Exploiting AFSCN Ranging Data for Catalog Maintenance

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ABSTRACT

The Air Force Satellite Control Network (AFSCN) is composed of eight worldwide fixed remote tracking stations (Space Ground Link Stations, SGLS) hosting 15 antennas, plus two mission control nodes, one at Onizuka AFB, CA and the other at Schriever AFB, CO. One of the AFSCN message formats provides AFSCN metric data (range, range-rate, azimuth, and elevation). Currently the AFSCN metric data are not used by the Space Control Center for catalog maintenance. AFSCN satellite data are received at a central processing facility and immediately diverted to the particular Space Operation Squadron (SOPS) in charge of the satellite. Element sets are produced by the SOPS, but the resulting element sets are not in a format usable by Space Command, and no procedure is in place to transfer them to Cheyenne Mountain. There are several advantages to incorporating the AFSCN data into the Space Control Center (SCC) catalog. The AFSCN range measurement is accurate to the 1-meter level, if the site locations are precisely determined and if atmospheric corrections and carefully calibrated transponder and site biases are applied. This paper describes the Lincoln Laboratory effort to make the AFSCN ranging data available to the SCC for use in both catalog maintenance and, since the data is of such high quality, for use in the separate special perturbations catalog at the Mountain. The specific plan for obtaining the AFSCN data, calibrating it in near real-time, reformatting the observations for submission to Space Command, and transmitting the data to Cheyenne Mountain will be described in detail.

1. INTRODUCTION

The Air Force Satellite Control Network Satellite Ground Link System Automated Remote Tracking Stations (AFSCN/SGLS/ARTS) are used to obtain S-band up and down link telemetry. For satellites equipped with an S-band transponder, metric data (azimuth, elevation, and range) from this network are available. If the S-band transponder is coherent, then range-rate data are also available. The network consists of fifteen "stations" positioned at 8 different locations around the globe. The stations are listed in Table 1 with their coordinates re-surveyed by the Defense Mapping Agency (DMA) in 1992 and 1993.

The AFSCN tracks more than 60 satellites, including: MSX, GPS, DSP, FltSat, and several experimental low altitude satellites. Currently, AFSCN data are not used by Space Command for catalog maintenance.

The Air Force Space Command Directorate of Operations at Peterson AFB sponsored an initial study at Lincoln Laboratory to assess the metric performance of AFSCN data and to see if it could be reformatted for use in catalog maintenance. This study ended in September 1999. The Lincoln study concluded that if the AFSCN data are properly calibrated, the measured range is accurate to 7m, the range-rate to 3 cm/s, and the azimuth and elevation to 20 mdeg. In fact, Lincoln study concluded that meter-level range accuracy is obtainable if site locations are precisely determined. AFSCN data are therefore of high enough quality that they can be used to support the special perturbations catalog at Cheyenne Mountain.

Based on the outcome of this study, a follow-on project is being currently sponsored at Lincoln with the aim of building a prototype calibration workstation. The goal is to produce and transfer to Cheyenne Mountain metric observations in B3 format on all AFSCN satellites. To accomplish this, AFSCN calibration satellites must be selected, methods of data flow established, and calibration and reformatting software developed and tested with sample AFSCN data. Initially, the AFSCN data will be sent from Schriever AFB to the SCC via the Millstone Hill Radar. Eventually the data will flow directly from Schriever AFB to the SCC, although some subset of the AFSCN data will continue to be sent to Millstone to allow for on-going calibration monitoring and calculation of the sensor biases.

