Super-regenerative Receiver By Tan See Teck 3 March 2002

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### 1 Introduction

The super-regenerative receiver operates on the direct conversion principle where an oscillator can perform RF detection. This resulted in a low component-count receiver. In comparison, the more commonly used super-heterodyne receiver operates by mixing the RF signal down to IF for demodulation. The performance is hence better but the tradeoff is a more complex receiver.

In 1922, Armstrong invented super-regenerative receiver architecture. However, super-regenerative receiver architecture was progressively abandoned followed his later invention of super-heterodyne receiver architecture, which give better selectivity and sensitivity performance.

Currently, super-regenerative receives implemented using discrete components are still being used in low cost application where performance is not critical. The advantages are: low power consumption, simple architecture, small silicon size and lower cost as external IF filter are not required. The disadvantages are: low data rate, only work on on-off keying, poor sensitivity and poor selectivity. Hence, it can only serve in niche application where performance is not critical.

Companies such as Telecontrolli and Mipot have products that using super-regenerative principle.

Literatures and papers on principle of super-regenerative receiver are rare. A search through IEEE explorer for the relevant papers resulted in less than 10 hits. The more relevant are: [1], [2] and [3]. There is only one book that devoured entirely to the principle of super-regenerative receiver [4].

The papers are very difficult to understand as lots of mathematical derivations and circuit details are hidden.

The principle of operation will not be explained in this report as this will require substantial amount of effort to re-produce lots of material into the report.

The purpose of the report is to understand the quench waveform on the performance of super-regenerative receiver. In the process, two analytical equations for linear mode of operation [4] will be compared to the result of circuit simulation.

# 2 Overview Of Super-regenerative Receiver



The LNA provides matching and gain for RF signal. It also provides reverse isolation to prevent the oscillation signal of oscillator from re-radiate to the air. Envelope detector extracts the envelope of the oscillation signal. After low pass filtering, data slicer produces the digital waveform.

The quench generator supplies the quench signal for the oscillator. Due to variation of temperature, supply voltage and processes, it is necessary to have an AGC to maintained the desired operating region of the receiver.

# 3 Mode Of Operation

Super-regenerative receiver has two modes of operation: linear and logarithmic.

The figure below shows the linear mode of operation. RF input is a 100% on-off keying signal. The quench signal showed is trapezoidal-shaped. Different quench waveform will give different performance tradeoff. Waveform such as rectangular, sine, saw-tooth are possible, though the resulting receiver performances have their own strengths and weaknesses.



Linear mode is characterized by linear relation between the amplitude of the RF input signal and the amplitude of the envelope. In this mode, the oscillator does not reach its steady-state during the quench period.



The figure above shows the logarithmic mode. The logarithmic mode is characterized by a logarithmic relation between the amplitude of the RF input signal and the amplitude of the demodulated output. In this mode, the oscillator reaches its steady-state amplitude at each quench cycle.

# 4 Quenching Signal

In [4], analytical equations are derived for two quenching signals: sine and square waveform. Note that these equations are meant for linear-mode only. Sine wave has a sloped zero-crossing whereas square wave has a step zero-crossing.

The core of the super-regenerative receiver is the oscillator, which can be represented as parallel combination of R, L and C in its simplest form. L and C act as the resonator or tank of the oscillator. G(t) represents the loss of the tank circuit and the negative conductance provided by active element. RFin is the RF signal represented as a current source.



When G(t) is positive, oscillation is not possible. When G(t) is negative, oscillation occurs.

The two equations are extracted and simplified for discussion.

When G(t) is a sine waveform, the equation is:



# $Vosc = Vrf * \mu o * \mu t * S * sin[Wo * t + (W-Wo)t1]$

Where:

Voltage Amplitude of RF input	Vrf = A/G0	A	Current Amplitude of RF input
		GO	Conductance of Tank
Slope Gain	$\mu o = G0 \sqrt{\frac{\pi}{C G'(t1) }}$	G'(t1)	Rate of Zero Cross of G(t) at t=t1
Super-regenerative Gain	A-	С	Capacitance of Tank
1 0	$\mu t = e^{\overline{2C}}$	A-	Area of $G(t) < 0$
Total Gain	$G = \mu o * \mu t$		
Selectivity	$-4\pi^2 C(f-fo)^2$	f	Input Frequency
	$S = \frac{f}{fo} e^{-\frac{1}{ G'(t1) }}$	fo	Tank Resonant Frequency

When G(t) is a square waveform, the equation is:



$$Vosc = Vrf * \mu o * \mu t * S * sin[Wo * t]$$

Where:

Voltage Amplitude of	Vrf = A/G0	А	Current Amplitude of RF input
RF input		G0	Conductance of Tank
Step Gain	$\mu o = \frac{G0 +  G1 }{ G1 }$	G1	Peak Negative Conductance
Super-regenerative Gain	<u>A–</u>	С	Capacitance of Tank
	$\mu t = e^{2C}$	A-	Area of $G(t) < 0$
Total Gain	$G = \mu o * \mu t$		
Selectivity	S =	W	$=2\pi f$
	$\frac{\frac{G0G1}{4C^2}}{\sqrt{(W-Wo)^2 + \left(\frac{G0}{2C}\right)^2}\sqrt{(W-Wo)^2 + \left(\frac{G1}{2C}\right)^2}}$	Wo	=2πfo

## 5 Comparison

To compare performance of super-regenerative receiver in the linear mode, two quenching signals are generated for comparison.

