THE STEERING OF GPS TIME

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ABSTRACT

The Navstar Global Positioning System (GPS) will be one of the most widely available means by which to distribute exact time. By agreement between the GPS Control Segment and the US Naval Observatory (USNO), GPS time will be maintained an integral number of seconds, n, from UTC, with an error less than or equal to one microsecond:

$$T = \text{GPS-UTC-n} \leq 1 \ \mu \text{ sec},$$

where n is the number of leap seconds which will have elapsed between early 1980 and current time. The GPS Navigation Message will give the value of T to 100 nanoseconds or better, real time. After the fact, values of the GPS-UTC offset should be available to qualified users with accuracy of 20 nanoseconds or better. GPS time will be steered by altering its adopted offset bias and drift from a Reference Clock. This paper summarizes the mathematics of the steering algorithm, and the interface between the USNO and the GPS Controller.

INTRODUCTION

The Global Positioning System (GPS) of satellites is designed to disseminate to its users, along with the spacecraft ephemeris information necessary to derive user position, the current value of UTC. The maintenance of GPS time is a responsibility of the Master Control Station (MCS) of the GPS Control Segment, which serves as the directing center for all data collection and data generation, and also as the primary point of contact with such supporting agencies as the US Naval Observatory (USNO) and the Defense Mapping Agency (DMA). The MCS controls the uploading of navigational messages to the GPS satellites, and these messages include the parameters input to users' receiver sets to convert from GPS time to UTC. Feedback is provided by the USNO, which monitors the GPS navigational messages, and continually estimates the GPS-UTC offset in time and frequency.

The Navigation Data Message represents this GPS-UTC offset as

$$\text{GPS-UTC} = a_0 + a_1 t + n ,$$

where a_0 and a_1 are values appropriate to the clock of the satellite broadcasting the message, and n is the number of GPS leap seconds which have accumulated since the GPS epoch of 6 January 1980. Thus, GPS time is offset from International Atomic Time (TAI) by approximately 19 seconds. The exact value of the offset between GPS time and either TAI or UTC depends, of course, on how precisely GPS time/frequency can be estimated and, once estimated, how precisely it can be steered. This paper will be addressed only to the problem of steering.

The tolerance allowed in the steering of GPS time is defined for the final phase of GPS development, the Operational Control Segment (OCS), as follows (Reference 1):

> GPS Time is defined in the OCS as the time determined from a particular MS Clock (the Reference Clock), when offset by a bias and drift. The offset bias and drift of the Reference Clock are not estimated in the Kalman Filter but are assumed to be fixed in value. The offset bias and drift can be modified using a controller directive, and hence GPS Time can be "steered" into alignment with UTC. In particular, GPS time will be steered to attempt to maintain

$$\left|\text{UTC (USNO)} - t_{GPS} \quad + \Delta \text{LS} \left[\equiv \text{n, above}\right] \right| \leq 1 \text{ microsecond.}$$

No such requirements are specified for the present Interim Control Segment (ICS), but it is understood that the ICS will satisfy the OCS requirement as nearly as circumstances permit.

This Interim Control Segment, which has been used throughout the Phase I Concept Validation Phase, consists of four Monitor Stations (MS), an Upload Station (ULS), and a Master Control Station (MCS). The Monitor Stations are located at Hawaii; Elmendorf AFB, Alaska; Guam; and Vandenberg AFB, California. The remote Monitor Stations are unmanned data-collection centers under direct control of the MCS. Each MS contains a four-channel user-type receiver, environmental data sensors, an atomic frequency standard, and a computer processor. The receiver measures the pseudorange and delta pseudorange (integrated doppler) of the satellite spread-spectrum signal with respect to the atomic standard. It also detects the navigation data on the spread-spectrum signal. The environmental sensors collect local meteorological data for later tropospheric signal delay corrections at the MCS. The computer processor controls all data collection at the MS, and provides the data interface with the MCS. All data obtained by the MS is buffered at the MS and then relayed upon request to the MCS for processing.

The ULS, located at Vandenberg AFB, provides the interface between the Control Segment and the satellites. Its function is to utilize an S-band uplink to upload data into a satellite navigation processor. This upload data can be user navigation data, requests for processor diagnostics, or commands to change the satellite time provided by the user.

The MCS is also located at Vandenberg AFB, and completely controls the operation of the Control Segment. It performs the computations necessary to determine satellite ephemeris and atomic clock errors, generates satellite upload of user navigation data, and maintains a record of satellite navigation processor contents and status. The MCS also has interfaces with the Satellite Control Facility (SCF) and Naval Surface Weapons Center (NSWC). The SCF provides a backup upload capability in case of ULS failure and also provides satellite telemetry and command information. NSWC generates a predicted reference ephemeris from MCS-smooth pseudorange measurements for use by the MCS in the ephemeris estimation process.

The current configuraton at the Master Control Station has been upgraded by an IBM 3033 computer, which will provide increased reliability and capacity for the Phase II Development and System Test Program support. The converted software will provide for operational enhancements as well as the navigation message changes required to be compatible with the Phase II User Equipment. The upgraded configuration has been installed and is operating at Vandenberg Air Force Base.

The IBM 3033 computer will eventually be installed in the Operational Control System (OCS), which is currently under development and scheduled to initiate satellite operations support in 1985. The OCS will provide worldwide coverage for monitoring and uploading of the full eighteen to twenty-one satellite constellation. The OCS will also consolidate into a single facility the functions currently performed by the AFSCF and NSWC (see Figure 1).

