GPS-UTC TIME SYNCHRONIZATION

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Abstract

Two automatic algorithms for synchronizing the GPS time standard to the UTC time standard are evaluated. Both algorithms control GPS-UTC offsets to within 10 nanoseconds, reduce operator workloads, and are simple to implement and maintain.

INTRODUCTION

The Global Positioning System (GPS) is required to synchronize its broadcast time standard to within one microsecond of the time standard maintained by the US Naval Observatory (USNO), Coordinated Universal Time (UTC) (Figure 1). (GPS will also broadcast the measured difference between GPS and UTC standards with an error no larger than 10% of the maximum allowed offset, allowing GPS users to synchronize to UTC time within 100 nanoseconds.)

Currently, GPS-UTC offsets measured at USNO are relayed to the GPS master control station at Falcon Air Force Base where master clock corrections are manually computed to "steer" the GPS time to UTC time (Figure 2).

New ground software, developed by IBM Federal Systems Division, to be implemented in early 1990 will automatically steer GPS clock states under supervision by an operator. A modified bang-bang control law will be used to compute steering commands. We analyzed this law and a proportional phase-plus-frequency law to assess performance.

An automatic master-clock steering algorithm will improve synchronization and reduce operator workloads. The steering law must not exceed a GPS frequency-drift command limit of 1.5 nsec/day^2, imposed to maintain user accuracy. The steering law must also be robust (insensitive to bad or missing data, human error, degraded clock performance, etc.) and simple to implement and maintain.

SYSTEM MODELS

Figure 3 shows a highly-aggregated block diagram of the GPS clock-steering process. The frequency-drift command is integrated twice (GPS-steering block) to obtain a GPS-time correction. We ignore satellite updating lags because the update process is fast compared to the clock-steering response. Feedback drives compensated GPS time (GPS physical clock output plus steering time correction) to UTC time. GPS-UTC phase-offset measurements drive the steering law.

GPS clock phase is modeled as a two-stage integration process with random walk phase and frequency components (Figure 4). Two types of clocks are considered, a single Cesium clock and an ensemble of hydrogen-maser (H-Maser) clocks.

GPS-UTC phase-offset measurements to different GPS satellites are obtained at about 15-minute intervals. Our model assumes 20 nsec (1σ)

white measurement noise, reflecting primarily satellite-clock and ephemeris errors and assuming independence between satellites. USNO phase-offset measurements are directly transmitted to Falcon and processed by a two-state Kalman filter. (Currently, phase and frequency offsets derived from least-squares-processing of measurements are transmitted from USNO to Falcon.) The filter is supplied with the steering-command time history and measurements are edited to remove outliers.

STEERING CONTROL LAWS

Two automatic steering control laws have been proposed, one by the GPS ground-system contractor (IBM) and the other by The Aerospace Corporation.

IBM's modified bang-bang control law (Reference 1) attempts to null phase and frequency offsets in minimum time subject to a frequency-drift command limit of 1.5 nsec/day^2 (Figure 5). The algorithm computes a discriminant, D, every ΔT seconds which is used to determine the frequency-drift command for that interval. Aerospace's proportional phase-plus-frequency law (Figure 6) is a standard position-plus-rate feedback law modified by the addition of a limiter on the frequency-drift command.

LINEAR ANALYSIS OF AEROSPACE LAW

A covariance analysis of the proportional Aerospace law is possible (see Appendix). (The nonlinear IBM law can only be evaluated by simulation.) Figures 7-10 summarize predicted performance and parameter sensitivities of the Aerospace law. The control gains can be selected to minimize the phase-error covariance while keeping the maximum RMS frequency-drift command less than 1.5 nsec/day^2. The covariance analysis predicts a steering error of about 7 nsec for the cesium clock

(Figure 7) and 1.5 nsec for the H-Maser ensemble (Figure 8). Control gains can be varied significantly about their optimal values without significantly degrading steering performance, which allows the same gains to be used for either cesium and H-Maser clock systems. The cesium clock system is more sensitive than the H-Maser clock ensemble to clock noise variations, however.

SIMULATION OF IBM AND AEROSPACE CONTROL LAWS

Typical time response of the two control laws is illustrated in Figure 11. The IBM bang-bang law nulls the initial rate offset slightly faster than the Aerospace proportional law. Averaged steady-state errors are summarized for simulated cesium clock (Table 1) and H-Maser ensemble (Table 2) systems. The performance of the Aerospace law agrees with covariance analysis predictions. The performance of the IBM law is comparable to the Aerospace law for 15-minute updates, but worse with daily updates because its bang-bang action generates maximum RMS frequency-drift commands.

CONCLUSION

Both the IBM and Aerospace laws control GPS-UTC offsets to within 10 nsec, significantly better than the one microsecond requirement and the 100 nsec required broadcast accuracy. In fact, the residual steering error will likely be dominated by unmodelled factors such as data transmission errors between USNO and Falcon. The Aerospace law is smoother; the bang-bang IBM law reduces large initial offsets more quickly. Either law is straightforward to implement and maintain.

