

## ARCHITECTURE AND PERFORMANCE OF A NEW GPS TIME TRANSFER AND POSITIONING RECEIVER

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### ABSTRACT

This paper describes the Interstate Electronics 4200 GPS Receiver System that has been developed for time transfer and low dynamic positioning applications. The receiver employs the NAVSTAR Global Positioning System (GPS) L<sub>1</sub> C/A-code and has three optional solution modes for the clock/navigation state estimation:

- A time transfer-only mode while tracking at least one satellite, with a solution set containing user-clock and oscillator-bias states. Typically this mode can be used for about 12 hours per day with the current NAVSTAR GPS satellite constellation.
- A two-dimensional (2-D) navigation-plus-time transfer mode, with a solution set containing clock and oscillator bias, plus user latitude and longitude states. This mode is operable on three satellites simultaneously, which makes it usable for about 4 hours per day with the current GPS constellation.
- A three-dimensional (3-D) navigation-plus-time transfer mode, with a solution set as for 2-D except for the addition of an altitude state, making it usable for about 2 hours per day at present.

The system consists of a separate preamplifier/antenna and processing unit (5-1/4 inches high by 17-1/4 inches wide by 24 inches deep). The processor has the following four circuitboard assemblies: (1) an RF converter that converts the preamplifier output to baseband for digitizing; (2) a digital signal processor containing a digital correlator, numerically controlled oscillators, and a code generator; (3) a tracking controller equipped with a user clock, digital phase-stepper that fully synchronizes the 1-pps output signal to the nanosecond level, and a microprocessor that operates in conjunction with the signal processor to close the tracking loops; and (4) a data processor for executive control, input/output management, and clock/navigation state estimation.

The processing unit can optionally use either an external frequency reference or its own crystal oscillator. The control/display unit, which is built into the processor's front panel, has a four-line, 40-character liquid crystal display and a 4X4 keypad for mode control and data input. Standard computer interfaces are included.

The paper also summarizes the results of system performance in terms of both single- and multiple-satellite operation.

## INTRODUCTION

The Interstate 4200 GPS receiver has been designed for time transfer, 2-D positioning, and 3-D positioning. The time transfer function is handled in a manner that is completely compatible with the time transfer community. A fully synchronized 1-pps output is supplied. The receiver can handle positioning applications in either an absolute- or relative-navigation mode. It can also be used at either fixed or mobile sites.

The receiver operates on the GPS  $L_1$  C/A-code via a single-channel, sequential multiplex. A broadband RF converter converts the GPS signals to baseband, where they are digitized before being processed in a digital signal processor.

The receiver design capitalizes on the latest advances in electronic technology. Two advanced 16-bit microprocessors with 32-bit internal arithmetic are used: one for the carrier and code tracking loop filters, and the other for the clock and navigation state estimation software.

The system's state estimation filter is a five-state U-D factorized<sup>1</sup> Kalman-filter formulation with a state vector consisting of clock bias, oscillator bias, latitude, longitude, and altitude. For time transfer, only the first one or two clock states are estimated. The two clock states with latitude and longitude are estimated for 2-D positioning and time transfer; all five states are estimated for 3-D positioning and time transfer.

The receiver thus permits maximum use of satellites now orbiting in the Navstar constellation. At fixed sites, time transfers with the system can be realized for about 12 hours per day in most areas, by using only one satellite. This makes time transfer an immediately feasible application. On mobile sites — particularly ships — time transfer and 2-D positioning can be achieved with three satellites during about 4 hours per day. With four satellites, a redundant solution in the 2-D mode yields improved accuracy. The 2-D GPS solution, it has been shown,<sup>2</sup> always yields a more accurate horizontal solution, when altitude is known precisely, than does the 3-D solution for the same number of satellites. The 3-D positioning mode now can be used for about 2 hours per day in most areas, either for precise receiver location in time transfer or for applications where specifically a 3-D position solution is needed.

These combined time transfer/positioning features make the compact receiver especially suitable for fixed instrumentation systems; portable, van-based tracking systems; and shipboard navigation systems.

#### OVERALL CHARACTERISTICS

Figure 1 shows the 4200 receiver system. Its major characteristics are summarized in table 1.

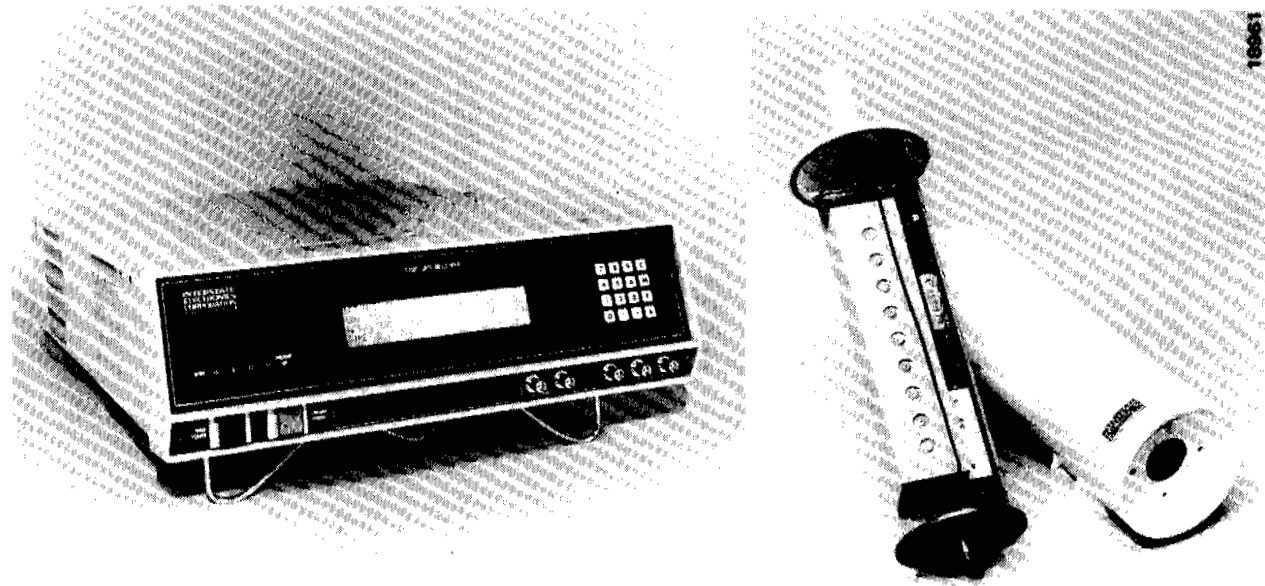


Fig. 1—GPS receiver with antenna/preamplifier

#### Mounting and Access

The antenna/preamplifier assembly may be mounted either on a tripod or fixed mast with no additional ground plane structure at a distance of up to 200 feet from the receiver. The receiver itself either can be rack- or bench-mounted. The major processing modules can be reached or removed through the front panel, which hinges up and locks in place. The power supplies, reference oscillator, and line filter can be accessed simply by removing the top cover. Reference inputs and signal outputs are accessible on both the front and rear panels.

