

YAMAHA

**The Acoustics
of Microtuning**

DX7 II·FD/D
DIGITAL PROGRAMMABLE ALGORITHM SYNTHESIZER
SUPPLEMENTAL BOOKLET

Welcome

The first two booklets in the microtuning series, "Exploring the Preset Microtunings" and "The Mathematics & History of Microtuning," present an overview of the presets found in the DX7 II as well as the mathematical and historical foundations upon which the entire field of microtuning is based. This, the third booklet in the series, continues the presentation of microtonal concepts and their relationship to the DX7 II in four sections.

Section 1 presents the fundamental concepts of acoustics appropriate to the study of microtuning.

Section 2 describes the process whereby new microtunings can be created with the DX7 II.

Section 3 outlines the procedures for saving new microtunings in the internal memory, in a RAM cartridge, and on a floppy disk (for owners of the DX7 II FD).

Section 4 presents the tuning data for eight new microtunings which can be realized in the DX7 II. These scales contain twelve or fewer tones per octave.

For continuing information concerning the DX7 II FD/D, consult AfterTouch, the official publication of the Yamaha Users Group. Many advanced functions will be discussed in its pages in the coming months. There will also be information concerning the availability of other materials concerning more advanced applications. To receive a free copy of AfterTouch every month, send your request to AfterTouch, P.O. Box 7938, Northridge, CA 91323-7938. On your letter or postcard, be sure to indicate that you are the owner of a DX7 II FD/D.

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Acoustics

The second booklet in the microtuning series presented the basic mathematics of scales and intervals. This section continues the discussion of musical science by exploring some of the relevant principles of acoustics. These principles describe the physical nature of sound as it is generated and perceived. In order to fully benefit from the information in this section, you should be familiar with the mathematics found in "The Mathematics & History of Microtuning."

Waveforms

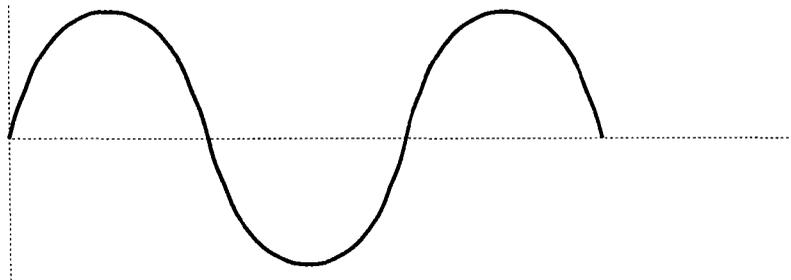
As you learned in the second booklet of the microtuning series, we perceive sound whenever our eardrums are stimulated to vibrate in response to the movement of the air molecules immediately adjacent to them. The result of the motion caused by neighboring molecules colliding with each other is an example of a physical phenomenon known as waves.

Ocean waves may be more familiar than sound waves to many people. There is only one major difference between ocean waves and sound waves. Water molecules in the ocean move up and down (vertically) as an ocean wave moves horizontally. This is known as a transverse wave. Air molecules move from side to side (horizontally) as a sound wave moves horizontally. This type of wave is called a longitudinal wave.

Musical sound waves are generally the result of very regular vibrations which repeat themselves periodically. Such periodic vibrations are known as waveforms. The exact shape of these waveforms determines the quality of the sound we hear. Waveforms are usually drawn in the form of a graph. Several of these graphs will be presented shortly.

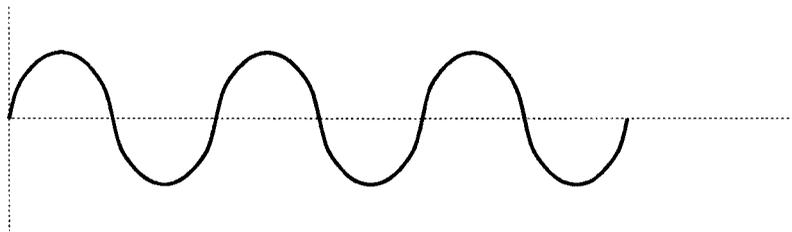
The simplest waveform is called a sine wave. The reason for this name is found in the study of geometry and trigonometry. For now, it is only important to know that this is the most fundamental of any waveform. The quality of the sound represented by a sine wave is very pure and simple. Each of the six operators (or twelve in dual mode) used to create sounds on the DX7 produce sine waves. The graph of this waveform is shown below.

A Sine Wave



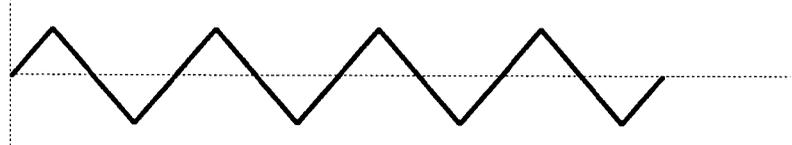
Such graphs reveal more than the shape of the waveform. Amplitude (loudness) and frequency (pitch) are also represented. For example, the following graph represents a sine wave which is softer in volume and higher in pitch than the waveform depicted on the previous page.

*A Softer and Higher Pitched
Sine Wave*

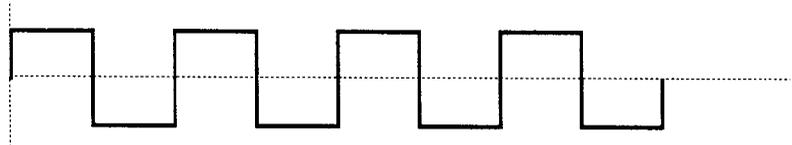


Of course, there is an infinite variety of waveforms. Triangle, square, and sawtooth waves are among the most common synthesizer waveforms. Their graphs appear below.

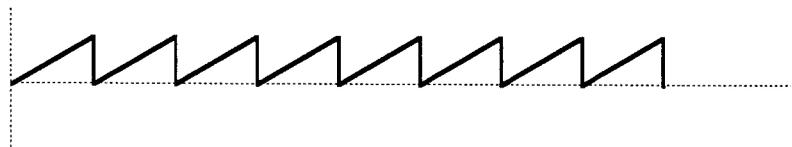
A Triangle Wave



A Square Wave



A Sawtooth Wave



Harmonic Spectrum

The waveforms associated with musical sounds are rarely pure sine waves. They are generally quite complex. One of the most interesting discoveries in the study of acoustics is the fact that sine waves of different frequencies and amplitudes can be combined to produce a periodic waveform of any complexity. This is the basis of a technique in electronic music known as additive synthesis.

Conversely, any complex periodic waveform can be distilled or separated into its component sine waves. This process, known as Fourier analysis after the French mathematician responsible for developing it, reveals what is known as the harmonic spectrum of the waveform under investigation. The sine waves in the harmonic spectrum are known as harmonics or partials. The harmonic with the lowest frequency is called the fundamental. The partials above the fundamental are called overtones as well. Our auditory system usually associates the frequency of the fundamental with the overall pitch of a note with a complex waveform.

