VERITAS tracking system

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Overview

- The problem:
  - Interesting targets are scattered throughout the sky and telescopes must be pointed at them
  - Unavoidable rotation and motion of the Earth through the heavens must be compensated for
- The solution:
  - Positioner – safety, motors, encoders, feedback, C&C
  - Tracking software – safety, astronomy, GUI, logging

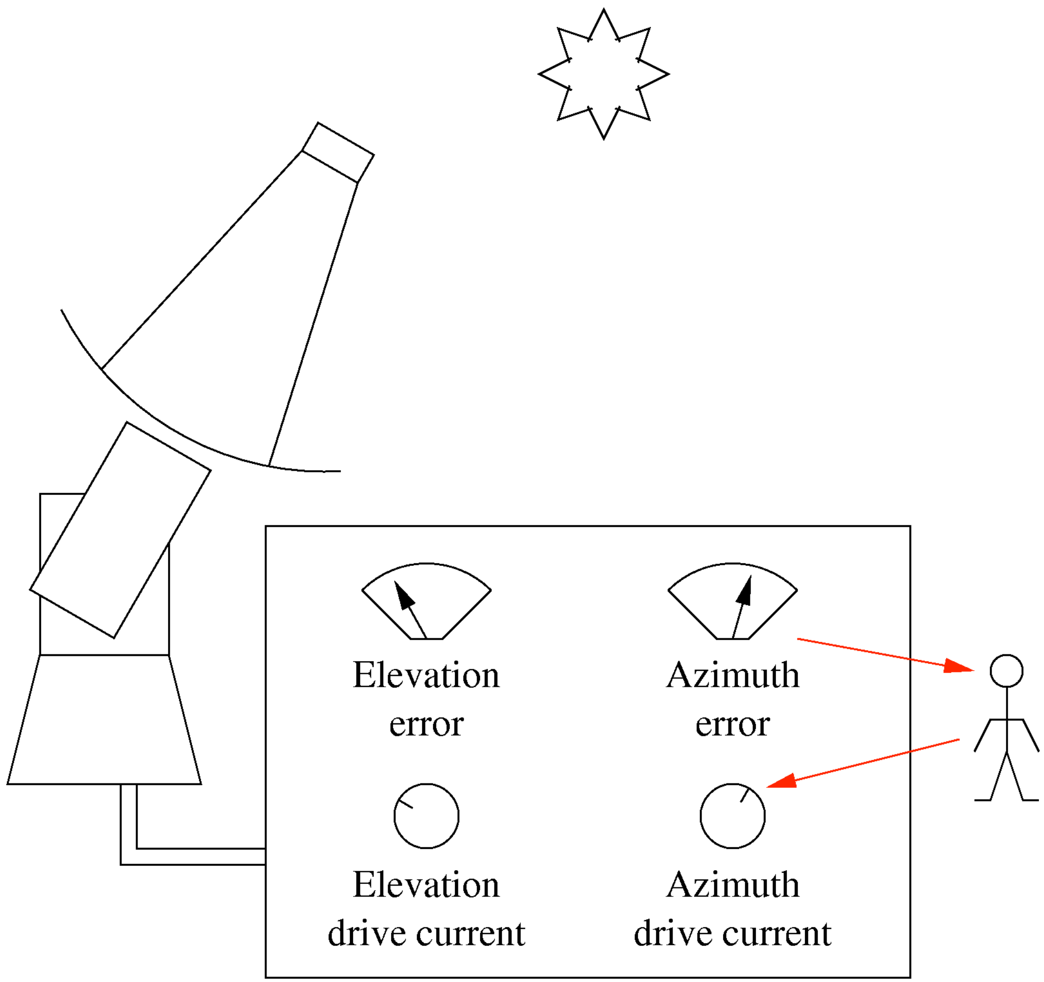
Positioner

- Rotating Precision Mechanisms model PG4003 (www.rpm-psi.com)
- Dual axis – elevation over azimuth (Alt/Az)
- Two drives per axis with integral brakes – Cleveland Motion Control model BMR4000, brushless DC motors (www.cmccontrols.com)
- Gear boxes – 3 stages – 25308:1 (Az) 25650:1 (El)
- Absolute encoders, tachometers, limits switches
- Control system

Motion control introduction

- The essential problem of motion control is: how much power to apply to achieve required motion?
- For example: in your car's cruise control – how wide should the throttle be opened to maintain correct speed. How much should it change as a function of road inclination, weather etc.
- People solve this kind of problem instinctively through feedback – “closed loop” system.
- Same with motion control systems.

Closed loop control



- Far from target?
  - Go faster
- Always lagging behind when tracking?
  - Go faster
- Target moving away from you?
  - Go faster

PID loop

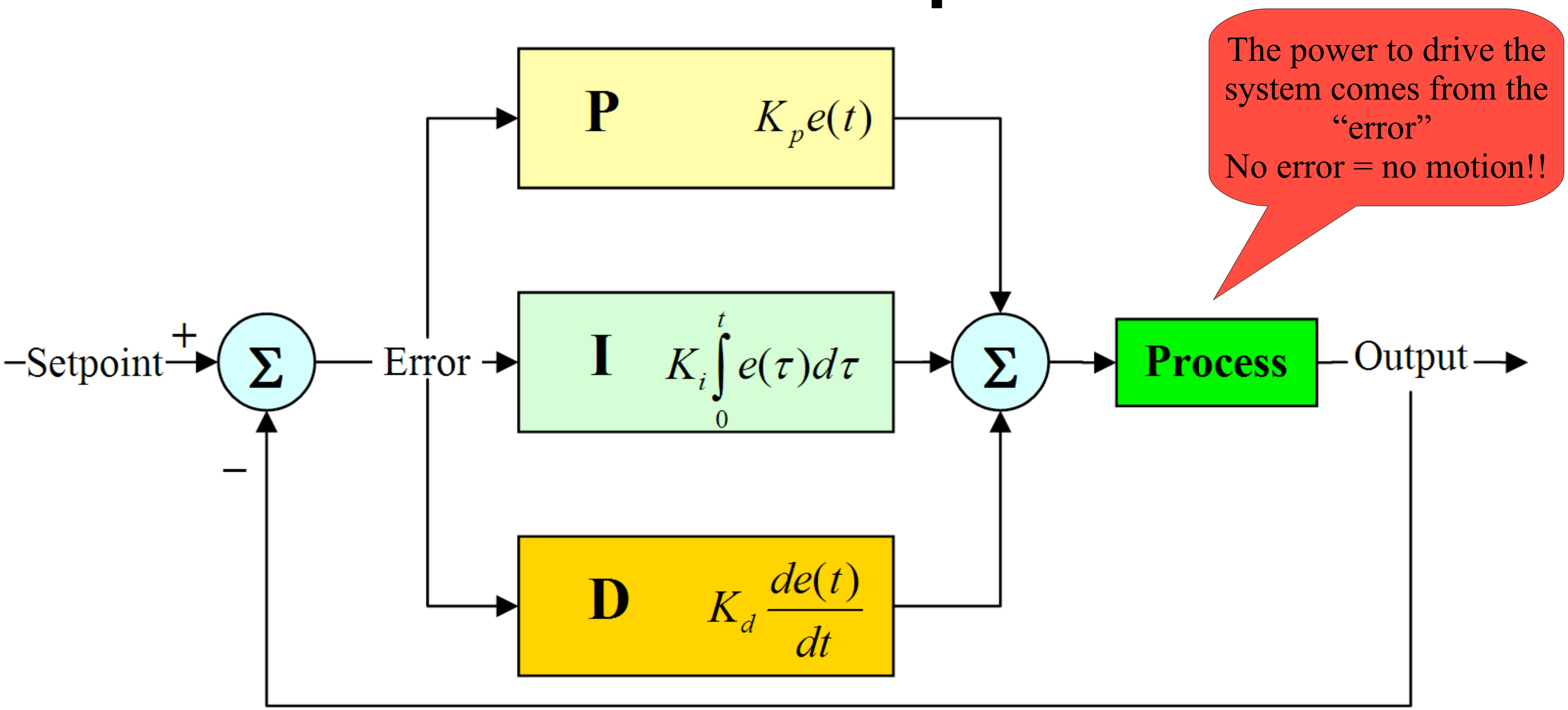


Figure: wikipedia

Parameters: Kp, Ki, Kd, and usually something to limit integral component, which can become very large and cause serious overshoot. Gains chosen to compromise between having responsive system and having serious over-shoot and oscillation.

