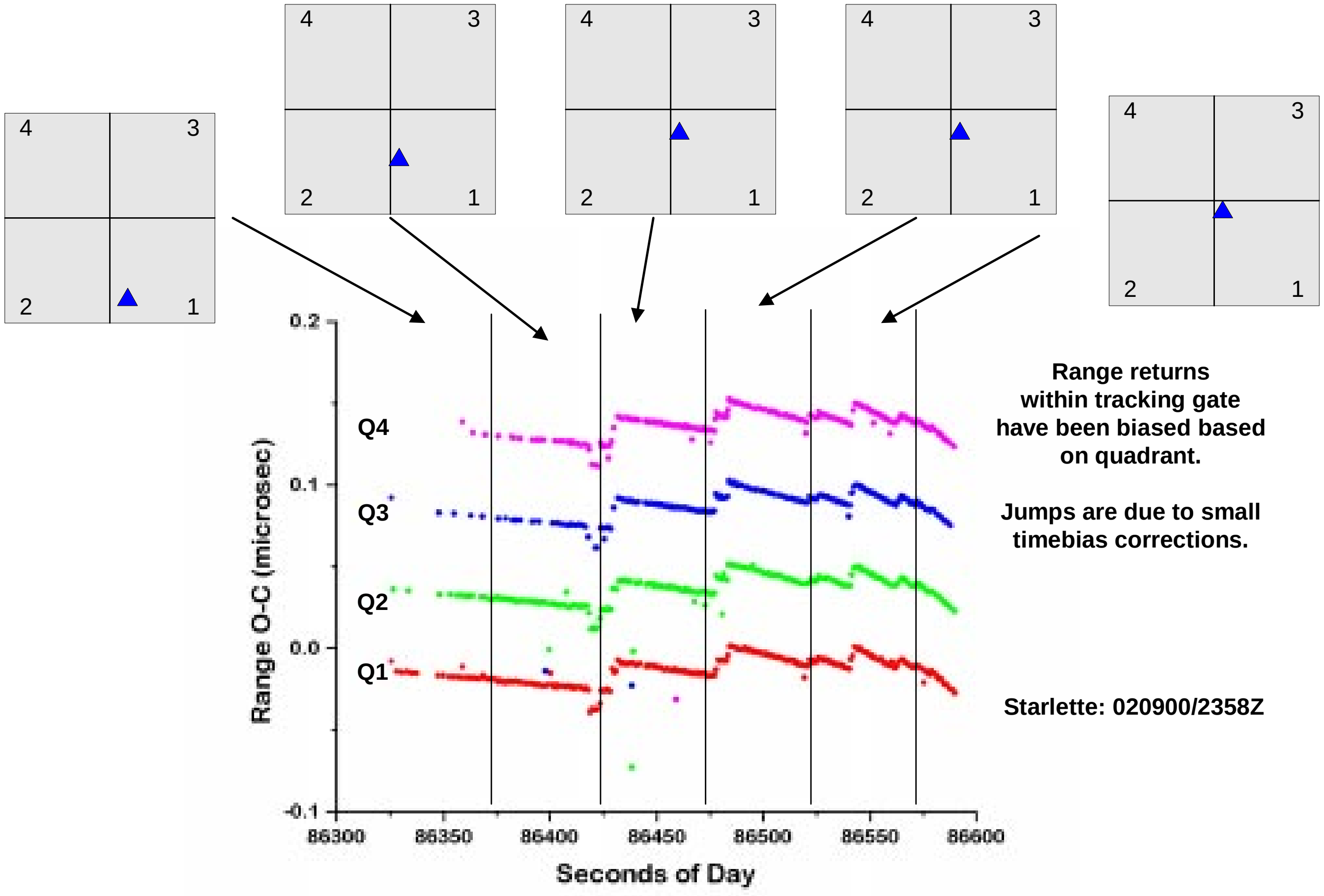


Figure 7: 1.2m Telescope Setup for SLR2000 Algorithm Testing with QMCP. QMCP FOV in 1.2m system is ~ 1 arcmin. Image size is ~ 50% of FOV.

Satellite Tracking at 1.2m Telescope
using SLR2000 4QMCP



Range returns within tracking gate have been biased based on quadrant.

Jumps are due to small timebias corrections.

Starlette: 020900/2358Z

Figure 8: STARLETTE ranging results at 1.2m telescope using the SLR2000 Quadrant MCP. As tracking is optimized, the quadrant detector shows returns moving toward the center of the FOV.

Software testing results

What has been tested using RAT and simulation:

- scheduling (schedule development, use, and required overrides)
- satellite logging (POP recording of data and pickup by DAN for post-process)
- star calibrations (performance and analysis)
- dome control and DCS interface checkout
- signal processing (detection of satellite returns and rejection of noise)
- circular buffer handling of multiple fires in flight
- response of system to error conditions

What we hope to test on the 1.2m telescope system

- angular and range search during acquistion
- calculation of timebias and range biases from signal range data
- calculation of angular biases from quadrant information

What remains to be tested using RAT and the simulation software:

- satellite acquisition and tracking, with specific satellite characteristics and responses
- system reaction to seeing clouds along the scheduled path (starcal and satellite)
- automated bias calculation from signal returns
- sun avoidance

Summary

The SLR2000 software is about 85% coded, excluding the Health and Safety subsystem which is just being started. Most subsystems have been extensively tested individually, however, there is still a lot of system testing to be done, including more pre-integration system simulation testing, finishing the ACQ/TRK algorithm testing at the 1.2m telescope, and the complete system checkout after mount delivery and system integration.

We feel that the simulation approach to testing will pay off in the long run by speeding up the entire testing and debugging process in the integrated system, and by allowing us to uncover more of the software problems early on than would be possible otherwise. It has been a proven way to test software systems for flight use, and we feel it will be of great benefit to our automated ground systems as well.

Acknowledgments

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