*Every Instrument has a Unique
Harmonic Spectrum*

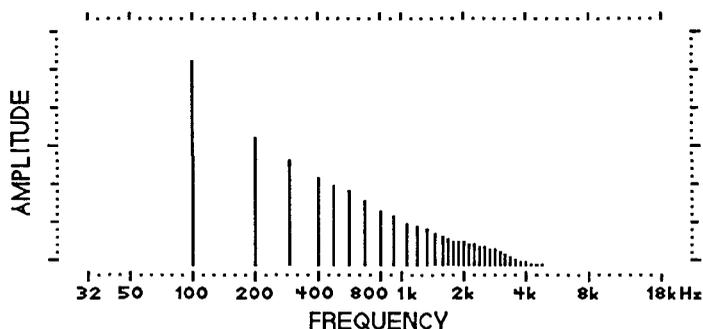
That each musical instrument has a unique harmonic spectrum is the primary reason we are able to distinguish one instrument from another. The harmonic spectrum determines the timbre, or tone color, of each instrument. As you will soon see, it also plays an important role in the selection of appropriate scales and tunings for different instruments.

The amplitude, or volume, of each partial in a harmonic spectrum varies over the duration of a note. This variation, particularly during the attack and release portions of the sound, provides our ears with the information necessary to identify the sound of a trombone, violin, or any other instrument.

However, it is the frequencies of the partials in a harmonic spectrum which are of the most interest to microtonal explorers. These frequencies do not vary significantly over time and depend on the type of instrument producing the sound. The relationships between the frequency ratios of the partials in a harmonic spectrum and the notes in a scale can have an enormous impact on the character of the music made with them.

The harmonic spectra of virtually all wind and string instruments share one important characteristic. The frequencies of the overtones in these spectra are whole number multiples of the fundamental frequency. For example, the frequency of the first overtone is twice the fundamental frequency, the frequency of the second overtone is three times the fundamental frequency, and so on. This pattern results in what is known as a linear harmonic spectrum.

Harmonic spectra are often depicted in a bar graph. Each bar represents one partial. The length of a bar indicates the amplitude or loudness of the partial it represents. The position a bar occupies indicates the frequency of the partial. The following graph depicts a typical linear harmonic spectrum.



Linear Harmonic Spectrum

Wind and string instruments exhibit a linear harmonic spectrum because they vibrate in only one direction at a time. As a string is plucked or bowed, it vibrates in the direction which is perpendicular (at a right angle) to the direction defined by the string itself. The molecules in the column of air found within a wind instrument vibrate in the same direction as that defined by the air column.

The ratios representing the intervals between the various overtones and the fundamental in a linear harmonic spectrum consist of small whole numbers. As you may recall from the second booklet in the microtuning series, this is also the guiding principle behind just intonation. This means that useful scales can be created using the ratios found in this type of spectrum.

The following table reveals the ratios associated with the first 32 partials of this harmonic spectrum. The octave above the fundamental in which the partials occur is indicated. The interval between each partial and the fundamental is first specified as an absolute ratio. This ratio is then divided by 2, 4, 8, or 16 as necessary in order to bring it within the scope of one octave. The diatonic ratio closest to this adjusted ratio follows in the next column. The scale degree corresponding to the closest diatonic ratio occupies the final column.

The First 32 Partial of the Harmonic Spectrum

<i>Harmonic Number</i>	<i>Absolute Ratio</i>	<i>Adjusted Ratio</i>	<i>Closest Diatonic Ratio</i>	<i>Closest Scale Degree</i>
<i>First Octave</i>				
1	1/1	1/1	1/1	Root
<i>Second Octave</i>				
2	2/1	1/1	1/1	Root
3	3/1	3/2	3/2	Perfect Fifth
<i>Third Octave</i>				
4	4/1	1/1	1/1	Root
5	5/1	5/4	5/4	Major Third
6	6/1	3/2	3/2	Perfect Fifth
7	7/1	7/4	16/9	Minor Seventh
<i>Fourth Octave</i>				
8	8/1	1/1	1/1	Root
9	9/1	9/8	9/8	Major Second
10	10/1	5/4	5/4	Major Third
11	11/1	11/8	45/32	Diminished Fifth
12	12/1	3/2	3/2	Perfect Fifth
13	13/1	13/8	8/5	Minor Sixth
14	14/1	7/4	16/9	Minor Seventh
15	15/1	15/8	15/8	Major Seventh
<i>Fifth Octave</i>				
16	16/1	1/1	1/1	Root
17	17/1	17/16	16/15	Minor Second
18	18/1	9/8	9/8	Major Second
19	19/1	19/16	6/5	Minor Third
20	20/1	5/4	5/4	Major Third
21	21/1	21/16	4/3	Perfect Fourth
22	22/1	11/8	45/32	Diminished Fifth
23	23/1	23/16	64/45	Augmented Fourth
24	24/1	3/2	3/2	Perfect Fifth
25	25/1	25/16		
26	26/1	13/8	8/5	Minor Sixth
27	27/1	27/16	5/3	Major Sixth
28	28/1	7/4	16/9	Minor Seventh
29	29/1	29/16		
30	30/1	15/8	15/8	Major Seventh
31	31/1	31/16		
<i>Sixth Octave</i>				
32	32/1	1/1	1/1	Root

*Scales within the Linear
Harmonic Spectrum*

There are several interesting properties to notice about this harmonic spectrum. First, the ratios found in one octave repeat themselves in each subsequent octave. Second, each octave contains twice the number of partials found in the preceding octave. Specifically, the first octave contains one partial (the fundamental). The second octave contains two partials, the third octave contains four partials, the fourth octave contains eight partials, and the fifth octave contains sixteen partials. These are the same numbers by which the ratios in the corresponding octave are divided in order to bring them within the scope of one octave.

As a consequence of this increase in the number of partials found in each octave, the intervals between adjacent partials get smaller as the harmonic spectrum is ascended. A series of pitches similar to the major diatonic scale is evident in the fourth octave. The fifth octave contains a scale which resembles the twelve tone chromatic scale with the addition of some extra notes. Notice that many of the ratios in the harmonic spectrum do not correspond exactly with the ratios of the traditional diatonic scale. The pattern of frequencies found in this harmonic spectrum suggests the use of scales based on the ratios therein.