Then the overall MCS operation with regard to maintaining GPS time can be resolved into three tasks:

a) The weight of each satellite contributing to GPS time must be assigned, based on some objective criterion of satellite performance;

b) GPS time must be calculated in such a way that it does not change discontinuously when clocks are added or dropped;

c) the daily estimates of GPS time offset, which are received from the USNO in the form

$$(1) \quad \text{GPS} - \text{UTC} = a_0 + a_1 t ,$$

must be combined into an ongoing, long term sequence of messages, somewhat as the hour-by-hour measurements of pseudorange are combined by the Kalman filter to provide an estimate of the dynamical history of each ephemeris and clock parameter.

Figure 2 illustrates the estimates of the GPS-UTC offsets actually logged at Vandenberg MCS in the beginning of this year. Figure 3 shows GPS - UTC values for the middle of 1983 as determined by the USNO, and the results of several efforts of steering, as recorded in the MCS log.

Any method proposed by which to steer GPS time at the present Interim Control Facility must reckon with the constraints imposed by the present ICS software. To be sure, many of these constraints will be relaxed when the superior OCS software is delivered.

The present system (Phase I) does automatically maintain continuity in GPS time when the master clock is switched. However, it does not maintain continuity in rate. Furthermore, there is no provision in the Phase I system for automatic steering of time, by any algorithm. The operator must change the frequency by hand whenever steering is required (Reference 2). Therefore, the effort of the analysts at Vandenberg has been, not to implement the principles of control theory according to textbook, but to satisfy certain practical requirements:

1) The algorithm used must be simple. The more complicated the algorithm, the more likely becomes an operator error.

2) The algorithm must not introduce errors in Kalman filter determination of clock and ephemeris parameters. Now, the only algorithm implemented in the Kalman filter for estimation of clock states is a second order polynomial:

$$\Delta T = A_0 + A_1 T + A_2 T^2,$$

where ΔT is any clock offset being solved for,
ΔT is GPS time,
A_0, A_1, and A_2 may either be solved for or held fixed by imposing _a priori_ values.

3) The steering must not interfere with the determination of the GPS - UTC offset -- e.g., by the Naval Observatory. Practically, this means that any frequency drift rate imposed in the steering operation must be small. In fact, the working rule of thumb is that frequency changes shall not exceed 1 part in 10^{13} per day

$$= 8.64 \text{ nanoseconds/day}^2.$$

Several methods of steering have been proposed to satisfy these working conditions.

The simplest and most direct approach was suggested by Gernot Winkler (Reference 3). The operator is to make only small changes, not to exceed 1 part in 10^{13} per day. After each change, he observes the effect by means of the US Naval Observatory determinations of GPS - UTC value and rate. The operator makes these changes only when indicated, according to four simple rules (Figure 4):

I) If $|GPS - UTC|$ is sensibly increasing, first reduce the rate to zero. Do not attempt to reverse the rate while it is still nonzero.

II) If $|GPS - UTC|$ is rapidly decreasing, reduce the rate to zero.

III) If $|GPS - UTC|$ is slowly decreasing, DO NOTHING!

IV) If GPS - UTC is about to change sign, reduce the rate to zero.

An independent proposal for GPS time steering was made by R. Castro (Reference 4). He observed that the most nearly error-free way to steer at present is to input a frequency drift term manually and to allow it to operate for a preselected time. Mathematically, this is equivalent to letting the quantity GPS - UTC change as a second order polynomial of time -- in other words, to move along a parabola. Castro considered the case when GPS - UTC is slowly decreasing. He observes the rate of change 0, which is the frequency offset between GPS time and UTC. Let S be the preassigned span of time over which a frequency drift is to be imposed. He calculates the parameters of the parabola which will bring the GPS - UTC offset to zero in both value and rate:

$$\phi_0 + \dot{\phi}_0 (t_1 - t_0) + \frac{\ddot{\phi}_0}{2} (t_1 - t_0)^2$$

where $t_1 - t_0 \equiv S$,
and where ϕ_0, $\dot{\phi}_0$, and $\ddot{\phi}_0$ are GPS - UTC
and its first and second derivatives,
t_0 is the time (date) at which steering is to begin,
and t_1 is where it is to end,
and S is preassigned in such a way as not to
violate the constraint that $\ddot{\phi}_0$ must not
exceed the aforementioned part in 10^{13} per day.

In practice, the quantities ϕ_0 and $\dot{\phi}_0$ are known from USNO reports, and one solves for the quantities t_1 and $\ddot{\phi}_0$ (Figure 5).

At the October meeting of the Data Analysis Working Group at Vandenberg, the author proposed a method similar to Castro's, but replacing the parabola by the function which characterizes the critically damped oscillator (Figure 6).

The function

$$y = (K_1 + K_2 t)e^{-\lambda t}$$

approaches zero asymptotically. As is well known, it displays three forms, depending on the sign of K_2. In Figure 7, the three cases are displayed, assuming that K_1 and λ are positive. Then, if $K_2 > 0$, the curve of y(t) at first rises, dominated by the first term $(K_1 + K_2 t)$, and then declines nearly exponentially to zero. If $K_2 = 0$, only the second term remains, and of course the curve declines exactly exponentially to zero. If $K_2 < 0$, the curve first crosses the t = 0 axis, and then returns toward that axis nearly exponentially. The speed of approach is determined by λ; and $1/\lambda$ corresponds to the preassigned time span S in the Castro method. It was proposed that one steer by the following steps:

1) Smoothed values of GPS - UTC from the US Naval Observatory should be employed, using five day means.