APPENDIX

COVARIANCE ANALYSIS OF AEROSPACE STEERING LAW

The Aerospace clock-steering model in Figure 6 (neglecting the limiter on the steering command) is described by:

$$x(k+1) = Ax(k) + Bw(k) \qquad \mathrm{cov}[w] = Q \tag{A1}$$

$$A = \begin{bmatrix} 1 & T & 0 & 0 \\ 0 & 1 & -K_1T & -K_2T \\ G_1 & G_1T & 1-G_1 & T(1-G_1) \\ G_2 & G_2T & -G_2-K_1T & 1-T(G_2+K_2) \end{bmatrix}$$

$$B = \begin{bmatrix} T & 0 & 0 \\ 0 & T & 0 \\ G_1T & 0 & G_1 \\ G_2T & 0 & G_2 \end{bmatrix}$$

$$x(k) = \begin{bmatrix} \theta(k) \\ \omega(k) \\ \hat{\theta}(k) \\ \hat{\omega}(k) \end{bmatrix} \qquad w(k) = \begin{bmatrix} w_1(k) \\ w_2(k) \\ v(k) \end{bmatrix}$$

where

$\theta(k)$ = clock-phase offset

$\omega(k)$ = clock-frequency offset

$\hat{\theta}(k)$ = estimated clock-phase offset

$\hat{\omega}(k)$ = estimated clock-frequency offset

K_1 = phase-control gain

K_2 = frequency-control gain

T = time step

G_1 = phase Kalman gain

G_2 = frequency Kalman gain

$w_1(k)$ = phase clock noise

$w_2(k)$ = frequency clock noise

$v(k)$ = measurement noise

The covariance of $x(k)$ is given by

$$P(k+1) = AP(k)A' + BQB' \tag{A2}$$

The steady-state covariance was determined by the methods in References 2 and 3. The covariance of the frequency-drift command is given by

$$\mathrm{cov}[\theta_c] = K_1^2 \mathrm{cov}\ [\theta] + 2\ K_1 K_2 \mathrm{cov}\ [\theta,\omega] + K_2^2 \mathrm{cov}\ [\omega] \tag{A3}$$