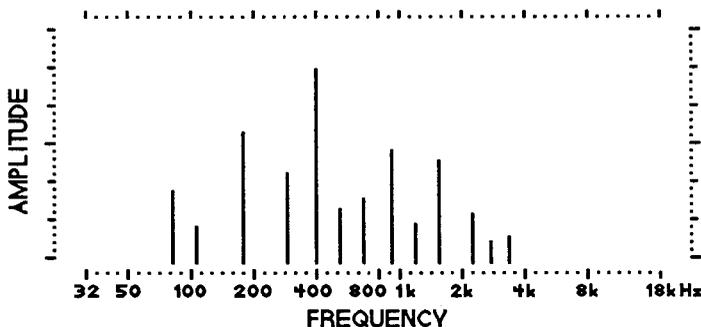
This harmonic spectrum is also known as the overtone series. It describes the natural scale of bugles and valveless horns such as hunting horns and Swiss alphorns. A performer plays different notes by varying the tension in the lips and the force with which air is blown into the instrument. Physical limitations prevent these instruments from playing much higher than the notes in the fourth octave. Much music was written for such instruments in this scale before the invention of valves was applied to brass-like instruments.

Electronic instruments suffer no such physical limitations. The scale represented in any octave of the overtone series can be easily realized using the DX7 II. Section 4 of this booklet contains the tuning data for scales found in the fourth and fifth octaves of this harmonic spectrum. Subsequent booklets will present the tuning data for scales found in higher octaves of the overtone series.

Percussion

The harmonic spectra of percussion instruments such as drums, mallet instruments, and bells are generally much more complex than those of wind and string instruments. The harmonic spectra of these instruments consist of partials with frequencies related by ratios not expressible in whole numbers. In fact, the frequency with which our ears associate a pitch (if a pitch can be discerned at all) may not be that of the fundamental. The following graph depicts a typical percussion (nonlinear) harmonic spectrum.

Nonlinear Harmonic Spectrum



The reason for this complexity lies in the fact that, unlike winds and strings, percussion instruments vibrate in as many as three directions at once. This creates a harmonic spectrum of many sine waves with frequencies in very complex relationships combining to form the timbre of each instrument. Despite the difficulty with which these spectra are analyzed, however, they play an important part in the determination of appropriate scales and tunings to be used with percussion instruments. This will be discussed in more detail shortly.

FM Synthesis

All of the instruments in Yamaha's DX series of synthesizers employ the technique of FM (Frequency Modulation) synthesis to create different sounds. This technique involves the modulation of one oscillator's frequency with the signal from another oscillator. In DX terminology, oscillators are known as operators. The modulated operator is called the carrier and the modulating operator is called the modulator. If you are new to FM synthesis, the Bibliography of the DX7 II Owner's Manual contains several references which may be of interest.

One of the advantages of FM synthesis is the relative ease with which complex harmonic spectra can be created. This type of synthesis is particularly adept at simulating bell, chime, and gong timbres which are difficult to achieve using other techniques. The linear spectra of wind and string instruments can also be realized. This wide range of possibilities provides the flexibility and freedom to create timbres and tunings with complementary character.

Beats

One of the most important acoustical phenomena found in the study of microtuning is known as beating. This occurs when two notes of slightly different frequencies are sounded simultaneously. Under these conditions, you will perceive a single pitch being modulated to grow alternately louder and softer. The cycles of this amplitude modulation are called beats. The frequency of the perceived pitch is the average of the two actual frequencies. This average is obtained by adding the two frequencies together and dividing the result by two. The rate at which the beats occur is merely the difference between the two actual frequencies.

For example, suppose that two tones with frequencies of 440 Hz and 442 Hz are sounded simultaneously. These tones are separated by an interval of only 7.85 cents. Under these conditions, you would perceive a single tone with a frequency of 441 Hz (mathematically, $440 \text{ Hz} + 442 \text{ Hz} = 882 \text{ Hz}$ and $882/2 = 441 \text{ Hz}$). The amplitude of this single perceived tone would be modulated (that is, growing louder and softer) at the rate of 2 Hz ($442 \text{ Hz} - 440 \text{ Hz} = 2 \text{ Hz}$). This modulation rate is called the beat frequency.

Timbre & Tuning

Beats can occur between various partials in the harmonic spectra of two complex tones sounding simultaneously. This is easily demonstrated using tones with linear harmonic spectra. For example, the note a perfect fifth above C is G. If these two notes are played together on an instrument with a linear harmonic spectrum, the second overtone above C should coincide with the first overtone above G. If the fundamental frequencies of these notes are not exactly in the ratio of $3/2$, the coincident overtones will not share exactly the same frequency. The resulting beats will occur as described above. Similar beats will also occur between many of the other partials in the two spectra.

The harmonic spectrum of a musical sound can be used to determine the most appropriate tuning for that timbre. Playing an equal tempered major triad with a linear spectrum will result in many overtone beats because the partials will not precisely coincide. The overall harmonic quality will be quite "rough." However, a major triad consisting of a pure third and fifth will sound very "smooth" because many of the partials in the linear harmonic spectrum will coincide exactly and exhibit no beats. This suggests an entire scale for use with linear harmonic timbres based on the ratios found in the linear spectrum. Such a scale is presented in Section 4.

The nonlinear spectra of percussion instruments are best suited for different scales and tunings. In general, neither equal tempered nor just tunings are appropriate for such instruments. Intervals and chords played in these tunings usually result in many overtone beats and a characteristic "rough" sound. The relationships between the partials in a nonlinear harmonic spectrum should be used to determine the intervals in more suitable tunings. Such tunings may not have any whole number ratios at all, not even a pure octave. However, there will be little or no overtone beating as intervals and chords are played. The music so performed will have a very "smooth" harmonic quality which simply sounds "right."

2

Creating Microtunings

While the preset microtunings provide some fundamental and useful examples of alternate intonations, the real fun begins when you start creating tunings of your own. This section shows you how to create new tunings by editing one of the presets. These new tunings can then be saved in the internal memory, in a RAM cartridge, or on floppy disk (if you are using a DX7 II FD).

Many of the procedures in this section also appear in the first booklet in the microtuning series, "Exploring the Preset Microtunings." These procedures are used to select different microtunings as well as display and examine their tuning data. They are also used to edit the tuning data of any preset. For convenience, these procedures are repeated in this section.

Editing Microtuning Data

Any preset tuning can be edited to create new intonations. The tuning data is edited in the following manner.