TABLE 1

SGLS Stations (Geodetic WGS-84)*

Common Name	SGLS Site Number	Lat. (N) (deg)	Long. (E) (deg)	Hgt. (m)
Hula A	654	21.562280000	201.757891389	428.42
Hula B	622	21.568978333	201.737703056	317.70
Lion A	626	51.115097889	359.093909306	140.059
Lion B	629	51.117873806	359.093574806	138.585
Boss A	657	42.947833333	288.373441111	204.62
Boss B	623	42.944754444	288.369681389	194.60
Cook A	649	34.822609417	239.498148250	271.53
Cook B	620	34.825636194	239.494601000	267.60
Guam A	660	13.615194444	144.855794722	216.90
Guam B	625	13.615880278	144.855167222	211.100
Pike	633	38.805935278	255.471520000	1899.100
Pogo A	624	76.515959950	291.400024730	141.760
Pogo B	628	76.515364390	291.401141690	147.030
Pogo C	634	76.515702500	291.395008055	146.386
Reef	637	-7.270022778	72.370023056	-56.8000

(obtained through [1]).

Table 2 gives an assessment of the improvement in the quality of orbits produced at the SCC that results from the inclusion of the AFSCN data. This assessment was provided by the use of the orbit overlap technique. There were two sets of data analyzed. The first set consisted of all the SCC observations on a DSCS satellite for a two-week period. The second set consisted of the SCC observations plus the AFSCN observations. The AFSCN observations were sampled at every 30 seconds and assigned a 10-meter error. Two eight-day orbit fits were computed, each with a one-day overlap. The average range difference was computed between this one-day overlap for the two sets of data. Without the SGLS data, the range difference between the two orbits was greater than 1.3 km. With the SGLS data, the range difference between the two orbits was less than 300 m. Even though this range error includes all errors in each orbit fit, it can be used to interpret the benefits of the SGLS data to the SCC catalog. Clearly the addition of the AFSCN data will be of use to the SCC.

This paper is divided into the following sections. Section II gives a brief description of the current and past analysis of AFSCN data at Lincoln Laboratory. Section III includes a discussion of the specific AFSCN satellites being considered as calibration targets, and the procedures being developed to monitor the site and transponder biases. Section IV addresses both the communication issues and the design of the workstation and its various software processing components. Finally, Section V summarizes the project to date, and outlines the remaining work.

TABLE 2.
ORBIT ACCURACY ASSESSED BY ORBIT OVERLAP FOR DSCS SATELLITE

Orbit Accuracy Assessed by Orbit Overlap for DSCS

	Total Range Error RMS (m)
Without SGLS	1343
With SGLS	288

- Combined error in both orbits
- SGLS data sampled every 30 s and assigned 10 m error

2. LINCOLN ANALYSIS OF AFSCN DATA

Lincoln Laboratory has been involved with the analysis of the AFSCN data since 1989 when the SGLS data was initially analyzed prior to the MSX launch. Other AFSCN studies with Lincoln involvement include the New Boston refraction test in 1994. The New Boston refraction test was primarily concerned with evaluating the accuracy of the refraction models being used in the AFSCN processing. As can be seen in Figure 1, which shows the AFSCN range residuals on a GPS satellite using the UNB4 tropospheric model [2,3] and the International Reference Ionosphere model [4,5], range accuracies of less than 2 meters are attainable with the AFSCN data. The conclusion of the New Boston study was that 1 meter sensor data from the AFSCN can be achieved using GPS reference orbits if corrections to the site coordinates and offsets to the time variable are applied (in New Boston a 1.35 ms time offset and a –1.1 m coordinate correction in the z direction were solved for) in addition to the tropospheric and ionospheric refraction corrections.

