Introduction to Pipe Scales

By Blair Batty

Forward

I am a retired organbuilder. This PDF is some of my personal notes about pipe scales, which I gathered over my lifetime. It was intended for my own education and interest; I never intended to publish. As such, I freely plagiarized and copied anything interesting, and often failed to keep track of sources. I am not an academic; this is a hobby that got away out-of-hand…

This book is intended to give the reader a basic understanding of what is meant by pipe organ scaling. I start by explaining how the diameter affects the sound of the pipe. Then I explain the Topfer HT method of graphing scales. A quick history of systems of laying out scales is given. Finally, a brief description is given about how scales are chosen and used.

This book also contains information send to me by friends, as well as information from various books and publications. Much of it I wrote down decades ago. I apologise for the messiness of my notes. Many were made decades ago and time and my arthritis preclude redoing it. I'm to blame for the typing and design; Microsoft Word is truly cryptic.

If I've used your photo or material, please contact me and I'll either acknowledge you, or remove it; however you wish. Do contact me, if you have any comments, corrections, sources or questions. I won't be offended…

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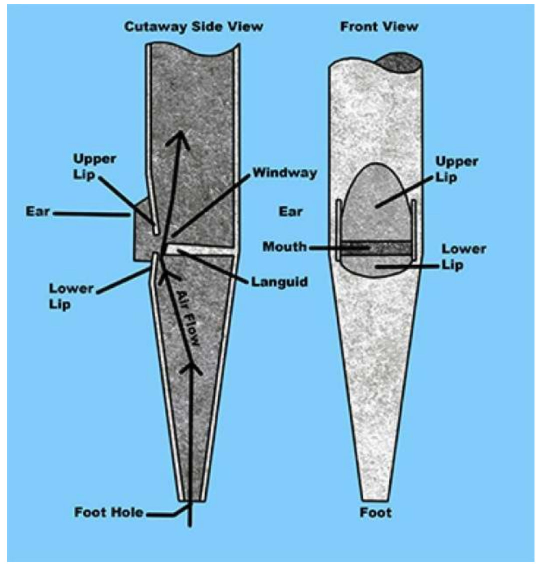
How A Pipe Works



An organ pipe consists of two closely coupled parts: the mouth, and air inside the resonator. The mouth acts as a broadband noise generator, issuing energy in the form of wind, setting the air in the resonator in motion.

That air resonates in the tube. The sound of the pipe is the natural resonances - excited, selected and amplified from the broadband noise, by the tube.

The length of the tube sets the pitch of the pipe. The resonator has a feedback loop forcing the mouth to lock in phase to the body's pitch.

The mouth's cutup acts as a filter. Raising the cutup attenuates higher frequencies in the noise generated by the mouth. The diameter of the tube also acts as a filter. Narrowing the tube attenuates the lower frequencies.

Both the mouth and the resonator control the tone quality of the pipe, and they are closely coupled together while the pipe is sounding.

About Pipe Scales

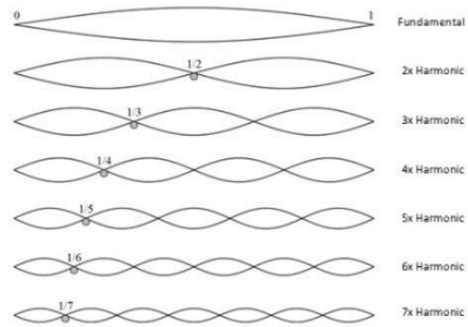
Pipe scales are the dimensions of the pipes. Tonal character and loudness depend upon the scale and voicing of the pipes. Scaling can refer to just the diameter, or it can refer to a bunch of pipe measurements: the pipe inside diameter, mouth width, cutup, flue and toe hole. Differences in scaling and voicing are why a Willis organ sounds different than a Metzler.

The scale, or pipe diameter *(always inside diameter)*, is the most significant measure, because it is fixed and unchangeable once the pipemaker builds the pipes. The voicer can adjust most of the other variables. The scales are determined by the tonal director, in accordance with company tradition, his experience and in reference to the room's size and acoustics. In historical surveys, it is common to measure all the "C" notes.

Pipe makers start by laying out and cutting the parts of a pipe as flat pieces, which are most conveniently measured by circumference. Pipemakers will work with circumferences when laying out the scale. *(Photo at left shows stacks of pipe bodies and feet, one stop per stack. They are ready to be rolled up and soldered.)*

On the other hand, consultants, designers, voicers, tonal directors, pseudo-experts and theorists like to measure existing and historical pipes. Its difficult to measure inside circumferences, but easy to measure in diameters, so they always work with diameters. In this book I'll be using diameters, except when working with pipemaker layout methods, which use circumferences.

Harmonics

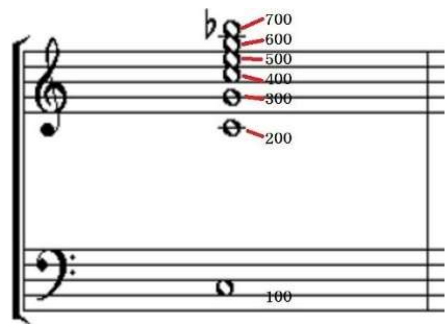


A vibrating string has only one vibrating part, so only produces a fundamental frequency, plus harmonic overtones (integer multiples of the fundamental). Harmonics occur at nodes where the string's motion is minimal.

The harmonic series follows fractions of the string length (e.g., 1/2, 1/3, 1/4), corresponding to intervals like octaves, fifths, and thirds. For a string fixed at both ends, the frequencies of the harmonics follow a simple relationship:

$$\mathbf{f_n = n \times f_1}$$

- f_n = frequency of the nth harmonic,
- n = harmonic number (1, 2, 3...)
- f_1 = fundamental frequency.



So, for example, with a fundamental harmonic of 100Hz you've a harmonic series of 100, 200, 300, 400, 500, 600Hz…

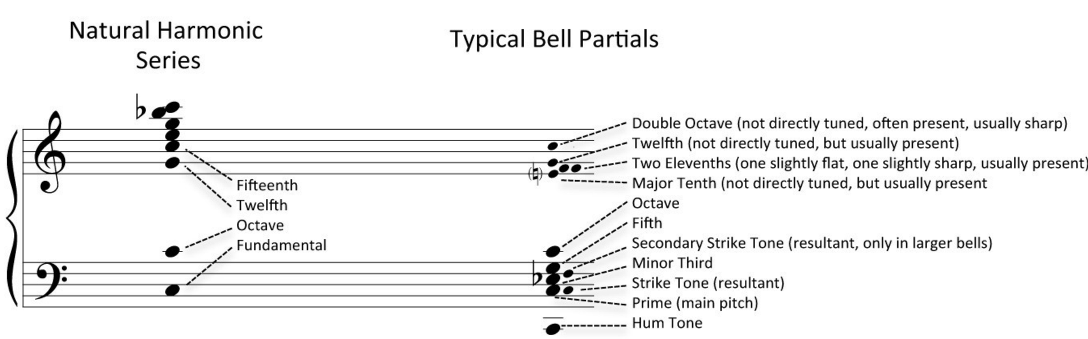
If the fundamental were a C note, you would get overtones of G, C, E, G… These harmonics are where we get our western music scale from, because they sound concordant to us.

Resonances

Every object or system has a frequency *(or frequencies)* at which it naturally vibrates when disturbed; these are called natural resonances. These resonances are not necessarily harmonic and can sometimes be quite discordant.

When struck, bells produce sound through a complex interplay of resonance, frequency, and harmonics. A bell has a dominant fundamental and harmonic series. But because of the bell's complex shape it also has other resonances, some of which could be highly discordant to the dominant fundamental.

Different parts of the bell are responsible for the various resonances. The bell maker trims the insides of the bell on a lathe, to tune the fundamental and various harmonics and resonances to improve concordances.



Organ Pipe Resonances

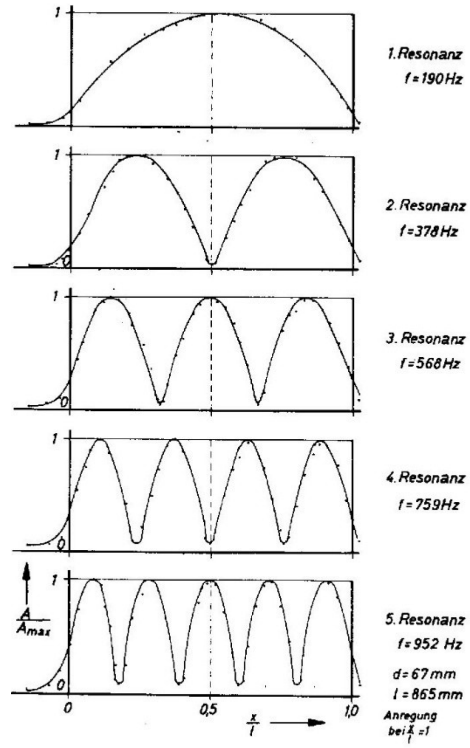
If we forget about the pipe foot for now, we can imagine the pipe resonator to be a simple tube, open at both ends. At one end is the circular opening of the top of the pipe. The other end is the rectangular opening of the mouth.

Pipe resonance is the sound wave travelling the length of the tube and bouncing back and forth. The longer the tube, the longer it takes that sound wave to traverse the length of the pipe, and the lower the frequency of the resonance. It's easy to calculate the theoretical resonance of a tube.

$$f_n = nv/2L$$

n=1,2,3, f = frequency, V = the speed of sound, L = tube length

However, harmonics and resonance are not the same thing. There is an experiment where you put a speaker connected to a sound sweep generator near the pipe opening. Using a spectrum analyzer, you can measure the frequency of each resonance of the pipe. Do it, and you'll discover the fundamental of the tube is actually a little longer than the theoretical. This is because the sound wave overshoots each end of tube due to inertia, so that the sound wave ends up stretched a little longer than the tube.



This error, at each end of the tube, is called the end-correction. The end-correction of the fundamental, for one end of the tube, is about 0.6 times the tube radius. Being larger, the overshoot is greater at the top of the pipe than at the mouth. This explains why the node, and harmonic hole placement *(of a harmonic pipe*) is 5:9 along the resonator. The higher the harmonic frequency, the more the end correction affects it. Because the natural resonances of the tube don't quite line up with the harmonics, the resonances don't reinforce the harmonics as much as you would expect.

The openings at each end of the tube are tuned ports, and has impedance that affects end-correction. Raising the cutup, tuning slots, ears, rollers, beards and other appliances and treatments, to either end, will also change the impedance and the end-correction.

Resonance, Scales and Tone

Finally, we get to the interesting bit. Wider tubes have a larger end correction, meaning the frequency mismatch of resonances to harmonics is more significant for wider tubes. This pushes the fundamental out of phase with the overtones, suppressing reinforcement of the harmonics: the sound gets duller. This effect is more pronounced as the harmonics get higher pitched. Conversely, narrower tubes have harmonics that are closer in phase, better in tune, making the sound brighter. Different amount of mismatch means different levels of reinforcement.