1. Press the Performance button.
2. Select a patch with which to play various notes and intervals while modifying one of the presets. The Grand Harpsichord patch (ROM Cartridge Bank 1 #18) works well.
3. Press the Edit button.
4. Press the Micro Tune button (#29) to access the Control Mode LCD display. Depending on what you have done before entering this mode, you may need to press the Micro Tune button a number of times until the words "Micro tuning" appear in the LCD display.
5. Use the -1/+1 buttons or the data entry slider to select the tuning you wish to modify. In many cases, modifying the Equal Temperament preset will be the most direct approach. This is how some of the presets were created in the first place. In some cases, one of the key-based presets will be more appropriate. The tunings in Section 4 specify the preset to modify during their creation.
6. Position the cursor using the cursor keys and make sure that the A and B parameters are ON using the -1/+1 keys. Otherwise, editing the tuning data will have no effect.
7. Press the Tune button (#14) to access the Edit mode LCD display. Depending on what you have done before entering this mode, you may need to press the Tune button a number of times until the words "Micro tuning" appear in the LCD display.
8. The note (and consequently, the key on the keyboard) available for editing is displayed in the >>>> <<<<< section of the display. The notes immediately above and below the selected note are displayed to the right and left respectively. The note selected for editing is displayed with its coarse and fine tuning parameter values and the absolute number of tuning units which represent the note. These values will be explained shortly.
9. There are two ways to select a note for editing.
 - a. Use the Internal and Cartridge buttons as left and right cursor controls to select adjacent notes for editing.
 - b. Hold the key corresponding to the note you wish to edit and press either the Internal or Cartridge key. The note you held will be displayed in the >>>> <<<<< section of the display.
10. Use the cursor keys to select the coarse or fine tuning parameter.
11. Use the data entry slider or the +1/-1 buttons to adjust the coarse or fine tuning parameters to the desired value.

Note:

You can switch directly between the Micro Tuning Control Mode display and the Edit Mode display by pressing the appropriate button (#29 and #14). This is very useful for selecting different presets and displaying their tuning data.

Coarse Tuning

The coarse tuning parameter allows you to assign any note in the equal tempered chromatic scale to the selected key on the keyboard. You could go so far as to assign all the keys on the DX7 II to the same note!

In more practical applications, the coarse tuning parameter provides the ability to create scales with varying numbers of notes. For example, a scale with nineteen notes per octave could be created. The 1/4 tone and 1/8 tone presets illustrate this concept as well. Take a look at the tuning data for these scales. It can be examined directly in the LCD display of the DX7 II or by referring to the first booklet in this series, "Exploring the Preset Microtunings."

The coarse tuning parameter is controlled by using the cursor keys to position the cursor next to the word "Coarse." The -1/+1 keys are used to specify the equal tempered pitch assigned to the note you wish to edit. Try changing the coarse tuning parameter while playing the note on the keyboard after each unit is added. You will hear the pitch played by that key change by equal semitones.

In the creation of scales with twelve tones, it is generally not necessary to assign a note which is different than the one indicated by the name of the key. This is evident in most of the twelve tone presets. This is another reason for using the equal temperament preset as a good starting point from which to create a key independent twelve tone tuning. The Pure Major, Pure Minor, Mean Tone, and Pythagorean presets all provide good starting points for key-based tunings.

Fine Tuning

The fine tuning parameter provides highly accurate control over the frequency of each note. It allows the addition or subtraction of one tuning unit from the number representing the note being edited. This tuning unit represents a very small frequency increment and will be discussed in depth shortly.

Examine the tuning data for any of the presets numbered from 2 to 8. Each note on the keyboard retains its original note value from the equal tempered chromatic scale, indicating that the coarse tuning parameter has not been changed in these tunings. However, the fine tuning parameter has been edited for almost every note. The degree to which each note has been adjusted away from equal temperament is indicated with a "+" or "-" followed by a number of tuning units.

Tuning Units

The fine tuning parameter is controlled by using the cursor keys to position the cursor next to the word "Fine." The -1/+1 keys are used to add or subtract one tuning unit from the absolute number of tuning units representing the note you wish to edit.

Try playing a note, releasing it, adding one tuning unit to the TU value, and playing the note again. Repeat this procedure several times. Can you hear a difference in pitch as each tuning unit is added to the note? The ability to perceive such small changes in pitch varies from person to person. It also depends on the range in which the edited pitch is found. The perception of small changes in pitch is more difficult for low notes than it is for high notes. This concept will be discussed in more detail in a subsequent booklet.

The DX7 II divides the octave into 1024 fine tuning units (abbreviated TU). As you'll recall, there are 1200 cents per octave (or 100 cents per equal tempered semitone). This means that each TU represents 1.17 cents ($1200/1024 = 1.17$).

Any coarse tuning parameter value can be adjusted by as much as +/- 42 TU. This means that an equal tempered semitone is equal to 85 TU (including the +0 fine tune value). To put it precisely, $85 \text{ TU} = 99.61 \text{ cents}$. The fact that TU do not correspond exactly with cents means that four of the equal tempered semitones must be assigned 86 TU in order to maintain perfect octaves. The C#, E, G, and A# coarse tune parameters can therefore be adjusted by as much as + 42/- 43 TU.

As you can see in the Edit mode LCD display, each note in the DX7 II is represented by an absolute number of tuning units. This number appears in parentheses next to the fine tuning parameter value. The corresponding absolute number of tuning units also appears under the notes adjacent to the note selected for editing. The range of values for these tuning units is 0 (C-2, 13.75 Hz) to 10794 (one quarter tone higher than G8, 12515.56 Hz).

Intervals & Tuning Units

The number of tuning units which most closely approximate the standard diatonic intervals are listed in the following table.

<i>Ratio</i>	<i>Interval</i>	<i>Number of Tuning Units</i>
2/1	Octave	1024
3/2	Perfect Fifth	599
4/3	Perfect Fourth	425
5/4	Major Third	330
6/5	Minor Third	269
5/3	Major Sixth	755
8/5	Minor Sixth	694
15/8	Major Seventh	929
9/5	Minor Seventh	868
9/8	Major Second	174
16/15	Minor Second	95
45/32	Tritone	504

Tuning Procedures

Tuning by Tuning Units

There are two basic procedures by which new microtunings are created for the DX7 II. These procedures are outlined below.

If the intervals between consecutive notes in the scale you wish to specify are known, you can calculate the absolute number of tuning units for each note. Here is the procedure for creating new microtunings on the DX7 II in this manner.

1. Select the scale or microtuning you wish to implement.
2. Determine the ratios of the intervals between consecutive notes.
3. Use the formula described in the second booklet in the microtuning series to convert the ratios between consecutive notes into DX7 II tuning units (TU). For this purpose, the formula is divided by 1.17 (the number of cents per TU) and given below. The letter "r" represents the decimal equivalent of the ratio under conversion. The letters "TU" represent the number of tuning units which span the interval described by the ratio.

$$TU = 3401.654369 \times \log r$$

4. Select the preset microtuning to be modified into the desired scale. If possible, choose a tuning which resembles your scale in its pattern of intervals. If your scale is key-based, select the Pure Major, Pure Minor, Mean Tone, or Pythagorean presets. Specify the key in which you plan to set the scale.
5. Select a note and a corresponding absolute number of tuning units to use as a reference pitch. It is to this pitch that the remaining notes will be tuned. Recall that each note in the DX7 II is represented by an absolute number of tuning units. Any one of these values may be used for the reference pitch.
6. If your scale bears much resemblance to the traditional diatonic scale, you may wish to leave the note A unchanged ($A3 = 5802$ TU) to be used as a reference pitch in order to retain the overall pitch level of the instrument.
7. Select the the pattern of keys on the keyboard which are best suited to play your scale. Baroque temperaments work best using the standard group of seven white and five black keys. Seven tone scales such as the Greek genera described in Section 4 fit well on the white keys without using the black keys at all. Scales with more than twelve notes per octave and scales without pure octaves require more radical modifications to the relationship between the keyboard and the notes it will play.
8. Select the initial range of pitches which is to be repeated in different ranges of the keyboard. Many microtunings use the octave as the measure of one musical pitch cycle. The notes found in one octave are repeated in the other octaves. In the DX7 II, octaves are determined by adding or subtracting 1024 to the number of TU representing any note. The range C3 - C4 is often used as the initial range.

