CHAPTER

25 The GPS navigation system

The basic idea of GPS navigation is simple. A GPS receiver simultaneously monitors ("tracks") the signals from four GPS satellites. Using a highly accurate onboard clock, each satellite effectively stamps its signals with the time at which they are transmitted. The receiver has an internal clock and can, therefore, determine the apparent travel time of the signals from each satellite. Let τ_i denote the travel time of the signal from the i-th satellite. The receiver contains a database and can look up the position of the i-th satellite, x_i, y_i, and z_i, corresponding to the time of transmission. Let x, y, and z represent the (unknown) position of the receiver. For each of the four satellites, *distance* = *rate* × *time*, so we can immediately write four equations:

$$\begin{aligned}
(x-x_1)^2+(y-y_1)^2+(z-z_1)^2 &= c^2(\tau_1-\Delta)^2\\
(x-x_2)^2+(y-y_2)^2+(z-z_2)^2 &= c^2(\tau_2-\Delta)^2\\
(x-x_3)^2+(y-y_3)^2+(z-z_3)^2 &= c^2(\tau_3-\Delta)^2\\
(x-x_4)^2+(y-y_4)^2+(z-z_4)^2 &= c^2(\tau_4-\Delta)^2,
\end{aligned} \tag{25.1}$$

where c is the speed of light and Δ is the offset (error) in the receiver's clock (the same error that made determination of longitude a challenge for early navigators). Because there are four equations and four unknowns, a unique solution can be found for x, y, z, and Δ, thus determining both position and time from scratch. (The receiver's clock error does not matter.) While these equations are nonlinear, the ample processing power available, even in hand-held receivers, makes the solution process easy. An obvious method is to begin with an estimated position, e.g., the last determined position, and then linearize and solve Equations (25.1) in the vicinity of this position.

25.1 System description

The GPS system is operated by the U.S. Department of Defense. In 1993 the system began running a full complement of 24 active satellites, with four satellites

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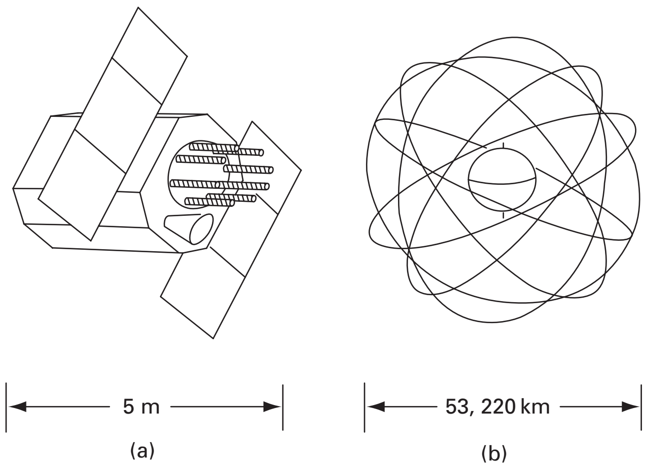


Figure 25.1. (a) Block IIa GPS satellite, 1816 kg; (b) GPS satellite orbits.

in each of six orbital planes, inclined at 55° with respect to the equatorial plane. The satellites were in 12-hour circular Earth-centric orbits, 20 200 km (3.17 Earth radii) above the surface of the Earth as shown in Figure 25.1.

At any point on the Earth, from six to twelve satellites will be above the horizon at any time. As the number of active satellites was increased to 31, the constellation was modified to provide better availability in the event of satellite failures. Orbits are adjusted once a year. The satellites have had operational lifetimes of approximately 10 years.

25.2 GPS broadcast format and time encoding

The system uses two L-band frequencies, 1575.42 MHz ("L1") and 1227.6 MHz ("L2"). Each satellite transmits on both of these frequencies using CDMA (code division multiple access) modulation. The L1 signal contains a "navigation message," described below, which is transmitted repeatedly as a continuous 50-Hz bit stream. Before transmission, this slow bit stream is exclusive-ORed (modulus-2 added) with a one-bit pseudorandom noise (PRN) sequence (the CDMA code) having a high clock rate. This produces a fast bit stream, spread out in bandwidth to approximately the clock rate ("chip" rate) of the PRN code. The L2 signal may also be modulated by the data stream, but is usually modulated only by the PRN code, equivalent to sending a data stream of all 1's. Each satellite is assigned a unique PRN code. In order to receive data from the *i*-th satellite the receiver converts the incoming signal L1 to baseband and multiplies it with a replica of that satellite's PRN code. When the replica, whose binary levels are ±1, is precisely positioned (phased), in order to decode or "strip" the code from the signal, it reproduces the original 50-Hz bit stream, as shown in Figure 25.2.

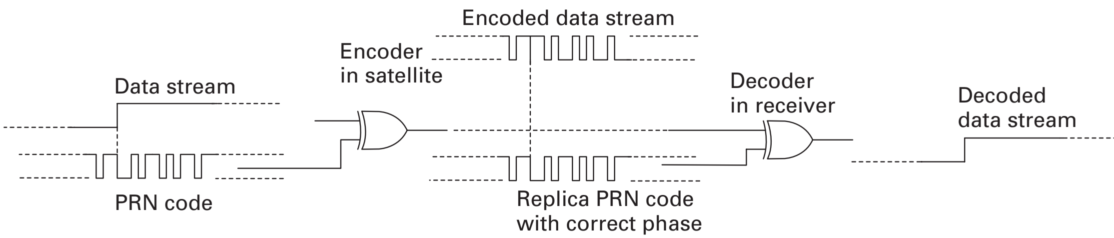


Figure 25.2. CDMA coding (spreading) and decoding (de-spreading).

