# High-Speed Digital Operation: Frequency and Delay Requirements


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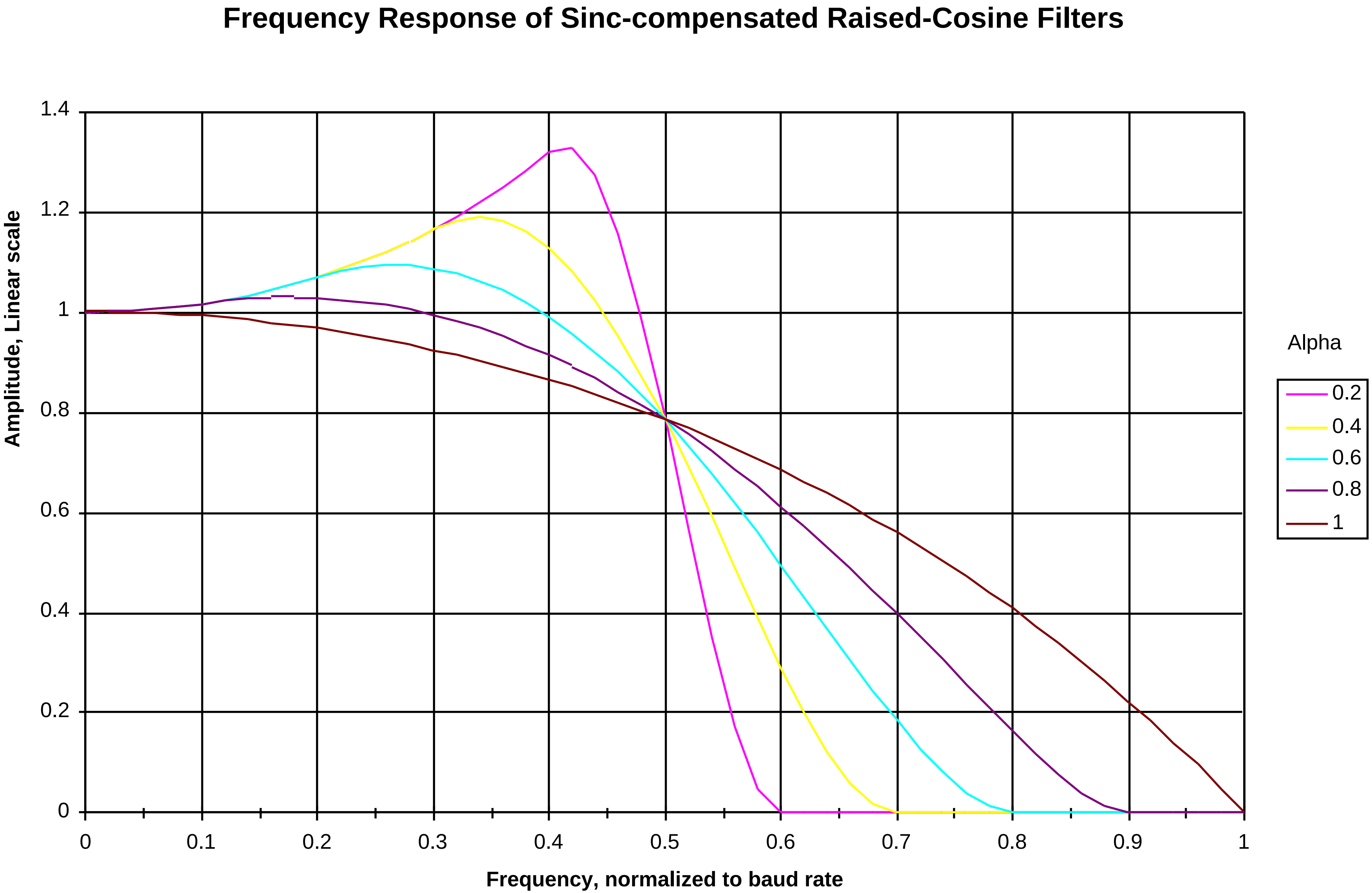
# Outline

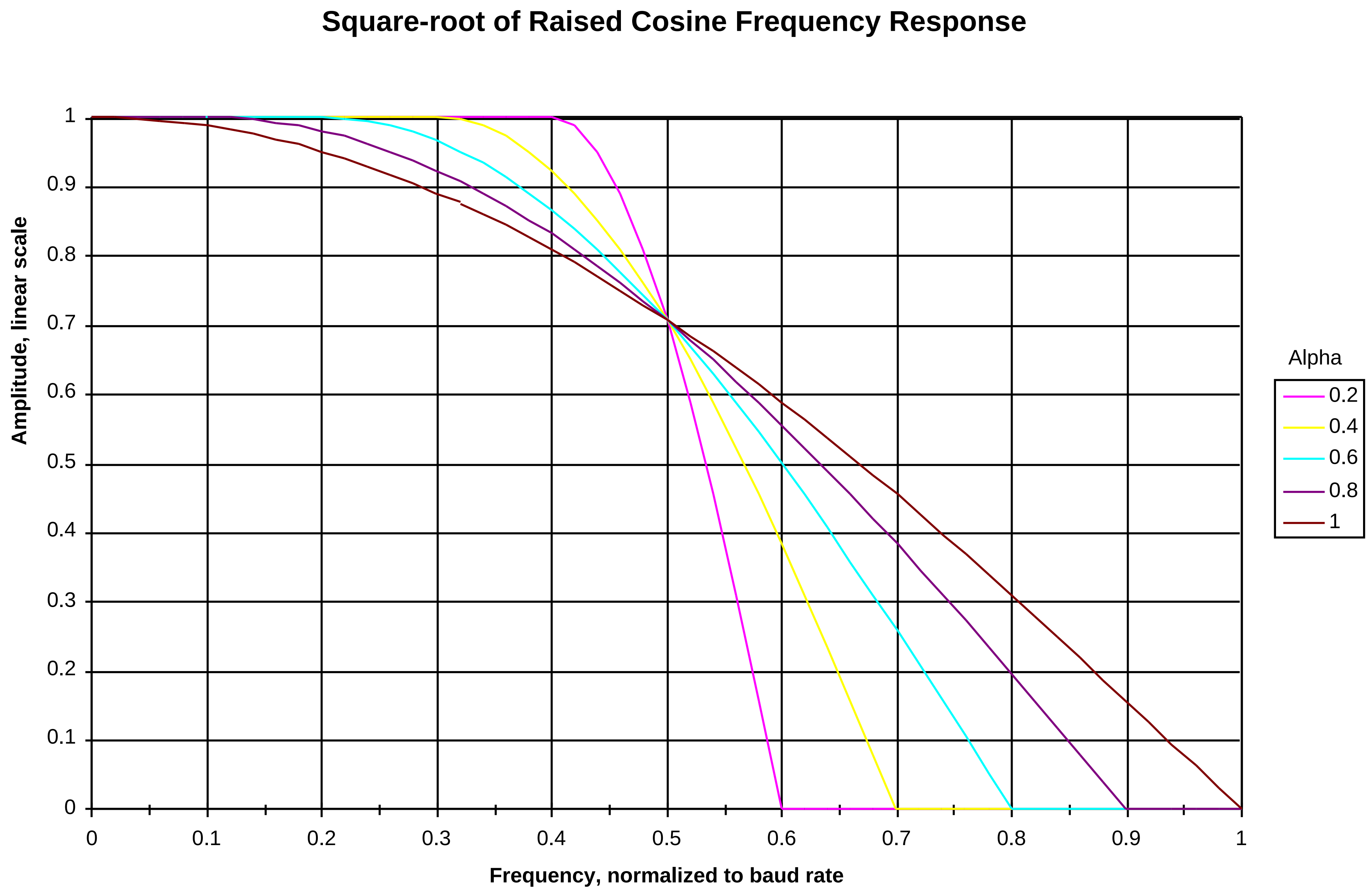
- Frequency and Group Delay response of optimum Channel
- Partitioning the Response: Modem vs. Radio
- Relationship between Phase and Group delay
- High-pass, Low-pass, All-pass, Band-pass responses
- Equalization
- Some Measured radio responses (with thanks to Bob Morgan, WB5AOH)

# 6 Rules for Filter Response

- The channel response must be symmetrical around 1/2 the data rate (Nyquist’s second theorem, the vestigial symmetry theorem).
- The response should have linear phase.
- The response should cross through the 1/2 amplitude point at one-half the data rate, in baud (Nyquist’s first theorem, the minimum bandwidth theorem).
- The spectral shape of the source must be compensated. Generally, we must multiply a square-wave by x/sin(x).
- The filter transition from passband to stopband should be gentle, not abrupt.
- OPTIONAL:
- To minimize zero-crossing jitter, the impulse response should cross 1/2 amplitude at the one-half bit time.