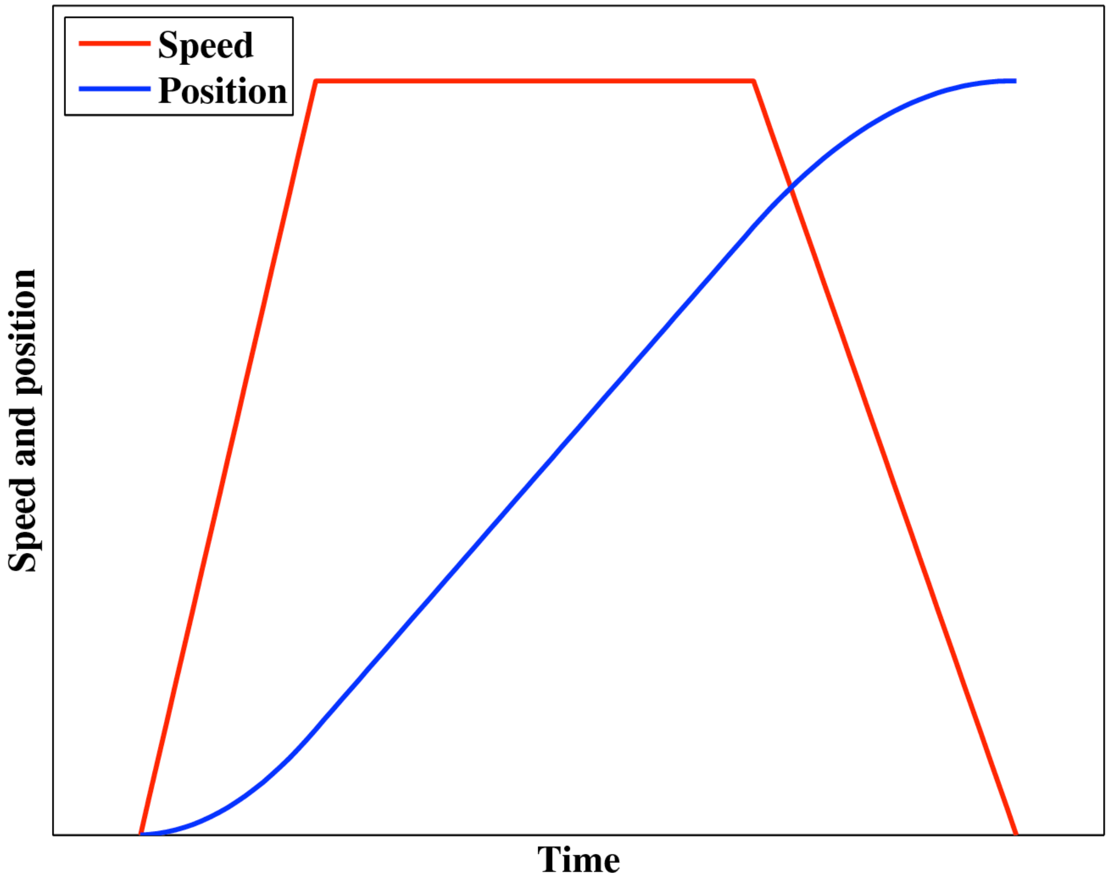
Many nested loops

- Output of "*position loop*" is a signal that system should try to move to minimize position error:
  - Large output – system should try to move quickly
  - Small output – system should try to move slowly
- Output could be amplified and sent directly to motors.. better to interpret as a "velocity request"
- Use as input (set-point) of "*velocity loop*" which compares to motor speed (tachometer).
- O/P of velocity loop is a "torque request" - used in a "*torque loop*" (A/K/A "*current loop*").

What set-point?

- Imagine you have a telescope system that must track within 0.1deg, and needed 1Amp to move at sidereal rate.
- So PID loop must generate signal for 1Amp with an error on scale of 0.1deg.
- What happens when you want to slew to target 100deg away – PID system would try to generate 1000Amp!
- Better to increment set-point in a controlled way.

Trajectory generator



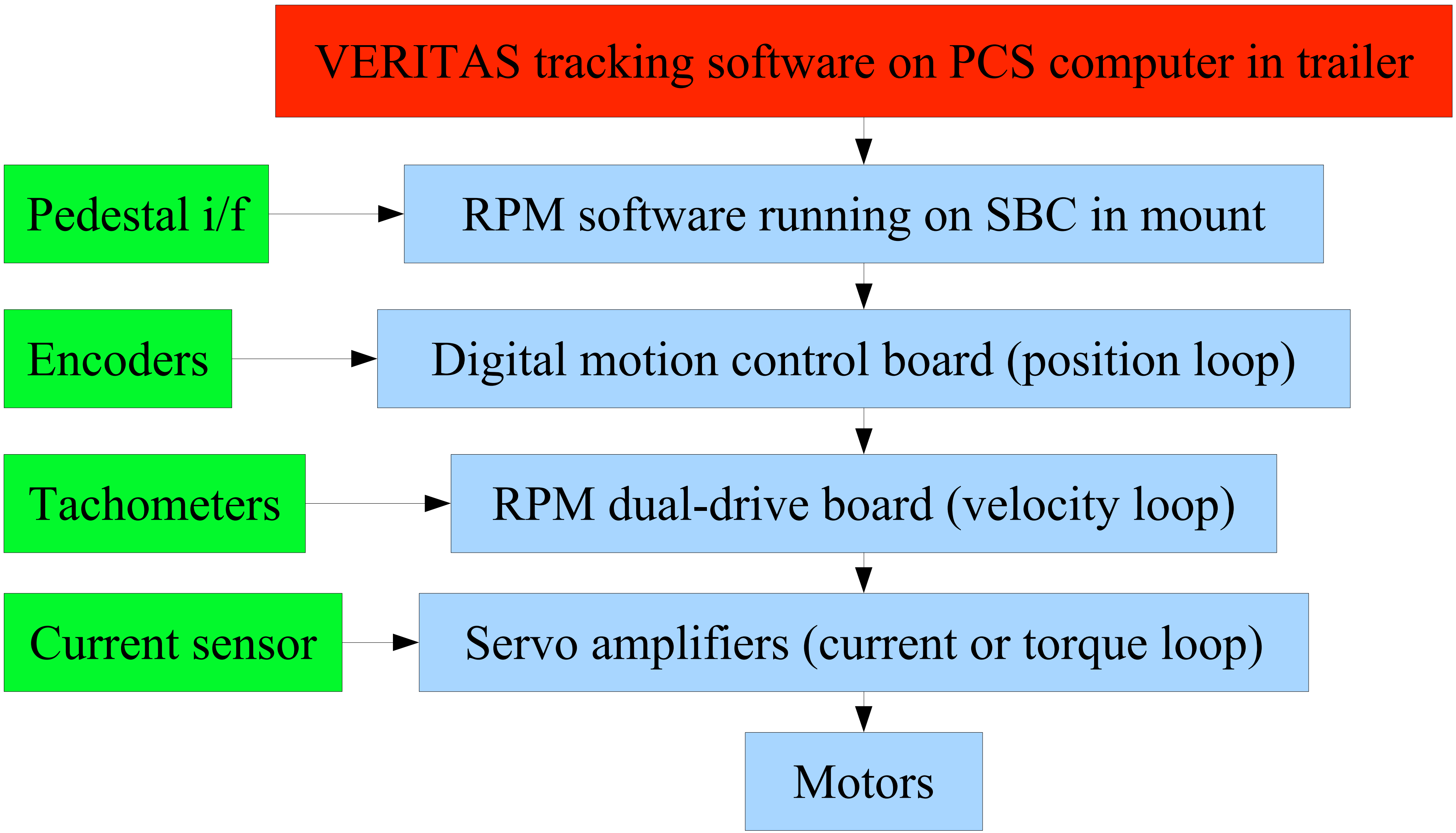
Parameters: Acceleration rate, maximum speed, deceleration rate.

