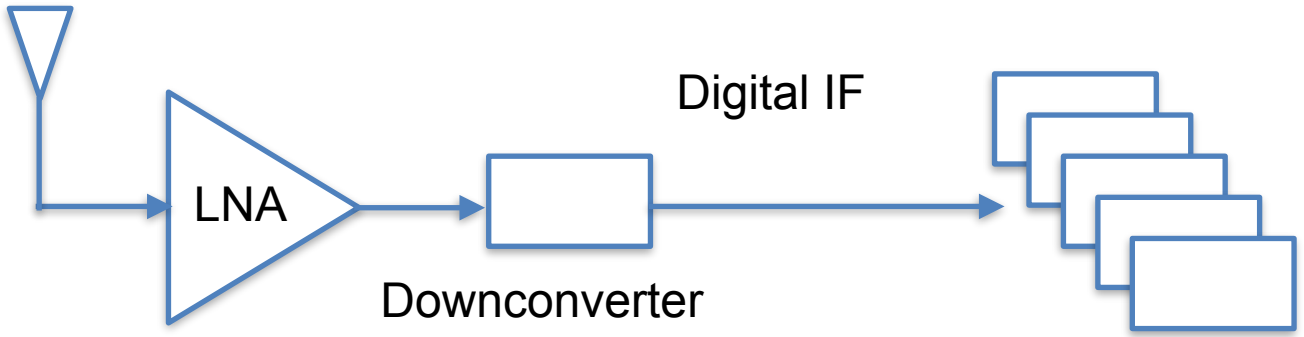
Lection Summary

GNSS Receiver Design:

- Receiver Block diagram
- RF Frontend
- Link Budget
- Signal Tracking
- Multipath
- Signal Acquisition

Receiver Block Diagram

Antenna



RF frontend

Tracking channels

Link Budget

$$P_T = 27\,W = 44.3\,\text{dBm}$$

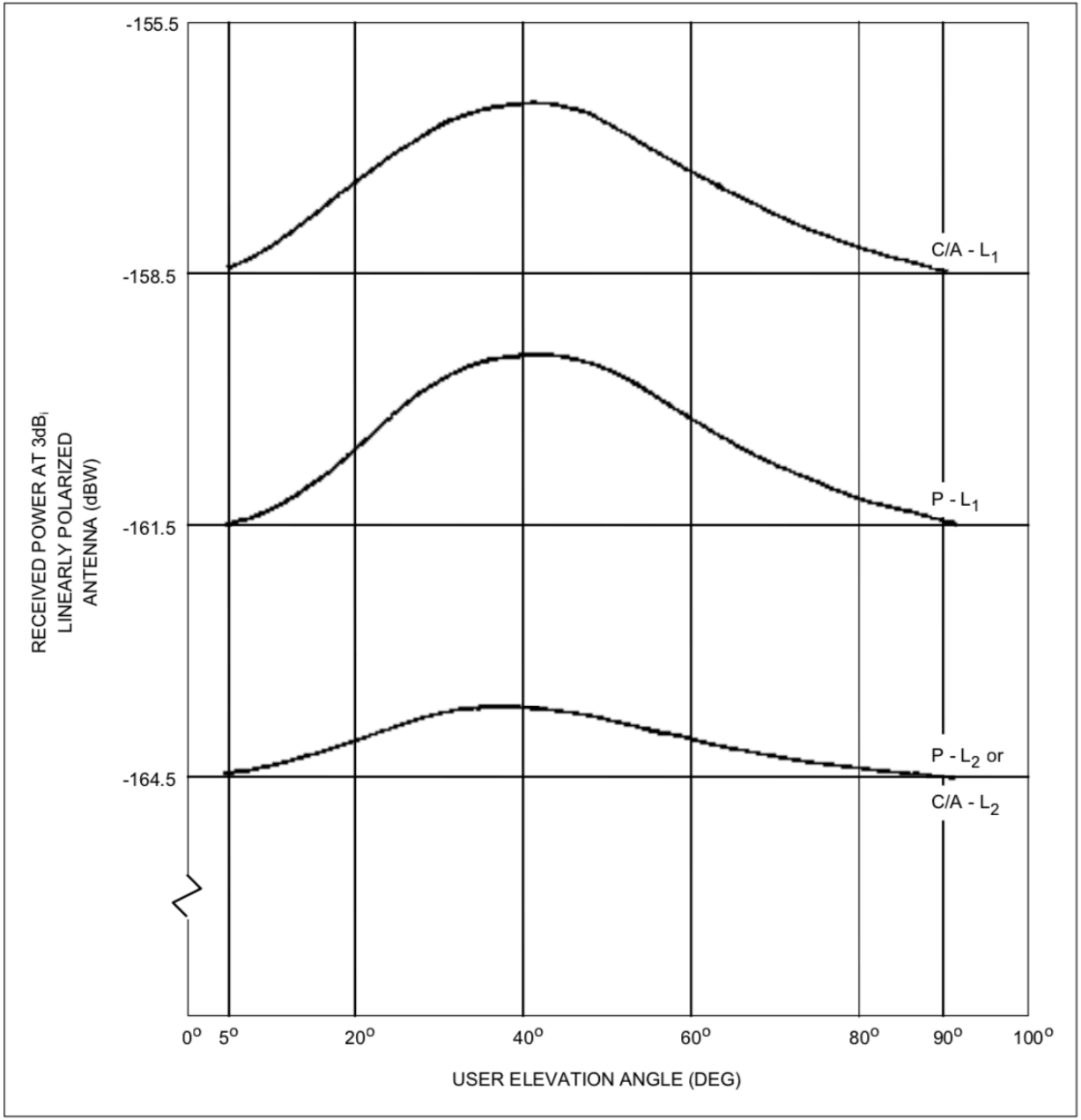
$$G_T = 10.2 - 12.3\,\text{dB}$$

$$EIRP = 240 - 470\,W$$

$$PL = 157\,\text{dB}$$

$$P_R = P_T + G_T + G_R - PL = 1.41 \cdot 10^{-16}\,W = -128.5\,\text{dBm}$$

Antenna Gain



Noise Temperature

$$N_0 = kT_{eq} \text{ [W/Hz]}$$

$$k = 1.38 \cdot 10^{-23} \text{ J/K}$$

$$N = N_0 B_n \text{ [W]}$$

Friis Formula

$$T_{eff} = T_a + (F_1 - 1)T + \frac{(F_2 - 1)T}{G_1} + \frac{(F_3 - 1)T}{G_1 G_2} + \frac{(F_4 - 1)T}{G_1 G_2 G_3}$$

Antenna T_a

Cable + Filter $G_1 = 1/F_1$ | LNA G_2, F_2 | Cable + Filter $G_3 = 1/F_3$ | Downconverter G_4, F_4

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$T_a = 130$ K $\quad G_2 = 25$ dB $\quad T_{eff} = 296.4$ K

$T = 290$ K $\quad F_2 = 1.9$ dB $\quad N_0 = -203.9$ dBW-Hz

Carrier to Noise Density Ratio

$$C/N_0 = \text{[W] / [W/Hz]} = \text{[Hz]}$$

$$10\log_{10} C/N_0 = \text{[dB-Hz]}$$

$$C/N = \frac{C}{N_0 Bn}, \qquad B_n = \text{bandwidth [Hz]}$$

$$C = -158.5 \text{ dBW}$$

$$C/N_0 = -158.5 - (-203.9) = 45.4 \text{ dBW-Hz}$$

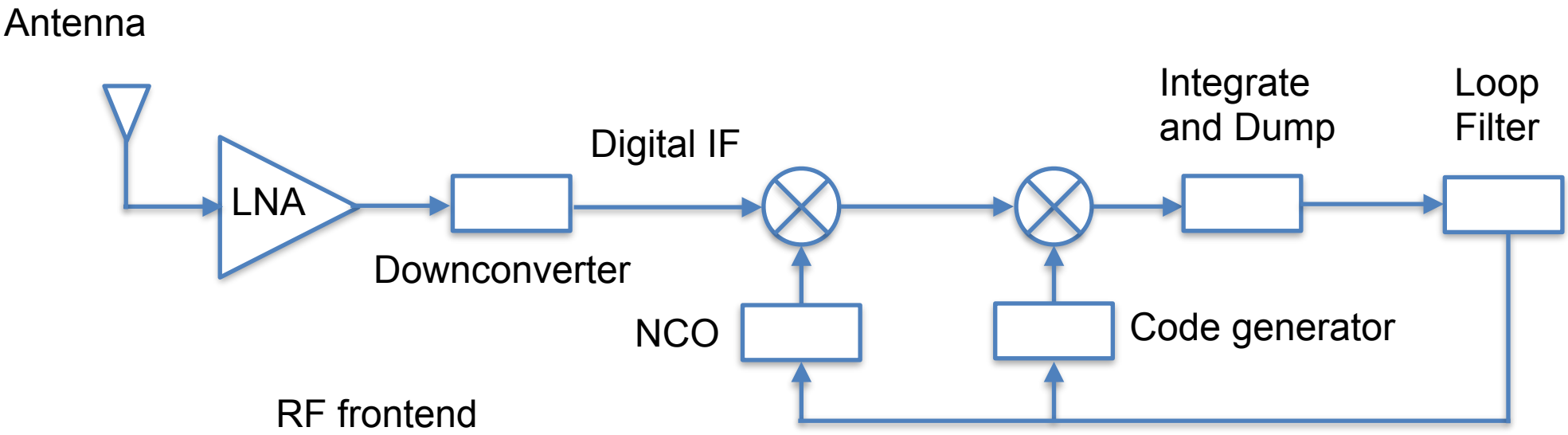
$$B_n = 10 \text{ MHz}$$

$$SNR = 45.4 - 70 = -25.4 \text{ dB}$$

Quantization Loss

Bit number	Optimal AGC Gain	Minimum Loss (dB)
1		-1.96
2	$1/\sigma_{IF}$	-0.55 dB
3	$1.71/\sigma_{IF}$	-0.165 dB
4	$2.98/\sigma_{IF}$	-0.05 dB
5	$5.315/\sigma_{IF}$	-0.015 dB