Frequency Response of Sinc-compensated Raised-Cosine Filters
Amplitude, Linear scale
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Frequency, normalized to baud rate
Alpha
0.2
0.4
0.6
0.8
1


Square-root of Raised Cosine Frequency Response
Amplitude, linear scale
Frequency, normalized to baud rate
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Alpha
0.2
0.4
0.6
0.8
1

# Response Partitioning

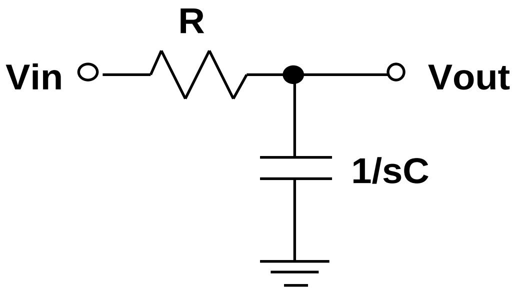
- Response needs to be well controlled for good performance.
- This is difficult to achieve in the radio - the modem usually contains the precision filters.
- Thus the radio response should be flat in amplitude, and linear in phase
- Linear phase means flat group delay

# Amplitude and Phase of Responses

- All possible responses can be described as a transfer function using complex numbers
- The response consists of Poles and Zeros
- Knowing the poles and zeros gives complete knowledge of amplitude, phase and group delay
- These can be individually compensated.

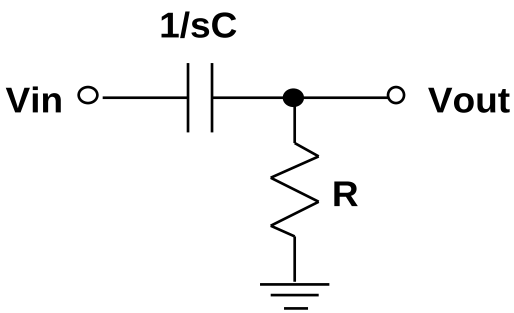
# Filters normalized to RC = 1 (1 radian/second)

