TRAC Design Competition Winner

A new demodulator for single sideband

One of six winners of the TRAC design competition, Mike Button, has devised a new solution to ssb modulation and demodulation that is only practicable using the TRAC concept.

The arrival of the TRAC devices on the electronics market has led to the possibility of solutions which have hitherto been only possible by either complex pcb with many op amps and passive components or by expensive digital signal processors.

As a radio amateur I have been intrigued by the possibility of obtaining single sideband modulation or demodulation without recourse to expensive filters The 'third method' of obtaining the sum and difference frequency components of two signals at low intermediate frequencies is now a low cost possibility

Behind ssb

If two sinusoidal signals of different frequencies are multiplied together it can be shown that the result of the multiplication is given by the following,

$$A\sin xB\sin y = AB\frac{\cos(x-y)+\cos(x+y)}{2} \qquad (1)$$

$$A\cos xB\cos y = AB\frac{\cos(x-y)-\cos(x+y)}{2} \qquad (2)$$

$$A\sin xB\cos y = AB\frac{\sin(x-y)+\sin(x+y)}{2} \qquad (3)$$

These equations show that the result of the multiplication comprises of two new frequency components, one the sum and the other the difference of the two frequencies.

Each of these three equations represents the mathematics for an amplitude-modulated signal when a perfect balanced modulator is used to mix a low audio frequency with a high frequency In practice, no mixer can be made perfect. Consequently, there will always be a component of the high frequency in the equation.

Assuming the higher frequency to be y and K to be the leakage factor of the mixer then an amplitude-modulated signal will comprise of the following components,

$$K\sin yAB\frac{\sin(x-y)+\sin(x+y)}{2}$$

An amplitude-modulated signal comprises upper and lower sidebands plus some component of the modulating frequency. Because each of the sidebands contains all the intelligence of the modulating frequency it was soon realised by both professionals and the amateur radio fraternity that the bandwidth of the modulated signal could be reduced to less than half if only one sideband was transmitted. Reducing the bandwidth meant that allotted radio frequency bands could be used more efficiently – i.e. more channels in a given radio band.

Currently, most ssb radio transmitters and receivers use one of two methods to to remove the unwanted components produced by the mixers. A good example of a direct-conversion receiver is presented in the February issue of *Electronics*

More winners

These are the remaining five winners of the TRAC design competition. Each will receive a TRAC development kit worth £600.

400Hz three-phase exciter. Ben Sullivan's exciter is primarily for aircraft equipment testing. Its three-phase oscillator can lock to an external signal and has an out-of-lock indicator

Amplitude modulator. Designed by Franck Bigrat, this modulator is implemented from the mathematical formula for an AM signal.

Digitally controlled audio preamplifier. Andrew Wilkes' amplifier uses one TRAC IC to produce a four input-source stereo preamp with tape deck support and a 4-bit, i.e. 16 log step, volume control

Power meter. Charles Bacon's design is a meter for measuring power dissipation in a transistor. It makes use of TRAC's log, addition and antilog abilities to calculate power dissipated in real time, by multiplying observed current with voltage.

Two tone oscillator. This entry is a circuit is for linearity testing of wireless transmitters, for example at hf. Designed by Ian March, it uses TRAC's log function as limiter

World This method relies on the inherent low-pass filtering of an audio amplifier

Another method, preferred because of its greater sensitivity and frequency selection is the use of intermediate frequency, or frequencies, employing high gain amplifiers with very close tolerance filters to remove the unwanted components

The 'Third Method' of modulating and demodulating ssb signals has been known since the beginning of the century, but up to now the other two methods have been cheaper or easier to implement.

You can see that by adding or subtracting the result of equations 1 and 2 above, then either the frequency sum component or the frequency difference component can be isolated. In this way, an audio signal can be retrieved from a ssb signal by 'mixing' the ssb signal with a frequency equal to the original modulating frequency. Alternatively, an ssb signal can be produced from an audio frequency mixed with the required radio frequency.

TRAC calculations

Constraints. The *TRAC* device provides an inversion for both the log and antilog functions – i.e. a negative output is obtained for a positive input, and that both functions give a '0V' output for a '0V' input. This caused me to revise my understanding of elementary mathematics, which led me to believe that the log of zero was minus infinity and the antilog of zero was one.