2) The value of λ in the damped oscillator function just given be fixed _a priori_. Simulations have shown that λ = 1/20 days would be appropriate.

3) Using this _a priori_ λ and the USNO value and rate of GPS - UTC for current epoch, one should determine the other two parameters K_1 and K_2 of the damped oscillator function.

The equations are

$$\Delta T(t) = (K_1 + K_2 t)\, e^{-\lambda t}$$

$$\Delta \dot{T}(t) = K_2 e^{-\lambda t} - \lambda (K_1 + K_2 t)\, e^{-\lambda t}$$

$$\Delta \ddot{T}(t) = \lambda^2 (K_1 + K_2 t)\, e^{-\lambda t} - 2 \lambda K_2 e^{-\lambda t}$$

so that, at current time t = 0,

$$\Delta T_0 = K_1$$

$$\Delta \dot{T}_0 = K_2 - \lambda K_1$$

$$\Delta \ddot{T}_0 = \lambda^2 K_1 - 2 \lambda K_2$$

Therefore, since the US Naval Observatory supplies ΔT and $\Delta \dot{T}$ (GPS - UTC offset and rate), we may compute

$$K_1 = \Delta T_0$$

$$K_2 = \lambda K_1 + \Delta \dot{T}_0$$

and apply

$$\Delta \ddot{T} \equiv \ddot{\phi} = \lambda^2 K_1 - 2 \lambda K_2 ,$$

which is the steering rate, that is, the frequency offset to be applied each day, as in Castro's method.

Figure 8 shows what the effect would have been if the damped oscillator algorithm had been applied during the crucial events of this past year. For the computer simulations illustrated here, the value of λ was chosen to give an exponential decay time of 20 days. The results seem quite satisfactory. The maximum steering rate $\Delta \ddot{T}$

never exceeds one part in 10^{13} per day (= 8.64 nanoseconds/day^2). The exponential decay is sufficiently gradual that neither the US Naval Observatory nor system users will be affected. Above all, the damped oscillator algorithm prevents oversteering, and so minimizes an important source of user error Thus, it preserves the best Features of Methods I and II.

CONCLUSIONS:

The mathematics of GPS time steering are straightforward. To put the mathematics into practice should be equally straightforward, now that the IBM 3033 is available at the Vandenberg Master Control Station. We expect that software embodying the principles presented here will be implemented in the coming year.

References

1) Interface Control Document GPS 202, "Navstar GPS Control Segment/ US Naval Observatory Time Transfer Interfaces", Section 3.2.1.2.1.2, preliminary draft 12 April 1982.

2) Fran Varnum, Memo for Record to OAO and IBM/V, 3 November 1982.

3) Gernot Winkler, private communication, 7 October 1983.

4) R. Castro, OAO Corporation Memorandum, 5 October 1983.