- Define trajectory of set-points including:
  - Acceleration phase
  - Constant speed
  - Deceleration
- Trapezoidal trajectory generator
- PID loop responsible for following the trajectory

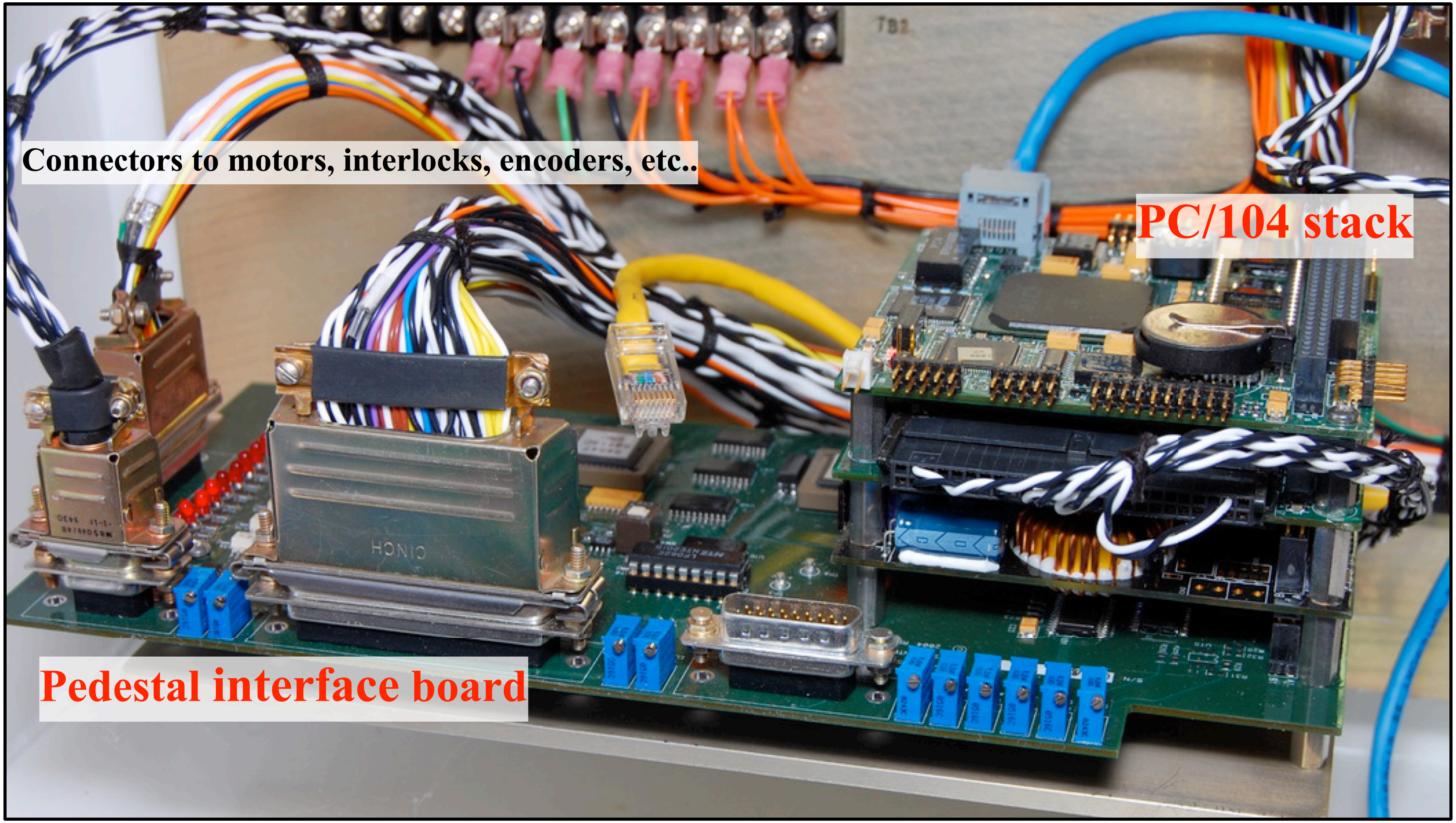
VERITAS control system

- Electronic stack – PC/104 bus
  - Single board computer (Micro/sys – SBC1491)
  - Interface and control software (RPM sub-contractor)
  - Digital motion control (ACSTech80 - 595x Series)
  - Power supply board
  - Pedestal interface board + firmware (RPM – custom)
- Dual-drive board (RPM - custom)
- Servo amplifiers (Advanced Motion Control B25A20AC)