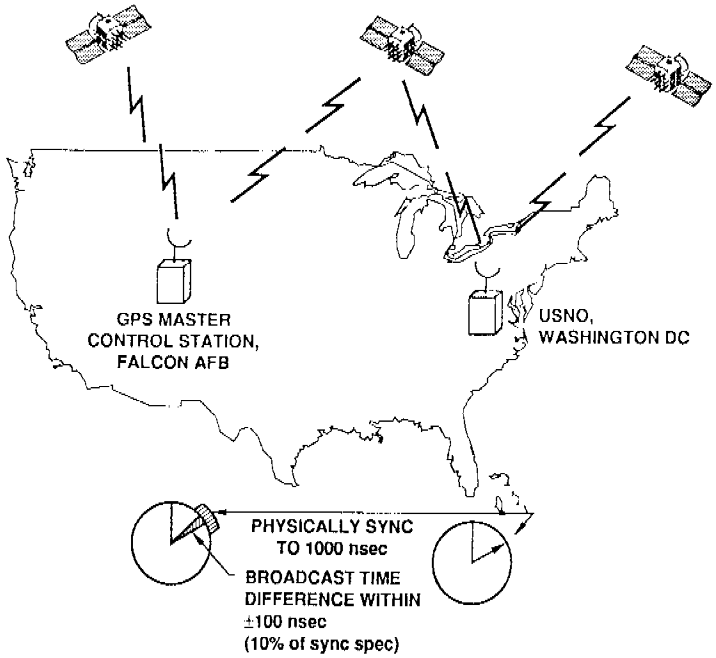


FIGURE 1. GPS-UTC SYNCHRONIZATION REQUIREMENTS

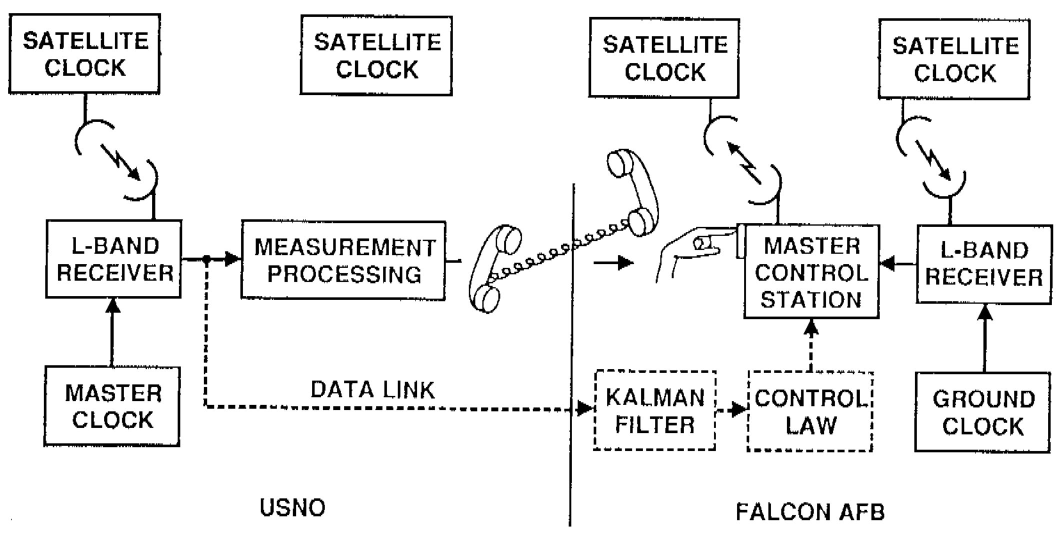


FIGURE 2. GPS-UTC SYNCHRONIZATION

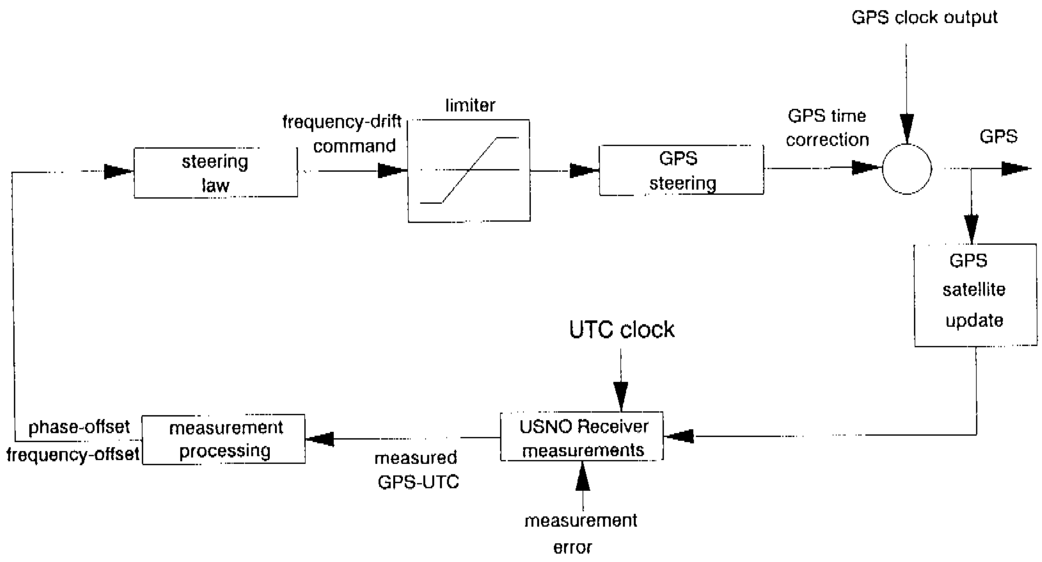
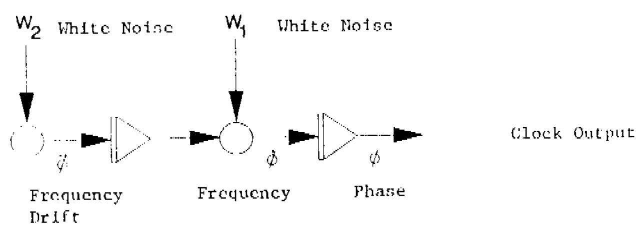


FIGURE 3. GPS CLOCK STEERING MODEL



CLOCK	1σ RANDOM WALK PHASE AT 1 DAY (σ_p)	1σ RANDOM WALK FREQUENCY AT 1 DAY (σ_f)
SINGLE-CESIUM	3 NSEC	1 NSEC/DAY
H-MASER ENSEMBLE	0.3 NSEC	0.1 NSEC/DAY

FIGURE 4. GPS CLOCK MODELS

DEFINE DISCRIMINANT = D

$$D(b,f) = b + \frac{f|f|}{2U}$$

b = CURRENT GPS-UTC PHASE OFFSET (SEC)

f = CURRENT GPS-UTC FREQUENCY OFFSET (SEC/SEC)

COMPUTE FREQUENCY-DRIFT STEERING COMMAND = $\dot{f}$

IF $|D(b,f)| < \mathrm{TOL}$ THEN $\dot{f} = -\,\mathrm{SGN}(f)\cdot \mathrm{MIN}\,(U, |f|/\Delta T)$

IF $|D(b,f)| \geq \mathrm{TOL}$

IF $|f| < f_{max}$ or $f \cdot D(b,f) > 0$

$\dot{f} = -\,U \cdot \mathrm{SGN}(D(b,f))$

OTHERWISE

$\dot{f} = 0$

PARAMETERS: $U = 2\times10^{-19}$ SEC/SEC^2 (MAXIMUM FREQUENCY DRIFT)

$f_{max} = 5\mathrm{X}10^{-14}$ SEC/SEC (MAXIMUM FREQUENCY)

TOL = 10^{-9} SEC (BIAS ERROR TOLERANCE)

ΔT = STEERING-LOOP UPDATE PERIOD (NOMINALLY 900 SECONDS)