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FIGURE 1

Navstar Program Evolution

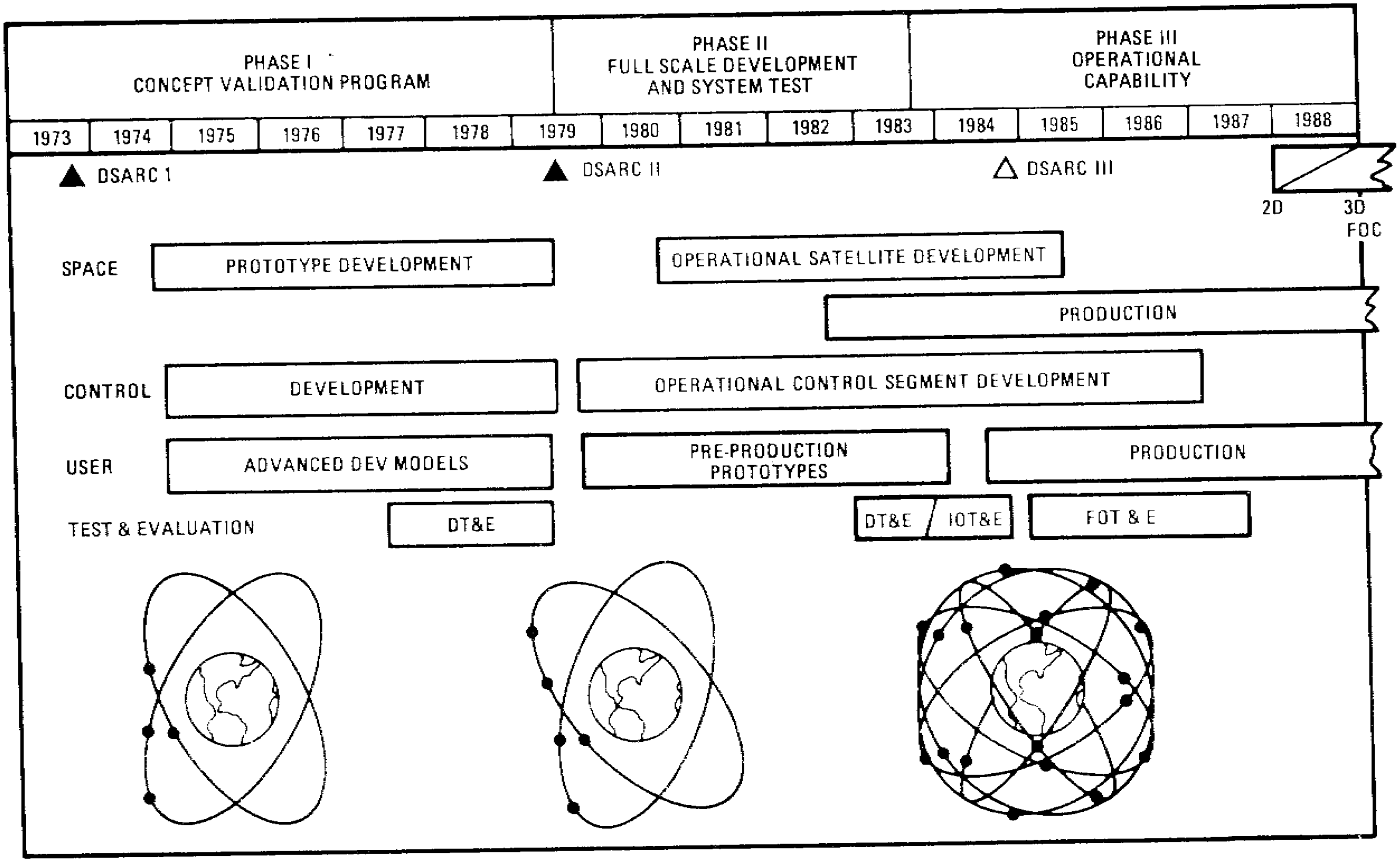

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FIGURE 2