Don't worry if you don't understand this; the last couple of pages just says that fat pipes are dull, skinny pipes sound bright! To learn more the best reference is "Orgeln, Kirchen und Akustik" by Werner Lottermoser *(written in German)*.

Mouth width

The more energy that flows thru a pipe in the form of wind, the louder the pipe is. So, mouth size shows loudness intent; if you want a loud pipe, you give it a bigger mouth. Organ pipemouths are usually calibrated in fractions of the pipe circumference, for example: 2/7, ¼, 2/9, 1/5 and 1/6 of the circumference. One quarter of the circumference of the resonator is considered normal.

Since the scale and mouth width are baked into the pipes by the pipemaker and not alterable by the voicer, they are the surest sign of the designer's intent. The mouth size is a proportion of the scale *(the mouth gets bigger if the scale increases).* If the designer chooses a larger scale and keeps a ¼ mouth, you know they want a bigger sound. But if they choose a bigger scale, but make the mouth smaller than the standard ¼ size, you know they wanted a flutier, but not louder sound.

The size of the mouth opening *(mouth x cutup)* affects the tone of the pipe. A wide mouth with a low cutup, compared to a narrow mouth with a higher cutup (equivalent area openings), will sound similar. The bigger the mouth area is, the greater the end correction, and the duller the pipe

Getting Back to Scales

The most important scale measurement is the diameter, which strongly relates to the loudness of the fundamental. A bigger diameter pipe has a larger mass of air resonating inside it. The larger pipe also has a proportionally larger mouth, larger windway, larger toehole and larger airflow, driving that resonating air mass harder. This results in a louder pipe.

You will remember on the previous page we learned that because of end correction, larger diameter tubes become duller: the upper harmonics are reinforced less. In the same way, when you increase the scale of an organ pipe the fundamental get louder and so do the harmonics. But the harmonics don't gain a much as the fundamental, because of end correction. So, a bigger pipe sounds louder but duller.

Thus, changing the diameter of the pipe give you a range of loudness and tone. This ranges from softer, narrower Giegen Diapason, all the way up to loud, dull Phonon Diapasons. However, if you go too narrow you get a Dulciana; too fat and it becomes an open Flute.

Of course there is a little room for adjustment. If a pipe is too narrow you can make it sound a little bigger by giving it more wind and cutting it up a little. If a pipe is too fat you can make it sound a little smaller by closing the toe and using a lower cutup.

Diameter determines the loudness of the fundamental.
Cutup fine-tunes the harmonic content.
Toehole/mouthwidth/windway fine-tunes the loudness.

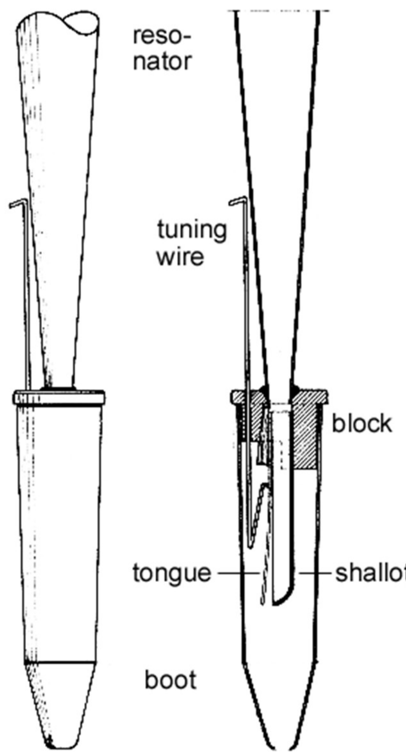
A pipe works best when it is driven properly. If you give it too much or not enough wind, it will speak poorly and inefficiently. It's impossible to get a loud fundamental out of a skinny pipe. So, you should choose the scale according to the strength of the fundamental you require. You can adjust the harmonics *(pipe brightness)* by adjusting the cutups.

Cutups

Cutup is the distance between the upper and lower lips of the mouth. Since the mouth width is fixed by the pipemaker, the cutup is the main way the voicer can influence the tone *(and toe holes are the main way the voicer can influence loudness)*. You raise the cutup, to "cut out" brightness.

How a Trumpet Speaks

Before we talk about flue pipes, let's review how a reed pipe works. When the organist plays a key, it allows pressurized air to flow into the "boot" of the Trumpet pipe. In the boot is the shallot: a small, brass tube with a narrow opening. Covering this opening is a thin, flexible strip of brass called the tongue.



The pressurized air rushes past the tongue, thru the shallot and forces the tongue to vibrate. This vibration is the primary source of the sound, creating a rich, complex bundle of frequencies *(a "brassy" buzz)*. The vibrating air column from the tongue/shallot now travels up into the resonator *(the long, conical tube above it)*. The resonator amplifies the sound.

The length of the brass tongue determines the pitch, and that length can be adjusted by the tuning wire. The amount of curve in the tongue controls the airflow, hence the loudness. The thickness of the tongue controls the tone. A thin tongue has more "snap" to it, sending squared, more harmonically rich air pulses into the resonator. Also, a stiff, harder brass has more snap to it.

Wind pressure also affects the tone. Higher wind pressure requires thicker tongues with a stronger curve. These tongues have much less snap to them; they make smooth, sinusoidal pulses into the resonator. You can't get a good French Trumpet with wind over 4" *(Clicquot max'd at 4")*. You can't get a smooth English Trumpet with less than 6". And you need 13" for a decent Tuba. *(Fr Willis standard pressures were 3½", 7" and 14".)*

The resonator doesn't just make the sound louder; it acts as an acoustic filter. It reinforces certain harmonics and suppresses others, from the tongue's complex vibration.

If the tongue is sharp of the resonator length, the pipe is bright. If the tongue is flat of the resonator length, the tone becomes fundamental. So, adjusting the resonator length is an effective tone control.

Back to Flue Pipes

Between the lower lip and the languid is a windway, from which blows a thin, flat ribbon of air, sideswiping the outside of the upper lip of the pipe. The ribbon acts like a trumpet tongue: oscillating, blowing pulses of wind into the mouth of the pipe. These periodic pulses excite the natural resonances of the pipe, making it speak.

Why does the Ribbon Oscillate?

This is quite simple. The thin ribbon of air blows out of the windway of the foot, across the mouth, sideswiping the outside of the upper lip. This flow of air across the outside of the mouth draws air from inside the resonator *(venturi effect),* creating a low-pressure zone inside the mouth. That low pressure sucks the ribbon of air into the pipe. The ribbon of air now blows air into the mouth, changing the low-pressure zone inside the mouth into a high-pressure zone, which pushes the ribbon out. And the cycle repeats, as a positive feedback loop.

The resonator forces the air reed to lock in phase with the resonator's natural harmonics.

Cutup and Tone

The windway is very narrow, and the issuing jet of air is also very narrow, turbulent and high velocity. The turbulence generates a complex waveform with many upper partials *(overtones)* and broadband noise. As the air stream moves away from the orifice, it broadens, slows down, becomes more laminar, and gets stiffer and less able to support higher frequencies.

As an analogy, think of whistling thru your lips. If you purse your lips tightly you create a fast, focused jet of air *(a "ssss" sound)*. If you relax your lips, you create a broad, slow jet of air *(a "whoosh" sound)*.

So, by raising the cutup, you lengthen *(hence slow-down, thicken)* the ribbon of air resulting in fewer overtones to excite the resonator, hence duller pipe sounds.

Widening the windway (or adding nicks, which diffuses or widens the air ribbon) will also dull the pipe. I've noticed that high pressure pipes (>4") want very wide windways and heavy nicking to speak properly.

Raising the foot wind pressure will louden the pipe. But it also speeds up the flue air velocity, stiffening the ribbon, sharpening its pitch and brightening the pipe.

For a given frequency, what matters is:

- the cutup
- flue air velocity *(foot pressure)*
- thickness of the air ribbon

Ising Numbers

Dr Hartmut Ising developed a formula to show how well the above three variables match the resonator *(i.e. frequency)*. It provides an intonation number (I), a dimensionless value that represents a pipe's timbre and efficiency. An Ising of 2 is an ideal match, the pipe works most efficiently.

$$\text{Ising} = \frac{1}{\frac{1}{(Hertz * Cutup/10)} * FLUEVELOSITY * \sqrt{\frac{Windway}{10} / \frac{Cutup}{10}}}$$

Fortunately, there are spreadsheets that will calculate Ising numbers, decibel loudness, and other neat calculations. But you need some experience to make sense of the numbers. As Ising numbers get larger, the sound gets brighter; I=3 makes a good string. I=1.4 is typical for a Stopped Diapason. I find an Open Diapason 8' with an I=2 *(the most efficient)* to be a bit dull, and prefer I=2.3 at middle "c". In fact, it is normal for the Ising value to be variable throughout the compass.

I recommend measuring stops you like, and develop your own preferences.

Wind

Chest Pressure

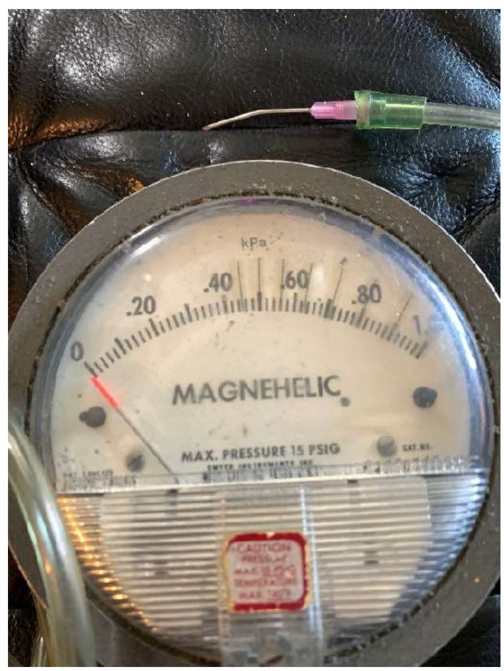
The blower provides the wind at a relatively high pressure and sends it to the bellows. The bellows *(and/or schwimmer)* reduces it to the desired wind pressure and stores a reserve of wind. There are many factors that affect your choice of pressure.

The higher the pressure, the louder the pipes are blown. Obviously, you need to provide enough pressure that your pipes are loud enough. Because you can reduce the amount of wind going to a pipe by closing it's toehole, you can choose to make the pressure higher than the pipes need, and throttle the wind back at the toe. But why would you do that?

Let's say, for example, you have a small room and the pipes only need about 2" of wind. But you want a nice Trumpet 8'. A trumpet wants about 3" to have stable speech and nice tone. If you wind a trumpet on 2", the reed tongues will be so thin that the trumpet with sound thin, buzzy and unstable. So, the simple solution is to wind the organ on 3" for the sake of the Trumpet, and close the toes of the rest of the pipes to reduce their pressure.

