

# **Index**

- 2-D PQN, 181  
    CF of, 181  
2-D characteristic function, 40  
2-D probability density function, 35  
2-D quantization, 173–223  
2-D sampling theorem, 177  
2-D sampling theory, 174–179
- A-law, 332  
A/D conversion, 9  
A/D converters, testing of, 650  
Abramowitz, M., 325, 651, 662, W5  
ADC, *see* Analog-to-digital conversion  
Addition of random variables, 46  
“Advanced” CDF, 71  
Amiantov, I. N., 544  
Analog-to-digital conversion, 630, W33  
Analog-to-digital converter in control,  
    432  
Anti-alias filter, 22  
Anti-alias filtering and quantization, 485  
Approximation of Sheppard’s corrections  
    for Gaussian input, 226–233  
Area sampling, 27, 62  
Arithmetic quantizer, 445  
Arithmetic rounding, 7  
Arsac, J., 14, W25  
Audio, 500, 510, 550, 623–628  
Autocorrelation function, 42  
Azegami, K., 548
- Bandlimited CF, example when all moments exist, 594  
Bandlimited characteristic function, 591  
Basic quantizer, 4  
Bayes’ rule, 39
- Bed of nails, 176  
Bell curve, 28, 55  
Bendat, J. S., 554, 563  
Bennett, W. R., 540, 542, 543, 563  
Bernoulli numbers, 91, W4  
Bernoulli polynomial, W5  
Bertram bound, 11, 455, 461  
Bertram, J. E., 455  
Bessel functions, 662  
Biased rounding, *see* Rounding, towards...  
BIBO system, 455  
Bifurcation diagram, 472  
Binomial PDF, 47  
Bit number for fixed-point, XI  
Bit numbers for single/double precision,  
    346  
Block floating-point number representation, 386, 394  
Borel, E., 13  
Bounded input, bounded output system,  
    455  
Bounds for residual errors, 642  
Bracewell, R. N., 17, 535  
Bremermann, H., 14, W25  
Buck, J. R., 11, 376, 383, 386, 389
- Campbell, L. L., W25  
Cascades of quantizers, 355  
CCITT, 262, 332  
CD, *see* Compact disc  
Census data  
    of Hungary, 87  
    of the USA, 77  
Central Limit Theorem, 50  
Centralized moment, 606

- Centralized random variable, 152  
CF, *see* Characteristic function  
CF of 2-D PQN, 181  
CF of output of 2-D quantization, 184  
Chaotic system, 465–482  
Characteristic function, 27, 33  
    joint, 40  
Characteristic function method  
    for moments, 33  
Characteristic function of  $x'$ , 65  
Checkweigher, *see* Weightchecker  
Chi-square distribution, 669  
Churchill, R. V., 597  
Claasen, T. A. C. M., 540, 548, 549, 556,  
    563  
Clock, digital, 109  
Coefficient quantization, 567–587  
Coherent sampling, 398  
Compact disc, 355, 522  
Complex multiplication, 385  
Compressor, 261, 263  
Condition number, 705  
Condition of whiteness, uniform, 558  
Conditional CF, 493, 626  
Conditional moment, 626  
Conditional PDF, 38, 626  
Control systems, 431  
Convergent rounding, *see* Rounding, convergent  
Cooley, J. W., 383  
Correlation coefficient of quantization noises, 202  
Correlation coefficient, Eq. (3.39), 42  
Correlation function, 42  
Correlator  
    hybrid sign, W29  
    polarity coincidence, W30  
    relay, W29  
    ring, W29  
Correspondences between sampling and quantization, 65  
Covariance, 42  
Covariance between  $x$  and  $v$ , 117  
Covariance of input and noise  
    for Gaussian input, 237–242  
Covariance of quantization noises, 201  
Covariances of inputs and noises, 213  
Cramér, H., W9  
Crosscorrelation  
    between quantization noise and quantizer input, 113  
Crosscorrelation function, 42  
Crossover point, 358  
Cumulative distribution function, 71  
Cumulative distribution function, interpolation of, W23  
De Moor, B., 705  
Dead zone, 6  
Decimation-in-frequency, 398  