9. Start a list of TU values by writing down the number of TU chosen as the reference. Add the number of TU in the interval between the reference pitch and the next note. Include this value in the list. Add the number of TU in the interval between this note and the next note. Continue this process until you have a list of the TU values for all the notes in the initial range.
10. Using the procedures outlined above, display the note data for the reference pitch in the Edit Mode. If necessary, use the coarse and fine parameters to specify the TU value for the reference pitch.
11. Display the note data for all notes in the initial range and set the TU value for each according to your list.
12. If your scale uses the octave as one musical pitch cycle, display the tuning data for the notes which form octaves with the notes in the initial range. Add or subtract 1024 from the initial range TU values as necessary to set the TU values for the rest of the keyboard.

Tuning by Ear

Many historical temperaments are set by detuning certain intervals by ear. This involves listening for the beat frequencies between coincident partials as described in Section 1 of this booklet. There are several specific methods for tuning these temperaments by ear. The Bibliography includes references to works which specify these methods. For now, here is a general procedure for tuning historical temperaments by ear.

1. Select the temperament you wish to set.
2. Select the patch with which to play various notes as you set the temperament. The Grand Harpsichord (ROM Cartridge Bank 1 #18) works well with historical tunings.
3. Select the preset to modify into the desired temperament. Since most Baroque temperaments can be played in any key, the equal tempered preset usually provides a good starting point.
4. Select the octave in which you will initially set the temperament. C3 - C4 is usually chosen for this purpose.
5. Select a reference pitch within the initial range to which the other notes in the initial octave will be tuned. As described earlier, A is usually selected for this purpose in order to maintain the overall pitch level of the instrument. However, the tuning instructions found in some of the references in the Bibliography start on C. It matters little which note you choose since the overall pitch level of the DX7 II can be adjusted with the Master Tune parameter. Select a reference note based on the instructions you are following for the specific temperament.

6. Tune the intervals in the initial range according to the instructions for the desired temperament using the fine tuning parameter in the Edit mode. This will usually involve tuning perfect fourths and fifths. Some of these intervals will be tuned “pure” to exhibit no beats between the fundamentals or the partials. Others will be tuned pure and then detuned until certain beat frequencies are heard among the partials. This is the result of reducing a pure fourth or fifth by a fraction of a Pythagorean comma. Some tuning methods specify the fractional comma between the appropriate notes while other methods specify the beat frequencies. Older tuning methods use instructions such as “reduce the interval by as much as the ear can tolerate.” Of course, this is a very subjective evaluation.
7. Once the temperament is set in the initial range, tune pure octaves between the notes therein and the corresponding notes in the other octaves. This can be done in two ways.
 - a. Add or subtract 1024 from the absolute number of tuning units which represent the notes in the initial range to determine the number of TU to assign the notes which form octaves with them. Use the fine tuning parameter to assign these TU values.
 - b. Play each note in the initial range and the note with which it forms an octave simultaneously. Adjust the fine tuning parameter of the note outside of the initial range until it forms a pure octave with its counterpart within the initial range.
8. Repeat Step 7 in the different octaves until the entire keyboard has been tuned.

3

Saving Microtunings

Once you have created a tuning, you will probably wish to save it for future use or modification. Tunings can be saved in the internal memory, a RAM cartridge, or on floppy disk (in the case of the DX7 II FD).

Internal Memory

The internal memory has two locations in which your tunings may be saved. These locations are called User 1 and User 2. The procedure for storing a tuning in one of these locations is outlined below.

1. Since you are already in Edit mode, the tuning data is probably displayed in the LCD.
2. Press the Tune button (#14) several times until the Master tuning/Memory protect display appears.
3. Move the cursor to the INT Memory protect parameter and press the -1/NO button to turn the internal memory protection OFF.
4. Press the Tune button (#14) to display the tuning data again.
5. Press and hold the Store button. The LCD display will indicate in which part of the memory (Internal or Cartridge) the data will be stored.
6. Press the Internal button while continuing to hold the Store button.
7. Press either the 1 or 2 number button to specify the desired user tuning memory location while continuing to hold the Store button.
8. Press the +1/YES button while continuing to hold the Store button.

Your tuning data has now been stored in the selected internal memory location.

Cartridge

Up to 63 microtunings can be stored in a Yamaha RAM4 Data Cartridge. The cartridge must first be formatted to store this type of data. The formatting procedure is outlined below.

Formatting a Cartridge

1. Make sure that the cartridge Memory Protect switch is turned OFF.
2. Press the Edit button.
3. Press the Tune button (#14) to access the Master tuning/Memory protect LCD display.
4. Move the cursor to the CRT Memory protect parameter and press the -1/NO button to turn the cartridge memory protection OFF.
5. Press the Cartridge button (#15) several times until the "Micro tuning" display appears.
6. Press the right cursor button (>) to move the cursor to the format parameter.
7. Press the +1/YES button. The message "Are you sure?" will appear in the LCD display.
8. Press the +1/YES button once again to confirm your action.

The cartridge is now formatted to store microtuning data.

Saving Data on a Cartridge

Each microtuning that you create is saved in the cartridge individually. Any of the preset or user microtunings found in the internal memory can be modified and stored in the cartridge. The procedure for storing this data is outlined below.

1. Make sure that the cartridge Memory Protect switch is turned OFF.
2. Since you are already in Edit mode, the tuning data is probably displayed in the LCD.
3. Press the Tune button (#14) several times until the Master tuning/Memory protect display appears.
4. Move the cursor to the CRT Memory protect parameter and press the -1/NO button to turn the cartridge memory protection OFF.
5. Press the Tune button (#14) to display the tuning data again.
6. Press and hold the Store button. The LCD display will indicate the part of memory last specified for storage.
7. Press the Cartridge button while continuing to hold the Store button.
8. Press any of the number buttons (and the 1-32/33-64 button if necessary) to specify the desired cartridge memory location while continuing to hold the Store button.
9. Press the +1/YES button while continuing to hold the Store button.

Your microtuning data has now been stored in the selected cartridge memory location. As you can repeat this procedure for as many as 63 different microtunings, you may wish to keep a log of their names and numerical locations in the cartridge.