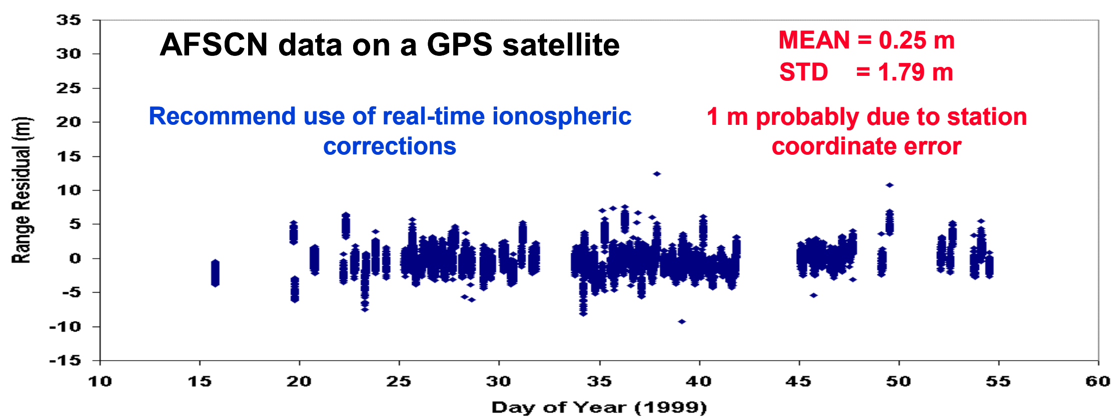

Figure 1. Recent AFSCN residuals using a GPS satellite. Station Coordinates used were from Table 1. If these were adjusted, as was done in the New Boston study, the standard deviation would likely be less than a meter.

MIT Lincoln Laboratory has been monitoring the position of the MSX satellite using AFSCN data since it was launched into an 898-km orbit on 25 April 1996. MSX carries a suite of sensors for Space Based Space Surveillance, including the Space Based Visible (SBV) sensor. As such, the MSX satellite serves as an observing platform for these sensors. The accuracy of measurements from these sensors depends on the position accuracy of MSX. Based on an error budget determined for the SBV measurement, the requirement for the MSX position accuracy was set at 15 m or less (1 sigma). An MSX orbit determination procedure was developed at Lincoln based on AFSCN data that yields a post-fit satellite ephemeris accurate to 7 m, [6]. These orbits have been produced since 1996. The MSX data accuracy does not show the 1 m accuracy of the AFSCN GPS data primarily because of an unexplained elevation dependence. This elevation dependence, which is also apparent in the range-rate data, does not seem to be refraction dependent. It is seen in some, but not all, of the AFSCN satellite data analyzed by Lincoln. Additional data analysis from other AFSCN satellites may help explain this phenomenon.

Based on Lincoln's experience with the MSX orbits, it appears that correct determination of the site and transponder biases is required to maintain the 7 m or better accuracy of this data In particular, hardware changes at the sites can lead to fairly abrupt changes in the site biases. It is essential to continuously monitor the calibration of the sites to maintain the 7 m accuracy of the data. Based on our analysis, the transponder biases (biases at the satellite) are generally on the order of 300 m, but these biases are usually constant and, once solved for, do not change. Nominal site biases can be up to 600 m and corrections to these can be up to 50 meters. The zenith tropospheric effect is 2.5 m and maps to several hundreds of meters at low elevations. The ionospheric effect can be up to 20 m at solar maximum, which is the peak of the 11-year solar cycle depending on the site and time of day. We have just recently past the current solar maximum in approximately April 2000 [7]. Bad estimates of the transponder and site biases will make the data useless. Bad estimates of the atmospheric corrections will degrade its use. It is also be useful to correctly weight the data in the orbit determination process (typically the lower elevation data which is more susceptible to refraction effects is of less inherent accuracy).

Two examples of the abrupt changes in site biases are shown in the Figure 2 and 3. The first shows a 10-m jump in the range residuals (computed minus observed range) for the MSX satellite, while the second shows the changes observed in the MSX range residuals at four of the SGLS sites from 11/1/98-6/23/00. A sudden change in average range residual of a satellite whose orbit is well understood can be attributed to a change in the site bias. From these plots, the necessity of continually monitoring these biases is apparent.