Decimation-in-time, 389, 398  
Decreased precision, 702  
Defocusing the optics, 505  
 $\Delta$ , Eq. (12.1), 259  
Delta-sigma modulation, *see* Sigma-delta modulation  
Denormalized number, 343, 344  
Derivative of CF, 34  
DFT  
    grouped, 396  
DFT, roundoff noise, 388, 396  
Differential nonlinearity, 631  
Digital dither, 687–697  
Digital feedback control systems, 431  
Digital Gaussian dither, 691  
Digital triangular distribution, 695  
Digital uniform distribution, 692  
Digital wall clock, 109  
Digital watch, 109  
Digital-to-analog converter in control, 432  
Dirac delta function, scaling of, 16  
Dirac delta functions, train of, 16  
Dirac impulse sheet, 134, 154, 538  
Direct calculation of the DFT, 388  
Distribution  
    binomial, 47  
    chi-square, 669  
    digital triangular, 695  
    digital uniform, 692  
    example, bandlimited CF, all moments exist, 594  
    exponential, 672

- gamma, 674  
 Gaussian, 225, 635  
 “house”, 684  
 Laplacian, 676  
 normal, *see* Distribution, Gaussian other than sinusoidal, 665  
 Rayleigh, 666, 678  
 sinusoidal, 639, 641, 679  
 triangular, 665, 682  
 uniform, 681  
 with all moments for a bandlimited CF, 594
- Dither**, 485–529, W49  
*r*th-order, 496  
 defocusing the optics, 505  
 digital, 687–697  
 digitally first-order, 697  
 digitally zero-order, 693  
 first-order, 497, 500  
 Gaussian, 502  
 Gaussian, digital, 691  
 high-pass, 500  
 non-subtractive, 493  
 non-subtractive, CF of, W49  
 normally distributed, 502  
 normally distributed, digital, 691  
*r*th-order, W55  
 sinusoidal, 503, 557  
 subtractive, 506  
 triangularly distributed, 499, 708  
 triangularly distributed, digital, 695  
 tringularly distributed, 500  
 two-dimensional, 504, 505  
 uniformly distributed, 497  
 uniformly distributed, digital, 692  
 zero-order, 508
- Dither for floating-point, 512  
 Dithered roundoff, 516–520  
 Divisible distribution, 102  
 DNL, *see* Differential nonlinearity  
 Domokos, G., 482  
 Double rounding, 718  
 DVD, 356  
 Dynamic range  
 in fixed-point, 11  
 in floating-point, 345, 346
- in number representation, 355–359  
 in spectrum analysis, 394, 398, 400, 558
- Effective value, 29  
 Elderton, W. P., W15  
 Envelope of error, 639  
 eps, 351  
 Erdelyi, A., 678  
 Ergodicity, 43, 623  
 “Error” filter, 569  
 Errors to Sheppard’s corrections, 84, 599  
 Euler-Maclaurin summation formula, W3  
 Exact expressions of moments for sine input, 650
- Example**  
 2-D dither, 505  
 autocorrelation of quantized sine wave, 546  
 calculation of CFs from joint CF, 160  
 correlation between input and noise for sine, 646  
 covariance of quantization noise of identical inputs, 202  
 error in Sheppard’s correction for sine wave, 644  
 error of the mean value in ADCs, 631  
 for autocorrelation function of Gaussian Markov process, 250  
 general expression of correlation, 153  
 general expression of covariance, 153  
 good and bad conditioning of product, 707  
 harmonic distortion in ADCs, 632  
 higher joint moment, 151  
 interpolation of Gaussian PDF, 77  
 limit-cycle oscillation, 412  
 LS solution of a linear equation, 710  
 marginal distribution of joint PDFs, 137, 144, 156, 158  
 mutually independent variables which are not independent, 491  
 non-associative matrix product, 705

- non-fulfillment of 2-D QT III/A  
with fulfilled one-dimensional  
QT III/A, 205
- paradoxical dependence of random  
variables, 493
- properties of quantized sinusoid, 648
