Precision Telescope Control System

PTCS/SN/6: PTCS System Design

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1	Created	3/11/03	KTC
2	Added presentation	3/14/03	KTC
3	Expanded introduction and overview	3/23/03	RMP
4	Minor modifications after discussions between KTC and RMP	3/25/03	RMP
5	Further modifications after more feedback, add Figure 2 and explanation	3/27/03	RMP

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Abstract

This document presents a conceptual outline of the PTCS system design, with specific emphasis on the Precision Control System and Precision Measurement System components.

1 Introduction

The Precision Telescope Control System (PTCS) is the integration of metrology components, servomechanisms, and estimators/controllers to allow precise control of the GBT optical elements for 3mm operation. Servomechanisms to be controlled currently include the azimuth and elevation main drives, the subreflector mount and the active surface; future mechanisms may include the Gregorian receiver turret and feed rotator, and a tertiary chopper. Metrology systems currently available or planned include the laser rangefinders, structural temperature sensors, the quadrant detector and the weather stations. In the future, we may add accelerometers, hot-wire anemometers, and so on. The focus of the PTCS system design work leading up to the Conceptual Design Review has been to outline a control strategy which is elegant, robust and extensible, a measurement strategy that will support this control strategy, and the division of the overall PTCS into a number of well-defined modules with clearly separated functionality and clean interfaces. In proposing this design, we have tried not to be adversely influenced or constrained by the existing antenna control design, but at the same time we believe that the proposed design can be developed by a series of incremental upgrades to the existing GBT control system.

2 Overview of the Proposed System Design

A high-level functional block diagram of the complete PTCS is shown in Figure 1. To the left on the diagram is the High Frequency Observing System (HFOS). On the right of the diagram are the various servos, which will be controlled by the PTCS. These are shown external to the PTCS to emphasize that, although the PTCS will be closing control loops about the plant, we do not intend to replace the actual low-level servo systems provided by the contractor. A dashed line around a subset of the PTCS indicates the functionality provided by the current Antenna Control Unit (ACU).

The main components of the PTCS are as follows:

Antenna Manager

The Antenna Manager provides the interface between the higher level observing system and the other PTCS components. The Antenna Manager will present a similar track-segment based interface to the HFOS as the current ACU, with extensions as required to allow the HFOS to exploit the full functionality of the PTCS. The Antenna Manager will be a standard Device Manager, which presents the standard command interface, and implements the standard state machine. Note that the other components of the PTCS are not device managers, but are analogous to the other modules in the current ACU. At all times, the Antenna Manager will be generating real-time, fixed rate demands for the Precision Control System (PCS). While in the "Ready" state, the Antenna Manager will generate demands which will simply cause the Antenna to track the previously specified position. In "Activating", the Antenna Manager will generate demands which will cause the main drives and other optical elements to adopt the correction initial conditions for the scan. (The PCS will maintain the best possible collimation and pointing while the antenna moves to the scan start). In "Running", the Antenna Manager will convert the track segments provided by the HFOS to the corresponding demands for the various optical elements.

Astrometrics/Refraction

This block will be used by the Antenna Manager to perform the required transformations in the conversion from input track segments (which may be in specified in a variety of astronomical co-ordinate schemes) to generated topocentric azimuth and elevation demands for the PCS; this includes the refraction correction.

In the PTCS design this block does **not** apply the traditional pointing model; this is now the responsibility of the PCS.

Precision Control System (PCS)

The PCS uses information provided by the Precision Measurement System to control the GBT optical elements, and ultimately generates the demands that are used by the low-level servo systems. The PCS has configurable control strategies, and the ability to specify various "optimal" configurations (e.g. the subreflector should be positioned to produce minimum aberrations and maximum efficiency). The PCS is a real-time system which will used fixed sample rates. It is described in more detail in Section 3.

Precision Measurement System (PMS)

The PMS is the production system for measurement of the GBT optics and pointing. The PMS uses all available data including the laser rangefinders, inclinometers, and on on. PMS data inputs are in general irregularly sampled in time, outputs are predictions (in time) to be used by the Precision Control System. The PMS is described in more detail in Section 4.

Engineering Measurement System (EMS)

The Engineering Measurement System is designed to make use of the metrology systems, independently of the PMS and normal astronomical observations. It will be available as a GBT surveying tool, and form the algorithm test bed for the PMS. The EMS will be implemented in a signal flow graph/graphical programming environment and is designed primarily for Laser Rangefinder (LRF) data reduction and analysis.

