GEO UPLINK SUBSYSTEM (GUS) CLOCK STEERING ALGORITHMS PERFORMANCE, VALIDATION, AND TEST RESULTS

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Abstract

Raytheon Systems Company is currently designing the algorithms of the FAA's Wide Area Augmentation System (WAAS). This paper will discuss the GUS clock steering performance, validation, and test results.

The clock steering algorithms reside in the GEO Uplink Subsystem processor. The WAAS Type 9 messages (GEO Navigation message), which are used as inputs to the GUS WAAS Message Processor, are provided by the Wide Area Master Station (WMS).

The GUS calculates clock adjustments and tunes the local frequency standard to speed up or slow the GUS clock. The GUS cesium standard is controlled through very small frequency control signals so that the normal operation of the code and frequency control loops of the downlink signals will not be disturbed.

Test results for the primary and backup GUS are discussed in the paper. The typical tracking error results are within ± 250 ns (excluding the effects of GEO maneuvers and GUS or WMS switchovers) for the primary GUS using INMARSAT's Atlantic Ocean Region-West (AOR-W) GEO satellite. For the AOR-W backup GUS, the system settled to ± 550 ns. The typical tracking error results for the primary GUS using INMARSAT's Pacific Ocean Region (POR) GEO satellite are within ± 450 ns (excluding the effects of GEO maneuvers, and GUS or WMS switchovers). For POR's backup GUS, the system settled to ± 550 ns.

INTRODUCTION

Raytheon Systems Company is currently developing the WAAS under contract with the Federal Aviation Administration (FAA)*. WAAS is a GPS-based navigation system that is intended to become the primary navigational aid for aviation during all phases of flight-from en-route through Category I precision approach. This system will make use of a network of Wide-Area Reference Stations (WRSs) distributed throughout the U.S. National Airspace System. Figure 1 provides a top-level view of the WAAS architecture [1].

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These reference stations will collect pseudorange measurements and send them to the WAAS Wide-Area Master Stations (WMSs). The Master Stations will process the data to provide correctional and integrity information for each GEO and GPS satellite. The correction information will include as separate components the satellite ephemeris errors, clock bias, and ionospheric estimation data. The corrections from the WMS will be sent to the Ground Uplink Subsystem (GUS) for uplink to the GEO.

The GUS receives integrity and correction data and WAAS specific messages from the WMS, adds forward error correction (FEC) encoding, and transmits the messages via a C-Band uplink to the GEO satellites for broadcast to the WAAS user. The GUS uplink signal uses the GPS standard positioning service waveform (C/A code, BPSK modulation); however, the data rate is higher (250 bits per second). The 250 bits of data are encoded with a one-half rate convolutional code, resulting in 500 symbols per second transmission rate.

Each symbol is modulated by the C/A code - a 1.023 X 10^6 chips/sec pseudo-random sequence to provide a spread spectrum signal. This signal is then BPSK modulated by the GUS onto an intermediate frequency (IF) carrier, upconverted to a C-Band frequency, and uplinked to the GEO. It is the C/A code modulation that provides the ranging capability if its phase is properly controlled. Control of the carrier frequency and phase is also required to eliminate uplink Doppler and to maintain coherency between code and carrier. The GUS monitors the C-Band and L1 downlinks from the GEO to provide closed-loop control of the PRN code and L1 carrier coherency. GUS steering algorithms are shown for the Primary and Backup GEO uplink subsystems [2, 3].

The GUS also contains the WAAS clock steering algorithm. This algorithm uses the WAAS Type 9 messages from the Wide-Area Master Station to align the GEO's epoch with the GPS epoch. The WAAS Type 9 message contains a term referred to as a_0 or clock offset. This offset represents a correction, or time difference, between the GEOs epoch and WAAS Network Time (WNT). WNT is the internal time reference scale of WAAS and is required to track the GPS time scale, while at the same time providing the users with the translation to UTC. Since GPS master time is not directly obtainable, the WAAS architecture requires that WNT be computed at multiple WMSs using potentially differing sets of measurements from potentially differing sets of receivers and clocks (WAAS Reference Stations). WNT is required to agree with GPS to within $\pm$ 50 ns. At the same time, the WNT to UTC offset must be provided to the user, with the offset being accurate to 20 nanoseconds. The GUS calculates local clock adjustments. Based upon these clock adjustments, the frequency standard can be made to speed up or slow the GUS clock. This will keep the total GEO clock offset within the range allowed by the WAAS Type 9 message so that users can make the proper clock corrections in their algorithms.