Receiver block diagram



Correlator Model

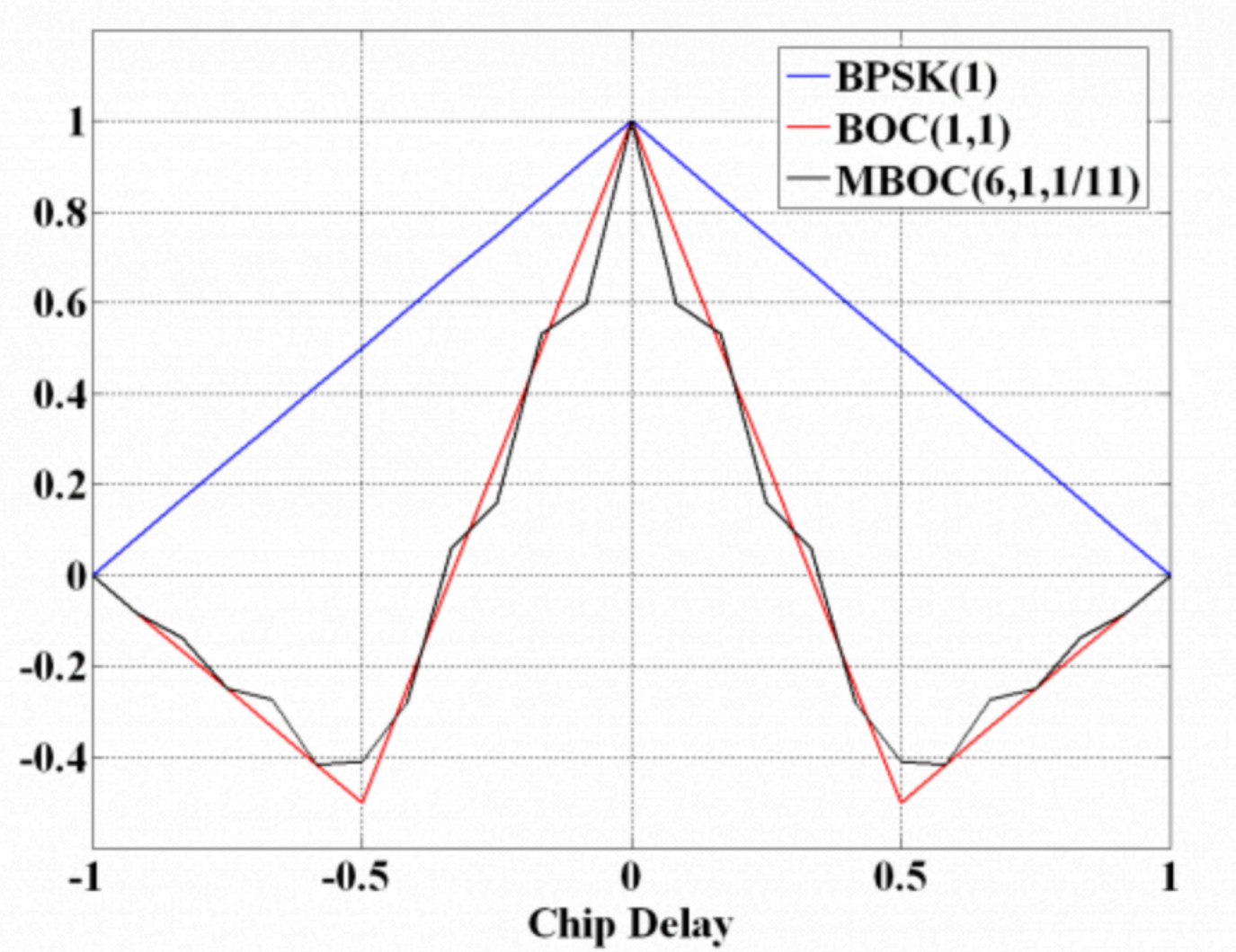
$$I = \frac{A}{\sqrt{2}} \cdot T_{pdi} \cdot D \cdot R\left(\delta\hat{t}\right) \cdot \mathrm{sinc}\left(\delta\hat{f} T_{pdi}\right) \cdot \cos\left(\delta\hat{\phi}\right) + \eta_I$$

$$Q = \frac{A}{\sqrt{2}} \cdot T_{pdi} \cdot D \cdot R\left(\delta\hat{t}\right) \cdot \mathrm{sinc}\left(\delta\hat{f} T_{pdi}\right) \cdot \sin\left(\delta\hat{\phi}\right) + \eta_Q$$

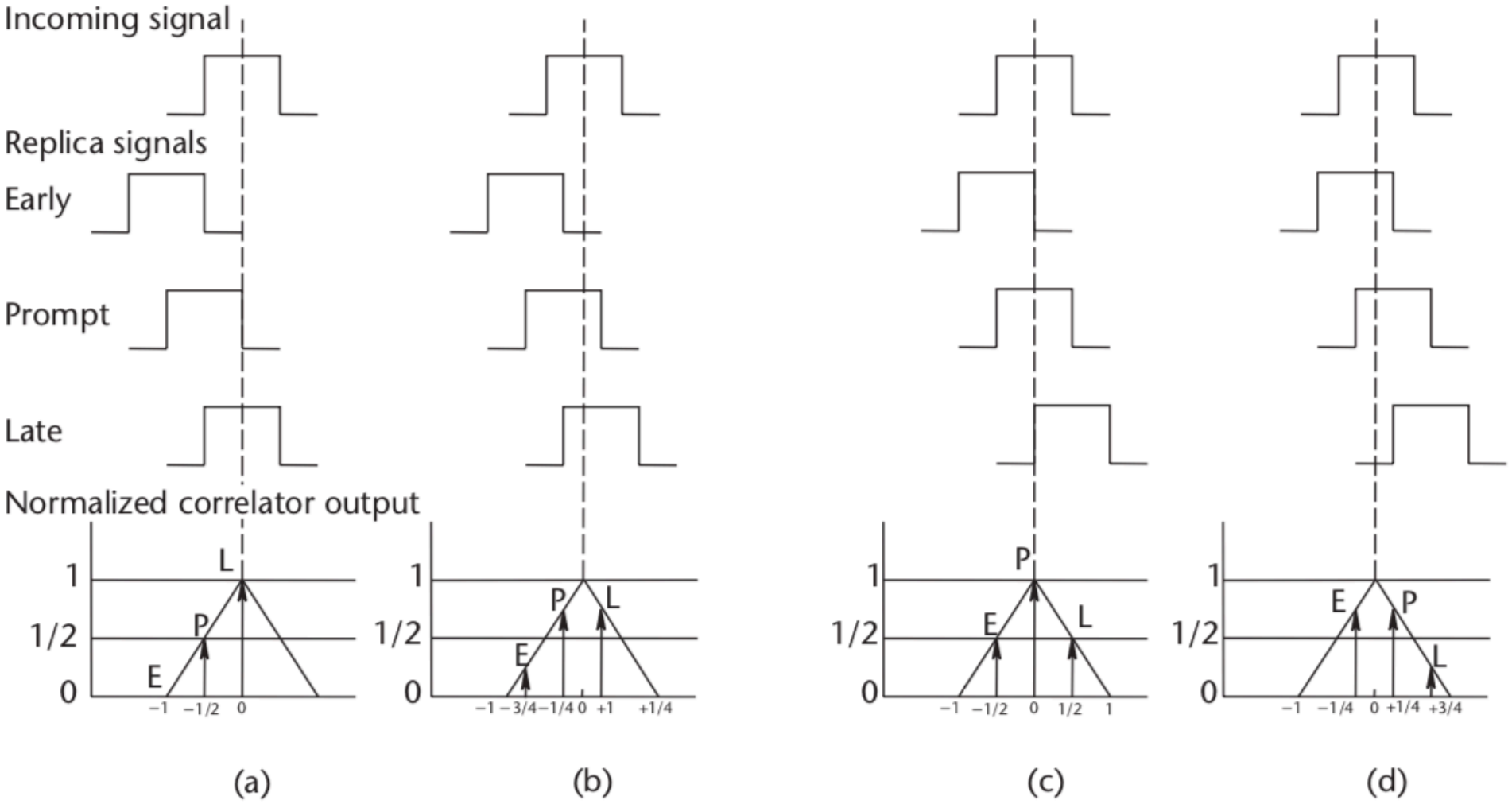
$$\mathrm{E}[\eta_i] = \mathrm{E}[\eta_Q] = 0$$

$$\mathrm{E}[\eta_i^2] = \mathrm{E}[\eta_Q^2] = N\sigma_n^2$$

Auto Correlation Function

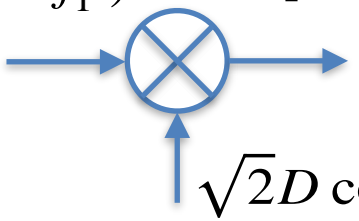


Delay Locked Loop



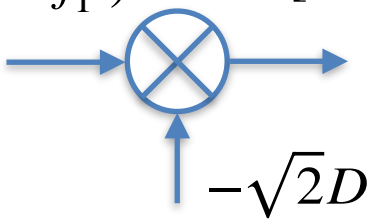
Mixers

$\sqrt{2}D\cos(2\pi f_1 t)$ $\quad D[\cos\left(2\pi(f_1 - f_2)t\right) + \cos\left(2\pi(f_1 + f_2)t\right)]$



$\sqrt{2}D\cos(2\pi f_2 t)$

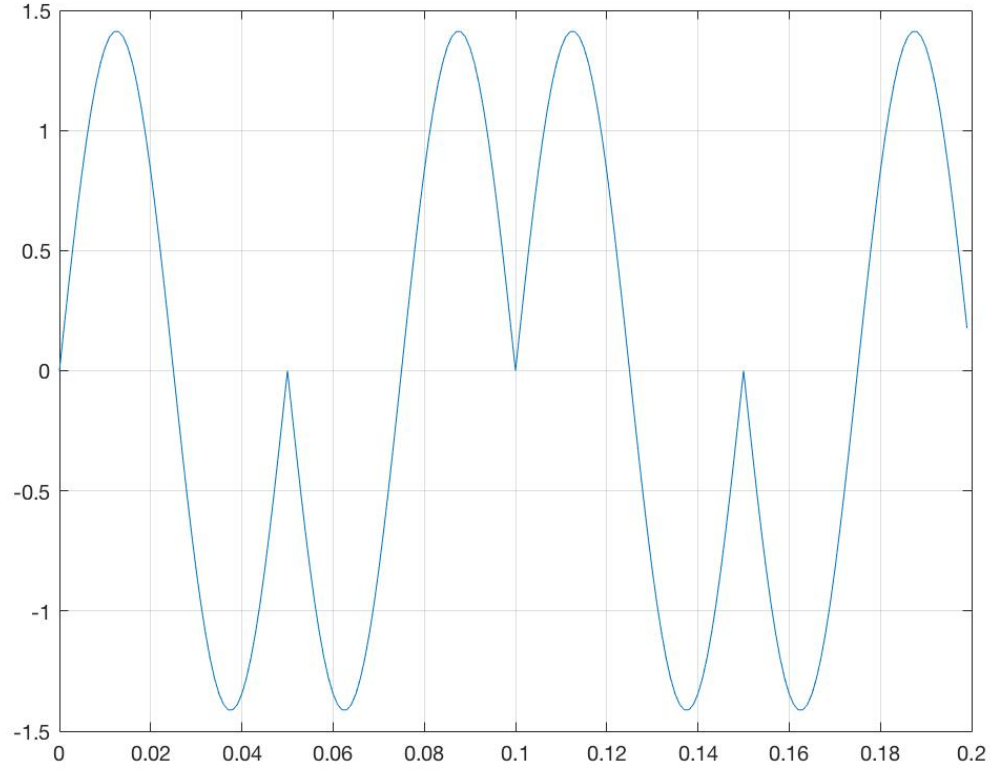
$\sqrt{2}D\cos(2\pi f_1 t)$ $\quad D[\sin\left(2\pi(f_1 - f_2)t\right) + \sin\left(2\pi(f_1 + f_2)t\right)]$



