# Digital Modulation, from ASK to OQPSK

Is it QPSK or 4-QAM? Or OOK? Don't worry, just ASK Don (or is that DON?). Then get out your bowl and soup spoon; we're about to serve up a byte-size portion of the alphabet soup called digital modulation (lots of letters for a bunch of ones and zeros!).

By Don Rotolo, N2IRZ (N2IRZ@compuserve.com)

Anyone who's read the past five months' columns should now have at least a general feel for what it takes to get a network node on the air. It was my intention to get everyone familiar with the process, to gain the courage to try it themselves. I urge you to try it. Don't be intimidated by existing networks, or by those who look down upon 1200-baud links—if there's a need for data transport services, fill it.

Once you've cut your teeth at 1200 baud, you might want greater speed. If you do, be prepared for a challenge. Trying to start a new network at 56k, for example, is a triple challenge: figuring out the network, the RF, and how to pay for it all can be discouraging if taken all at once. Instead, take it step by step. The reason I'm so enthusiastic about FlexNet (see June and July "Digital Data Link") is that it's very scalable—it will grow in size and speed with your network. Again, I also have to emphasize: FlexNet is an excellent network, but when you run TCP/IP through it, you're really getting into the powerful stuff. Try it!

## Digital Modulation Techniques

This month, we'll take a (necessarily brief) look in another direction of digital data: data modulation techniques. Although it's possible to just push bits into a transmitter, a little effort and thought can make the process much more efficient.

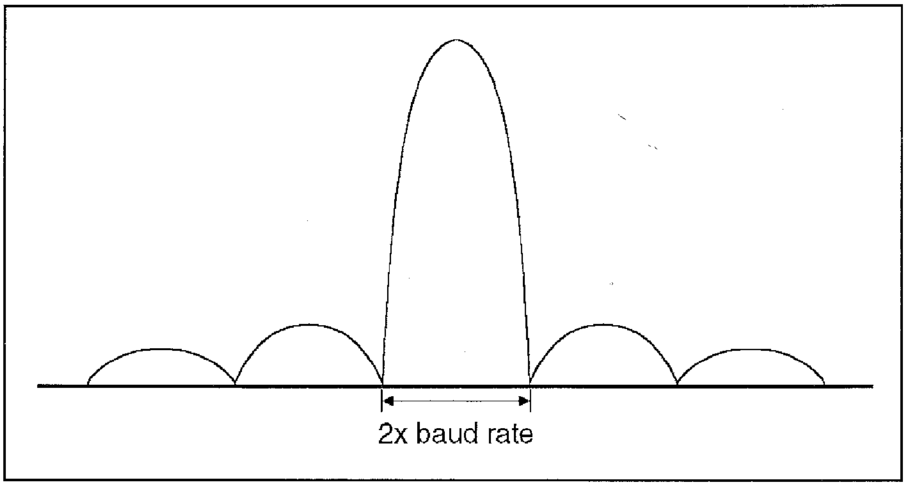

*Figure 1. The spectrum bandwidth of a single-frequency transmitter that's turned on and off every so often. The bandwidth of the main carrier is equal to twice the baud rate, expressed in Hz.*

There are three goals in any digital modulation scheme:

1. Minimize transmitted bandwidth;
2. Minimize the Bit Error Rate (BER) for a given power level; and
3. Maximize resistance to various forms of interference.

Data communications are considered either *power-limited* or *bandwidth-limited*. Commercial services are generally bandwidth-limited: they only can get an allocation for a small slice of spectrum (often paying millions for the privilege), so they have to maximize throughput (efficiency of data transfer) with what they've got. Compared to spectrum, RF power is cheap. In the amateur service, data communications are generally power-limited: There's plenty of spectrum to play with (for free!), especially in the microwave bands, so the costs associated with greater transmit power become a significant fraction of the total system cost.

What this means is that hams have an advantage over commercial services, namely the ability to trade power requirements for bandwidth. It should be noted that, in general, modulation schemes that use bandwidth less efficiently tend to require less power for a given BER (and the lower the BER, the higher the throughput).