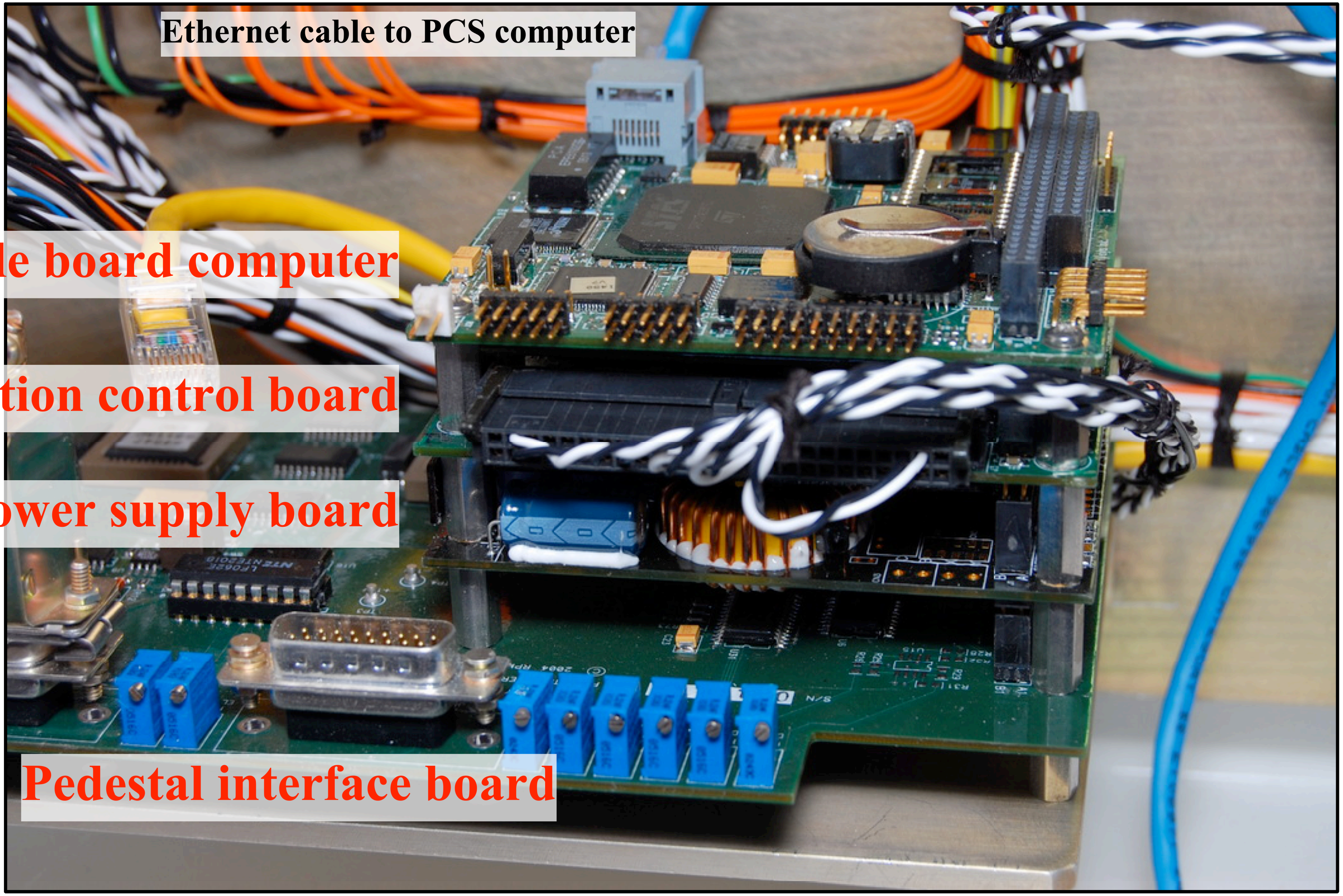
Simplified command flow



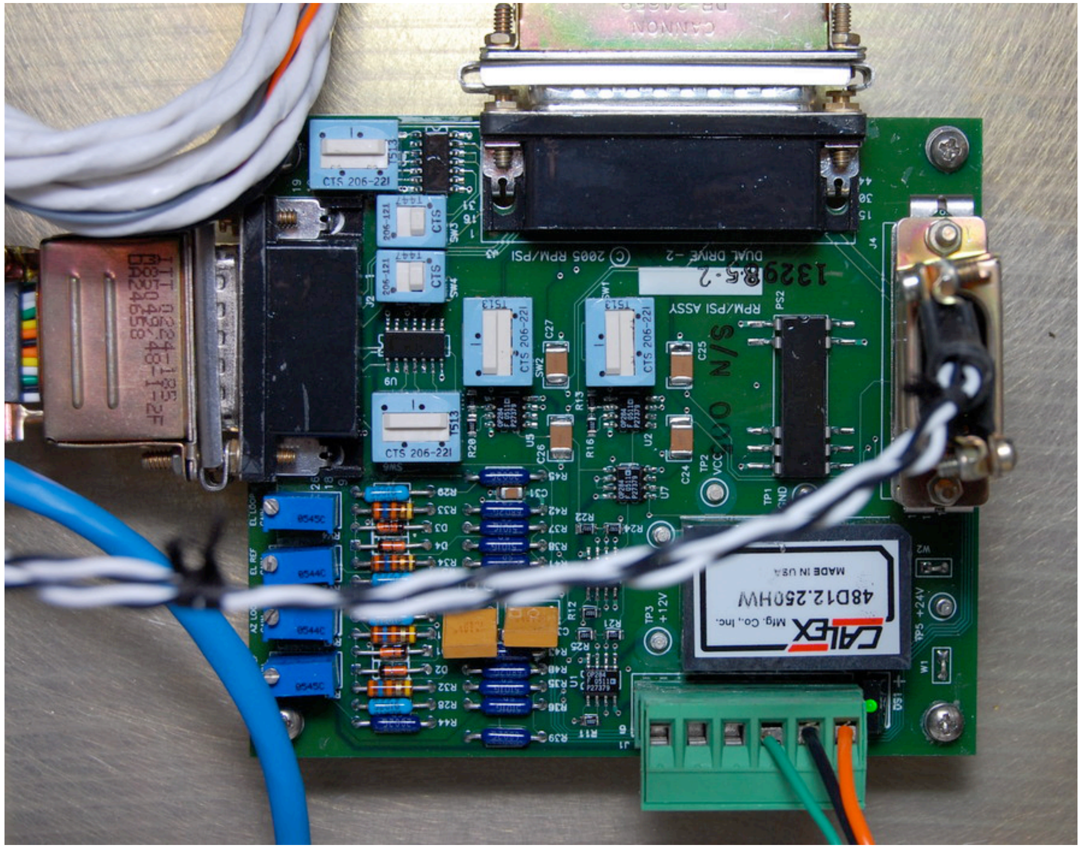
Pedestal interface board



PC/104 stack


Ethernet cable to PCS computer
Single board computer
Motion control board
Power supply board
Pedestal interface board

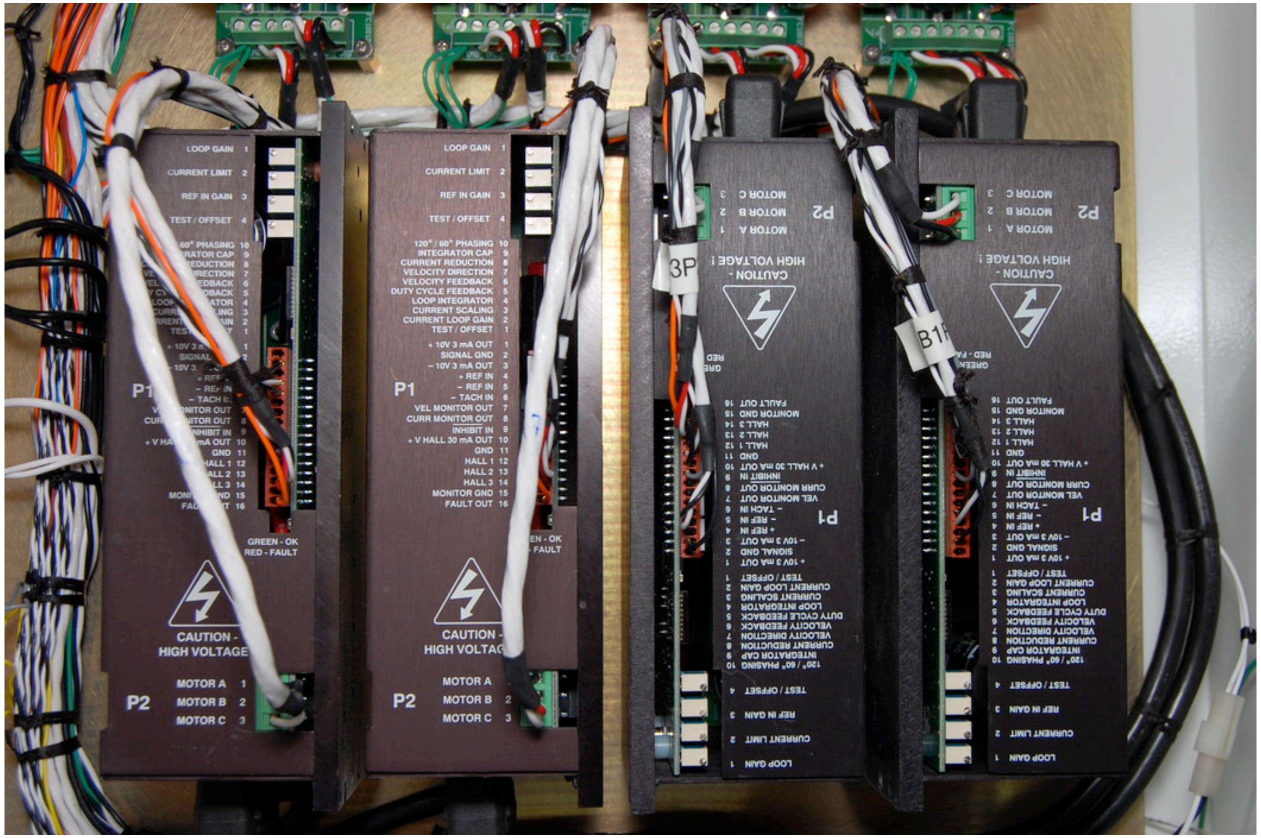
Dual-drive board



Inputs: (1) output from position loop and (2) motor tachometers
Output: current set-points for servo amps

- Two drives per axis
  - Better for high wind
  - Faster slewing
  - Eliminate backlash
- Stationary: drives push a different directions at 10% of max. torque
- Moving fast: work together (1% cur. diff.)
- Velocity loop

Servo amplifiers



Inputs: (1) current/torque request from dual-drive board and (2) motor shaft positions from hall probes
Output: 3 phase currents to motors

- Servo amplifiers generate high currents for brushless motors
- In our system they operate in *current feedback* mode
- Current loop

SBC + interface software

- Commands/responses sent over UDP/IP & Ethernet (A0058IF_RevD_ENET.doc) e.g.:

```
SEND: [? 0x0D
RECV: [?3027F92478F3005300552200004100 0x0D
```

- Primary commands:
  - *Get status:* get the position and status of instrument
  - *Point:* point telescope to given position
  - *Standby:* immediately stop telescope and apply brakes
- Relays commands to RPM system via PC/104 interface.

Hardware safety

- Interlock loop controls AC power flow to servo amplifiers through relays (K1 and K3) – opening loop removes AC power from amplifiers
  - Run/Safe
  - Stow switches (2x2): on Az/El stow pins
  - Failsafe limit switches (2x2): up, down, CW, CCW
  - Hatch switches (2+1): two to El area, 1 to Az
  - Drill adapter: El and Az drill adapter must be in place
  - Az pull cord: 270 degree rotation pull-cord in Az area

Motion control parameters

- Digital motion control board:
  - Kp – position loop proportional gain
  - Ki – position loop integral gain
  - Kd – position loop derivative gain
  - Ilim – position loop integral limit
  - Max A – trajectory maximum acceleration
  - Max V – trajectory maximum speed
- Dual drive board:
  - Velocity loop gain (analog – potentiometer)
- Servo amplifiers: read manual!!

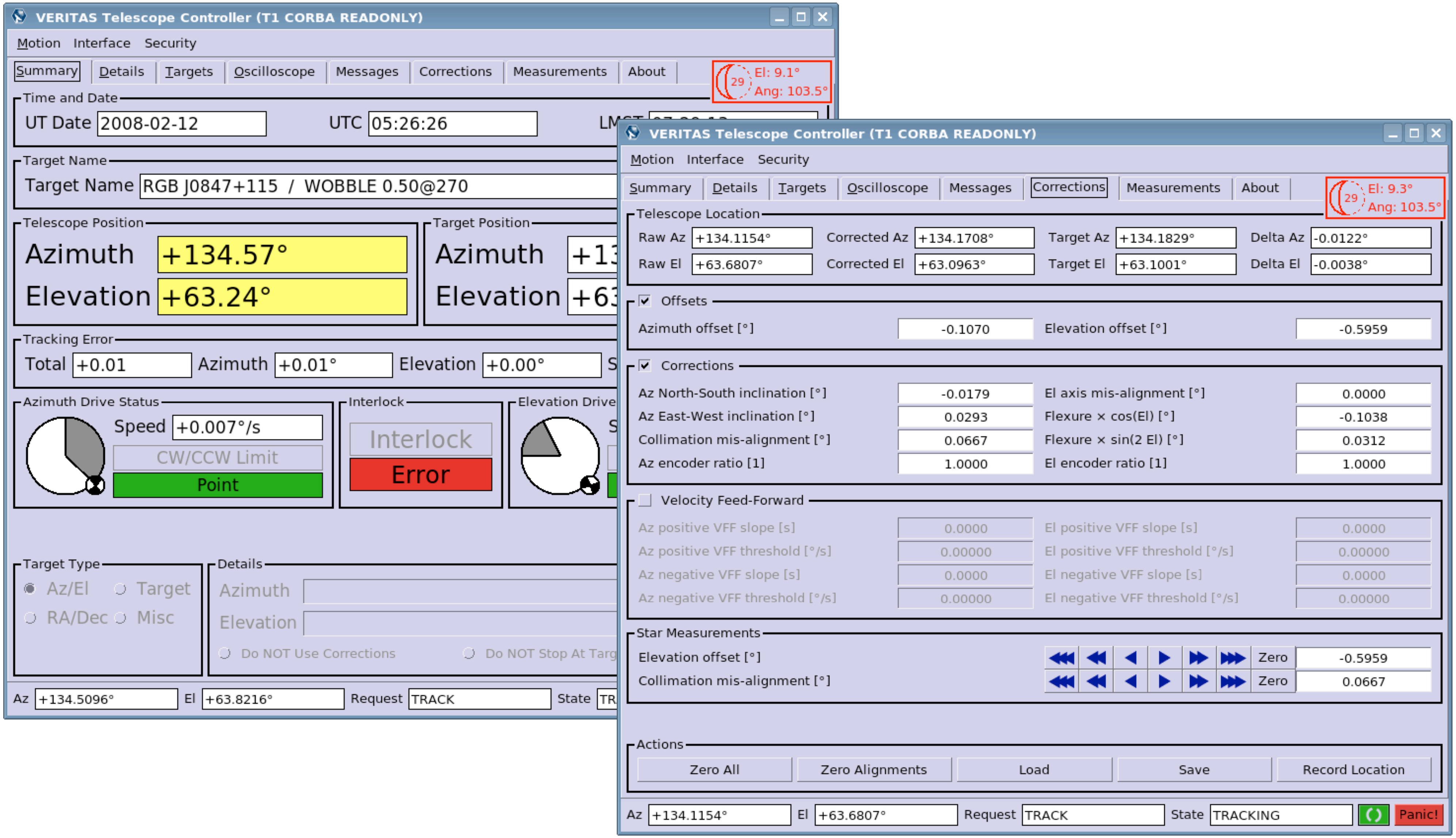
Tracking software (features)

