DFM Engineering, Inc.
1035 Delaware Avenue, Unit D
Longmont, Colorado 80501
Phone: 303-678-8143
Fax: 303-772-9411
Web: www.dfmengineering.com

TCSGALIL OPTIMIZED 2.0 OPERATIONS MANUAL

Revision 1.3

TABLE OF CONTENTS

WARRANTY

All DFM parts and labor specified in this contract are warranted by DFM Engineering, Inc. to be free from defects in materials and workmanship for a period of 12 months from the acceptance date. DFM will assign all manufacturers' warranties for parts that are not manufactured by DFM, but DFM gives no warranty and assumes no liability for those parts. ALL OTHER WARRANTIES, EXPRESS OR IMPLIED, SPECIFICALLY INCLUDING WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE, ARE HEREBY DISCLAIMED.

Remedies for breach of this warranty are limited to repair or replacement of defects only, at the option and expense of DFM. In the event of any repair or replacement required by this warranty, such work shall be warranted for one year from completion under the terms of this warranty. DFM shall have no liability for any loss or damage arising from breach of this warranty, including incidental or consequential damages, except as expressly provided herein. DFM shall have no liability for defects or damages resulting from misuse, acts of God, war, vandalism, or theft. All maintenance during the warranty period shall be performed by or with the written consent from DFM, and any unauthorized maintenance shall relieve DFM from any liability under this warranty.

In the event DFM performs any work not covered by this warranty, the customer shall be fully responsible for all labor and material expenses incurred by DFM. The terms for such work shall be agreed to by the parties in writing prior to any work done by DFM.

ATTORNEY'S FEES

In the event DFM retains an attorney because of the customer's failure to pay any amounts under this contract, the customer shall be responsible for all reasonable attorney's fees incurred by DFM, in addition to any other damages.

LICENSE AGREEMENT

LICENSE AGREEMENT BETWEEN CUSTOMER AND DFM ENGINEERING, INC. FOR RIGHTS IN TECHNICAL DATA AND COMPUTER SOFTWARE

DEFINITIONS

1. COMPUTER, as used in this agreement, means a data processing device capable of accepting data, performing prescribed operations on the data, supplying the results of these operations, and/or performing control functions based upon commands supplied, or logical decisions made using input data or commands.

2. COMPUTER DATA BASE, as used in this agreement, means a collection of data in a form capable of being processed and operated on by a computer.

3. COMPUTER PROGRAM, as used in this agreement, means a series of instructions, statements, procedures, etc. in a form acceptable to a computer, designed to cause the computer to execute an operation or operations. Computer programs include operating systems, assemblers, compilers, interpreters, data management systems, utility programs, sort-merge programs, real time control programs, etc. Computer programs may be either machine-dependent or machine-independent, and may be general purpose in nature or be designed to satisfy the requirements of a particular user.

4. COMPUTER SOFTWARE, as used in this agreement, means computer programs, software, and/or computer data bases. This includes source code, binary code, memory images, or any intermediate form of the programs.

5. COMPUTER SOFTWARE DOCUMENTATION, as used in this agreement, includes technical data, including computer listings and printouts, in human-readable or machine readable form which (a) documents the design or details of computer software, (b) explains the capabilities of the software, or (c) provides operating instructions for using the software to obtain desired results from the control system or computer.

6. TECHNICAL DATA, as used in this agreement, means recorded information, regardless of form or method of recording.

7. DETAILED DESIGN DATA, as used in this agreement, means technical information or data that describes the physical or electrical configuration and performance characteristics of an item or component in sufficient detail to allow understanding of its function or to allow duplication of the item or component. Examples include, but are not limited to, drawings, CAD files, schematics, software listings, flow charts, etc.

8. LIMITED RIGHTS as used in this agreement means rights to use, duplicate, or disclose technical data, in whole or in part, by the customer or any of the customer's employees or staff with the express limitation that such technical data shall not, without written permission of DFM Engineering, Inc. , be: (i) released or disclosed to a third party, or (ii) used for any purpose except in conjunction with a DFM Engineering, Inc. product. Detailed design data (examples include, but are not limited to, mechanical and electrical drawings or schematics) shall not be used for manufacture or preparation of the same or similar devices.

9. RESTRICTED RIGHTS as used in this agreement means rights to use, duplicate, or disclose technical data in whole or in part by the customer without written permission of DFM Engineering, Inc. This data may be used, duplicated, or disclosed to a third party subject to the following express limitations: The data may be used, duplicated, or disclosed in whole or in part only in a human-readable form and at no cost to the third party.

LICENSE TO CUSTOMER

The customer is granted LIMITED RIGHTS to the technical data and computer software. The software may be copied for safekeeping (archives) or backup purposes only. The software may be used with a backup computer only when the computer it was supplied for is non functional. The software may only be used at the original site that it was supplied for and may not be transported to another site even if the computer which it was supplied for is transported to another site. The software may not be used in whole or in part as a portion of another computer program. The detailed design data may not be used for manufacture or preparation of the same or a similar device.

The customer is granted RESTRICTED RIGHTS TO the computer data base containing the data for the library of objects as supplied by DFM Engineering, Inc. The customer may add to, change, or subtract from this data base as they deem necessary for efficient operation.

Acceptance of the technical data acknowledges the acceptance of this agreement in totality and customer agrees to pay all costs involved in prosecution required to enforce this agreement and to pay all damages to DFM Engineering Inc. for unauthorized use of the technical data. This agreement shall remain in effect until the year 2030 AD.

THE TCSGALIL SOFTWARE SUITE

The TCSGalil suite consists of two primary programs, TCSGalil and the Pointing Model Tool. Both programs are native 32-bit Windows applications written in Delphi. It is a good idea to keep a copy of TCSGalil Software Suite so that the system can be restored in case of a major failure. Copying the entire directory (folder) containing the TCSGalil executable to external media is the only step needed.

TCSGALIL

TCSGalil is the primary operator application, providing a graphical user interface [GUI] with real-time feedback of the state and position of the telescope. Coordinate, equinox, precession, nutation, aberration, refraction, and mechanical and optical misalignments are all handled in real-time by the TCSGalil application.