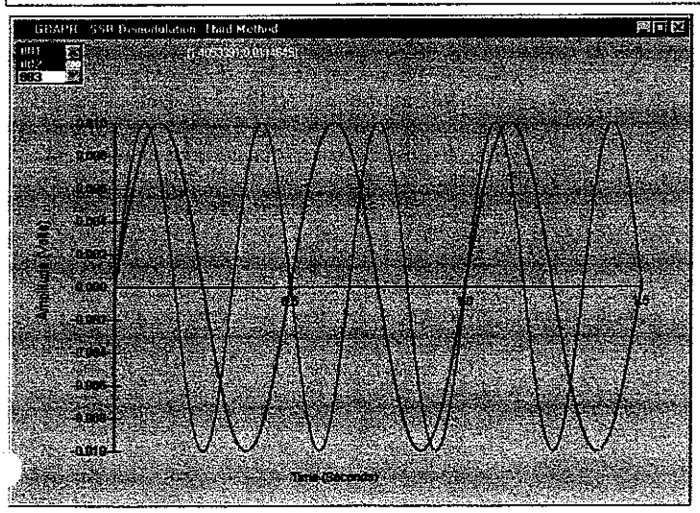
Furthermore, if a number is divided by itself, as in log*x*–log*x*=0 the result-

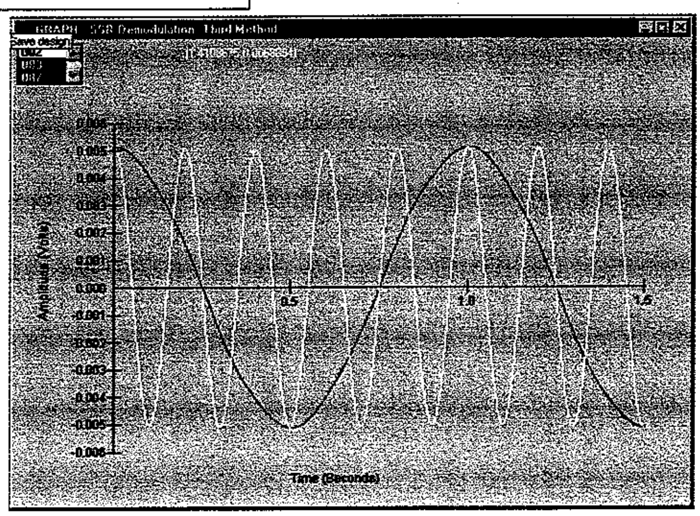
Four TRAC devices are used in the design, each having 20 functional blocks, giving a total of 80 functional blocks. The number of function blocks used is 40. The number of unused blocks is 5, giving 35 unusable blocks. These are pin functions of TRAC device 1.

Pin	Connection	Description	Pin function
1	INPUT	Sinusoidal input to be demodulated (Sig)	*A*sin*x*
2	INPUT	Sin wave input local oscillator (LO)	*B*sin*y*
3	Link to 15	Signal	*A*sin*x*
4	NIP	Local oscillator	*B*sin*y*
5	AUX		
6	AUX		
7	DIF	Signal differentiated to give 90° phase shift	d/d*x*(*A*sin*x*)=*KA*cos*x*
8	DIF	LO differentiated to give 90° phase shift	d/d*y*(*B*sin*y*)= *LB*cos*y*
9	AUX		
10	AUX		
11	AMP	Gain adjust to give phase shifted signal the same amplitude as unshifted signal	*A*cos*x*
12	AMP	Gain adjust to give phase shifted signal the same amplitude as unshifted signal	*B*cos*y*
13, 14	-		
15	Link from 3	Sig	
16	Link to 68	Sig inverted	–*A*sin*x*
17-24			

Pin functions of TRAC device 2.