## $s = j\,2\,\mathrm{PI}\,f$



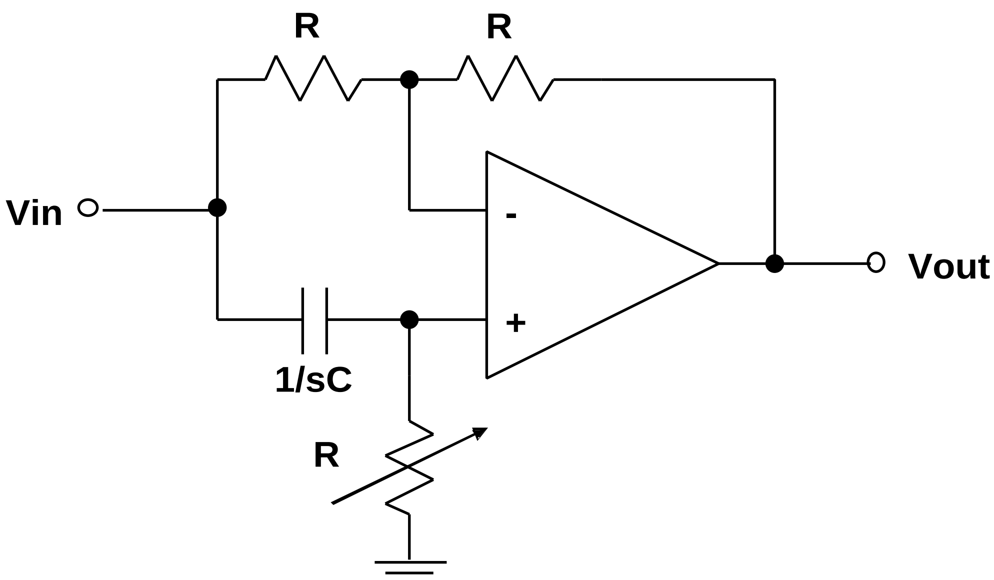

$$V_{out} = \frac{1/sC}{R + 1/sC} = \frac{1}{s+1}$$

**Low-pass filter**



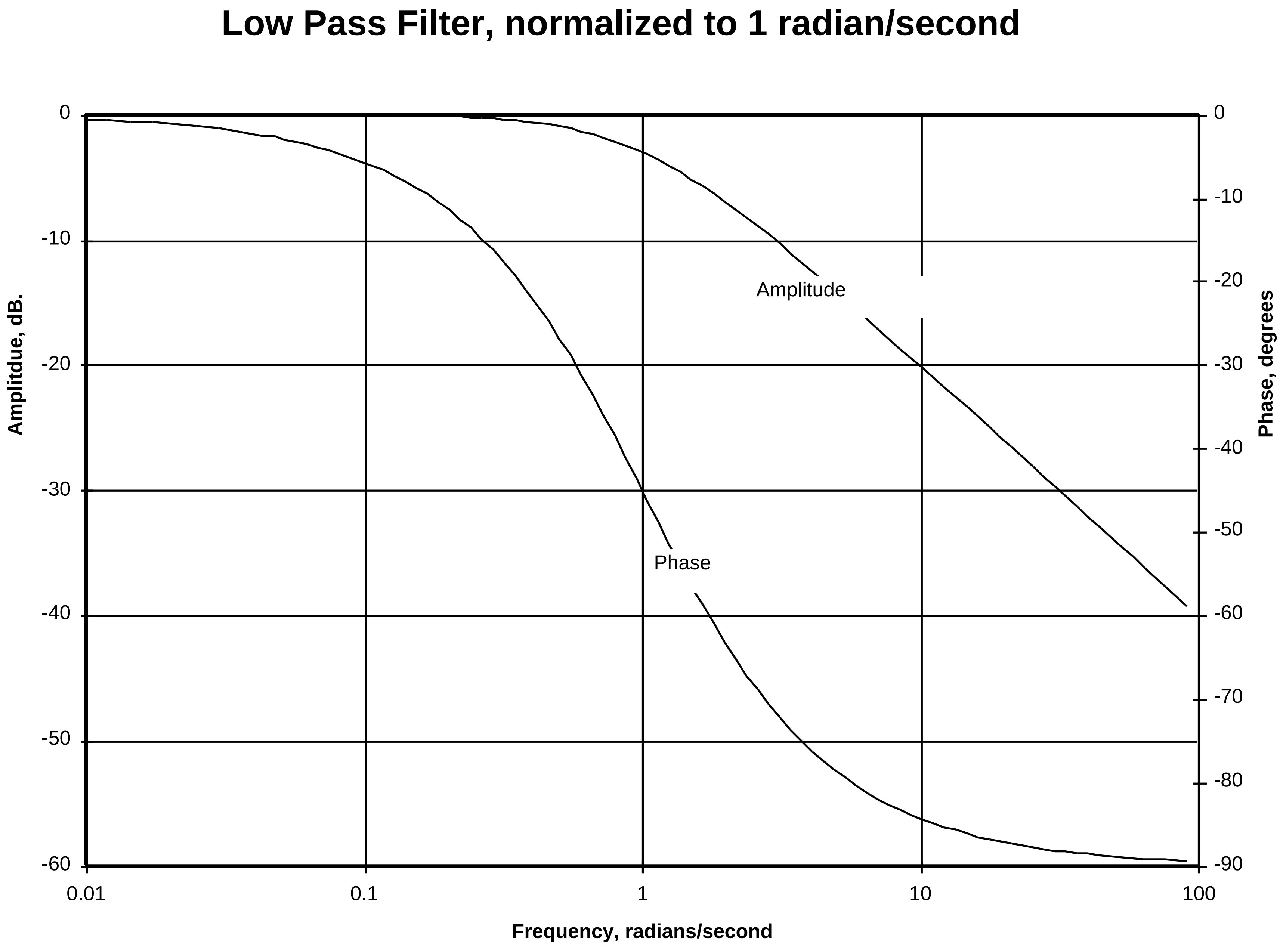

$$V_{out} = \frac{R}{R + 1/sC} = \frac{s}{s+1}$$

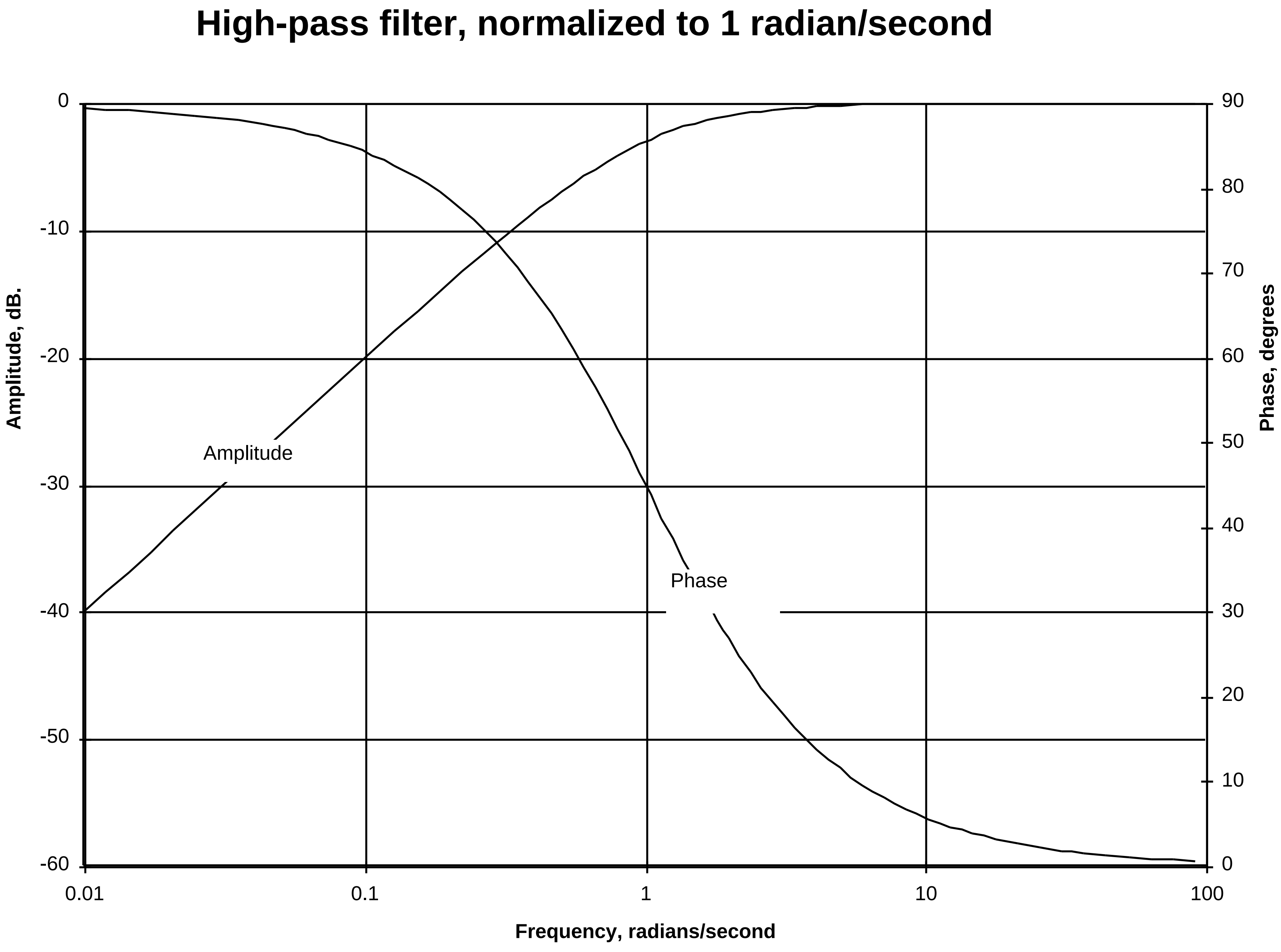
**High-pass filter**




$$V_{out} = \frac{s-1}{s+1}$$

**All-pass filter**


Low Pass Filter, normalized to 1 radian/second
Amplitdue, dB.
0
-10
-20
-30
-40
-50
-60
Phase, degrees
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
Amplitude
Phase
0.01
0.1
1
10
100
Frequency, radians/second


High-pass filter, normalized to 1 radian/second
0
-10
-20
-30
-40
-50
-60
Amplitude, dB.
90
80
70
60
50
40
30
20
10
0
Phase, degrees
Amplitude
Phase
0.01
0.1
1
10
100
Frequency, radians/second

# Group Delay

Group delay is the rate of phase-change versus frequency

$$= - \frac{d\ phi}{d\ freq}$$

this is the negative of the 'slope' of the phase versus frequency (negative of the derivative)

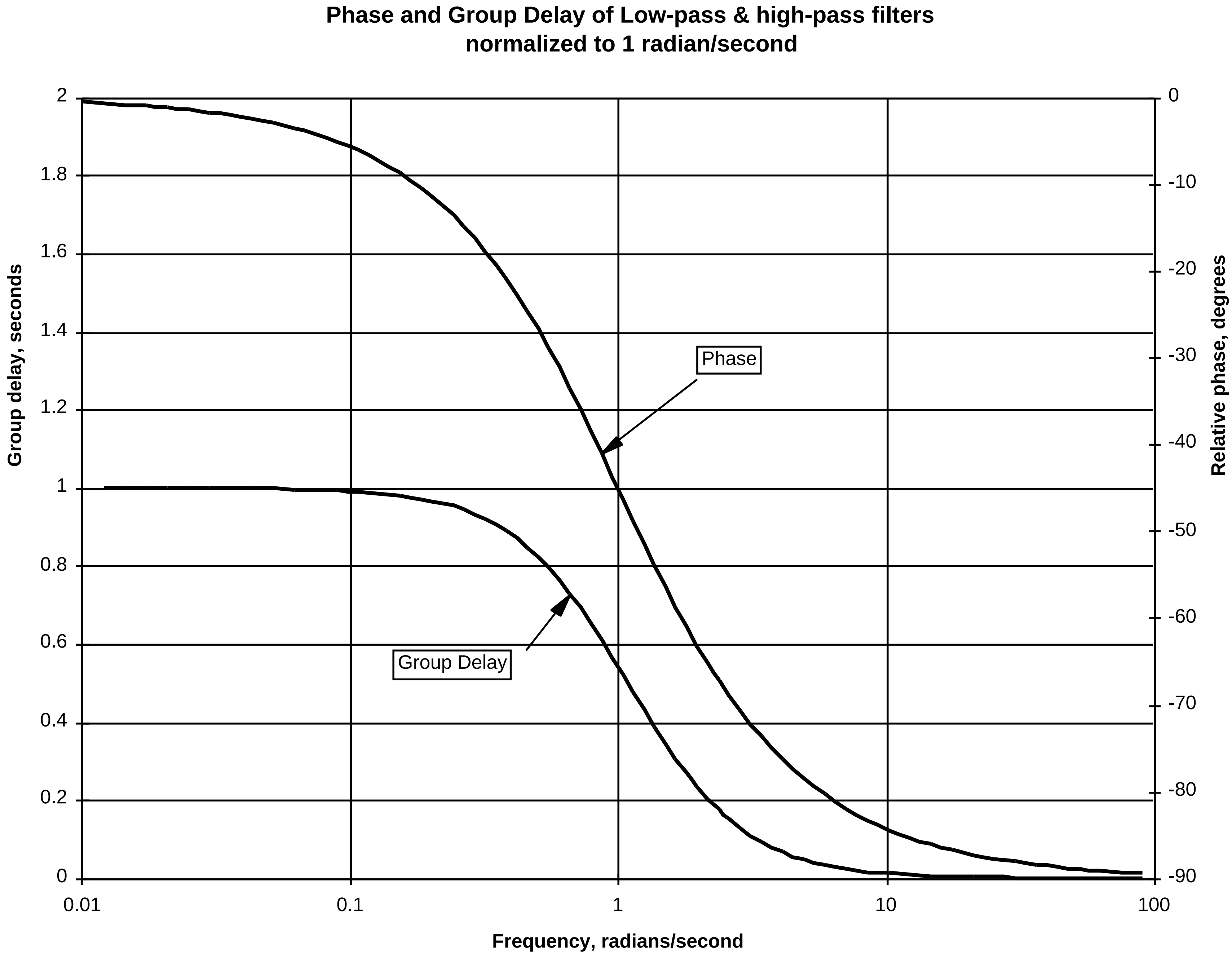
Converting units to seconds :