- PSD of a random bit sequence, 535
- PSD of quantization error of sine,  
547
- PSD of random telegraph signal, 536
- QT III in ADCs, 631
- quantization error of quantized  
Gaussian, 542
- quantization noise in a spectrum an-  
alyzer, 557
- quantization noise in audio, 550
- quantization noise with Gaussian in-  
put, 411
- quantization of a Gaussian signal,  
532
- quantization of a sine wave, 533
- roots of Wilkinson's polynomial, 709
- satisfaction of 2-D QT IV/B, 215
- satisfaction of QT III, 165
- satisfaction of QT III/A, 101, 102
- satisfaction of QT IV, 165
- satisfaction of QT IV/B, 166, 168
- Sheppard's corrections  
working in the wrong direction,  
W15
- Sheppard's corrections for Gaussian  
input, W10
- Sheppard's example: beta distribu-  
tion, W11
- sine applied to IIR filter, 410
- successive approximation ADC, 633
- testing A/D converters, 650
- upper bound of power of quantiza-  
tion noise for sine, 644
- weightchecker, 560
- Wilkinson's, 709
- zero correlation due to dithering, 505
- Exceptions to PQN: strange cases, 418
- Exercise  
being late on date, 54
- crate of chicken, 11, 109
- gemstones, 57
- historical film, 28
- "house" PDF, 55, 89, 171
- I am disorderly and precipitate, 54
- keys in drawers, 54
- liars, 54
- picket fence, 28
- prince and falling bridge, 56
- TV resolution, 193
- wheel turning backwards, 28
- Expander, 261, 263
- Exponent quantizer, 280
- Exponent, definition of, 257
- Exponential distribution, 672
- Extended precision, 343, 701
- Farley, D. T., W30
- Farnbach, J. S., 557
- Feedback control systems, 431
- Feller, W., 53
- Feller, W., 51
- FFT, 383–396, 398  
with block floating-point number  
representation, 394  
with fixed-point number repr., 388  
with floating-point number repr., 394
- $\Phi(u)$ , Eq. (2.17), 27
- $\dot{\Phi}(u)$ , 33
- FIR digital filters, 373–401
- First-order dither, 497, 500  
digital, 697
- Flannery, B. P., 708
- Floating-point dithering, 512
- Floating-point quantization in feedback,  
414–418
- Floating-point quantizer, 257
- Flush to zero, 344
- Forsythe, G., 708
- Fourier transform  
vanishing of sidelobes, 535
- Fourier transform, generalized, W25
- Fourier, J., 17
- Franklin, G. A., 431, 439
- Fubini's theorem, W25
- Fujii, A., 548
- Functional independence, 496

- Furman, G. G., 655  
 Fused multiply and add, *see* Multiply-and-add
- Gamma distribution, 674  
 Gaussian CF, Eq. (F.3), 635  
 Gaussian distribution, 225, 635  
     quantization of, 225  
 Gaussian dither, 502  
 Gaussian input, 84–85, 106–107, 123–125, 206–207, 225–254  
 Gaussian input, whiteness of quantization noise, 552  
 Gaussian PDF, 49, Eq. (F.1): 635  
 Gaussian variables, quantization of two, 242–251  
 General quantizing theorem for subtractive dither, *see* GQTSD  
 General statistical relations  
     in multidimensional quantization, 209  
     in one-dimensional quantization, 131  
 Generalized Fourier transform, W25  
 Geometric ratio, 461  
 Gersho, A., 262, 333  
 Godfrey, K., 526, 691  
 Goldberg, D., 343  
 Golub, G. G., 711  
 GQTSD (General quantizing theorem for subtractive dither), W55  
 Gradshteyn, I. S., W15  
 Gradual underflow, 344  
 Gray, R. M., 262, 333, 493, 500, 650, 653  
 Grouped DFT, 396  
 Growing power in FFT, 387
- Hagen, J. B., W29  
 Heaviside function, 652  
 Hejn, K., 650, 653  
 Hidden leading bit, 343, 346  
 Hidden quantizer, 261, 266–271  
     step size, 357  
 Higgins, J. R., 13  
 High-pass dither, 500  
 Histogram, 31  
 Horváth, G., 503
- “House” distribution, 684  