Table 1—4200 GPS receiver system characteristics

Antenna	
<ul style="list-style-type: none"> <li>● Polarization</li> <li>● Gain</li> </ul>	Righthand circular 0 dB at 5-deg elevation 5 dB at 90-deg elevation
Preamplifier	
<ul style="list-style-type: none"> <li>● Gain</li> <li>● Noise Figure</li> <li>● Bandwidth</li> <li>● Size</li> </ul>	42 dB 3.2 dB, typical 36 MHz 16 in. L, 4.75 in. dia
Receiver	
<ul style="list-style-type: none"> <li>● Input                             <ul style="list-style-type: none"> <li>● RF</li> <li>● Reference</li> <li>● Sync (Optional)</li> <li>● Power</li> </ul> </li> <li>● Output                             <ul style="list-style-type: none"> <li>● Time</li> <li>● Data*</li> </ul> </li> <li>● Size</li> </ul>	1575.42 MHz at 50 ohms; C/A-code at 1.023 Mb/s 5 MHz at 50 ohms 1 pps at 50 ohms  115-230 VAC, 50-60 Hz  1 pps synchronized to GPS/UTC time 5.115 MHz synchronized to 5-MHz reference  Latitude (deg, min., sec, tenths of sec); longitude (deg, min., sec, tenths of sec); altitude (m); time of Day (hr, min., sec); clock error (nsec); oscillator error (fractional); Kalman measurement residuals: <ul style="list-style-type: none"> <li>● Range (m)</li> <li>● Range rate (m/sec)</li> </ul> Satellite view times  5.25 in. H, 17.25 in. W, 24.00 in. D (rack-mounting option)
*Available on liquid crystal display, RS-232 serial I/O, and IEEE 488 parallel I/O (optional)	

## Power

The unit requires only primary AC power for basic operation. Conversion between 60 Hz/115 VAC and 50 Hz/230 VAC operation can be accomplished by changing a few jumper wires, but without changing any component. The main circuit breaker (mounted on the rear panel) applies standby power to the reference oscillator and enables the operate power switch (located on the front panel). This switch supplies operating voltages to all unit components and can be interlocked via the control keypad to preclude any unintentional power shutdown.

## Display/Keypad

Since the system is all-digital except for the RF converter, no manual adjustment is necessary. All control and data entries are made through the 16-element keypad. These entries are prompted and echoed on the display unit, a four-line by 40-character liquid crystal device.

## Expansion Capability

Although the unit is fully operational in its self-contained state, the data and control bus may be extended to an external unit to expand its processing capability, as shown in figure 2. The unit bus is based on the Motorola VERSAbus,\* which makes it compatible with either a Motorola EXORmacs\* development system or a single-board computer such as the VME 68/2.\* Extension to either type of unit permits the user to gain access to raw tracking and data block information in memory. This extended processing capacity may be used to expand the clock/navigation state filter or collect, process, and record data for experimental purposes.

## Outputs

Two RS-232 ports are available for outputs. One port can be converted (optionally) to a GPIB port. These ports are usable to output data to printers or recorders, and they also provide for input/output of differential correction parameters when two 4200 GPS receivers are used for relative navigation or time transfer applications. Additionally the ports accommodate remote control and monitoring in unattended-mode situations.

## HARDWARE

Figure 3 is a block diagram of the system highlighting its modular approach.

The receiver employs digital baseband correlation<sup>3,4</sup> rather than analog IF correlation of the signals with the reference code. The receiver chassis includes four main modules: (1) the RF converter, (2) signal processor, (3) controller, and (4) data processor. Each module is a plug-in unit that is removable through the receiver's hinged front panel.