TCSGalil uses three support files for initialization and configuration. All three files start with the letter J followed by a 3-4 digit code representing the DFM job code.

- J###.DMC is embedded code uploaded to the Galil DMC when TCSGalil is started. This file should not be altered except at the direction of DFM technicians.
- J###.INI file is used for storing user configuration information. This file is changed by the TCSGalil application regularly.
- J###.PARAM is a parameters file containing site tuning, configuration, and pointing model information for the TCSGalil application. DFM supplies a Pointing Model Tool to facilitate editing this file.

TARGET ACQUISITION MODES

Historically a telescope control system [TCS] had two fundamental modes: tracking and slewing. Tracking was usually handled with a clock drive system and slewing was done manually. When telescopes become motorized, it was still common to have two different motors controlling the HA axis, a tracking motor and a slew motor, with different gearing and different tolerances. This terminology, as well as the fundamental separation between the two modes, remains for many TCS's today. In order to support more advanced features, such as Low Earth Orbit [LEO] satellite tracking, it was necessary to modernize the design of the TCS. DFM has decided to use two different modes for following targets: Chase mode and Follow mode.

Follow mode is often referred to as open-loop since the velocity runs but the TCS doesn't go back and verify the position. Follow mode is the typical behavior of common GOTO telescopes and similar lower-priced amateur telescope mounts. The motors move the telescope at high speed until they reach their target and then switch into a steady velocity mode. It's assumed that the target object is moving at a constant rate (sidereal rate for stars, for example) and matching the velocity is all that's needed to keep the object in the field of view. Follow mode gets a little more complicated than moving at sidereal rate. Any pointing model used for correcting telescope position needs to be differentiated to determine what the rate correction at that position should be. In addition, a good TCS should be able to compensate for any periodic errors introduced by worm gears, harmonic drives, etc. The result is a rate that's close to the rate of the target, but the accuracy deteriorates as the tracking continues.

Chase mode is a closed-loop control system that continually compares the target's location with the current telescope position. Periodic errors are automatically corrected if the position encoder is placed after the gear train. The pointing model doesn't need to be differentiated because a new position is calculated regularly. In addition, unexpected disturbances such at friction drive slippage, bumping the telescope, and gear slop are automatically corrected for.

The TCSGalil system is capable of correcting positions at a rate near 100 Hz for properly tuned mounts. To reduce the effects of rapidly altering velocities, TCSGalil uses a unique Iterative Cubic Envelope Engine [ICEE] to calculate predicted motions and determine the ideal control path to reach them. This system slightly reduces the bandwidth of the control system while significantly improving image stability.

The choice of using Chase or Follow mode will depend on user requirements. Follow mode will always provide a smoother motion at the expense of accumulating errors. Chase mode is necessary for any objects that change velocity, such as satellites.

THE MAIN DISPLAY

The main TCSGalil display provides the user with a summary of system activity and status. The Position group at the top shows the telescope's mean coordinates in the display equinox followed by the target coordinates in its own equinox (if one has been entered). The target coordinates are updated in real-time for objects that move with respect to the celestial sphere. The Operating Mode group includes notices such as "East Side" or "West Side" pier operation (if applicable), target acquisition mode, and hand paddle commands. The Server Status group box displays the status of the TCP/IP and serial port interfaces for receiving external commands. The Time/Date group box shows the Universal Date and Time, Sidereal Time, and Julian Date.

The Rates group box shows the mount's current commanded rate, the calculated target object rate, track rates, track rate corrections (derived from the pointing model), and the handpaddle Guide and Set rates. The Mount Movement Limits group shows the status of both hardware and software limits which can limit telescope motion. If the target object dips below the software limit, an "OUT OF RANGE" notice will appear as well. The Axis Motor Torque shows the real-time torque being applied to the axis motor. The Status Messages group provides general purpose messages for various TCSGalil subsystems.

If supported, additional groups such as the Dome, Focuser, and Instrument Rotator will display below the Status Messages group. These groups will provide information about movements, positions, and limits where applicable. Finally, the status of the front panel switches is displayed at the bottom of the TCSGalil window.

THE MENUS

Menus to additional windows are available from the top menu bar.

FILE: SAVE POINT DATA

Save Point Data activates the pointing model data collection dialog box that lets the user collect, edit, and save data for deriving a pointing model. The Save Point Data dialog may be re-positioned on the display for convenience during pointing model tune-up. The "Save Point" button will flash slowly if a data point has not been saved near the telescope's current position.

FILE: EXIT

Closes the TCSGalil application and terminates any current motion.

TELESCOPE: INITIALIZATION

The Initialization window provides a convenient interface for redefining offsets of various subsystems. The Set Current Telescope Position is used for changing the mount encoder offsets. This is most useful when pointing to a known object and entering the coordinates in manually. The Use Target Position button is helpful if the user commanded a slew to a known object and then used the handpaddle to correct the centering of that object. This is equivalent to a "Sync" command in software such as TheSky. In addition, the Set Mount Encoder Offsets can be used to set the encoders for the zenith position or to reload the default values from when TCSGalil was started.

The Set Display Equinox box allows the user to change which equinox is used for displaying the telescope position.

TBAR is a correction factor for the refraction effects of the atmosphere. Atmospheric refraction can introduce several arc minutes of error in pointing accuracy and tracking accuracy during long exposures. For best performance the TBAR correction should be set to the nearest 100 meter increment of the local altitude and nearest degree Celsius of air temperature. Enter the values and use the “Calculate” button to calculate the proper TBAR value, then click “Apply.”

As an alternative, you can pick a TBAR value for the density altitude with this the equation:

TBAR = 1 – (0.000035714 x Density Altitude in feet).

The position of the instrument rotator, focuser, and dome can be modified from this window on systems that support those subsystems. For systems with a focuser fiducial, the auto-initialization procedure can be started from this window as well.

TELESCOPE: MOVEMENT

The Movement dialog box provides methods for defining the target object and the motion of the telescope mount. There are motion control buttons on the right side of the Movement dialog box for quick access. The “Chase Targets” button causes the mount to immediately start moving to the target object. Any changes to the target object coordinates are responded to immediately. The “Slew To Target” button will cause the telescope to begin a slew at high speed to the target object position. Once the telescope reaches its target (defined by the Capture Tolerance), the mount switches to Follow Target mode. The “Follow Target” button starts constant velocity mode without the initial slew. This mode was historically known as just turning on the tracking drive. The “Hold Position” button will stop mount motion and attempt to hold the current position.