If the phase of the replica code is shifted off by as little as one chip, the decoder output will be as random and as spread in frequency as its input. This decoding process is the way the receiver selects the desired signal. Signals from other GPS satellites will also be superposed in the received signal, but they have different PRN codes which, when multiplied by the selected code, average to zero for any value of phase shift. Thus, other signals appear as added noise. This added noise is insignificant, in that the received signal is already less than the thermal background noise by some 20–30 dB.[1]

The 50-Hz data streams contain the GPS time,[2] orbital corrections, satellite clock correction, propagation delay effects, and satellite condition, as well as an almanac of long-term satellite data and an auxiliary service, the current difference between GPS time and UTC time. But the precise time of transmission is inferred not from the data but from the phase of the PRN code. We saw in Chapter 21 that just such codes are used for pulse compression in radar to achieve high time resolution (and hence high range resolution) without using narrow high-power pulses. When PRN codes are correlated (convolved) with themselves, a sharp peak is formed, allowing precise time resolution. Thus, PRN coding does double duty in the GPS system; it provides multiple access (many satellites using the same frequency) and it also provides pulse compression for timing accuracy. The *P-code* (*P*recision), a high rate code transmitted on both L1 and L2, has a seven-day period. Therefore, a receiver that has successfully delayed the output of its replica code generator to match the incoming signal, i.e., to acquire the signal, can use that delay value to estimate the signal travel time. The P-code was originally intended only for military use.[3] The other transmitted code is the *C/A-code* (Coarse ranging and Acquisition). This code, always present, along with the P-code, on L1, has a 1.023-MHz chip rate vs. 10.23 MHz for the P-code. It therefore nominally provides only one-tenth the range resolution of the P-code. The C/A code is intended for civilian use; consumer GPS receivers use only the C/A code on L1. The C/A-code repeats every millisecond. This makes acquisition easier, but introduces a

[1] Assuming a receiving antenna with a gain of 3dB, the received power of a GPS signal is -160 dBW(10^{-16} watts).

[2] GPS time increases continuously, unlike Universal Coordinated Time (UTC) which is occasionally adjusted by a leap second. GPS and UTC coincided at the start of Jan. 6, 1980, UTC.

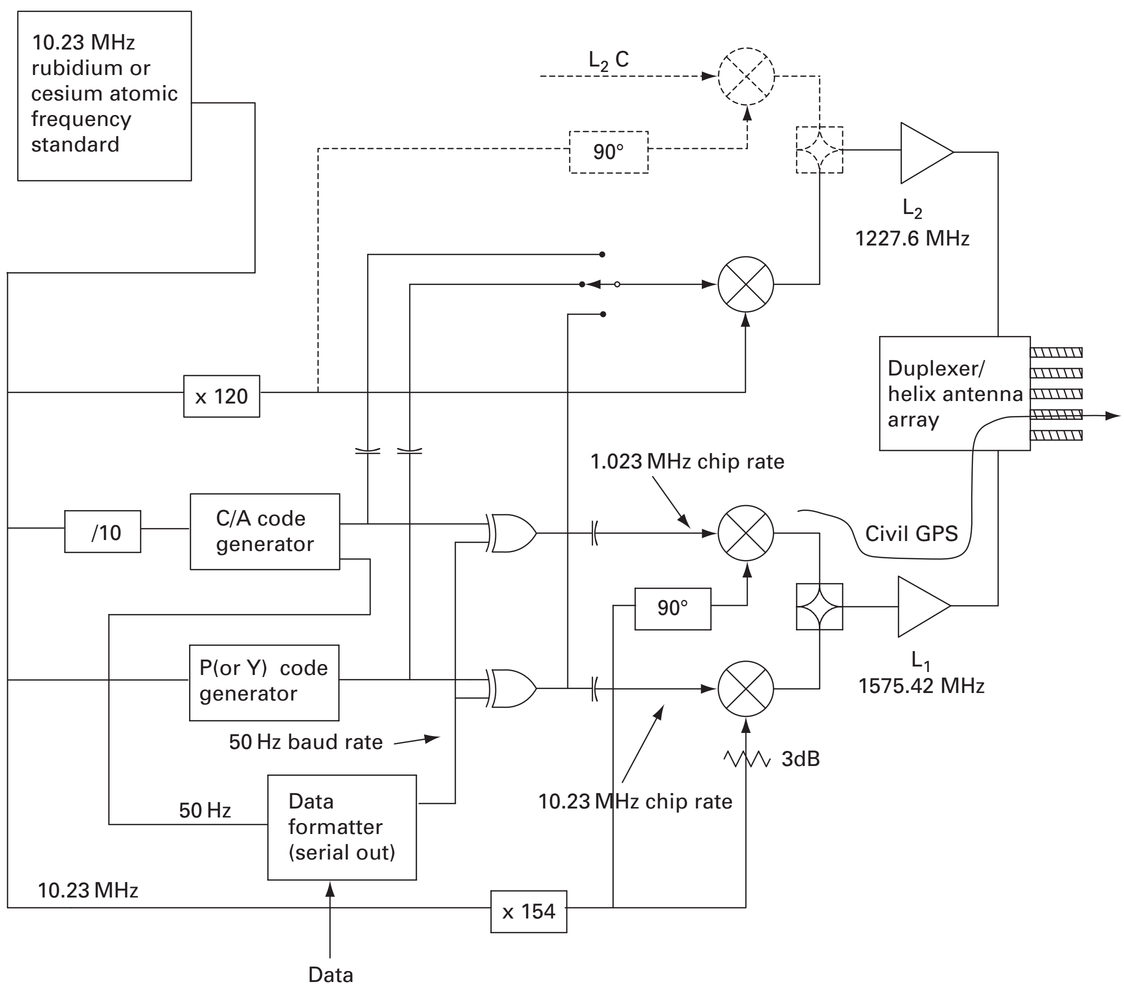
[3] Usually the P-code is referred to as the *P*(*Y*)-code because the published P-code can be replaced by a classified *Y-code* for military security.