The common circuit parameters are:

Parameter	Value	Remark
L	5nH	Inductor value
QL	20	Q factor of Inductor
Fo	1GHz	Tank resonation frequency
Fq	2.5MHz	Quenching frequency
А	1uA	Current amplitude of RF input

The two quenching signals are generated for comparison.



The parameters for sine quenching signal are:

Parameter	Value	Remark
G0	1.592m	Tank conductance
G'(t1)	-30	Zero-crossing rate of G(t) at t1
t1	44	Time of zero-crossing (positive-to-negative transition of G(t)).
t2	156	Time of zero-crossing (negative-to-positive transition of G(t)).
Aminu	67p	Area of $G(t) < 0$

The parameters for square quenching signal are:

Parameter	Value	Remark
G0	1.592m	Tank conductance
G1	-638u	Peak negative conductance
Tb	114ns	Build up period
Aminu	75.34p	Area of $G(t) < 0$

The respectively total gain (calculated using equations) of super-regenerative receiver using the two quenching signals is:

	Sine	Square
Total Gain	74.63dB	75.45dB

Note that the total gains are adjusted to almost equal for comparison.





The result shows that sine quenching signal will have better selectivity. Hence to have good selectivity, the zero-crossing of G(t) must be sloped.





The Top-left plot is sine quenching signal using equation and Bottom-left plot is sine quenching signal using circuit simulation. The results are very closed with only 0.2dB of error.

The Top-right plot is square quenching signal using equation and Bottom-right plot is square quenching signal using circuit simulation. The results are reasonably closed with 3dB of error.

This confirms that the two equations are very accurate and circuit simulations are correctly done.

### 6 Conclusion

The validation of the two equations for linear-mode is done.

To carry on the work, the steps could be:

- 1 Perform circuit simulation using envelope simulator instead of transient simulator. Transient simulator is not possible for large circuit. Thus far, the elements used in the circuit simulation are only simple R, L and C. They are only four of them. With more elements, envelope simulator has to be used.
- 2 With envelope simulator, design the oscillator. Then investigate its performance for linear and logarithmic mode. Quenching signal generator must also be designed.
- 3 With the knowledge gained in step 2, studied the necessity of AGC and design it.

With those steps completed, the essential or the more difficult and uncertain part of the super-regenerative receiver design is completed.