Disk

Formatting a Disk

The DX7 II FD includes a 3.5 inch floppy disk drive which can also be used to store microtuning data. A disk must first be formatted before it can accept microtuning data. This procedure is outlined below.

1. Press the Edit button.
2. Press the Disk button (#16) to access the Disk format LCD display.
3. Make sure that the memory protect tab covers the small square hole in the upper right corner of the 3.5 inch disk you intend to use.
4. Insert the disk into the disk drive slot on the left side of the instrument.
5. Press the +1/YES button. The LCD display will ask "Are you sure?" This will remind you that formatting a disk will erase any data already stored on it.
6. Press the +1/YES button again. The formatting process will take about 70 seconds.

Saving Data on a Disk

As you may recall from the DX7 II Owner's Manual, a formatted floppy disk can be used to save the entire contents of the internal or cartridge memory. The Memory Layout diagram found on page 62 of that manual indicates that microtuning data can only be saved on a disk from a cartridge. This is known as a "bulk dump" because all of the microtuning data in the cartridge is saved on the disk at once. The procedure for performing a microtuning data "bulk dump" from cartridge to disk is outlined below.

1. Press the Edit button.
2. Press the Disk button (#16) to access the Disk CRT LCD display.
3. Make sure that the memory protect tab covers the small square hole in the upper right corner of the 3.5 inch disk you intend to use.
4. Insert the 3.5 inch disk into the disk drive slot on the left side of the instrument.
5. Press the +1/YES button. Then use the +1/-1 buttons to access a blank file location.
6. Press the right cursor button (>) once.
7. Press and hold the Edit/Character button, and type in a name for the file you wish to save on the disk.
8. Press the +1/YES button again. The display will ask "Are you sure?"
9. Press the +1/YES button once again to confirm your action.

Loading Data from a Disk

In order to use or edit microtunings, they must be located in a cartridge or internal memory. If the microtunings you wish to use are saved on a disk but not on a cartridge, they must first be transferred to a cartridge. This procedure is outlined below.

1. Insert the cartridge to which the microtuning data will be loaded. Make sure that the memory protect switch is OFF.
2. Press the Edit button.
3. Press the Tune button (#14) to access the Master tuning/Memory protect LCD display.
4. Move the cursor to the CRT Memory protect parameter and press the -1/NO button to turn the cartridge memory protection OFF.
5. Press the Disk button (#16) to access the Disk CRT LCD display.
6. Insert the disk containing the microtuning file you wish to load into the disk drive slot on the left side of the instrument.
7. Press the +1/YES button.
8. Use the +1/-1 buttons to select the file you wish to load.
9. Press the right cursor button (>) twice.
10. Press the +1/YES button. The display will show the format of the RAM cartridge currently in the cartridge port and ask "ok?"
11. Press the +1/YES button again. The display will ask "Are you sure?"
12. Press the +1/YES button once again to confirm your action. The selected file of microtunings will be loaded into the cartridge from the disk.

4

Twelve Tone Tunings

The first three booklets in this series have presented much information concerning microtuning and the DX7 II. A comprehensive outline of the preset microtunings was followed by a summary of the mathematics and history of microtonality. This booklet presents the relevant principles of acoustics as well as the procedures by which new microtunings are created and saved on the DX7 II. All of this material is in preparation for the presentation of new tuning data you can use with your DX7 II.

This section presents the tuning data for several microtunings with twelve or fewer notes per octave. These microtunings are well suited to the conventional keyboard of the DX7 II. Each table of tuning data is accompanied by a short description and the DX7 II preset from which it is derived. In the case of microtunings with fewer than twelve notes per octave, only those keys which are used will be listed. Any keys not listed in a table are not used with that particular microtuning.

Ling Lun

As discussed in the second booklet of the microtuning series, Ling Lun was the first recorded musical theorist. He created two sets of six bamboo tubes called lu which formed two whole tone scales. These scales were one half step apart. Although the two sets of lu were probably not used together, this is the first recorded occurrence of a twelve tone scale.

Consecutive notes in this twelve tone scale are separated by one of two intervals. The ratios of these “half steps” are $256/243$ (90.2 cents or 77 TU) and $2187/2048$ (113.7 cents or 97 TU). If you examine the tuning data for the Pythagorean preset presented in the first booklet of the microtuning series, you’ll see that it bears a close resemblance to the scale of Ling Lun. This is no surprise since both scales are derived using the method of Harmonic Proportion. As you may recall, this tuning procedure divides a vibrating object (a string or a bamboo tube) into smaller pieces based on a fraction of the original object’s length (the fraction is $1/3$ in this case).

The Pythagorean preset in the key of C is modified according to the following table to produce the scale of Ling Lun. There are two sets of notes forming pentatonic scales which were probably used most often. They can be heard by playing the keys C, D, E, G, A and C#, D#, E# (F), G#, A# on the DX7 II keyboard. The two whole tone scales produced by the lu can be heard by playing the keys C, D, E, F#, G#, A# and Db, Eb, F, G, A, B. The DoubleHarp-SongFlute patch (ROM Bank 1 #23) works well to simulate the sound of end-blown bamboo tubes and a plucked string instrument.

Note Name	Coarse Tune	Fine Tune	Tuning Units	Δ ET Cents	Interval Size TU	Interval Size Cents
>>> C 3 <<<	C 3	-5	(5029)	-5.86	97	113.67
>>> C#3 <<<	C# 3	+6	(5126)	+7.03	77	90.23
>>> D 3 <<<	D 3	-2	(5203)	-2.34	97	113.67
>>> D#3 <<<	D# 3	+10	(5300)	+11.72	77	90.23
>>> E 3 <<<	E 3	+1	(5377)	+1.17	97	113.67
>>> F 3 <<<	F 3	+13	(5474)	+15.23	77	90.23
>>> F#3 <<<	F# 3	+5	(5551)	+5.86	77	90.23
>>> G 3 <<<	G 3	-4	(5628)	-4.69	97	113.67
>>> G#3 <<<	G# 3	+8	(5725)	+9.38	77	90.23
>>> A 3 <<<	A 3	+0	(5802)	+0.00	97	113.67
>>> A#3 <<<	A# 3	+11	(5899)	+12.89	77	90.23
>>> B 3 <<<	B 3	+3	(5976)	+3.52	77	90.23
>>> C 4 <<<	C 4	-5	(6053)	-5.86		

Scholar's Lute

The "Scholar's Lute" is a Chinese bronze stringed instrument which dates from before the third century B.C. Its seven tone scale is based on small number ratios.

1/1	8/7	6/5	5/4	4/3	3/2	5/3	2/1
	8/7	21/20	25/24	16/15	9/8	9/8	6/5

As this is a form of just intonation, the Pure (Major) preset in the key of C is modified according to the table below. The DX7 II keys to play in order to hear the scale are C, D, D#, E, F, G, and A. The other keys on the keyboard are not used. The HarpStrum voice (INT 11) in the DoubleHarp-SongFlute patch (ROM Bank 1 #23) or the Koto voice (INT 29) in the Temple Gong-Shami patch (ROM Bank 1 #29) work well with this tuning.