1-msec ambiguity in the time, which must be resolved using time information transmitted in the data stream.

25.3 GPS satellite transmitter

Figure 25.3 is a functional block diagram of the transmitter aboard a GPS satellite and shows the signals that modulate L1 and L2. All signals are derived from an onboard 10.23-MHz atomic frequency standard. Newer satellites carry two rubidium and two cesium frequency standards. A data formatter produces the continuous one-bit data stream at a 50-Hz baud rate (20 msec/baud). This stream is exclusive-ORed separately with the C/A code and the P-code to create two-bit streams, with respective (main lobe) bandwidths of 1.023 MHz and

Figure 25.3. GPS satellite transmitter block diagram.



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10.23 MHz. The streams are offset to be symmetric about zero volts (indicated by a coupling capacitor on the diagram) and then multiplied by sine waves at 154×10.23 MHz $=1575.42$ MHz, one shifted 90° with respect to the other. These products are summed to form the L1 signal. The output of each multiplier is a double-sideband suppressed carrier (DSSC) signal. The sum of these two signals, as we have seen, is known as quadrature AM modulation (QAM).[4] The modulating signal fed to each mixer has only two values, $+V$ or $-V$, which determine the polarity of the mixer output, so these mixers can also be called BPSK (binary 0 and 180° phase-shift keying) modulators. The L1 C/A "Civil GPS" signal path is indicated on the diagram.

The original L2 signal is produced by a single mixer, whose signal input can set by the ground control station to be the C/A code, the P-code, or the exclusive-OR of the data and the P-code. Normally the P-code is selected and the L2 signal provides dual-frequency operation for ionospheric delay correction (described below). Newer satellites also provide an "L2C" civil L2 signal, as shown in dotted lines. This signal will provide civil users with dual-frequency capability for high-precision surveying.

25.4 Signal tracking

To see how tracking can be done, we will first consider the case of the L2 signal carrying only the long PRN code and no navigation data. We will then describe the somewhat more complicated case of tracking a signal containing the navigation data, exclusively-ORed with the short C/A code.

25.4.1 Tracking the L2 signal

Figure 25.4 is a block diagram of a hypothetical receiver set up to track this signal. The IF band, which is 20.46 MHz wide to contain the P-coded signal, is established by a bandpass filter which precedes the mixer but follows the low-noise amplifier (LNA), in order that the filter loss not degrade the receiver's noise figure.

Surface acoustic wave (SAW) filters are common in this very small fractional bandwidth application. A 20-MHz lowpass filter (LPF), probably not extending down quite all the way to dc, further defines the bandpass and eliminates the sum frequency component from the mixer. The IF signal is sampled at 41 MHz

[4] QAM is normally used to transmit two independent signals which will be independently recovered. In this case, however, the two signals have been made independent by the coding, so they could be algebraically added, with the sum feeding a single mixer. This would introduce "self noise," but a GPS receiver is dominated by thermal noise, so the system performance would not suffer. The QAM system has the advantage of producing a constant-amplitude signal which does not require a linear power amplifier.