Metrology

This block represents the various metrology systems available to the PTCS, specifically devices that are measuring the structural properties of the GBT itself. Measurements from these devices may be used during observing by the PMS, or "off-line" by the Engineering Measurement System. As noted, the metrology systems currently available or planned for the near term include the laser rangefinders, structural temperature sensors and the quadrant detector. In addition, in this block we include other measurements provided by the lower-level servo systems, for example the servo currents from the main drives. Future devices might include accelerometers, inclinometers, hot-wire anemometers and so on.

Environmental Monitoring

The only environmental monitoring systems currently available to the observing system are the various GBT weather stations, which are used primarily to determine the atmospheric refraction corrections. In the future, the site phase monitor and water vapor radiometer will be included in this block, as would any devices developed to measure line-of-site anomalous refraction corrections.

3 Precision Control System Design

3.1 Introduction to the PCS Design

A very simplified schematic of the PCS block diagram is presented in Figure 2 (this is expanded in detail in Figure 3). Each of the main elements that the PTCS must measure and/or control is indicated by a separate block: the Active Surface, subreflector, feed control (selection of feed, Gregorian feed rotator), tertiary and main drives. The four items on the left of the diagram control the optical alignment of the antenna; their positions and, where relevant orientations and shapes will be measured by the metrology system in co-ordinate systems tied to the tipping structure. The main drives on the right control the overall pointing of the antenna (although other optical elements may correct for residual pointing, as described in more detail below). The various labeled arrows indicate the flow of commands/strategy, estimated positions, error signals and metrology data through the system. In the case of the main drives and Active Surface, the commands include the (az,el) demands generated by the Antenna Manager from the commanded track provided by the High Frequency Observing System. In the case of the subreflector, this arrow might represent an offset demand from the nominal focus-tracking position; the selection of which focus-tracking strategy to employ, or both. Metrology data is shown flowing into each main control block. These data are used by the Precision Measurement System, on behalf of the PCS, to estimate the actual location, orientation and shape of each component. These estimated positions, along with an estimate of the transformation from tipping to topocentric co-ordinates, are then passed to the "Optical Model" shown in the center of the diagram. The Optical Model determines the normal to the exiting wavefront in topocentric co-ordinates. This is then compared to the commanded pointing direction, and a residual pointing error signal derived. Again depending upon the observing strategy, this error signal may be allocated to the main drives, subreflector or tertiaty via the error triplexor.

3.2 PCS Functional Block Diagram and Notes

This detailed function block diagram for the PCS is shown in Figure 3. Additional notes on the diagrams are as follows.

General Notes

- Some accuracy is sacrificed for clarity in the block diagrams.
- $\Omega \equiv$ a vector or list of parameters, e.g., Ωae is nominally the commanded topocentric azimuth and elevation of the GBT.

  $\tilde{\Omega} \equiv$ is an estimate of the actual values of Ω, as determined by the PMS using metrology data.
- The receiver feed rotator is left out for clarity. A control and estimation block will be inserted into the calculation of Ωfh (feed horn).
- Basic control flow is as follows:

  The primary is driven to a paraboloid as a function of elevation angle (ϕ). Nominal feed location and tertiary position determine the subreflector second focus location. Estimated prime focus and second focus locations are used to determine the subreflector position and orientation. An optical model uses estimates of primary, feed, and subreflector positions, shapes, and orientations along with an estimate of the transformation from tipping to topocentric coordinates in order to determine the normal to the exiting wavefront in topocentric coordinates. This is compared to commanded pointing, and the error is allocated to main drives, subreflector, and tertiary elements via a triplexor.
- Coordinate systems and transformations are not shown. The basic coordinates are topocentric az-el (note that commanded position is corrected for atmospheric refraction), tipping structure (nominally Lee King's elevation coordinates, or the equivalent from Michael Goldman), and the control and description frames of the optical elements themselves, e.g., {u,v,w} for the primary where w is the piston motion, etc.
- Summing nodes may include functions such as interpolation and rate conversion.
- Some correction signals, e.g., the pointing correction applied to the subreflector, can be applied in several ways, e.g., translate or tilt or both. The block diagram assumes that a method is in place without specifying it.
- Blocks with shaded upper left corners are control-estimate blocks. See Figure 4 for the generic content of these blocks.
- Parallelograms indicate estimation procedures, where multiple streams of measurements are synthesized into a best estimate of a quantity of interest and propagate the uncertainty of the constituent measurements to the uncertainty of the derived quantity These estimators may be implemented as Kalman filters (for dynamics) or nonlinear least squares, etc. A simple example is the high rate estimate of feed arm position from accelerometers, Laser Rangefinders, and Quadrant Detector. These blocks span PCS and PMS since some of the inputs are uniformly sampled in time and

real-time, e.g., encoder data used in the CCU), while other data are neither real-time or uniformly sampled, e.g., laser rangefinder based estimates of azimuth and elevation angles.