Note Name	Coarse Tune	Fine Tune	Tuning Units	Δ ET Cents	Interval Size	
					TU	Cents
>>> C 3 <<<	C 3	+13	(5047)	15.23		
>>> D 3 <<<	D 3	+41	(5246)	48.05	199	233.20
>>> D#3 <<<	D# 3	+28	(5318)	32.81	72	84.38
>>> E 3 <<<	E 3	+2	(5378)	2.34	60	70.31
>>> F 3 <<<	F 3	+12	(5473)	14.06	95	111.33
>>> G 3 <<<	G 3	+15	(5647)	17.58	174	203.91
>>> A 3 <<<	A 3	+0	(5802)	0.00	155	181.64
>>> C 4 <<<	C 4	+13	(6071)	15.23	269	315.23

Greek Tetrachords & Genera

The scales of ancient Greece are based on descending four note sequences called tetrachords. The outer notes of a tetrachord form the interval of a pure perfect fourth (4/3). There were many different distributions of the notes within a tetrachord. In modern musical terms, a tetrachord might be specified as E D C B or A G F E.

By joining two tetrachords, a seven tone scale results. Such a joining is called conjunct if one note from each tetrachord is coincident. For example, the two tetrachords above can be joined conjunctly by starting with A G F E and ending with E D C B and adding an extra A to form an octave with the first note (A G F E D C B A). The first tetrachord in the scale ends on an E and the second one begins on an E making this the coincident note. The joining of two tetrachords can also be disjunct if the two tetrachords are separated by a pure major second (9/8). For example, a disjunct scale can be constructed by starting with E D C B and ending with A G F E (E D C B A D F E). The notes B and A are separated by a pure major second (9/8).

Genera

The tetrachords and scales formed in this manner fall into three basic categories called genera (pronounced gen-a-ra). These are known as the diatonic, chromatic, and enharmonic genera. Ptolemy (139 A.D. - ?) was instrumental in the compilation of the various scales which comprise the genera. Each genus is characterized by the specific intervals between the notes in the two tetrachords. These characteristics will be discussed as the tuning data for an example of each genus is presented.

In all three of the following examples, the Equal Temperament preset is modified to create the scales. These are seven tone scales played on the white keys from E to E. The black keys are therefore not used. There are several ROM sounds which work well with these microtunings including both voices (INT 11, INT 16) in the DoubleHarp-SongFlute patch (ROM Bank 1 #23), the PickGuitar voice (INT 3) in the Acoustic PickGuitar patch (ROM Bank 1 #13), and the Englishorn voice (CRT 25) in the StringPad-Englishorn patch (ROM Bank 2 #24).

Diatonic Genera

The diatonic tetrachord consists of two “whole steps” and one “half step.” Two such tetrachords are joined disjunctly to form a seven tone scale. As you can see in the pattern below, there are actually two different whole steps.

$$\begin{array}{cccccccc} 1/1 & 16/15 & 6/5 & 4/3 & 3/2 & 8/5 & 9/5 & 2/1 \\ & 16/15 & 9/8 & 10/9 & 9/8 & 16/15 & 9/8 & 10/9 \end{array}$$

The tuning data below uses only the white keys on the DX7 II keyboard. The scale is arranged to begin and end on E rather than on C for reasons of convention and tradition.

Note Name	Coarse Tune	Fine Tune	Tuning Units	Δ ET Cents	Interval Size	
					TU	Cents
>>> C 3 <<<	C 3	+13	(5047)	15.23		
>>> D 3 <<<	D 3	+16	(5221)	18.75	174	203.91
>>> E 3 <<<	E 3	+1	(5377)	1.17	156	182.81
>>> F 3 <<<	F 3	+11	(5472)	12.89	95	111.33
>>> G 3 <<<	G 3	+14	(5646)	16.41	174	203.91
>>> A 3 <<<	A 3	+0	(5802)	0.00	156	182.81
>>> B 3 <<<	B 3	+3	(5976)	3.52	174	203.91
>>> C 4 <<<	C 4	+13	(6071)	15.23	95	111.33

Chromatic Genera

The chromatic tetrachord consists of one "quarter step," one "half step," and one minor third. As in the previous example, two tetrachords are joined disjunctly to form a seven tone scale.

$\frac{1}{1}$ $\frac{28}{27}$ $\frac{10}{9}$ $\frac{4}{3}$ $\frac{3}{2}$ $\frac{14}{9}$ $\frac{5}{3}$ $\frac{2}{1}$
 $\frac{28}{27}$ $\frac{15}{14}$ $\frac{6}{5}$ $\frac{9}{8}$ $\frac{28}{27}$ $\frac{15}{14}$ $\frac{6}{5}$

Again, the tuning data below is arranged to play this scale from E to E on the DX7 II keyboard.

Note Name	Coarse Tune	Fine Tune	Tuning Units	Δ ET Cents	Interval Size TU	Interval Size Cents
>>> C 3 <<<	C 3	-28	(5006)	-32.81		
>>> D 3 <<<	C# 3	-12	(5108)	-113.67	102	119.53
>>> E 3 <<<	E 3	+1	(5377)	1.17	269	315.23
>>> F 3 <<<	F 3	-30	(5431)	-35.16	54	63.28
>>> G 3 <<<	F# 3	-13	(5533)	-116.02	102	119.53
>>> A 3 <<<	A 3	+0	(5802)	0.00	269	315.23
>>> B 3 <<<	B 3	+3	(5976)	3.52	174	203.91
>>> C 4 <<<	C 4	-28	(6030)	-32.81	54	63.28

Enharmonic Genera

The enharmonic tetrachord consists of two “quartertones” and a major third. The scale below is typical of this genus.

$\frac{1}{1}$ $\frac{28}{27}$ $\frac{16}{15}$ $\frac{4}{3}$ $\frac{3}{2}$ $\frac{14}{9}$ $\frac{8}{5}$ $\frac{2}{1}$
 $\frac{28}{27}$ $\frac{36}{35}$ $\frac{5}{4}$ $\frac{9}{8}$ $\frac{28}{27}$ $\frac{36}{35}$ $\frac{5}{4}$

As before, the tuning data below is played from E to E on the DX7 II keyboard.