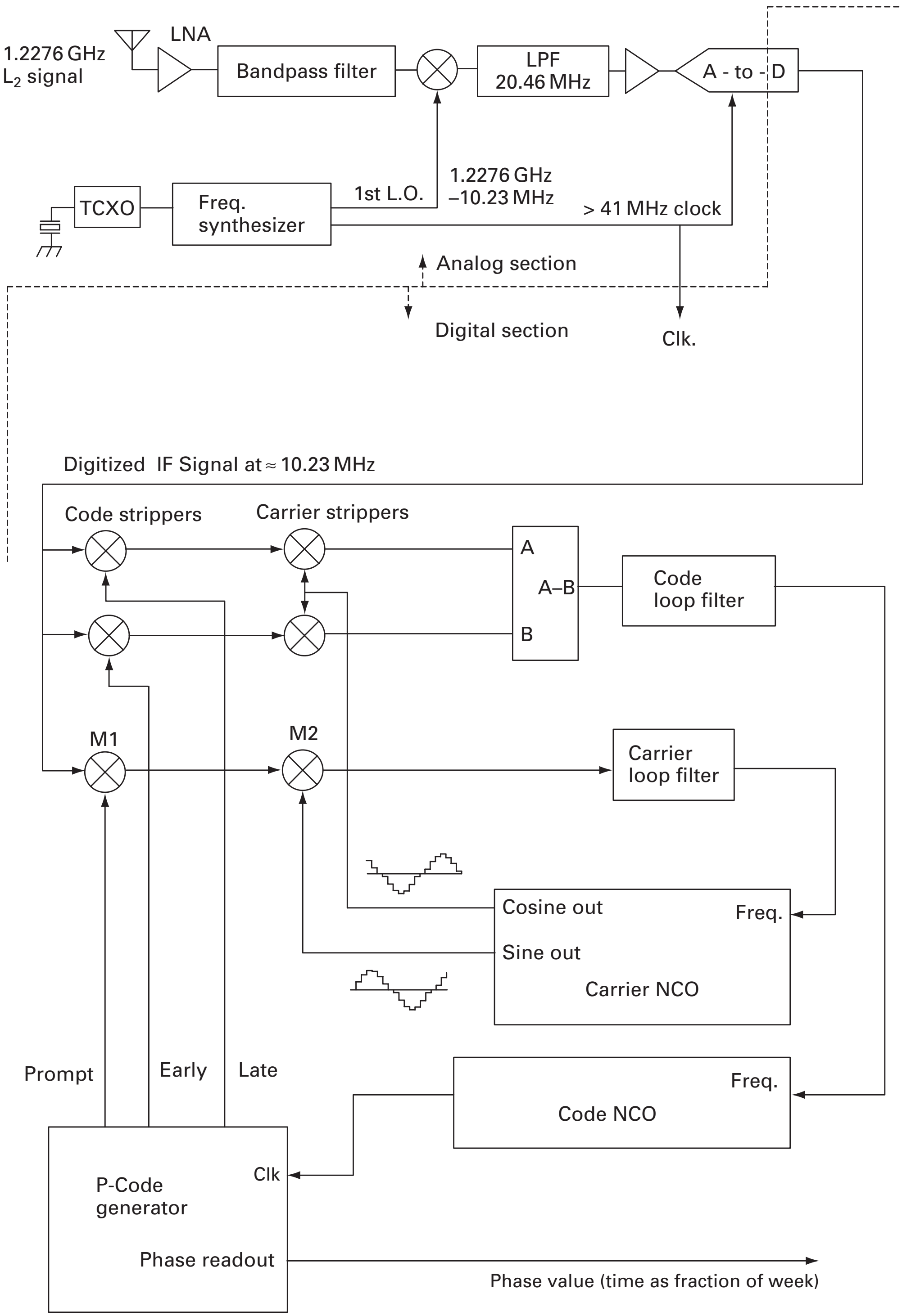

Figure 25.4. A GPS navigation receiver tracking the L2 signal.

(Nyquist sampling at twice the signal bandwidth to avoid aliasing). From this point on, the receiver uses all-digital processing.

The digital portion of the block diagram includes the blocks necessary to track the L2 signal from one satellite. This entire section would be duplicated n times in a receiver that receives signals simultaneously from n satellites. The receiver synchronously (coherently) detects the signal by stripping off the PRN code and also mixing down to dc (stripping off the carrier). These operations can be done in either order. Once these stripping operations are working properly, the phase of the replica code will be aligned with the code on the incoming signal, allowing the time of transmission to be inferred, as described above. The L.O. used to strip the carrier is the *carrier NCO*, a numerically controlled oscillator in a digital phase lock loop. To convert the signal to precisely zero frequency, the receiver must tune the carrier NCO to compensate for Doppler shift, caused by line-sight-velocity, and by inevitable error in the first L.O. frequency.

Mixer M1 (a digital multiplier) multiplies the digital IF signal by a correctly phased replica of the ± 1 PRN code for the desired satellite. This strips the code from the signal, leaving just the ≈ 10.23 MHz carrier signal. This carrier signal feeds mixer M2, as the reference signal for the PLL. Two additional code stripper mixers are provided. One is fed by the replica code, advanced by half a chip (*early* code), while the other is fed by the replica code, delayed by half a chip (*late* code). The outputs of these code strippers are mixed down to dc. The carrier NCO is part of a conventional PLL, so its phase is in quadrature with the phase of the reference. Therefore, a version shifted by 90° (the "cosine" output) is provided to synchronously demodulate the code-stripped early and late signals. When the code is in perfect alignment with the satellite signal, the demodulated early and late signals will have equal average values, half the value they would have if they had been on time ("prompt"). But if the alignment shifts slightly, the demodulated early and late signals will be different. A subtractor forms this difference and uses it to increase or decrease the frequency of the *code NCO*, which is the time base for the code generator. Thus, the code loop is also a conventional PLL.

Note that the two loops, while they can run independently, are related. Suppose that, while both loops are tracking a satellite signal, the line-of-sight velocity suddenly increases. The increase in Doppler shift causes the carrier loop to shift the L.O. by an amount $\Delta\omega/\omega_0 = \Delta v/c$. Since range = velocity × time, we can expect that the code tracking loop will shift the code NCO by the same fractional amount. In fact, the code loop can be assisted by properly scaling the carrier NCO frequency control value and adding it directly to the code NCO's frequency command. The scaling is chosen to make the fractional frequency shifts equal. Using this *assisted tracking* technique, the bandwidth of the code loop can be narrowed, for more accurate tracking. Note that it does not matter that the carrier NCO frequency is determined partly by frequency error in the first L.O., because the code NCO loop will pump up a bias to counteract this non-Doppler component.