PRIMARY GUS CLOCK STEERING ALGORITHM

The GUS clock steering algorithm calculates the fractional frequency control adjustment required to slowly steer the GUS's cesium frequency standard to align the GEO's epoch. These small frequency control signals are very small, so normal operation of the code and frequency control loops of any user receiver are not disturbed. Figure 3 shows the primary GUS's closed-loop control system block diagram. The primary GUS is the active uplink dedicated to either the AOR-W or POR GEO satellite. If this primary GUS fails, then the hot "backup GUS" is switched to Primary.

The Clock Steering algorithm is designed using a proportional and integral (P.I.) controller. This algorithm allows one to optimize by adjusting the parameters α, β, and T. Values of α and β are optimized to 0.707 damping ratio.

The value $\overline{a_o}(t_k)$ is the range residual for the Primary GUS.

$$\overline{a}_o(t_k) = \frac{\sum_{n=1}^{N} a_o(t_{k-n})}{N}$$

The value $f_c(t_k)$ is the frequency control signal to be applied at time t_k to the GUS cesium frequency standard

$$f_c(t_k) = -\left[\frac{\alpha}{T}\bar{a}_o(t_k) + \frac{\beta}{T^2}\int_0^{t_k}\bar{a}_0(t)dt\right]$$

Where:

T = large time constant

α and β = free parameters

N = number of data points within period t

t = time of averaging period

t_k = time when the frequency control signal is applied to the cesium frequency standard

$a_o(t_k)$ = time offset for GEO at time t_k provided by WMS for primary GUS

S = Laplacian Operator (see Figure 3)

BACKUP GUS STEERING ALGORITHM

The backup GUS must employ a different algorithm for calculating the range residual. Since the backup GUS is not transmitting to the satellite, the WMS can not model the clock drift at the backup GUS and, therefore, an a_0 term is not present in the WAAS Type 9 message. In lieu of the a_0 term provided by the WMS, the backup GUS calculates an equivalent a_0 parameter.

The range residual $a_0(t_k)$ for the backup GUS is calculated as follows [4]:

$$a_0(t_k) = [B_{RE} - R_{WMS}]/c - S(t_k)$$

Where:

B_{RE} = Range estimate in the Backup Range Estimator

R_{WMS} = Range estimate calculated from the GEO position supplied by WMS Type 9 Message

c = speed of light

$S(t_k)$ = Sagnac effect correction in an inertial frame

The Backup GUS uses the same algorithm $f_c(t_k)$ as in the primary GUS.

CLOCK STEERING TEST RESULTS DESCRIPTION

AOR-W Primary (Clarksburg, MD)

Figure 4 shows the first 3 days had cold start transients and WMS switch overs (LA to DC, and DC to LA). From the 3rd to 6th day, the clock stayed within ± 250 ns. At the end of the 6th day, a maneuver took place and caused a small transient and the clock offset went to –750 ns. On the 8th day, the primary GUS was switched to Santa Paula, and another transient was observed. Clock steering command limits are ± 138.89 x 10^{-13}. Limits on the clock offset from the WAAS Type 9 messages are ± 953.7 ns.

AOR-W Backup (Santa Paula, CA)

Figure 5 shows the backup GUS stayed within ± 550 nsec, for the first 6 days after initial transients. At the end of the 6th day, a GEO maneuver caused a transient.

POR Primary (Brewster, WA)

Figure 6 shows cold start transients and WMS switch overs (LA to DC, and DC to LA), the primary GUS stayed within ± 450 ns after initial transients. There was a GUS switch over after the 7th day, which caused transients.