\**VERSAbus, EXORmacs, and VME 68/2 are trademarks of Motorola, Inc.*

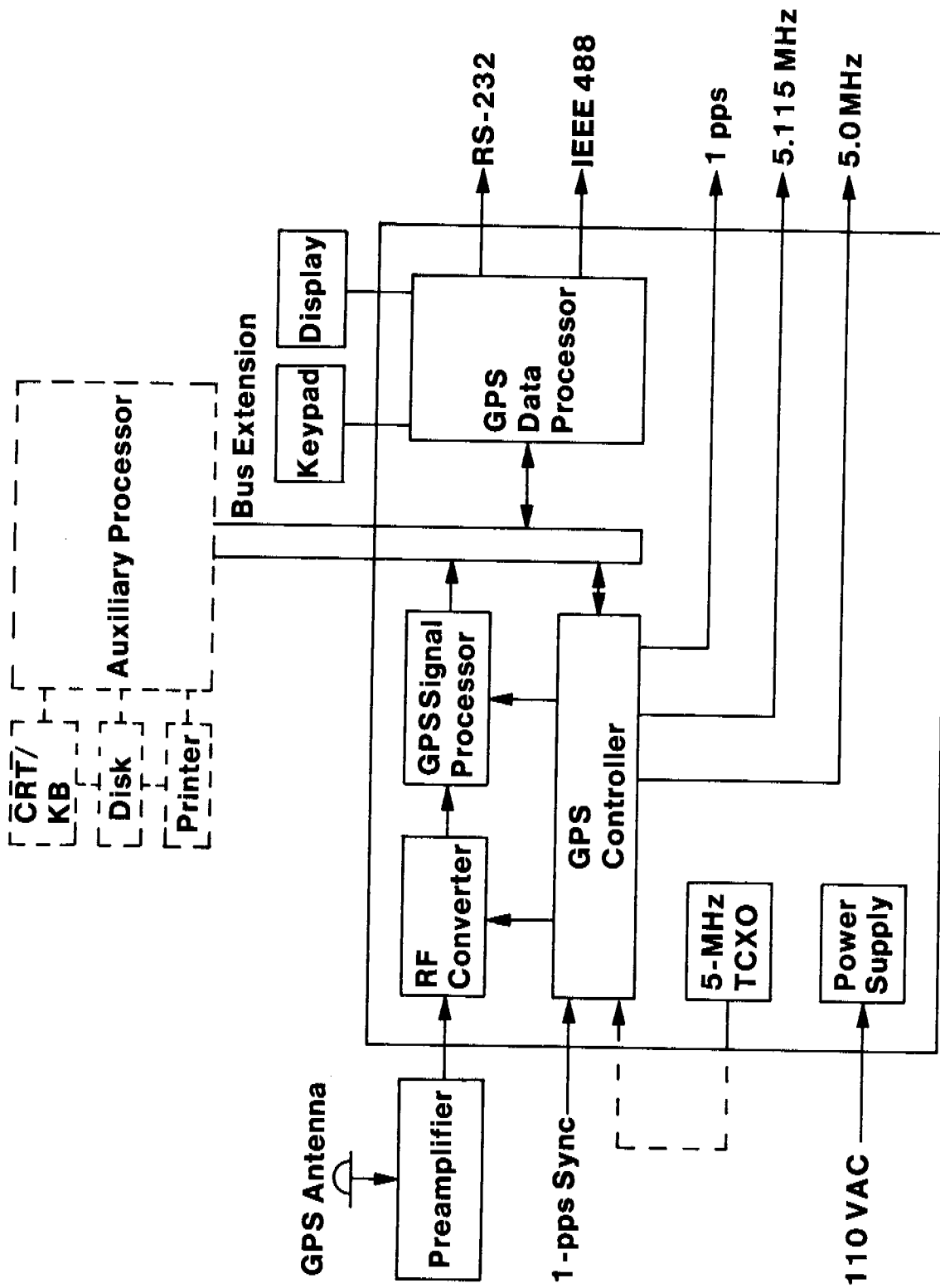


Fig. 2—System architecture

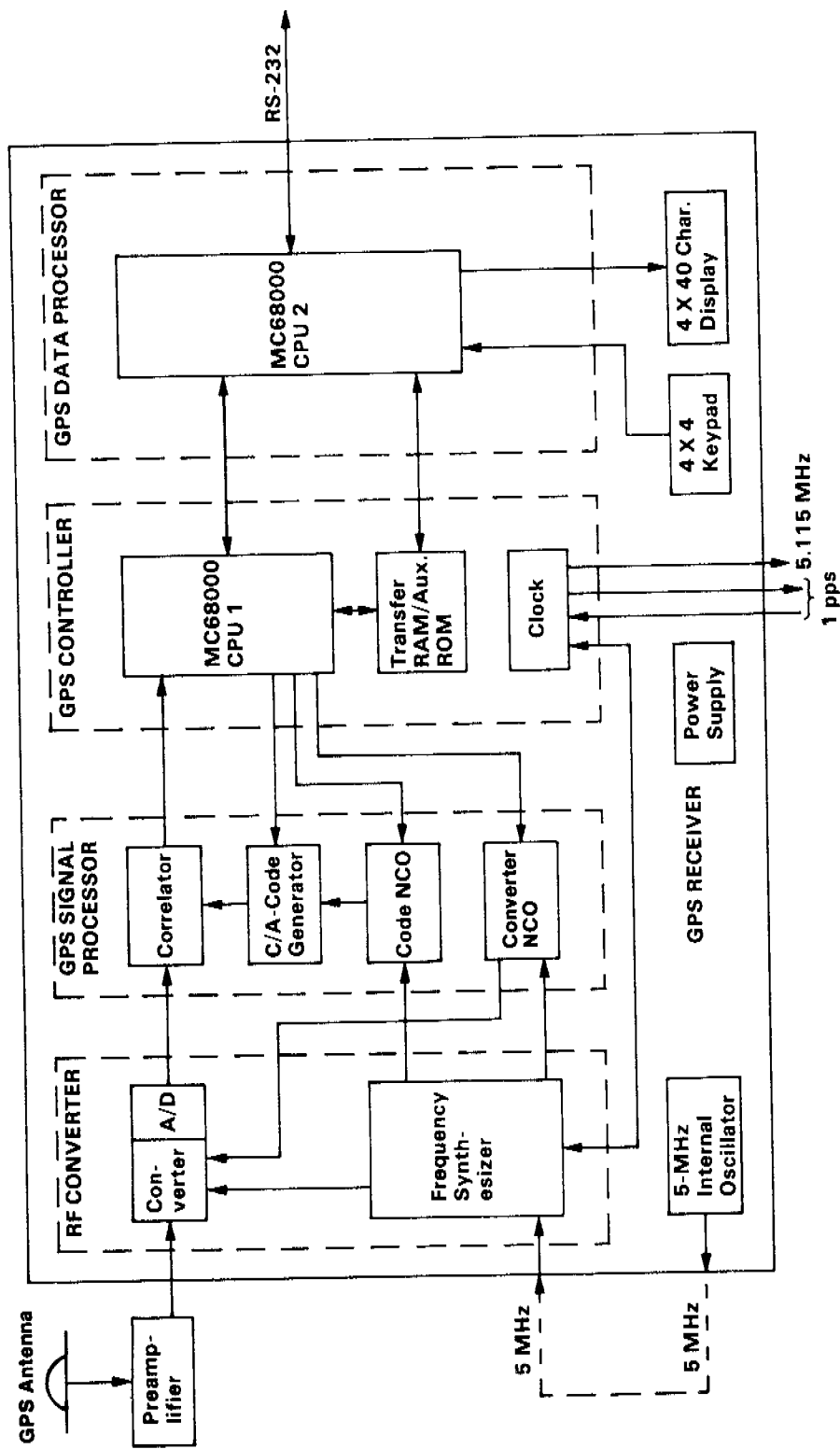


Fig. 3—Block diagram of receiver hardware

### Antenna/Preamplifier

The antenna/preamplifier is a separate unit that is powered through a coaxial cable connecting to the main chassis. Figure 4 shows the configurations of both the antenna/preamplifier and the down converter. This circuitry converts an input 1575.42-MHz GPS signal to baseband in-phase (I) and quadrature (Q) components, which then are digitized to 1-bit words. All subsequent processing is performed digitally.

### RF Converter

The RF converter module includes a frequency synthesizer that synthesizes all signal frequencies received from the 5-MHz internal or external reference. A digitally controlled synthesizer in the module generates a finely controlled, phase-shifted 0.115-MHz signal from the 5-MHz input. In conjunction with this phase-shifted signal, a 5.115-MHz signal is generated that can be shifted in very fine phase steps (1/1000 cycle or about 0.2 nanosecond) under the data processor's control. (See figure 5.) This 5.115-MHz signal is then used to generate all references and clocks for the system, and allows phase control to precisely align the output 1 pps to estimated GPS or UTC time. It also provides the feature, if desired, of correcting frequency offsets in the 5-MHz reference, which would be present in the use of the internal crystal oscillator. In this case the crystal reference oscillator can be corrected up to  $\pm 0.25$  Hz to approximate the corrected satellite oscillator while a satellite is being tracked. The mechanism for supplying digital inputs to the digitally controlled synthesizer is the clock bias state from the Kalman filter. The phase-shifting allows the clock bias state to be driven to zero, which, if continued over a period of time, effectively corrects for the offset of the 5-MHz reference oscillator.

The converter module is constructed with off-the-shelf components and its overall volume is approximately 100 cubic inches. Simplicity of the design also lends itself to production in hybrid form for applications where size and power consumption are critical factors.

### GPS Signal Processor

The GPS signal processor (figure 6) operates on the sampled baseband data from the RF converter to generate the I and Q components of the early, on-time, and late correlation coefficients from which all tracking and data recovery parameters are derived.

In its current configuration, the processor consists of 112 standard integrated circuits on a 126-square-inch (or 9-by-14-inch) circuitboard. Straightforwardness of the baseband digital processing accommodates production of the signal processor in custom gate-array devices to achieve cost-effective, low-power systems.