 HP 3582A spectrum analyzer, 557  
 Hui, D., 630  
 Hungarian census data, 87  
 Hybrid sign correlator, W29  
 Hyperbolic sine, 350  
 Hysteresis, 4, 463
- IEEE standard, 343, 346, 700  
 IIR digital filters, 403–430  
 Impulse carrier, 14, 16  
     two-dimensional, 176  
 Impulse sheet, 134, 141, 154, 538  
 Impulse train, 63  
 Independence, functional, 496  
 INL, *see* Integral nonlinearity  
 Inose, H., W33  
 Integral nonlinearity, 631  
 Interpolation formula, 13, Eq. (2.13): 22, W24  
 Interpolation of the CDF, W23  
 Interpolator, 432–437  
 Interval arithmetic, 708  
 Iteration diagram, 471
- J. Kontro, 333  
 Jensen, R. V., 470  
 Jerri, A. J., 13  
 Joint CF, 40  
     of quantizer input and noise, 141  
     of quantizer input and output, 132  
     of quantizer input, noise and output, 159  
     of quantizer output and noise, 155  
 Joint CF of inputs and noises, 210  
 Joint PDF, 35  
     of inputs and noises, 209  
     of quantizer input and noise, 140  
     of quantizer input and output, 131  
     of quantizer input, noise and output, 158  
     of quantizer output and noise, 154  
 Jongepier, A., 540, 548, 549, 556, 563
- Kalliojärvi, K., 333  
 Kaneko, T., 394  
 Katzenelson, J., 543, 563

- Kind corrections, W81  
     for two variables, W81  
 Kollár, I., 562, 563, 650, W31  
 Korn, G. A., 91, 553, W4  
 Korn, T. M., 91, W4  
 Kotel'nikov, V. A., 13  
 Kramarski, L., 650, 653
- Laplacian distribution, 676  
 Leading bit, 343  
 Least significant bit, 343  
 Least squares solution, 711  
 Leon-Garcia, A., 51  
 Lighthill, M. J., 14, W25  
 Limit-cycle oscillation, 412–413  
 Limits of applicability of quantization theory, 623  
 Linearity, small-perturbation, 467  
 Linvill, W. K., 14, 17, 22  
 Lipshitz, S. P., 493, 688  
 Liu, B., 394  
 Loève, M., 51  
 Logistic map, 470  
 Long double number, 700  
 LS solution, 711  
 LSB, *see* Least significant bit  
 Lukacs, E., 592, 597
- $M_1$ , Eq. (B.3): 600  
 $M_2$ , Eq. (B.4): 601  
 $M_3$ , Eq. (B.5): 602  
 $M_4$ , Eq. (B.6): 604  
 $M_r$ , Eq. (4.27): 81  
 $M_r$ , Eq. (B.1): 599  
 $\tilde{M}_r$ , Eq. (T.4): W63  
 MAC operation, *see* Multiply-and-add  
 Machine epsilon, 351  
 Magnitude-and-sign number representation, 11  
 Mantissa, 259, 343  
 Marginal PDF, 38  
 Marker-based movement analysis, 194  
 Marks, R. J. II., 13  
 Matlab, 713  
 Memoryless operations, 43  
 Mid-riser quantizer, 4, 6, 12, 90, 111, 129, 655, 695
- Mid-tread quantizer, 6, 12, 167, 168, 695  
 Middleton, D., 14  
 Milne-Thomson, L. M., W3  
 Modulation principle, 540, 546  
 Modulation product, 623  
 Moler, C., 708  
 Moment, 33  
     calculation from derivatives of CF, 34  
 Moment difference, 82, W63  
 Moments of noise  
     for Gaussian input, 233–237  
 Moorer, J. A., 356  
 Moving average, 373  
 $\mu$ -law, 332  
 Multiple precision, 700  
 Multiplication, complex, 385  
 Multiply-and-accumulate, *see* Multiply-and-add  
 Multiply-and-add, 278, 374, 701  
 Multivariable PQN model, 184  
 Multivariable quantization, 184  
 Murakami, J., W33
- $N_1$ , Eq. (B.3): 600  
 $N_2$ , Eq. (B.4): 601  
 $N_3$ , Eq. (B.5): 602  
 $N_4$ , Eq. (B.6): 604  
 $N_r$ , Eq. (B.1): 599  
 $N_{1v}$ , Eq. (5.24): 103  
 $N_{2v}$ , Eq. (5.29): 104  
 $N_{3v}$ , Eq. (5.33): 105  
 $N_{4v}$ , Eq. (5.35): 106  
 $\tilde{N}_1$ , Eq. (T.12): W65  
 $\tilde{N}_2$ , Eq. (T.13): W67  
 $\tilde{N}_{2v}$ , Eq. (5.31): 104  
 $\tilde{N}_3$ , Eq. (T.14): W69  
 $\tilde{N}_4$ , Eq. (T.15): W72  
 Nails, bed of, 176  