Specific Notes (refer to corresponding note numbers on Figure 3)

1. Primary shape, vertex location, and orientation is a pre-computed function of elevation angle, i.e., perturbing environmental effects are compensated for by closed loop controls. The pre-computed shape could be Don Well's best-fit-paraboloid, or any other shape. The diagram indicates a look-up-table representation, but it could also be a parametric functional form. Note that there can (will) be enumerated strategies that can be switched by replacing tables or a similar implementation dependent method.

2. Primary offsets could take many forms. One could be Zernike polynomials.

3. The "2" next to the input leg of this summer indicates multiplication by two.

4. Active surface control and estimation (as well as for the subreflector, main drives, etc.) will be elaborated later. These details are not needed at this level of discussion.

5. This arrow indicates external data used in estimation, e.g., Laser Rangefinder data, inclinometers, etc.

6. This is a generic compensator (in the classical control sense) that provides loop stability for the PMS-mediated outer loop, improves response, and assures tracking performance, e.g., no error in tracking a ramp input. Note that this closes a control loop <u>outside</u> of the active surface controller, and uses additional information to do so (inclusive of LVDTs).

7. Optimal (desired) subreflector position as a function of prime focus and feed position is precomputed and stored as a look-up-table or some other representation. Note that there can (will) be enumerated strategies that can be switched by replacing tables or some such-like implementation dependent method.

8. $\tilde{\Omega}_{f2}$ is the estimated position of the "virtual" feed – which may not coincide with the real feed (e.g., the image of the real feed viewed from the tertiary mirror).

9. The feed estimator uses a variety of data, e.g. Laser Rangefinder measurements of the feed house, to estimate the "fiducial" (center-of-flange) feed location. Actual feed locations can be established using feed offsets.

10. Estimates of tertiary position and orientation (with respect to the feed) are from off-line measurements and tertiary encoder data. The basic tertiary position is "home" and is modulated by offsets, pointing corrections, and chopping signals.

11. The linear approximations of $\frac{d\Omega_{sr}}{d\varepsilon}$ and $\frac{d\Omega_t}{d\varepsilon}$ are used to generate error signals from the pointing error allocated to the element *in topocentric coordinates.* In the case of the subreflector, the mapping of pointing error to motions of the full six degrees of freedom (three translational, three rotational) is one to many since a pointing change can be accomplished by a tilt or translation or combination of both. The appropriate reduction of this degeneracy has not been determined, but is assumed to occur at this point in the block diagram.

12. The subreflector control and estimate uses various data, e.g., inclinometers, Laser Rangefinders, etc. A separate estimator provides the estimate of the Stewart platform feed-arm mount location and orientation.

13. The optical model predicts the normal unit vector to the GBT plane wavefront in tipping coordinates and then transforms it to topocentric coordinates using the estimated relationship of the coordinate systems. This model may also be expanded to include predictions of GBT Point Spread Function (PSF), efficiency, etc. The plate scales of the subreflector and tertiary are also computed (see Note 11).

14. The tip-to-topo estimator uses main drive encoder data and Laser Rangefinder data, the structural finite element model, etc.

15. The main drive control and estimate includes both the traditional pointing model and its inverse function.

16. The triplexor allocates residual pointing errors to various components – Note that this is the outer-most control loop, and feedback compensation may be required even if not explicitly shown here. The structure for partitioning the error is conceptual, and provides that the allocated errors approximately sum to the total error (although the allocations can be defeated in order to provide a specific observing scenario function):
$\tilde{\varepsilon} \cong \tilde{\varepsilon}_{ae} + \tilde{\varepsilon}_{sr} + \tilde{\varepsilon}_{t}$
$\tilde{\varepsilon}_{ae}$: DC to less than the main drive limit cycle modes (~ 0.06 Hz), possibly with polynomial smoothing. Errors include thermal and average wind load structural deformations and effects not modeled in the traditional pointing model, e.g., azimuth track "waviness".
$\tilde{\varepsilon}_{sr}$: Low frequency (<0.06 Hz) to ~ 0.4 Hz corrections, specifically including the ~ 0.3 Hz main drive servo resonances that have been found experimentally. This may be a system-ID process, i.e., finding specific sinusoidal errors. Errors include main drive limit cycles and resonances, thermal distortions of the feed arm, some transient wind effects.
$\tilde{\varepsilon}_{t}$: ~ 0.4 Hz to tertiary control bandwidth. Errors include structural vibration effects, transient wind effects.