Or perhaps you are building a small tracker whose pipes only need 45mm of wind. You might choose to close the pipe feet and raise the pressure for several reasons. Because of space constrains in a compact instrument, the pallets and wind channels will be small. A higher pressure will push more wind thru, so you will have less wind robbing. A higher pressure will also increase pallet pluck, improving the "feel" of the keyboard. There are lots of electropneumatic windchests that can't function on less than 3½".

Foot Windpressure



When analyzing pipework, we don't care what the chest pressure is, what matters is the wind pressure inside the foot of the pipe. There are formulas that compare the cross-sectional area of the mouth windway, and the area of the toehole, factoring in the related orifice resistances and turbulence to calculate the foot pressure. But I've not always found these formulas reliable.

For foot pressure, I've found direct measurement to the best. You can drill a 2mm hole in the foot and measure the foot pressure, then plug it with a drop of solder or glue. Or you can attach a hypodermic needle to your manometer hose and shove the needle through the windway into the foot. But be careful, or you'll create another nick!

Besides measuring the foot pressure, it's also useful to also record the foot pressure as a percentage of the chest pressure. When designing, I prefer the foot pressure to be a maximum of 80% of the chest pressure. That gives you some latitude during tonal finishing to make a pipe louder. Its common in organs for the foot pressure to be much less that the chest pressure, and lower in the bass and higher in the treble.

Toeholes

A pipe receives the wind that blows the pipe, through a hole in the bottom of the pipe foot. Bigger pipes need more wind, so the toe hole is in proportion to the diameter *(scale),* of the pipe. Because voicers generally want the same loudness across the compass of the rank, they try to graduate the hole sizes very evenly, almost mathematically. In our shop we have a special set of drills and charts *(next page)* to aid in sizing the toes, saving a lot of time. The drill sizes have been carefully selected; can you figure out why?

I've found that the square root of the pipe diameter, makes a good toe hole size for a principal. It is large enough to give the pipe a fresh flush of air, so it speaks efficiently. Yet it is still small enough that you can adjust the toehole size to regulate the loudness, and allows normal width windways.

$$toehole = 1\sqrt{pipe\ diameter}$$

Of course it is never that simple. You might choose to supply a higher windpressure than the pipes need, for the sake of the reeds. Then you'd use smaller toe holes to compensate. Strings usually want less wind, perhaps $0.6\sqrt{dia}$. But a Harmonic Flute generally wants more wind, perhaps $1.2\sqrt{dia}$. You might want to soften the bass of a Twelfth, so you do the bass $0.7\sqrt{dia}$, the treble $0.9\sqrt{dia}$ and graduate in between.

It is very common to have lower pressures if the feet of bass pipes, increasing into the treble.

In other words, the drills and chart are tools; you still have to be the craftman that uses them intelligently.

A good way to start, is to make some sample pipes on the voicing machine. Measure their toes and find them on the chart. Then follow the chart for drilling the rest of the toes. Pipes on higher pressures generally want smaller toeholes.

Toehole Analysis

But for us here, the chart *(see next page)* provides a very useful way to analyse toeholes in organs you are studying. Use the toehole size and pipe diameter, to find the column with the correct X *(just pick the closest numbers)*. By comparing X for different pipes, you learn a lot about how the voicer sized pipe holes. Notice that X stays in proportion to scale, simplifying analysis.

$$Toehole = x\sqrt{Pipe\ Diameter}$$

For example: 6mm toe, 55mm pipe. Follow the toe hole row for 5.9mm to the column with a pipe diameter of 54mm. At the top of that column you see the formula of $0.8\sqrt{dia}$. Therefore x=0.8.

Drilling Chart for Pipe Feet

Drill mm	1.4√dia	1.3√dia	1.2√dia	1.1√dia	√dia	0.9√dia	0.8√dia	0.7√dia	0.6√dia
1							1.6	2	2.8
1.3						2.1	2.6	3.4	4.7
1.5			1.6	1.9	2.3	2.8	3.5	4.6	6.3
1.8		1.9	2.3	2.7	3.2	4	5	6.6	9
2	2	2.4	2.8	3.3	4	4.9	6.3	8.2	11.1
2.3	2.7	3.1	3.7	4.4	5.3	6.5	8.3	10.8	14.7
2.5	3.2	3.7	4.3	5.2	6.3	7.7	9.8	12.7	17.4
2.8	4	4.6	5.4	6.5	7.8	9.7	12.3	16	21.8
3	4.6	5.3	6.3	7.4	9	11	14	18.3	25
3.3	5.5	6.4	7.6	9	10	13.4	17	22	30
3.5	6.3	7.2	8.5	10.1	12	15	19.1	25	34
3.7	7	8.1	9.5	11.3	14	16.9	21.4	27.9	40
4	8.2	9.5	11	13.2	16	19.8	25	32.6	44.5
4.2	9	10.4	12.3	14.6	18	21.8	27.6	36	49
4.5	10.3	11.9	14	16.8	20	25	31	41.3	56.3
4.7	11.3	13	15.3	18.3	22	27	34.5	45	61
5	12.7	14.8	17.2	20.7	25	30.9	39	51	69.4
5.3	14.4	16.3	19.4	23.2	28	34.7	43.8	57	76
5.6	16	18.5	21.8	26	31.3	38.7	49	64	87
5.9	17.7	20.6	24.1	28.8	35	43	54	71	97
6.3	20	23.5	27.6	32.8	40	49	62	81	110
6.7	23	26.5	31.2	37.2	45	55.4	70	91.6	125
7.1	25.6	30	35	41.7	50	62.2	78.8	109	140
7.5	28.7	33.3	39.1	46.5	56	69.4	88	115	156
7.9	31.8	36.9	43	51.6	62.4	77	98	127	174
8.4	36	41.7	49	58.3	70.6	87	110	144	196
8.9	40.4	46.9	55.3	65.5	79	97.8	124	161	220
9.4	45	52.3	61.3	73	96	109	138	180	245
10	51	59	69	82.6	100	123.5	156	204	277
10.6	57	66.4	78	93	112	139	176	229	
11.2	64	74	87	104	125	155	196	256	
11.9	72.3	83.7	98.2	117	142	174	221		
12.6	81	94	110	131	159	196	248		
13.3	90	104	123	146	177	218			
14.1	101	118	138	164	200	245			
15	115	133	156	185	225	278			
16	130	151	178	221	256				
17	147	170	201	239	289				
18	165	192	225	266					
	Open toe		63mm Tracker		71mm ep Ahrend	80 mm	90 mm	100 mm	114 mm

The numbers in the left column are the toe hole diameters in mm. The remaining are the various pipe diameters arranged in columns according to their $\sqrt{dia}$.

So…

All these things, *(diameter, mouthwidth, cutup, flue, toehole)* must work together to have a successful pipe. A good designer will use all of them. If they plan a louder organ, they won't just throw a couple of bricks on the bellows. The proper way is to raise the wind pressure a bit, increase the scale a bit which will also increase the mouth width a bit, they will raise the cutup a bit, and open the flue and toehole a bit.

These variables are all under the control of the voicer, who uses them, especially the toeholes to adjust air flow, hence loudness of the pipes. Increasing the toe size will make the pipe louder, but it will also make it brighter. So, the voicer may also need to raise the cutup slightly, to maintain a similar tone.

My intent here is not to teach tonal design, voicing or finishing. Simply, that by examining the measurements, especially in a graphic form *(Topfer Normalmensur)*, we can grasp the designer's and voicer's intent.

Töpfer

In 1812, J. G. Töpfer wrote his book of organ building. He proposed using logarithms to layout the progression of pipe scales. His favourite progression for principal pipes was "17th halving." For example, if bottom "C" pipe was 88 mm diameter, and you counted up to the 17th pipe, an "e", it would have a diameter of 88/2=44 millimeters. The spacing of the intervening pipes would be logarithmic.

Töpfer's 17th halving ratio, is equivalent to an octave ratio of ($\sqrt[4]{8}$) or 1.682. That is close to the traditional ratio 3:5 or 1:1.666.

Töpfer decided that *(to his ears)* the Ideal Open Diapason had a bottom "C" diameter of 155.5 mm and 17th halving. In his opinion, this stop had the most consistent tone and even loudness throughout the compass. But nobody uses his "Ideal Open" in their organs. However, the Töpfer Normalmensur is important as a reference standard, useful when analyzing scales.

Coincidentally(?), Cavaille-Coll's Montre #1 standard scale is almost identical to Topfer's "Ideal Open Diapason".

Pipe Diameters, Normal Scale, in millimeters

H.T.	note	32'	16'	8'	4'	2'	1'	1/2'	1/4'	1/8'	H.T.
	C	439.7	261.5	155.5	92.2	54.9	32.6	19.3	11.5	6.8	12
-1	C#	421.2	250.4	148.9	88.5	52.6	31.3	18.6	11.0	6.5	11
-2	D	403.2	239.8	142.6	84.7	50.4	29.9	17.8	10.5	6.3	10
-3	D#	386.2	229.6	136.5	81.1	48.2	28.4	16.9	10.1	6.0	9
-4	E	369.9	219.9	130.7	77.7	46.2	27.4	16.3	9.7	5.7	8
-5	F	354.1	210.6	125.2	74.4	44.2	26.3	15.6	9.3	5.5	7
-6	F#	339.1	201.6	119.9	71.3	42.3	25.2	14.9	8.8	5.2	6
-7	G	324.7	193.1	114.8	68.2	40.5	24.1	14.3	8.5	5.0	5
-8	G#	311.0	184.9	109.9	65.3	38.8	23.1	13.7	8.1	4.8	4
-9	A	297.8	177.4	105.3	62.6	37.2	22.1	13.1	7.8	4.6	3
-10	A#	285.2	169.5	100.8	59.9	35.6	21.1	12.6	7.4	4.4	2
-11	B	273.1	162.3	96.5	57.4	34.1	20.2	12.0	7.1	4.2	1

In Töpfer Normalmensur, the unit of measurement is the "half-tone", HT. A half-tone is a semi-tone, the distance between two adjacent pipes. C is 4HT lower than E. For example, if I told you that a 2' C pipe was 71 mm diameter, it probably wouldn't mean much. But if it was 6 pipes (+6HT) larger than Töpfer's Normalmensur, you'd visualize a flute. If a pipe was -10HT, you'd think it was stringy.

Also, millimeters are linear, scales are logarithmic. If you add 4 mm to an 8' pipe's diameter, tone change is hardly noticeable. But adding 4 mm to the top pipe of a Fifteenth would double its diameter. Just going by millimeters can be hard to judge. I'll refer to Töpfer half-tones throughout this text. Half-tones can be absolute, as in the distance from Normalmensur *(e.g. 5HT larger than Töpfer's Normalmensur)*. Half-tones can be relative *(e.g., the 4' Flute is 5HT larger than the 4' Principal)*.