 Neuhoff, D. L., 630  
 Neuvo, Y., 333  
 Newton's algorithm, 704  
 Newtonian notation of derivatives, 33  
 NFPQNP, *see* Normalized floating-point quantization noise power  
 Noise modulation, 497, 500, 623, 627

- Noise moments  
     for Gaussian input, 233–237  
     short-time dependence on  $x$ , 625
- Noise propagation  
     in floating-point, 395
- Noise shaping, W34
- Noisy quantizer, 6
- Non-subtractive dither, 493  
     CF of, W49
- Nonlinear dynamic system, 465–482
- Nonnegative definite function, 592
- Normal distribution, *see* Gaussian distribution
- Normalized floating-point quantization noise power, 282, 302
- Normalized number, 343, 346
- Normally distributed digital dither, 691
- Normally distributed dither, 502
- Norsworthy, S., W35
- $v$ , Eq. (1.1): 3
- Number of bits for fixed-point, XI
- Number representation, 7, 11
- Nyquist, H., 13
- One's complement number representation, 11
- Oppenheim, A. V., 7, 11, 376, 383, 386, 389, 567, W25
- Optics  
     defocusing, 505
- Ord, J. K., 91, W3
- Orthogonality, 42, 126
- Output of 2-D quantization, CF of, 184
- Overflow, 345
- Overlap of spectra, desirable, 551
- Overrepresentation, 650
- Overview of quantizing theorems, 162
- Pacut, A., 650, 653
- Paduart, J., 700
- Papoulis, A., 254, 337, 544
- Paradox, 192, 493, 505
- PDF, *see* Probability density function
- Peebles, P. Z., 540, 546, 547, 563
- Pendergrass, N. A., 557
- Perfectly bandlimited CF, 591
- Periodogram, 398
- Phase-modulated sine wave, 547
- Picket fence effect, 28, 401, 558
- Piecewise constant signal, 432
- Piersol, A. G., 554, 563
- Pintelon, R., 700
- Pohlmann, K. C., 356
- Poisson point process, 536
- Polarity coincidence correlator, W30
- Powell, J. D., 431, 439
- Power spectral density, 532
- PQN model, *see* Pseudo quantization noise model
- Precision  
     double, 343, 346  
     extended, 343, 701  
     in floating-point, 343  
     increased, 699  
     multiple, 700  
     single, 343, 346
- Press, W. H., 708
- Price theorem, 254
- Probability density function, 31  
     conditional, 38  
     joint, 35  
     marginal, 38
- PSD, *see* Power spectral density
- Pseudo quantization noise (PQN) model, 61–111, 140, 146, 161, 184, 197, 233  
     exceptions to, in feedback, 418  
     for floating-point, 302  
     multivariable, 184  
     two-dimensional, 181  
     two-dimensional, CF of, 181
- $\Psi$ , Eq. (4.12): 65
- Pyramidal PDF, 261
- QDSP, 718
- QT I (Quantizing theorem I), 69  
     for  $N$  variables, 186  
     for two variables, 186
- QT II, 69  
     for  $N$  variables, 187  
     for two variables, 187
- QT III, 150

- N*-dimensional, proof of, 223  
 for *N* variables, 216  
 proof of, 619
- QT III/A, 99  
 for *N* variables, 204
- QT III/B, 126
- QT IV, 152  
 for *N* variables, 217  
 proof of, 620
- QT IV/A, 101
- QT IV/B, 128  
 for *N* variables, 214  
 multidimensional, 526
- QTD III (Quantizing theorem III for dither), 496
- QTD IV (Quantizing theorem IV for dither), 496
- QTD-ACF (Quantizing theorem for dither, concerning the autocorrelation function), 505
- QTDD (Quantizing theorem for digital dither), 688
- QTs, overview of, 162
- QTSD (Quantizing theorem for subtractive dither), 508, 524  
 general, W55
- Quantization  
 as sampling in amplitude, 9, 65  
 in control, 6  
 in measurement, 6  
 short-time properties, 623–628
- Quantization error  
 total, 490, 493–497
- Quantization in feedback with floating-point, 414–418
- Quantization noise, 3, 93  
 floating-point, 260  
 two-dimensional, 197  