For user convenience there is a Stow Mount at Zenith Position button. This sets the target object as zenith with mount velocities set to zero. Motion begins when the button is pressed.

TELESCOPE: MOVEMENT: DEFINE TARGET

The Define Target tab allows the user to manually enter celestial coordinates, including the velocity and acceleration, of the target object. The Equinox can be set for this target as well. If the equinox is left at zero, the equinox currently displayed on the main form is used. Horizon safety checks are performed before any motion. If the target object is below the telescope horizon, a “Target Out of Range” notice will appear in the main TCSGalil window and the telescope will switch to Follow Target mode.

TELESCOPE: MOVEMENT: OFFSET

This sets a new target object with coordinates relative to the current mount coordinates in the display epoch. Input is in seconds of arc. The speed of the offset is a function of the distance to be offset and not specified by the user. The RA offset is divided by the cosine of declination, providing a movement that’s perpendicular to the DEC axis at any point in the sky.

TELESCOPE: MOVEMENT: DFM OBJECT LIBRARY

This is a slew to a library of objects that are stored in the computer memory. All objects are stored in epoch 2000. The objects are the "Sommers-Bausch Observatory Catalog of Astronomical Objects". The catalog includes a set of ephemeris stars at one hour intervals that are useful for initializing the telescope position in the northern hemisphere. TCSGalil displays the library in a spreadsheet format and allows sort and search capability.

TELESCOPE: MOVEMENT: MARK / MOVE TABLE

This dialog allows the user to load, save Mark files as well as edit mark file entries, make entries of current telescope position and slew to Marked positions. There are 500 entries possible for each file.

TELESCOPE: RATES

The normal and auxiliary track rates may be configured here. The auxiliary track rate can be selected either from the front panel switch or from the Misc menu option. For external computer operation, only the Normal track rates can be changed.

Guide Speed is a traditional hand paddle function with rates superimposed on the track rate when in follow mode. Speeds between 3 and 10 arcseconds per second are recommended. Set Speed is typically faster than guide and convenient values are 50 to 300 arcseconds per second. The slow and fast focus speeds are defined as a percentage of the maximum safe rate for the motor.

TELESCOPE: MISC: SETTINGS

East / West: For applicable mounts, this option allows for choosing which side of the pier the OTA is currently working in.

Cosine Declination: For handpaddle operation (both physical and virtual), this feature divides the commanded Right Ascension rate by the cosine of the declination so that the apparent motion of the object in the eyepiece is constant.

Rate Correction: This command turns on the track rate correction feature of the control system. Rate corrections are calculated by differentiating the pointing model. These values are only used for "Follow" mode.

Capture Threshold: This is the distance at which the mount control switches from Slew To Target mode to Follow mode. Setting a smaller value will increase the time required to complete a slew. Setting the capture threshold value smaller than the pointing accuracy of the mount, or smaller than the seeing limit, is usually not beneficial.

TELESCOPE: MISC: FOCUS

Move focus position: This command allows the user to change the telescope focus position using the focus encoder for feedback. Movement starts when the Apply button is clicked.

TELESCOPE: MISC: DOME

Dome Mode: This command is used to set the operating mode of the dome controller. The “Track Telescope” mode calculates and moves the dome to keep the telescope slit oriented with respect to the telescope mount. The “Go Home” mode starts a rotation which continues until the dome home switch is encountered. Upon reaching the dome home switch, the dome position is set to the pre-defined home value. The “Go To Azimuth” mode allows the user to set an Azimuth Target for the dome to rotate to. In “Manual” mode, the dome responds to handpaddle commands only. The “Dome Home” and “Auto Dome Off” front panel switches will override any modes set in software.

Dome rotation and shutter operation buttons are latching and can be used to manually operate the dome.

TELESCOPE: MISC: MIRROR DOORS

If equipped, the OTA mirror doors can be actuated from this menu.

VIEW: VIRTUAL HAND PADDLE

The virtual hand paddle provides the same functionality as the physical hand paddle.

COMMUNICATIONS: COMMAND SERVERS

The communications window allows the user to configure servers which listen for external commands. Both a serial port and a TCP port can be assigned to listen and respond to commands. Appendix A of this document has a list of supported commands.

COMMUNICATIONS: UDP SERVER

A UDP server is used to receive rapid sensor data from the Galil DMC. This window is just for informational and debugging purposes.

COMMUNICATIONS: GALIL CONNECTION

This window allows for configuration of the TCP network connection to the Galil DMC. These settings should only be altered at the request of DFM technicians. The user can turn off Auto Connect and Auto Initialize here if they do not wish to immediately connect to the Galil controller.

COMMUNICATIONS: ASCOM INTERFACES

TCSGalil advertises itself as an ASCOM telescope, and ASCOM focuser, and an ASCOM dome. From the ASCOM Interfaces window, the user can verify the state of various ASCOM connections. In addition, communication logging can be turned on here.

OPTIONS: DEFAULTS

When TCSGalil terminates, some values are written to disk and restored when TCSGalil restarts. These settings can be saved or restored manually from this menu. In addition, the default window location and size can be saved.

HELP

TCSGalil features an online help document. Just click on the Help Menu and select Contents or Index.

POINTING MODEL TOOL

The Pointing Model Tool is used to analyze data from TCSGalil to develop and tune a mount pointing model. The Pointing Model Tool also provides a convenient interface for adjusting some of the operational constants used in TCSGalil.

A POINTING MODEL

A pointing model is a mathematical mapping from where the telescope is pointing to what the actual location in the sky is. Due to various imperfections in encoders, mount alignment, and other factors, the telescope does not always point precisely at the location in the sky expected. The Pointing Model Tool program can be used to tune a pointing model to match a data set.

The mathematical terms chosen for the pointing model correspond to mechanical characteristics of the system. While the pointing model will help compensate for some small imperfections, making a mechanical adjustment is always preferred over using the model to try and hide the behavior.