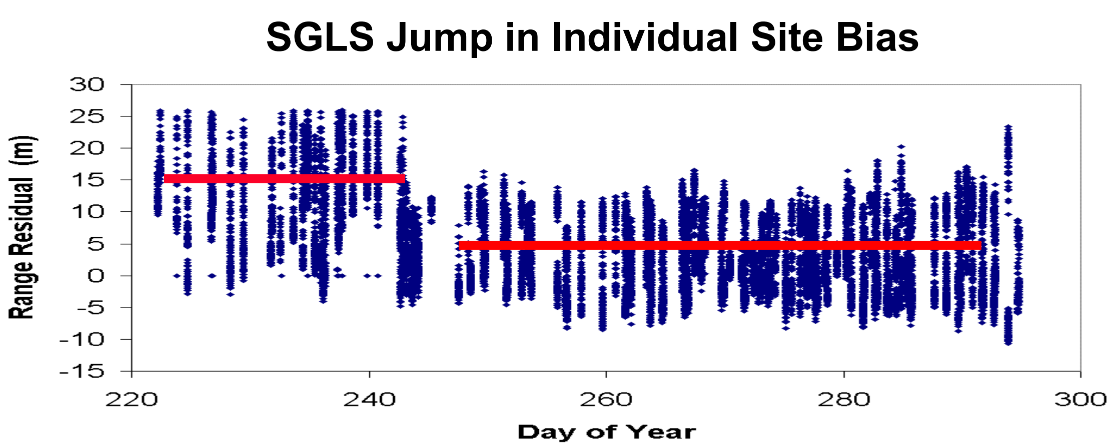

Figure 2. Abrupt change in the site bias as measured at single site.

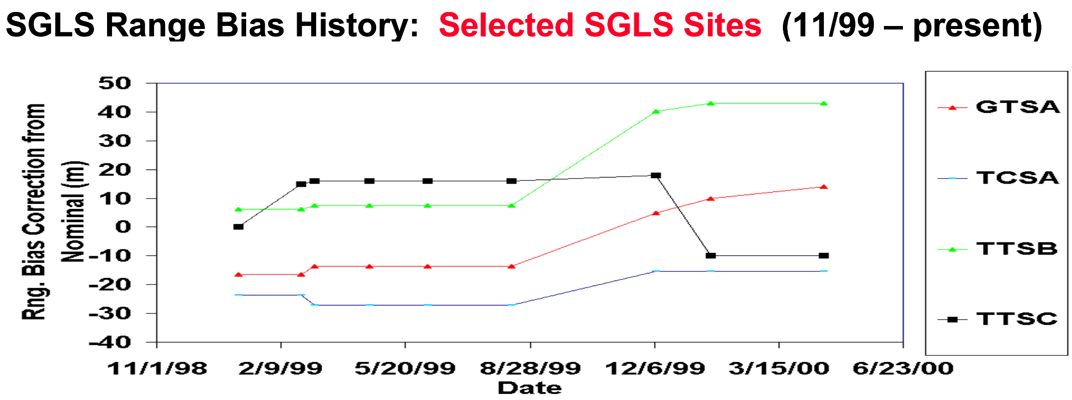

Figure 3. Changes in observed in the site biases from 11/1/98-6/23/00 at four of the SGLS sites.

Procedures to monitor these biases are based on careful analysis of the range residuals for AFSCN satellites whose orbits are well modeled. If there is a sudden unexplained jump in the range residuals of these satellites, then this can be attributed to a change in the site bias. The data shown in Figure 2 and 3 was taken from our ongoing work with the MSX satellite. AFSCN tracking data is received and orbits computed daily as discussed in [6]. The accuracy requirements for the MSX satellite position (<15 m) necessitate a stringent calibration of the AFSCN data. Therefore, the range residuals of the data from the high precision orbit determination are monitored weekly. These range residuals show linear trends, jumps, and periodicities. The AFSCN range biases as determined with MSX are also compared with the AF satellite operators and other relevant users of the data.