 with Gaussian input, 106
- Quantization noise moments  
 for Gaussian input, 233–237
- Quantization of Gaussian distribution, 225
- Quantization of two Gaussian variables, 242–251
- Quantization within feedback loop, 404
- Quantized DSP simulation toolbox, 718
- Quantizer  
 arithmetic, 445  
 basic, 4  
 definition, 3  
 floating-point, 257  
 mid-riser, 4, 6, 12, 90, 111, 129, 655, 695  
 mid-tread, 6, 12, 167, 168, 695  
 noisy, 6  
 shifted, 90, 110, 129  
 uniform, 3
- Quantizing theorem, *see* QT
- Quantizing theorem for digital dither, *see* QTDD
- Quantizing theorem for dither, *see* QTD
- Quantizing theorem for dither, concerning the autocorrelation function, *see* QTD-ACF
- Quantizing theorem for subtractive dither, *see* QTSD
- Quantizing theorems, overview of, 162
- $R_1$ , Eq. (B.8): 604
- $R_2$ , Eq. (B.10): 605
- $R_3$ , Eq. (B.13): 607
- $R_4$ , Eq. (B.16): 608
- $\tilde{R}_1$ , W72
- $\tilde{R}_2$ , Eq. (T.17): W72
- $\tilde{R}_3$ , Eq. (T.19): W73
- $\tilde{R}_4$ , Eq. (T.21): W75
- Ragazzini, J. R., 14
- Random bit sequence, 535
- Random process, 43, 623
- Random telegraph signal, 536
- Random walk, 47
- Rank of matrix, 711
- Rayleigh distribution, 666, 678
- Re-quantization, 418, 687, 690
- Recording, soft (low-level), 355, 627
- Recovery of moments, 80
- Recovery of the input PDF, 70
- Recovery of time function from samples, 18
- Reference value in calculations, 699
- Relay correlator, W29

- Remez, 376  
 Representable number, 688  
 Representation of numbers, 7, 11  
 Residual errors, bounds of, 642  
 Return map, 471  
 Ring correlator, W29  
 RMS, XVI  
 Roberts, G. L., 506, 521, 524  
 Robertson, G. H., 545, 555, 563  
 Rolain, Y., 700  
 Round to even, *see* Rounding, convergent  
 Rounding, 7, 12  
     convergent, 11, 351, 386, 396, 705  
     towards  $-\infty$ , 652  
     towards  $\infty$ , 12  
     towards zero, 12  
 Rounding, biased, *see* Rounding, towards...  
 Rounding, unbiased, *see* Rounding, convergent  
 Roundoff error  
     in FFT, 399  
 Roundoff noise in DFT, 388, 396  
 Roundoff, dithered, 516–520  
 $r$ th-order dither, W55  
 $r$ th-order dither, 496  
 Ryzhik, I. M., W15  
 $S_{1\dots 5}$ , Eq. (4.31): 83  
 Samples of a sine wave, joint PDF and CF, 655  
 Sampling and quantization, 9, 65  
 Sampling theorem, 18  
     in two dimensions, 177  
 Sampling theory, 13  
 Sampling wattmeter, 29  
 Satisfaction of 2-D QT IV/B, 215  
 Satisfaction of QT III, 165  
 Satisfaction of QT III/A, 101, 102  
 Satisfaction of QT IV, 165  
 Satisfaction of QT IV/B, 166, 168  
 Saturation effects, 628  
 Saturation of quantizer, 4  
 Scaling in an FIR filter, 378  
 Scaling of signal in feedback loop, 442  
 Scalloping loss, 401  
 Schafer, R. W., 7, 11, 376, 383, 386, 389, 567  
 Schoukens, J., 700  
 Schreier, R., W35  
 Schuchman, L., 524  
 Schultheiss, P. M., 551  
 Scientific computations, 699  
 SEC, *see* Stochastic–ergodic converter  
 Shannon, C., 13  
 Sheppard's corrections, 80, 82  
     and the CF method, W3  
     errors to, 84, 599  
     for Gaussian input, 84, 226–233  
     in two dimensions, 184, 190  
     paradox for, 192  
 Sheppard, W. F., 83, 86, W3  
 Shifted quantizer, 90, 110, 129  
 Short-time properties of quantization, 623–628  
 Sigma-delta modulation, W33  
 Sign bit, 343  
 Signal scaling in feedback loop, 442  
 Significand, 343  
 Simulation of roundoff in Matlab, 713–721  
 Sinc function, 615–617  
 Sine wave testing, 650  
 Sine wave, joint PDF and CF of samples, 655  