17. The calculation of the apparent (or "virtual") feed location is naturally part of the optical model (Note 13). This implementation assumes that the tertiary elements are truly planar (and thus a simple reflection is all that needs to be modeled). Since chopping control and virtual feed location are closely coupled at this level of detail the process is not included in the generic optical model. It may be that tertiary designs will use non-planar mirrors, at which point the calculation of the virtual feed location will properly belong in an optical model- but this breaks the current paradigm that the optical model is used only to calculate the wavefront normal and optical properties.

18. A pointing error metric , e.g., the radial pointing error, is calculated and compared to a threshold set external to the control system. This output flag would be used to control back-ends, for example. The threshold could (should) be observing frequency dependent, i.e., main beam width dependent. Whether an observer sets the threshold in angle (explicit control) or beam width (implicit control) is TBD.

19. An alignment metric is calculated, e.g., a combination of RMS, path length, position, and orientation of all optical elements, and compared to a threshold. This output flag would be used to control back-ends, for example.

20. This switch permits the subreflector positioning to be optimized for the position of the virtual feed (e.g., the center of the receive flange), or the position of the selected physical feed.

3.3 Discussion of the proposed PCS design

In developing the eventual PCS system design, we considered a number of potential alternative solutions.

- The option presented: the PCS is classical closed SISO loop control (single-input-single-output). In this case, control loops executing in parallel are independent; for example the six subreflector link actuators, or the azimuth and elevation drives. The system contains nested control loops; for example the loop shown closing around the Main Drives uses the LRF estimates of actual az/el versus encoder az/el. This approach has the advantage that it is easy to visualize; it is not necessarily optimal, or at least the optimality criteria are not explicit.

- The first alternative considered was the PCS as a modern closed (multiple-input-multiple-output) loop control. This approach models interactions of subsystems, e.g., az-el coupling. The servo subsystems dynamics are closed loop controllers; the system has explicit optimality criteria and explicit controllability/observability. In this case, the commanded scan is a trajectory through GBT parameter space, and the controller minimizes error/cost of actual versus commanded location in that parameter space.

- The second alternative considered was based on open loop learned compensations. Individual subsystem control uses parametric or nonparametric corrections based upon offline measurements ,e.g., LRFs, or astronomical correlations with indirect measurements, e.g., defocused beam maps for primary figure, correlations with temperature, elevation, or pointing correction as a function of feed arm temperature/temperature gradient.

We have selected the classical approach for now, on the basis that it is easier to visualize and configure; the control tasks are not demanding (small and slow perturbations); there is no quantitative evidence that subsystem interactions are problematic (e.g. az/el coupling instabilities) and with this approach an incremental approach is considerably more feasible. Finally, the estimation blocks can subsume the open-loop learned compensation design, so we can take advantage of both these approaches.

Some of the paradigms adopted in developing the PCS system design were as follows:

- Incremental approach. It should be possible to implement the framework of the PCS, and then deliver additional functionality incrementally. Legacy implementations will be unaffected as much as possible, without compromising system performance, and as far as possible without compromising an elegant design. The current Antenna Control Unit will definitely be affected, but as far as possible the existing interface to the higher level control systems will be retained unchanged. If necessary, a translator layer will be implemented so that development on the HFOS and the PTCS can proceed in parallel.

- The objective is to achieve the scientific requirements in default observing modes. It should not be necessary to be an "expert user", or execute a complex configuration procedure to observe at 3mm.

- The design of the PCS will be validated through the development of Observing Scenarios (see PTCS/SN/m). These consist of a variety of standard observing, engineering and failure mode observation descriptions, for which the PTCS behavior will be described in detail. The intent is that for all cases the PTCS operation will be correct, robust and intuitive. This will give us some confidence that the PTCS will be able to handle currently unanticipated observing modes in a similar manner.

External control and configuration of the PCS from the High Frequency Observing System will consist of:

- Selecting strategies for operation; for example that the primary should always attempt to conform to the Best Fit Parabola, the subreflector should be driven such that the prime focus is imaged on the selected feed with minimum aberrations, and residual pointing errors should be distributed to all optical elements. We would expect that the default strategies would be appropriate for the majority of observers (who would not then need to concern themselves with the details), but these could be easily over-ridden by more sophisticated users.

- Providing offsets from nominal positions. For example, a subreflector collimation check could be performed by driving the subreflector from the nominal focus-tracking position.

- Enabling/inhibiting control loops, pointing error mappings. This would allow complete fine-grained control of the PCS if necessary.

As noted, the PCS contains an embedded optical model, which will continually generate the best estimates of actual pointing, both for control, and for recording with the data for off-line analysis (e.g. regridding OTF maps). Once advantage of using the optical model even in advance of full operation with the PMS is that the reported antenna positions will have full knowledge of the actual position of the subreflector (not the case in the current system). In the longer term, the optical model will also be able to provide best estimates of efficiency, beam shape, etc.