It is for this reason that orbits from various AFSCN satellites are being studied by Lincoln for the on going monitoring of the AFSCN calibration. To do this correctly, selected AFSCN satellites, whose orbits are well determined, have to serve as calibration targets. This year, a major focus has been to select AFSCN calibration targets. Based on Lincoln's experience with MSX, this satellite will definitely serve as one of the targets. In addition, Center for Research Support (CERES) has provided us data on a continual basis since day 63, 2000 on 4 AFSCN satellites: FltSat F1, DSCS II, and two DSP's. We anticipate using one or more of these satellites as additional calibration targets. Finally, based on conversations at Schriever AFB, we have learned that the 1/Sec message format is routinely available on GPS satellites. Precise orbits of GPS satellites (accurate to the 10-cm or better level) are available from a variety of sources including the Jet Propulsion Laboratory (JPL) and the National Geodetic Service (NGS). We anticipate using the precision orbits provided by JPL as our truth reference. The advantage to having a very precise, outside reference standard is that in addition to being able to monitor the site biases, the capability is there to resurvey the position of the site's location. This should enable us to produce the best possible metric observations from the AFSCN data.

3. COMMUNICATIONS ISSUES AND WORKSTATION DESIGN

3.1 Communication Issues

The most critical issue in this project is that of the data communication between sites. The primary focus has been in establishing the real-time data link between Schriever AFB and Millstone Hill Radar. The communication link between Schriever AFB and Millstone is for the AFSCN 1/sec message format only. This message format is unclassified, and has no satellite ID attached to it. We anticipate the maximum amount of data to be 4Kb/s at peak. 2SOPS has provided us software that reads and translates this message format into a useable data format. Up until now, we have been working with a processed version of this format using the data provided to us on a weekly basis by CERES.

Additional communication issues involve the flow of reformatted and calibrated AFSCN data into the SCC, and eventually, links between a workstation at Schriever AFB, the SCC, and the Millstone Hill radar. The procedure of sending the calibrated AFSCN data into the SCC from the Millstone Hill radar is essentially already in place, as Millstone routinely sends observations into the SCC from other sites such as TOSS. The critical issue here is that the SCC must be prepared to accept these observations (i.e. their data bases must include the correct coordinates and site IDs for each of the 15 AFSCN sites.)

3.2 1/Sec Message Format

The 1/Sec message format is just one of several message formats received by the AFSCN. It is, however, the only AFSCN message format that is required for producing AFSCN metric observations. The 1/Sec message format is unclassified for all satellites. It is composed of 348 Bytes, of which only a small subset are of interest; those bytes containing the site ID, the time tag, and the 5 RDT data words which include the azimuth, elevation, range-rate, and range data. This message format has no satellite ID attached to it.

3.3 Workstation

The plan is to develop two turn-key workstations, one located in Colorado Springs and the other at the MIT/LL Millstone facility. Software on the workstations will accomplish the following tasks: observation processing, status monitoring, orbit fitting, and plotting. More detailed functional descriptions are given below. Also, the data required for maintaining the system will be discussed. Cleanup utilities, which are not described here, will be run on a timer. Both workstations will be capable of handling the observation processing and status-monitoring functions. Only the Millstone workstation will also include the orbit fitting and plotting functions. The first milestone is to complete the workstation at Millstone.

3.4 Observation Processing

Raw observations from the AFSCN network will be transmitted to the workstation. In order to be used in orbit-fitting applications, these raw observations must be corrected for transponder and sensor biases, ionospheric and tropospheric refraction errors and be weighted appropriately. Finally, the observations must be formatted.

The binary one-second data provides the following information: sensor, time, azimuth, elevation, range and sometimes range-rate. Since the observations provided in the 1/sec data do not indicate which satellite is being observed, a method of correlation is needed. The first method being considered is Space Command's Astrodynamics Standard ROTAS (Report Of Track Association), which, given a collection of satellite element sets, will determine the order of best fit to the observations. Also being considered is Space Command's IOMOD (Initial Orbit MODule) which will create an initial uncorrected element set for a given set of observations. This element set can then be compared with the most recent element sets for the AFSCN satellites. Comparison can be accomplished with ROTAS (which does element to element correlation as well as observation to element), or some other comparison method. The goal is to identify the simplest yet most robust technique to use as an unattended correlation process, allowing the observations to be tagged before they are passed on to the SCC.