Before we get into the details, I first want to acknowledge that a considerable

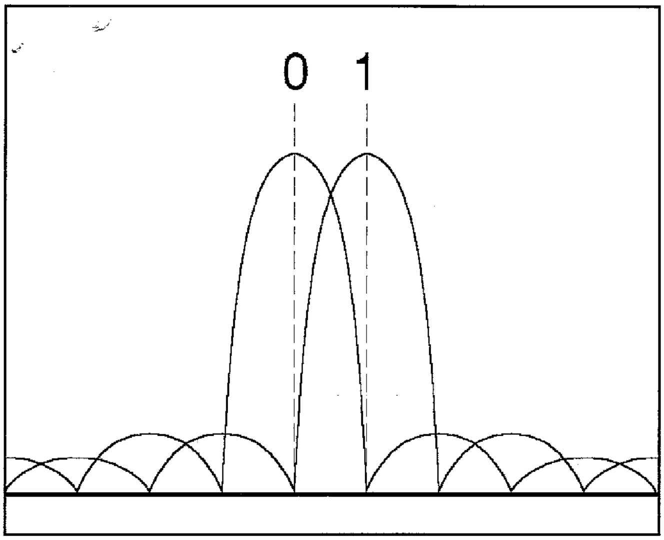

*Figure 2. The spectrum view of two optimally spaced FSK carriers. No energy from the "one" carrier is detected by the "zero" receiver, and vice versa, because each signal's amplitude is always zero at the other signal's frequency.*

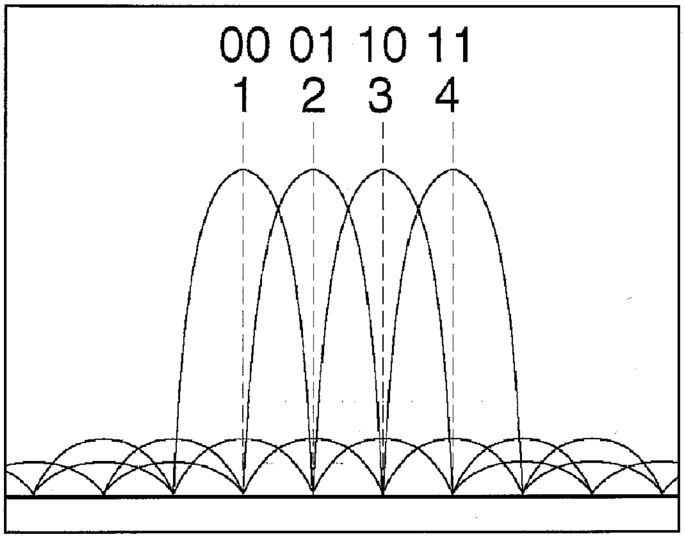

*Figure 3. The output spectrum of a 4-FSK signal, which sends 2 bits per signaling period. The di-bit numbers of 00, 01, 10, and 11 correspond to carrier number 1, 2, 3, or 4 being on, with the other three being off. For OFDM (see text), the carriers are switched on and off independently, thus sending 4 bits per signaling period.*

portion of the information presented here is taken from the book *Wireless Digital Communications: Design and Theory* by Tom McDermott, N5EG. This book is published by the friendly folks at the Tucson Amateur Packet Radio Corp. (TAPR), and it's available directly from them or from your local bookstore. This book is jam-packed with just what the title says. I can only dream of having the level of understanding and expertise on the topic that Tom has, and I wish I could explain such complex subjects as well as he does in this book. The writing is clear, concise, and understandable, while retaining all of the sometimes difficult content so essential to comprehension. Even if you're only mildly interested in wireless data, I heartily recommend this book.

Now, let's look at some common types of data modulation (*get ready to digest that alphabet soup!—ed.*).

## FSK

One of the simplest modulation schemes is *Frequency Shift Keying (FSK)*. Basically, you transmit on one frequency to send a binary "one," and on another frequency to send a binary "zero." It is an advantage for the frequencies to be near each other, allowing a single receiver to be used, but not so near that they interfere with each other.

The ideal distance apart can be calculated (If you want to know how, buy Tom's book!). Take a look at Figure 1, which shows the spectrum bandwidth of a single-frequency transmitter that's turned on and off every so often. (Each FSK frequency is essentially a CW carrier switched on or off, which is the same as an AM transmitter with two modulation levels: 0% and 100%). The signal level drops off to zero at a certain distance from the carrier, then rises again to some lower level—this is a sideband. The distance between null points is exactly twice the baud rate, expressed in Hz (see "Bits and Bauds," elsewhere in this article).