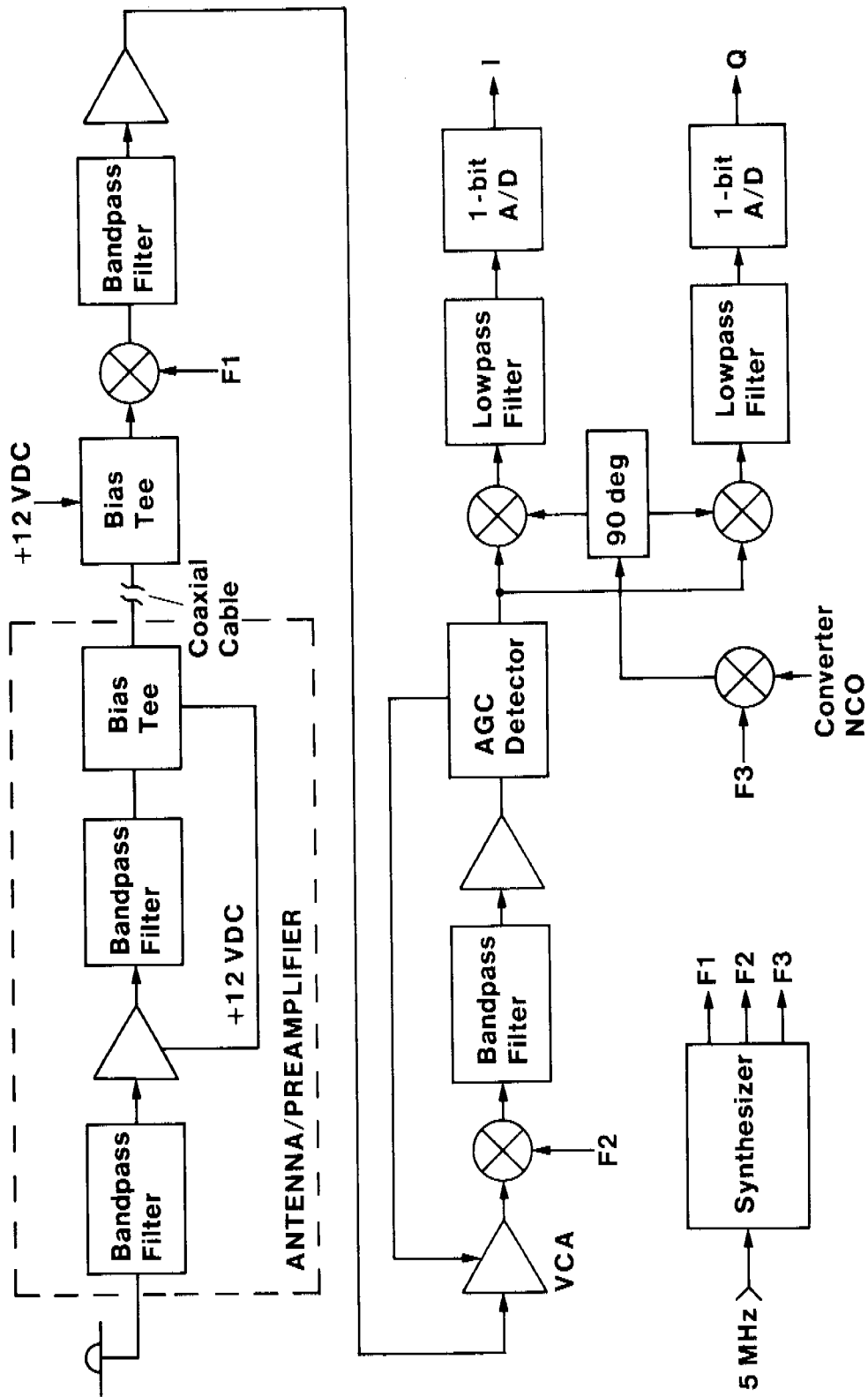
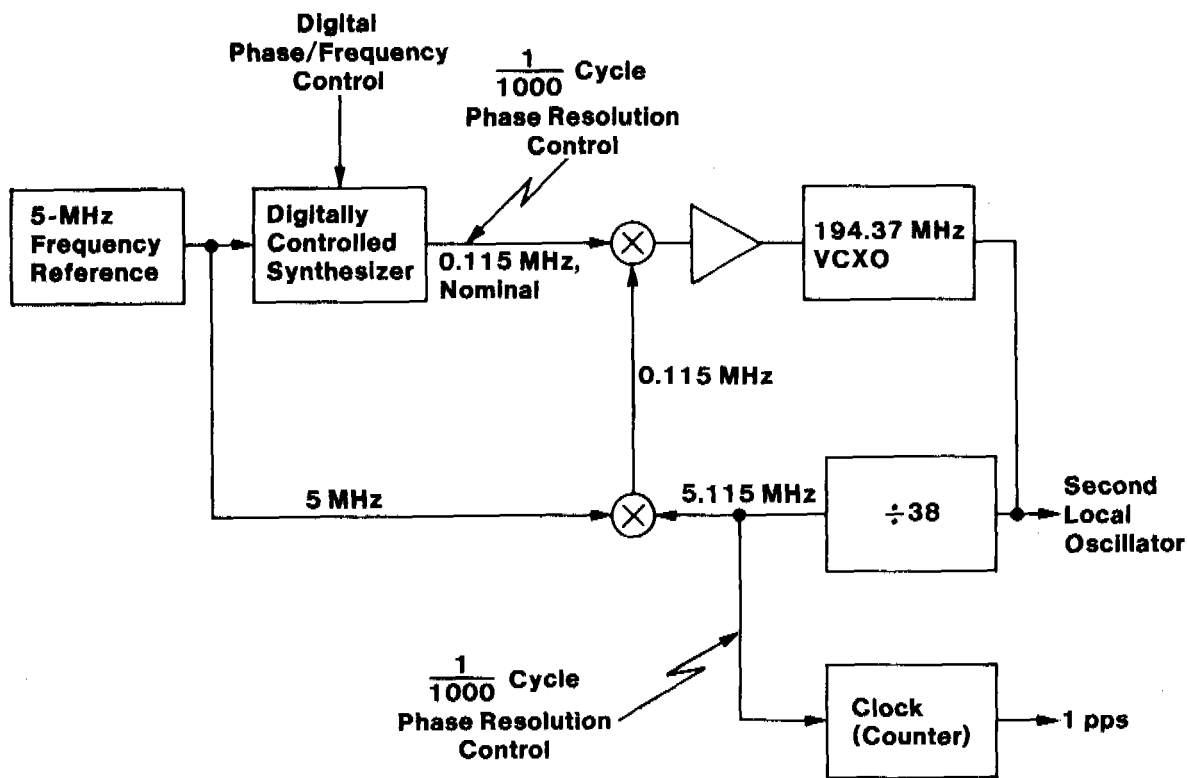
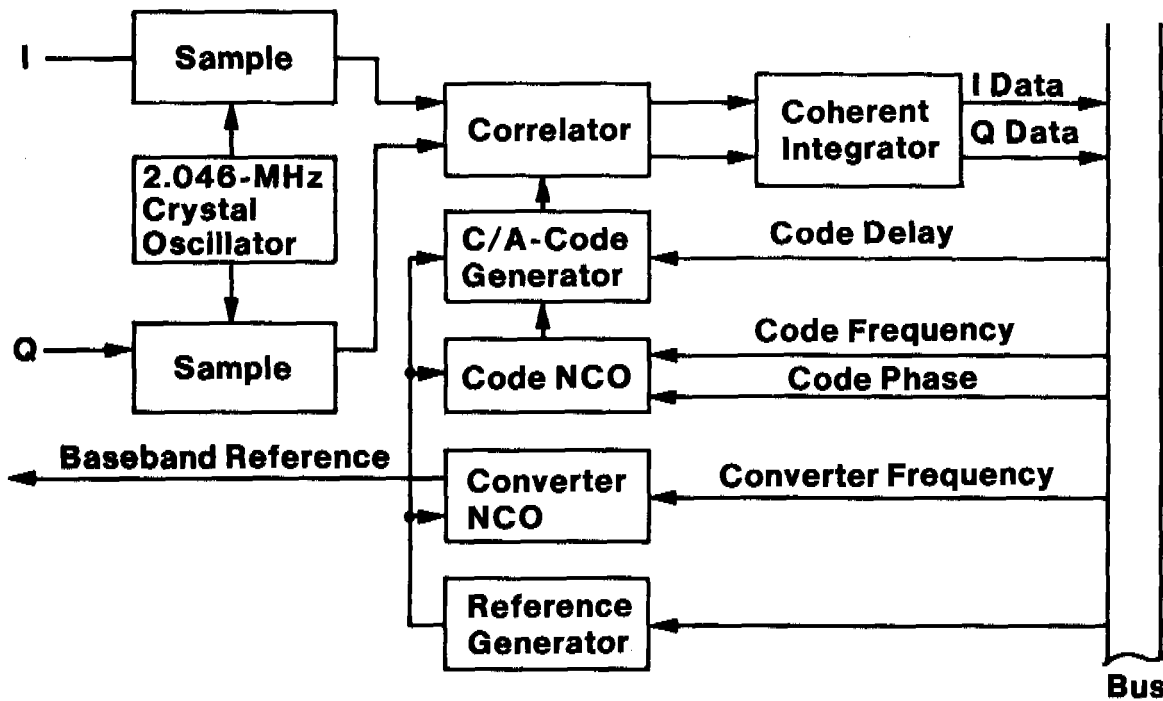


Fig. 4 - Antenna/preamplifier and RF converter



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Fig. 5—Operation of digital phase-shifter