# 7 Simulation Setup (ADS)

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·	• • •	Tdata=1/Edata	Gp=1/Rp	• •	InGmB=sqrt(2	*geléctron*	ItailB*N	BW)	• •	• •	• •	·	• •
·		Wdata=2*pi*Edata	$C = 1/00(\alpha^2)0(\alpha^2 L)$	· ·	1 nGmB≐lnG	mB/sort/NBV	νi i		• •	• •	• •	•	
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	Fcarrier=1G			• •	• •	•	• •	• •	• •	•	•	• •	•	•	·	•	•	·	•	•
	OOK1=(1+AM)*sin(2*p	i*E carriel	r*time).	1.01		•	• •	• •	• •	•	·	• •	•	·	·	·	·	·	·	·
	OOK2=if abs(OOK1)>U	1.5 then (	JOK1 ek	se u er	ndiț	•														
	OOK=A*OOK2																			
	CVV=A*sin(2*pi*Fcarrie	r*time)																		
						ſ	<u> </u>	'AR							·	•		·	•	
				• •	• •		B	othSlop	eStep	•	•	• •	•	•	·	·	·	·	·	•
7	VAR + + + + +		• • •	• •	• •	•	⊢ A	.=1u +	• •	·	·	• •	•	·	·	·	·	·	·	·
	EitherSlope					•	. V	's=A/Go	о											
	t0=0						G	o=Gp												
	t1=44n						G	1=638.	5u 👘											
	t2=156n			• •		•	- W	Vcarrier	=2*pi*	Fcar	rier	• •	•	•	·	•	•	·	•	•
	T1=t1-t0 1 1 1	• • •	• • •	• •	• •	•	i Za	- 0=	• •	•	·	• •	•	·	·	·	·	·	·	·
	T2=t2-t0 + + + +					•	<ul> <li>A</li> </ul>	f=Go/(4	4*pi*C	'sqrt(	((Fea	arriei	r-Fo)	)^2+(	(Go,	/(4*	pi*C	))^(	2))	·
	Greg=Go*sqrt(pi/(C*ab	s(Gpr_T	1))) .				. Q	!o≑QL												
	Aminu=67p						G	pr_T1=	-30K)											
	Aplus=385p						Ġ	pr T2=	abs(G	pr T	1) -									
	Gsr=exp(Aminu/(2*C))		• • •	• •	• •	•	• •	·		· -		• •	•	•	·	·	·	·	·	•
	Gtot=Greg*Gsr					•	· ·	• •	• •	·	•	• •	•	•	·	·	·	·	·	•
	SHAPEsr=Gsr*exp(-Gp	or T2*z^	2/(4*C))																	
			borrior V	0.6-3.6-23	1.1. 2.0															
•	St=(VVcarrierA/Vo)*exp TimeShift=t0	(-(C*((VV)	Carnersy	v0)^2)	/abs(0	Gpr_T	1,))) .	• •			•	• •	•		•	•	•	•	•	
	St=(VVcarrier/Vo)*exp TimeShift=t0 Vo_slope=Vs*Greq*Gs	(-(C*((VV) sr*exp(-(	Gpr T2*	(time_1	/abs(C FimeSh	Spr_T hift_T2	1))) 2)^2/(4	kómis	(f*sin()	Wo*(	time.	Time	shit	t)+0	Nos	arrie	er-V	Vol*	(†1)	•
	St=(Wcarrier/Wo)*exp TimeShift=t0 Vo_slope=Vs*Greg*Gs Vo_cond_t1mustlarget	(-(C*((VV sr*exp(-( han=(6/c	Gpr_T2*	(time_1	/abs(C FimeSh	Spr_T hift-T2	1))) 2)^2/(4	₩C)))*S	(f*sin	Wo*(	time	Time	Shit	ft)+(\	Nca	arrie	er-V	Vo)*	·T1)	
	St=(/Vcarrier//Vo)*exp TimeShift=t0 Vo_slope=Vs*Greg*Gs Vo_cond_t1mustlarget	(-(C*((VV sr*exp(-( han=(6/¢	Gpr_T2* bi)*Qo*To	(time_1	/abs(C FimeSh	Spr_T hift-T2	1))) 2)^2/(4	₩Ċ)))*S	f*sin(	Wo*(	time	Time	shit	t)+()	Nca	arrie	er-V	Vo)*	(T1)	• • •
	St=(VVcarrier//Vo)*exp TimeShift=t0 Vo_slope=Vs*Greg*Gs Vo_cond_t1mustlarget	(-(C*((VV sr*exp(-( han=(6/¢	Gpr_T2* bi)*Qo*Tc	(time_1	/abs(C	∋pr_T hift-T2	1.))) 2)^2/(4	ŀ*Ċ)))*S	f*sin()	Wo*(	time	Time	Shit	t)+(\	Nca	arrie	er-V	Vo)*	(T1)	