Looking at Figure 2, we see that a good place for the second carrier frequency would be at the null in the first frequency's spectrum. This would make it easiest to tell one frequency from the other, making it an "all or nothing" decision. If the carriers were too close, we would lose some of this "all or nothing," making it necessary to have a better signal quality to ensure a given BER.

## Orthogonality

In the above discussion, it was implied that, if the spacing between signals was too close, the energy of one carrier would reduce the signal margin on the other carrier, and vice-versa. While this is essentially true, one thing was left out: only one of the carriers is on at any given moment. We are sending either a one, or a zero, but never both at the same time. We can say that these two carriers are *orthogonal* with each other, that is, one cannot be mistaken for the other.

Orthogonality also comes in degrees. If the carriers were closer than ideal, they would be less than 100% orthogonal because some of the desired signal's energy would be detectable by the undesired signal's detector. If the desired frequency experienced a fade, but not the portion detected by the other detector, we might not be able to decide if it is a one or a zero. Such an occurrence would have the undesirable effect of increasing the BER. With a fully orthogonal signal, it would be much more difficult to make such an error.

Orthogonality can be accomplished at the transmitted frequency, as in this example, as well as at the baseband data level. This was discussed in greater detail in the column on Spread Spectrum in the May, 1997, issue of *CQ VHF*.

## 2, 4, 6, 8...

FSK using two carriers is also called *2-FSK* and sends 1 bit per signaling period (bit rate = baud rate). To increase the number of bits sent per baud, we can use more carriers (again, see "Bits and Bauds"). Figure 3 shows the spectrum of a *4-FSK* signal, which sends 2 bits per signaling period (baud rate = 1/2 bit rate, or bit rate = 2 • baud rate, or twice the baud rate). The *di-bit* (or 2-bit-long) numbers of 00, 01, 10 and 11 correspond to carrier number 1, 2, 3, or 4 being on, with the other three being off.

This can be extended to as many carrier frequencies as you like, which actual-

> ***"Data communications are considered either power-limited or bandwidth-limited. Commercial services are generally bandwidth-limited....In the amateur service, data communications are generally power-limited...."***

ly improves performance. If we were to increase the number of carriers to infinity, the BER would become very small for a given Eb/No*. However, the penalty for increasing bandwidth is increased susceptibility to interference and noise.

## OFDM

A similar modulation scheme is *Orthogonal Frequency Division Multiplexing*, or *OFDM* (refer back to Figure 3). In OFDM, instead of switching on and off each carrier one at a time, each is controlled independently, meaning that more than one signal at a time may be "on." For example, with an 8-carrier OFDM system, an entire byte (8 bits) of data is sent during each signaling period. The penalty here is that the power is equally distributed among the "on" carriers. This reduces the power of any given bit, decreasing the signal-to-noise (S/N) ratio, thus increasing the BER. Also, the variability of the signal level (the power per carrier if all 8 are on is much lower than if only one is on) causes further complications.

## The PSK Family

If we can detect *phase* accurately, we can use only a single carrier frequency, changing only the carrier's phase to indicate a data bit. Phase is a *time-shifting* (usually a delay) of a periodic signal (such as a sine or square wave), expressed in degrees, where 360 degrees equals one full *period*. Period is defined as the time from a point on one wave in a string of similar waves to the same point on the next wave. Detecting the phase of a carrier implies that we have available to us a reference signal to which we can compare the incoming signal. As it turns out, it's not difficult to regenerate such a reference carrier *from* the incoming signal.

This leads us to *Phase Shift Keying*, or *PSK*. The more accurately we can regenerate the reference carrier, the smaller the phase change we can detect. For example, even if our reference carrier swings wildly, varying by ±70 degrees, it is still no problem to detect a 180-degree phase change. If we can hold the reference to a few degrees, though, detecting a phase shift of, say, 10 degrees isn't difficult, either. The difficulty is that holding the reference carrier so closely requires a greater Eb/No ratio for a given BER. This means having either more signal (higher power) or less noise (a quieter channel).

Figure 4 shows the possible phase angles for a *4-PSK* system, sending 2 bits of data per signaling time. The carrier phase can take any one of the four values, each representing a di-bit data number (well, not exactly, but just accept this for now). Because of the 90-degree phase differences, this technique is also called *Quadrature Phase Shift Keying*, or *QPSK*.