- Array, single telescope and failsafe interfaces
- Client-server architecture means that tracking server is monitoring telescope regardless of CORBA failure, GUI slowness, etc...
- Well integrated with database (commands, positions, targets, corrections)
- Support for taking star measurements and calculating corrections with on-board solver
- Safety layer enforces limits on motion

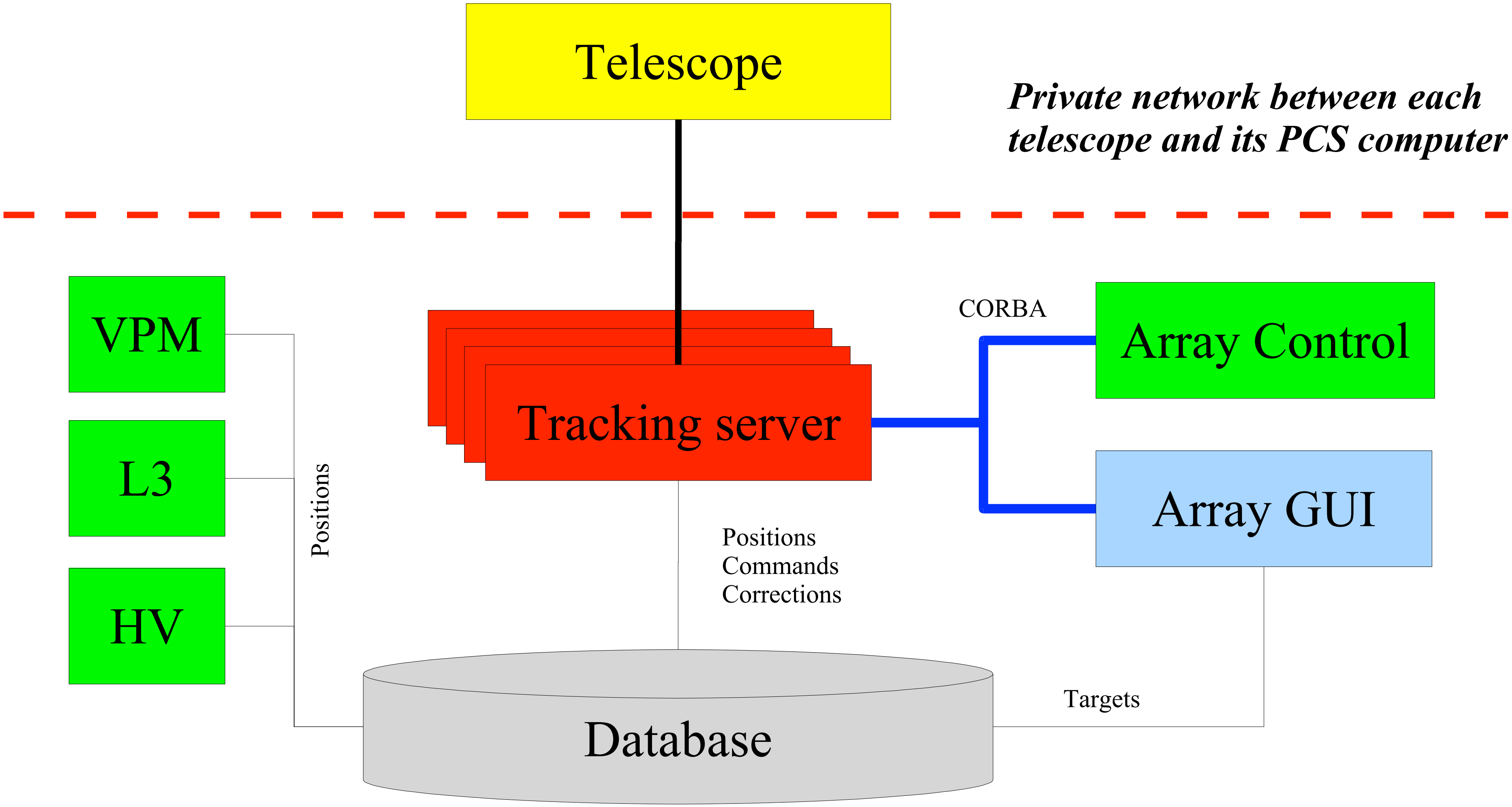
Array GUI

VERITAS Array Controller
Motion Database Settings Server
Array T1 T2 T3 T4 Targets GRB Messages About
El: 9.6°
T1: 103.5°
Time and Date
UT Date 2008-02-12
UTC 05:23:54.0
LMST 07:26:40.9
MJD 54508.224930
Target
Name RGB J0847+115 / ON
RA 08:47:41.5
Dec +11:31:59
Az +132.6635°
El +62.5363°
Telescope 1 (Hillas)
Telescope 2 (Jelley)
Telescope 3 (Porter)
Telescope 4 (Chudakov)
RGB J0847+115 / WOBBLE 0.50@270
133.49°
133.50°
62.85°
ERROR
TRACKING
Array
Target Type
Az/El
Target
RA/Dec
Misc
GRB
Details
RGB J0847+115
Load Targets
On Source
On/Off
Go
STOP
T1: ERROR
T2: TRACKING
T3: TRACKING
T4: TRACKING
Panic All!