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25.4.2 Tracking the C/A code on the L1 signal

Figure 25.5 shows a hypothetical consumer GPS receiver tracking the L1 short C/A code-plus-data signal on L1. The RF section is tuned to L1, and, for the slower chip rate code, the IF bandwidth is now just 2.046 MHz. The presence of the 50-Hz data stream will cause the polarity of the carrier stripper outputs to change sign, according to whether a given data bit is a one or a zero. This will defeat the operation of the conventional PLLs used above for a signal with no data. A remedy for this is to use loops that detect the signals before subtracting them to form the loop error signals.

Consider the loop controlling the code NCO. The detected early and late signals are lowpass filtered, i.e., time averaged, over an interval substantially shorter than one data baud. Then they are squared (detected) and the difference of these power values forms the loop's error signal. The hypothetical carrier loop shown here works in the same way. Two carrier stripping mixers are fed quadrature L.O. signals (−45° and +45°). When the loop is locked, these mixers will produce equal powers. The carrier NCO also provides a 0° output, in phase with the original carrier, which feeds mixer M2 which strips the carrier to produce the data stream. The 0° carrier is also used for the code loop.

Since the C/A code repeats every millisecond, rather than every week, the phase of the code generator provides only the LSBs of the time. The MSBs come from data contained in the navigation message. The 50-baud data is divided into 300-bit subframes, so a new subframe begins every six seconds. Every subframe contains a TOW (time of week) word, which is the GPS elapsed time, measured in units of six seconds (6000 msec) from the start of the current week, that corresponds to the transmission of the first bit in the next subframe. A distinctive header word identifies the beginning of each subframe. (Every subframe also contains the PRN code i.d. number that identifies the satellite[5].) The receiver has a millisecond counter synchronized to the code generator, i.e., the counter is clocked at the each time the code cycles through its starting point. The receiver's control block checks to verify that the MSBs of the millisecond counter are correct in relation to the TOW word. If incorrect, the control block enables the counter to synchronously set itself to the TOW × 6000 at the beginning of the next 1-msec C/A code cycle. The complete time value from the receiver is, therefore, the time, rounded to milliseconds, from the counter plus the code generator phase, in fractions of a millisecond with submicrosecond precision.

25.5 Acquisition

From the discussion of tracking, you can see that neither loop can lock unless the other is also locked; they track simultaneously or not at all. Acquisition of

[5] Reference [1] contains a detailed format for a complete 12.5-minute navigation message, made of 25 frames, each having five subframes made of ten 30-bit words.

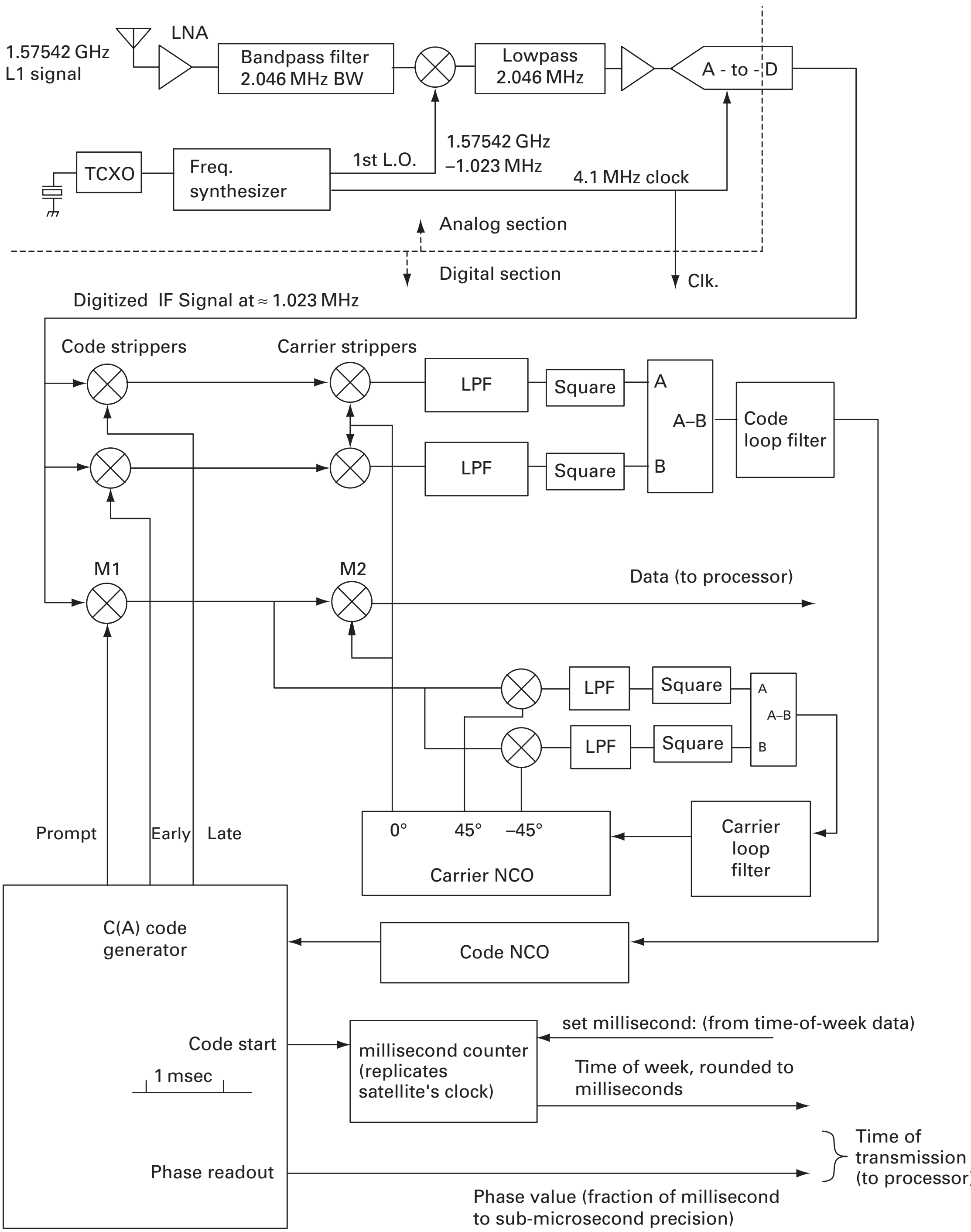

Figure 25.5. A GPS navigation receiver tracking the L1 C/A signal.