FIGURE 5. IBM STEERING LAW

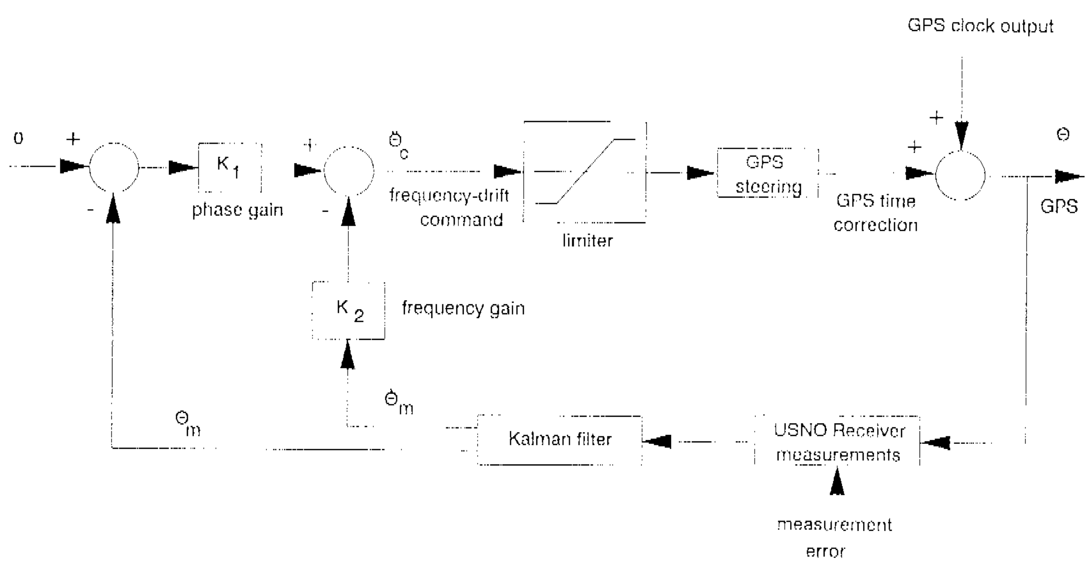


FIGURE 6. AEROSPACE STEERING SYSTEM

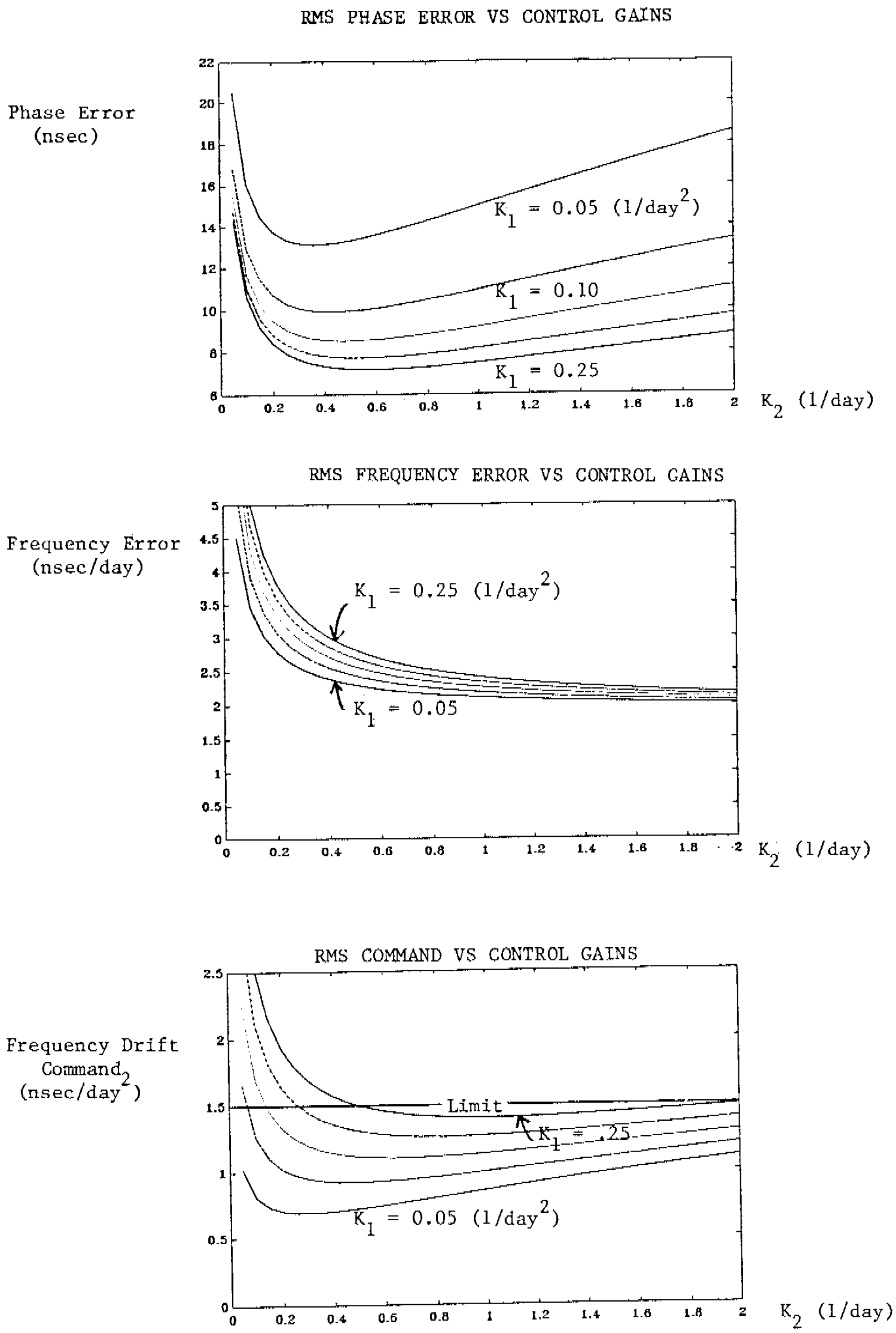