GPS-UTC

AS LOGGED AT THE GPS MASTER CONTROL STATION

(EARLY 1983)

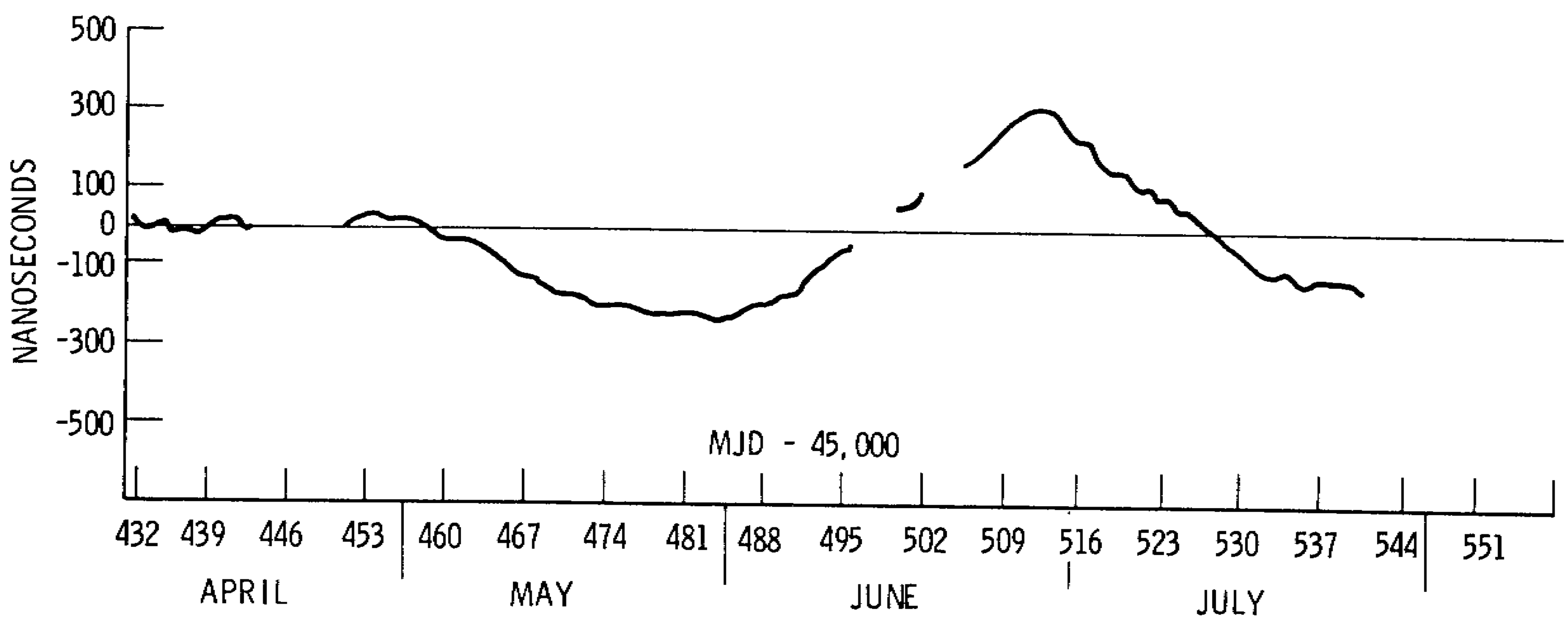
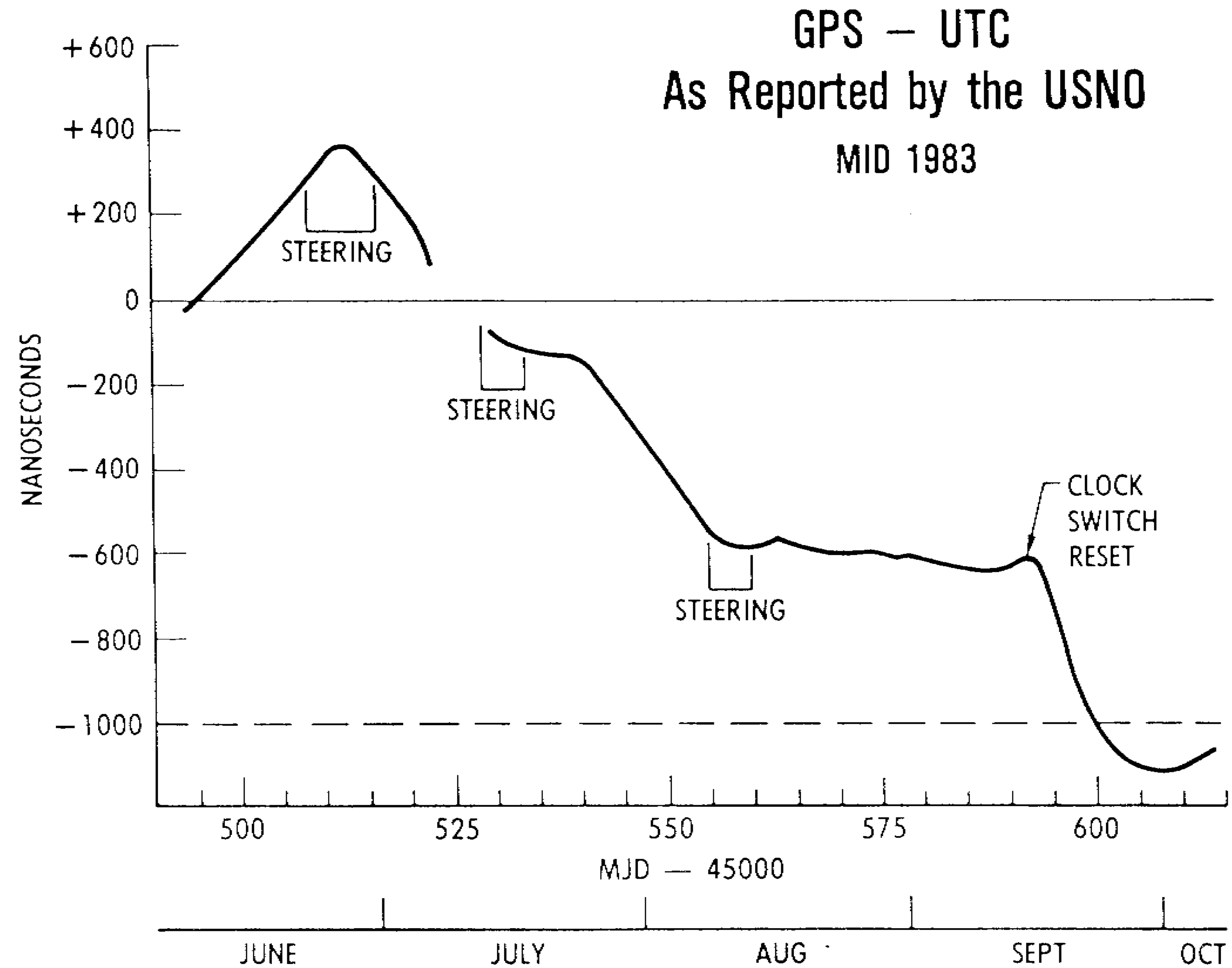