 Sine wave, whiteness of quantization noise, 556  
 Sinh function, 350  
 Sinusoidal distribution, 639, 641, 679  
 Sinusoidal dither, 503, 557  
 Skyscraper PDF, 261  
 Slope, average, 558  
 Small-perturbation linearity, 467  
 SNR, 355–359  
 Snyder, D. L., 100, 200, 204, 246, 539, 542, 552, 553, 563  
 Soft (low-level) recording, 355, 627  
 SOS, *see* Sum of squares  
 Spang, H. A., 551  
 Spectrum of quantization noise, 531  
 $S_r, r = 1\dots 5$ , Eq. (4.31): 83

- Sripad, A. B., 100, 200, 204, 246, 539, 542, 552, 553, 563  
Standard IEEE, for floating-point, 343, 700  
Statistical description of quantization, 25, 61  
Stegun, I. A., 325, 651, 662, W5  
Stochastic process, 43, 623  
Stochastic–ergodic converter, 498, 505  
Stockham, Jr, T. G., 493, 500  
Stuart, A., 91, W4  
Subtractive dither, 506  
Sum of squares, 451  
Szász, D., 482
- Tapped delay line, 373  
Temes, G. C., W35  
Testing of A/D converters, 650  
Teukolsky, S. A., 708  
Three-dimensional CF, 158  
Three-dimensional PDF, 158  
Tikhonov, V. I., 544  
Total quantization error, 490, 493–497  
Total quantization noise, W49  
Total quantization noise at plant output, 442, 447  
Train of impulses, 16  
Triangle wave, joint PDF and CF of samples, W37  
Triangular distribution, 665, 682 digital, 695  
Triangular dither, 497  
Triangularly distributed digital dither, 695  
Triangularly distributed dither, 499, 500, 708  
Truncation, 7, 12  
Tukey, J. W., 383  
Tumart, S., 498  
TV norm, 193  
Two Gaussian variables, quantization of, 242–251  
Two’s complement number representation, 11  
Two-dimensional characteristic function, 40  
Two-dimensional dither, 505
- Two-dimensional PQN, 181  
Two-dimensional probability density function, 35  
Two-dimensional quantization, 173–223  
Two-dimensional sampling theorem, 177  
Two-dimensional sampling theory, 174–179  
Two-variable quantization, 173
- ULP, *see* Unit in the last place  
Unbiased rounding, *see* Rounding, convergent  
Uncorrelatedness, 42 independent of mean value, 115, 126, 127  
Underflow, 345 gradual, 344  
Uniform condition of whiteness, 558  
Uniform distribution, 681 digital, 692  
Uniform quantizer, 3  
Uniformly distributed digital dither, 692  
Uniformly distributed dither, 497  
Unit in the last place (ULP), 701  
Unit step function, 652  
USA census data, 77
- van Loan, C. F., 711  
Vanderkooy, J., 493, 688  
Vanishing of sidelobes of Fourier transform, 535  
Velichkin, A. I., 544  
Vetterling, W. T. , 708
- Wall clock, digital, 109  
Wannamaker, R. A., 493, 505, 688, W49  
Watch, digital, 109  
Wattmeter, sampling, 29  
Website of the book, VIII, 87, 89, 253, 424, 481, 492, 493, 522, 650  
Wehrmann, W., 498  
Weightchecker, 560  
Weinstein, C. J., 395, 396  
Welch, P. D., 394  
White spectrum, 550  
Whiteness, 531

- Whiteness of quantization noise of Gaussian input, 552  
Whiteness of quantization noise of sine wave, 556  
Whittaker, E. T., 13  
Whittaker, J. M., 13  
Widrow, B., 14, 27, 69, 71, 198, 553, 563  
Wilkinson, J. H., 705, 708  
Willsky, A. S., W25  
Woodward, P. M., 51  
Workman, M. L., 431, 439  
Wright, J. N., 493, 688
- $\tilde{x}$ , zero-mean variable, Eq. (3.13): 34  
 $x'$ , quantized variable, 3
- Yasuda, Y., W33  
Young, I. T., W25
- Zadeh, L. A., 14  
Zakai, M., W23  
Zemanian, A. H., 14, W25  
Zero-order dither, 508  
    digital, 693  
Zero-order hold, 432
- $\Delta$ , Eq. (12.1), 259  
 $\Phi(u)$ , Eq. (2.17), 27  
 $\dot{\Phi}(u)$ , 33  
 $\mu$ -law, 332  
 $v$ , Eq. (1.1): 3  
 $\Psi$ , Eq. (4.12): 65