d phi is in radians,  d freq is in radians/second.  So the units are seconds

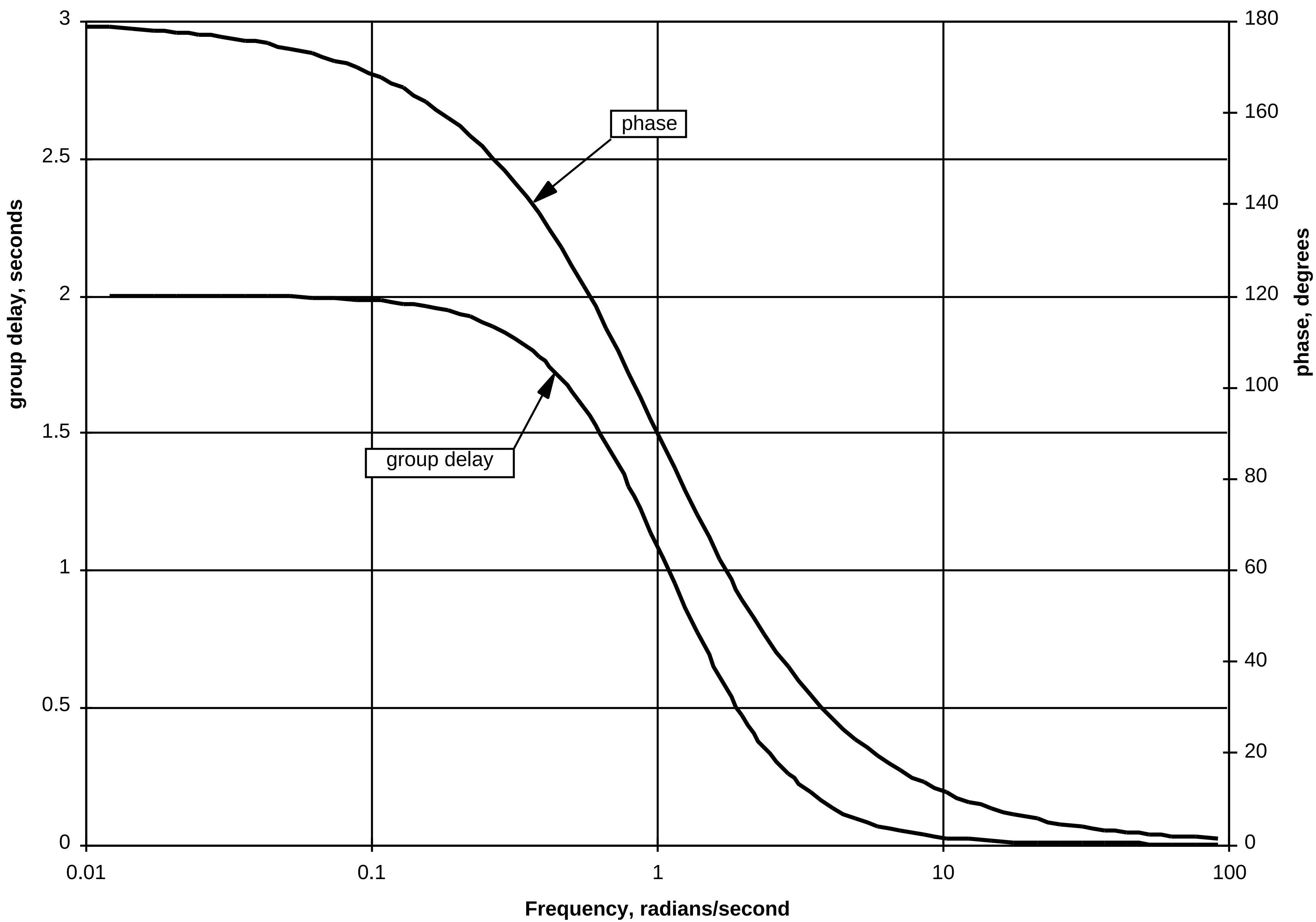
Radians = Degrees *PI / 180

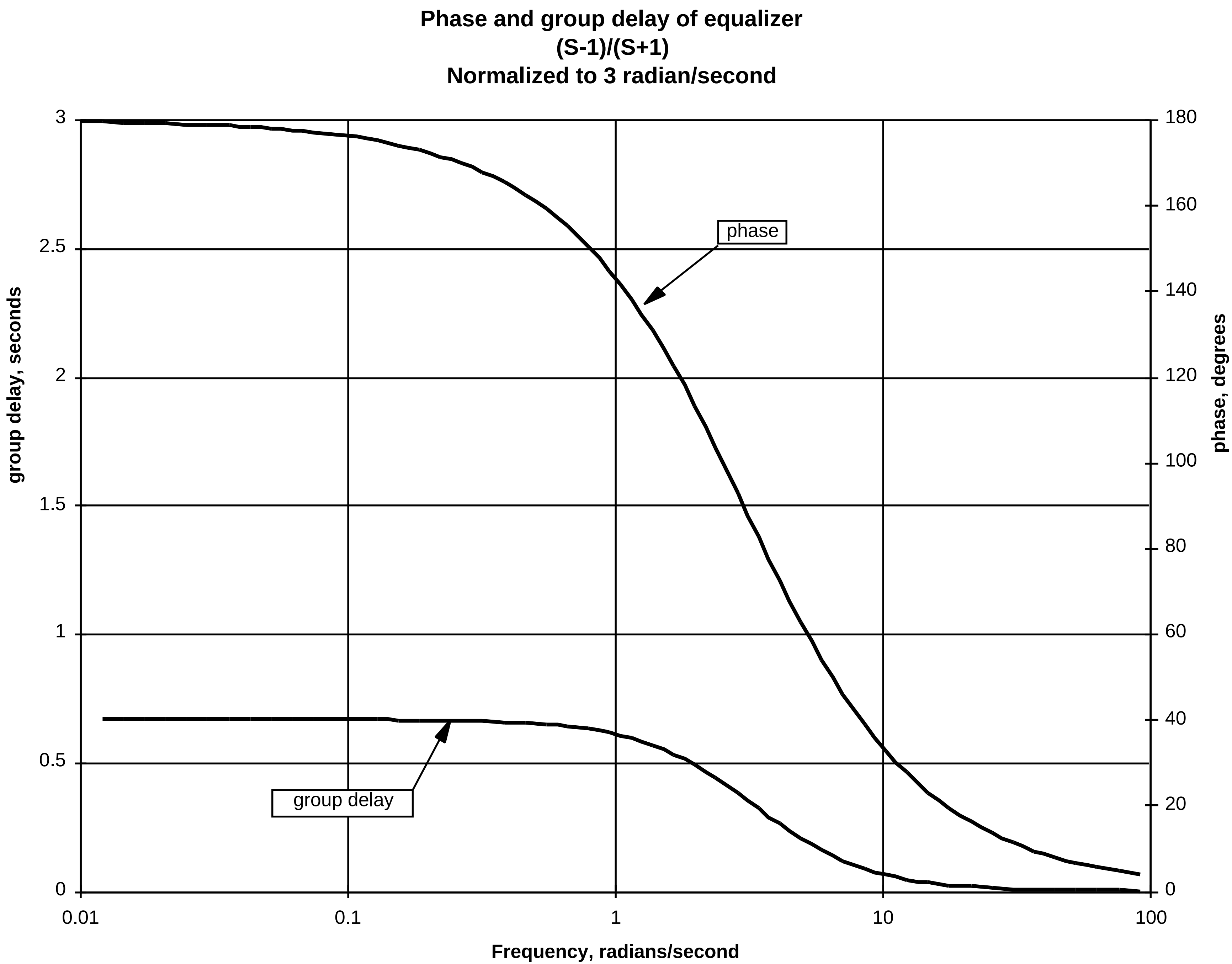
Radians / second = (Cycles / second) * 2 * PI