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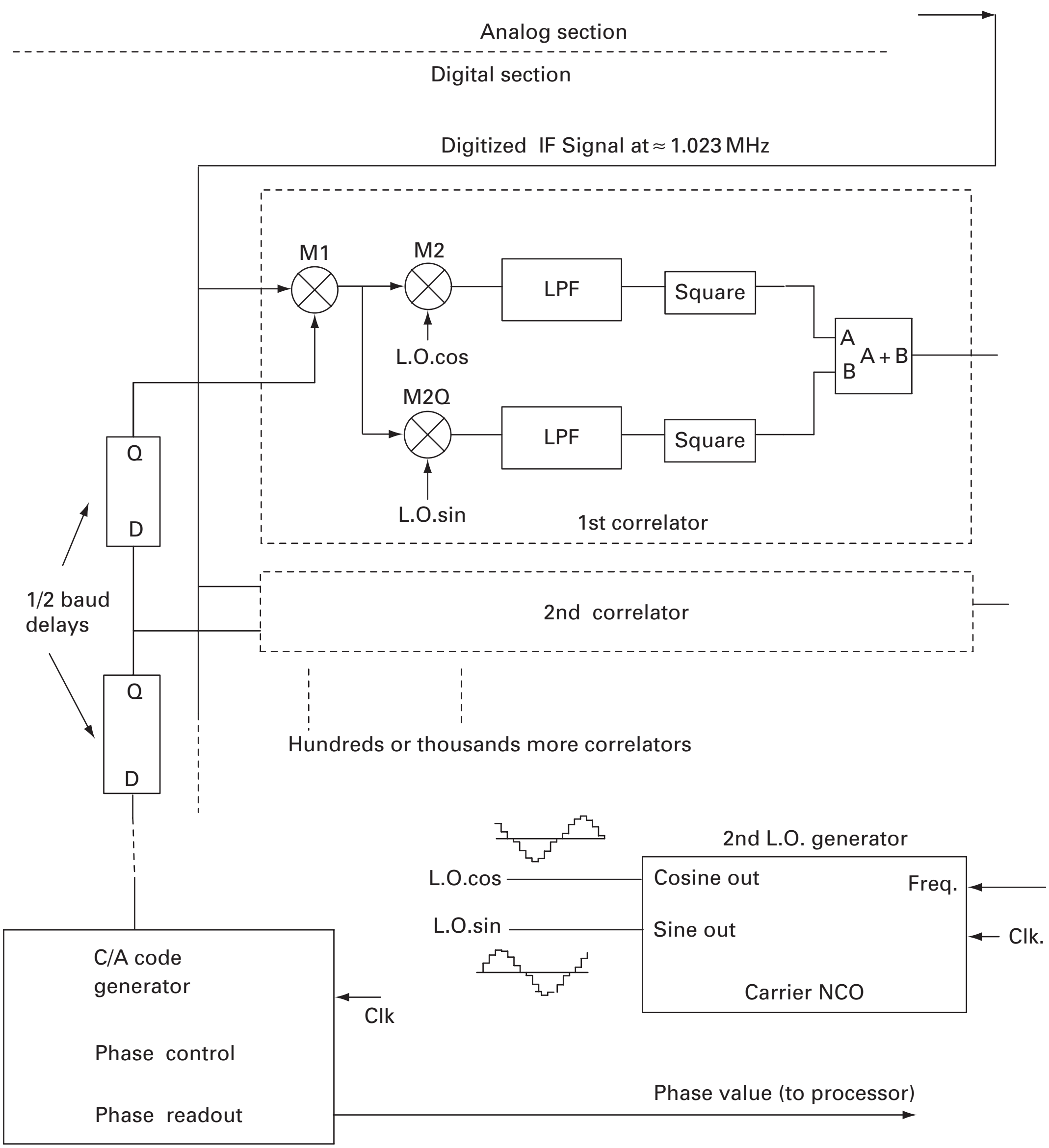

Figure 25.6. GPS navigation receiver in acquisition mode.

the signal therefore requires that the receiver perform a two-dimensional search over both frequency space and code phase. Enough digital processing power is usually available so that the search can be done in a parallel fashion. Figure 25.6 shows a setup for acquisition processing.