Refraction corrections will be computed using the UNB4 tropospheric model [2,3] and the International Reference Ionospheric model [4,5]. Eventually we would like to use a real-time data-driven ionospheric model to produce the ionospheric corrections required by the AFSCN stations. Figure 4 shows the data flow design for the two workstations. The dark shaded area refers to processing that will be on both workstations, while the lighter shaded area refers to processing that will be developed only on the Millstone Hill workstation.

Data Flow Overview

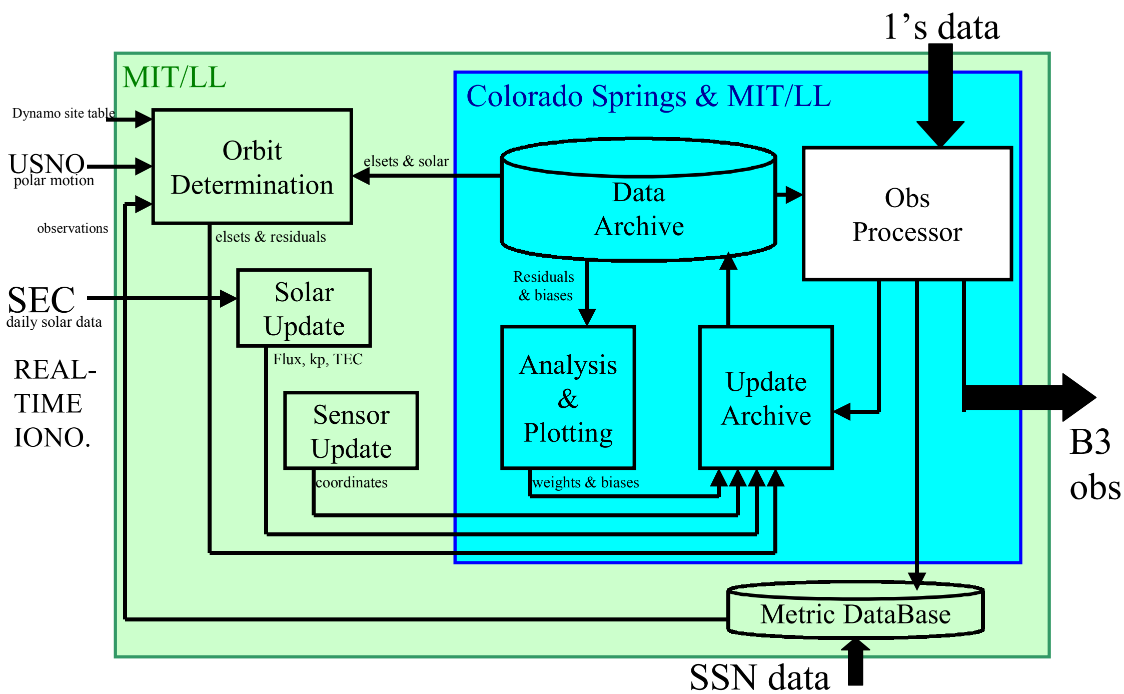

Figure 4. Workstation Design: Data Flow Overview

4. SUMMARY

MIT Lincoln Laboratory is in the process of building a workstation for calibrating and reformatting AFSCN metric observations with the goal of transmitting these observations into the SCC. The 50th SW and AF DOYS are working with us to establish the data communication links for the 1-sec message format. The workstation design is finalized and several of the software components are completed. It is anticipated that as soon as the data flow is established between Schriever AFB and the Millstone Hill Radar, only a few months will be required to finalize the software and produce processed AFSCN observations ready for data transmission into the SCC. Figure 5 shows the final architecture proposed by Lincoln for the calibration, reformatting, and transmission of the AFSCN metric data. The high quality of the AFSCN metric observations will be a significant addition to the SCC catalog.