FIGURE 7. STEERING PERFORMANCE VS. CONTROL GAINS FOR CESIUM CLOCK

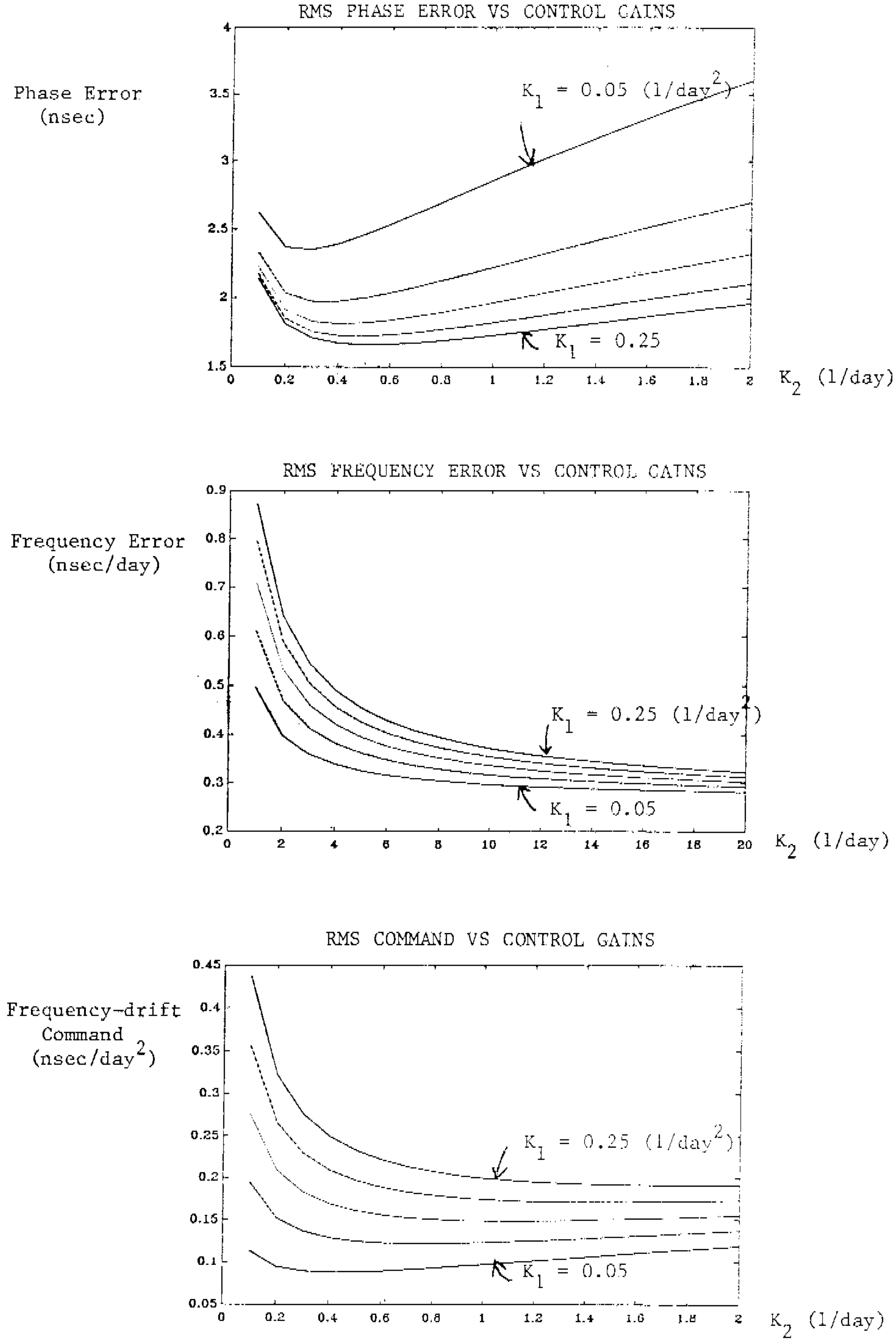
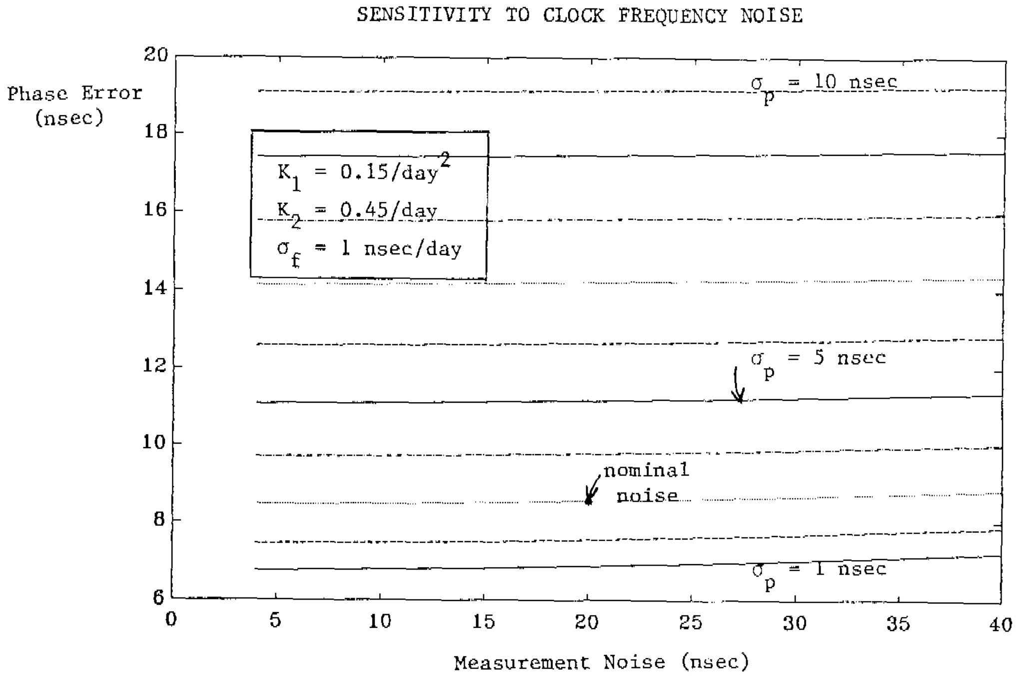