FIGURE 3



GPS — UTC
As Reported by the USNO
MID 1983
NANOSECONDS
+600
+400
+200
0
−200
−400
−600
−800
−1000
STEERING
STEERING
STEERING
CLOCK SWITCH RESET
500
525
550
575
600
MJD — 45000
JUNE
JULY
AUG
SEPT
OCT

FIGURE 4

GPS Steering Methods (I)

THE FOURFOLD WAY

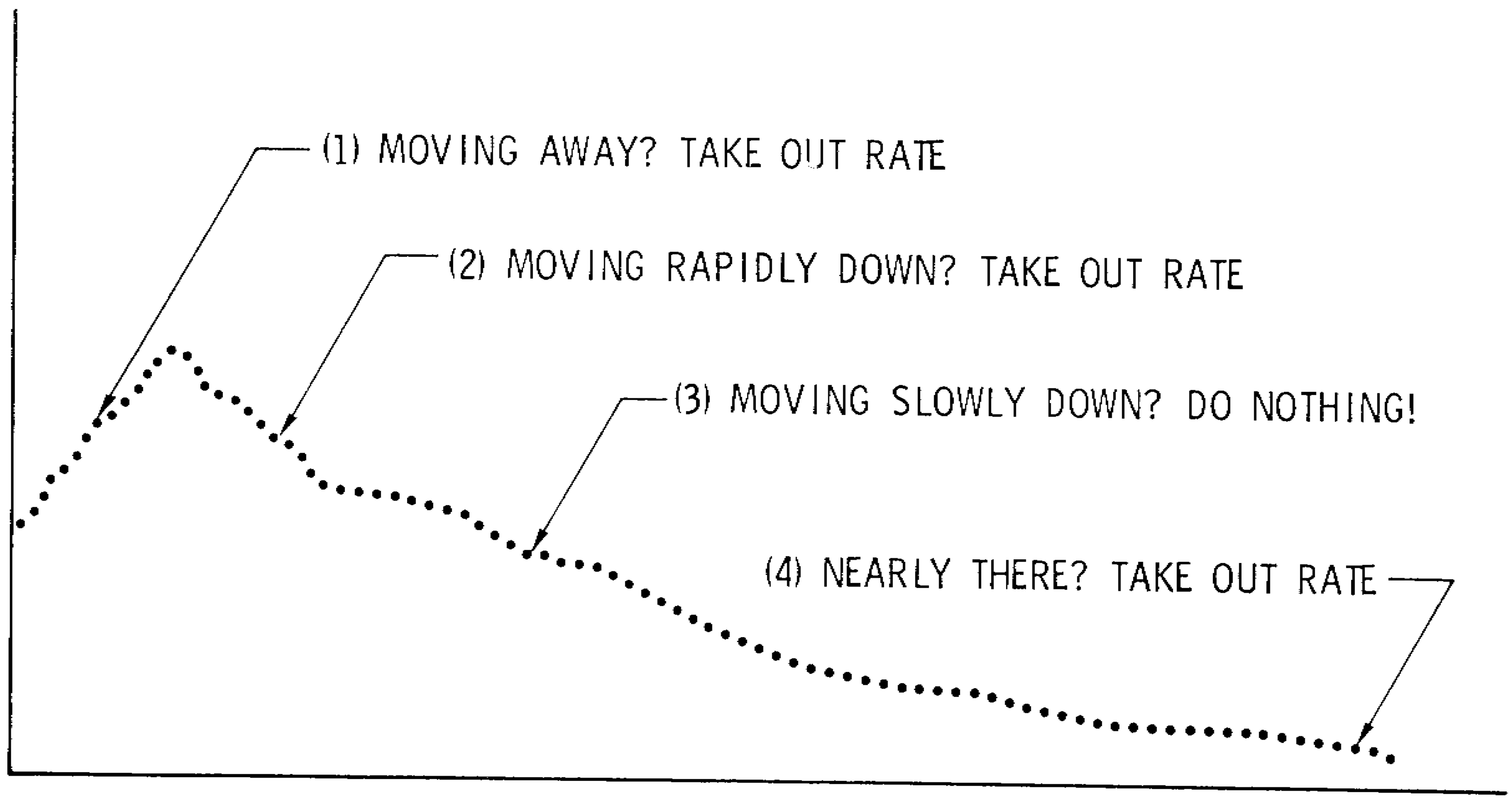


FIGURE 5

GPS Steering Methods (II)