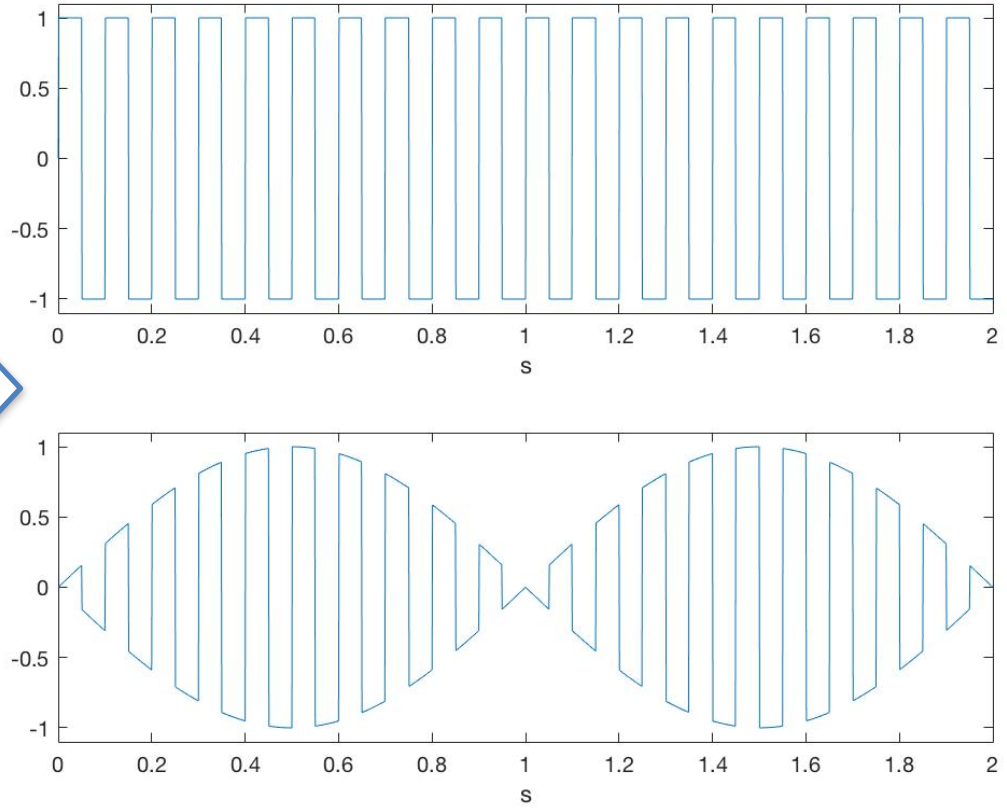
$-\sqrt{2}D\sin(2\pi f_2 t)$

Doppler Residual Error

Received signal



Perfect carrier wipe-off



Carrier wipe-off with residual 0.5 Hz error

Carrier Tracking Loops

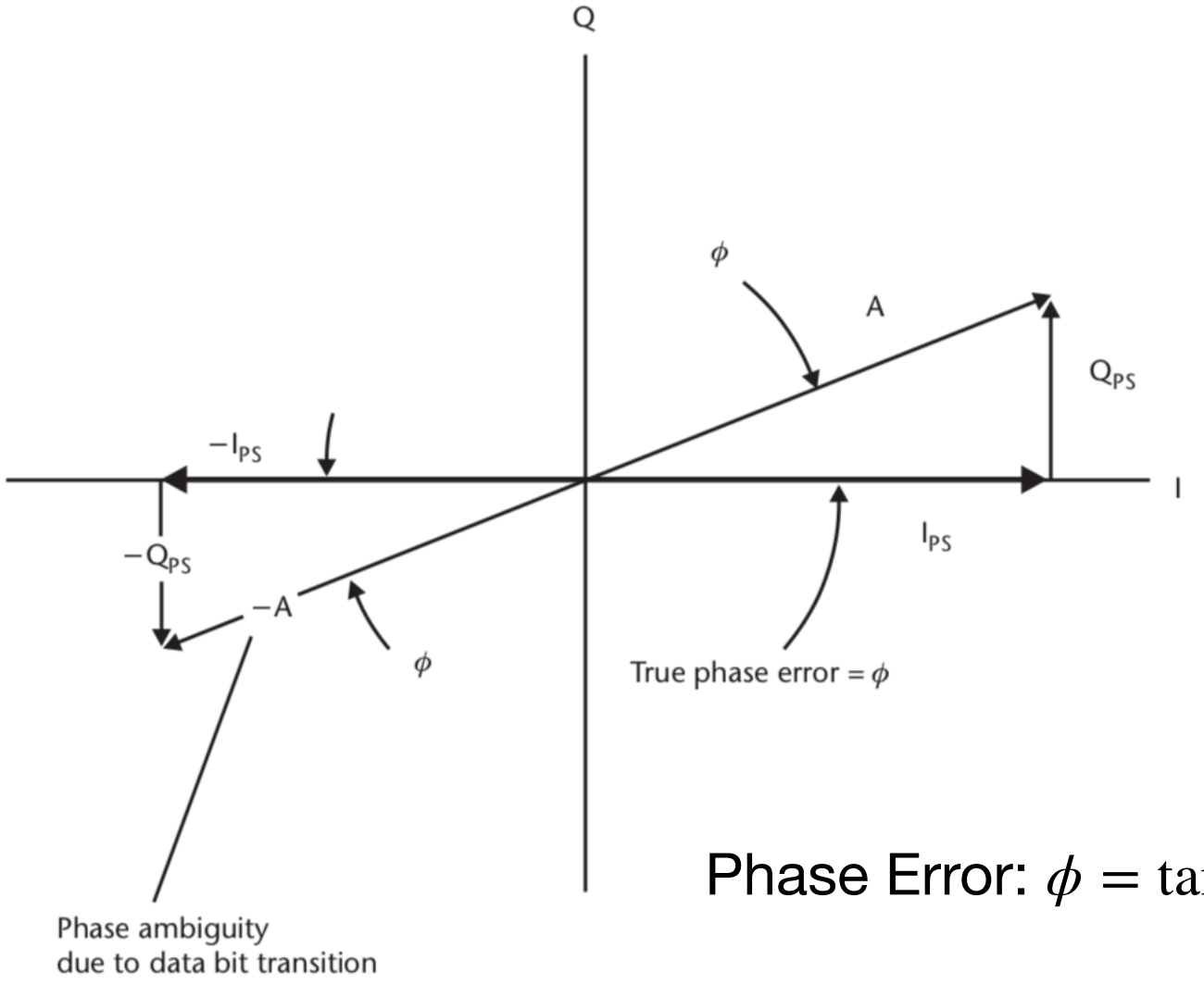
Frequency Locked Loop (FLL)

- Attempts to drive the incoming-minus-replica frequency residual to zero
- Phase is allowed to wander
- More robust than a phase-locked loop
- Produces ambiguous range measurements with decimeter-level noise

Phase Locked Loop (PLL)

- Attempts to drive the incoming-minus-replica phase residual to zero
  Incoming and replica phases are aligned
- Sensitive to dynamic stresses
- Produces ambiguous range measurements with millimeter-level noise

Phase Locked Loop



Phase Error: $\phi = \tan^{-1}\left(\frac{Q}{I}\right)$

Lock Indicator: $P = I^2 + Q^2$

Lock Detectors

Wideband Power (WBP): $WBP_m = \sum_{i=1}^{M} \left(I_i^2 + Q_i^2 \right)$

Narrowband Power (NBP): $NBP_m = \left(\sum_{i=1}^{M} I_i^2 \right) + \left(\sum_{i=1}^{M} Q_i^2 \right)$

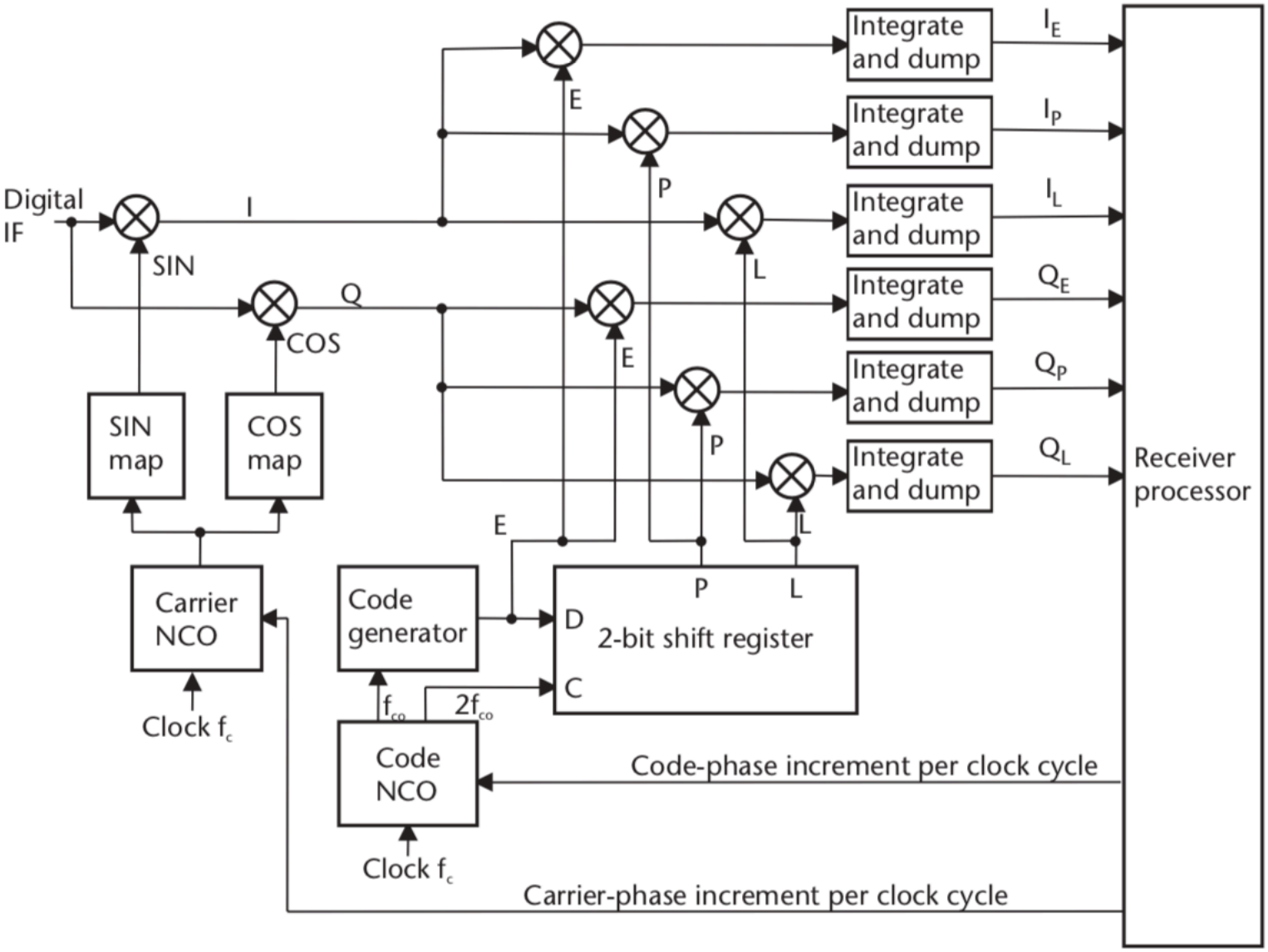
Normalized Power (NP): $NP_m = \frac{NBP_m}{WBP_m}$

Code Lock Detector: $\mu_{NP} = \frac{1}{K} \sum_{m=1}^{K} NP_m$

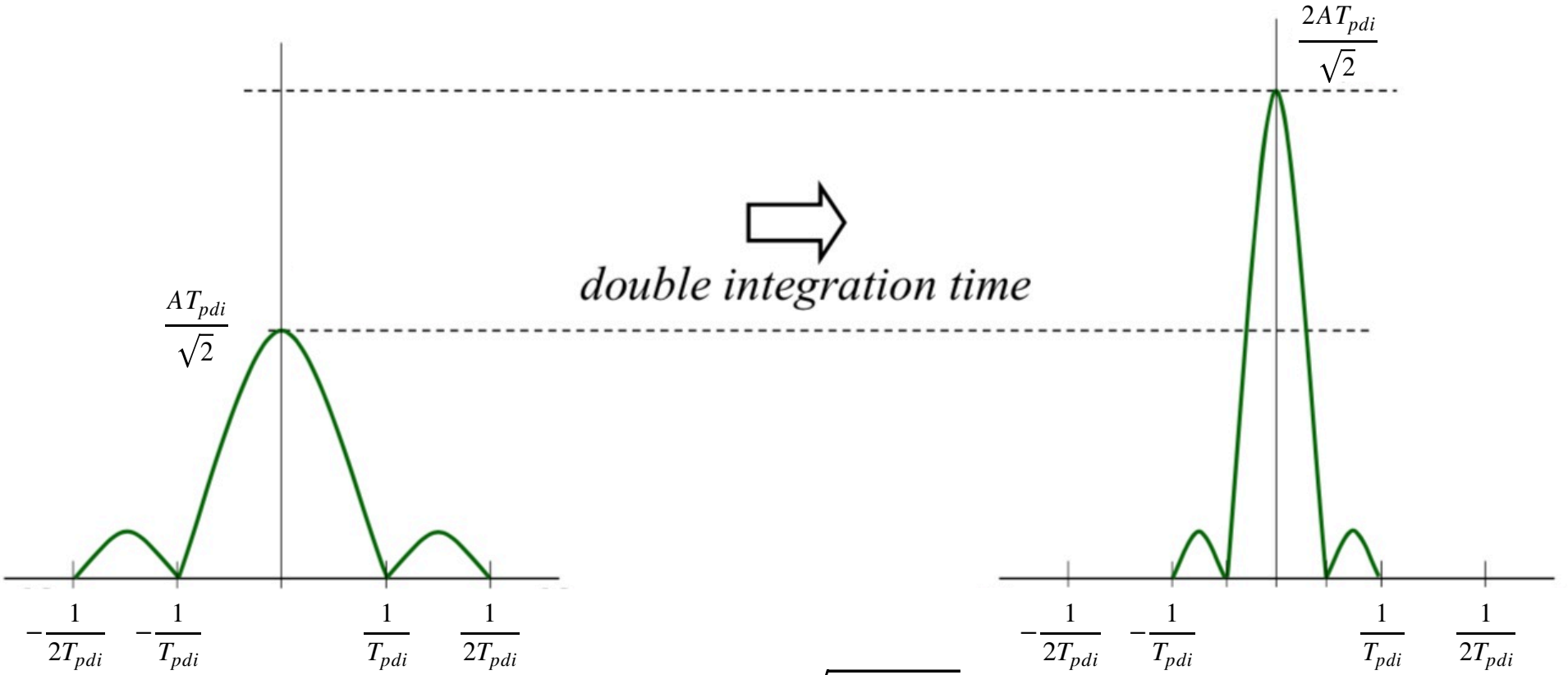
Narrowband Power Difference (NBD): $NBD_m = \left(\sum_{i=1}^{M} I_i^2 \right) - \left(\sum_{i=1}^{M} Q_i^2 \right)$