FIGURE 8. STEERING PERFORMANCE VS. CONTROL GAINS FOR H-MASER CLOCK ENSEMBLE



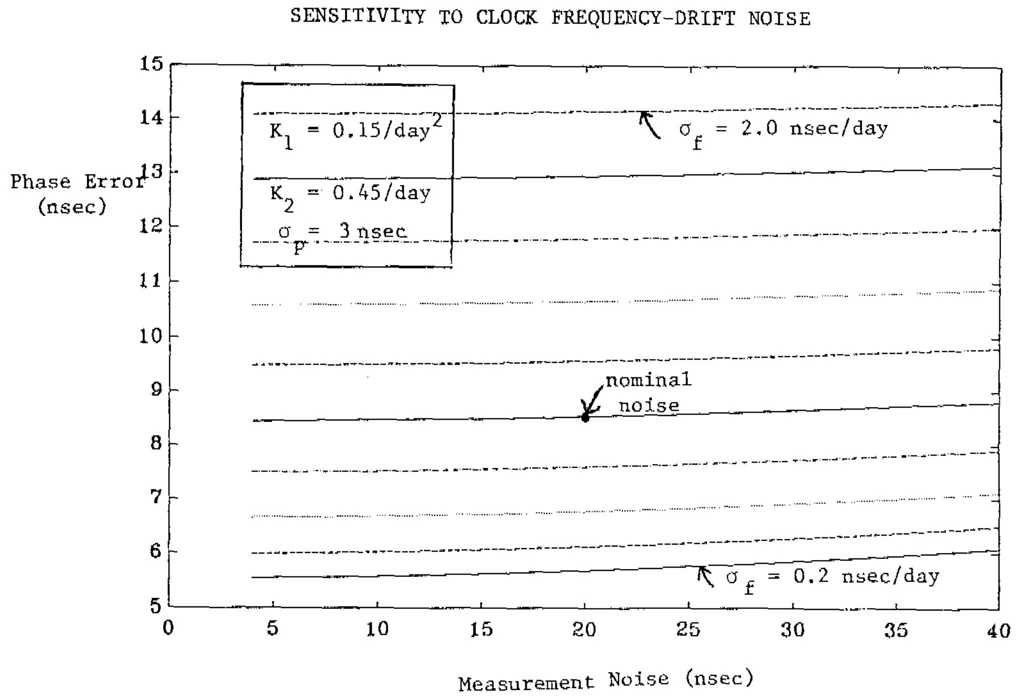


FIGURE 9. STEERING PERFORMANCE SENSITIVITY TO CLOCK AND MEASUREMENT NOISE FOR CESIUM CLOCK

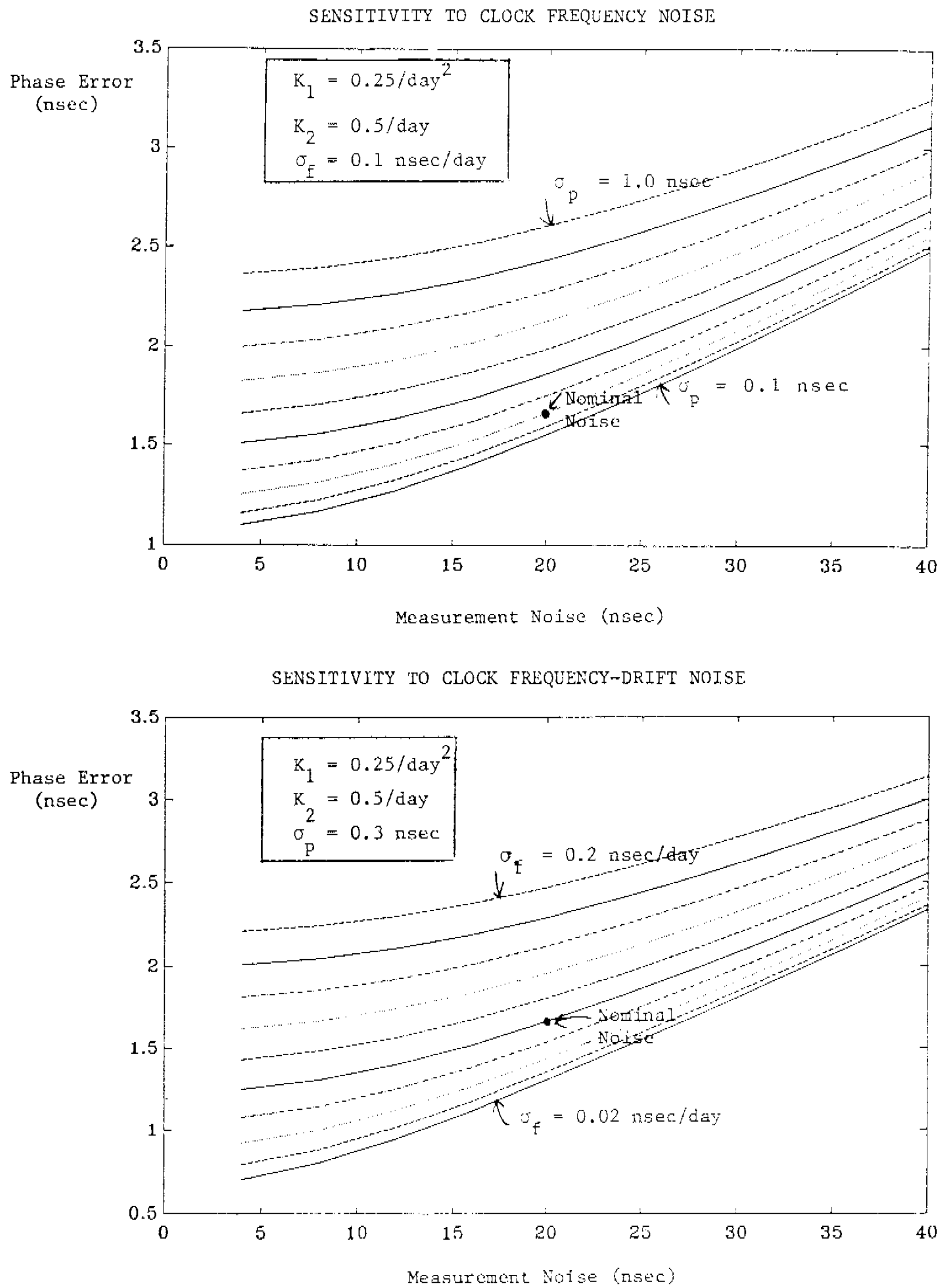


FIGURE 10. STEERING PERFORMANCE SENSITIVITY TO CLOCK AND MEASUREMENT NOISE FOR H-MASER CLOCK ENSEMBLE

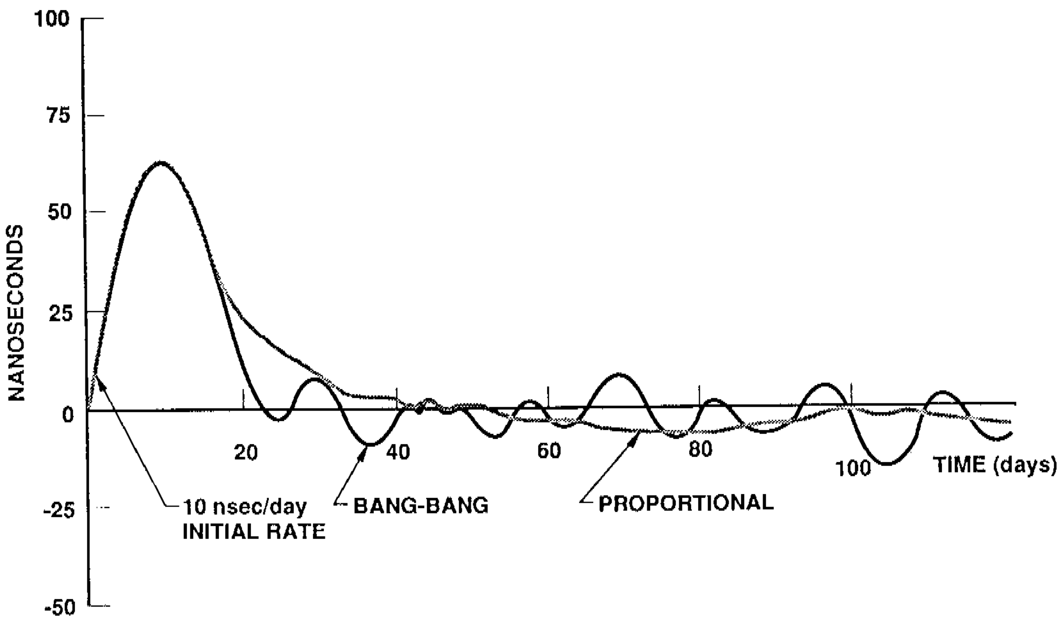


FIGURE 11. TRANSIENT RESPONSES

References

(1) Brown, K., "Optimal Ensembling for GPS and Other Systems of Clocks", IBM Federal Systems Division Draft, 14 July 1987.

(2) Lewis, Frank L., "Optimal Estimation", 1986.

(3) Brewer, John W., "Kronecker Products and Matrix Calculus in Systems Theory", IEEE Transactions on Circuits and Systems, September 1978.

QUESTIONS AND ANSWERS

AL KIRK, JPL: Are you trying to steer all the clocks on the satellites, or only the master clock at Falcon?

MS MCKENZIE: Currently, only the master clock is steered.

MR. KIRK: But you do plan to steer all the clocks eventually?

ANSWER FROM THE AUDIENCE, NOT INTO THE MICROPHONE, INDECIPHERABLE

UNIDENTIFIED QUESTIONER: Since this is one of my favorite subjects at (unclear on the tape), I couldn't resist making some comments here. One is that the current implementation, I believe there is a requirement that there be a man in the loop to steer them rather than using an automatic control. We have had a great deal of discussion with them on the installation of timing systems out there and they insist on that. An automatic control would not be implemented in that case.

MS MCKENZIE: My understanding is there is automatic control under the supervision of an operator.