Pin	Connection	Description	Function on pin
23	Link from 15	Signal	*A*sin*x*
24	INPUT	Input dc bias	*E*
25	ADD	Addition of bias to signal (inverted)	–(*E*+*A*sin*x*)
26	NIP	DC bias	*E*
27	LOG	Positive log of signal plus bias	{+log}(*E*+*A*sin*x*)
28	LOG	Inverted log of dc bias	{–log}(*E*)
29	ADD	Log of signal plus bias divided by dc bias	{–log}(1+*A*/*E*sin*x*)
30	NEG	Positive log of dc bias	{+log}(*E*)
31	Link from 4	Local oscillator	*B*sin*y*
32	Link from 26	DC bias	*E*
33	ADD	Adds dc bias to local oscillator (inverted)	–(*E*+*B*sin*y*)
34		-	
35	LOG	Positive log of local oscillator plus bias	{+log}(*E*+*B*sin*y*)
36	Link from 28	Inverted log of dc bias	{–log}(*E*)
37	ADD	Log of LO plus bias divided by dc bias	{–log}(1+*B*/*E*sin*y*)
38	Link from 29	Log of signal plus bias divided by dc bias	{+log}(1+*A*/*E*sin*x*)
39	ADD	Sum and negate log outputs, ie multiply	{+log}((1+*A*/*E*sin*x*).(1+*B*/*E*sin*y*)) ={–log}(1+*A*/*E*sin*x*+*B*/*E*sin*y*+*AB*/*E*/*E*sin*x*.sin*y*)
40	Link from 30	Positive log of dc bias	{+log}(*E*)
41	ADD	Multiply result by *E* (negated)	{–log}((*E*+*A*sin*x*+*B*sin*y*+*AB*/*E*sin*x*sin*y*)
42	Link from 32	DC bias	*E*
43	ANT	Antilog of multiplication	*E*+*A*sin*x*+*B*sin*y*+*AB*/*E*sin*x*.sin*y*
44	NEG	Negated dc bias	–*E*





Displays of the ssb modulator/demodulator produced by the TRAC simulator, inputs on the left, outputs on the right. Pin 1 is the higher frequency curve on the left and pin 2 is the lower. On the right, pin 83 is the lower frequency and pin 87 the higher.

ing antilog should be 1 This infers that the zero level input to the log and antilog functions represents a unity-level signal After delving further into the misty past of my O-Level mathematics, I realised that if you scaled the inputs and outputs to meet the available logarithmic range, any multiply or divide calculation is possible.

Once I understood that a '0V' input is the low end of the logarithmic dynamic range and that a '1.4V' was the high end then all was clear Investigations using the simulator gave a dynamic range for the log/antilog function of 87dB.

The fact that the log/antilog functions were inverting also produced wrong results, until I realised that if a multiplication was required to a negative log output then the multiplicand had to be subtracted, rather than added Conversely division needs an addition.

Also, the log and antilog functions needed the input to be wholly negative or wholly positive to obtain a correct multiplication or division.

Defining the inputs. Let the two input signals be,

$$A.\sin x \quad (4)$$
$$B.\sin y \quad (5)$$

The input to the log function must be wholly negative or positive and a dc bias voltage is necessary to lift the ac inputs above 0V Let E be the dc bias voltage

Functions. To obtain the necessary cosine function, as required by equation 2, the two ac input signals need to be differentiated i e $\cos x = d/dx(\sin x)$

$$A\cos x \quad (6)$$
$$B\cos y \quad (7)$$

There are now available the necessary functions to calculate the sum and difference components of the two inputs To ensure that the inputs to the log functions never go below the zero level, a dc bias must be added to the inputs prior to performing a log function. Adding bias voltage E to equations 6 and 7 gives,

$$E+A\sin x \quad (8)$$
$$E+B\sin y \quad (9)$$

where E must be greater than the larger of A or B.

To keep the signals within the dynamic range of the TRAC, these signals have to be divided by E prior to multiplication.