•	St=(Wcarrier/Wo)*exp TimeShift=t0 Vo_slope=Vs*Greg*Gs Vo_cond_t1mustlarget	(-(C*((VV sr*exp(-( han=(6/¢ VAR othFs	Gpr_T2* bi)*Qo*To	(time-1	/abs(C	∋pr_T hift-T2	1))) 2)^2/(4	⊧c)))∗s	if*sin()	/Vo*(	time	Time	eShit	t)+(1	Nca	arrie	er-V	Vo)*	(Ť1)	
	St=(VVcarrier//Vo)*exp TimeShift=t0 Vo_slope=Vs*Greg*Gs Vo_cond_t1mustlarget	(-(C*((W sr*exp(-( han=(6/k VAR othFs Fsper	Gpr_T2* bi)*Qo*To pecEnv c_stope1	(time_1	/abs(C FimeSh rt(pi*C	Spr_T hift-T2 /Gpr_	1,))) 2)^2/(4 _T2)*e	ι∗C)))*S ×p(-4*κ	i*sin()	Wo*( F*C≬	time Gpr_	Time T2)	shit	t)+(\	Nca	arrie	er-V	Vo)*	(T1)	
1	St=(VVcarrier//Vo)*exp TimeShift=t0 Vo_slope=Vs*Greg*Gs Vo_cond_t1mustlarget	(-(C*((W sr*exp(-( han=(6/) VAR othFs Fsper Fsper	Gpr_T2* bi)*Qo*Tc pecEnv c_stope1 c_stope2	(time_1 )  =2*sq 2=Fspe	/abs(C FimeSh rt(pi*C ec_q*F	Gpr_T ) )/Gpr_ )spec	1,))) ?)^2/(4 _T2)*e _slope	₩C)))*S xp(-4*p e1	if*sin() i*pi*F*	Wo*( F*C∕i	time Gpr_	Time T2)	Shit	ť)+()	Nca	arrie	er-V	Vo)*	• (†1) -	· · ·
	St=(VVcarrier//Vo)*exp TimeShift=t0 Vo_slope=Vs*Greg*Gs Vo_cond_t1mustlarget VAR EitherStep t0=42n	(-(C*((W) sr*exp(-( han=(6/k VAR othFs othFs Fsper Fsper Fs1=(	Gpr_T2* bi)*Qo*Tc pecEnv c_stope1 Go/(2*C)	(time-1) )  =2*sq 2=Fspe	/abs(C FimeSh rt(pi*C ec_q*F	Spr_T hift-T2 //Gpr_ spec	1,))) 2)^2/(4 _T2)*e _slope	₩C)))*S xp(-4*p e1	)f*sin() )i*pi*F*	VVo*( F*C≬	time Gpr_	Time T2)	eShit	t)+()	Nca	arrie	er-V	Vo)*	(†1)	
7	St=(VVcarrier//Vo)*exp TimeShift=t0 Vo_slope=Vs*Greg*Gs Vo_cond_t1must/arget VAR EitherStep t0=42n tb=156n	(-(C*((W sr*exp(-( han=(6/) VAR othFs Fsper Fsper Fs1=( Fs2=(	Gpr_T2* bi)*Qo*Tc pecEnv c_slope1 Go/(2*C) G1/(2*C)	(time-1) )  =2*sq 2=Fspe	/abs(C FimeSh rt(pi*C ec_q*F	Spr_T hift-T2 //Gpr_ spec	1,))) ?)^2/(4 _T2)*e _slope	4*C)))*S xp(-4*p e1	if*sin() i*pi*F*	VVo*( F*C∕i	time Gpr_	Time T2)	Shit	t)+()	Nca	arrie	er-V	Vo)*	(†1)	· · · · · · ·
	St=(VVcarrier//Vo)*exp TimeShift=t0 Vo_slope=Vs*Greg*Gs Vo_cond_t1must/arget VaR EitherStep t0=42n tb=156n Tb=tb=t0	(-(C*((W han=(6/k othFs othFs Fsper Fsper Fs1=( Fs2=( Fsper	Gpr_T2* i)*Qo*Tc pecEnv c_slope1 Go/(2*C) G1/(2*C) c_step1:	(time-1) ) l=2*sq 2=Fspe     =2*(Fs	/abs(C FimeSh rt(pi*C ec_q*F 1+Fs2	3pr_T hift-T2 //Gpr_ spec )*(Fs1	1,))) 2)^2/(4 _T2)*e _slope 1*Fs2-	I*C)))*S ×p(-4*k ⊧1 +(2*pi*F	;f*sin() ;i*pi*F* ;)^2)/(	///o*( F*C/( ((2*p	time Gpr_ i*F)^	Time [T2] 2+F:	s1*F∶	ťt)+() s1)*(	/Vca	arrie pi*F	er-V	Vo)* +Fs	•T1) 2*F	)