Tube Flexure is a measure of the bending of the optical system due to gravitational pull. This term is usually just modeled out because correcting this physically involves stiffening up the optical stack.

TBAR is a correction for the atmospheric refraction. This is best calculated within TCSGO given an ambient temperature and site elevation. Tuning this value within the pointing model tool is usually not necessary if set correctly before taking the data.

DEC Encoder Scale and HA Encoder Scale set the size of the encoder steps on the declination and hour angle position encoders. For mounts with on-axis absolute encoders, this value is known and should not be changed. These values are set during initial install and will rarely change unless the encoder system is modified.

DEC Eccentricity and HA Eccentricity deal with the mechanical offsets of the center of the encoder from the center of the axis. This eccentricity has a phase angle associated with it. Adjusting the phase angle changes the direction of the eccentricity offset. For some extended polar axle equatorial mounts and English mounts with the counterweight not symmetrically opposite the OTA, the eccentricity terms can be used to remove the twist in the polar axle. For polar axle twist, the associated phase angle is usually near zero.

To adjust the eccentricity and phase angle terms, it's usually best to introduce some eccentricity correction and then vary the phase angle to see how the data moves. After the eccentricity and phase angle have been applied, there are higher order "4X" terms that can be used to model out periodic eccentricity issues.

Non-perpendicularity is a function of the mechanical build of the mount. When the two primary axes are not perfectly perpendicular, changes in one axis introduce a small change in the other axis. This term usually doesn't change over the life of the mount. Changing instruments or changing pier sides (when applicable) can alter the non-perpendicularity.

Collimation is the angular error of the optical axis. This term will change any time the optics are removed and reinstalled due to cleaning, alignment, etc. Values larger than ~20 should be corrected mechanically.

Elevation Misalignment and Azimuth Misalignment are measures of the polar alignment of the mount. DFM typically aligns a telescope to the refracted pole, intentionally requiring roughly an arcminute correction in the Elevation Misalignment term. Anything further than an arcminute from the refracted pole, in either term, should be corrected mechanically.

POINTING DATA FILE

The pointing data file (ending in .PAT) used by the Pointing Model Tool is a space-delimited text document with the following data in columns:

Julian Date
Sidereal Time
Telescope Mount HA
Telescope Mount DEC
Target RA
Target DEC

The equinox used for the target object should be J2000.

TAKING POINTING DATA

It is desirable for the physical misalignments to be small before the computer model is calibrated because the interaction of terms will then be small. The drift test for azimuth and elevation should be at the level of a few arc seconds of drift in one half hour or better. Large collimation errors (greater than 25 seconds of time) should be corrected mechanically by adjusting the tip-tilt of the primary mirror. Refraction can be adjusted in software to compensate for the altitude and temperature of the site. The tube flexure and non perpendicularity terms are mechanical characteristics of the mount.

TCSGalil can record pointing model data in the format defined above. To begin, slew the telescope to a star near zenith and use the "Use Target Position" in the Initialization window (or "Sync" command in TheSky) to initialize the telescope on its first star. Open up the File – Save Pointing Data dialog box and click the "Take Point" button to record the position of this first star. Record a set of stars that lie near the meridian (near zero Hour Angle), this is called the DEC sweep. Continue to record an additional set of stars near the equator (near zero DEC), this is called the RA sweep. Stars should be about 10 or 15 degrees apart, and can be found easily in the Bright Star Catalog of "The Astronomical Almanac". These two sweeps across the sky are important because they isolate the pointing model terms. A set of 20 stars is usually sufficient for generating a pointing model.

Note: The first star in the data must be a star recently used to initialize the telescope position for valid error calculations.

After saving the pointing data, run the Pointing Model Tool program.

USING THE POINTING MODEL TOOL

Use the File menu to open a parameter file for a particular telescope, as well as a pointing data file. Four graphs will appear illustrating the errors in the positional data. There are 14 user-adjustable parameters which are used to generate the pointing model. This is a physical model and each term has real significance that is directly related to some aspect of the telescope mount.

Each parameter is listed with its previous value (loaded from the .PARAM file) in a gray box followed by the currently adjustable value in the white box. Changing a parameter value in a white box will alter the graphs and calculate new RMS error values.

The determination of pointing model coefficients should be done in a methodical way that isolates individual terms by working on the shapes of the graphs. Attempts to minimize the overall error with any single term will result in poor pointing. Each term should be adjusted to remove the corresponding slope or curvature. Hovering over a term will display a hint describing the graph property targeted.

The pointing coefficients have the following units:

HA/DEC encoder scale	encoder counts per degree	
Tube Flexure	arcseconds	
TBAR	no units	
Elevation Misalignment	arcseconds	(+ = above pole)
Azimuth Misalignment	arcseconds	(+ = NW--SE)
Collimation	seconds	
Non-perpendicularity	seconds	non-perpendicularity of axes
Eccentricity	seconds	
Eccentricity phase angle	degrees	

There are also higher-order eccentricity terms which are useful for on-axis encoders.

POINTING MODEL GRAPHS

The most important thing to remember is that the goal is to remove slope and curvature. Hyper-optimizing for minimum residuals, at the expense of producing smooth graphs, will usually result in poor performance.

DEC ERROR OVER DEC GRAPH

This graph shows the DEC scale factor in its slope. This slope should only be adjusted for mounts with off-axis encoders. The asymmetric terms are refraction and tube flexure. For a telescope with an on-axis Dec encoder the curvature is DEC encoder eccentricity and phase angle. The DEC 4x terms correct the residual higher frequency error after the eccentricity is corrected.

RA ERROR OVER HA GRAPH

This graph shows the RA scale factor in its slope. This slope should only be adjusted for mounts with off-axis encoders. The asymmetric term is refraction. Symmetric shape is polar axle twist and offset, of encoder eccentricity and phase angle for an on-axis encoder. The HA 4x terms correct the residual higher frequency error after the eccentricity is corrected.

DEC ERROR OVER HA GRAPH

This graph shows the elevation and azimuth misalignment of the polar axle. The elevation is curvature, and the azimuth is slope.