$$1+\frac{A}{E}\sin x \quad (10)$$

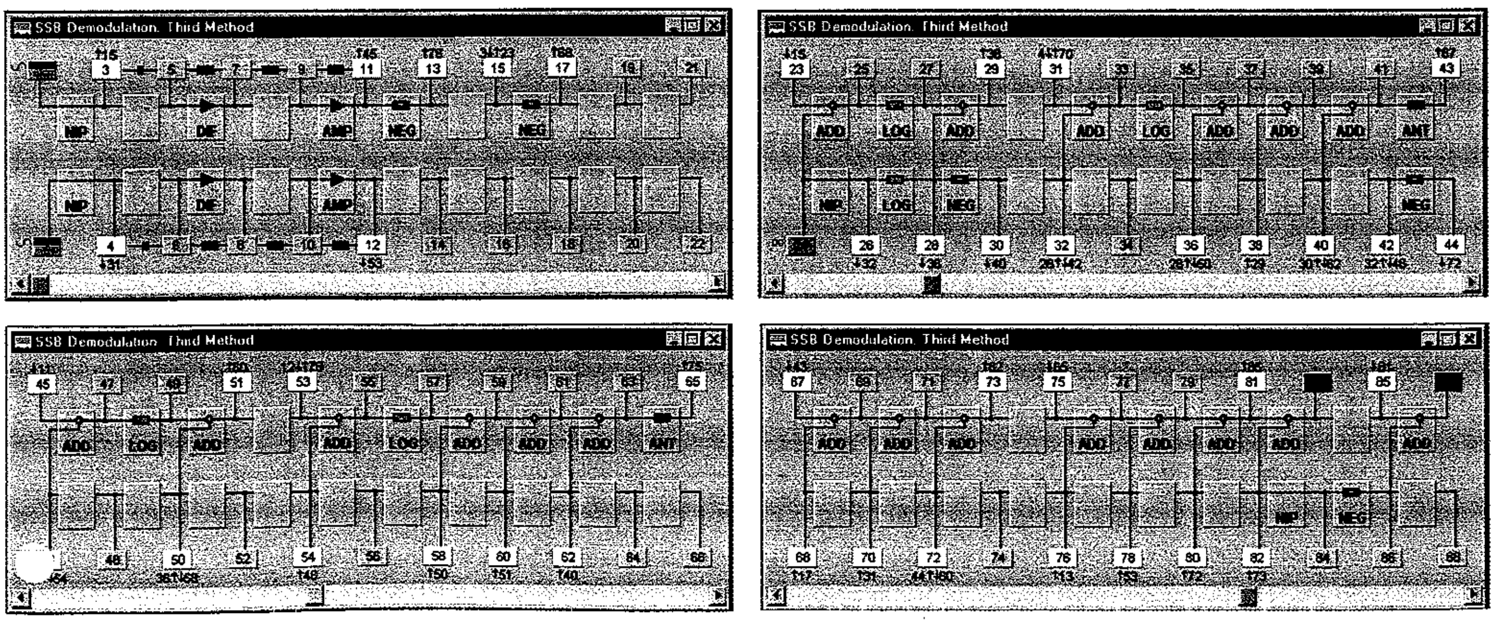
$$1+\frac{B}{E}\sin y \quad (11)$$

Multiplying equations 10 and 11 gives,

$$1+\frac{A}{E}\sin x+\frac{B}{E}\sin y+AB\frac{\sin x \sin y}{E^2} \quad (12)$$

Pin functions of TRAC device 3.

Pin	Connection	Description	Pin function
45	Link from 11	Signal	$A\cos x$
46	Link from 42	DC bias	E
47	ADD	Addition of bias to signal (inverted)	$-(E+A\cos x)$
48			
49	LOG	Positive log of signal plus bias	{+log}($E+A\cos x$)
50	Link from36	Inverted log of dc bias	{–log}(E)
51	ADD	Log of signal plus bias divided by dc bias	{–log}($1+A/E\cos x$)
52			
53	Link from 4	Local oscillator	$B\cos y$
54	Link from 46	DC bias	E
55	ADD	Add dc bias to local oscillator (inverted)	$-(E+B\cos y)$
56			
57	LOG	Positive log of local oscillator plus bias	{+log}($E+B\cos y$)
58	Link from 50	Inverted log of dc bias	{–log}(E)
59	ADD	Log of LO plus bias divided by dc bias	{+log}($1+B/E\cos y$)
60	Link from 51	Log of signal plus bias divided by dc bias	{+log}($1+A/E\cos x$)
61	ADD	Sum and negate log outputs, ie multiply	{–log}(($1+A/E\cos x$).($1+B/E.\cos y$)) = {–log}($1+A/E\cos x+B/E.\cos y+AB/E/E.\cos x\cos y$)
62	Link from 40	Positive log of dc bias	{+log}(E)
63	ADD	Multiply result by E (negated)	{+log}(($E+A\cos x+B\cos y+A.B/E\cos x.\cos y$)
64			
65	ANT	Antilog of multiplication	$-(E+A\cos x+B\cos y+A.B/E\cos x\cos y)$
66			



Each of the four TRAC devices needed to implement the ssb modulator and demodulator. Numbering on the pins indicates which device is which.