54	St=(VVcarrier//V0)*exp TimeShift=t0 Vo_slope=Vs*Greg*Gs Vo_cond_t1must/arget VAR EitherStep t0=42n tb=156n Tb=tb-t0 Greg=(Go+G1)/G1	(-(C*((W han=(6/k othFs othFs Fsper Fsper Fs1=( Fs2=( Fsper Fsper Fsper	Gpr_T2* Gpr_T2* ii)*Qo*Tc c_stope1 c_stope2 Go/(2*C) G1/(2*C) c_step1 c_step2	(time-1) ) !=2*sq 2=Fspe =2*(Fs =Fspec	/abs(C FimeSh rt(pi*C c_q*F 1+Fs2 c_q*Fs	<pre>&gt;pr_T hift-T2 //Gpr_ spec )*(Fs1 spec_</pre>	1.))) 2)^2/(4 _T2)*e _slope 1*Fs2- step1	L*C)))*S xp(-4*k e1 +(2*pi*F	;f*sin() ;i*pi*F* ;)^2)/(;	///o*( F*C/( ((2*p	time Gpr_ i*F)^	Time [T2] 2+Fs	s1*F	ť)+(\ s1)*(	/Vcs	arrie pi*F	er-V	Vo)* +Fs	°T1) 2*F	)
24	St=(VVcarrier//V0)*exp TimeShift=t0 Vo_slope=Vs*Greg*Gs Vo_cond_t1must/arget VAR EitherStep t0=42n tb=156n Tb=tb-t0 Greg=(Go+G1)/G1 Amínu=75.34p	(-(C*((W han=(6/k othFs othFs Fsper Fsper Fs1=( Fs2=( Fsper Fsper Fsper Fsper F=0	Gpr_T2* Gpr_T2* ii)*Qo*Tc c_stope1 c_stope2 Go/(2*C) G1/(2*C) c_step1 c_step2	(time_1) ) !=2*sq 2=Fspe =2*(Fs =Fspec	/abs(C FimeSh rt(pi*C ec_q*F 1+Fs2 c_q*Fs	<pre>&gt;pr_T hift-T2 //Gpr_ spec_ )*(Fs1 spec_</pre>	1.))) 2)^2/(4 _T2)*e _slope 1*Fs2- step1	xp(-4*; +(2*pi*F	;f*sin() ;i*pi*F* ;)^2)/(;	/Vo*( F*C/( ((2*p	time Gpr_ i*F)^	Time [T2] 2+F:	s1*F	ťt)+() s1)*(	/\cs ((2*	arrie pi*F	er-V )^2	Vo)* +Fs	•T1) 2*F	)
70	St=(VVcarrier//V0)*exp TimeShift=t0 Vo_slope=Vs*Greg*Gs Vo_cond_t1must/arget VAR EitherStep t0=42n tb=156n Tb=tb-t0 Greg=(Go+G1)/G1 Amínu=75.34p Aplus=448.8p	(-(C*((VV han=(6/k othFs Fspei Fspei Fs1=! Fs2=! Fspei Fspei Fspei Fspei Fspei Fspei Fspei	Gpr_T2* Gpr_T2* ii)*Qo*Tc c_stope1 c_stope2 G0/(2*C) G1/(2*C) c_step1: c_step2: c_step2: c_step2:	(time_1) ) !=2*sq !=Spe =2*(Fs =Fspec :m(F,F)	/abs(C FimeSh rt(pi*C ec_q*F 1+Fs2 c_q*Fs q)≖0 t⊭	Gpr_T hift-T2 Gpr_ spec_ her 1	1.))) 2)^2/(4 _T2)*e _slope 1*Fs2- step1 else 1	xp(-4*; =1 +(2*pi*F =-12 ei	if*sin() i*pi*F* ()^2)/()	/Vo*( F*C/ ((2*p	time. Gpr_ i*F)^	-Time (T2) 2+F	eShit s1*F	t)+() s1)*(	/Vca	arrie pi*F	er-V )^2	Vo)* +Fs	•T1) 2*F	
70	St=(vvcarrier//vo)*exp TimeShift=t0 Vo_slope=Vs*Greg*Gs Vo_cond_t1must/arget VAR EitherStep t0=42n tb=156n Tb=tb-t0 Greg=(Go+G1)/G1 Aminu=75.34p Aplus=448.8p Gsr=exp(Aminu/(2*C))	(-(C*((VV han=(6/k othFs othFs Fspei Fspei Fs1=( Fs2=( Fspei Fspei Fspei Fspei Fspei Fspei	Gpr_T2* Gpr_T2* ii)*Qo*Tc c_stope1 c_stope2 Go/(2*C) G1/(2*C) c_step1: c_step2: c_step2: c_step2:	(time_1) ) l=2*sq 2=Fspe =2*(Fs =Fspec m(F,F)	/abs(C FimeSh rt(pi*C c_q*F c_q*Fs q)≖0 tk	Gpr_T hift-T2 (Gpr_ spec_ )*(Fs1 spec_ hen 1	1.))) 2)^2/(4 _T2)*e _slope 1*Fs2 step1 else 1	xp(-4*; =1 +(2*pi*F e-12 ei	;f*sin() ;i*pi*F* ;)^2)/() ndif	√Vo*( F*C/( ((2*p	time. Gpr_		s1*F:	t)+() s1)*(	/Vca	pi*F	er-V )^2	Vo)* +Fs	•T1) 2*F	; ; ; ; ; ; ; ; ;