SAME PERSON: He would control it, input it or simply watch its operation? I am not sure about that. Automatic control is what bothers me about that. The other comment is about orbital errors being significantly less than clock errors. I would have to disagree about that. I think that the basic error of the system shows the clock and orbital errors being about the same magnitude. It is not clear that they have been separated out in the system so you can discount them in a steering mode like this.

ANSWER FROM THE AUDIENCE: The clocks that are in the current GPS are performing, most of them at least, much better than specifications. The comments are related mostly to the specifications than to actual achieved performance at this point in time. The original Block One clocks were specified at 2×10^{13}. We are achieving much better than that, and therefor the clock performance is good. What we are talking about in terms of clock performance is the ability to predict the clock, and the ability to predict the ephemeris. Ephemeris predictions are pretty stable. They are more bounded, but pretty stable in the prediction time, whereas the clocks randomly deviate from their upload values. For that reason we are saying that the clocks themselves, in prediction, are worse than the ephemeris in prediction. In the analysis the clock and ephemeris are part of the noise as received by USNO. In other words, when they receive time, it is a summation of the two. That was modeled as noise in the simulation. As to the question of manual *vs.* automatic: daily reports are received from USNO and are used for steering currently. Its a manual process and maybe the steering commands are set up once a month, or something like that, because of stability of the system and the requirements of the system don't dictate more frequent steering. This concept, and what is going to be implemented shortly, is that daily things are received and are input manually, not automatically, but still daily. The analysis included the time delay of one day in the steering.