Phase Lock Detector: $PLD_m = \frac{NBD_m}{NBP_m}$

Receiver Block Diagram



Extending the Integration Time

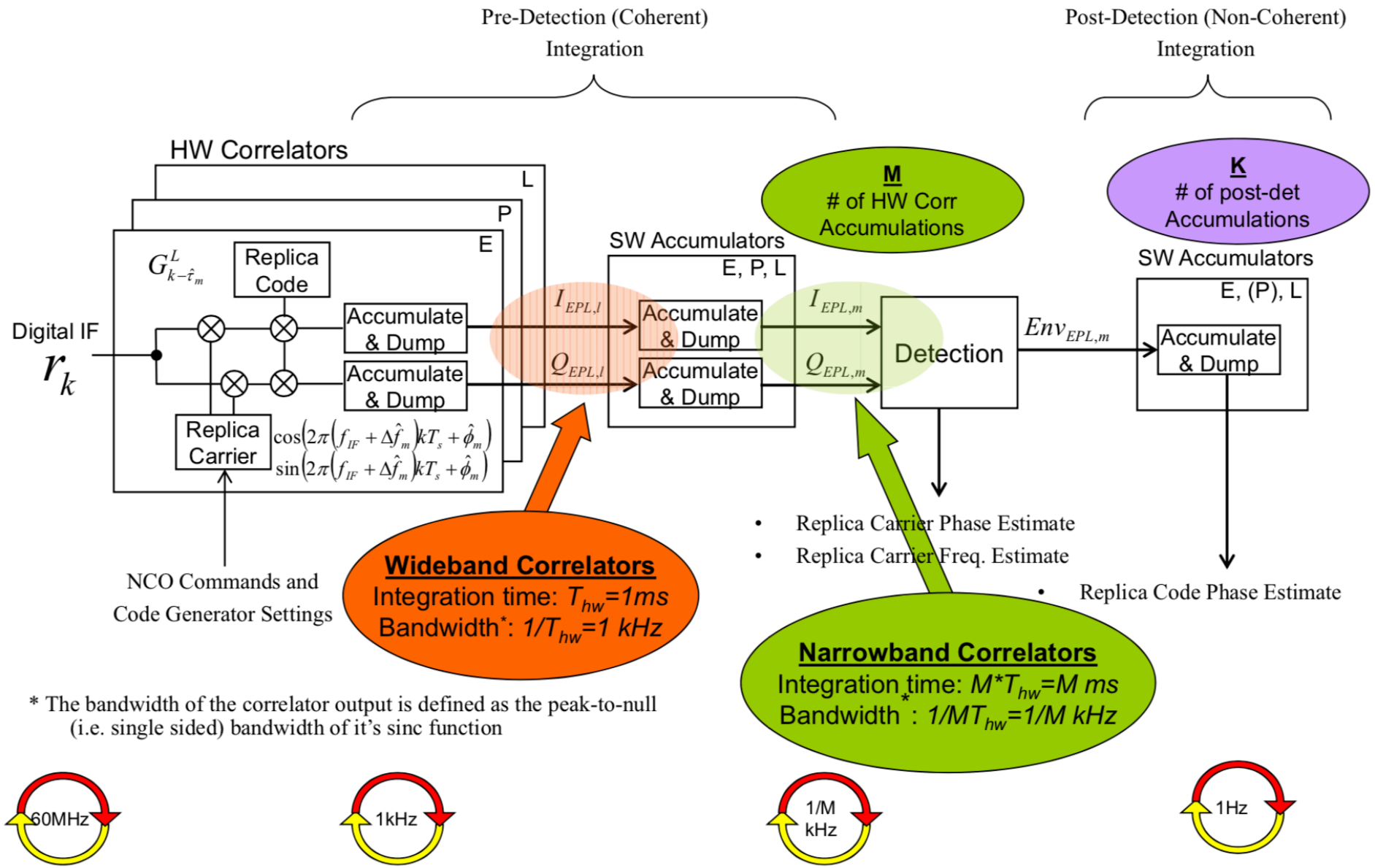


Signal Envelope: $Z = \sqrt{I^2 + Q^2}$

Useful Signal Envelope: $Z_s = \frac{AT_{pdi}}{\sqrt{2}} \rightarrow \frac{2AT_{pdi}}{\sqrt{2}}$

Noise Envelope: $Z_n = \sqrt{T_{pdi}}\sigma_N \rightarrow \sqrt{2T_{pdi}}\sigma_N$

Receiver Block Diagram



* The bandwidth of the correlator output is defined as the peak-to-null (i.e. single sided) bandwidth of it's sinc function

Loop Filters Order

First Order

Sensitive to velocity stress.

Unconditionally stable at all noise bandwidths.

Second Order

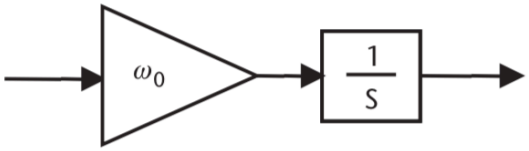
Sensitive to acceleration stress.

Unconditionally stable at all noise bandwidths.

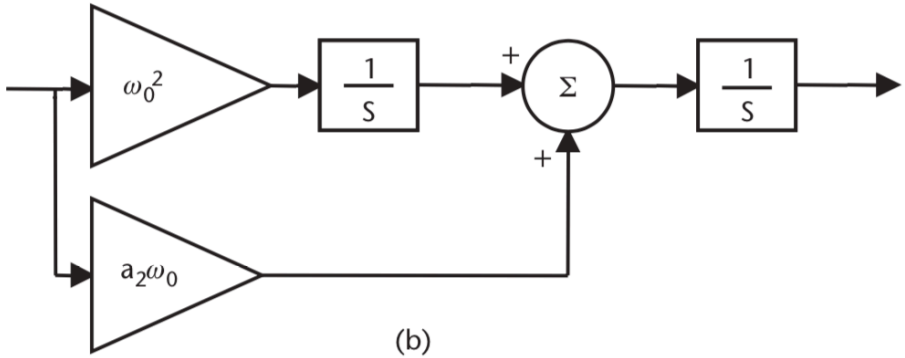
Third Order

Sensitive to jerk stress.

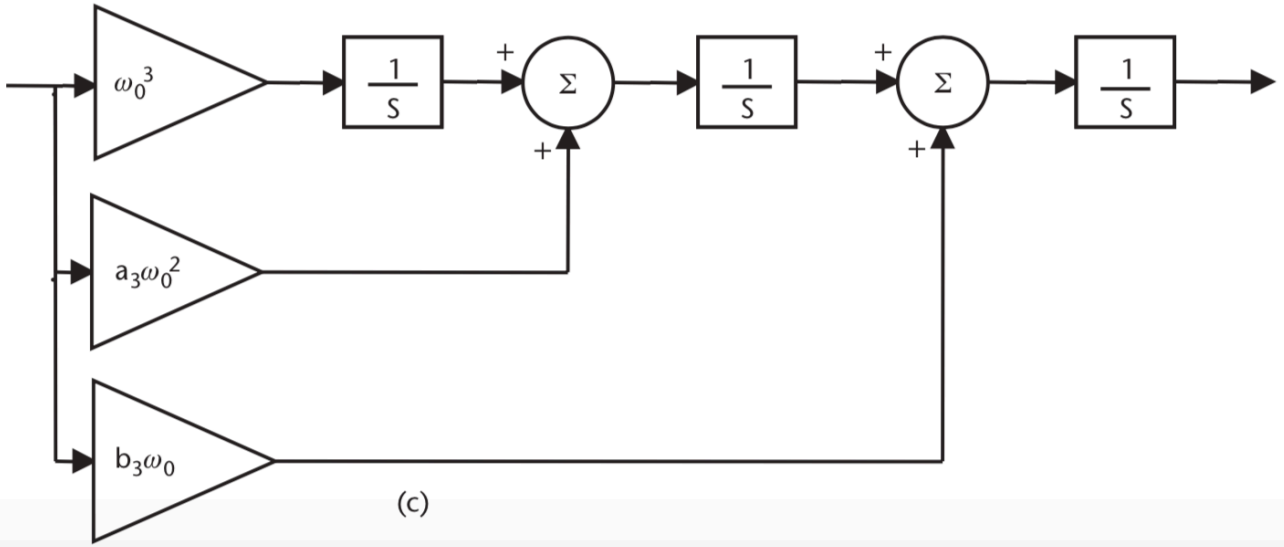
Remains stable at $B \leq 18$ Hz.