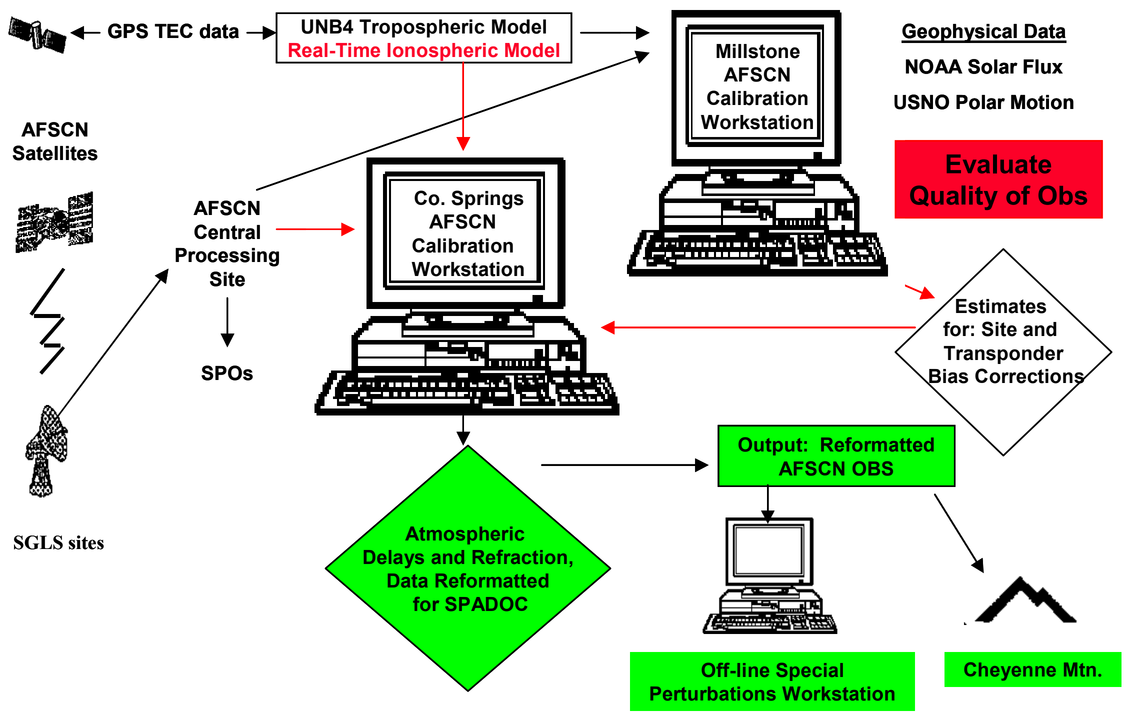

Figure 5. Final architecture of AFSCN Calibration/Reformatting Workstations

5. REFERENCES

[1] van Volkinburg, personal communication.

[2] Collins, P., R. Langley, and J. LaMance (1996). "Limiting Factors in Tropospheric Propagation Delay Error Modelling for GPS Airborne Navigation.", Proceedings of The Institute of Navigation 52nd Annual Meeting, Cambridge, MA, U.S.A., 19-21 June 1996; pp. 519-528.

[3] Collins, P. and R. B. Langley, "Tropospheric Delay-Prediction for the WAAS User", *GPS World* **10** (7), 1999, pp. 52-58.

[4] Bilitza, D. (ed.), International Reference Ionosphere 1990, NSSDC 90-22, Greenbelt, Maryland, 1990.

[5] Bilitza, D., K. Rawer, L. Bossy, and T. Gulyaeva, International Reference Ionosphere - Past, Present, Future, Adv. Space Res. 13, #3, 3-23, 1993.

[6] Abbot, R.I., "Midcourse Space Experiment Precision Ephemeris," Journal of Guidance, Control, and Dynamics, Vol. 23, No. 1, January-February 2000. p. 186-190.

[7] Kunches, J., private communication, Solar Environment Laboratory, NOAA, 2001.