Single telescope GUI



Network neighborhood



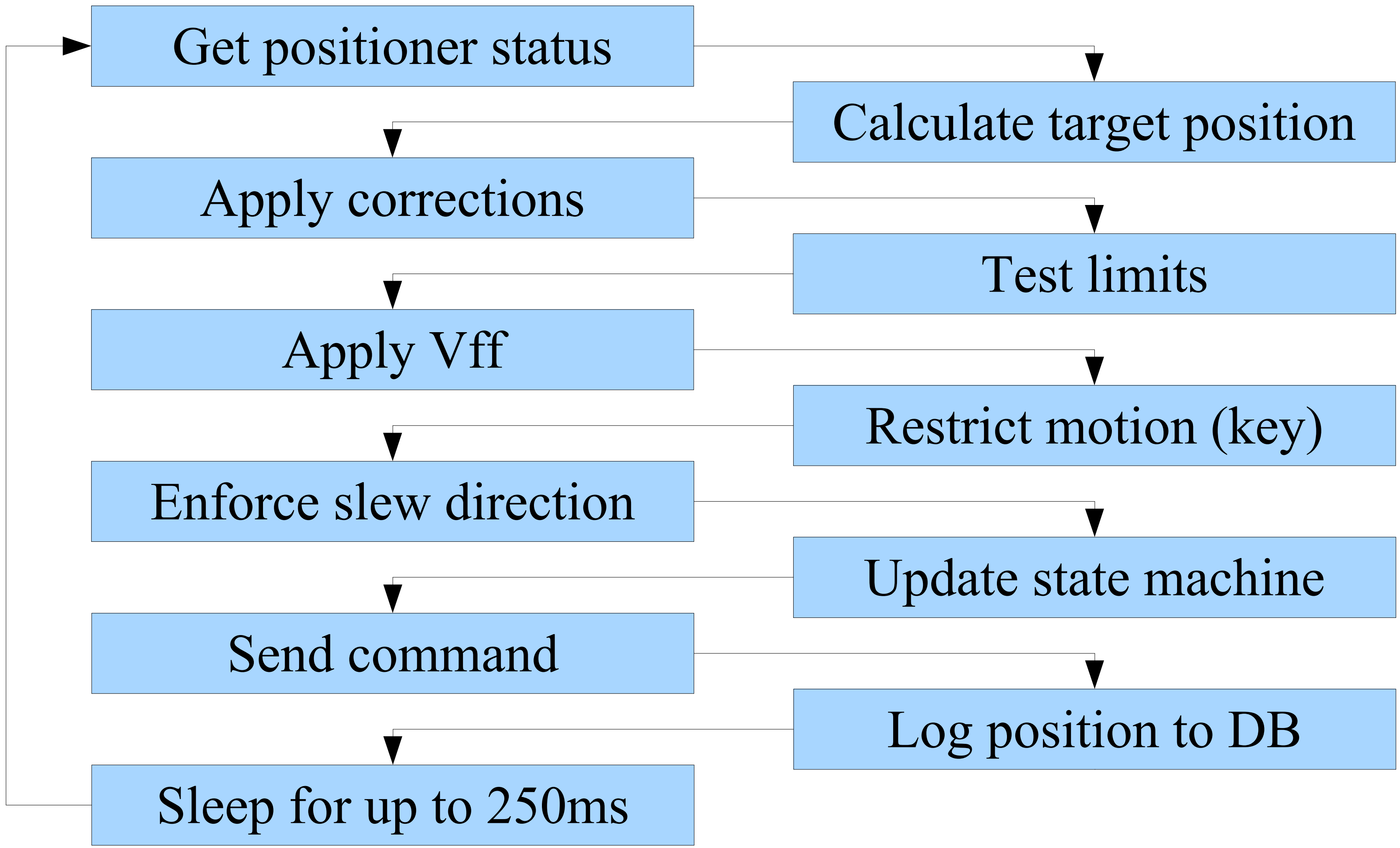
Tracking software (internals)

- *Scope API* – send/receive commands from scope
- *Failsafe UI* – text interface to *Scope API* - **CAUTION**
- *Telescope controller (Local)*
  - Loop to monitor pedestal and send target position commands to telescope and log to database
- *Single telescope GUI* – old interface
- *Telescope controller (Remote)*
  - Proxy for *Telescope Controller (Local)* using CORBA
- *Array GUI* – talk to multiple telescopes

Operating modes

- Text based failsafe UI directly to telescope. Like using RPM TCU but with less feedback. No limits.
- Single telescope GUI on PCS computer directly to telescope (`./serial_tracking`)
- Tracking server on PCS computer directly to telescope (`./tracking_server`)
- Single telescope GUI to tracking server with CORBA (`./one_tracking_t1`)
- Array GUI with CORBA (`./array_tracking`)

Telescope contoller loop



Corrections

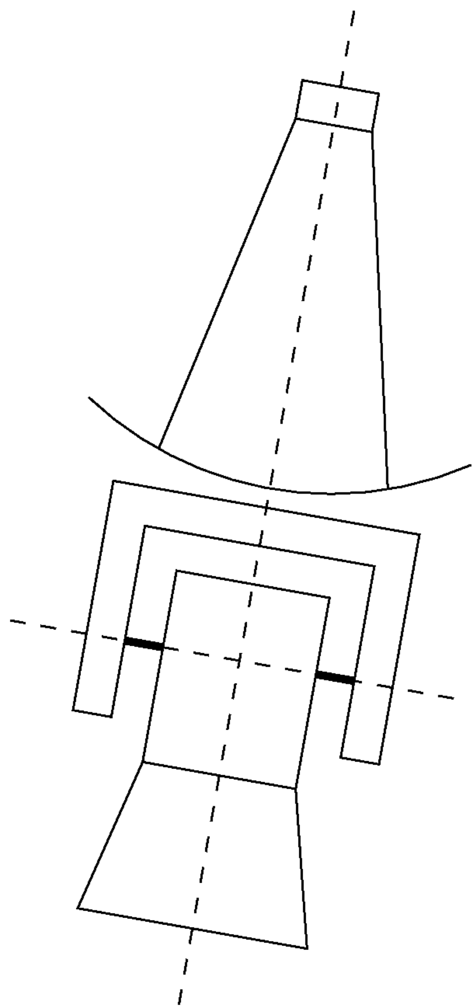
- 10 parameter model of Alt/Az behavior
  - Azimuth and Elevation offsets (2)
  - Azimuth N/S and E/W inclination (2)
  - Elevation axis mis-alignment (1)
  - Collimation mis-alignment (1)
  - Flexure of focus box (2)
  - Encoder ratios (2)

Every telescope orientation corresponds to somewhere in sky. Not every sky position has a corresponding telescope orientation.

- Can control 2 drive axes – but 3 Euler angles required to describe orientation of rigid bodies.
- 8 parameter “Velocity feed-forward” - not used

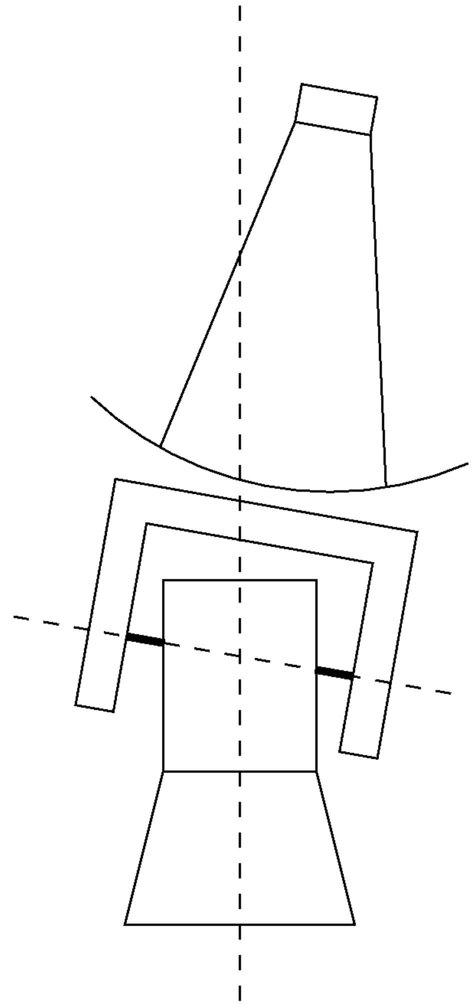
Azimuth N/S, E/W inclination

- Describes angles of inclination of an axis perpendicular to the azimuth bearing with respect to the zenith
- N/S and E/W angles
- T1 angles today:
  - NS: -0.0081°
  - EW: 0.0276°