24	St=(vvcarrier//vo)*exp TimeShift=t0 Vo_slope=Vs*Greg*Gs Vo_cond_t1must/arget VaR EitherStep t0=42n tb=156n Tb=tb-t0 Greg=(Go+G1)/G1 Aminu=75.34p Aplus=448.8p Gsr=exp(Aminu/(2*C)) Gtot=Grea*Gsr	(-(C*((VV han=(6/k othFs othFs Fspei Fspei Fs1=( Fs2=( Fspei Fspei Fspei Fspei Fspei	Gpr_T2* Gpr_T2* i)*Qo*Tc c_stope1 C_stope2 G0/(2*C) G1/(2*C) C_step1: c_step2: c_step2: c_q=if re	(time_1) ) l=2*sq 2=Fspe =2*(Fs =Fspe m(F,F)	/abs(C FimeSh rt(pi*C c_q*F c_q*Fs q)≖0 t⊧	Gpr_T hift-T2 //Gpr_ spec_ hen 1	1.))) 2)^2/(4 _T2)*e _slope 1*Fs2- step1 else 1	µC)))*S xp(-4*; ≈1 +(2*pi*F e-12 ei	i*pi*F* )^2)/( ndif	/Vo*( F*C/( ((2*p	time Gpr_	Time [T2): 2+F:	eShit	t)+(\ s1)*(	/Vca	arrie pi*F	er-V )^2	Vo)* +Fs	•T1) 2*F	
34	St=(vvcarrier//v0)*exp TimeShift=t0 Vo_slope=Vs*Greg*Gs Vo_cond_t1must/arget VaR EitherStep t0=42n tb=156n Tb=tb-t0 Greg=(Go+G1)/G1 Aminu=75.34p Aplus=448.8p Gsr=exp(Aminu/(2*C)) Gtot=Greg*Gsr SHAPEsr=if z=0 then e	(-(C*((VV sr*exp(-( han=(6/k othFs othFs Fspei Fspei Fspei Fspei Fspei Fspei Fspei Fspei	Gpr_T2* Gpr_T2* i)*Qo*Tc pecEnv c_slope1 C_slope2 G0/(2*C) G1/(2*C) c_step1: c_step2: c_step2: c_q=if re	(time_1) ) l=2*sq 2=Fspe =2*(Fs =Fspe m(F,F)	/abs(C fimeSh rt(pi*C c_q*F c_q*Fs q)≖0 tk q)≖0 tk	<pre>&gt;pr_T hift-T2 //Gpr_ spec_ pec_s hen 1 //2*C1)</pre>	1.))) 2)*2/(4 _T2)*e _slope 1*Fs2- step1 else 1	+(2*pi*F +(2*pi*F e-12 ei	;f*sin() ;i*pi*F* ;)^2)/() ndif	///o*( F*C// ((2*p	time Gpr_ i*F)^	T2) 2+F:	eShit	t)+() s1)*(	((2*)	pi*F	er-V	Vo)* +Fs	9T1) 2*F	
	St=(vvcarrier//vo)*exp TimeShift=t0 Vo_slope=Vs*Greg*Gs Vo_cond_t1must/arget VaR EitherStep t0=42n tb=156n Tb=tb-t0 Greg=(Go+G1)/G1 Aminu=75.34p Aplus=448.8p Gsr=exp(Aminu/(2*C)) Gtot=Greg*Gsr SHAPEsr=if z<0 then e St=GotG1 (/4C*C*sorth	(-(C*((VV sr*exp(-( han=(6/k othFs othFs Fspei Fspei Fspei Fspei Fspei Fspei Fspei Fspei	Gpr_T2* Gpr_T2* i)*Qo*Tc c_slope1 C_slope1 Go/(2*C) G1/(2*C) c_step1: c_step2: c_step2: c_q=if re b/(2*C))*	(time_1) ) ==2*sq ==2*(Fs ==Fspec ==Fspec :=m(F,F) *exp(Q	/abs(C fimeSf rt(pi*C c_q*F c_q*Fs q)≖0 tF q)≖0 tF c_q*C	<pre>&gt;pr_T hift-T2 //Gpr_ spec_ pec_s hen 1 ((2*C)) /^2)*er</pre>	1.))) 2)*2/(4 _T2)*e _slope 1*Fs2- step1 else 1 0 else	xp(-4*; e1 +(2*pi*F e-12 er exp(G1	i*pi*F*	((2*p ((2*p 2*C)*i	time. Gpr_ i*F)^ exp(	-Time [T2): 2+F:	s1*F:	t)+() s1)*(	/Vcs ((2*)	arrie pi*F	er-V )^2	Vo)* +Fs	•T1)	