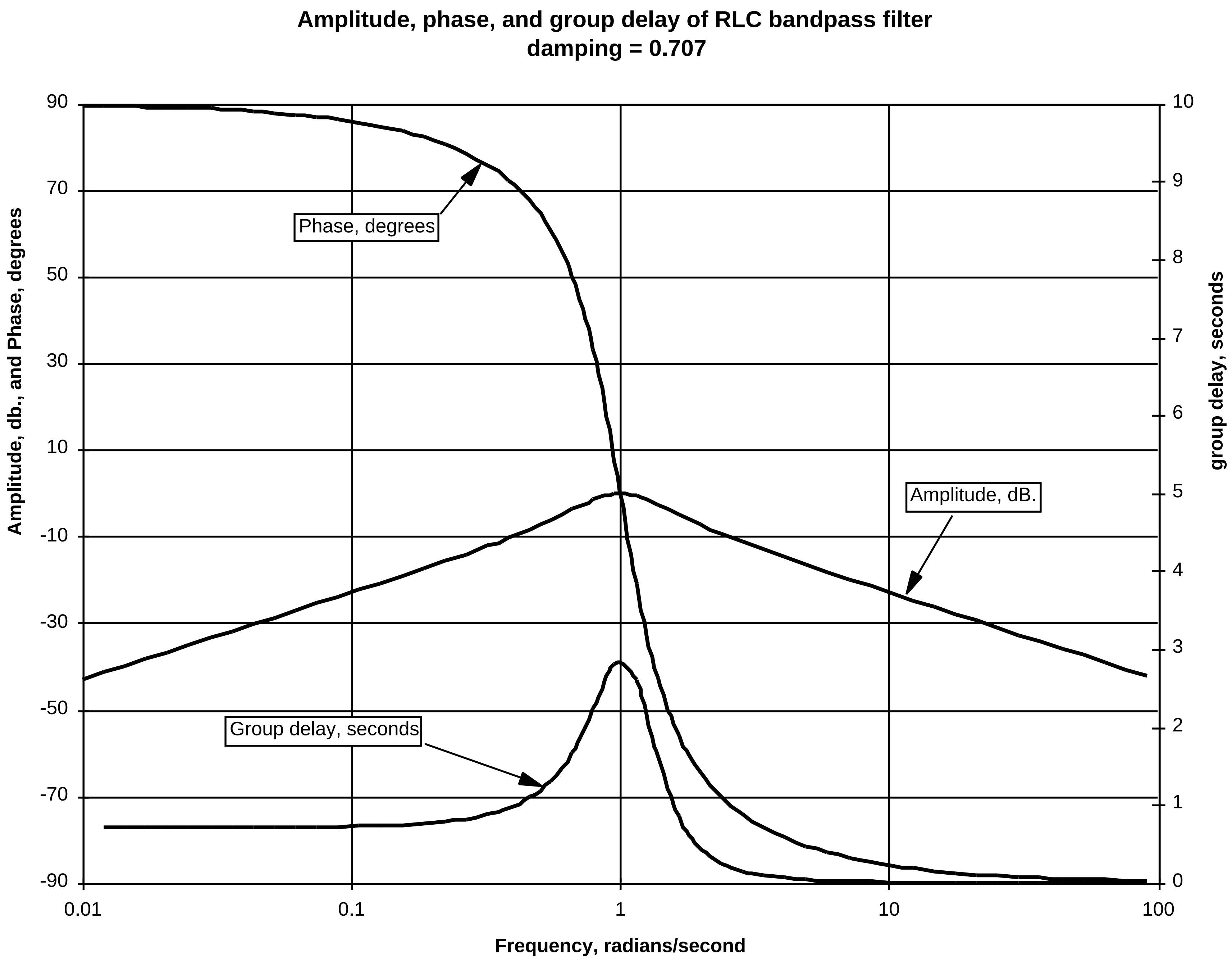
So, seconds = (degrees *PI / 180)  /  (cycles/sec * 2 * PI)   =  degrees/hertz * 1/360


Phase and Group Delay of Low-pass & high-pass filters
normalized to 1 radian/second
Group delay, seconds
Relative phase, degrees
Frequency, radians/second
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
0.01
0.1
1
10
100
Phase
Group Delay

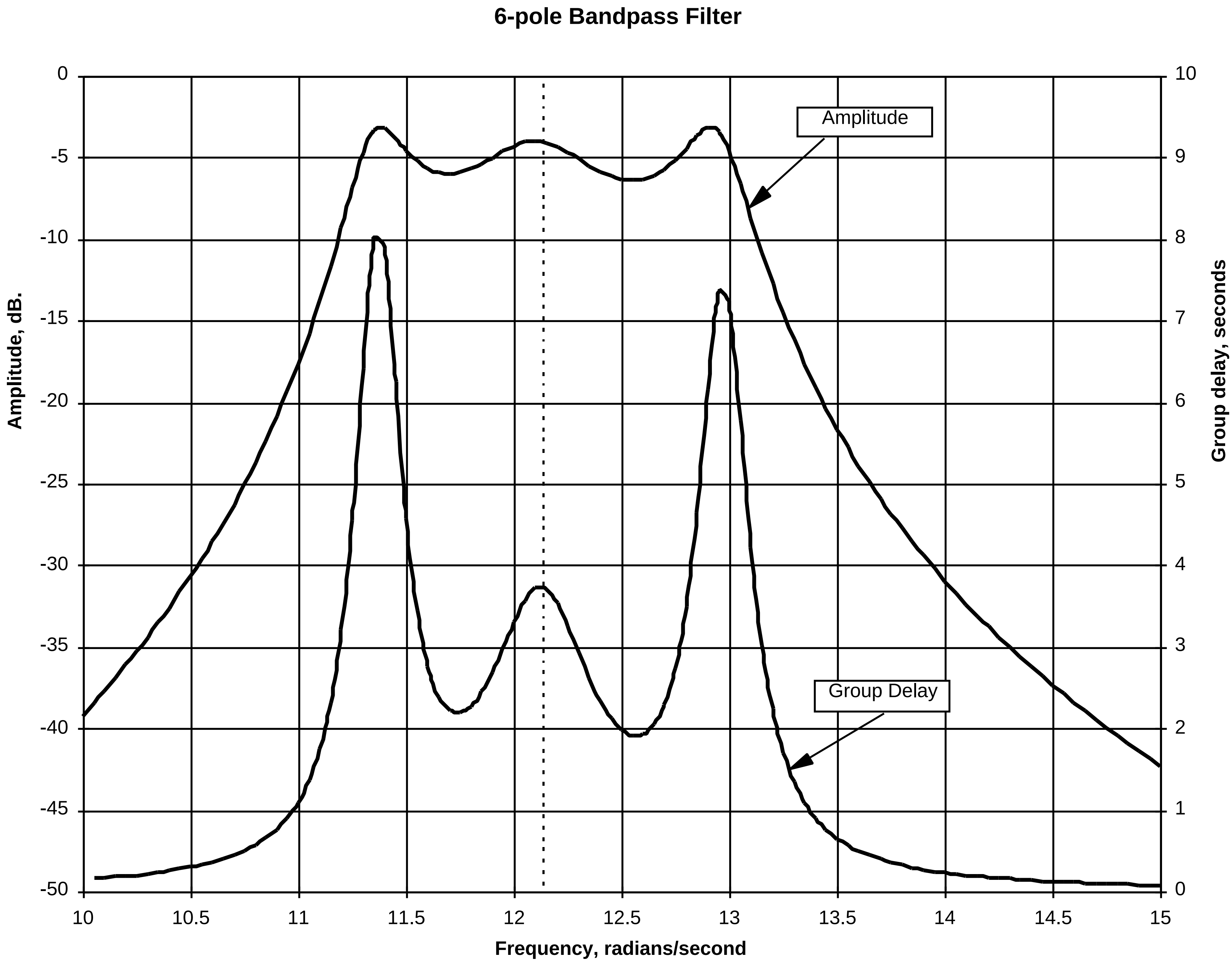
**Phase and group delay of equalizer**
**(S-1)/(S+1)**
**Normalized to 1 radian/second**