RA ERROR OVER DEC GRAPH

This graph shows the collimation and non perpendicularity of the DEC and HA axes. Collimation appears as curvature and non perpendicularity appears as slope. Due to cross-coupling effects, try starting with the non-perpendicularity and the collimation terms before applying any polar misalignment correction.

APPENDIX A: EXTERNAL COMMANDS

The TCSGalil application accepts external commands from either a serial or a TCP/IP connection. The desired interface(s) must be activated using the communications menu in TCSGalil. This feature is designed to provide a telescope control system that can be slaved to a data acquisition computer or general observatory computer used to provide a customer provided interface to the telescope control system.

The commands used by the external computer are the same as those used internally by TCSGalil. Serial port connections require transmit, receive, and ground connections. Commands are packetized beginning with "#", subsequent numbers are separated with a comma, and packets are terminated with a semicolon and a carriage return (0x0d). For example, a SET TARGET OBJECT command looks like this:

#6,18.3457,35.3456,2002.5;

All commands accept floating point numbers. Values are truncated where necessary.

2: INITIALIZE DOME POSITION – Initializes the dome encoder. North is zero azimuth, and azimuth increases going east. If 360 is entered as the dome azimuth, TCSGalil will set the dome azimuth based on the current telescope position.

Command Number	2
Azimuth (degrees 0->360)	270

Data returned: NONE

3: INITIALIZE MOUNT POSITION – Initializes the mount encoders (for telescope with relative focus encoders). This command will use the current display equinox if an equinox value of zero is used. The target object coordinates will be used if all three parameters are set to zero.

Command Number	3
RA (hours)	12.012345
DEC (degrees)	12.345678
Equinox	2038.5

Data returned: NONE

4: INITIALIZE INSTRUMENT ROTATOR – Initializes the instrument rotator encoders (if supported).

Command Number	4
Azimuth (degrees)	4.4

Data returned: NONE

5: INITIALIZE FOCUS POSITION – Initializes the focus encoder (if supported).

Command Number	5
Position (microns)	2010

Data returned: NONE

6: SET TARGET OBJECT – Sets the coordinates of the target object. This command will use the current display equinox if an equinox value of zero is entered. If the telescope is not already in Chase mode, a Mount Mode Command (command #12) is required to initiate the slew. If the coordinates are below the telescope horizon, the TARGET OUT OF RANGE status bit will be set.

Command Number	6
RA (hours)	12.012345
DEC (degrees)	12.345678
Equinox	1950.5

Data returned: NONE

7: OFFSET TARGET OBJECT – Changes the target coordinates relative to the current target coordinates. The speed of the offset is a function of the offset distance. If not already in “Chase” mode, a command #12 must be sent to move the telescope to the new coordinates. The offset in RA is divided by the cosine of the declination, ensuring that offset is perpendicular to the declination axis.

Command Number	7
Offset RA (arcseconds) + is east	100
Offset DEC (arcseconds) + is north	150

Data returned: NONE

8: SET TARGET OBJECT FROM LIBRARY –This sets the target object coordinates to a library object that is stored in TCSGalil. All objects are stored in equinox 2000. The objects are the Sommers-Bausch Observatory Catalog of Astronomical Objects. The catalog includes a set of ephemeris stars at one hour intervals that are useful for initializing the telescope position in the northern hemisphere. A library for southern hemisphere users as well as custom libraries is available. If the telescope is not already in CHASE mode, a Mount Mode Command (command #12) is required to initiate the slew. If the coordinates are below the telescope horizon, the TARGET OUT OF RANGE status bit will be set.

Command Number	8
Library Object #	13

Data returned: NONE

9: SET TARGET OBJECT FROM TABLE – This command is the partner of the Set table entry (MARK) command in the Miscellaneous submenu and is used to set the target object coordinates to a location previously stored in memory with the Set Table entry command. There are 40 entries possible. If the telescope is not already in CHASE mode, a Mount Mode Command (command #12) is required to initiate the slew. If the coordinates are below the telescope horizon, the TARGET OUT OF RANGE status bit will be set.

Command Number	9

Table Line #	32

Data returned: NONE

10: SET TARGET OBJECT TO ZENITH – Sets the target object coordinates to the zenith position with no velocity in HA or DEC. If the telescope is not already in CHASE mode, a Mount Mode Command (command #12) is required to initiate the slew. No additional parameters are needed beyond the command number.

Data returned: NONE

12: SET MOUNT MODE – Changes the current behavior of mount control.

Command Number	12
0: Hold Position 1: Follow Target 2: Slew to Target 3: Chase Target	1

Data returned: NONE

13: STOP MOUNT – Changes the mount control mode to Hold Position. No additional parameters are needed beyond the command number.

Data returned: NONE

14: SET TRACK RATES – Modifies the HA and DEC track rates. Positive HA rate is west, positive DEC rate is north.

Command Number	14
HA Rate (arcseconds/second)	15.041
DEC Rate (arcseconds/second)	.05
AUX HA Rate (arcseconds/second)	14.454
AUX DEC Rate (arcseconds/second)	0.0

Data returned: NONE

15: CHANGE GUIDE RATE – Changes the handpaddle Guide rate. Rates between 3 and 10 arcseconds per second are recommended.

Command Number	15
Rate (arcseconds/second)	7.3764

Data returned: NONE

16: CHANGE SET RATE – Changes the handpaddle Set rate. Rates between 50 and 300 arcseconds per second are recommended.

Command Number	16
Rate (arcseconds/second)	200.1000

Data returned: NONE

18: USE COSINE OF DECLINATION – For handpaddle operation (both physical and virtual), this feature divides the commanded Right Ascension rate by the cosine of the declination so that the apparent motion of the object in the eyepiece is constant.

Command Number	18
1 for ON, 0 for OFF	0

Data returned: NONE

19: USE RATE CORRECTIONS – Applies the refraction and pointing corrections to the "Follow" mode tracking rate.

Command Number	19
1 for ON, 0 for OFF	1

Data returned: NONE

20: SET DOME MODE – Sets the dome control mode. This function only works if the front panel AUTODOME switch is on.

Command Number	20
0: Manual 1: Track Telescope 2: GoTo Azimuth 3: Find Home	1

Data returned: NONE

22: SET DISPLAY EQUINOX – Sets the equinox used for displaying celestial coordinates.