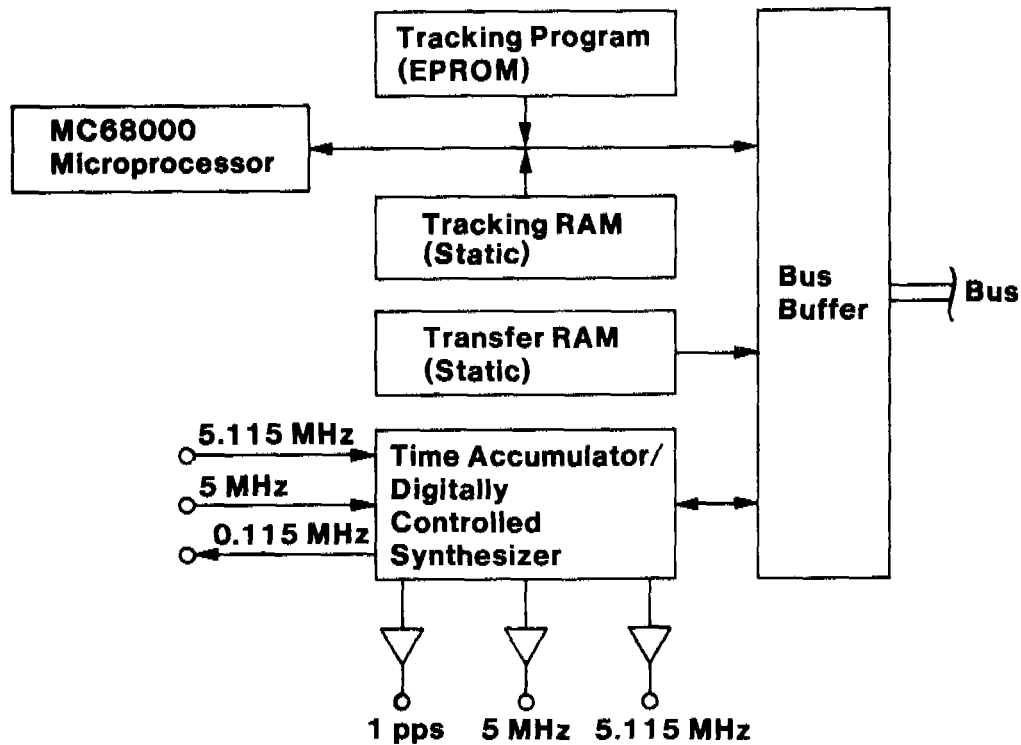
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Fig. 6—GPS signal processor

## GPS Controller

The GPS controller module (figure 7) is a microprocessor-based loop filter for the code and carrier loops. This module also includes a time accumulator and digitally controlled synthesizer. Communications with the GPS data processor module are provided through the transfer RAM.

Firmware for the controller module is written in MC68000 assembly language. The controller's primary functions are the search algorithms, code-loop and carrier-loop filtering, and decoding of the data block.



18968

Fig. 7—GPS controller

## GPS Data Processor

The GPS data processor (figure 8) is a general-purpose, microprocessor-based computer that performs the system's executive function and executes the clock/navigation software algorithms.

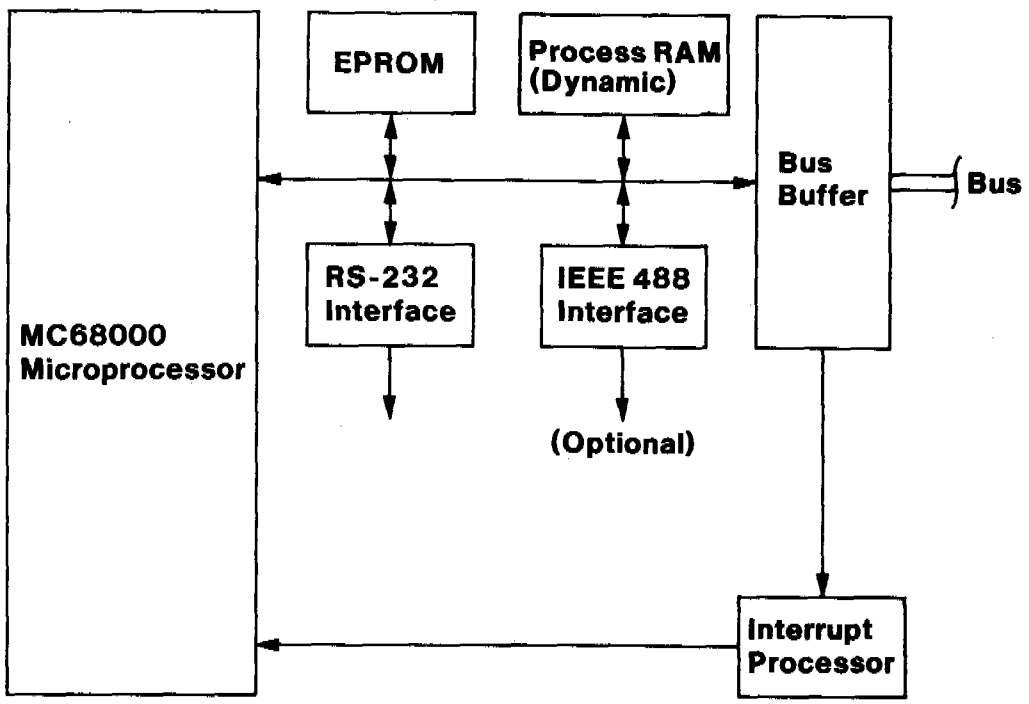


Fig. 8-- GPS data processor

**SOFTWARE DESIGN**

During initial checkout and development of the 4200 GPS Receiver System, the software used was developed on a single MC68000-based microprocessor<sup>4</sup> as a developmental tool for evaluating the receiver system; thus, because this software was initially designed for only one microprocessor, it operates in a serial mode to perform all system software functions and therefore sequences between satellites at the rather slow rate of 10 seconds. New software is being developed at Interstate to capitalize on the use of two microprocessors in the design; this will yield sequencing between satellites at the rate of every few milliseconds.

**Phase Correction Feature**

Figure 9 highlights the overall interaction between the software in the system's two microprocessors and its hardware. Of particular interest in this block diagram is the interaction and control of the digitally controlled synthesizer in the GPS controller module. As noted previously, this synthesizer provides the option of fine phase control on the input 5-MHz signal and also allows optional alignment of the 1-pps signal to corrected time. Under software control, this permits a continuous phase correction to be made which can, in effect, correct for the offset of the reference oscillator. The basis for these corrections is the clock-bias state from the Kalman filter, which is zeroed by this phase correction process.