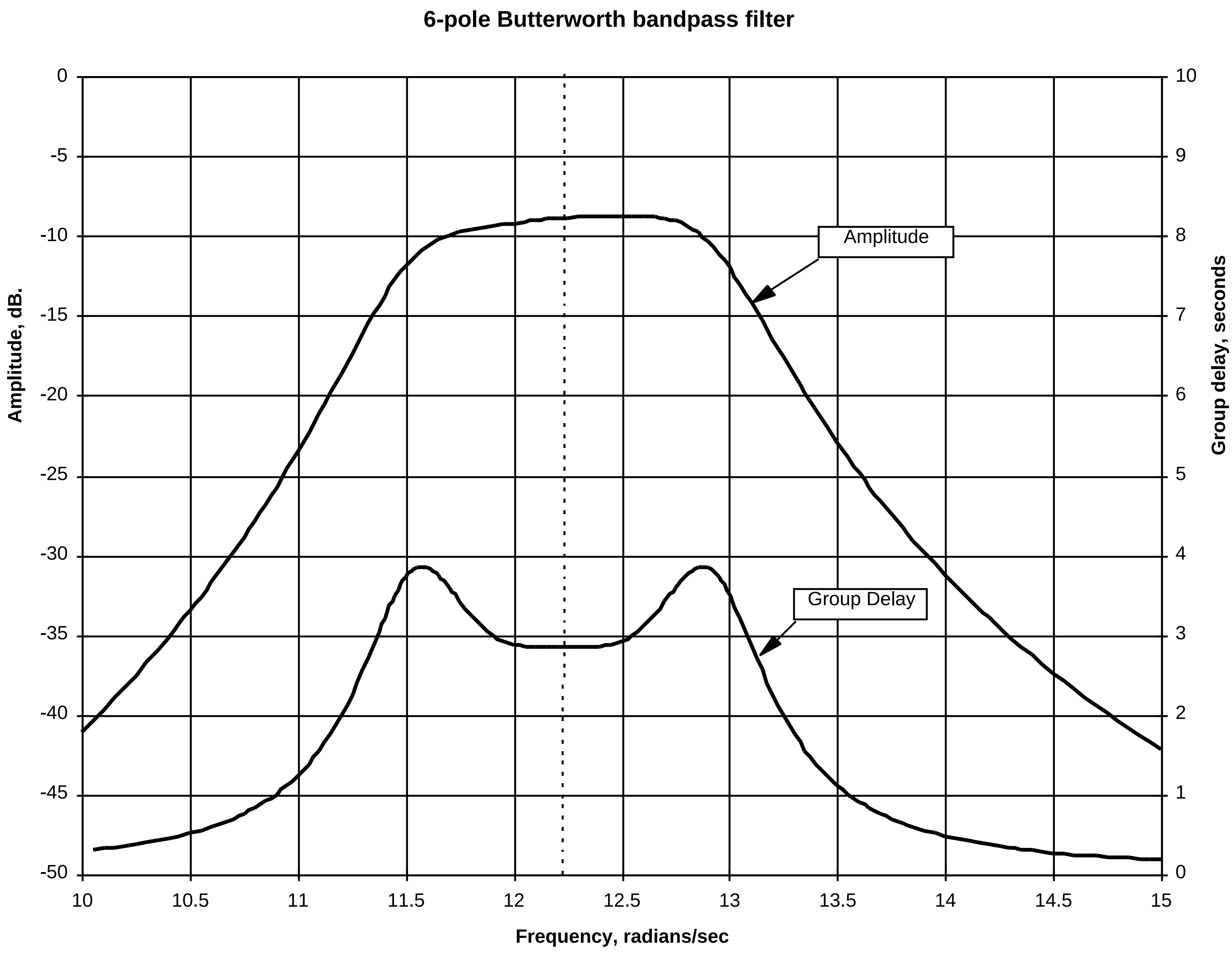


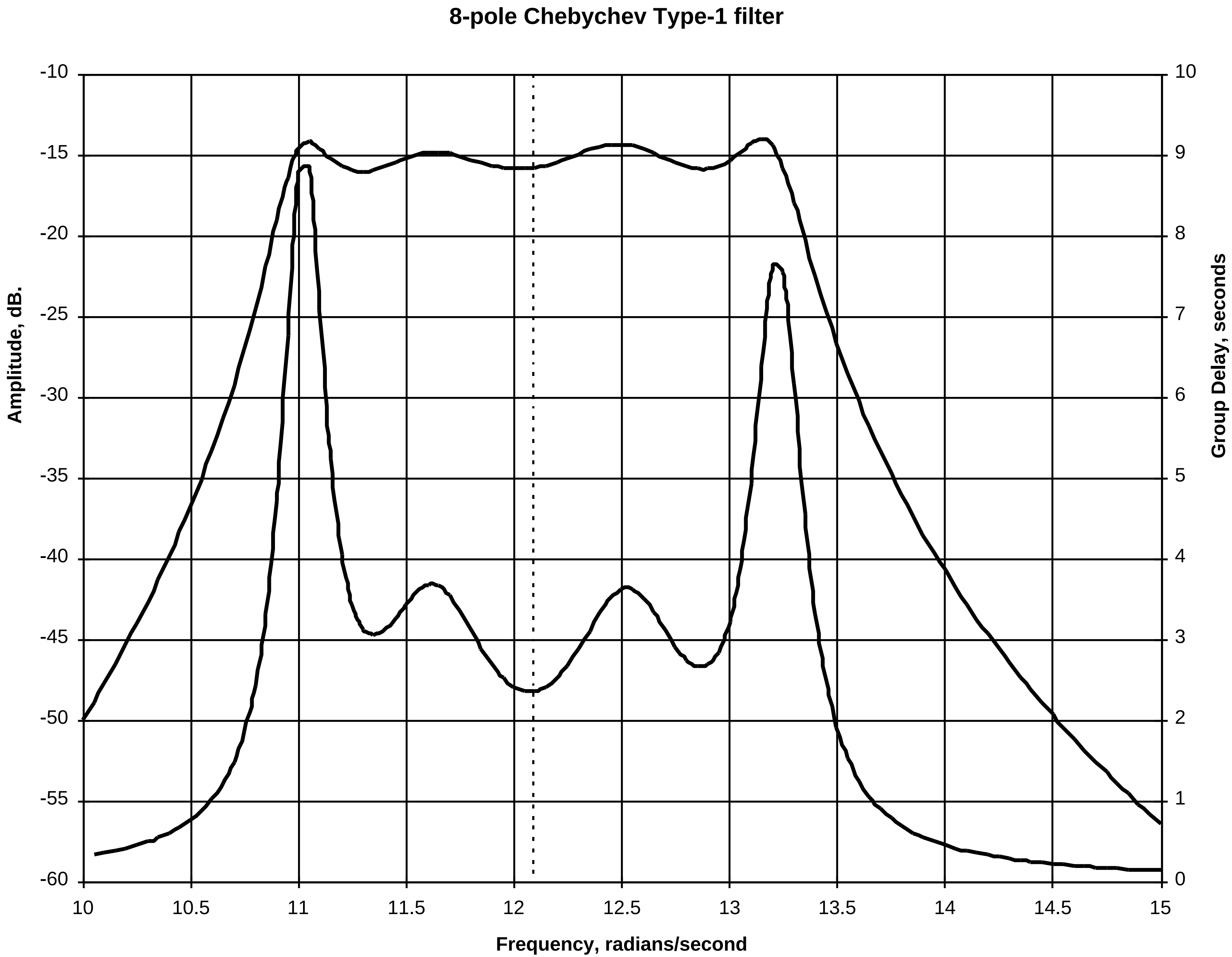

Phase and group delay of equalizer
(S-1)/(S+1)
Normalized to 3 radian/second
group delay, seconds
phase, degrees
Frequency, radians/second
3
2.5
2
1.5
1
0.5
0
180
160
140
120
100
80
60
40
20
0
0.01
0.1
1
10
100
phase
group delay