POR Backup (Santa Paula, CA)

Figure 7 shows cold start transients. After initial transients, the backup GUS stayed within ± 550 ns for 9 days.

The clock offsets in all four cases are less than ± 953.7 ns (limit on WAAS Type 9 Message) for 9 days.

SUMMARY AND CONCLUSION

A Proportional and Integral (PI) type of control system has been designed to null out the clock offset between the GEO and WNT provided by WMS. α and β coefficients are optimized to give a small amount of overshoot (underdamped system). Field results for the AOR-W primary GUS converged to a ± 200 nsec (1 sigma) tracking error after initial transients. The AOR-W backup GUS converged to ± 500 ns. Test results for the POR primary converged to ± 400 ns after initial transients from WMS and GUS switching. The POR backup GUS converged to ± 500 ns. In the next phase, plans include the design of a PID (Proportional, Integral, and Derivative) control system to drive the GEO clock offsets closer to zero.

ACKNOWLEDGMENTS

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REFERENCES

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2. GEO Uplink System (GUS) Clock Steering Algorithms, Raytheon Systems Company's ENB, April 13, 1998.
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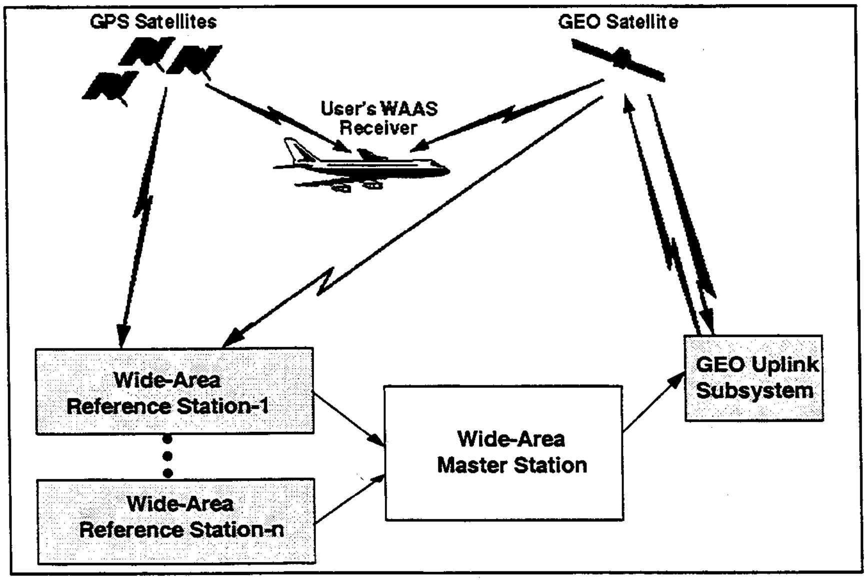

Figure 1: WAAS Top Level View. *The GEO Uplink Subsystem includes a closed-loop control algorithm and special signal generator hardware. These ensure that the downlink signal to the users is controlled adequately to be used as a ranging source to supplement the GPS satellites in view.*