3.4 PCS Simulation

Note that the proposed design includes both nested and parallel SISO servo controls. We consider it essential that the PCS is simulated in detail before any implementation commences. We would also expect to simulate any new strategies/configurations in advance of deploying these on the real antenna. This simulation will allow us to discover performance and stability issues and make concrete decisions about sample rates and parameter sets. We have obtained a copy of the original RSI/PCD antenna simulation, and will augment this with a simple model of the subreflector link drives, and an assumed tertiary design and performance. Metrology and derived measurements will not be modeled, but the PCS estimator blocks will have reasonable stochastic models of the estimation error. The simulation will be performed using Simulink.

The completed simulation will provide a template for implementation. It will determine sample rates, an estimation of error requirements to achieve the required performance, choice of parameters and representations for built-in functions (e.g., primary shape). It will allow us to characterize performance over some range of specific environmental effects. The simulation may evolve to: a test bed for PTCS configuration; assist with preplanning observations; aid in debugging implementations; a test bed for new algorithms, and a mechanism for evaluation of proposed tertiary designs.

4 Precision Measurement System Design

The PMS conceptual design is in progress, but this is not as mature as for the PCS. While the conceptual design will be completed shortly, the intention is that the PMS detailed design is sequential with the development of the Engineering Measurement System, and EMS based explorations of instrument properties and measurement algorithms.