Command Number	22
Equinox	2000.0

Data returned: NONE

23: SET TABLE OBJECT – Sets a list of coordinates that may be chosen as target object destinations using the MOVE command. An entry number and three zeroes will use the present telescope location as coordinates. There are 40 entries possible. The table is initialized to zeros.

Command Number	23
Table Line #	18
RA (hours)	21.7494
DEC (degrees)	12.8839
Equinox	2000.0

Data returned: NONE

24: CHANGE POINTING COEFFICIENTS – Changes the pointing model coefficients in real-time.

Command Number	24
TBAR	1.02
Elevation Misalignment (arcseconds)	120
Azimuth Misalignment (arcseconds)	35
Collimation (arcseconds)	10
Non-perpendicularity (arcseconds)	3
HA Encoder Eccentricity	24.5
HA Encoder Eccentricity Phase Angle (degrees)	13.2
HA Encoder Eccentricity X4	2.2
HA Encoder Eccentricity Phase Angle X4 (degrees)	0
DEC Encoder Eccentricity	14.1
DEC Encoder Eccentricity Phase Angle (degrees)	10.1
DEC Encoder Eccentricity X4	-2.4
DEC Encoder Eccentricity Phase Angle X4 (degrees)	28.1
Tube Flexure [sine] (arcseconds)	12.1
Tube Flexure [tangent] (arcseconds)	1.1
Fork Flexure (arcseconds)	9.5
Declination Axis Flexure (arcseconds)	50.0

Data returned: NONE

25: READ MOUNT COORDINATES – Query TCSGalil for the current telescope coordinates. No additional parameters are needed beyond the command number.

Data returned:

Apparent Hour Angle (hours)	2.034567
Mean Right Ascension (hours)	20.034567
Mean Declination (degrees)	33.483251
Equinox	1994.5
Airmass	1.3551
Zenith Distance (degrees)	15.6
Azimuth (degrees)	138.2
Sidereal Time (hours)	22.034523
Universal Time (hours)	5.258487
Date (decimal years)	2138.82345

26: READ TCS STATUS – Returns eight bytes indicating the internal state of TCSGalil. No additional parameters are needed beyond the command number.

Data returned: Eight unsigned integers separated by commas.

#58,0,30,0,12,94,24,0;

Byte 0 represents the front panel switches (where applicable)

Byte 0 bit 0	(Main) Drives Switch Up
Byte 0 bit 1	Track Switch Up
Byte 0 bit 2	Aux Track Switch Up
Byte 0 bit 3	Dome Track Switch Up
Byte 0 bit 4	Auto Dome Switch Up
Byte 0 bit 5	Amplifiers Switch Up
Byte 0 bit 6	
Byte 0 bit 7	

Byte 1 represents the hand paddle (ASCOM PulseGuide is considered a paddle input)

Byte 1 bit 0	North Button Pressed
Byte 1 bit 1	South Button Pressed

Byte 1 bit 2	East Button Pressed
Byte 1 bit 3	West Button Pressed
Byte 1 bit 4	Set Button Pressed
Byte 1 bit 5	Slew Button Pressed
Byte 1 bit 6	ASCOM is Pulseguiding
Byte 1 bit 7	

Byte 2 represents the mount limits

Byte 2 bit 0	Horizon Limit Reached
Byte 2 bit 1	East Travel Limit
Byte 2 bit 2	West Travel Limit
Byte 2 bit 3	North Travel Limit
Byte 2 bit 4	South Travel Limit
Byte 2 bit 5	Target Out Of Range
Byte 2 bit 6	Approaching Soft Limit
Byte 2 bit 7	Reached Soft Limit

Byte 3 represents the dome controller

Byte 3 bit 0	Find Home Mode
Byte 3 bit 1	GoTo Azimuth Mode
Byte 3 bit 2	Track Mode
Byte 3 bit 3	Rotating Left
Byte 3 bit 4	Rotating Right
Byte 3 bit 5	At Home
Byte 3 bit 6	Manual Mode
Byte 3 bit 7	

Byte 4 represents the focuser and instrument rotator controller

Byte 4 bit 0	Focus Moving In
Byte 4 bit 1	Focus Moving Out
Byte 4 bit 2	Focus at Outer Limit
Byte 4 bit 3	Focus at Inner Limit
Byte 4 bit 4	Instrument Rotator Rotating CCW / Left
Byte 4 bit 5	Instrument Rotator Rotating CW / Right
Byte 4 bit 6	
Byte 4 bit 7	

Byte 5

Byte 5 bit 0	Serial Comm Ready
Byte 5 bit 1	TCP/IP Comm Connected
Byte 5 bit 2	Use Cosine of Declination
Byte 5 bit 3	Use Rate Corrections
Byte 5 bit 4	East Side Pier Operation
Byte 5 bit 5	West Side Pier Operation
Byte 5 bit 6	Galil Data is Stale
Byte 5 bit 7	

Byte 6 represents the mount control mode

Byte 6 bit 0	Mount in Chase Target mode
Byte 6 bit 1	Mount in Slew To Target mode
Byte 6 bit 2	Mount in Follow Target mode
Byte 6 bit 3	Mount in Hold Position mode
Byte 6 bit 4	Target Captured*
Byte 6 bit 5	
Byte 6 bit 6	
Byte 6 bit 7	

* Target Captured indicates whether the distance between the telescope mount position and the target object position is less than the defined capture threshold. In Slew To Target mode, Target Captured is always 0. When the mount catches up with the target, the mount switches to Follow Target mode and Target Captured becomes 1. This bit is useful to determine if Chase Mode or Follow Mode are close to the target.

Byte 7 represents shutters

Byte 7 bit 0	Dome Upper Shutter Open
Byte 7 bit 1	Dome Upper Shutter Closed
Byte 7 bit 2	Dome Lower Shutter Open
Byte 7 bit 3	Dome Lower Shutter Closed
Byte 7 bit 4	Mirror Doors Open
Byte 7 bit 5	Mirror Doors Closed
Byte 7 bit 6	
Byte 7 bit 7	

27: MOVE FOCUS – Slew the focus mechanism to an encoder position.