More on TRAC

These comments have been added by David Winch of Fast Analog Solutions to help you get to grips with Mike's design more easily.

Using TRAC's LOG and ANT functions to multiply In theory, you can multiply by adding logs and then taking the antilog. This is also true with TRAC, *with provisos*.

The transfer function of the LOG cell is,

$$V_{out}=0\ 07474375(\log_{10}(V_{in})+10)$$

Here the logarithm base is shown as 10, but any other base is applicable, if you adjust the constants.

For the ANT cell, the transfer function is,

$$V_{out}=10^{(V_{in}/0\ 07474375)-10}$$

Again, any log base is applicable. The ADD cell is self explanatory. The operational limit of the LOG cell is $|V_{in}|<1.4V$ while that of the ANT cell is $0.1V<|V_{in}|<0.8V$. Equally importantly, the operational limit of the ADD cell is $|V_{out}|<1.4V$

For inputs from 0.1V to 1.0V, most usable logs are in the range 0.6V to 0.75V, so adding two together would take the signal outside the operational limit of the ANT function. This can be corrected by 'dividing by one', i.e. subtracting the log of 1.0V.

However, if the two V_{in} signals exceed about 0.25V, their logs will exceed 0.7V and so their sum will be outside the operational limit of the ADD function. To remove this possibility, the 'dividing by one' must be done before the ADD.

When multiplying more than two inputs together, this 'dividing by one' must be performed after all but the final input.

Using the LOG and ANT functions to multiply, divide and raise to powers

Some people have told us they have experienced difficulties using TRAC to multiply and divide by adding and subtracting logarithms. Let me try to make things clearer.

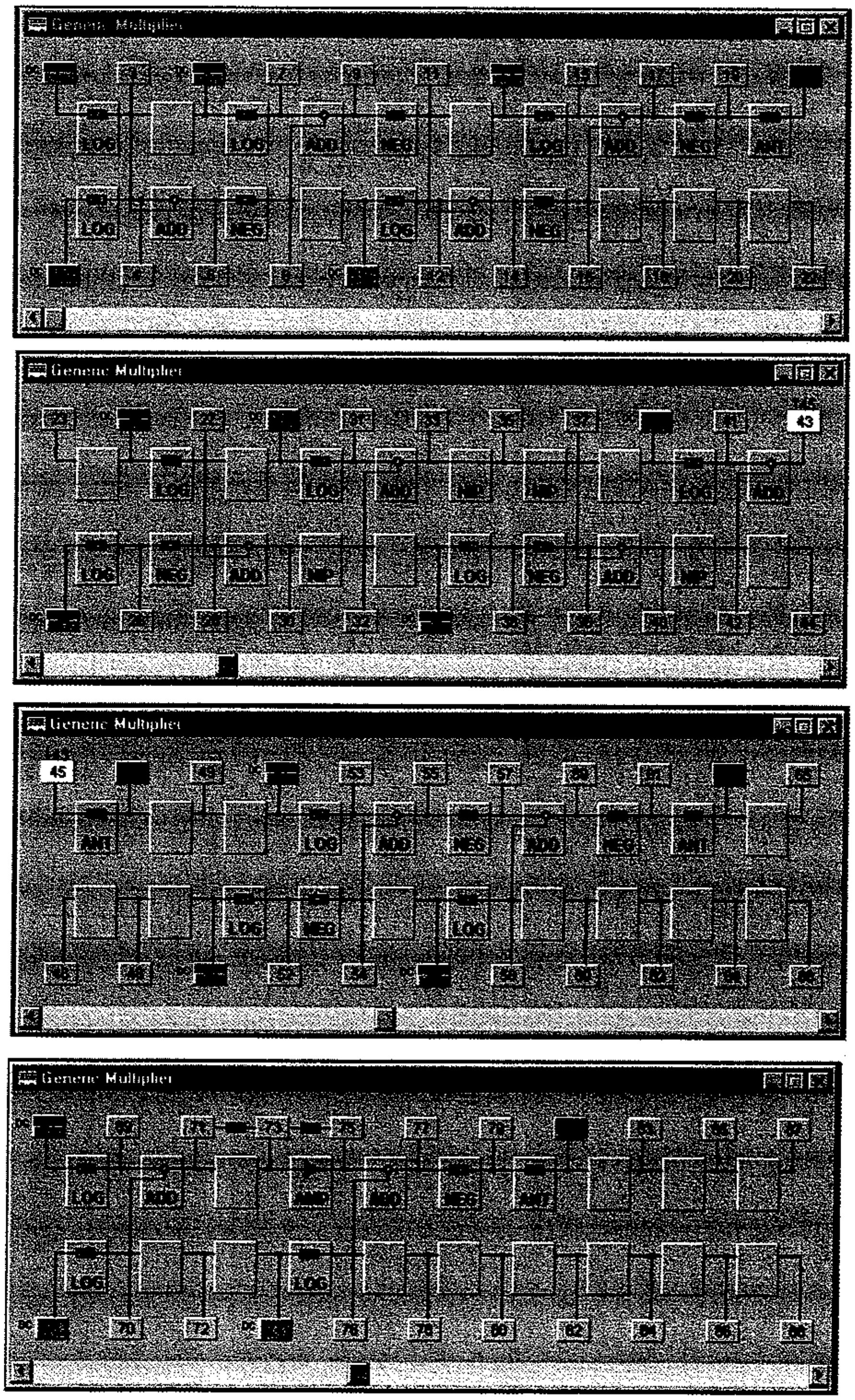
If you have used logs to base ten, or natural logs, to multiply numbers you may not have realised how much of a fortunate coincidence it is that the log of 1 to any base is zero. If this doesn't make sense, let me put it another way. What would you expect the answer to be if you multiplied 0.5 volts by 0.4 volts? Did you say 0.2 volts? Now, what should the answer be if you multiply 500mV by 400mV? Should it be 200 000mV or µV?