One problem with QPSK is the possibility of a 180-degree phase shift. This abrupt phase reversal, when passed through a Class C amplifier (typical for FM), causes a significant widening of the transmitted bandwidth. To help reduce this problem, we can limit each phase change to ± 90 degrees if we *offset* one of the data streams by $^{1}/2$ bit time. Figure 5(a) shows a regular QPSK di-bit data stream, and an *Offset QPSK (OQPSK)* data stream at 5(b).

## Phase Ambiguity

One important point regarding PSK is the *absolute phase* of the reference carrier. In many cases, we can regenerate a phase-stable reference, but *we cannot always determine the constant phase offset from the transmitted carrier*. In other words, if we detect a 4-PSK signal with a 90-degree phase difference compared to our reference, we don't know which of the four possible phases the signal was transmitted with.

Looking again at Figure 4, it is completely *incorrect* to assign a di-bit number to each phase, because we can't tell which of the four phases it really is. This so-called *phase ambiguity* is resolved by only transmitting a phase change to indicate that the value of the bit has changed—from 0 to 1 or 1 to 0. So, two

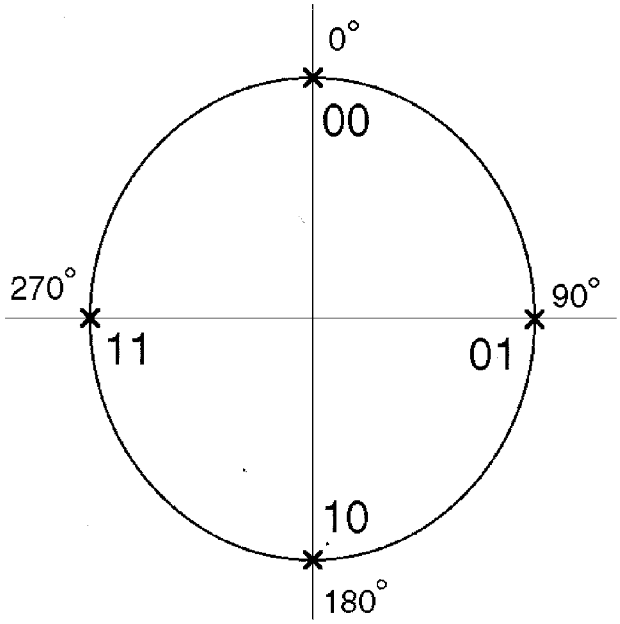

*Figure 4. This phase diagram shows the four possible phase angles for a 4-PSK system. Such a system sends 2 bits of data per signaling time. Commercial modems using 64-PSK are available, but they require a very high signal-to-noise ratio for good operation. Note that, due to phase ambiguity, it's incorrect to assign a specific di-bit number to a particular phase. We did it here only to aid in explanation.*

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* Eb = Bit Energy, No = Noise Spectral Density. Eb/No is a more accurate measure of channel conditions than the commonly used Signal-to-Noise (S/N) ratio. Shannon's Limit states that, for an arbitrarily small BER, the smallest Eb/No >= -1.6 dB.

TABLE

| Modulation Format | Applications | Advantages | Disadvantages |
|---|---|---|---|
| FM-AFSK | VHF/UHF point-to-point, Multipoint | Simple, compatible with most equipment. Tolerant of frequency and deviation errors between multiple stations. | Poor performance, limited speed, spectrally inefficient. |
| FSK | VHF/UHF point-to-point, Multipoint | Simple circuitry, OK for class C amplifiers, tolerant of frequency shift errors among multiple stations. | Moderate performance, wider bandwidth than other methods. |
| PSK | Satellite | Modest circuitry, excellent performance for higher data rates. | Requires higher signal level and linear amplification. |
| OQPSK | VHF/UHF point-to-point | Excellent performance with optimum demodulator, OK for class C amplifiers | More complicated circuitry, wider bandwidth than MSK. |
| MSK | VHF/UHF point-to-point | Excellent performance with optimum demodulator, good performance with ordinary FSK detector, OK for class C amplifiers. | Most complicated circuitry. |

*Table. A summary of the advantages and disadvantages of certain modulation techniques and applications.*

ones in a row wouldn't cause a phase change. You see, while we cannot determine the *absolute* phase, it's simple to see that the phase has changed, and by how much.