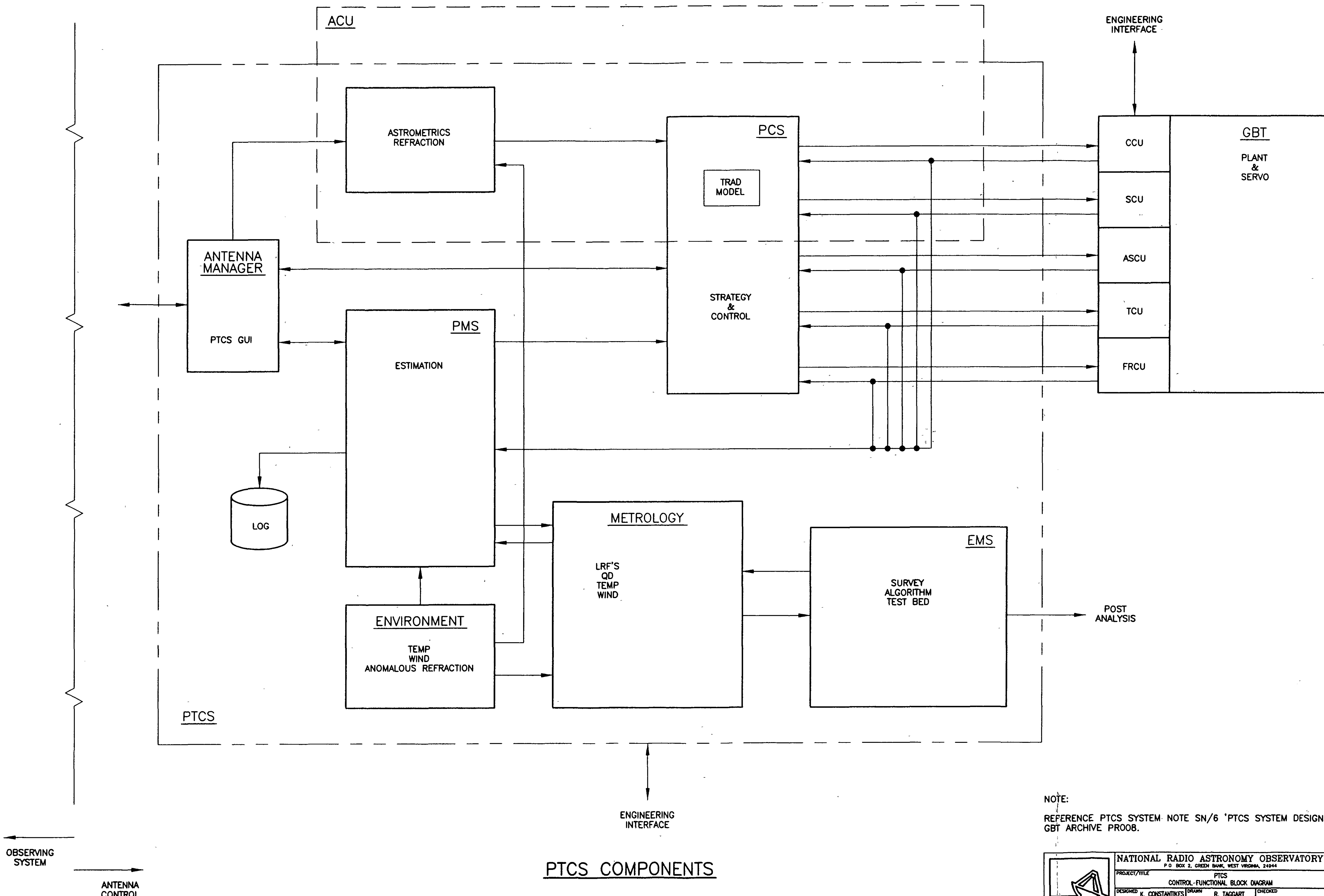
5 PCS Block Diagrams

Figure 1: "PTCS Components" GBT Drawing D44002K001-3

Figure 2: Schematic overview of the PTCS Control Functional Block Diagram

Figure 3: "PTCS Control Functional Bock Diagram" GBT Drawing D44002K001-1

Figure 4: "PTCS Control/Estimator Block" GBT Drawing D44002K001-2



PTCS COMPONENTS

NOTE:

REFERENCE PTCS SYSTEM NOTE SN/6 'PTCS SYSTEM DESIGN'
GBT ARCHIVE PROOB.