(a)

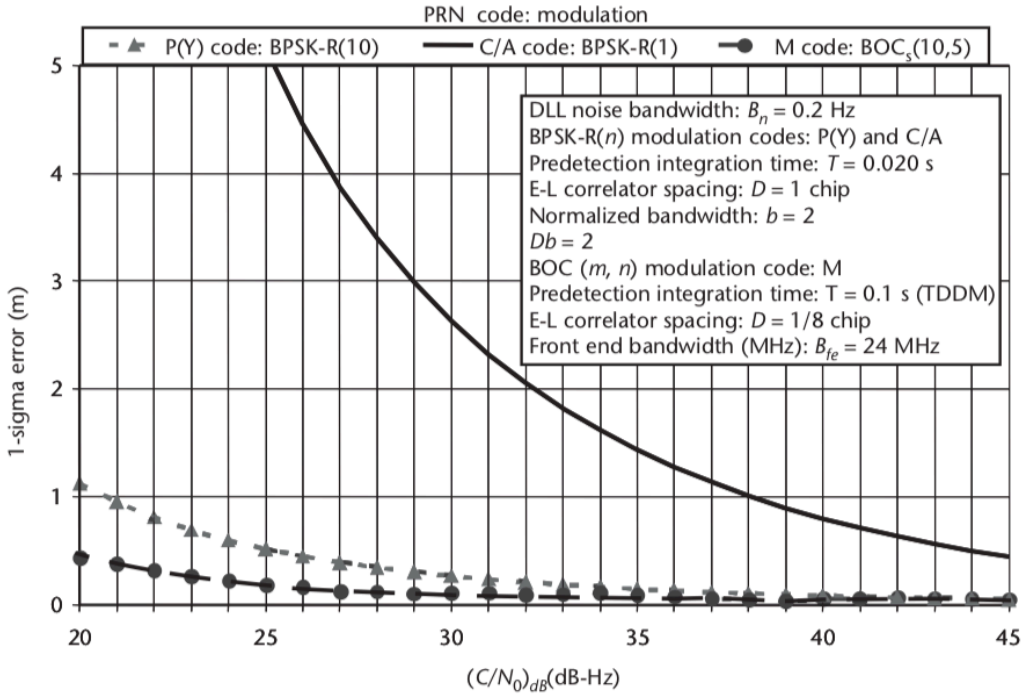


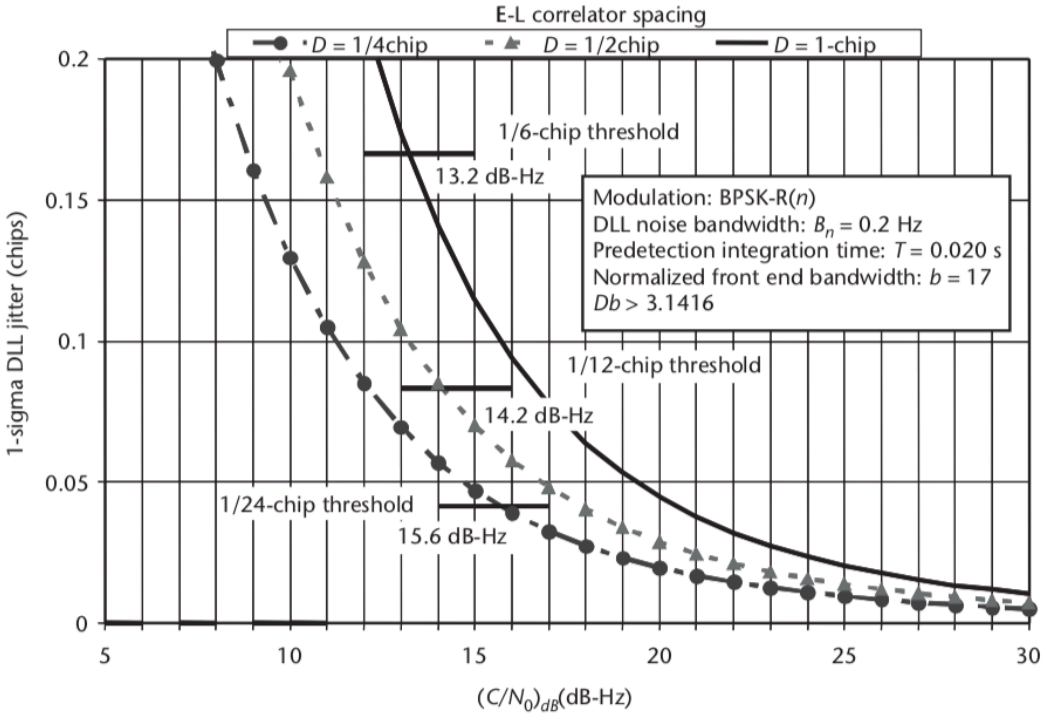
(b)



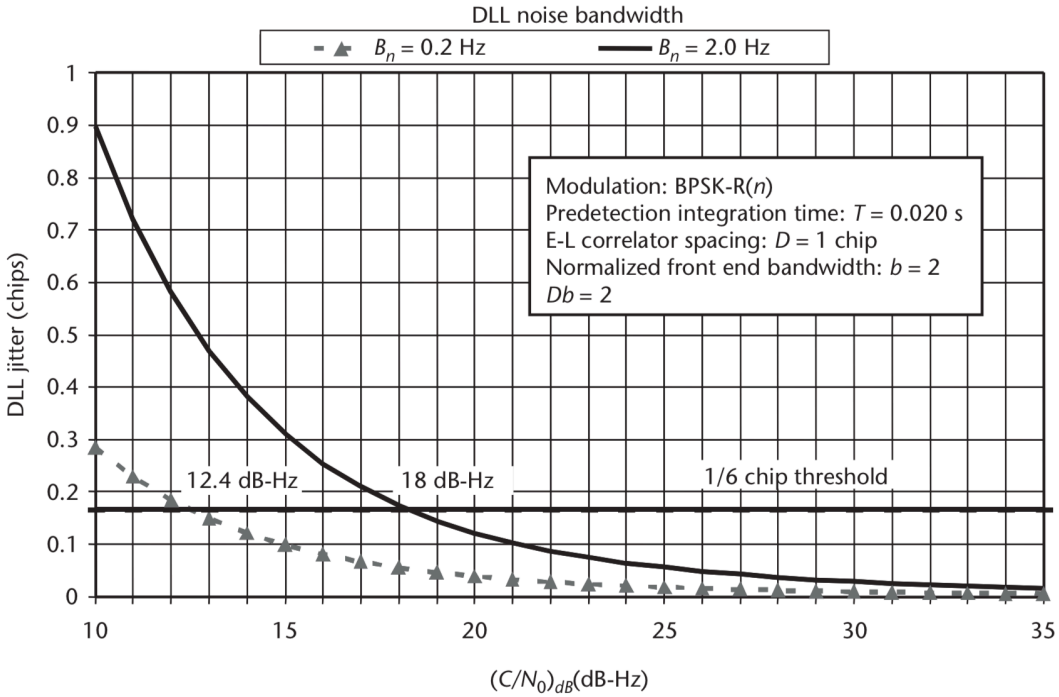
(c)