As I mentioned previously, the penalty for increasing the number of phases is the greater Eb/No required to hold the phase reference stable enough. For example, a certain 2-PSK system might need an Eb/No of 10 dB for a given BER, while a similar 32-PSK system would need a whopping 24 dB (nearly 25 times the signal level) for the same BER. However, for a very quiet channel (as is typical in the commercial sector), a 64-PSK system is both practical and efficient.

## OOK, ASK, and QAM

The first digital modulation technique, used since radio began, and still in use today, is *On-Off Keying (OOK)*. One well-known example is Morse code. This is generally unsuitable for automatic reception because it isn't orthogonal and is susceptible to noise while in the off state. Instead, we use *Amplitude Shift Keying (ASK)*, switching between a full-power signal and a reduced-power (50%) signal. This helps combat interference in the off state since there never is a complete off state in ASK.

It's difficult to add more levels to such a 2-ASK system, as the Eb/No requirements increase dramatically. Instead, we use a little trick: We can transmit a second 2-ASK carrier 90 degrees out of phase from the first signal. Amplitude-modulated signals that are in *quadrature* (90 degrees out of phase) do not interfere with each other (they're orthogonal), so we effectively double the data rate within the same bandwidth. This is called *Quadrature Amplitude Modulation*, or *QAM*. In this case, we added two 2-ASK signals together in quadrature, so we end up with *4-QAM*.

If we examine 4-QAM carefully, we can see that it is the same as QPSK. However, if we also vary the phase of each carrier, we can squeeze even more data in there, winding up with something like 16-QAM, a technique considerably more efficient than 16-PSK. In fact, QAM is the predominant modulation scheme used in commercial data systems.

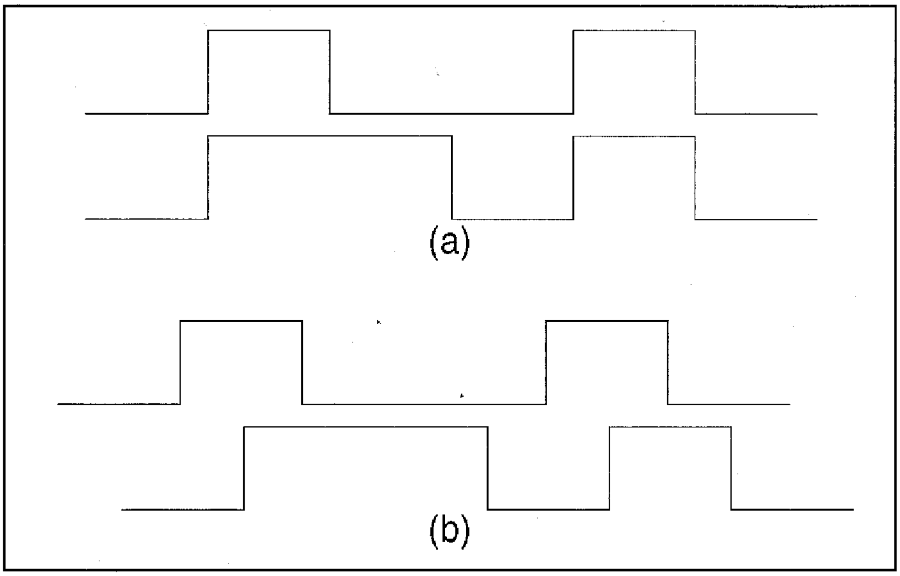

*Figure 5. (a) A regular QPSK di-bit data stream without any offset between the two data streams; (b) A di-bit OQPSK data stream. Note the 1/2 bit-time offset.*

If you take a look at the data transceiver chipsets offered by most manufacturers, they're nearly all set up for QAM. However, this technique is not very tolerant of noisy channels.

## Getting in Shape

So far, we've been only looking at data streams of rectangular bits. If we carefully shape each bit, using a sinusoid or similar shape, we sharply reduce the high-frequency content of the data stream. This reduces the transmitted signal's bandwidth by reducing the amplitude of the sidebands. Although other, more rigorous definitions exist, this is the essence of *Minimum Shift Keying*, or *MSK*.