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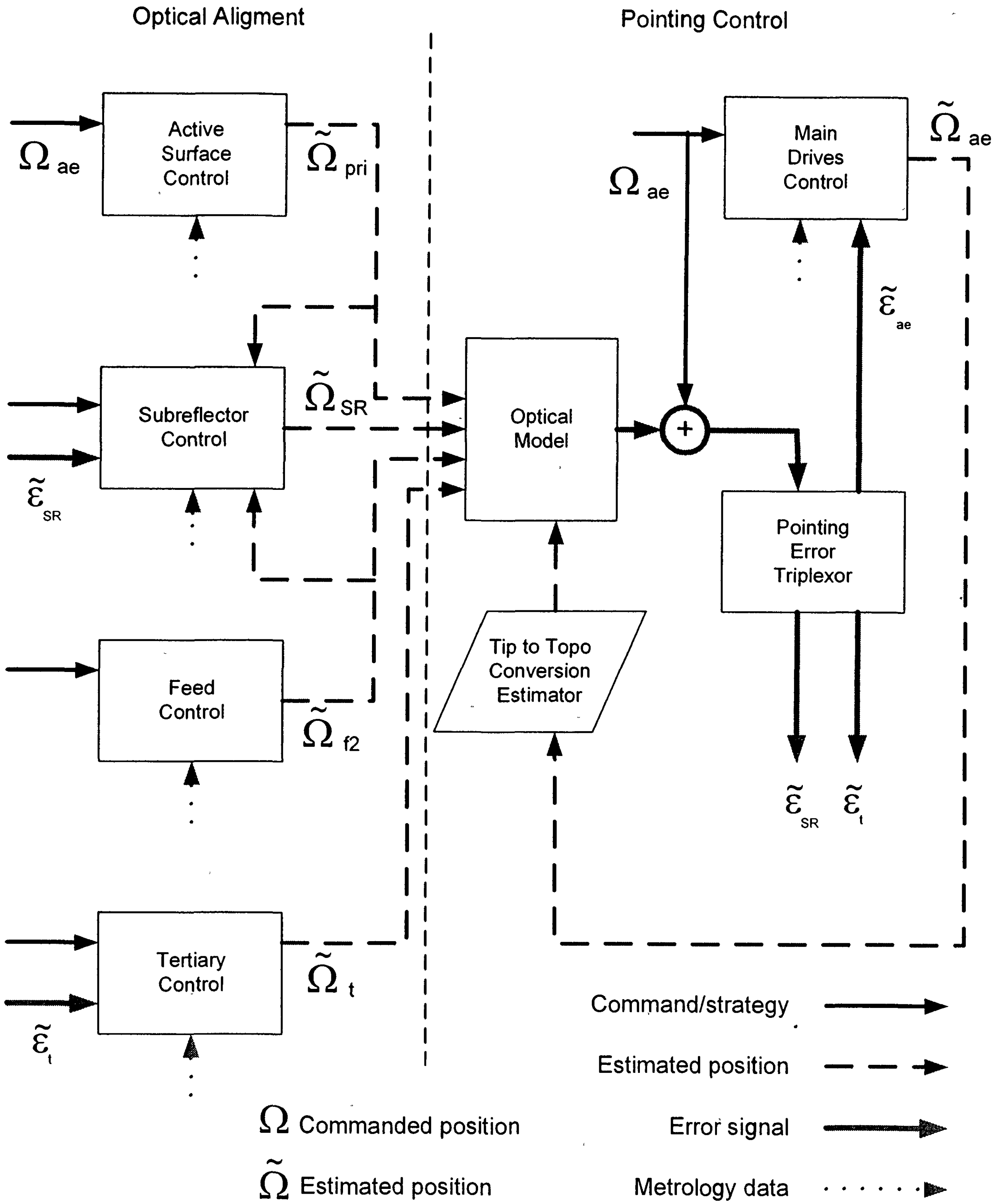
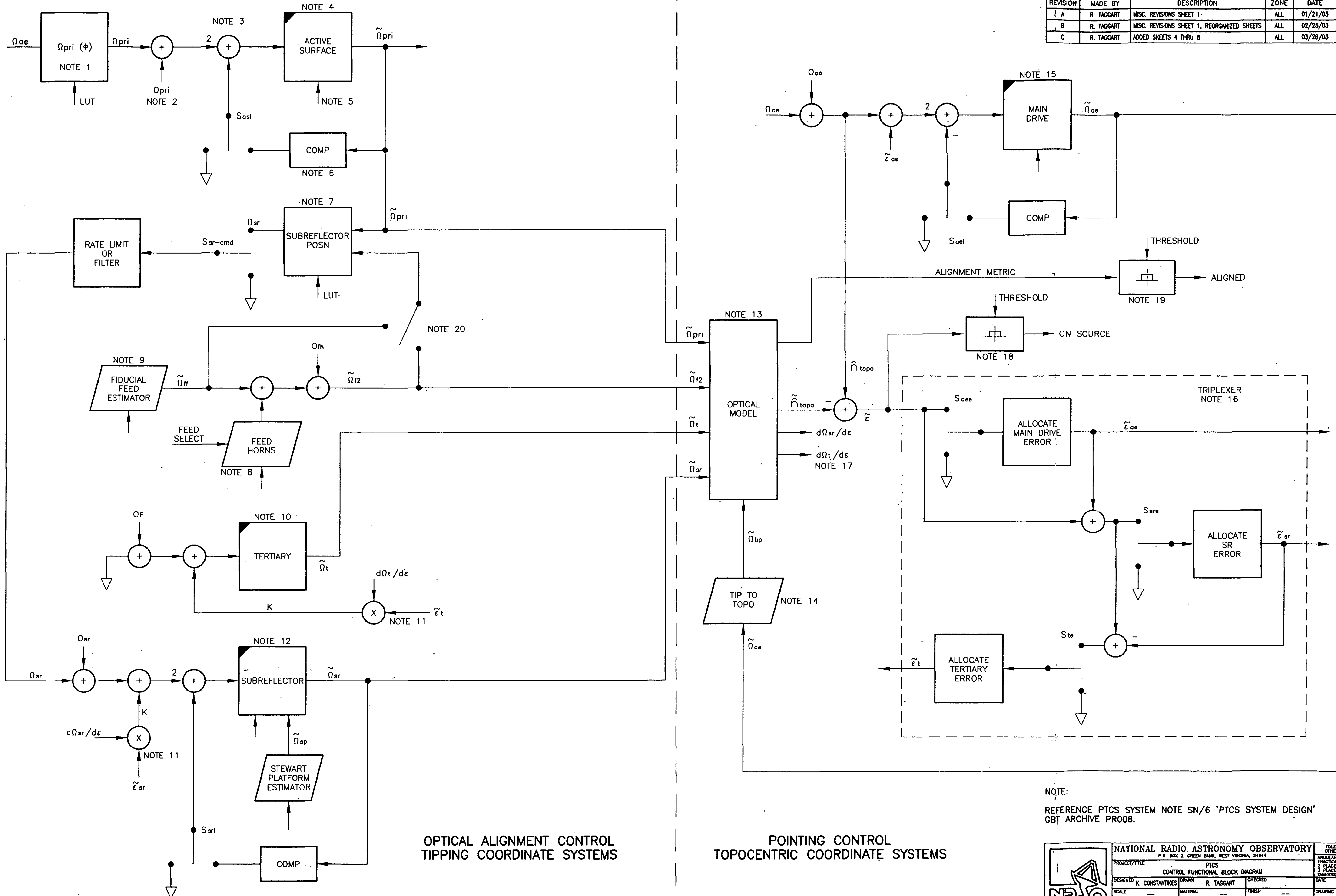


Figure 2.Overview of the PCS



OPTICAL ALIGNMENT CONTROL
TIPPING COORDINATE SYSTEMS

POINTING CONTROL
TOPOCENTRIC COORDINATE SYSTEMS

REVISIONS

REVISION	MADE BY	DESCRIPTION	ZONE	DATE	APPROVED
A	R TAGGART	MISC. REVISIONS SHEET 1	ALL	01/21/03	
B	R. TAGGART	MISC. REVISIONS SHEET 1, REORGANIZED SHEETS	ALL	02/25/03	
C	R. TAGGART	ADDED SHEETS 4 THRU 8	ALL	03/28/03	

NOTE:

REFERENCE PTCS SYSTEM NOTE SN/6 'PTCS SYSTEM DESIGN' GBT ARCHIVE PR008.