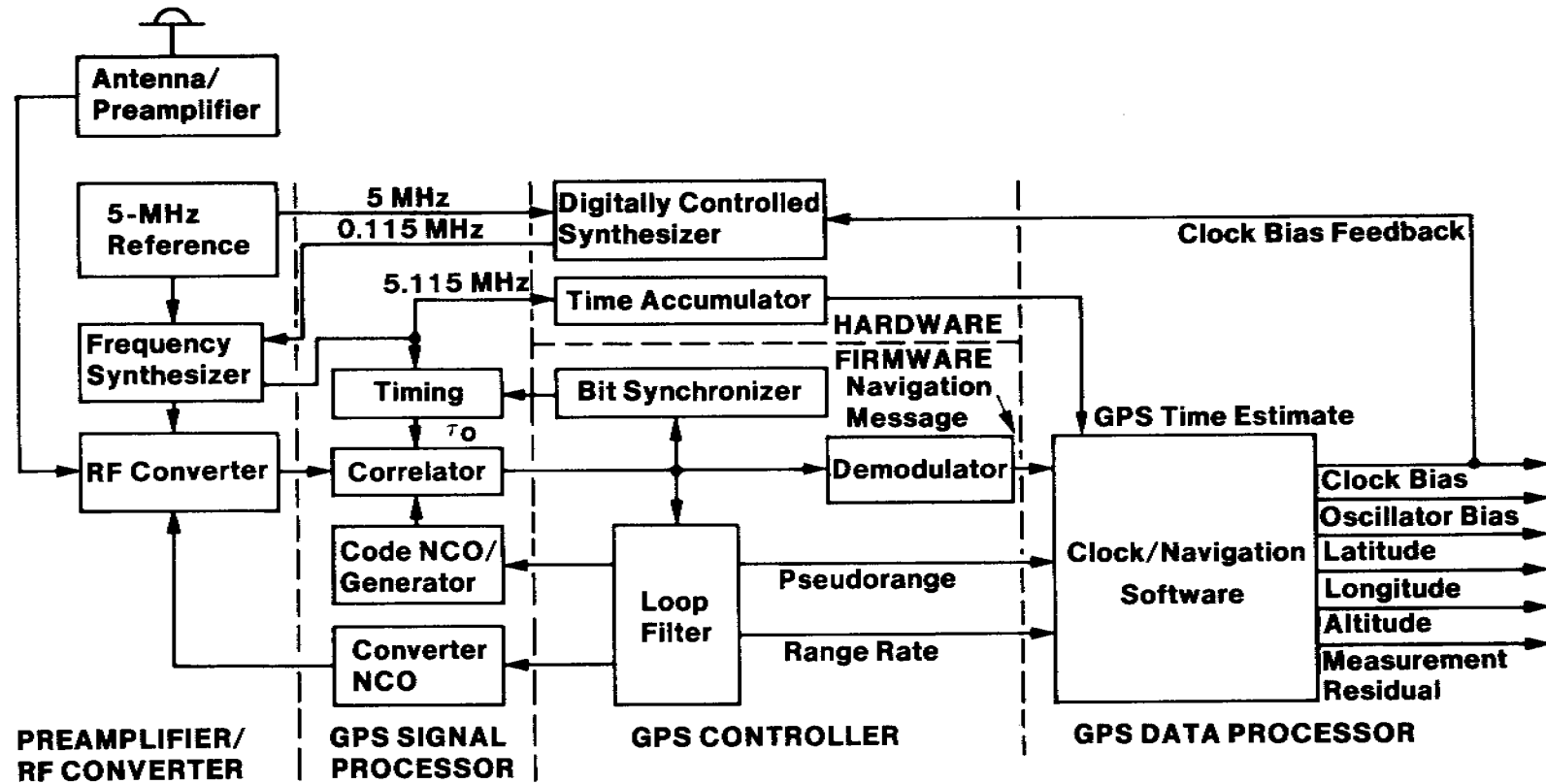


Fig. 9—System functional block diagram

## Clock/Navigation

The clock/navigation software (figure 10) estimates clock and navigation states based on pseudorange and range-rate measurements from up to four satellites. A Kalman filter is employed for state estimation using the Bierman U-D factorized measurement-update algorithm<sup>1</sup> to ensure numerical stability in the filter covariance computation. The filter state vector includes two clock-error states (i.e., clock and oscillator biases) and three position states (geodetic latitude, longitude, and altitude relative to the earth reference ellipsoid).

Basic inputs to the clock/navigation software processor are pseudorange and range-rate measurements, and satellite-navigation-message data blocks. The data block parameters with the GPS orbit and clock correction algorithms<sup>5</sup> are used to compute the satellite orbit and corrections which are applied to pseudorange and range-rate measurements. The corrected measurement set and satellite orbit, computed at the corrected time of signal transmission, are input to the filter.

The clock/navigation state filter operates in discrete time steps and is synchronized with the receiver measurement cycle. The filter states are partitioned to facilitate reduced satellite tracking and optional solution mode (i.e., time transfer, 2-D navigation, or 3-D navigation) processing. In the reduced-state operation, the filter updates only the mode selected states (may be reduced to a single clock-bias state) and retains the keyboard-entered values for the remaining states. The Kalman measurement residuals, which are an indication of filter convergence, are also output and displayed along with the estimated state vector. (The measurement corrections include compensation terms for satellite clock offset, relativistic effects, ionospheric and tropospheric propagation delays, and cable and RF hardware filter delays.)

### TIME TRANSFER OPERATIONAL MODES

Various time transfer modes are available for use with this system. The following list suggests many possibilities:

- Using either the internal crystal oscillator or an external atomic reference, the internal clock may be fully synchronized to GPS or UTC time by the internal digital phase shifter (figure 5). The 1-pps output is then aligned to corrected time.
- The internal clock may be left alone and monitored by the GPS measurements. The clock error can be output on the digital interface, or displayed.
- The internal clock can be driven into synchronization by an externally supplied 1-pps clock. In this case, the 5-MHz reference must also be supplied externally. The external clock can then be monitored, and its error from GPS or UTC time measured and then output on the display or digital interface.