Wood pipes

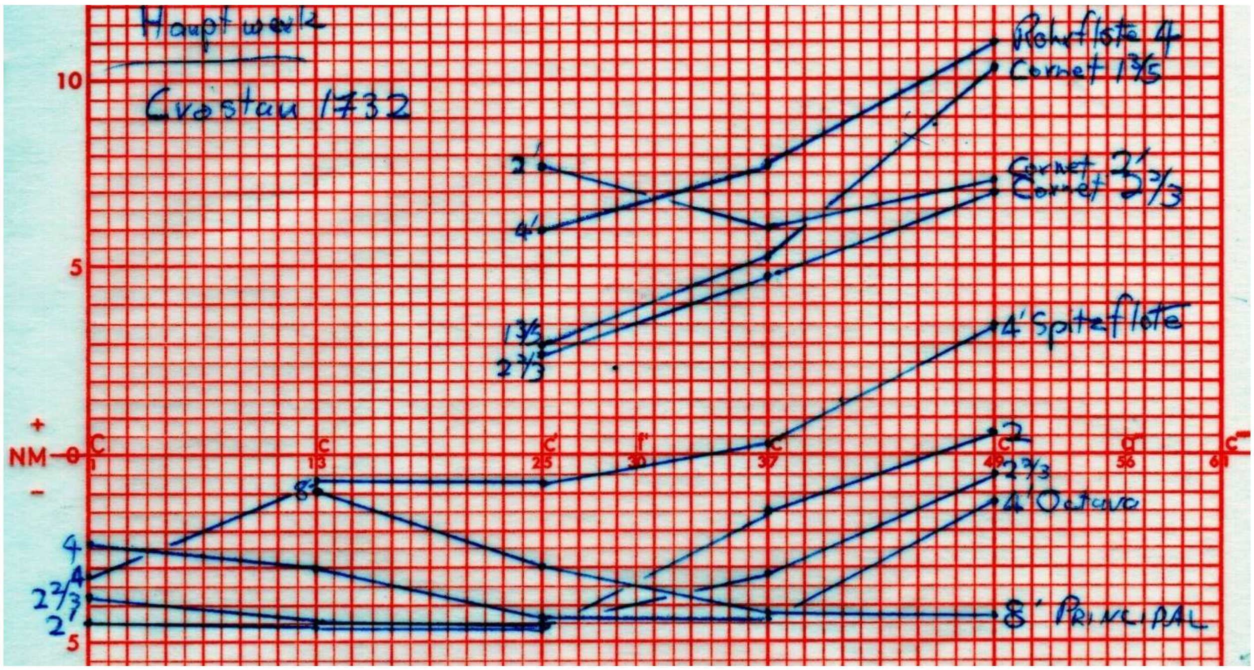
Wood pipes use the equivalent diameter, using the following formula:

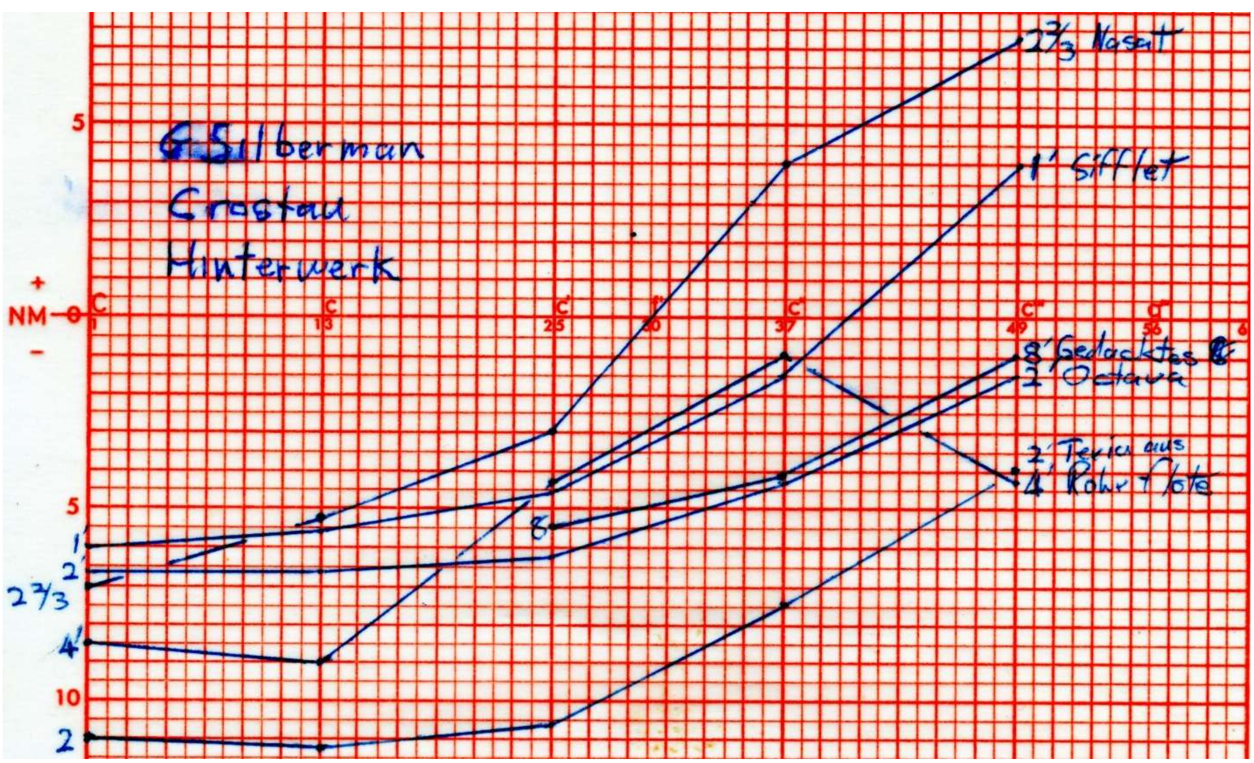
$$\text{Equivalent Diameter} = \text{Sqr}(\text{width} * \text{depth} * \frac{4}{\Omega})$$

Graphing Scales

The best way of visualizing scales is in units of Töpfer HT, plotted on a graph. I've plotted the principal chorus scales of the Hauptwerk and Hinterwerk of Gottfried Silbermann's organ at Crostau, 1732. The vertical scale is in HT steps. The horizontal scale relates to keys on the keyboard. So, the first vertical line, at the left, is bottom C, #1 of the keyboard. The far-right vertical line represents top C, #61.

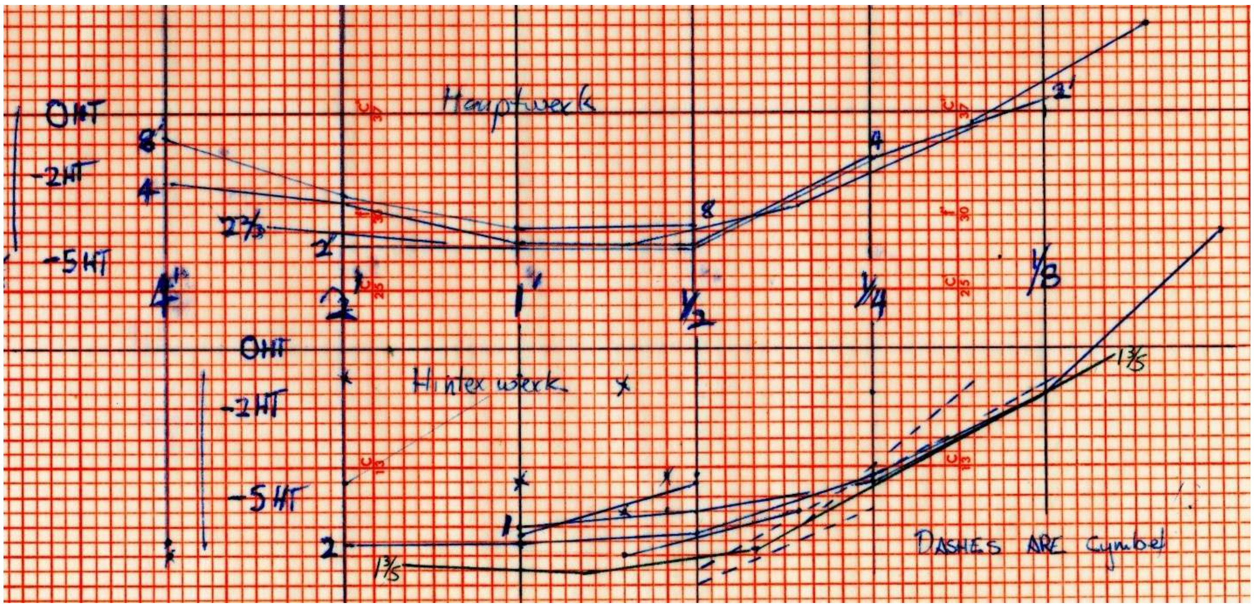
If you follow the middle "C" #25 vertical line, you can compare the size of all the pipes of that key. The scales all seem to follow curved lines, rather randomly.





The chart on this page is also the Crostau Organ. Like the other graphs, the vertical scale is in Töpfer HT. But the horizontal scale is different. The various stops have been shifted horizontally, to line up the pitches of the pipes. All of the 2' long pipes are on the same vertical line, and all of the 1' pipes have their own line, all in chromatic order.

In other words, middle “c” #25 of the Montre 8' is on the same vertical line, as the tenor “c” #13 of the Octave 4', or the bottom “C” #1 of the Fifteenth 2'. But the notes each still go chromatically, from left to right, bass to treble.



By graphing the stops this way, we’ve discovered that all of the ranks of the Hauptwerk lie one top of each other. They are the same scale *(allowing for measuring and pipemaker errors)*. And the scale shows a uniform curve, similar to French scales. That makes sense, because Gottfried trained with his brother Andreas in Strasbourg.

Looking at the Hinterwerk scales, we see they are similar, but transposed about two lines down *(two HT narrower)*. This graph has shown that Silbermann used the same scale for all of his principal chorus, but on the secondary division the scale is transposed about two pipes narrower.

Both charts are useful, but show us different things. This is much more useful than spreadsheets of measurements in millimeters.

Even though they may seem random and curvy, these are good scales. Gottfried Silbermann was famous for building good sounding organs. Scales that grow into the treble give a bold, ascendant sound without being shrill. Scales that grow into the bass give depth to the tone without muddying the tenor and middle.

The French curved scaling system is serendipitously quite clever. Compared to the Montre, the Prestant 4' is narrower in the bass, but grows in the treble. Similarly, the 2' Doublette is even narrower in the bass, and grows even more in the treble. This allows the bass of the 4' & 2' to be softer and blend better with the Montre. But the bigger scales in their treble make them louder and flutier, allowing treble ascendancy, without becoming screamy.