	ST=(VVcarrier//V0)*exp TimeShift=t0 Vo_slope=Vs*Greg*Gs Vo_cond_t1must/arget VaR EitherStep t0=42n tb=156n Tb=tb-t0 Greg=(Go+G1)/G1 Aminu=75.34p Aplus=448.8p Gsr=exp(Aminu/(2*C)) Gtot=Greg*Gsr SHAPEsr=if z<0 then e Sf=Go*G1/(4*C*C*sqrti timeShift=f0	(-(C*((W sr*exp(-( han=(6/k othFs othFs Fspei Fspei Fspei Fspei Fspei Fspei Fspei Fspei (Wcarrie	Gpr_T2* Gpr_T2* i)*Qo*Tc c_slope1 C_slope1 Go/(2*C) G1/(2*C) c_step1: c_step2: c_step2: c_q=if re b/(2*C))* er-Wo)*2	(time_1) ) l=2*sq 2=Fspe =2*(Fs =Fspe m(F,F) *exp(Q 2+(Go/	/abs(C fimeSh rt(pi*C c_q*F c_q*Fs q)≖0 t⊧ (2*C)) (2*C))	<pre>&gt;pr_T hift-T2 //Gpr_ spec_ pec_s hen 1 /(2*C)) ^2)*sc</pre>	1.))) 2)*2/(4 _T2)*e _slope 1*Fs2- step1 else 1 	xp(-4*; e1 +(2*pi*F e-12 ei exp(G1 /carrier	;f*sin() ;i*pi*F* ;)^2)/() ndif .*Tb/() .VVo)^	((2*p ((2*p 2*C)*i 2+(G	time. Gpr_ i*F)^ exp( 1/(2)	-Time [T2) 2+F: -Go <sup>o</sup>	s1*F: (z)/( 2))	t)+() s1)*(	/Vcs ((2*)	arrie pi*F ∙ndii	er-V )/*2	Vo)* +Fs	•T1)	s2)
	St=(vvcarrier//vo)*exp TimeShift=t0 Vo_slope=Vs*Greg*Gs Vo_cond_t1must/arget VaR EitherStep t0=42n tb=156n Tb=tb-t0 Greg=(Go+G1)/G1 Aminu=75.34p Aplus=448.8p Gsr=exp(Aminu/(2*C)) Gtot=Greg*Gsr SHAPEsr=if z<0 then e Sf=Go*G1/(4*C*C*sqrti TimeShift=t0 Vo_slope_shep==if time	(-(C*((W sr*exp(-( han=(6/k othFs othFs Fspei Fspei Fspei Fspei Fspei Fspei Fspei Fspei (Fspei Fspei (Wcarrie	Gpr_T2* Gpr_T2* i)*Qo*Tc c_stope1 C_stope2 G0/(2*C) G1/(2*C) c_step2: c_step2: c_q=if re b/(2*C))* pr_W0)*2 content of the the the the the the the the the the	(time_1) ) l=2*sq 2=Fspe =2*(Fs =Fspec *em(F,F) *exp(G 2+(Go/	/abs(C FimeSh rt(pi*C c_q*F c_q*Fs q)=0 tk (2*C)) ne:th>	<pre>&gt;pr_T hift-T2 //Gpr_ spec_ pec_s hen 1 (2*C)) /2)*sc (/2*C)</pre>	1.))) 2)^2/(4 	xp(-4*; e1 +(2*pi*F e-12 ei exp(G1 carrier.	i*pi*F* ()^2)/( ndif (*Tb/(2 -VVo)^	///o*( F*C// ((2*p 2*C)*i 2+(G	time Gpr_ i*F)^ exp( 1/(2*	-Time (T2): -Go (C))/	s1*F: (2)/( 2))	t)+() s1)*( (2*C)	/Vcs ((2*)	arrie pi*F	er-V	Vo)* +Fs	•T1) 2*F	· · · · · · · · · · · · · · · · · · ·
	St=(VVcarrier//V0)*exp TimeShift=t0 Vo_slope=Vs*Greg*Gs Vo_cond_t1must/arget VaR EitherStep t0=42n tb=156n Tb=tb-t0 Greg=(Go+G1)/G1 Aminu=75.34p Aplus=448.8p Gsr=exp(Aminu/(2*C)) Gtot=Greg*Gsr SHAPEsr=if z<0 then e Sf=Go*G1/(4*C*C*sqrtt TimeShift=t0 Vo_slope_shape=if tim Vo_slope_Shape=if tim	(-(C*((W) sr*exp(-( han=(6/k othFs othFs Fspei Fspei Fspei Fspei Fspei Fspei Fspei Fspei (Fspei Fspei (Wcarrie	Gpr_T2* Gpr_T2* i)*Qo*Tc c_stope1 c_stope2 Go/(2*C) G1/(2*C) c_step1: c_step2: c_step2: c_q=if re b/(2*C))* pr_Wo)*2 men exp( (2*C)*	(time_1) ) l=2*sq 2=Fspe =2*(Fs =Fspec *em(F,F) *exp(G 2+(Go/	/abs(C FimeSh rt(pi*C c_q*F c_q*Fs c] c] c] c] c] c] c] c] c] c]	<pre>&gt;pr_T hift-T2 //Gpr_ spec_ )*(Fs1 spec_ )*(Fs1 spec_ )*(Fs1 spec_ (2*C) /(2*C) /(2*C)</pre>	1.))) 2)^2/(4 	+(2*pi*F +(2*pi*F e-12 ei exp(G1 /carrier.	i*pi*F* ()^2)/( ndif (*Tb/(2 .VVo)^ ;o*(tim	(/2*p ((2*p 2*C)*i 2+(G e=tb)	time Gpr_ i*F)^ exp( 1/(2*(	-Time (T2) -Go (C))/ 3)) e	s1*F: (2)/( 2))	t)+() s1)*(	/Vcs ((2*)	arrie pi*F	er-V	Vo)*	°T1) 2*F	