Now do you start to see what happens when we multiply quantities rather than numbers? It depends on what you decide 'one' is!

Deciding what 'one' is means working *relative* to a fixed point. When multiplying *numbers* we work relative to 1, so using their logs we work relative to 0. So effectively we do nothing, or more probably we don't even realise we are doing nothing.

So what's different with TRAC? Well nothing actually. Using the TRAC LOG cell, the log of 1V is approximately 750mV, and the log function has a gain of approximately 75mV per decade, or approximately 23mV per octave.

The log function is not to any particular base. It just obeys the rule that multiplying the input by a constant changes the output by a constant amount, no matter what the original input. The TRAC antilog cell follows the inverse of the same curve.



Studying these implementations should help you grasp the idea of TRAC's log function not being to any particular base – if you haven't already of course. From the top, they are a generic multiplier, a generic divider, an alternate 'multiply-and-divide' and 'raise-to-a-positive-power' circuits respectively. Note that the generic divider overflows into the third TRAC chip by one element.

So the log of 0.5V is approximately 727mV and the log of 0.4V is approximately 720mV. The sum of these is 1447mV but the antilog of 1447mV would never get to the 2000 megavolts indicated by the mathematics. We have not worked relative to what 'one' is. If 1V is 'one' then we need to calculate,

{(log(0 5V)–log(1V)}+
{log(0 4V)–log(1V)}+log(1V)

Putting in quantities we get,

{727mV–750mV}+
{720mV–750mV}+750mV

Or in other words,

–23mV–30mV+750mV=697mV

and the antilog of 697mV is 0 2V

And if you think about it, this is what you do with numbers. Only that you work relative to log of 'one' is zero.

How does this apply to practical TRAC designs? Well, if you are multiplying you would need to subtract the log of 1V from each multiplicand and then add it back in once at the end. Practically you would just not subtract from the last multiplicand.

When dividing, you would need to subtract from every term and put it back in once at the end as well, but in this case you would practically add the log of 1V to every divisor but not the numerator at the beginning.

Raising to a power be it positive of negative, greater or less than unity, the same applies. Subtract the log of 1V, do the processing and add the log back in once again

A further practical problem is raised by the ADD cell of the TRAC. Its output saturates at approximately 1 4 volts. So you need to be careful exactly where in the design you subtract the log of 1V.

In multiplication, subtraction needs to happen before the log of the next multiplicand is added; in division, addition needs to happen after the log of the next divisor has been subtracted; and the same general principles apply to raising to a power.

If you think back to when you used a slide-rule, you'll remember that the easiest calculations were the ones with alternate multiplication and division. The same is true using TRAC. If you alternately subtract and add logs, and if there is one more multiplicand than divisor, the need to 'divide by one' is removed and the ADD function never saturates.