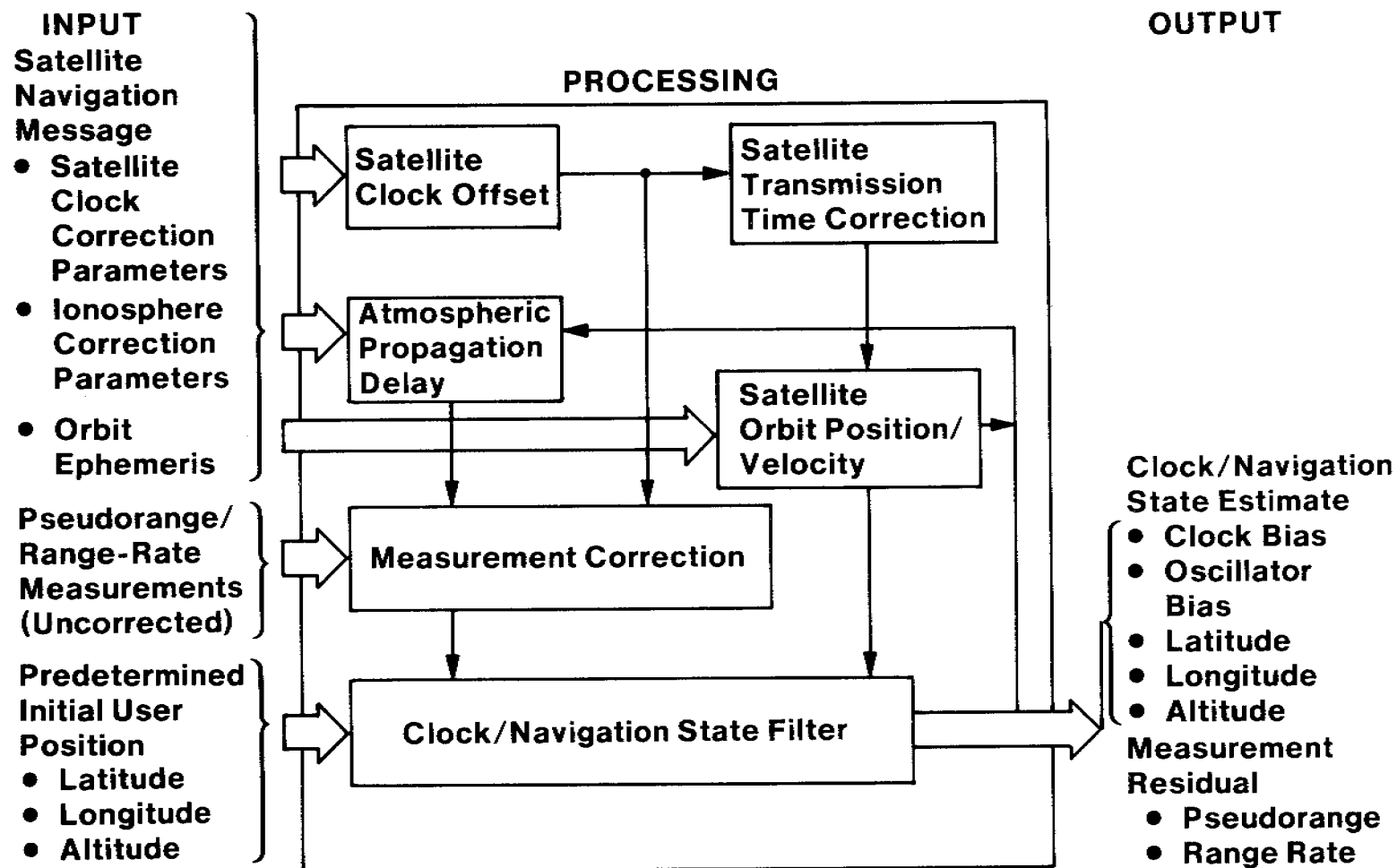


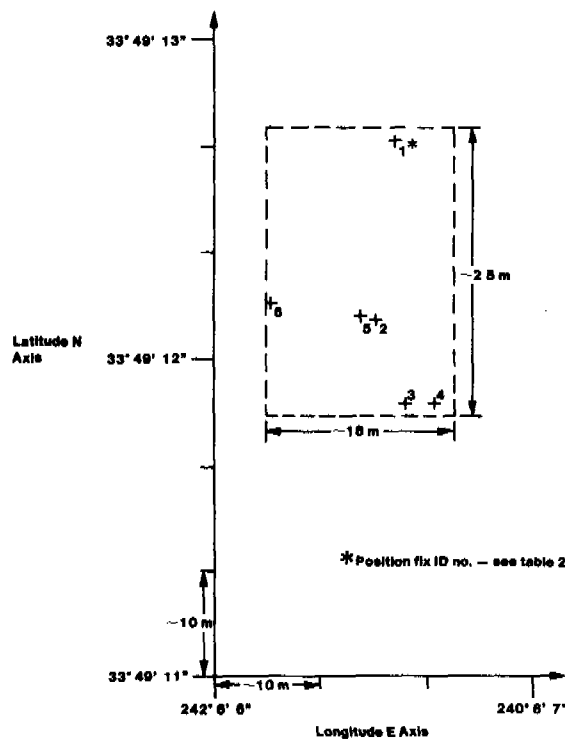
Fig. 10—Clock/navigation software

## SYSTEM PERFORMANCE

A computer-aided analysis of the receiver system's clock/navigation filter was undertaken to determine system performance in the 2-D navigation and time transfer modes, using actual NAVSTAR GPS satellite measurements.

### 2-D Navigation Capability

A number of position fixes (with the receiver antenna's fixed location at Interstate Electronics/Anaheim, California) were derived to verify the system's 2-D positioning capability. Each fix was independent and based on tracking of typically four GPS satellites for a period of less than one hour. The satellite data was processed sequentially, one satellite every 10 seconds. Table 2 summarizes the resulting antenna-location latitudinal and longitudinal state estimates for six independent position fixes, and figure 11 plots the position fix points relative to the latitudinal and longitudinal coordinate axes. The six sample points (identified by ID number in table 2) lie in a rectangular area with dimensions less than 18 by 25 meters; except for two extreme points (ID numbers 1 and 6), the remaining four points fall in a 10-by-10 meter area.



18875

Fig. 11 — 2-D position fix scatter



Table 2—2-D position fix (antenna fixed location) sample results

Position Fix ID	Date (1982)	GMT (hr:min.)	NAVSTAR	2-D Position State Estimate	
				Latitude (N)	Longitude (E)
1	27 Jul.	23:33	1,4,6	33°49'12.63"	242°6'6.55"
2	22 Nov.	14:57	3,4,5,6	33°49'12.09"	242°6'6.49"
3	22 Nov.	16:27	3,4,5,6	33°49'11.83"	242°6'6.58"
4	23 Nov.	15:19	3,4,5,6	33°49'11.84"	242°6'6.67"
5	24 Nov.	14:58	3,4,5,6	33°49'12.10"	242°6'6.45"
6	25 Nov.	15:14	3,4,5,6	33°49'12.13"	242°6'6.17"

### Time Transfer Capability

Time transfer mode outputs were analyzed for cesium-oscillator and crystal-clock-oscillator states. Figures 12 and 13 show the computer-derived time history plots for the filter-estimated cesium-oscillator and clock states respectively.

The cesium oscillator's bias state (figure 12) does not appear to be fully converged, as evidenced by the magnitude level of the estimated oscillator error. In figure 13, the clipping of points (or quantization effect) in the clock bias was caused by the computer routine plotting the clock bias with a large offset and not the result of either the GPS receiver hardware or software.

Figure 14 is a time history plot of the filter-estimated crystal-oscillator bias state. The magnitude level of the filter convergence appears to be consistent with expected crystal oscillator performance.

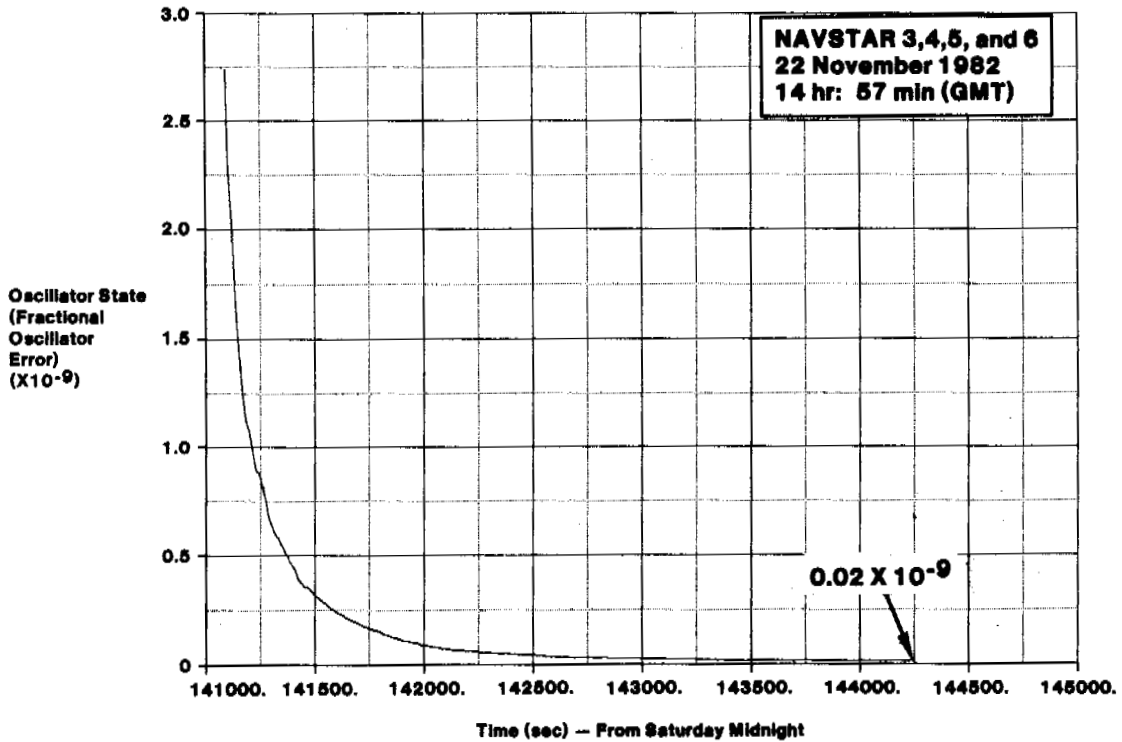
### Future Effort

These preliminary results are based on initial receiver system data acquisition and filter processing. Extensive GPS tracking data collection and analysis of filter data processing are planned for further evaluation of the 4200 receiver system's performance; this future effort will include a variance measure of the system's time transfer stability.