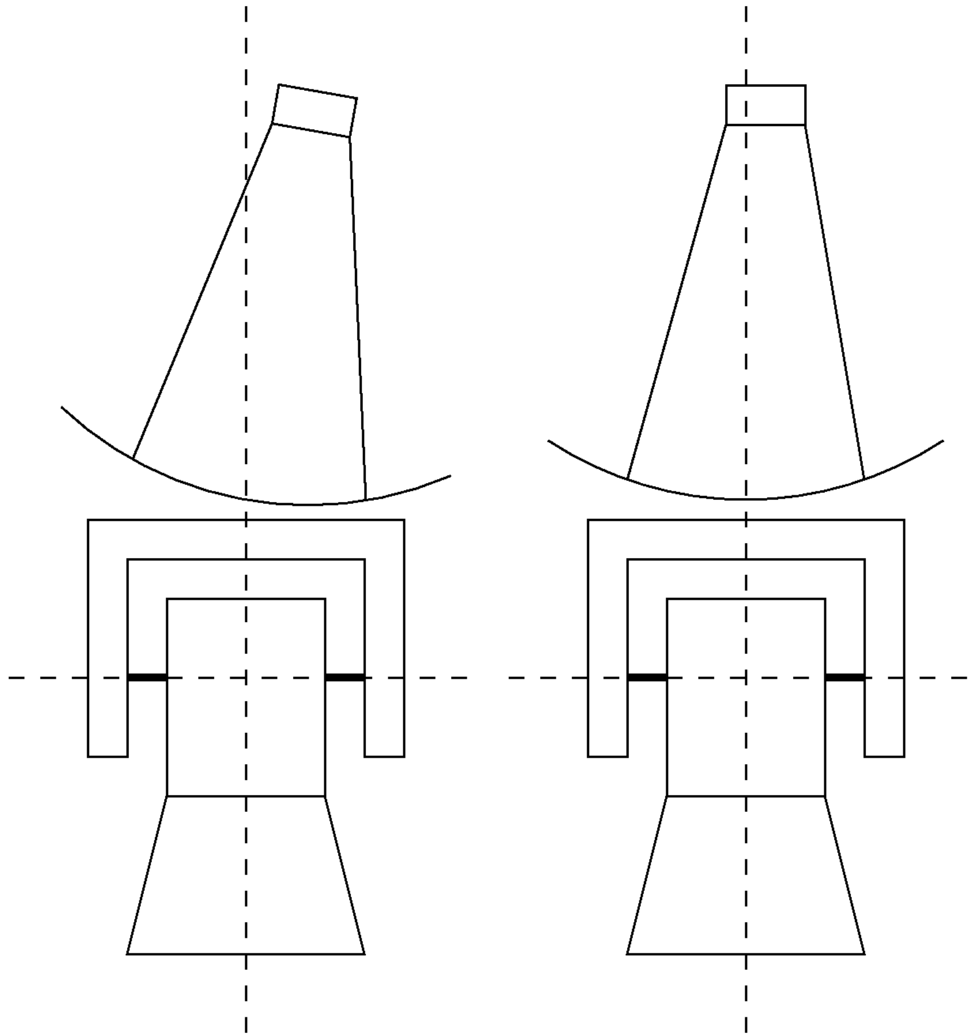
Elevation axis mis-alignment

- Ideally elevation axis is perpendicular to azimuth axis.
- In real telescope this is not necessarily so.
- We have never needed this correction for VERITAS telescopes.



Focal plane collimation

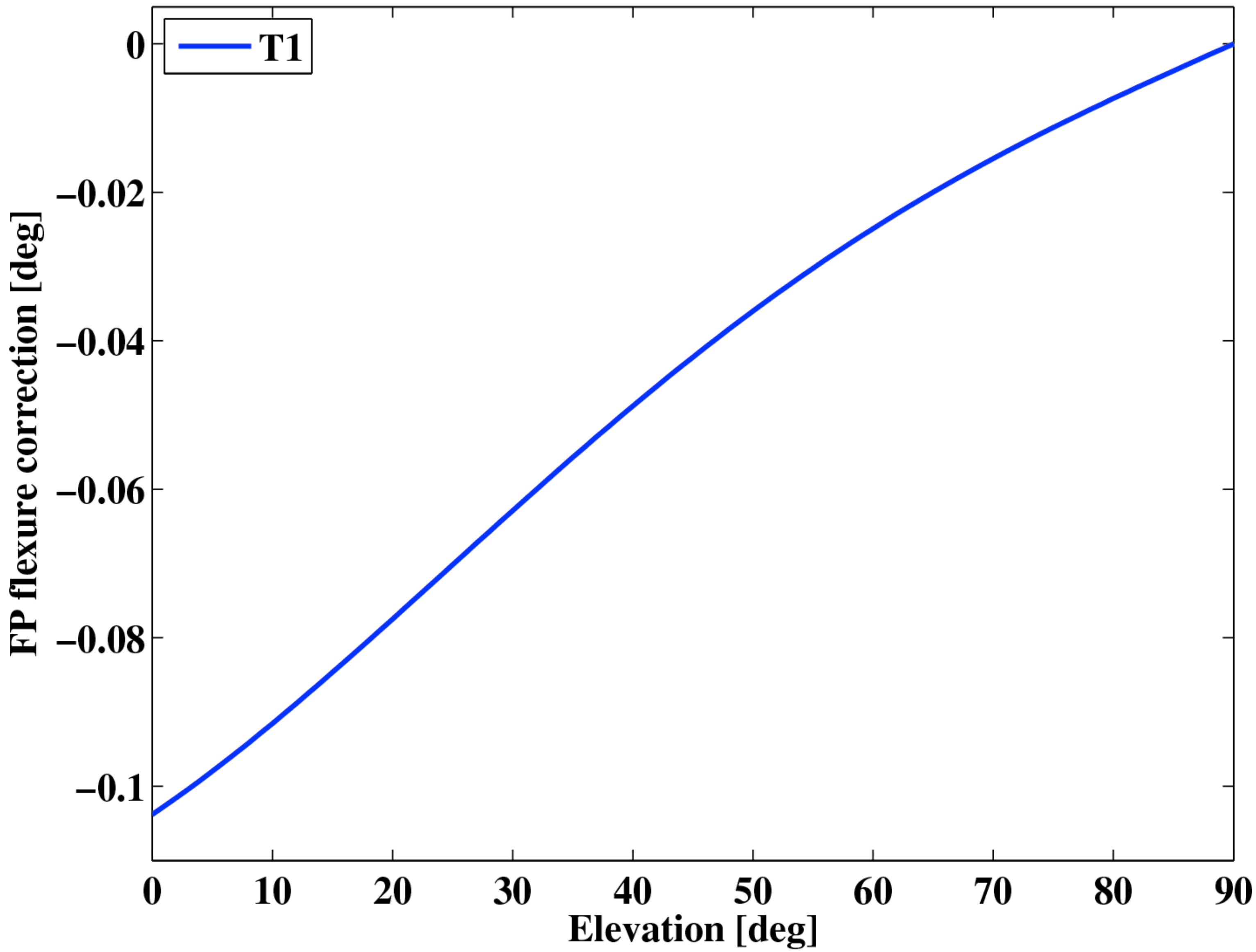
- Ideally light from a distant target lying in plane defined by the elevation axis is reflected into the center PMT
- Out of plane error is mis-collimation
- T1: 0.0667°



Offsets and flexure

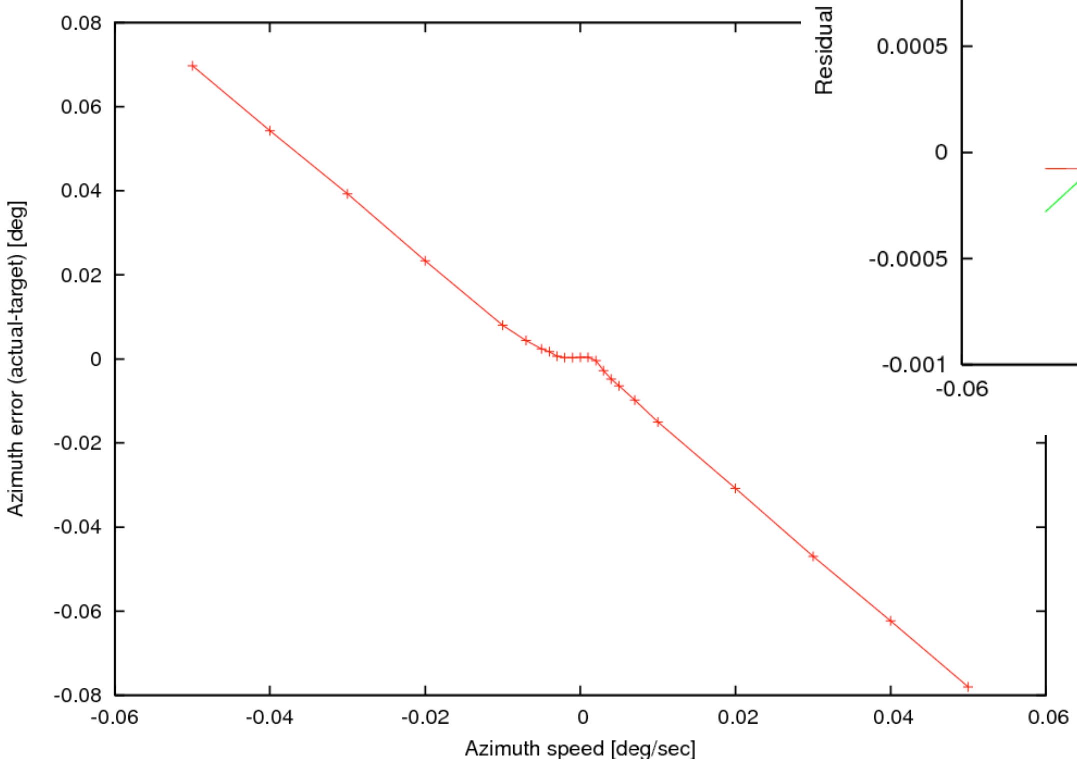
- Elevation and azimuth offsets describe “zero” point of encoders. The exact definition of the parameters are surprisingly difficult. For example the correction equivalent to “FP collimation”, but Up/Down in the camera is folded into El offset.
- Flexure – anomalous motion of camera has some functional form. Define it to be zero at zenith. Function can be expanded as Fourier series. First two non zero terms are A**cos(el)* and B**sin(2el)*.
  - T1: A=-0.1038°, B=0.0312°