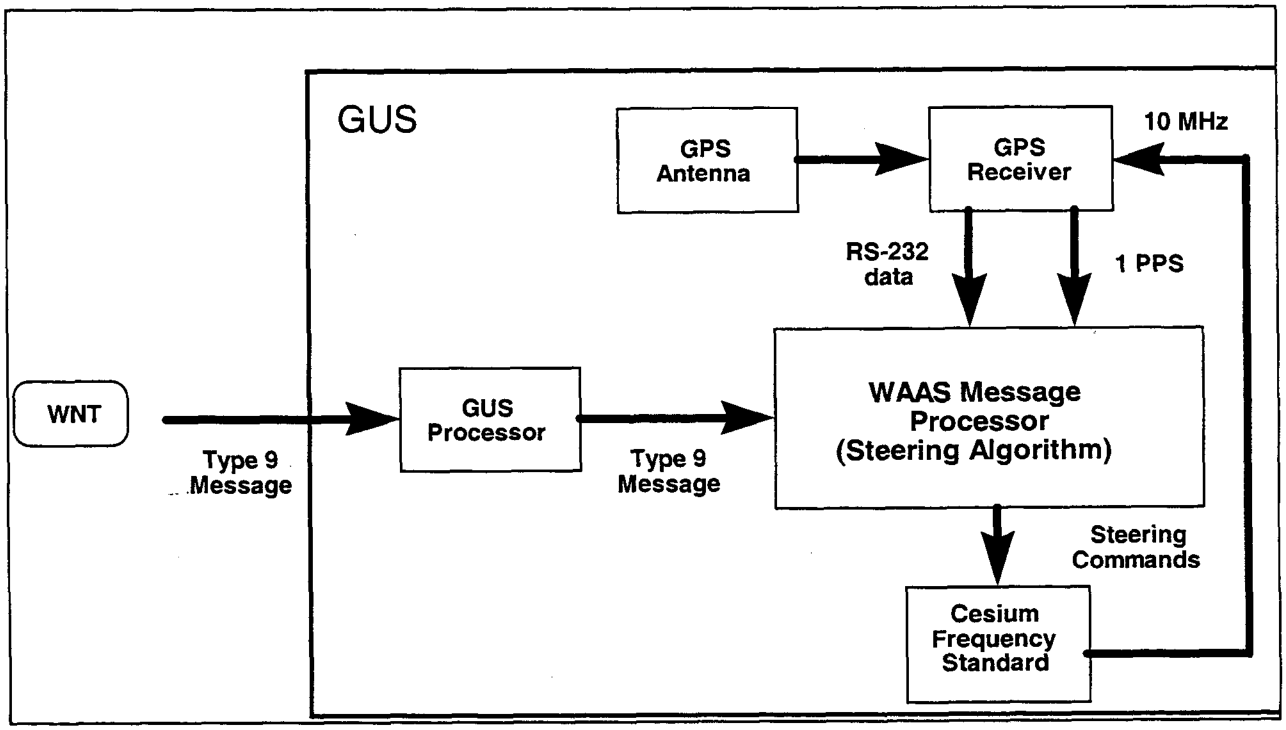

Figure 2: WMS to GUS Clock Steering

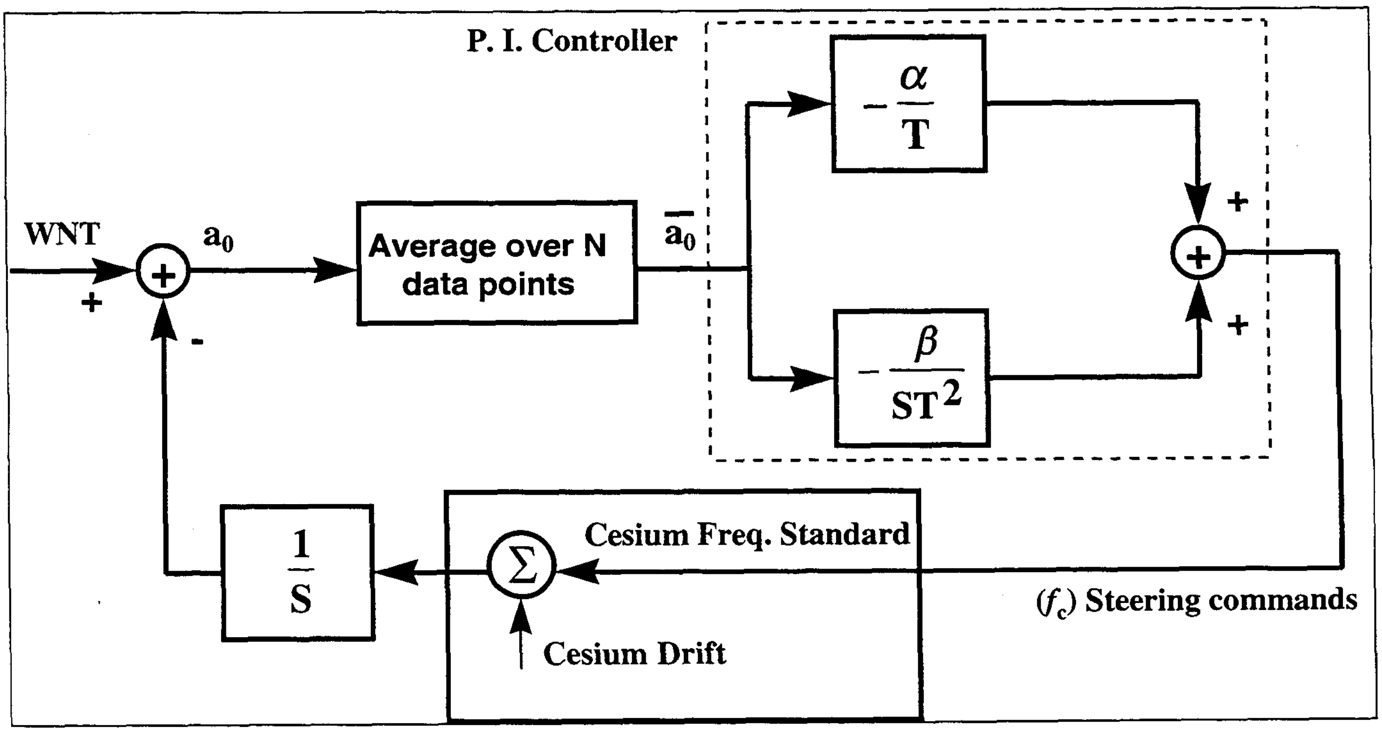

Figure 3: Clock Steering Block diagram