THE PARABOLIC METHOD

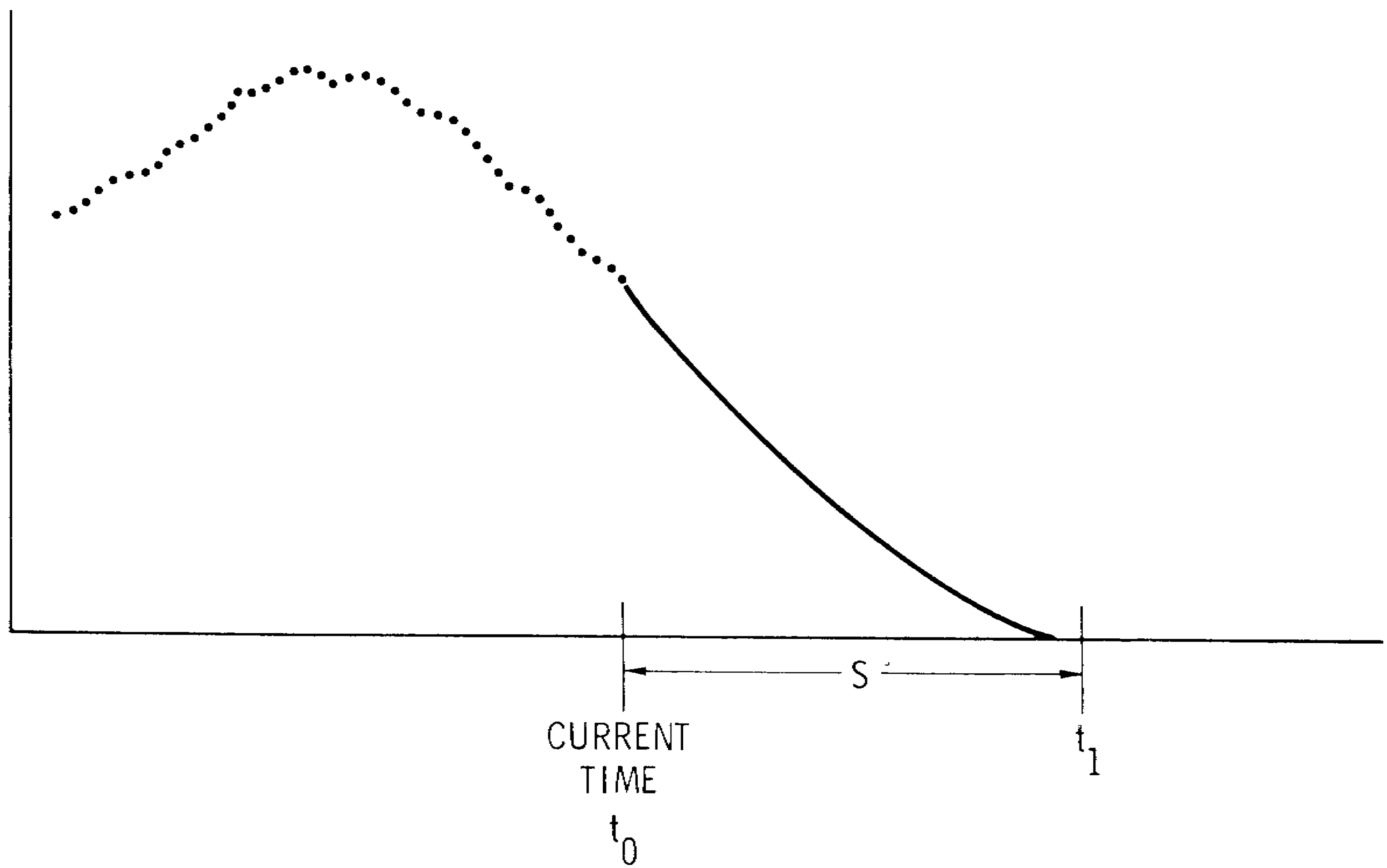
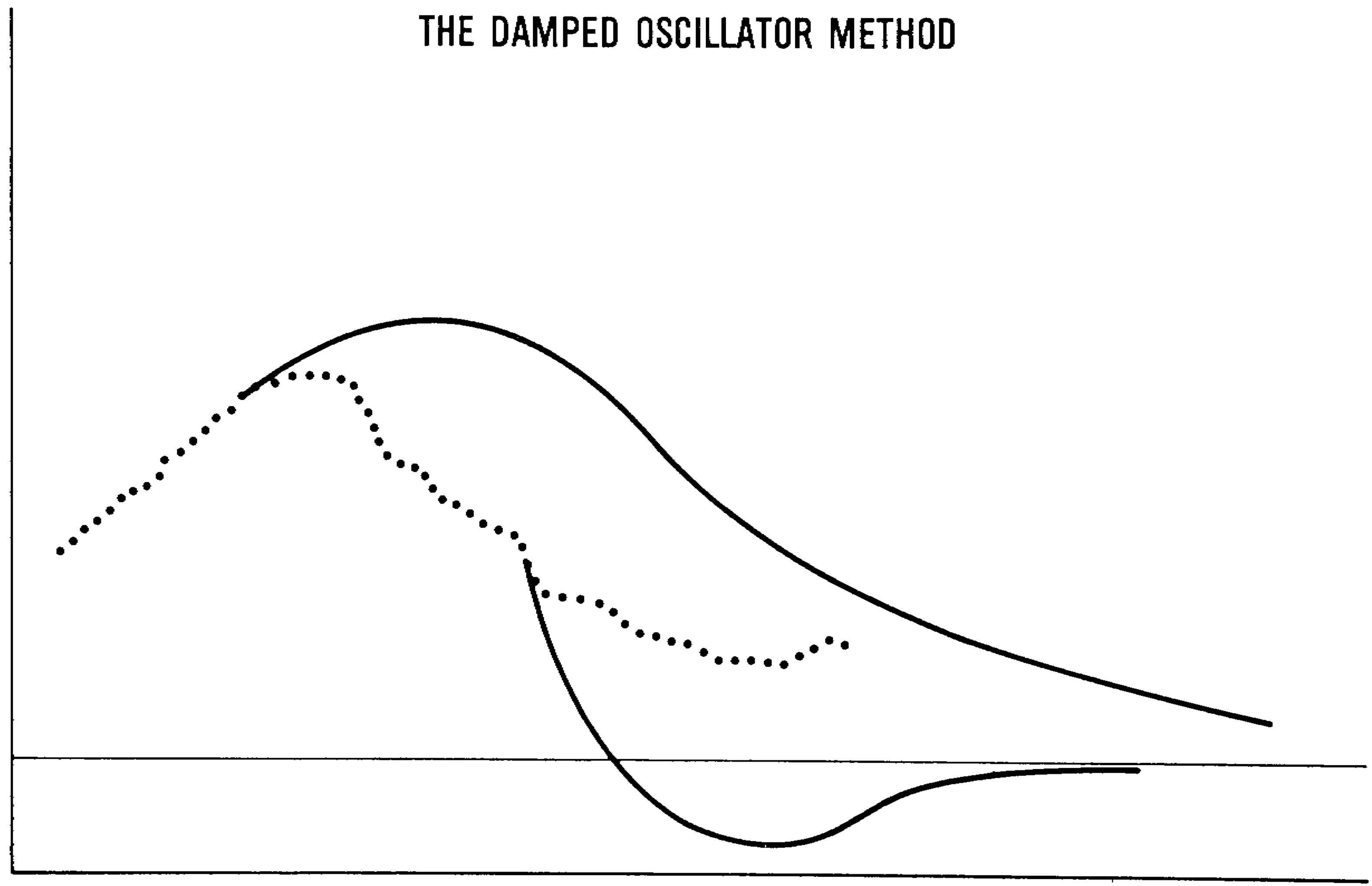


FIGURE 6

GPS Steering Methods (III)

THE DAMPED OSCILLATOR METHOD



Critically Damped Oscillator

$$y = (K_1 + K_2 t)\, e^{-\lambda t}$$

$K_2 > 0$:

$K_2 = 0$:

$K_2 < 0$:

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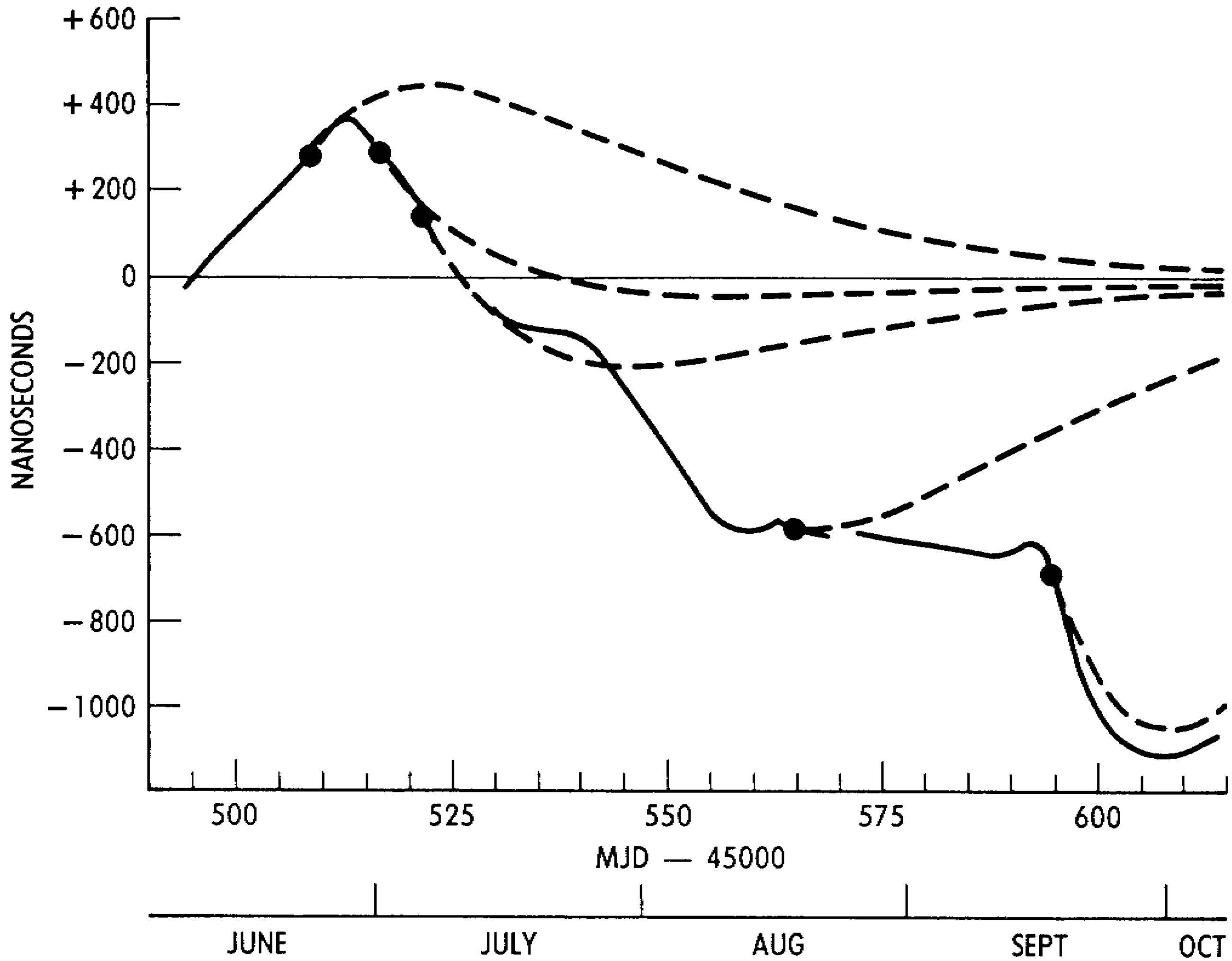
FIGURE 8

GPS — UTC Damped Oscillator Algorithm



QUESTIONS AND ANSWERS

MR. McCALLUM:

How does one decide between frequency steering and making steps, like leap seconds, or as we do in the navigation system, adding small increments 20 nanoseconds or whatever to the system? How do you decide bwtween these two strategies?

DR. FLIEGEL:

Well, the steps are verboten according to agreement, the software that has been delivered to the enhanced I.C.S. which we are using now does not permit the phase to change discontinually, that would be harmful to many users, but you can put in a step in frequency, and that is the technique that has been used up 'til now.

PROF. ALLEY:

Can you remind us please of physically how you are changing the frequency? Is it a magnetic field adjustment or are you doing it some digital electronic way?

DR. FLIEGEL:

I was afraid somebody would ask me that, because I really do not know. It is done on the GPS master clock. Somebody here may know, but I do not know physically how that adjustment is made?

DR. REINHARDT:

Gernot do you know?

DR. WINKLER:

It is simply done by instructing the computer to assume a different frequency of the dirving reference clock so it is a pure paper affair and it is reflected in the different messages which are uploaded into the satellites. There is really no one pulse per second reference tick available at the master station and it is a very complicated thing to make a time comparison directly. But, since I have the microphone, I cannot resist to make another comment. That is, the problem of steering as such would be quite simple, but you have to compare the situation with a bus which is driving over an icy road, and the problem is how do you instruct a committee how to steer that bus without falling off the road. There are two approaches to it, and one is to give it some simple rules the other one is replace the driver with a microprocessor and program it so that you have some reasonable slopes with which you can keep within the confines of the road. But the problem is really more with the committee rather than the roads.