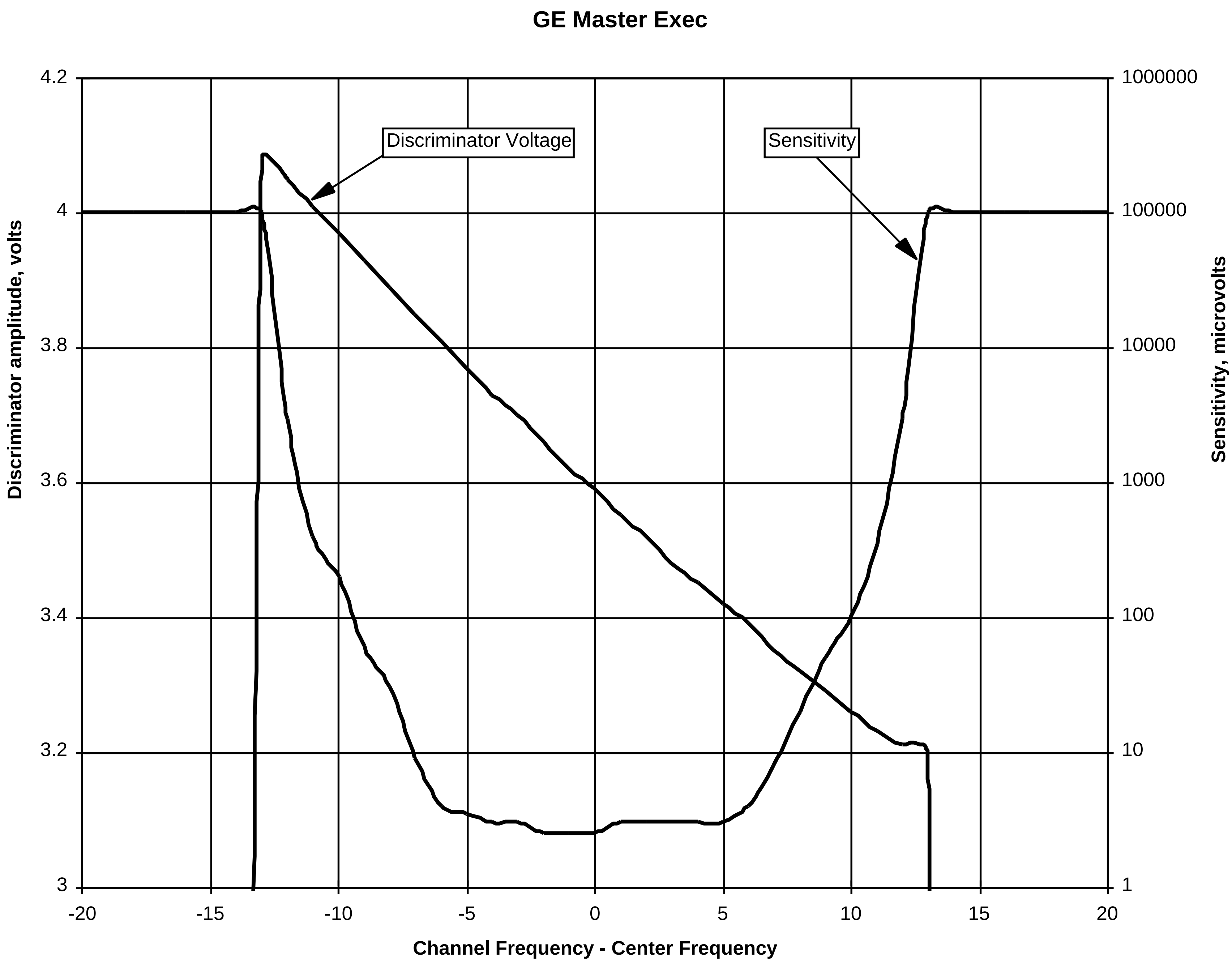


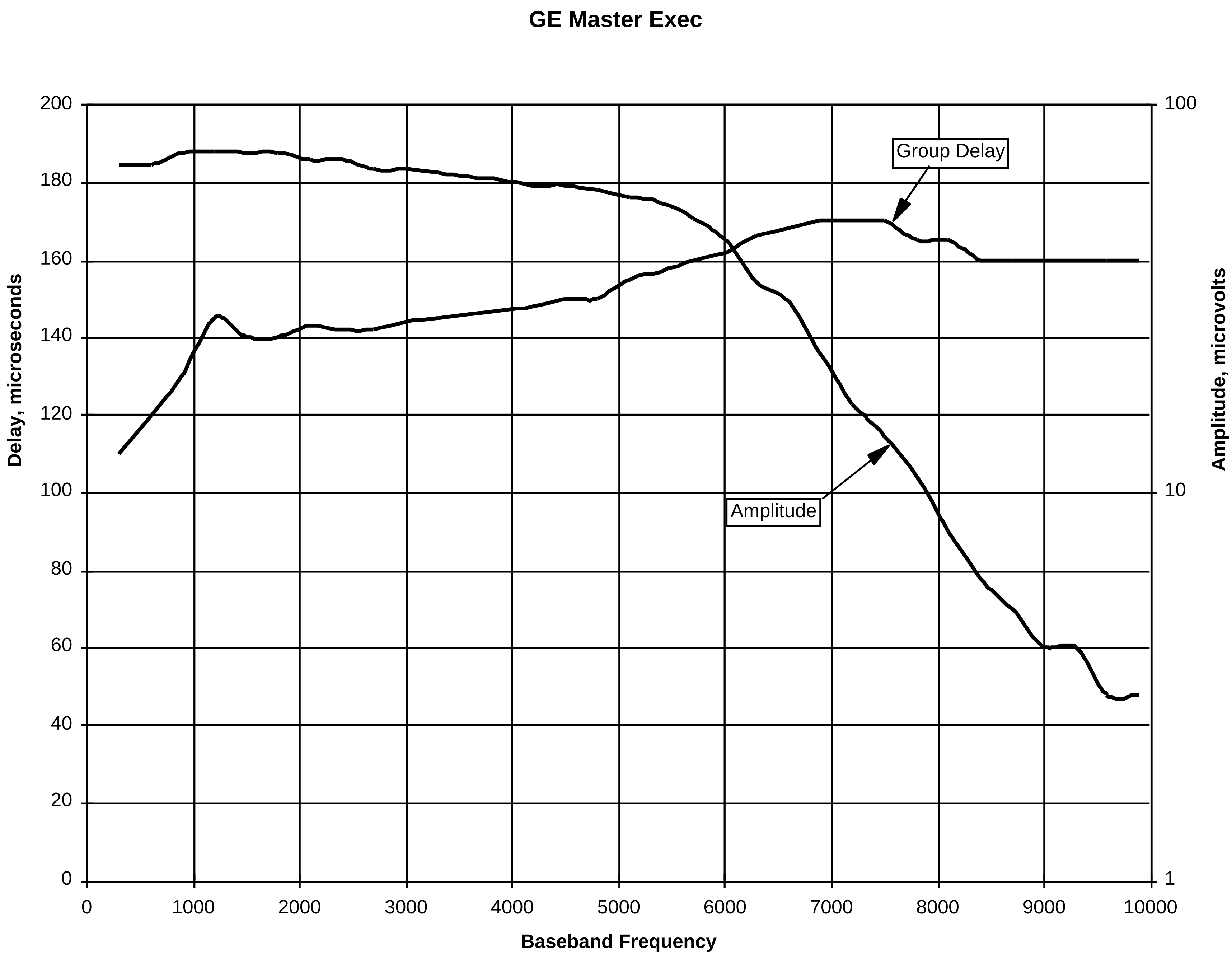
Amplitude, phase, and group delay of RLC bandpass filter
damping = 0.707
Phase, degrees
Amplitude, dB.
Group delay, seconds
Amplitude, db., and Phase, degrees
group delay, seconds
Frequency, radians/second
90
70
50
30
10
-10
-30
-50
-70
-90
10
9
8
7
6
5
4
3
2
1
0
0.01
0.1
1
10
100


6-pole Bandpass Filter
Amplitude
Group Delay
Amplitude, dB.
Group delay, seconds
Frequency, radians/second
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
10
9
8
7
6
5
4
3
2
1
0
10
10.5
11
11.5
12
12.5
13
13.5
14
14.5
15