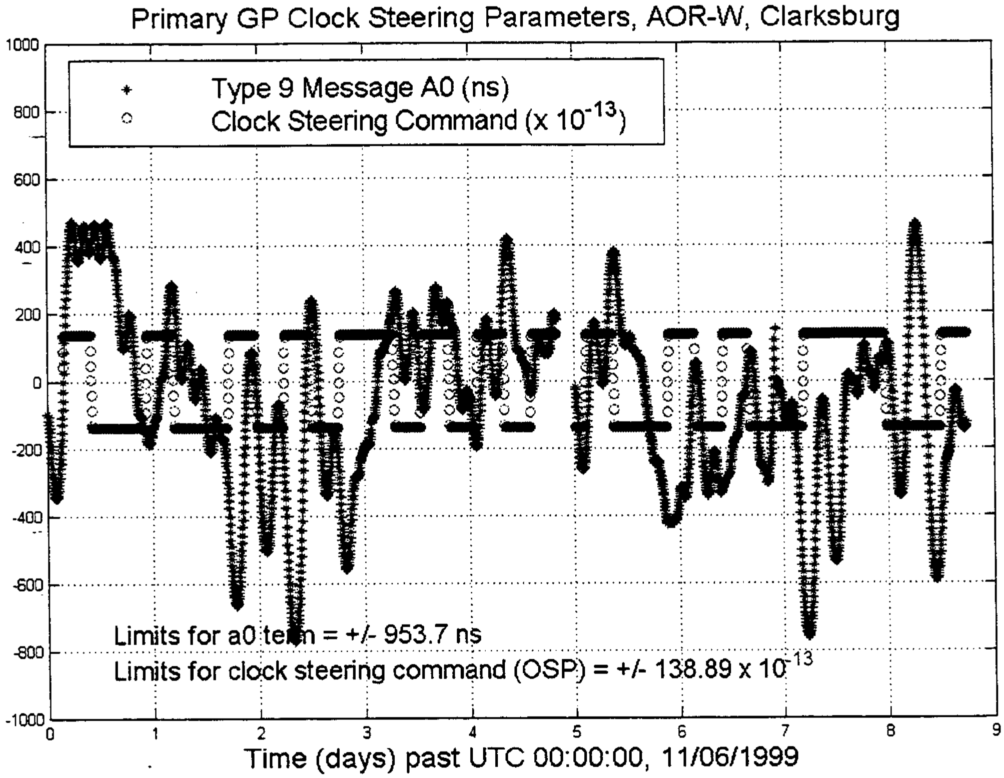

Figure 4: Primary GUS Processing (GP) Clock Steering for AOR-W (Clarksburg, MD)