UNIDENTIFIED QUESTIONER: You seemed to indicate that the proportional steering law resulted in a smaller rms than the bang–bang steering law. Why are you implementing the bang–bang steering law?

MS MCKENZIE: The bang–bang law does have a couple of advantages, one is that it is not necessary to select control gains, it also has a slightly faster response to transients. On the other hand, the proportional law gives a slightly better steady state result. There is not enough evidence to push for the implementation of the proportional law. IBM, the contractor, had experience with the bang–bang law and decided to implement that one. The steady state error for both laws is much better than the requirements.

AL GUEVARA, MCS: I am one of the individuals involved in determining the steering for GPS. One of my concerns with the bang–bang law—how often are you assuming the frequency and phase offsets are being updated in the MCS?

MS MCKENZIE: Measurements are processed daily, but there is a fifteen minute interpolation loop, so the commands can change every fifteen minutes.

MR. GUEVARA: So every fifteen minutes they are supposedly going to be looking at the data base inputs as the steering is implemented. Is that a correct assumption?

ANSWER FROM THE AUDIENCE, INDECIPHERABLE

GERNOT WINKLER, USNO: There is another point. That is the reliability and robustness of operation. It is a weakness of the bang–bang method that, in the absence of steering information or severance of the control loop, you are going to go off at maximum rate. I think that that is a mistake.

MS MCKENZIE: That is a good point.