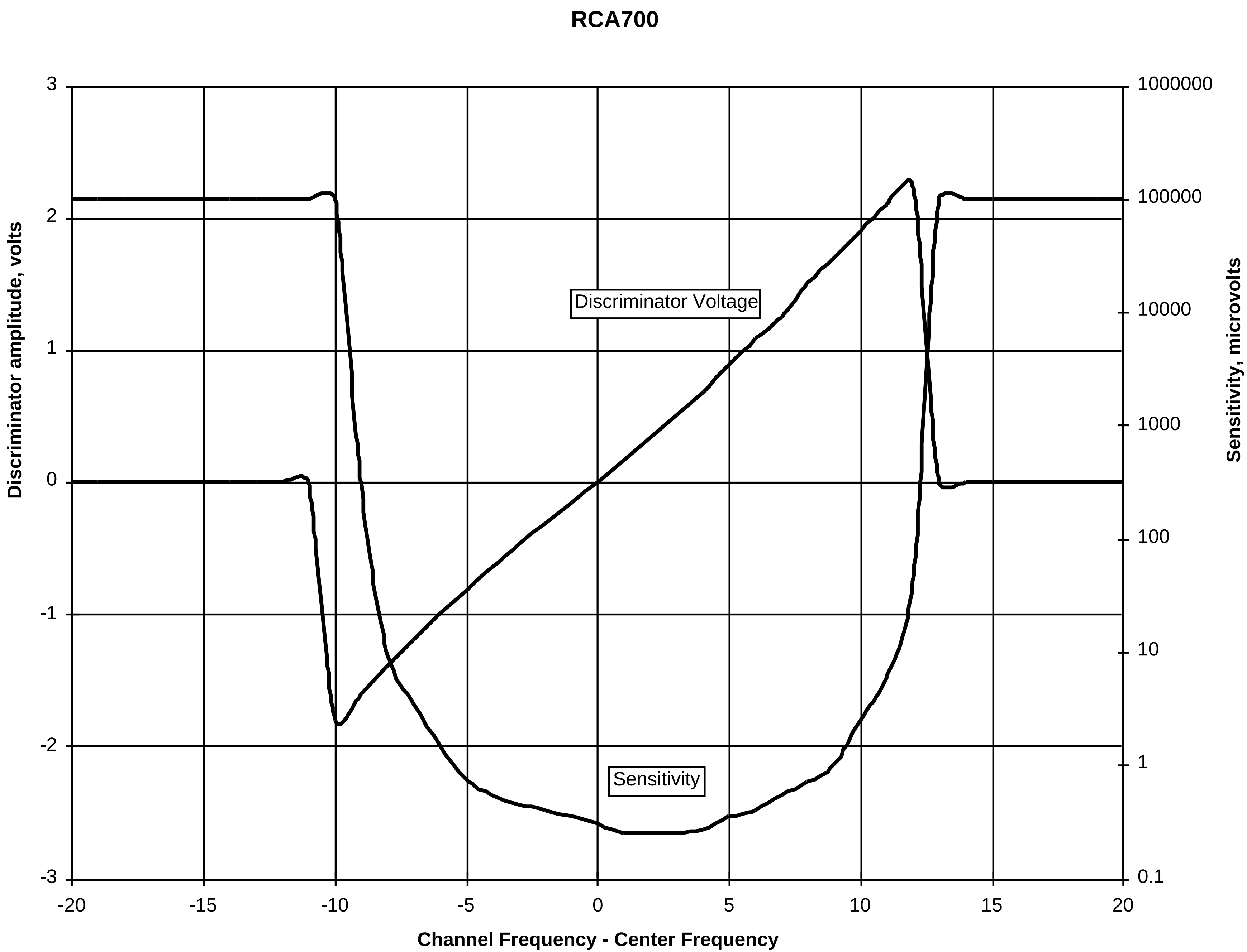

6-pole Butterworth bandpass filter
Amplitude
Group Delay
Amplitude, dB.
Group delay, seconds
Frequency, radians/sec
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
10
9
8
7
6
5
4
3
2
1
0
10
10.5
11
11.5
12
12.5
13
13.5
14
14.5
15


8-pole Chebychev Type-1 filter
Amplitude, dB.
Group Delay, seconds
Frequency, radians/second
-10
-15
-20
-25
-30
-35
-40
-45
-50
-55
-60
10
9
8
7
6
5
4
3
2
1
0
10
10.5
11
11.5
12
12.5
13
13.5
14
14.5
15

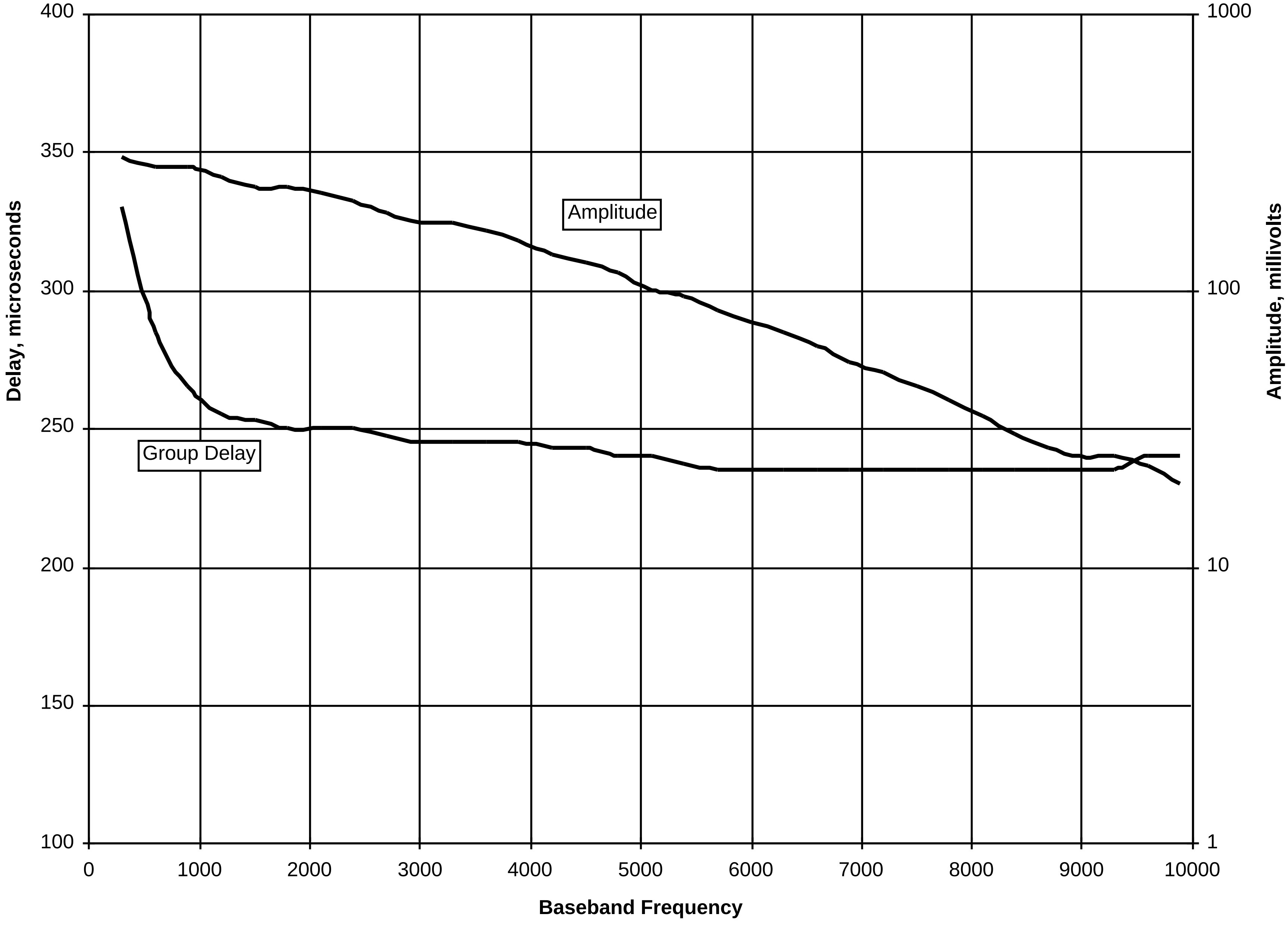

GE Master Exec
Discriminator Voltage
Sensitivity
Discriminator amplitude, volts
Sensitivity, microvolts
Channel Frequency - Center Frequency
4.2
4
3.8
3.6
3.4
3.2
3
1000000
100000
10000
1000
100
10
1
-20
-15
-10
-5
0
5
10
15
20



GE Master Exec
Delay, microseconds
Amplitude, microvolts
Baseband Frequency
Group Delay
Amplitude
0
20
40
60
80
100
120
140
160
180
200
1
10
100
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000


RCA700
Discriminator amplitude, volts
3
2
1
0
-1
-2
-3
Sensitivity, microvolts
1000000
100000
10000
1000
100
10
1
0.1
-20
-15
-10
-5
0
5
10
15
20
Channel Frequency - Center Frequency
Discriminator Voltage
Sensitivity

# RCA700



400
350
300
250
200
150
100
1000
100
10
1
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Delay, microseconds
Amplitude, millivolts
Baseband Frequency
Amplitude
Group Delay