Command Number	27
Position (microns)	-205

Data returned: NONE

28: READ POINT – Returns the position of the telescope in the format used by the pointing model program.

Command Number	28
Julian Date	7096.239089016
Sidereal Time	3.718825002
Telescope HA	2.000000
Telescope DEC	25.058285
Target Object RA	3.000000
Target Object DEC	25.000000

Data returned: NONE

29: ACTUATE MIRROR DOORS – Changes the state of the mirror doors.

Command Number	29
Direction (1 for open, 0 for close)	1

Data returned: NONE

30: SET ENCODER OFFSETS FOR ZENITH – Sets the mount encoders assuming the telescope is pointed to zenith. No additional parameters are needed beyond the command number.

Data returned: NONE

31: SET ENCODER OFFSETS TO DEFAULTS – Restores the mount encoders to their default value. No additional parameters are needed beyond the command number.

Data returned: NONE

32: READ TARGET OBJECT COORDINATES – Query TCSGalil for the current target object coordinates. If the object was defined with a velocity or an acceleration, the projected celestial position and velocity, based on the elapsed track time, will be given. No additional parameters are needed beyond the command number.

Data returned:

Elapsed Track Time (seconds)	233.8
Apparent Hour Angle (hours)	2.034567
Mean Right Ascension (hours)	20.034567
Mean Declination (degrees)	33.483251
Equinox	1994.5
Mean Right Ascension Velocity (arcseconds/second)	2837.2
Mean Declination Velocity (arcseconds/second)	1991.4
Airmass	1.3551
Zenith Distance (degrees)	15.6
Azimuth (degrees)	138.2

35: DOME STOP ROTATION – Stops the dome rotation and changes the dome control mode to Manual. No additional parameters are needed beyond the command number.

Data returned: NONE

36: ACTUATE DOME UPPER SHUTTER – Changes the position of the dome upper shutter.

Command Number	36
1 for open, 0 for close	1

Data returned: NONE

37: INITIALIZE FOCUS ENCODER – Performs an automatic focus position initialization. No additional parameters are needed beyond the command number.

Data returned: NONE

38: SET CELESTIAL TRAJECTORY – Set up the target object trajectory in a celestial reference frame. The track start time should be in hours since UTC midnight. If zero is entered as the start time, the current time will be used.

Command Number	38
RA Position (hours)	22.2001
DEC Position (degrees)	12.1135
Equinox	2000.5
RA Rate (arcseconds/second)	1870.522
DEC Rate (arcseconds/second)	1005.305
RA Acceleration (arcseconds/second/second)	0.002
DEC Acceleration (arcseconds/second/second)	0.000
Start Time (hours)	3.4861385

Data returned: NONE

39: SET MOUNT TRAJECTORY – Set up the target object trajectory in a mount reference frame. This command uses apparent coordinates and is intended for non-celestial applications.

Command Number	39
HA Position (hours)	22.2001
DEC Position (degrees)	12.1135
HA Rate (arcseconds/second)	1870.522
DEC Rate (arcseconds/second)	1005.305
HA Acceleration (arcseconds/second/second)	0.002
DEC Acceleration (arcseconds/second/second)	0.000

Data returned: NONE

40: DOME STOP UPPER SHUTTER – Stops the dome upper shutter motion. No additional parameters are needed beyond the command number.

Data returned: NONE

41: DOME STOP LOWER SHUTTER – Stops the dome upper lower shutter motion. No additional parameters are needed beyond the command number.

Data returned: NONE

42: SET PIER SIDE – Change the operating mode on pier-flip telescopes.

Command Number	42

1 for east, 0 for west	1

Data returned: NONE

43: SET DOME AZIMUTH TARGET – Sets the target dome azimuth for the GoTo Azimuth dome mode.

Command Number	43
Azimuth (degrees)	123.4

Data returned: NONE

44: ACTUATE DOME LOWER SHUTTER – Changes the position of the dome lower shutter.

Command Number	44
Direction (1 for open, 0 for close)	1

Data returned: NONE

50: START TRACKING – Starts moving the mount at the currently selected track rates. Internally, this sets a new target trajectory starting at the current position with a velocity equal to the track rate and sets the mount control mode to Follow Target. No additional parameters are needed beyond the command number.

Data returned: NONE

51: SET TRACKING MODE – Changes the tracking mode. This can be overwritten by the front panel switch.

Command Number	51
1 for normal track, 0 for aux track	1

Data returned: NONE

53: SET SLEW RATE – Changes the handpaddle slew rate.

Command Number	53
Rate (arcseconds/second)	7200

Data returned: NONE

54: SET SLOW FOCUS RATE – Changes the slow focus rate.

Command Number	54
% of max rate	10

Data returned: NONE

55: SET FAST FOCUS RATE – Changes the fast focus rate.

Command Number	55
% of max rate	70

Data returned: NONE

56: INITIALIZE TELESCSOPE ALT AZ – Changes the encoder offsets to match the desired telescope position.

Command Number	56
Altitude (degrees)	22.2
Azimuth (degrees)	33.3

Data returned: NONE

57: SET TARGET OBJECT ALT AZ – Set the target object position in an ALT-AZ coordinate system.

Command Number	57
Altitude (degrees)	22.2
Azimuth (degrees)	33.3

Data returned: NONE

58: PARK MOUNT – Send the mount to the park position. No additional parameters are needed beyond the command number.

Data returned: NONE

59: UNPARK MOUNT – Sets the state of the mount to unparked. This is primarily an ASCOM convenience. No additional parameters are needed beyond the command number.

Data returned: NONE

60: SET MOUNT PARKING POSITION – Sets the current mount position as the new park position. No additional parameters are needed beyond the command number.

Data returned: NONE

61: PULSE GUIDE – Simulates a hand paddle button press, initiating a Guide speed move in the desired direction for the desired duration. RA and DEC moves can be sent back to back and will execute simultaneously. Sending an additional move for an axis already moving will invalidate the old command and start the new one.

Command Number	61
Direction (0 for North, 1 for South, 2 for East, 3 for West)	0
Duration (milliseconds)	1250

Data returned: NONE

62: READ DOME AZIMUTH – Returns the current dome azimuth position. No additional parameters are needed beyond the command number.