	St=(VVcarrier//V0)*exp TimeShift=t0 Vo_slope=Vs*Greg*Gs Vo_cond_t1must/arget VaR EitherStep t0=42n tb=156n Tb=tb-t0 Greg=(Go+G1)/G1 Aminu=75.34p Aplus=448.8p Gsr=exp(Aminu/(2*C)) Gtot=Greg*Gsr SHAPEsr=if z<0 then e Sf=Go*G1/(4*C*C*sqrti TimeShift=t0 Vo_slope_shape=if tim Vo_slope=Vs*Greg*ex	(-(C*((W) sr*exp(-( han=(6/k othFs othFs Fspei Fspei Fspei Fspei Fspei Fspei Fspei Fspei (Fspei Fspei (Wcarrie (Wcarrie p(G1*Tb	Gpr_T2* Gpr_T2* i)*Qo*Tc c_stope1 c_stope2 Go/(2*C) G1/(2*C) c_step1: c_step2: c_step2: c_q=if re b/(2*C))* hen exp( /(2*C))*/	(time_1) )  =2*sq 2=Fspe =2*(Fs =Fspec *exp(G 2+(Go/ Co_slo >(C2+C)	/abs(C FimeSh rt(pi*C c_q*F c_q*Fs q)≖0 tk (2*C)) ne=tb); pe_sh	<pre>&gt;pr_T hift-T2 //Gpr_ spec_ pec_s hen 1 /(2*C)) /(2*C) /(2*C) /(2*C)</pre>	1.))) 2)^2/(4 _T2)*e _slope 1*Fs2- step1 else 1 	+(2*pi*F +(2*pi*F e-12 ei exp(G1 carrier exp(-C	i*pi*F* ()^2)/( ndif (*Tb/(2 .VVo)^ so*(tim ne_Tim	///o*( F*C// ((2*p ((2*p 2*C)*i 2+(G ie=tb) ieShi	time Gpr_ i*F)^ exp( 1/(2* (ft))	T2) 72) 2+F -Go (C)) (C)) e	s1*F (z)/( 2)) ndif	t)+() s1)*(	/Vcs ((2*)	arrie pi*F	)/2	Vo)*	°T1)	· · · · · · · · · · · · · · · · · · ·
	St=(vvcarrier//vo)*exp TimeShift=t0 Vo_slope=Vs*Greg*Gs Vo_cond_t1must/arget VAR EitherStep t0=42n tb=156n Tb=tb-t0 Greg=(Go+G1)/G1 Aminu=75.34p Aplus=448.8p Gsr=exp(Aminu/(2*C)) Gtot=Greg*Gsr SHAPEsr=if z<0 then e Sf=Go*G1/(4*C*C*sqrti TimeShift=t0 Vo_slope_shape=if tim Vo_slope=Vs*Greg*ex q_cond_mustlargethan	(-(C*((W sr*exp(-( han=(6/k othFs othFs Fspei Fspei Fspei Fspei Fspei Fspei Fspei Fspei (Fspei Fspei (Wcarrie (Wcarrie (Wcarrie (Q_conc	Gpr_T2* Gpr_T2* i)*Qo*Tc c_stope1 c_stope1 Go/(2*C) G1/(2*C) c_step1: c_step2: c_step2: c_q=if re b/(2*C))* irrevp(/(2*C))* irrev	(time_1) )  =2*sq 2=Fspe =2*(Fs =Fspec *exp(G 2+(Go/ G1*(tir /o_slo s/(2*C)	/abs(C FimeSh rt(pi*C c_q*F c_q*Fs q)=0 t⊧ (2*C)) ne=tb); pe_sh	<pre>&gt;pr_T hift-T2 //Gpr_ spec_ pec_ hen 1 (2*C) /(2*C) /(2*C) /(2*C)</pre>	1.))) 2)*2/(4 _T2)*e _slope 1*Fs2- step1 else 1 ) else qrt((W )) else	+(2*pi*F +(2*pi*F e-12 ei exp(G1 /carrier exp(-C	i*pi*F* i*pi*F* ()^2)/( ndif !*Tb/(2 .VVo)^ so*(tim ne_Tim	///o*( F*C// ((2*p 2*C)*( 2+(G ie-tb) ieShi	time Gpr_ i*F)^ exp( 1/(2*( ft))	T2) 72) 2+F -Go (C)) (C)) (C)) (C))	s1*F: (z)/( 2)) ndif	t)+() s1)*(	/Vcs ((2*)	arrie pi*F	er-V		9T1)	· · · · · · · · · · · · · · · · · · ·

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# 8 Reference

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