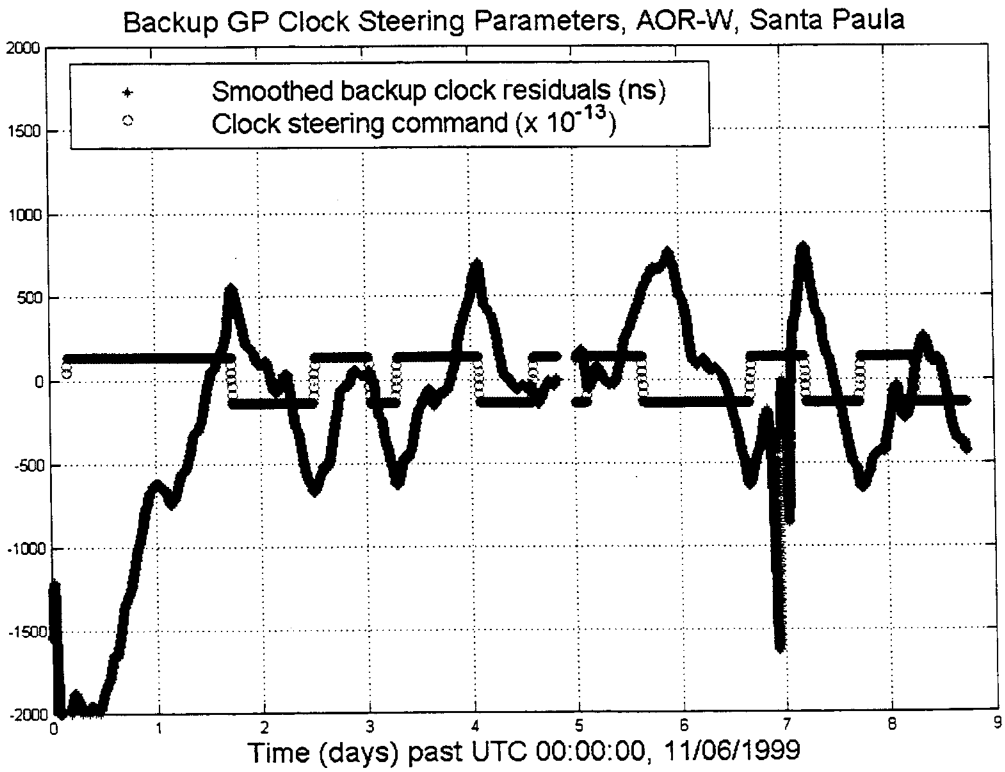

Figure 5: Backup GP Clock Steering for AOR-W (Santa Paula, CA)