Topfer Charts for Mouths

I've already explained about Töpfer Normalmensur (NM's) for diameters. It's traditional to express the width of a pipe mouth as a fraction of the pipe's circumference (e.g. 2/7, ¼, 2/9, 1/5, 1/6). One quarter mouth is considered typical and most used. If a pipe had a mouthwidth of 25mm and a circumference of 100mm, then the mouthwidth would be 25/100= ¼.

Though Topfer never did it, it's convenient to chart the mouth width, on the same Topfer NM graph with the diameter, in halftone units. Since a ¼ is the most commonly used mouthwidth, I'll use Topfer NM divided by four to be the reference mouth NM. So, a pipe with a 2/7 mouth would have the same size mouth, as a ¼ mouthed pipe which was three notes bigger. This fits appropriately on a standard Topfer graph.

For example:

3 NM = 2/7 mouth = 1/3.5 mouth
0 NM = 1/4 mouth = 1/4.0 mouth
-3 NM = 2/9 mouth = 1/4.5 mouth

Mouth Width, Normal Scale, in millimeters (circumference/4)

H.T.	note	32'	16'	8'	4'	2'	1'	1/2'	1/4'	1/8'	H.T.
	C	345.3	205.4	122.1	72.4	43.1	25.6	15.2	9.0	5.3	12
-1	C#	330.8	196.7	116.9	69.5	41.3	24.6	14.6	8.6	5.1	11
-2	D	316.7	188.3	112.0	66.5	39.6	23.5	14.0	8.2	4.9	10
-3	D#	303.3	180.3	107.2	63.7	37.9	22.3	13.3	7.9	4.7	9
-4	E	290.5	172.7	102.7	61.0	36.3	21.5	12.8	7.6	4.5	8
-5	F	278.1	165.4	98.3	58.4	34.7	20.7	12.3	7.3	4.3	7
-6	F#	266.3	158.3	94.2	56.0	33.2	19.8	11.7	6.9	4.1	6
-7	G	255.0	151.7	90.2	53.6	31.8	18.9	11.2	6.7	3.9	5
-8	G#	244.3	145.2	86.3	51.3	30.5	18.1	10.8	6.4	3.8	4
-9	A	233.9	139.3	82.7	49.2	29.2	17.4	10.3	6.1	3.6	3
-10	A#	224.0	133.1	79.2	47.0	28.0	16.6	9.9	5.8	3.5	2
-11	B	214.5	127.5	75.8	45.1	26.8	15.9	9.4	5.6	3.3	1

NM Charts from "The Sound of Pipe Organs"
by Michael McNeil

Cutups

Voicers traditionally relate the cutup as a fraction of the mouthwidth. For the convenience of a Topfer cutup reference, I chose a reference cutup to be 1/4 cutup on a ¼ mouthwidth. In other words, a 0HT cutup is 1/16th of a 0HT circumference.

I'm a little uncomfortable with this solution because with cutups you can end up with very large HT graph spreads and movements, especially with stopped pipes. It needs a representation that is perhaps compressed. However, I've done it this way for 50 years, on hundreds of graphs and I can't go back and revise, so you're stuck with it…

A Brief History of Scaling

The pipes in the earliest medieval organs were all same diameter, about the size of a pigeon's egg. The photo above shows an 11th-century copy, using original brass pipes that were buried by Crusaders, hidden in a Bethlehem cemetery, to protect it from invading Muslim armies. The organ originally had a blockwerk of 222 pipes. Unfortunately, pipes all the same size results a drastic tonal change, as you played up the scale. You could only have an acceptable compass of an octave.

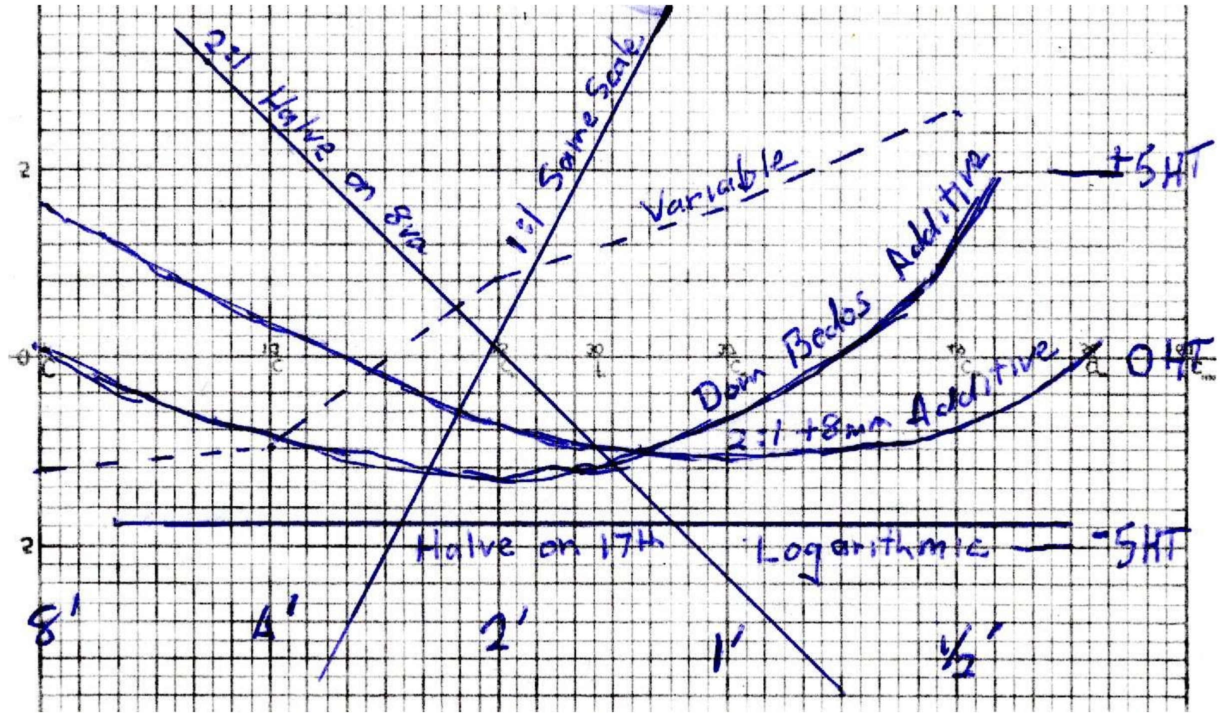
But organbuilders, being perceptive and clever, noticed that the length of pipes halved on the octave. They reasoned halving on the octave might also work for the diameter. In other words, middle C would be 1/4 the diameter of bottom C, and 1/2 diameter of tenor C. This was better, you could acceptably extend the compass to a couple of octaves.

But musicians wanted more. So, builders adapted one of the following three systems of scaling: additive, variable and logarithmic.

Scale Systems

In my casual observation, I see these traditions of pipe scaling:

- All pipes same size: 1:1, ancient.
- Halve on the octave, ancient.
- Additive: French tradition, where plotted pipes follow a curve: eg Bedos.
- Variable: where plotted pipes seem random, e.g Schnitger.
- Logarithmic: where plotted pipes follow straight line, e.g. Sorge, Topfer



This chart shows the various scaling systems graphically. The vertical axis of the Normalmensur chart above is in Halftones. The horizontal axis is the progression of the rank from bass to treble *(i.e. it corresponds to the footlength: 8", 4" of the pipe)*.

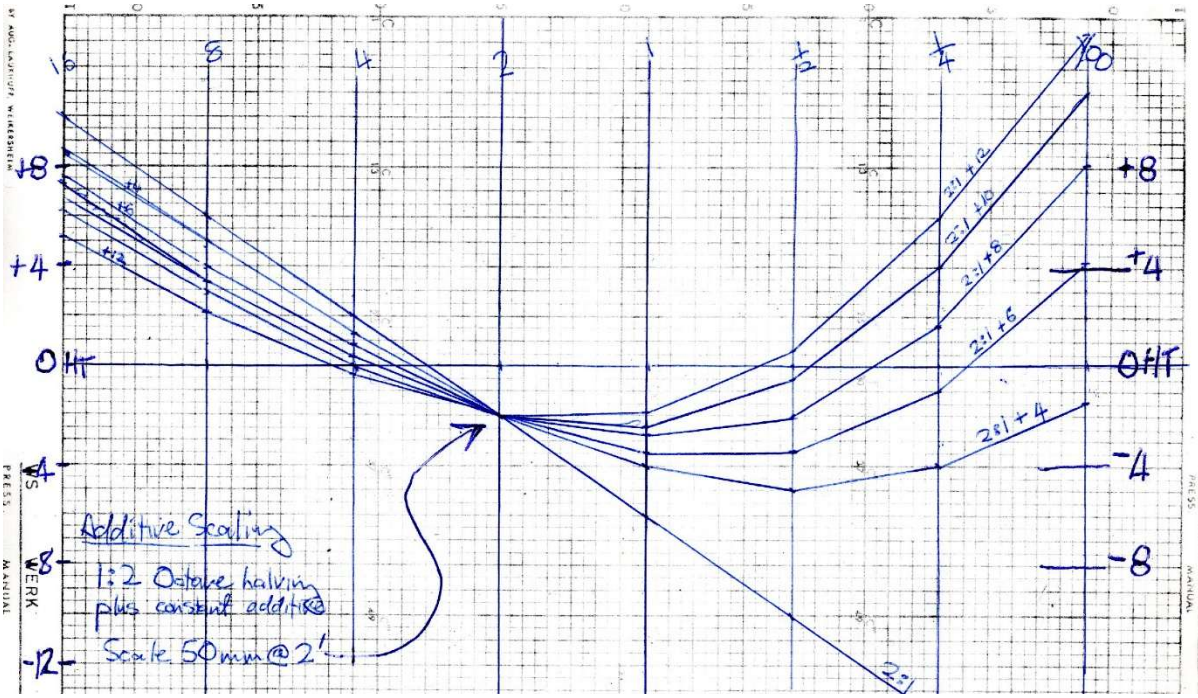
Additive Scaling

So those resourceful organbuilders thought that if the problem with halving on the octave made the treble too narrow, why don't we just add a little to each octave. This proved to be successful and allowed a compass of about four octaves. The builder might choose an additive factor of, say ¼".

- Start by dividing the bottom C circumference by 2, then add ¼" to get tenor C.
- Divide tenor C by 2 and add ¼" to get middle C,
- Divide middle C by 2 and add ¼" to get treble C,
- Etc., all the way up to top C.

Because the additive factor is linear, when viewed on a Topfer graph it adds more to the treble than the bass. This results in a concave curve on the graph, with a flat curve in the bass, curving stronger into the treble.

There were problems with this scaling method, but it was better than just halving on the octave. This method is described in very old organbuilding books.