The simple TRAC designs shown here should clarify the situation even further.

Multiplying by E gives,

$$E + A\sin x + B\sin y + AB\frac{\sin x \sin y}{E} \qquad (13)$$

Subtracting equations 4 and 5 from above gives,

$$E + AB\frac{\sin x \sin y}{E} \qquad (14)$$

Subtracting E and expanding gives,

$$\frac{AB}{2E}(\cos(x-y)+\cos(x+y)) \qquad (15)$$

Performing the same functions on equations 6 and 7 gives,

$$\frac{AB}{2E}(\cos(x-y)-\cos(x+y)) \qquad (16)$$

Adding or subtracting equations 15 and 16 gives,

$$\frac{AB}{E}\cos(x-y) \qquad (17)$$

Thus the sum or difference frequency components are thus obtained

In summary

Note that the differentiation function is used to obtain a $\pi/4$ phase shift (sin to cos function) and the amplitude of this function's output is frequency sensitive. The signal to be demodulated must, therefore, not vary in frequency by a significant amount or the amplitude of the cosine function will vary causing distortion on the output.

At the final 470kHz intermediate frequency of most receivers. this should not be a problem as the audio signal in the range 300Hz to 3.4kHz gives only a 0.7% deviation.

Provision of an ssb modulator using this method is not possible because the frequency deviation – and hence the amplitude deviation – of the $\pi/4$ phase-shifted output of an audio signal is too large.

Another look at the theory shows that if an audio signal $A\sin x$ is mixed with another constant frequency of $B\sin y$ and $B\cos y$ the resulting functions will be,

$$A\sin x B\sin y = AB\frac{\cos(x-y)+\cos(x+y)}{2}$$

$$A\sin x B\cos y = AB\frac{\sin(x-y)+\sin(x+y)}{2}$$

By filtering out the sum or difference component of the two equations, the sine and cosine functions of the audio frequency are available. Provided the frequency offset provided by the frequency y is taken into account then the functions thus obtained can be used as inputs to the *TRAC* functions given by this design.

Investigation of the data sheets show that the available bandwidth for low level signals is 4MHz. It should, therefore, be possible to perform a direct conversion on the 160m amateur band (1.8MHz) and possibly on 80 metres (3 5MHz). ■

Pin functions of TRAC device 4

Pin	Connection	Description	Function
67	Link from 43	Result of 'sin' multiplication	*E+Asinx+Bsiny +AB/Esinx siny)*
68	Link from 17	Sig inverted	*–Asinx*
69	ADD	Subtract Sig from result	*–(E+Bsiny+AB/Esinx siny*
70	Link from 31	Local osc	*Bsiny*
71	ADD	Subtract local osc from result	*–(E+AB/Esinx siny)*
72	Link from 44	Negative dc bias	*–E*
73	ADD	Subtract dc bias from result Sum of sum and difference frequencies obtained	*AB/Esinx siny =AB/E(cos(x–y)+cos(x+y))*
74			
75	Link from 65	Result of cosine multiplication	*E+Acosx+Bcosy+ AB/Ecosx cosy*
76	Link from 13	Cosine of Sig inverted	*–Acosx*
77	ADD	Subtract cosine of Sig from result	*–(E+Bcosy+AB/Ecosx cosy)*
78	Link from 53	Cosine of local oscillator	*Bcosy*
79	ADD	Subtract cosine of local oscillator from result	*–(E+AB/Ecosx cosy)*
80	Link from 72	Negative dc bias	*–E*
81	ADD	Subtract dc bias from result The difference of the sum & difference frequencies obtained.	*AB/Ecosx cosy =AB/E(cos(x–y)–cos(x+y))*
82	Link from 73	The sum of the sum & difference frequencies.	*AB/E(cos(x–y)+cos(x+y))*
83	ADD	Add the sum and difference to obtain the difference component of the signal and LO – **the required result**	*AB/Ecos(x–y)*
84	NIP		
85	Link from 81	Difference of sum and difference frequencies	*AB/E(cos(x–y)–cos(x+y))*
86	NEG	Invert	*–AB/E(cos(x–y)–cos(x+y))*
87	ADD	Subtract the sum and difference to obtain the sum component of the signal and LO – **the required result.**	*AB/Ecos(x+y)*
88			