Note Name	Coarse Tune	Fine Tune	Tuning Units	Δ ET Cents	Interval Size	
					TU	Cents
>>> C 3 <<<	C 3	-28	(5006)	-32.81		
>>> D 3 <<<	C 3	+14	(5048)	-183.98	42	49.22
>>> E 3 <<<	E 3	+1	(5377)	1.17	329	385.55
>>> F 3 <<<	F 3	-30	(5431)	-35.16	54	63.28
>>> G 3 <<<	F 3	+12	(5473)	-186.33	42	49.22
>>> A 3 <<<	A 3	+0	(5802)	0.00	329	385.55
>>> B 3 <<<	B 3	+3	(5976)	3.52	174	203.91
>>> C 4 <<<	C 4	-28	(6030)	-32.81	54	63.28

Barnes-Bach Temperament

In 1979, John Barnes performed a comprehensive statistical analysis of the use of various intervals in J. S. Bach's "Well Tempered Clavier." The purpose of this analysis was to determine the temperament most likely intended by Bach to be used in the performance of the pieces in this famous collection.

Barnes' conclusion was that Bach probably used a variation of the Vallotti & Young temperament. As you may recall from the first booklet in the microtuning series, this temperament is one of the presets found in the permanent memory of the DX7 II. It is based on a Pythagorean tuning of pure fifths in which the first six fifths are reduced by 1/6 of a Pythagorean comma. In Barnes' variation, the sixth fifth is tuned pure and the seventh fifth is reduced by 1/6 of a comma.

This variation is very easy to achieve by modifying the Vallotti & Young preset in the DX7 II. It requires that only one note be changed. The preset is derived starting on C, so the sixth fifth is between B and F#. Raising the F# by 3 TU ($1/6 \text{ comma} = 23.46/6 = 3.91 \text{ cents} = 3 \text{ TU}$) will simultaneously tune the fifth between B and F# pure while reducing the fifth between F# and C# by 1/6 comma.

The most suitable patch for this microtuning is the Grand Harpsichord (ROM Bank 1 #18). For a lighter harpsichord sound, use only the Harpsiwire voice (INT 64) in a single voice patch.

Note Name	Coarse Tune	Fine Tune	Tuning Units	Δ ET Cents	Interval Size TU	Interval Size Cents
>>> C 3 <<<	C 3	+5	(5039)	+5.86	81	94.92
>>> C#3 <<<	C# 3	+0	(5120)	+0.00	87	101.95
>>> D 3 <<<	D 3	+2	(5207)	+2.34	87	101.95
>>> D#3 <<<	D# 3	+4	(5294)	+4.69	80	93.75
>>> E 3 <<<	E 3	-2	(5374)	-2.34	94	110.16
>>> F 3 <<<	F 3	+7	(5468)	+8.20	79	92.58
>>> F#3 <<<	F# 3	+1	(5547)	+1.17	88	103.13
>>> G 3 <<<	G 3	+3	(5635)	+3.52	84	98.44
>>> G#3 <<<	G# 3	+2	(5719)	+2.34	83	97.27
>>> A 3 <<<	A 3	+0	(5802)	+0.00	91	106.64
>>> A#3 <<<	A# 3	+5	(5893)	+5.86	76	89.06
>>> B 3 <<<	B 3	-4	(5969)	-4.69	94	110.16
>>> C 4 <<<	C 4	+5	(6063)	+5.86		

Fourth Octave Harmonic

The fourth octave of the linear harmonic spectrum defines an eight tone scale which resembles the traditional major scale. It includes a sharp fourth degree, a flat sixth degree, and a flat seventh degree in addition to a pure major seventh. The ratios associated with this scale are given below. Notice the interesting pattern of the ratios between consecutive notes.

1/1	9/8	5/4	11/8	3/2	13/8	7/4	15/8	2/1
	9/8	10/9	11/10	12/11	13/12	14/13	15/14	16/15

This is a key-based tuning with a pure second, major third, fifth, and major seventh. The Pure Major preset in the key of C is therefore modified to create this scale. The relevant keys on the keyboard are C, D, E, F, G, A, A#, and B which correspond to the eighth through fifteenth harmonics. Any sound with a linear harmonic spectrum (such as strings or winds) will work well with this microtuning.

Note Name	Coarse Tune	Fine Tune	Tuning Units	Δ ET Cents	Interval Size	
					TU	Cents
>>> C 3 <<<	C# 3	-36	(5084)	58.59		
>>> D 3 <<<	D# 3	-32	(5258)	62.11	174	203.91
>>> E 3 <<<	E 3	+38	(5414)	44.53	156	182.81
>>> F 3 <<<	F# 3	+9	(5555)	110.16	141	165.23
>>> G 3 <<<	G# 3	-33	(5684)	60.94	129	151.17
>>> A 3 <<<	A 3	+0	(5802)	0.00	118	138.28
>>> A#3 <<<	A# 3	+23	(5911)	26.95	109	127.73
>>> B 3 <<<	B 3	+40	(6013)	46.88	102	119.53
>>> C 4 <<<	C# 4	-36	(6108)	58.59	95	111.33

Chromatic Fifth Octave Harmonic

An entire twelve tone chromatic scale can be created from the partials in the fifth octave of the linear harmonic spectrum. Since there are sixteen tones in the fifth octave, only twelve are used in this microtuning. The scale degrees which correspond with the pure just intervals are the major second, major third, perfect fifth, and major seventh. The ratios for the scale are given below.

1/1	17/16	9/8	19/16	5/4	21/16	11/8
17/16	18/17	19/18	20/19	21/20	22/21	
	3/2	13/8	27/16	7/4	15/8	2/1
12/11	13/12	27/26	28/27	15/14	16/15	

This microtuning is also based on the Pure (Major) preset in the key of C. It uses all twelve keys of the octave which correspond to the sixteenth, seventeenth, eighteenth, nineteenth, twentieth, twenty-first, twenty-second, twenty-fourth, twenty-sixth, twenty-seventh, twenty-eighth, and thirtieth partials. Any timbre with a linear harmonic spectrum is well suited to this microtuning.

Note Name	Coarse Tune	Fine Tune	Tuning Units	Δ ET Cents	Interval Size	
					TU	Cents
>>> C 3 <<<	C 3	-6	(5028)	-7.03		
>>> C#3 <<<	C# 3	-2	(5118)	-2.34	90	105.47
>>> D 3 <<<	D 3	-3	(5202)	-3.52	84	98.44
>>> D#3 <<<	D# 3	-8	(5282)	-9.38	80	93.75
>>> E 3 <<<	E 3	-18	(5358)	-21.09	76	89.06
>>> F 3 <<<	F 3	-31	(5430)	-36.33	72	84.38
>>> F#3 <<<	F 3	+38	(5499)	-55.08	69	80.86
>>> G 3 <<<	G 3	-4	(5628)	-4.69	129	151.17
>>> G#3 <<<	G# 3	+29	(5746)	33.98	118	138.28
>>> A 3 <<<	A 3	+0	(5802)	0.00	56	65.63
>>> A#3 <<<	A# 3	-32	(5856)	-37.50	54	63.28
>>> B 3 <<<	B 3	-15	(5958)	-17.58	102	119.53
>>> C 4 <<<	C 4	-6	(6052)	-7.03	94	110.16

Notes

Notes