Above is a hypothetical graph I made to demonstrate curves generated by this method. I arbitrarily started with a 2' *(placed in the center of the graph),* with a typical 50mm diameter, which is about -2HT. To get the 1' pipe: take it's circumference of 50, which is 157. Dividing 157 by 2 and adding 12 is 90.5, gives a diameter of 28.8, or about -2 HT at 1'.

Dom Bedos Scales

French organbuilders like Dom Bedos also used a form of additive scaling, but developed by a different method. You remember the French Dom Bédos scale is a curve on a Topfer scale chart, characteristic of classic French scales.

Fortunately, Dom Bédos documented in his book how he plotted scales. He first specified the inside circumference of the first pipe *(the biggest, C1)*. Second, he specified the inside circumference last pipe *(the smallest, c49)*. But how to calculate the remaining circumferences, between C1 and C49? You can't just divide them up equidistantly, the progression must be logarithmic. *(i.e., the space between C1 and C#2 is wider than the distance between b48 and c49)*.

Pipemaker length scale sticks

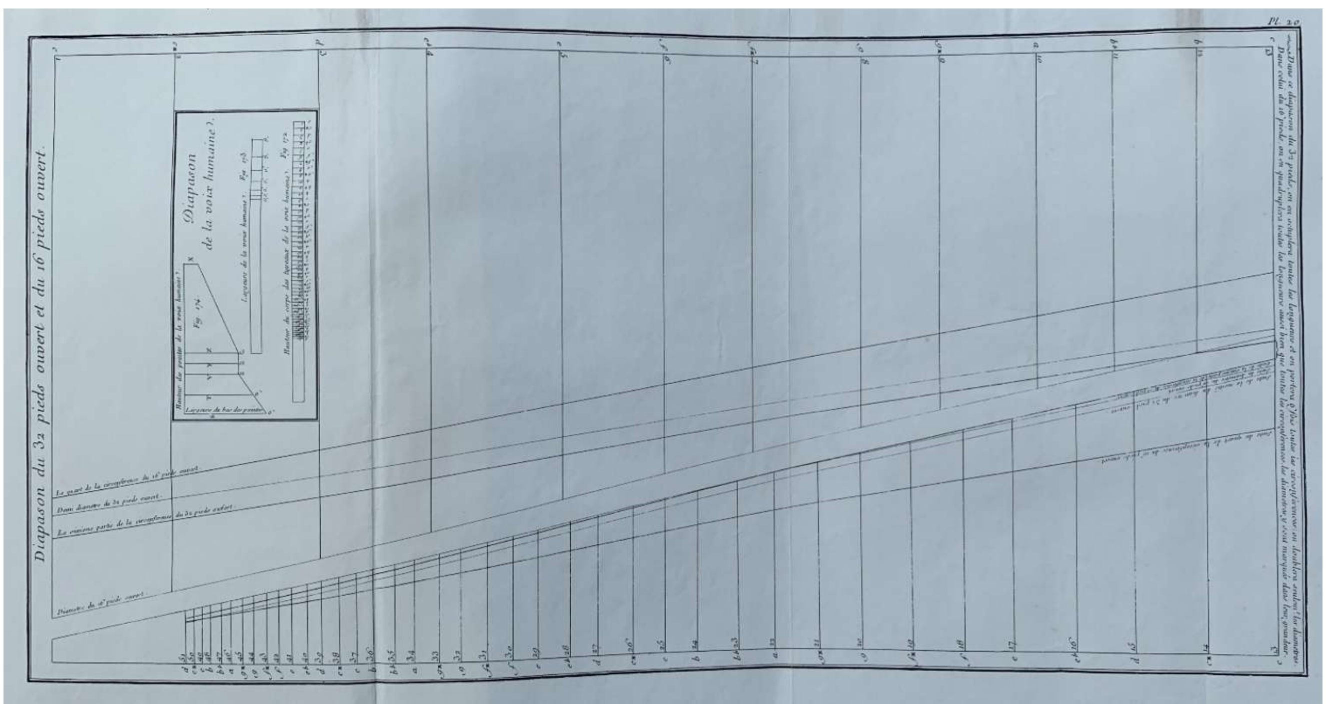
Bedos had seen similar progressions before, in pipe maker's length scale sticks, which show the pipemaker the distance from the languid to the pipe top. Length scales halve on about the octave. The 4' C is half as long as the 8' C; 2' C is half as long as the 4' C. That is logarithmic and will correctly show on log paper as a straight line, but with a different slope than a 17th progression.

But there was a problem. Because of an end-correction, the octave pipe will be slightly shorter than 1/2 pipe length. There is a similar error up each octave, so in practice a pipe length scale stick is a little shorter than log. This error gives a similar correction as the "additive factor" of historical Additive Scale methods.

	C 4'	C 2'	C 1'	C 1/2'	C 1/4'	C 1/8'
Theoretical	1,182 mm	591	295.5	147.8	73.9	36.9
Scale stick	1,182 mm	577	279	139	67.5	30
Difference	0 mm	-14	-16.4	-8.8	-6.3	-6.9

The above chart was made by measuring a 4' Octave length stick from my pipeshop. The theoretical measurements started with the scale stick's bottom C 4'; then dividing it by half recursively, for each octave. Because of this difference error, we get a curve when we plot French scales on a log chart. Bedos wasn't aware that we see a curve, but he was aware that his scales were sometimes too big in the bass and treble, and made adjustments to fix that.

As you can see from the Silbermann scale graph, some builders constructed many of the pipe scales from a shop master scale, perhaps transposing a few half-tones larger or smaller, as needed. They might have a standard principal master scale, flute master scale, and perhaps custom scales for harmonic flutes or other unusual stops. Dom Bedos was different. He created a custom scale for every stop. I expect he was unusual in this regard.



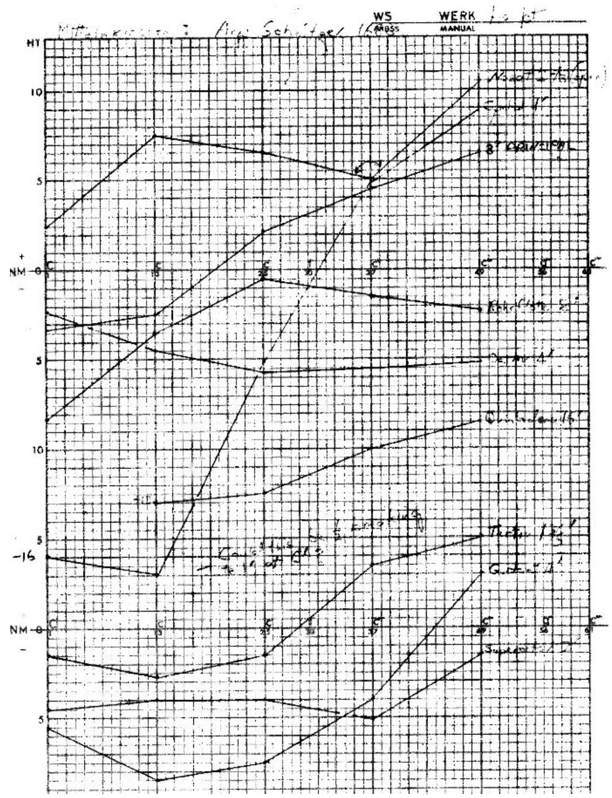
Above is a scale sheet from my copy of Bedos' book, for an open 32' stop. To not waste paper, Dom Bedos drew two scale graphs; one on the top-left, the other on the bottom right of the paper.

On the horizontal base-line, the scale spacing was copied from a pipemaker's length scale stick. Then perpendicular lines were drawn up from the base line. The circumference of the bottom pipe was marked on the bottom "C1" perpendicular. The circumference of the top c49 was marked on the c49 perpendicular. Then a straight line was drawn joining the two "C"s, which crossed the perpendiculars, indicating their circumferences.

You'll notice that several lines can be drawn across the graph, which could indicate mouthwidths, rohrflute chimney lengths and circumferences, foot lengths or whatever… Also, note that the horizontal baseline spacing is slightly irregular; could this be meantone temperament?

I have seen similar charts in active use, in several modern organ companies. One example had wood pipe scales drawn on planks of wood, but usually they were drawn on paper/mylar. Of course, modern scale sheet's baseline used Töpfer's 17th halving ratio, ($\sqrt[4]{8}$).

Variable Systems



Arp Schnitger (1648-1719) was the idol of the Orgelbewegung. His scaling was very inconsistent between organs, and even within the same organ. This was partly because he enthusiastically recycled pipework from previous instruments.

The recycled pipework was compatible with Schnitger's style of building. Also, Schnitger had a monopoly on organbuilding in the region, so other organbuilders had to work under him as subcontractors, whom brought their own methods.

And, I suspect pipe scaling wasn't particularly important to him, he could work with what he got. He doesn't seem to be following any mathematical, geometrical, proportional, logarithmic or additive scaling system.

However, people who enjoy analyzing pipe scales, find Schnitger's organs very frustrating. Certainly, the general concepts are correct: a Schnitger Quintadena is a narrow, stopped pipe with low cutups; his Gedackt is a fat, stopped pipe with high cutups. But Schnitger Gedackts, for example, can look very different from organ to organ, and even within an organ, for no apparent reason, while still being a Gedackt.

When studying his instruments, it is better to step back and look at the big picture, and not get stuck on the details. Also, variable scaling gives a liveliness and motion to the sound that you don't get from logarithmic scaling.

Modern builders that regularity use logarithmic *(Topfer)* scales, will also use variable scales when the need arises. For example, a Harmonic Flute might have a fast-rising scale in the bass, the flattens out in the treble and then begins to fall at the top.

Bear in mind that Topfer's 0HT Open, with 17th halving ratio, ¼ mouthwidth and ¼ cutup gave *(in Topfer's opinion)* the best tone, which was consistent in loudness and color throughout the compass, from bass to treble. However, most musical instruments are not like that *(sounds pretty dull)*. For musical reasons you might want the power to grow into the bass, or you might want treble ascendancy. You many want the tone colour to change throughout the compass. Variable scaling gives you that, and change is want makes music interesting.