### ACKNOWLEDGMENTS

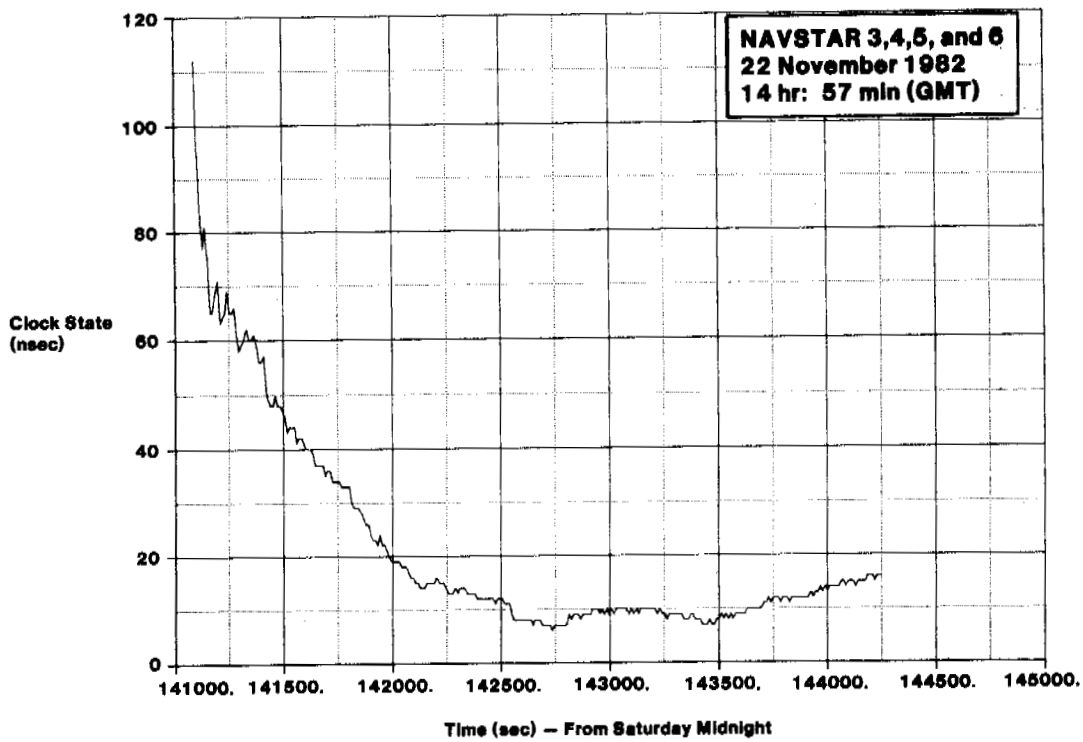
The authors acknowledge the assistance and support of numerous Interstate Electronics personnel and consultants who aided in development of the 4200 GPS Receiver System, particularly Dr. A.J. Mallinckrodt, for consultation on measurement and clock corrections; Dr. G.J. Bierman, for consultation on the U-D factorized measurement-update algorithm; Ms. C. Walls and Mr. E. Benton of Interstate Electronics for firmware and software development; Mr. S. Young of Interstate Electronics for the logic design of the GPS signal processor module and GPS controller module; Mr. J. Soapes of Interstate Electronics for the display/keypad interface as well as overall

hardware unit design; Mr. C. Craig of Interstate Electronics for design of the antenna/preamplifier and RF converter; Mr. A. Kurlovich for design of the frequency synthesizer and final timing-error calibration; Mr. C. Ota for an outstanding job of mechanical design; and last but not least, Messrs. D. Beech, H. Morris, and C. Hoefener of Interstate Electronics for managerial support to the project.



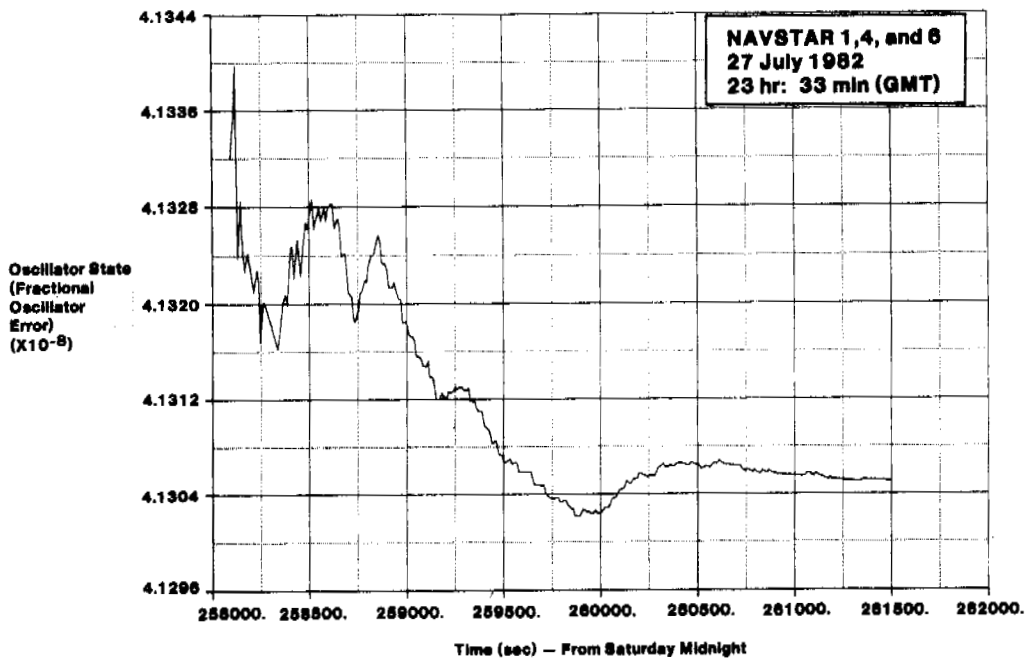
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Fig. 12— Time transfer mode output—cesium-oscillator state estimate



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Fig. 13—Time transfer mode output—clock (w/cesium oscillator) state estimate



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Fig. 14—Time transfer mode output—crystal-oscillator state estimate

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2. R.J. Milliken and W. Kizner, "A Comparison of Two- and Three- Dimensional Navstar Navigation Solutions," IEEE 1978 National Aerospace and Electronics Conference, NAECON 78, Vol. 1, pp. 22-31.
3. P.C. Ould and R.J. Van Wechel, "All-Digital GPS Receiver Mechanization," *Navigation: Journal of The Institute of Navigation*, Vol. 28, No. 3, Fall 1981, pp. 178-188.
4. P.C. Ould and R.J. Van Wechel, "Design Approach for a Microprocessor-Based GPS Time Transfer Receiver," *Proceedings of the Thirteenth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, December 1981, NASA Conference Publication 2220.
5. Space Vehicle Navigation Subsystem and NTS PRN Navigation Assembly/User System Segment and Monitor Station, Rockwell Interface Control Document MH08-00002-400, Revision G, 6 August 1979.

QUESTIONS AND ANSWERS

MR. P. HOYUP, NASA/GSFC

Is this unit available in the market currently?

MR. R. J. VAN WECHEL, Interstate Electronics Corporation

Well, we have built our first prototype and that is what you see there, and it will be available, yes.

MR. HOYUP:

Do you have a schedule for delivery?

MR. VAN WECHEL:

Well, I think it will be 6 to 9 months. It will be by quote out of the plant, and if you're really interested, come and see me but I think it will be in the 6 to 9 month range.

MR. HOYUP:

Thank you.

QUESTION FROM THE AUDIENCE:

What will be a typical price? Can you estimate that?

MR. VAN WECHEL:

Well, I don't know whether I ought to do that at this meeting. I would like to talk to you about it afterwards.

DR. VIG, Army Electronics Technology and Devices Laboratory

Why not this meeting?

MR. VAN WECHEL:

Well, it's really going to be quoted out of the company. There isn't a catalog price on it right now.

DR. VIG:

Do you have a ball park estimate?

MR. VAN WECHEL:

In singles, it will be in the \$70,000 range, as a ball park figure.

MR. D. MCCULLER, Oceanographics

A quick comment on the country coordinates for those of you who are not familiar with it, we weren't. They are done in State coordinates in this country, and those are converted rigorously to North American datum of 1927. This is not the same as WGS-72, which are the satellite coordinates. There are two versions of that, the broadcast the precise ephemeris, from the transit satellite which is your best reference system at the moment. If you make a first-order correction from NAD-27 to the satellite, WGS-72, in our area you are off about 16 meters. If you make no correction in our area you are off about 30 meters, so it isn't surprising to hear that you're off a little bit. That might be encouraging.

MR. VAN WECHEL:

That is encouraging. We were wondering about that.

MR. MCCULLER:

Then in the last step, if you want to get down to the meter level you would have to go to the precise ephemeris, and you need a correction from DMA on that to make that last correction. You can get, within about a week's time you can get a benchmark in your area that is within a meter or two.

MR. VAN WECHEL:

I see.

MR. MCCULLER:

Thank you.