One search process is as follows: Mixers (multipliers) M1, M2 and M2Q are provided for every code phase in increments of half a baud. Successively delayed versions of the replica code are fed to each of the M1 mixers. The M2 and M2Q mixers are all fed from a common L.O. generator. The L.O. frequency is stepped in equal frequency increments. At each frequency, the M2 mixer output signals are averaged (lowpass filtered) over an interval, a "dwell time," and the search ends when the detected power (the square of the sum of the two mixer outputs) exceeds a detection threshold. At that point, the L.O. frequency and carrier phase are close enough for a handover to the tracking mode. Longer dwell times require smaller frequency steps, so it takes more time to search for a weak signal. The changing data bits do not spoil the correlation as long as the dwell times are short compared to the data baud length (unless a dwell happens to straddle a data transition). The circuitry or processing resources for one Doppler/code phase cell is called a correlator. With enough correlators running in parallel, the GPS receiver can simultaneously search multiple frequency shifts, multiple code delays, and multiple satellites. Once the signals have been acquired, relatively little processing power is required for tracking.

The C/A signal is easier to acquire than the P-signal, as it has a higher signal-to-noise ratio and a shorter code (less space to search). Receivers that use the P-code usually acquire the C/A code as a first step in acquiring the P-code. (Hence the designation "C/A:" Civil and Acquisition.)

25.6 Ionospheric delay

GPS signals, at 1.5 GHz and 1.2 GHz, interact only slightly with the Earth's lower atmosphere, but the interaction with the ionosphere contributes the largest term to the measurement error budget. We saw in Chapter 20 that the ionosphere's free-electron gas, produced by ionizing ultraviolet solar radiation, changes the dielectric constant from ϵ_0, its vacuum value, to become

$$\epsilon = \epsilon_0 \left(1 - \frac{Ne^2}{\epsilon_0 m \omega^2} \right) = \epsilon_0 \epsilon_r, \tag{25.2}$$

where N is the electron density, e is the electronic charge, m is the electron mass, and ϵ_r is the relative dielectric constant (relative to ϵ_0). The phase velocity of the signal is given by $v_{\text{phase}} = \omega/k = (\mu_0 \epsilon)^{-1/2}$. From Equation (25.2) we see that, in the ionosphere, ϵ is less than ϵ_0. Therefore, v_{phase} is greater than the speed of light and the wavelength, $\lambda = 2\pi/k$, is longer than its vacuum value. Information, however travels at the group velocity,[6] $v_{\text{group}} = \mathrm{d}\omega/\mathrm{d}k$, which, as you can verify, turns out here to be

$$v_{\text{group}} = \frac{c^2}{v_{\text{phase}}} = c\sqrt{1 - Ne^2/(\epsilon_0 m \omega^2)}. \tag{25.3}$$

[6] Group velocity: A narrowband signal around $\omega = \omega_0$ can be represented by a Fourier integral as $V(t) = \int F(\omega')\mathrm{e}^{\mathrm{j}(\omega_0+\omega')t}\mathrm{d}\omega'$, where the function $F(\omega')$ is concentrated around zero. When this signal is launched as a wave into a dispersive medium where the wave number, k, can be approximated as $k \approx k_0 + \omega' \mathrm{d}k/\mathrm{d}\omega$, the wave at t, z becomes $V(t,z) = \mathrm{e}^{\mathrm{j}(\omega_0 t - k_0 z)} \int F(\omega')\mathrm{e}^{\mathrm{j}\omega'(t - z\,\mathrm{d}k/\mathrm{d}\omega)}\mathrm{d}\omega'$. Except for a phase factor (the first term on the right), $V(t,z)$ is identical to $V(t=0, z=0)$ when $z = t\mathrm{d}\omega/\mathrm{d}k = tv_{\text{group}}$.

Thus v_{group} is less than c, and the ionosphere increases the satellite-to-ground propagation delay. The propagation time is just $\int (v_{group})^{-1}\, ds$ over the signal path or

$$T_{prop} = c^{-1} \int \left[1 - \frac{Ne^2}{(\epsilon_0 m \omega^2)}\right]^{-1/2} ds \approx c^{-1} \int \left[1 + \frac{Ne^2}{2\epsilon_0 m \omega^2}\right] ds, \quad (25.4)$$

where we have assumed that the second term in the brackets is much less than unity. We see that the additional delay caused by the ionosphere is given by

$$\Delta T_{Iono} = \approx c^{-1} \int \frac{Ne^2 ds}{2\epsilon_0 m \omega^2} = \frac{cr_e}{2\omega^2} \int N ds = \frac{cr_e \mathrm{TEC}}{2\omega^2}, \quad (25.5)$$

where $r_e = e^2/(\epsilon_0\, m\, c^2) = 2.82 \times 10^{-15}$ m (the "classical electron radius"), and TEC = $\int N\, ds$, the total electron content, i.e., the number of electrons in a one square meter column along the signal path.

Under worst case conditions (the ionosphere enhanced by a solar storm and the satellite near the horizon), the value of TEC might reach 10^{19}, in which case ΔT_{iono} would be 43 nsec, corresponding to a position error of 14 m. Normally the ionospheric error would be less than one-tenth of this.