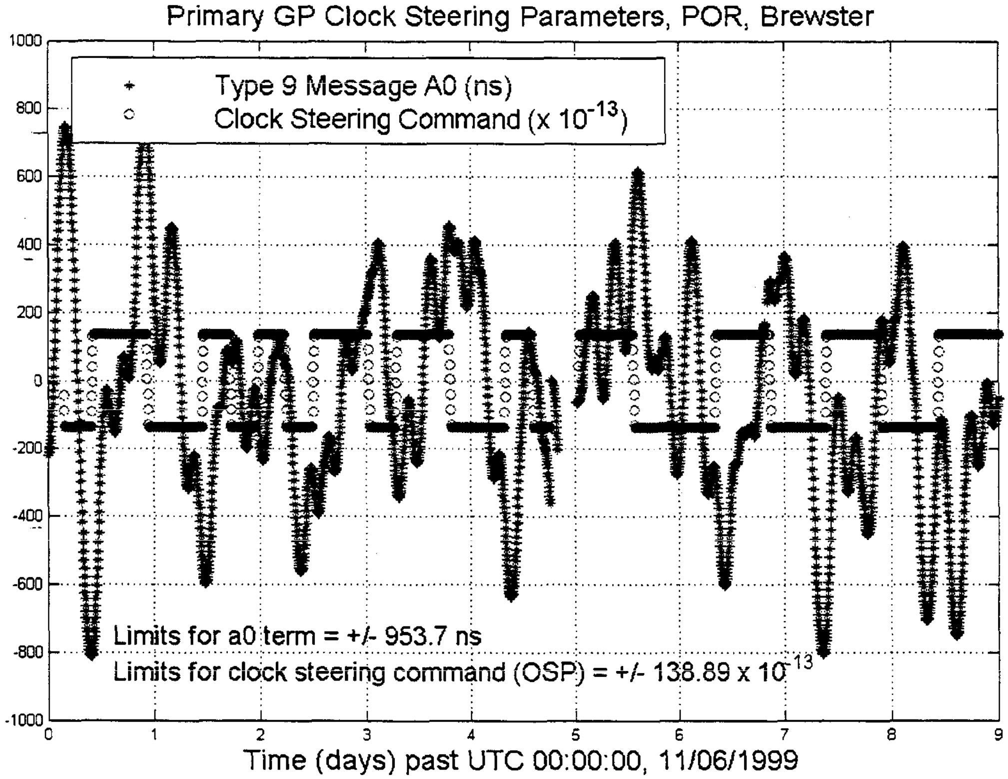

Figure 6: Primary GP Clock Steering for POR (Brewster, WA)

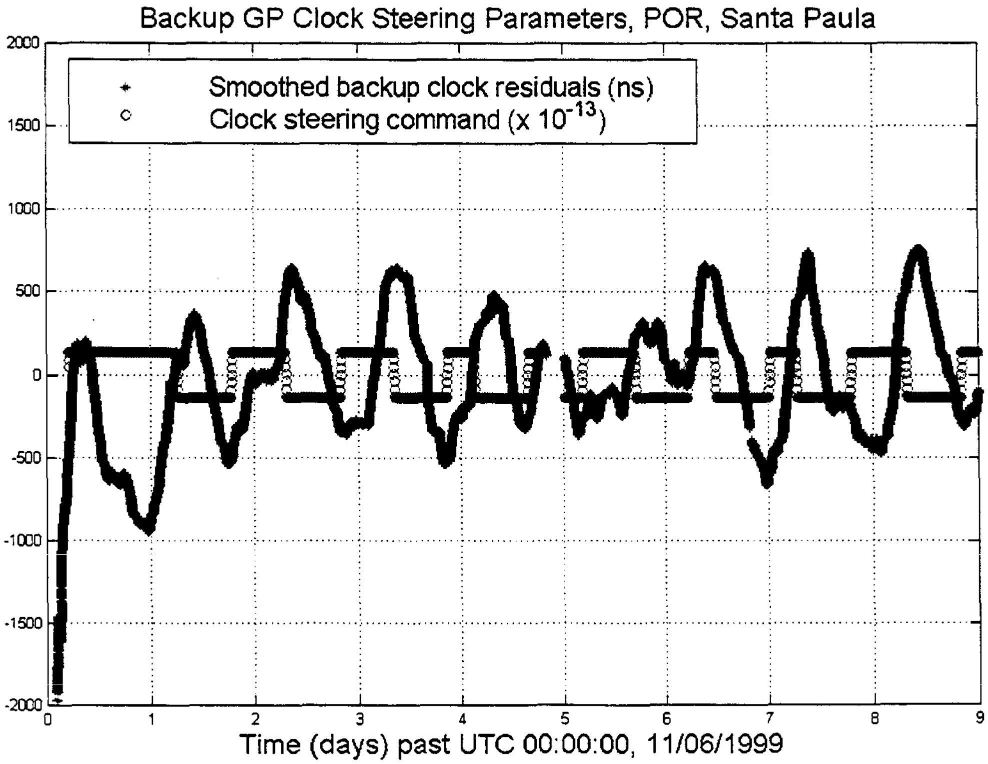

Figure 7: Backup GP Clock Steering for POR (Santa Paula, CA)