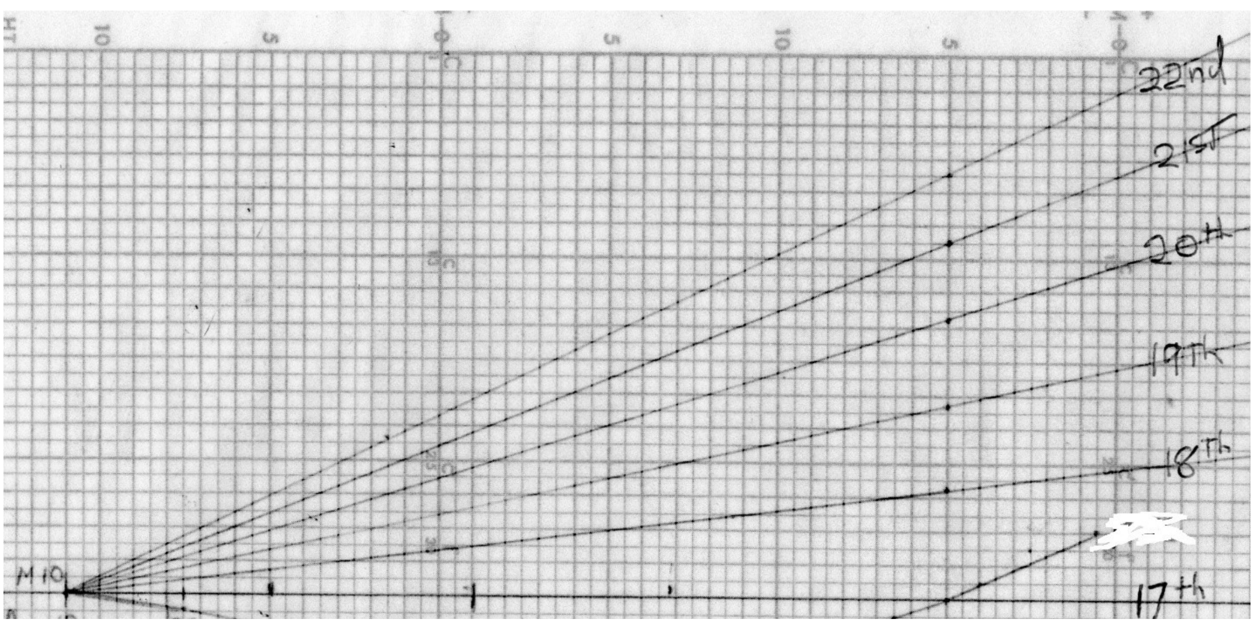
Logarithmic System

The German solution, commonly used in Northern Europe resulted in scales that drew relatively straight lines on a Topfer graph. Organbuilders chose to halve the diameter, not on the octave *(c-c)*, but on the 9th (c-d), minor 10th *(c-d#)*, or major 10th *(c-e)*. The major 10th *(c-e)* is the same as Töpfer's 17th halving ratio. It's reasonable to believe the intervening notes were the result of empirical trial and error, though by the mid-17th century, logarithms were a standard computational tool in Europe.

This scaling system was first described by GA Sorge, 1764, who used logarithms to get the remaining diameters. But the German system was likely around for a century before Sorge.

Johann Gottlob Töpfer (1791–1870) was a pivotal figure in 19th-century organ building, who authored Lehrbuch der Orgelbaukunst (1856), a seminal textbook on organ-building principles that systematized design and acoustics. I've already discussed his Normalmensur HT system, using logarithms. His theories emphasized balanced tonal architecture, influencing later builders. He standardized scaling, ensuring consistent pipe measurements for tonal balance.

By the 1850's organbuilding was transforming from small craftsman workshops, into huge industrial factories. Topfer's book, full of scientifically based pipe scales, windchest designs, etc, was just what the factories needed for industrial output. In 1851 the German builder Edmund Schulz brought Topfer style scaling to England, where it was greatly admired by some. Topfer methods of scaling and design were rapidly adapted by most industrial organbuilders worldwide until recently, because it worked.



Above is a Topfer graph showing different halving ratios.

Summing up

German scales are great for choruses, polyphonic Bach and smaller, dry churches. French scales make wonderful flutes, mutations and Cornets, but they tend toward Montres with muddy bass, a thin midrange, and bold, ascending cornetty trebles *(which help to fill large, reverberant rooms).* Bédos admitted that French scaling had some problems and gave work-arounds in his book.

But the French scale system gave the French what they wanted and it suited the French repertoire. Neither the French nor German system is wrong; they're just different. And each give their builders what they wanted. Otherwise, they wouldn't have used their respective scaling systems for centuries.

Though similar, Dom Bedos' scales curved somewhat differently than additive scales. Bedos scales had a fairly uniform curve, from bass to treble. Whereas typical Additive Scaling had a fairly steep, straighter 2:1 bass line, that upwards curved, more and more, into the treble. This is because Bedos used a different method to layout his scales.

Modern builders tend to use German scales for their choruses, and French scales for their mutations and cornets, even if they don't know the source.

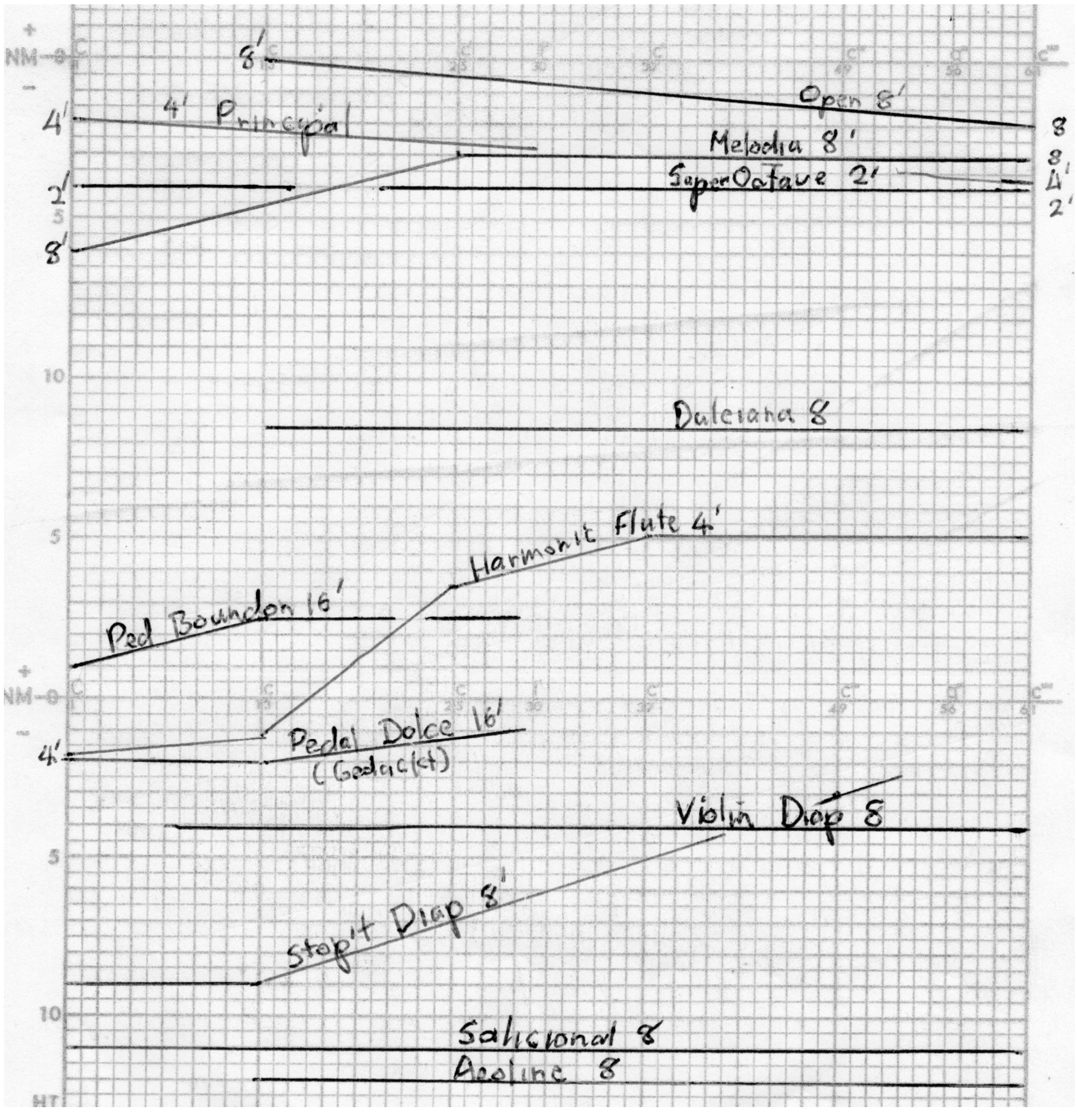
Random tradition scaling doesn't necessarily imply bad scaling. Their origin may be lost in the mists of time. Changes in the scale progression could be from copy errors, pipemaker errors or deliberate adjustments to correct the tone of the pipes. If it sounds good, it is a successful scale, no matter what it looks like on a graph.

Some English organbuilders, like Dallam, Harris and Harrison used French scaling methods, other English builders like Father Smith and Lewis used German methods. Given history and geography of England, this makes perfect sense.

Casavant: A Case History of Scaling

I must start by saying that I have never worked for Casavant, nor have access to Casavant's propriety information. I am basing this on pipes I have measured in old Casavant organs that I have worked on. I've had several discussions with Larry Phelps and worked for Gerhard Brunzema for several years.