Data returned:

Azimuth (degrees)	4.4

63: READ INSTRUMENT ROTATOR AZIMUTH – Returns the current instrument rotator azimuth position. No additional parameters are needed beyond the command number.

Data returned:

Azimuth (degrees)	4.4

64: READ FOCUSER POSITION – Returns the current position of the focuser. No additional parameters are needed beyond the command number.

Data returned:

Position (microns)	-208

66: APPLY MOUNT CORRECTIONS – Applies the pointing model to target positions.

Command Number	66
1 for ON, 0 for OFF	1

Data returned: NONE

67: APPLY MOUNT RATE CORRECTIONS – Applies the derivative of the pointing model to the track rate in “Follow” mode.

Command Number	67
1 for ON, 0 for OFF	1

Data returned: NONE

68: APPLY REFRACTION CORRECTIONS – Applies the refraction model to target positions.

Command Number	68
1 for ON, 0 for OFF	1

Data returned: NONE

69: APPLY REFRACTION RATE CORRECTIONS – Applies the derivative of the refraction model to the track rate in “Follow” mode.

Command Number	69
1 for ON, 0 for OFF	1

Data returned: NONE

70: APPLY PERIODIC ERROR CORRECTIONS – Applies the periodic error correction to the track rate in “Follow” mode.

Command Number	70
1 for ON, 0 for OFF	1

Data returned: NONE

APPENDIX B: GALIL MOTOR CONTROLLER SETUP

The Galil Digital Motion Controller is mounted in one side of the MDC. Power is provided to the controller from a 24VDC power supply in the MDC. Short cables run between the MDC motherboard and the Galil DMC. An Ethernet cable connects the Galil Controller to a dedicated LAN with the Ethernet cable routed to the TCS computer. The GalilTools program is used to connect to the Galil controller and assign it an IP address on the LAN. Once the IP address is assigned, the assignment information must be stored in TCSGalil. Once this is done, TCSGalil can connect to the Galil DMC.

A master reset of the DMC controller will return the controller to its factory settings. Master reset may be done by installing a jumper on the MRST pins before power up. A master reset of the DMC will enable the DHCP client which will assign an IP address to the controller. In this circumstance, the controller can be located in the NO IP Address tab where an IP address can be assigned. After a delay the controller will appear in the Available tab where it can be selected and the IP address Assigned. After connecting to the controller, type DH 0 to turn disable the DHCP client. Next issue a BN command to write this value to the controller's internal memory. The IP address of the controller can be set in TCSGalil with the Options–Galil Setup communications dialog. Once the fixed IP address is assigned, be sure to remove the jumper on MRST on the controller or it will be returned to the DHCP enable state upon power up.

DEDICATED LAN SETUP

The TCS control computer has 2 wired Ethernet adapters. One wired adapter is assigned the address 192.168.1.100 and is used for a private network for communication with the Galil motor controller. The motor controller is assigned the address 192.168.1.101. The 2nd adapter can be used to connect to the internet or to an observatory LAN.

APPENDIX C: ACRONYMS AND ABBREVIATIONS

CAD	Computer-Aided Design
DEC	Declination - a coordinate axis on the celestial pole
DFM	DFM Engineering, Inc. - a world-class telescope manufacturer in Longmont, Colorado
DMC	Galil Digital Motion Controller
GUI	Graphical User Interface
HA	Hour Angle - a coordinate axis based on the celestial pole
LEO	Low Earth-Orbit satellites
MDC	Motor Driver Chassis - a rack-mounted electronics chassis which houses the motor controller and support electronics
RA	Right Ascension - a coordinate axis on the celestial pole
TCS	Telescope Control System
UDP	User Datagram Protocol - a communication protocol with low latency and no packet control
UT	Universal Time
VFD	Variable Frequency Drive - a module for controlling the speed of AC motors

APPENDIX D: PERFORMING A POINTING RUN

Make sure site specific data is correct, including the local time and date, before tuning a pointing model. For setting up a new telescope:

1. Adjust the elevation with a bubble level protractor. Adjust the azimuth with a sighting of the north star (eyeball method).

2. Perform a drift test (described in Appendix E) to do the rough alignment using a reticle eyepiece or CCD camera.

3. Take pointing data (the DEC and RA sweeps).

4. Use the Pointing Model Tool to determine pointing coefficients. Make sure to save the new parameter file and restart TCSGalil for the new coefficients to take effect.

5. If the residual misalignments for azimuth or elevation are larger than 60 arc seconds, dial off the error mechanically using a magnetic base and dial indicator. After such an adjustment, an additional drift test should be performed to verify the sense (direction) of the residual alignment errors. The mechanical misalignment adjustments are made, set the Elevation Misalignment and Azimuth Misalignment terms to zero when saving the parameter file.

6. Take a second set of data, and determine the coefficients.

7. Take more data to confirm the pointing performance.

In a pointing tune-up of an established telescope there may be no need to correct the azimuth or elevation alignment if the mount has not been moved. For a telescope with on-axis encoders, the encoder offset and eccentricity terms may change if the encoder has been adjusted. The non-perpendicularity will be a constant for the life of the mount. A common problem is the model needing adjustment in collimation due to primary mirror movement after washing.

APPENDIX E: DRIFT TEST

The following procedure is recommended for polar alignment in the northern hemisphere:

Note: A star is drifting in the direction pushed on the handpaddle to re-center the star.

1. Orient cross hairs N-S, E-W in an illuminated reticle eyepiece or orient a CCD camera accordingly.
2. Track a star near the meridian and about 0 degrees declination.
    - If the star drifts south, then the polar axle is oriented NE-SW. Correct by rotating the north end of the telescope west or the south end of the telescope east.
    - If the star drifts north, then the polar axle is oriented NW-SE. Correct by rotating the north end of the telescope east or the south end of the telescope west.
3. Track a star at about 6 hours east or west and about 45 degrees declination.
    - If a star in the eastern sky drifts north (or if a star in the western sky drifts south), then the elevation of the polar axle is too high.
    - If a star in the eastern sky drifts south (or if a star in the western sky drifts north), then the elevation of the polar axle is too low.