If the receiver is able to measure the delay on both frequencies, L1 and L2, the delay caused by the ionosphere can be calculated and subtracted from the measured delay. From Equation (25.5), the difference between the measured propagation delays will be $T_{L2} - T_{L1} = \frac{1}{2}\, c\, r_e\, \mathrm{TEC}\, (1/\omega_2^2 - 1/\omega_1^2)$. This provides the value of TEC, from which we can calculate the true delay,

$$T = T_{L1} - \frac{\omega_2^2 (T_{L2} - T_{L1})}{2(\omega_2^2 - \omega_1^2)}. \quad (25.6)$$

25.7 Differential GPS

Over a limited area, GPS receivers tracking the same satellites will be subject to essentially the same systematic errors – satellite clock errors, ephemeris errors, ionospheric delay, and even intentional systematic errors. ("Selective availability" limited the accuracy for civil users by introducing pseudorandom errors in the satellite clocks which could be corrected only by authorized users. However, this was discontinued in 2000.) Thus, over the limited area, individual determinations of absolute position will be biased by the same amount, and calculated differential positions between them will be accurate. The U.S. Coast Guard maintains differential GPS reference stations at well-surveyed positions near harbors. They continuously broadcast the current correction to their GPS reading so that users, nominally aboard ships, can apply that correction to their own GPS reading. This system requires a means of transmission – dedicated beacon transmitters or piggybacking data on subcarriers of local FM stations. It also requires that the users be able to receive these signals and have GPS receivers equipped to apply the corrections.

In an even more accurate form of differential GPS used for precise surveying, the phase of the carrier itself is used to get extremely fine time resolution. This interferometric technique can produce accuracy better than 1 cm. This carrier phase tracking mode requires dual-frequency receivers for ionospheric correction. The maximum practical distance from the reference station is about 30 km.

25.8 Augmented GPS

The Federal Aviation Administration (FAA) has set up a large-scale "wide area augmentation system" (WAAS) with about 25 ground reference stations spread through the U.S. Each of these stations monitors all the GPS satellites within view, on both frequencies, L1 and L2. The data are consolidated at a central location where correction data are generated. The measured TEC values are used to create a model ionosphere in the form of a set of vertical TEC values, from which the TEC for an arbitrary path can be estimated. Correction data is also produced for the satellite clock and ephemerides errors. These data are sent to two geostationary satellites, which broadcast them back down to GPS users. The down-link is on the GPS L1 frequency, and provides the same signal strength as the GPS signals. The WAAS signals are spread with the same kind of C/A codes used by GPS, but with different PRN sequences. This allows a GPS receiver, equipped with suitable firmware, to receive correction data from a WAAS satellite as if it were just another GPS satellite.[7] The WAAS data is transmitted at a net rate of 250 bits/sec. Convolutional encoding for forward error correction is used at a rate of 1/2, so the data stream is 500 bits/sec. In practice, the use of WAAS data reduces C/A code ("Standard Positioning Service") GPS position errors to about 2 m.

25.9 Improvements to GPS

Replacement GPS satellites include the new L2C (Civil) signal, whose signal path is shown at the top of Figure 25.3. This signal is actually two time-multiplexed signals, a medium-length code, CM, and a long-length code, CL. The CL code is transmitted without data. It can, therefore, be tracked with the system shown in Figure 25.4, which uses conventional phase lock loops which provide better tracking than the loops used in Figure 25.5, for a signal containing the data stream. The CL2 signal also provides dual-frequency operation so that civil GPS receivers can correct for ionospheric delay. The CM code contains the data, but convolutionally encoded for forward error correction.

[7] The WAAS satellites contain atomic frequency standards and can, in fact, be used as additional GPS navigation satellites.

This slows the net data rate to 25 bits/sec. Both the CM and CL codes have a chip rate of 511.5 kHz. The CM code repeats every 20 msec, while the CL code repeats every 1.5 sec. The L2C multiplexes CL with CM+Data by alternating between them every 1/1.023 microseconds.

25.10 Other satellite navigation systems

The Russian *Glonass s*ystem and the European *Galileo* system (scheduled for operation in 2013) are very similar to GPS. Both are L-band systems, using PRN coding for time resolution. The Glonass system, however, does not use the PRN coding for multiple access. Instead, each satellite transmits on its own assigned frequency, which requires that receivers be tunable. The Chinese *Beidou* system began with two geostationary satellites, but is expected to eventually have five geostationary and 30 medium Earth orbit satellites. All of these systems were preceded by the interesting *Transit* or NAVSAT system, which operated from 1964 until 1991. A ship at sea could locate its position within 200 m by analyzing the curve of Doppler shift vs. time from a single satellite pass. With only five satellites, a given user could get a position fix only once every several hours.

Problems

Problem 25.1. The nominal GPS signal power is −160 dBW (10^{-16} W) at the output of the receiver antenna (at the L1 frequency assuming the antenna gain is 3 dB). Assume an antenna temperature of 290 K, since the low directivity of the antenna causes ground noise to dominate. (a) Assume that the receiver noise figure is 4 dB and calculate the signal-to-noise ratio for a bandwidth of 2.046 MHz (the nominal bandwidth of the C/A signal). (b) Use the Shannon formula, $C = B \log_2 (1+S/N)$, to calculate the channel capacity in bits/sec. Compare this with the 50-Hz data rate of the navigation signal.

Problem 25.2. Estimate the gain of the GPS satellite antenna, assuming the beam angle just encloses the Earth. Then use the information given in Problem 25.1 to estimate the power of the satellite transmitter.

Problem 25.3. "Selective Availability" (SA), a now-discontinued GPS security feature, degraded the navigation accuracy for civil users. Suggest some ways to implement this feature.

Problem 25.4. Describe how you would use off-the-shelf RF components, a deep-memory sampling oscilloscope, and a PC to make an "off-line" detection of a GPS satellite signal.

Problem 25.5. Devise an algorithm and write a computer program to solve the set of equations (25.1) for x, y, z, and Δ.

Problem 25.6. Derive an expression for the Doppler shift of the GPS signal, assuming the orbit passes directly overhead.

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