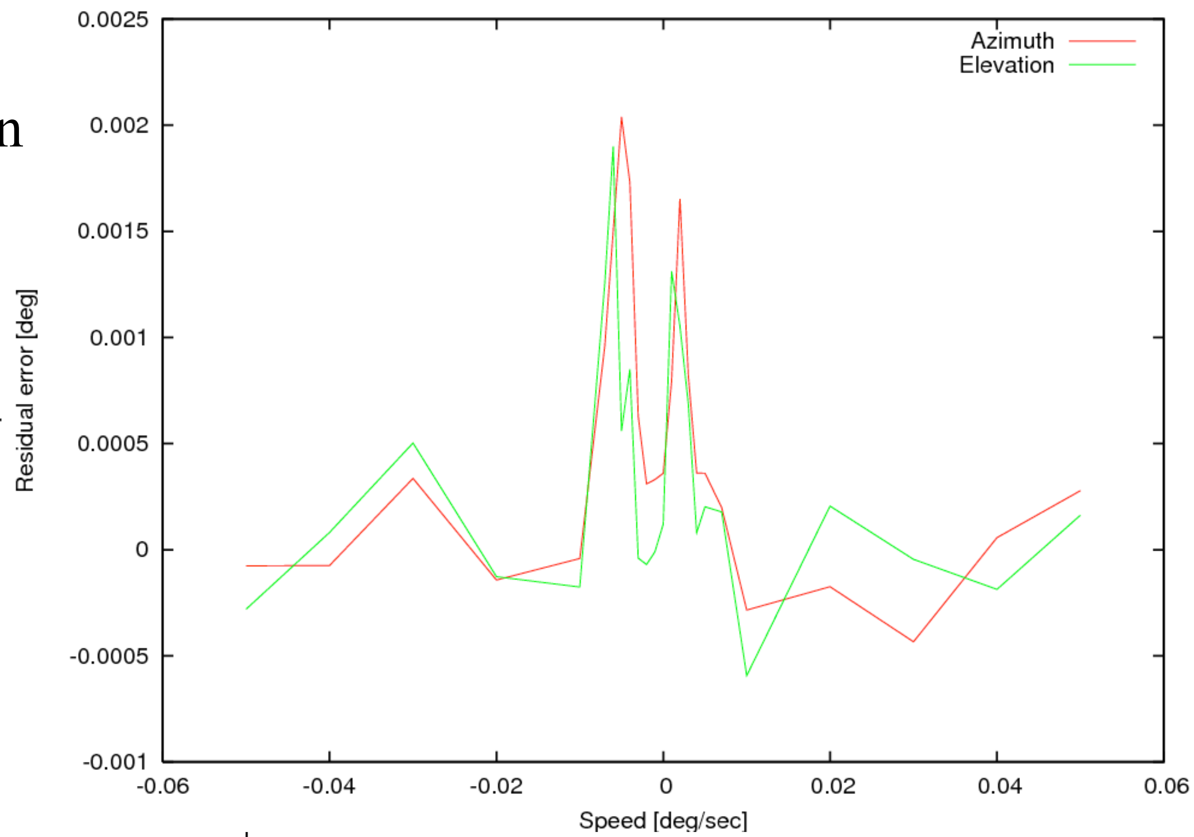
T1 flexure correction



Velocity feed-forward

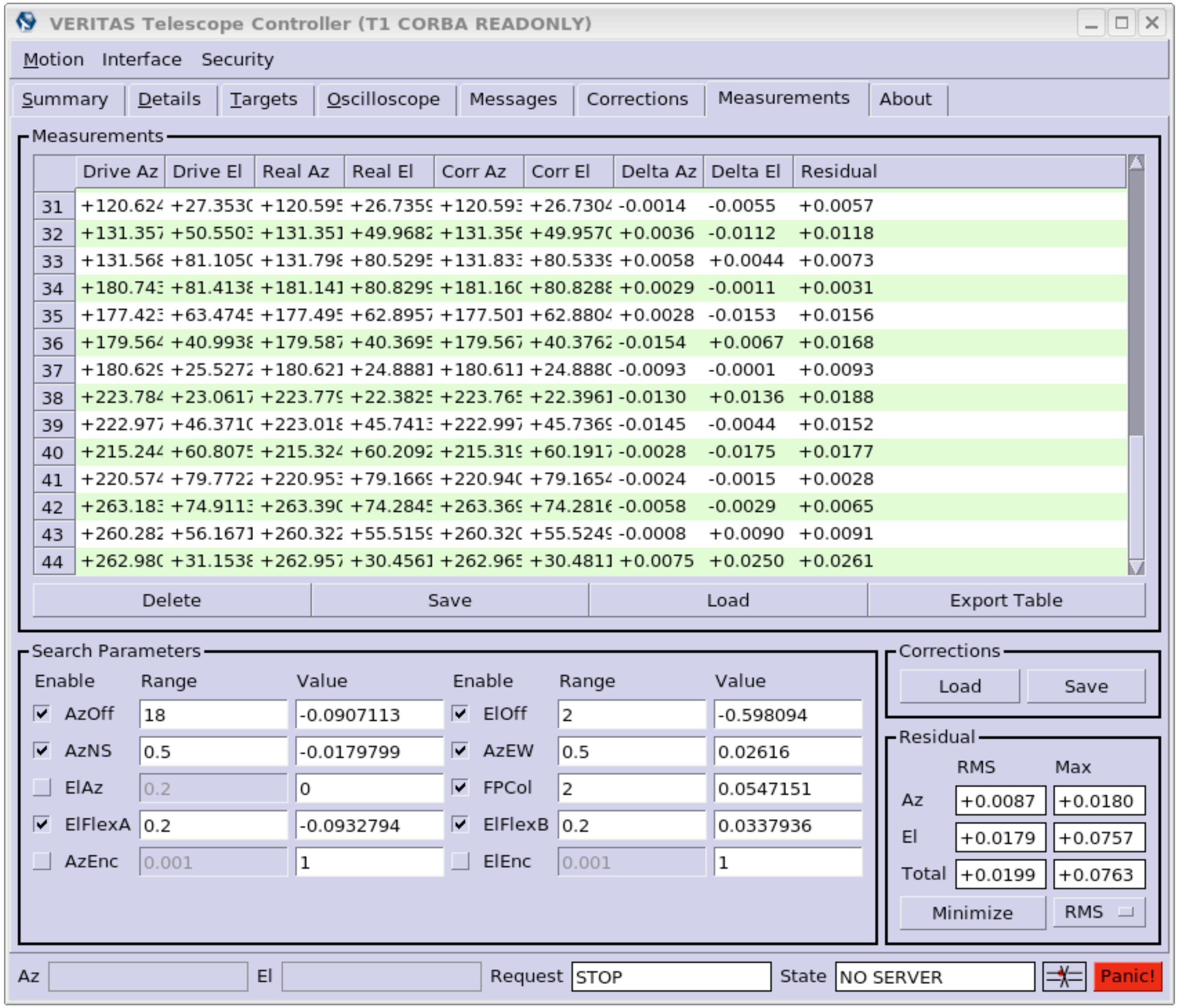
As mentioned earlier, current to drive motors derives from position error. No error mean there will be no motion! Plotted is error vs. speed of target.





Vff corrections consists of two linear fits to speed-error curve for each axis. When applied tracking program leads target, depending on its speed to minimize error.

Corrections fitting



- Fitting can be done from within single telescope GUI
- Be conservative with number of parameters
- Start with Az/ElOff and AzNS/EW.
- Add param and check solution improves.
- Never use AzEl or Az/ElEnc
- 0.010-0.025 good!

Software safety

- Motion below 20° forbidden.
  - Two windows for low elevation motion open: *platform* and *stow*.
  - Override option was previously available – not any longer after a few mishaps.
- Control loop is pretty simple and runs as a separate thread. Should not hang for any reason.
- Panic! buttons instantly stop motion and terminate control loop, so tracking servers would need to be restarted to resume motion.

Problems

- T1 control system sometime will not reach target, needs to be "reset" by pressing stop and start
- T2 has noticeable oscillations during regular observations
- T3 has violent oscillations when slewing downward at 0.06deg/sec – not usual during observation
- T4 has no problems at this time :-)

Further reading

- In "Specs" directory of tracking software:
  - MA4065_redux.pdf – Pedestal manual – lots of information (RPM)
  - PG4003_A4065_SAO.doc – Pedestal specifications – old (RPM)
  - A0058IF_RevD_ENET.doc – Control message specification (RPM)
  - acstech80_595x.pdf – Digital motion control board specs (ACS/Tech80)
  - pmd_HW_v101.pdf – Digital motion control manual (ACS/Tech80)
  - b25a-ac.pdf – Servo amplifier manual (AMC)
  - AMC_sectionG.pdf – Engineering notes from servo amp. Manufacturer (AMC)
  - bmr4000.pdf – Motor manual (CMC)
  - microsys_sbc1491_datasheet.pdf – SBC datasheet (Microsys)