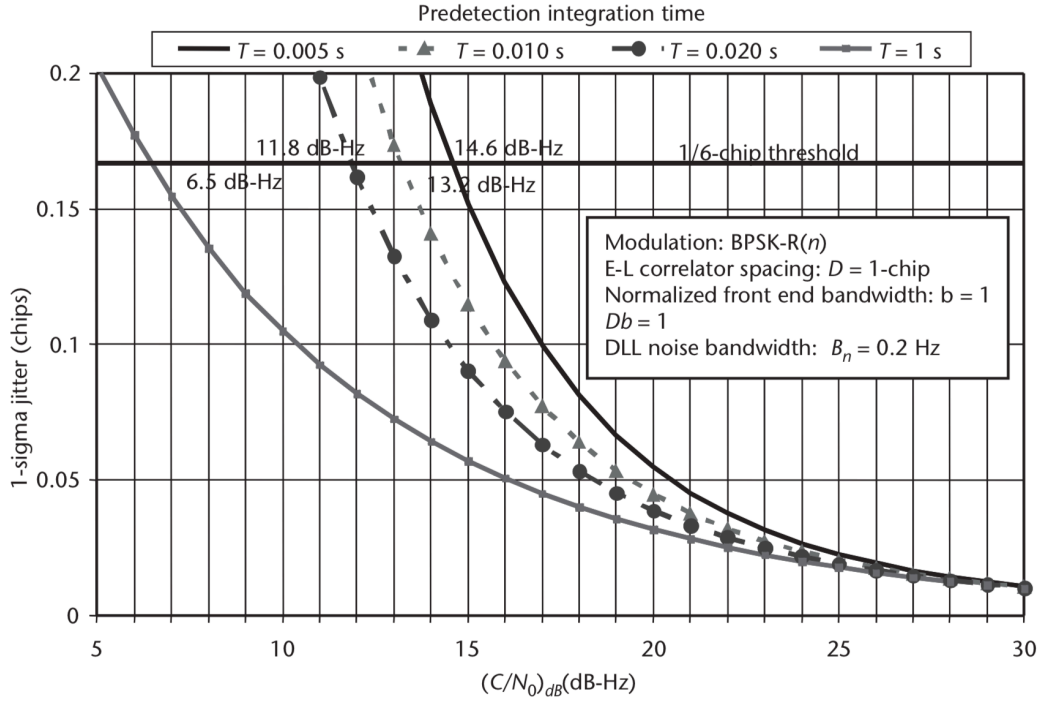
Tracking Performance



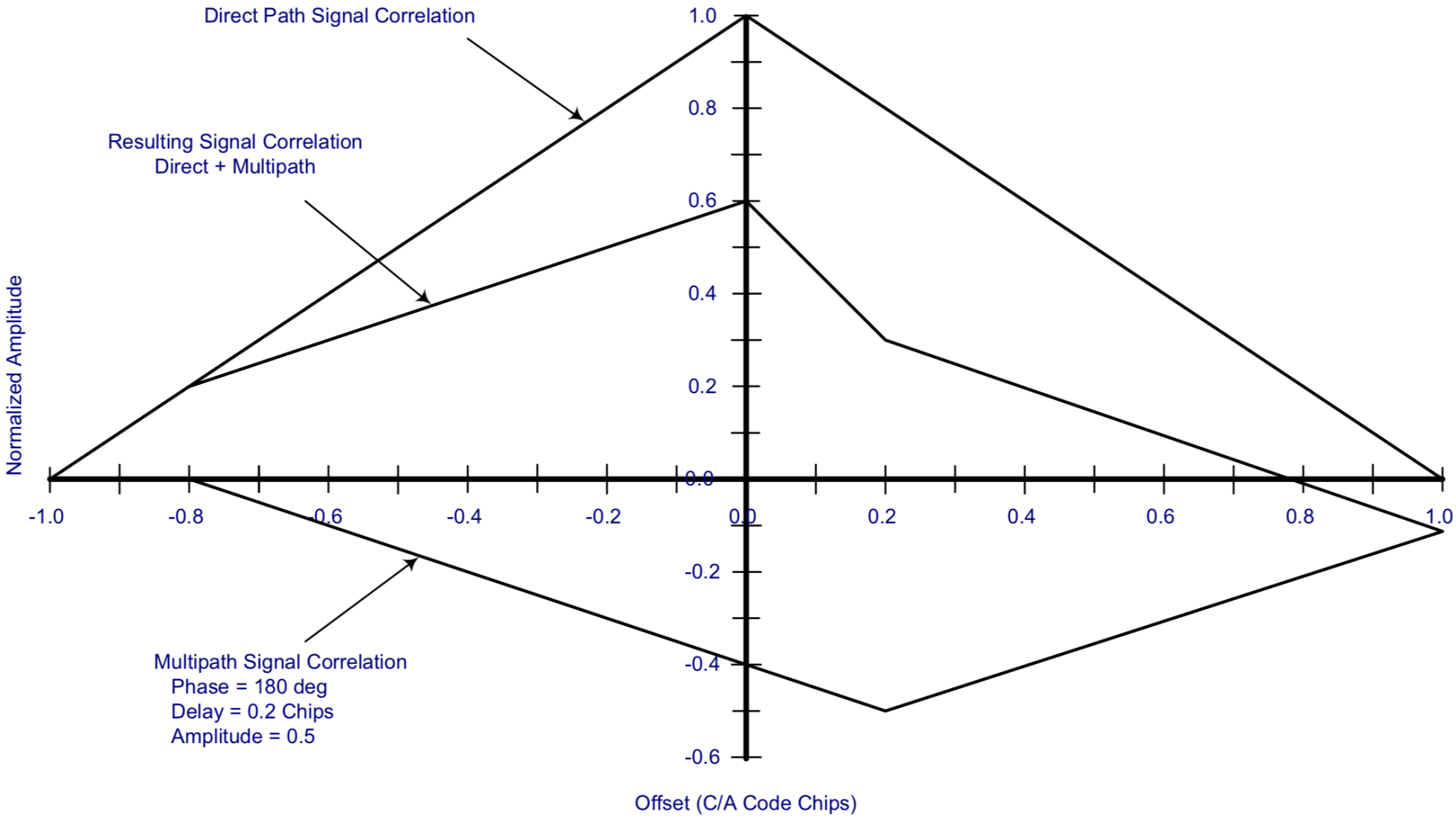


Tracking Performance

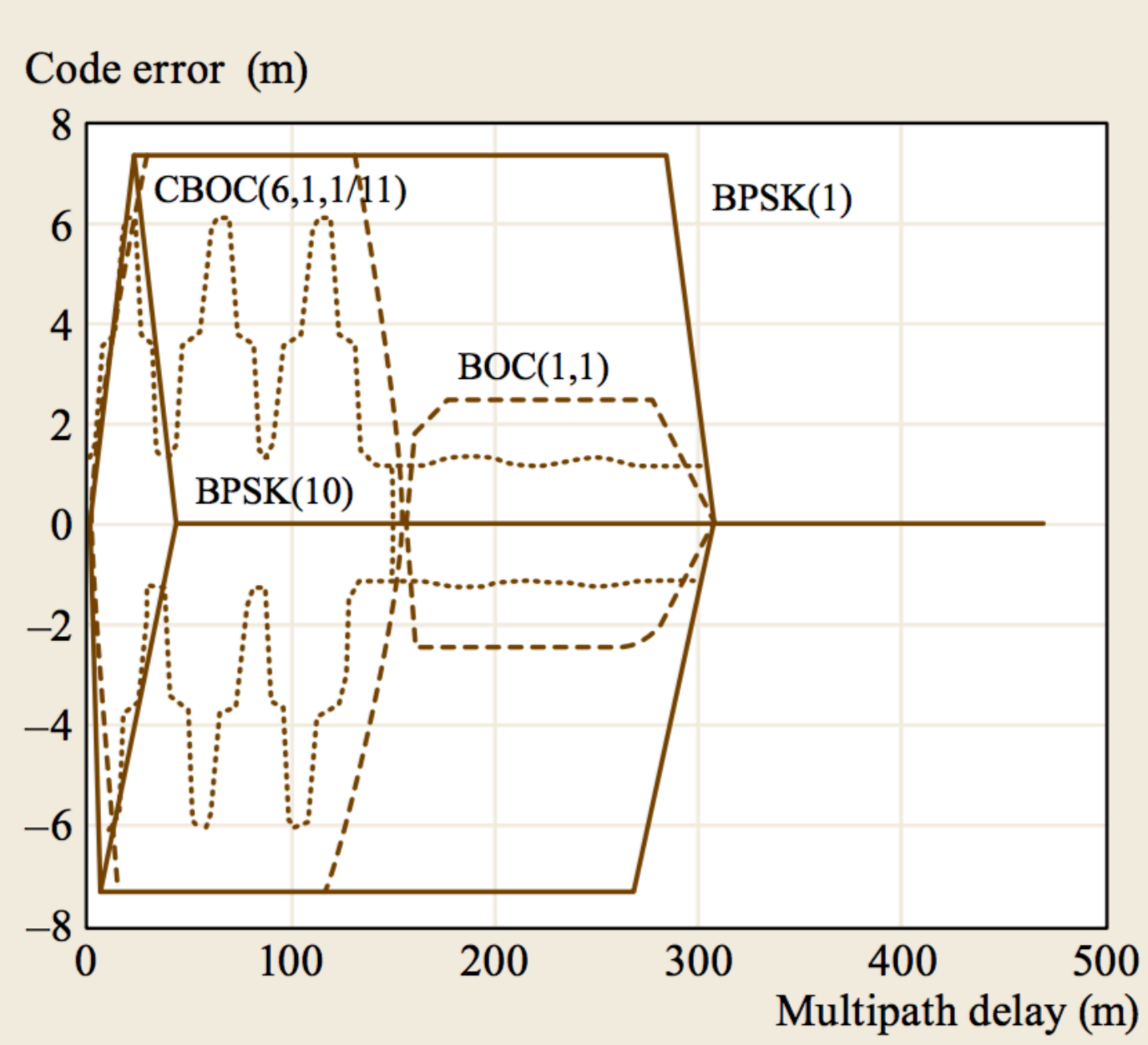




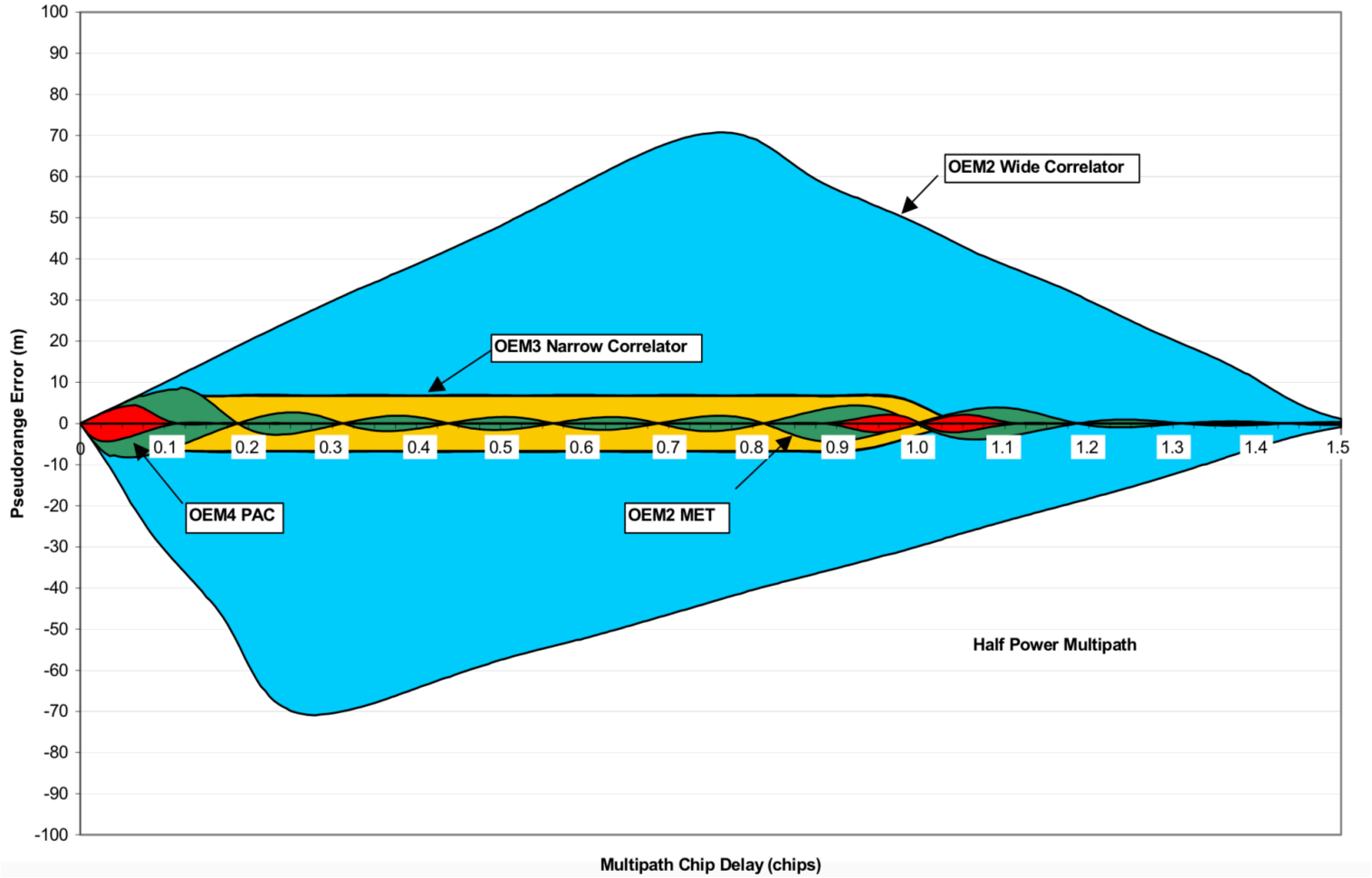
Multipath


Direct Path Signal Correlation
Resulting Signal Correlation
Direct + Multipath
Multipath Signal Correlation
Phase = 180 deg
Delay = 0.2 Chips
Amplitude = 0.5
Normalized Amplitude
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
Offset (C/A Code Chips)

Multipath Envelopes I/II



Multipath Envelopes II/II



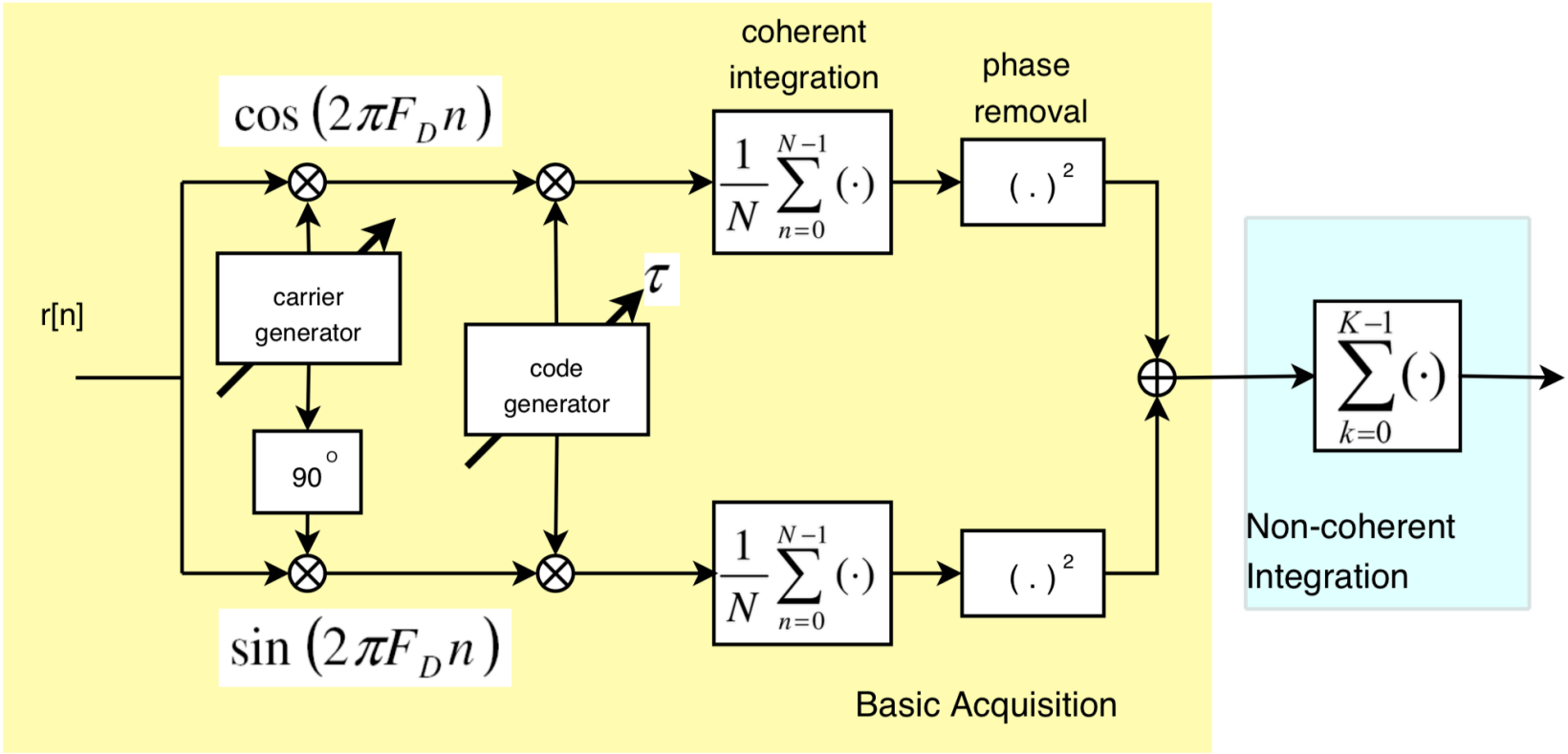
Example of different tracking loops performance from Novatel:

1992: Narrow Correlator

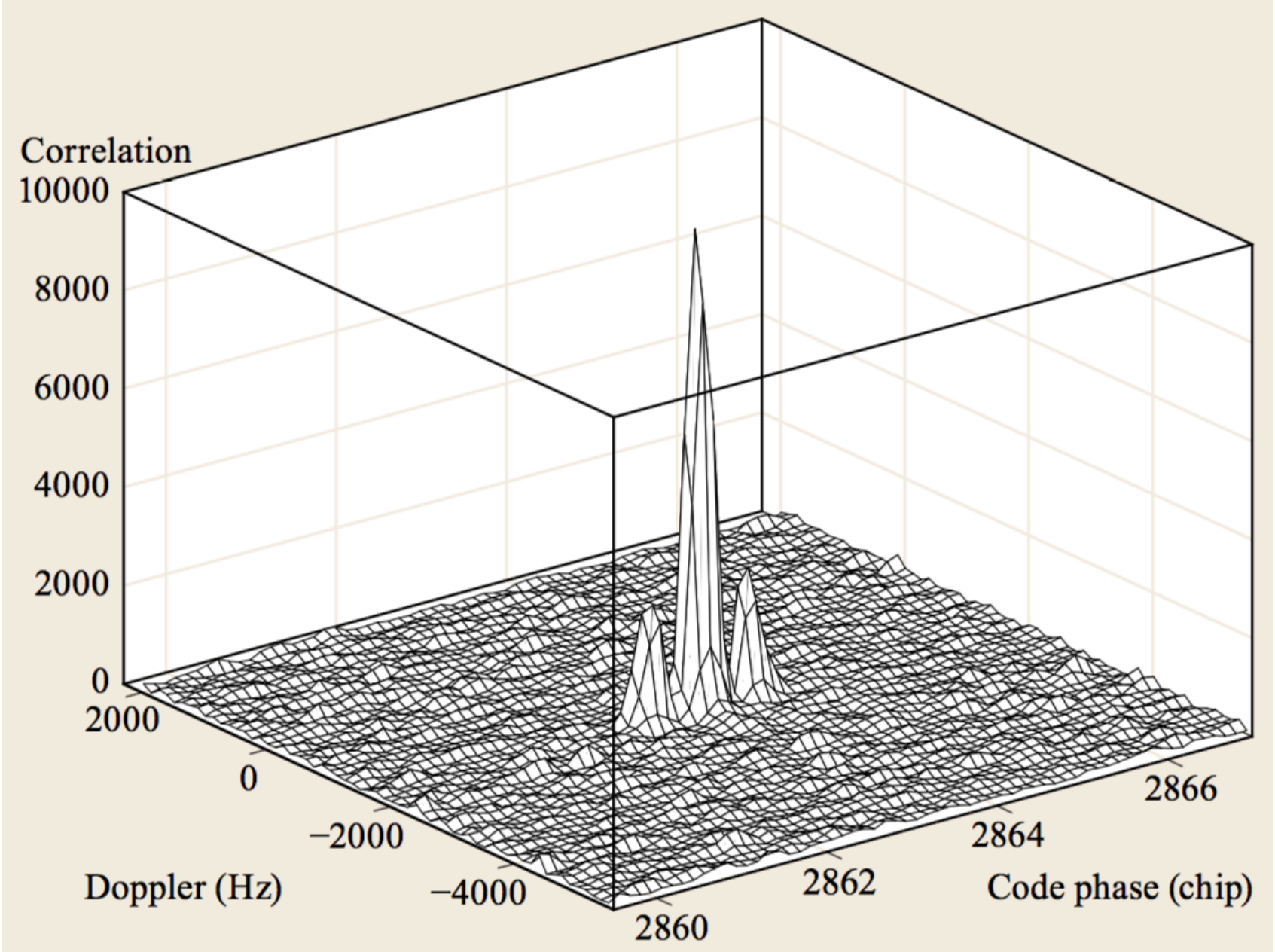
1994: Multipath Eliminating Technology (MET)

1999: Pulsed Aperture Correlator (PAC)