MSK is basically OQPSK with shaped data bits, which has the effect of making each phase transition less abrupt than the 90-degree jumps of OQPSK. Interestingly, the output spectrum looks just like an FSK signal with one-half the ideal carrier spacing. Thus, we can use either PSK or FSK techniques to generate the output signal. The basic technique of shaping the data pulses has advantages for most modulation techniques, but MSK is the nearly ideal case, thus the "Minimum" in the name. One well-known example of MSK techniques applied to FSK signaling is the G3RUH modem, commonly used for satellite work and available from most of the major TNC manufacturers.

## Looking Ahead in CQ VHF

CQ VHF Ham Radio Above 50 MHz

Here are some of the articles that we're working on for upcoming issues of *CQ VHF*:

- "Report on the *CQ VHF* National Foxhunting Weekend," by Joe Moell, K0OV
- "A Repeater-Internet Interface," by John Hansen, W2FS
- "The 6-Meter Calling Frequency Debate," by Bill Tynan, W3XO, and Ken Neubeck, WB2AMU

Plus...

- "Installing That New Radio in Your New Car," by Phil Salas, AD5X
- *CQ VHF* Review: Kenwood TH-G71 Handheld," by Gordon West, WB6NOA
- *CQ VHF* Book Review: WB2AMU's *Six Meters—A Guide to the Magic Band (Revised Edition)*, by Rich Moseson, W2VU

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## AFSK

The last modulation system we'll look at is *Audio Frequency Shift Keying*, or *AFSK*, the system most commonly used by hams for packet and radio teletype (RTTY). Here, we use an audio tone to signify a 0 or 1 bit. In the standard 1200-baud modems we all know and love, these tones are 1200 and 2200 Hz. The advantage to this system is that virtually any voice-grade communications channel can carry these (or similar) tones, as they fall within the standard voice passband of 300 to 3000 Hz. This technique is also very forgiving of frequency and, for FM, deviation differences between multiple stations on a channel. The disadvantage is that the data rate is somewhat limited by the choice of audio tones, as well as the equipment being used.

## What's the Best?

There is no ideal technique for all cases as each one has advantages over the others in certain circumstances. A summary of the advantages and disadvantages of these modulation techniques for certain applications is shown in the Table.

The main reason amateurs rarely use the modulation techniques used by commercial interests comes back to the distinction between power-limited and bandwidth-limited channels. Amateurs tend to select techniques which are technically easy to implement, while commercial systems have other priorities. There's little reason to adopt commercial techniques because, despite being more spectrally efficient, they would be more costly to implement by amateurs.

This also helps us understand why we haven't progressed much from our beginnings with 1200-baud AFSK. It is awfully simple (and cheap) to do, and 1200 baud was, until recently, quite adequate for what we were doing. The venerable G3RUH modem is still an excellent choice for most amateur work: it is reasonably efficient in its spectrum usage, it can be scaled up to hundreds of kilobytes per second, and it works well in power-limited applications. Most importantly, it's inexpensive and readily available.

## Bits and Bauds

Although many people use the terms "bits per second" and "baud" interchangeably, they are not the same. "Bits per second" is fairly straightforward, but "baud" actually means "signals per second." The important difference is that *there can be more than one bit per signal*! A 28.8-kilobit per second telephone modem, for example, uses a baud rate of only 1200, but it sends 24 bits per baud...and 1200 times 24 equals... you've got it: 28,800!

## Coming Up: A Melange of Modems

So there you have it—a brief introduction to some of the more common data modulation techniques. I wish I had the time to cover each of these in the detail they deserve, but that would (and did) take a book.

Next month, we'll take a look at some modems, and the APRS/Internet information I promised last month, which got preempted. After that, who knows? I've been playing with lasers lately, maybe something will come of that. Until then, get out there and build a network! 73,

—N2IRZ

## Resources

*Wireless Digital Communications: Design and Theory*, by Tom McDermott, N5EG, is available directly from Tucson Amateur Packet Radio, Inc., 8987-309 E. Tanque Verde Rd., #337, Tucson, AZ 85732; Phone: (940) 383-000; Fax: (940) 566-2544; E-mail: <tapr@tapr.org>; Web: <http://www.tapr.org>. You may also order it through your local bookstore. Ask for it by title and by its ISBN (International Standard Book Number), which is 0-9644707-2-1.