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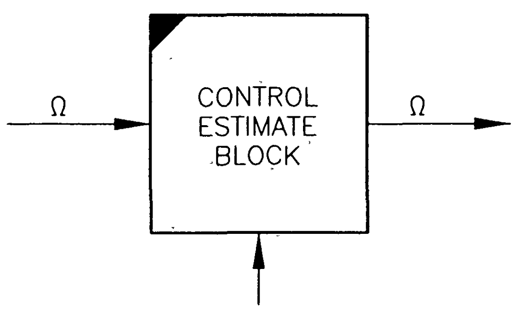

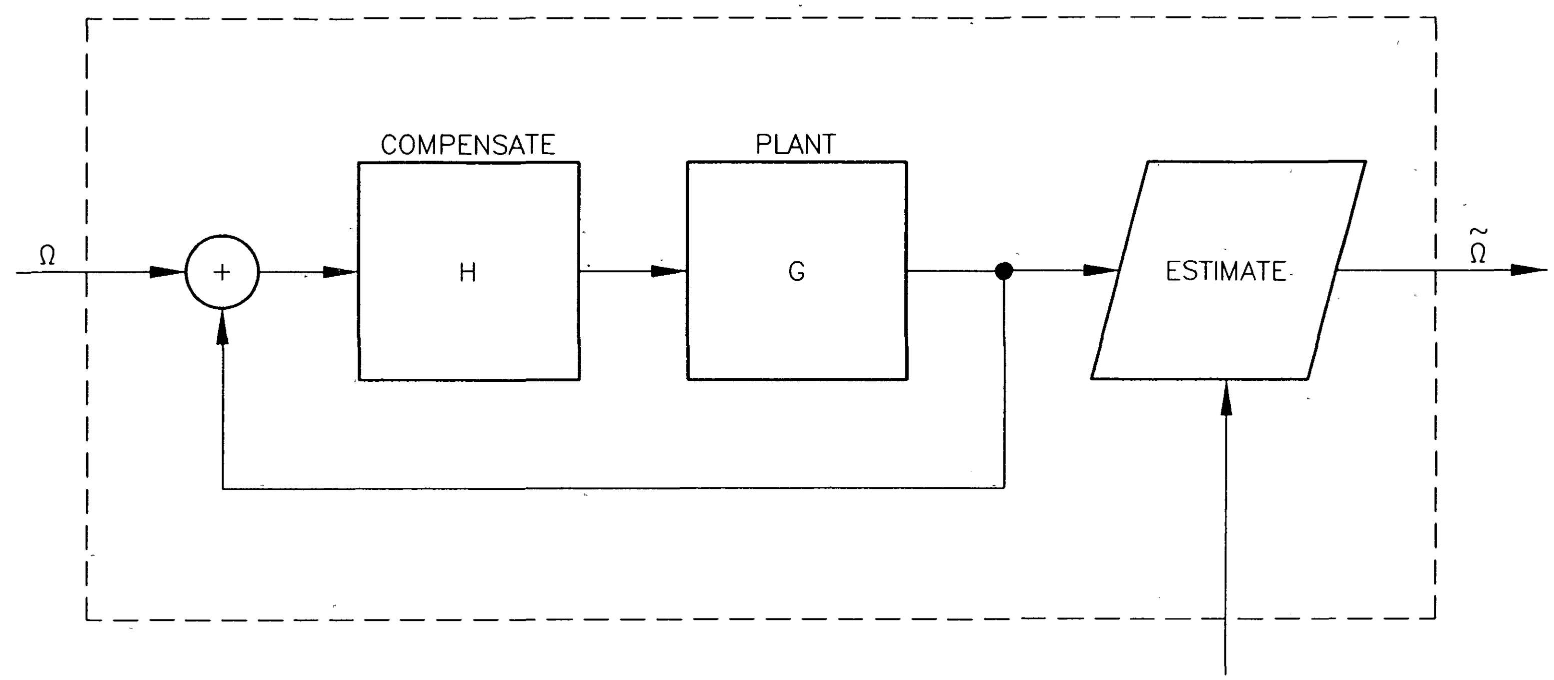

NOTE:

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