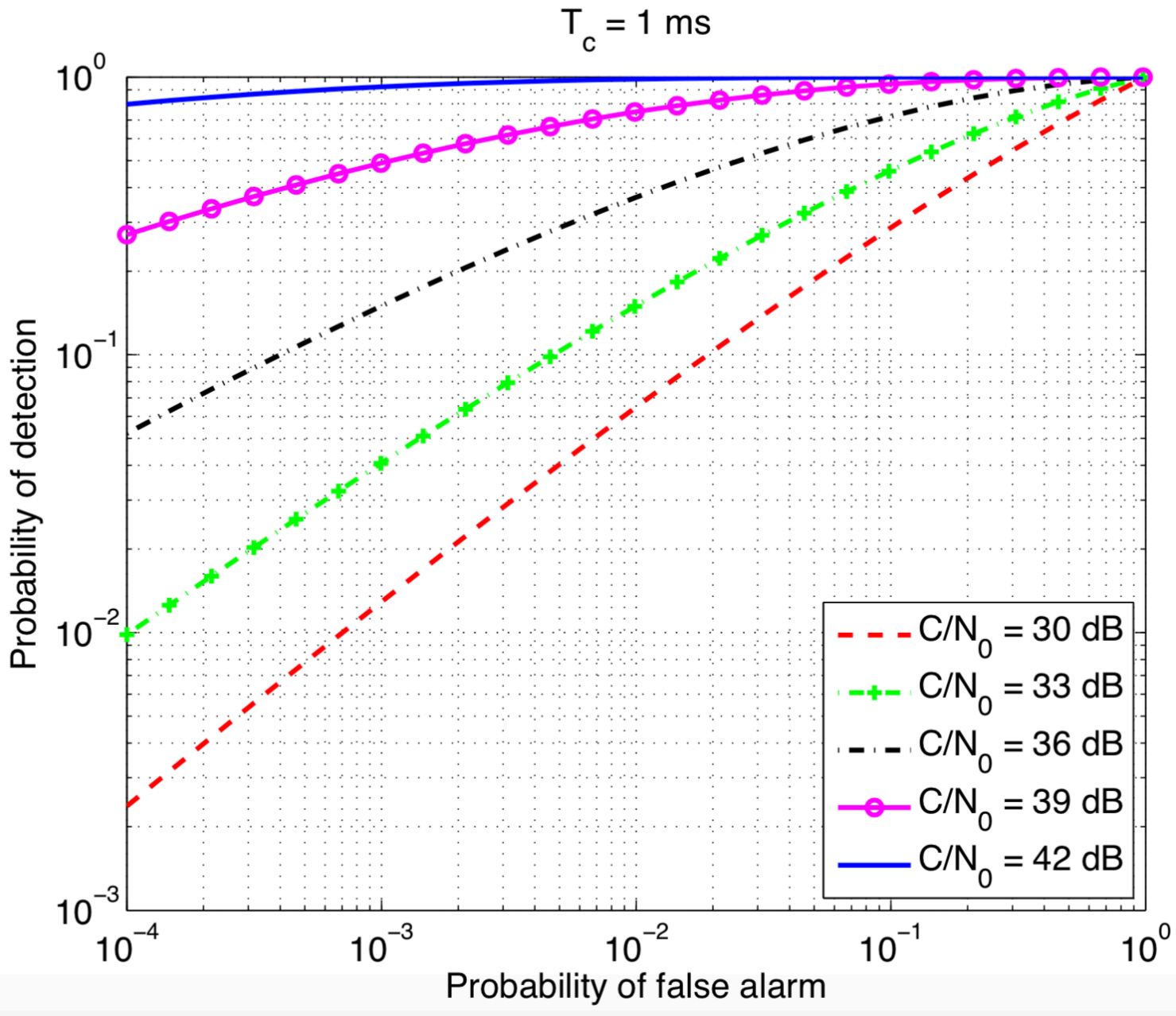
Signal Acquisition



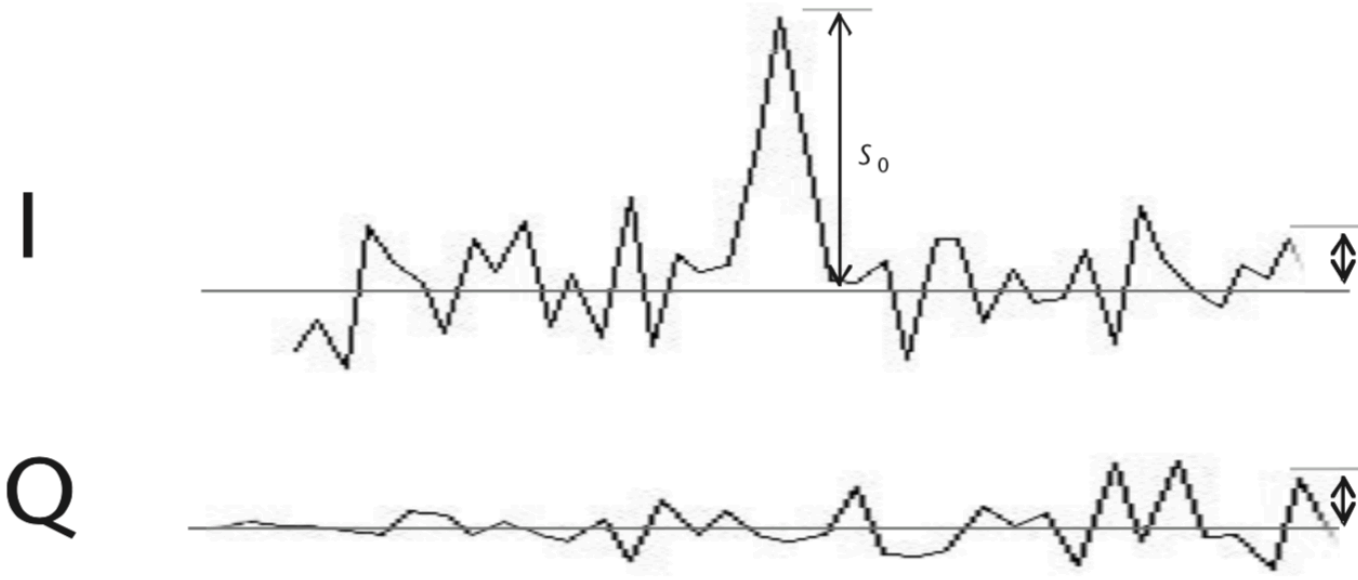
Signal Acquisition



Detection Probability



Squaring Loss

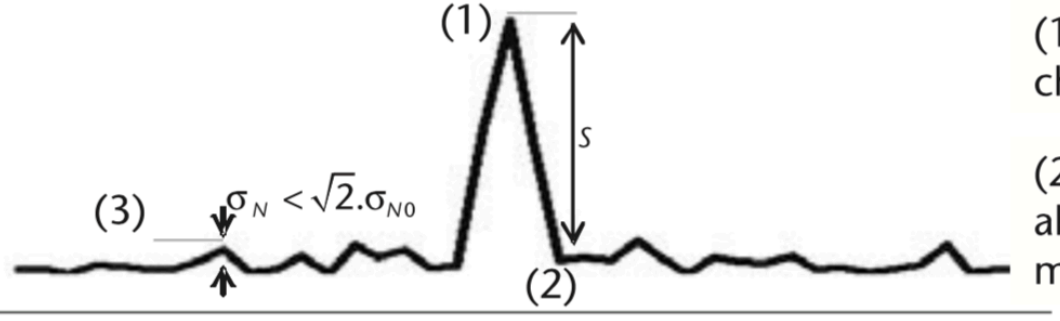


For this example, all signal energy is shown in I channel

Mean I noise = 0

Mean Q noise = 0

$\sqrt{I^2 + Q^2}$



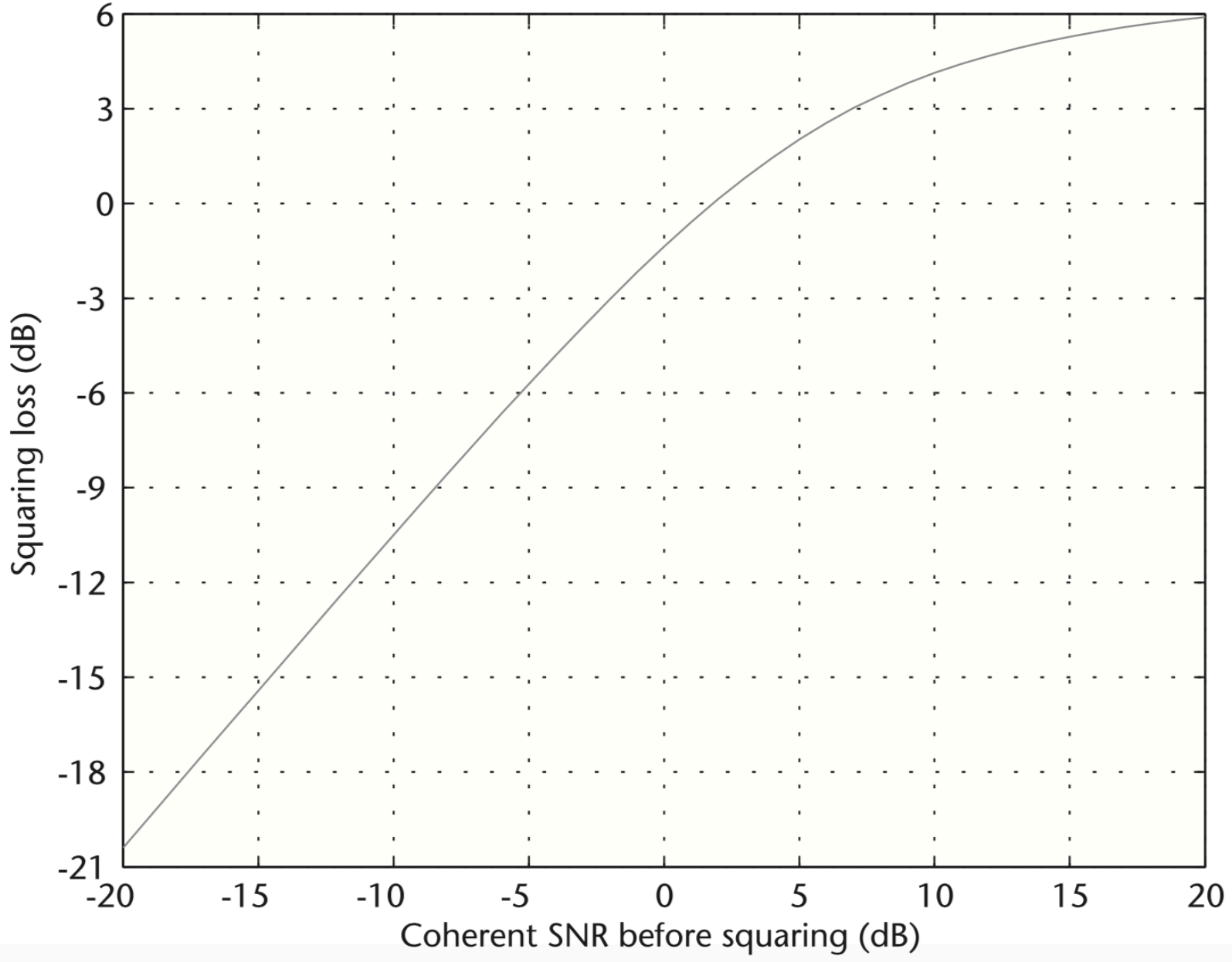
(1) The correlation peak magnitude changes

(2) The mean value of the noise is above zero. So the effective peak magnitude, *S*, is reduced.

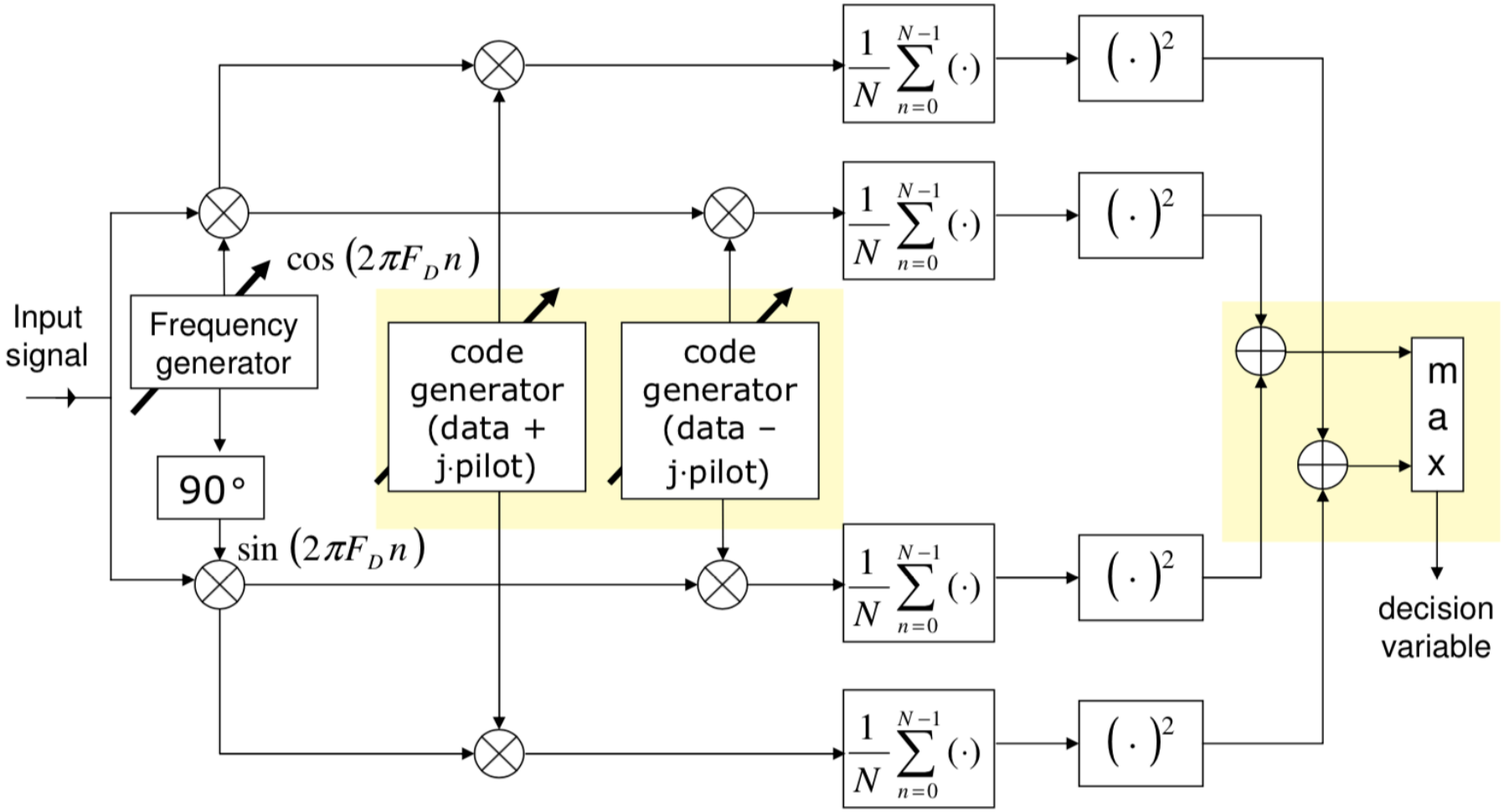
(3) The RSS operation changes the standard deviation of the noise

(1)+(2)+(3) = "squaring loss"

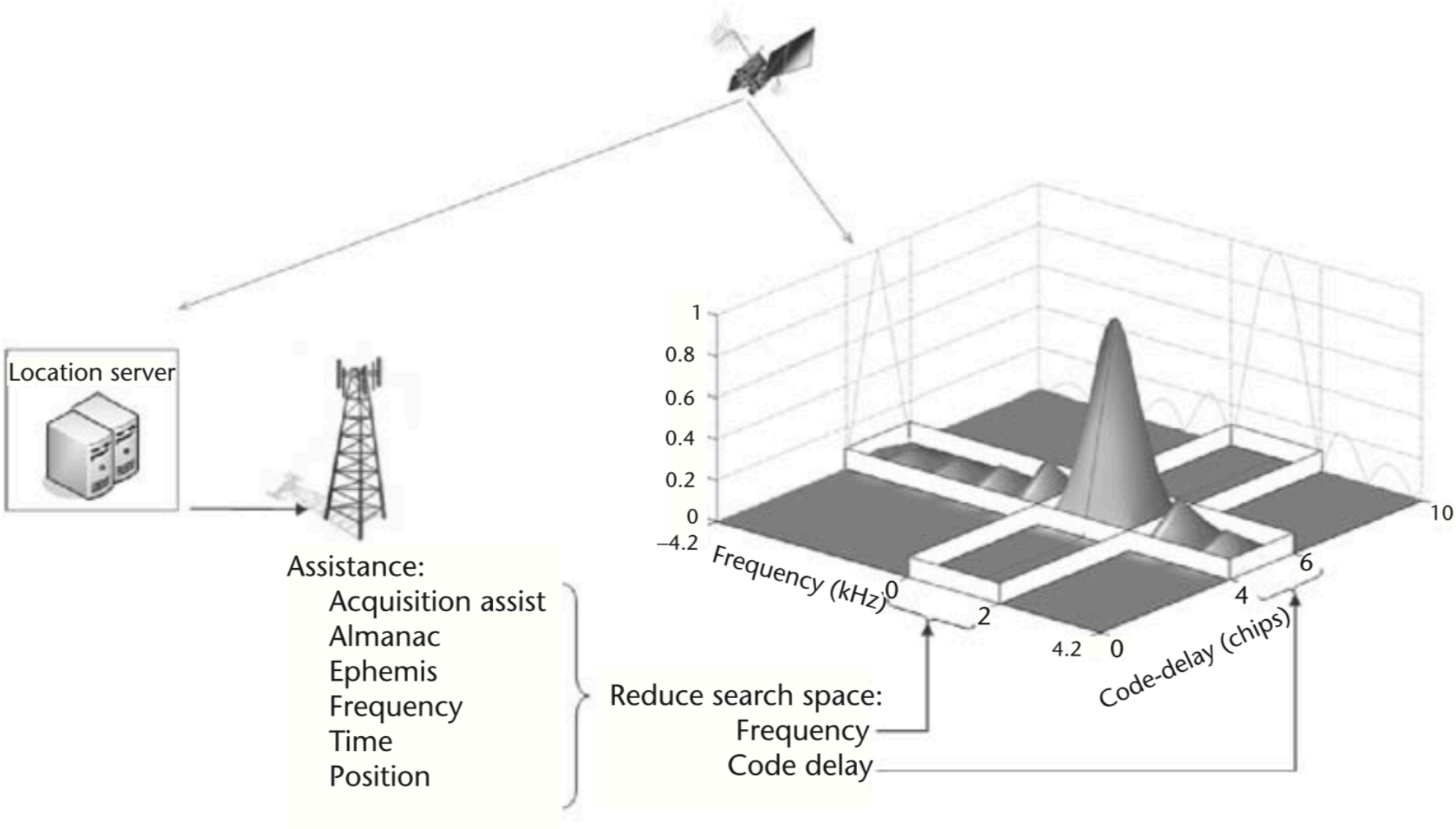
Squaring Loss



Signal Acquisition



Assisted GNSS



Search Space

Autonomous	Uncertainty (+/-)	Typical
Satellite Motion	4.2 kHz	
Clock (TCXO)	1.575 kHz/ppm	3 ppm
RX speed	0.146 kHz/100 km/h	160 km/h
Total Search Space	9.2 kHz	

Assisted	Uncertainty (+/-)	Typical
Assistance Time	1.6 Hz	+/- 2 s
Assistance Position	3 Hz	3 km
Clock (TCXO)	157.5 Hz	100 ppb
RX speed	2*0.146 kHz/100 km/h	160 km/h
Total Search Space	630 Hz	