1903 Casavant, opus 192 – Petrolia, On

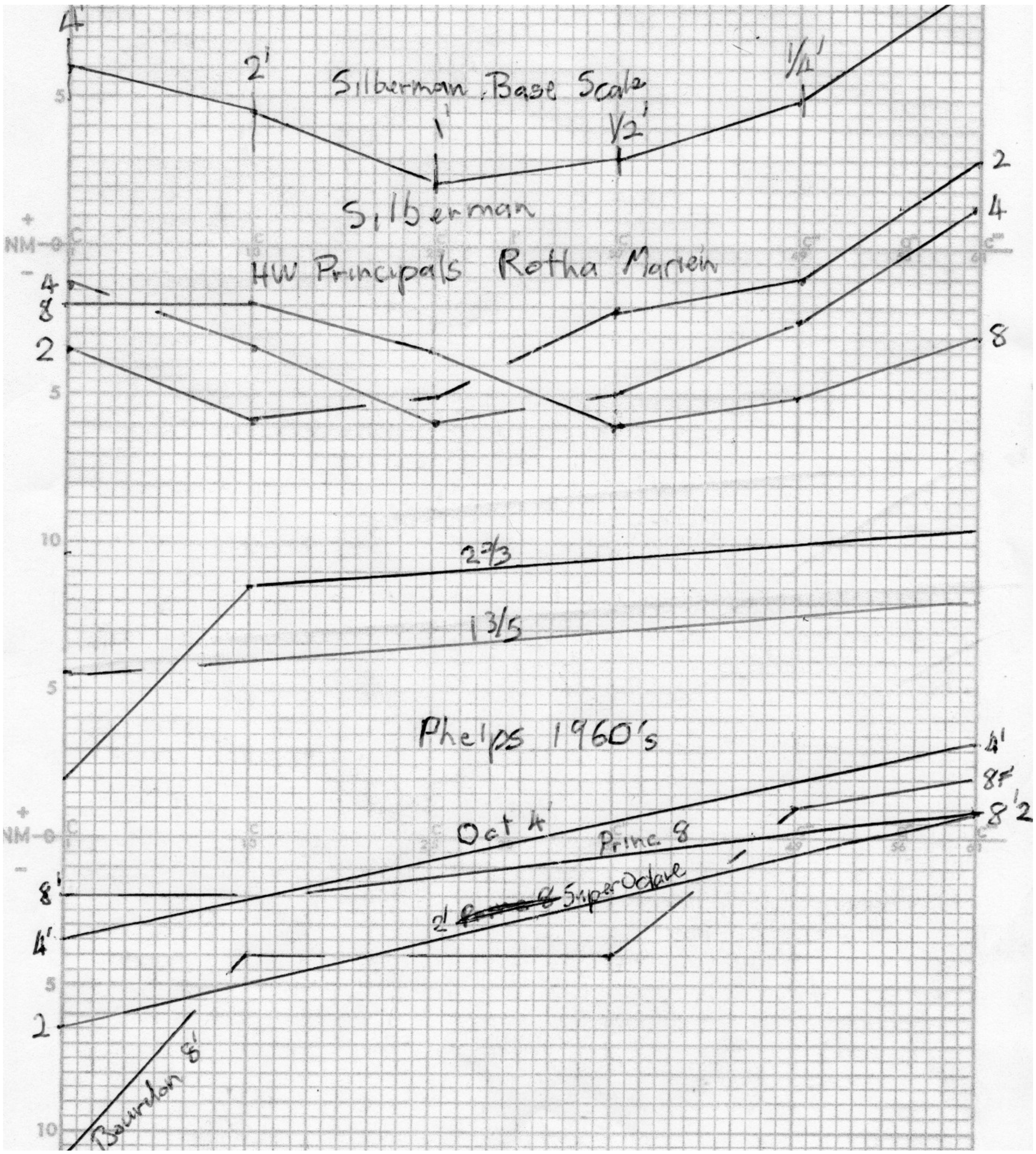


As typical of the period, most of the pipework here has Topferish halving on the 17th. The Great Open and Principal half on the 16th, perhaps so the supercoupler wouldn't offend. The wooden Stopped Diapason is halving on the 20th.

The metal Harmonic Flute 4' is interesting, as it is the only variable scaled stop. This probably follows some scales smuggled in from Paris…

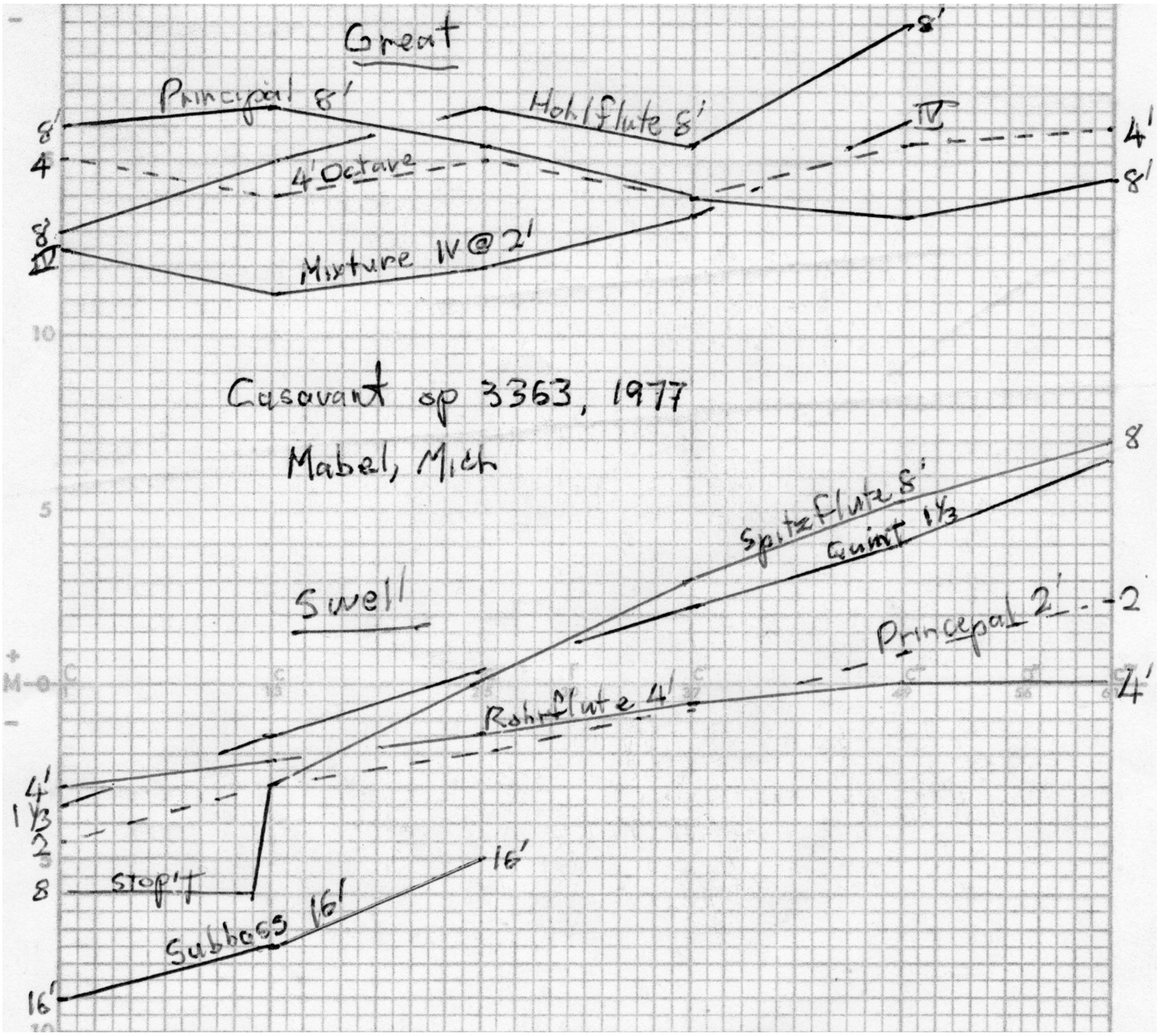
1960's: Larry Phelps and Casavant

By the 1950's, Casavant was in trouble. While Casavant workmanshop was first class, their tonal ideas were mired in the past with Melodias and Dulcianas. They had no idea how to make Cornets, Koppelflutes or Larigots which had become popular. So Casavant hired former Aeoline-Skinner voicer, Larry Phelps, to teach them how to make these new voices.



Phelps was a great admirer of Gottfried Silberman. Notice the Silberman Principal chorus at the top of the page. In the bass the 8' is the biggest scale and the 2' is the narrowest. But in the treble it is inversed, with the 2' as the biggest scale; *(because of additive scaling)*. Phelps does almost the same thing, emulating Silberman, but using log scaling. Phelp's new metal Bourdons did use variable scaling *(or rather, compound log)*. Also, Phelps Topfer style scales often grew into the treble. Phelps standardized his scaling and voicing which, unfortunately, made him redundant.

1977 Casavant: Brunzema

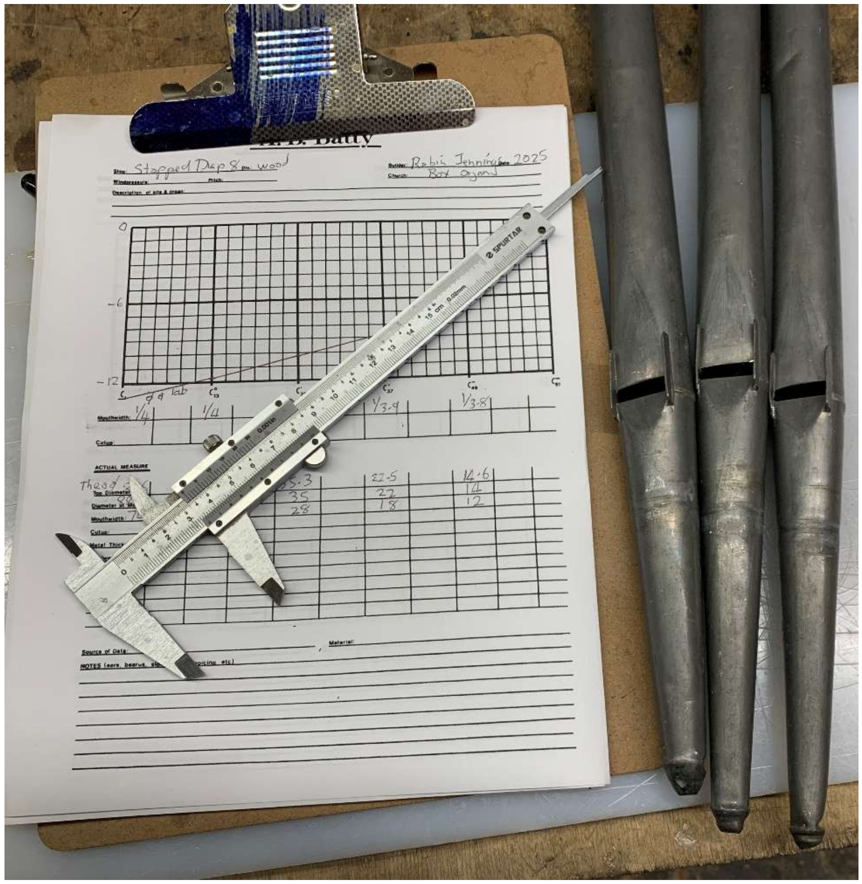


When Burnzema came to Casavant he didn't want to upset people by changing everything at once. Phelp's scales weren't bad, but like every reformer, he went too far. Brunzema started by fixing the obvious problems. He turned the strings back into strings again, by copying the best of Casavant's past work. Strings got rollers, tuning slots, nicked, closed toed, open windway, and they stopped chiffing!

Rooms were measured acoustically and the scales, mouths, cutups, toes and wind pressures were varied to suit the room. The Principal 4' of the great chorus became narrower that the 8' Open *(as it should be)*, so it wouldn't interfere with the vowel sound of the Mixture. A new scale, which was curved like the French scales, was made for Mixtures and Octave 2's. In later years, new variable scales were developed for the open and stopped Flutes.

Finally, Brunzema went to almost all the scales being variable and custom to a particular instrument. The pipeshop would be given all the "C" pipe measurements. This was built from historical examples and his experience, adjusted for the acoustics of the room and stoplist. The details of his decision process, he was reticent to share. But he was always pleased with the result. The advantage of working for a huge Company like Casavant is that you get lots of experience! The graph above shows an example of his variable scales.

Measuring scales



I have found it useful to build up a library of scales of stops that I like. I usually measure all the "c" and f#'s, and the pipes around any breaks. I use a pair of vernier calipers to measure with. There are lots of examples of this on my website. I measure the following:

- Inside Diameter
- Mouth width
- Cutup
- Windway
- Toehole
- Chest pressure
- Foot wind pressure
- Description of organ and room

Windways are very difficult to measure. Now I just estimate the windway by looking at it.