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National foreword

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Contents

Page

Foreword ... xxiii

0 Introduction ... xxv
0.1 Purpose ... xxv
0.2 Design criteria ... xxv

1 Scope ... 1

2 Normative references ... 3

3 Terms, definitions, symbols, and abbreviated terms ... 5
3.1 Terms and definitions ... 5
3.2 Notation, symbols, and abbreviated terms ... 6

4 Concepts ... 13
4.1 Overview ... 13
4.2 Coordinate-space, position-space, and object-space ... 15
4.2.1 Coordinate-space ... 15
4.2.2 Position-space and orthonormal frames ... 15
4.2.3 Object-space and normal embeddings ... 16
4.3 Coordinate systems ... 17
4.3.1 Abstract coordinate systems ... 17
4.3.2 Spatial coordinate systems ... 19
4.3.3 Temporal coordinate systems ... 19
4.4 Orientation ... 20
4.5 Reference datums ... 20
4.6 Object reference models ... 23
4.7 Spatial reference frames ... 25
4.8 Designated spatial surfaces and vertical offset surfaces ... 26
4.9 Spatial operations ... 27
4.10 Application program interface ... 28
4.11 Profiles ... 28
4.12 Registration ... 28
4.13 Conformance ... 29

5 Coordinate systems ... 31
5.1 Overview ... 31
5.2 Coordinate-space, position-space, and object-space ... 31
5.2.1 Coordinate-space ... 31
5.2.2 Orthonormal frames ... 32
5.2.3 Position-space ... 33
5.2.4 Object-space ... 34
5.2.5 Normal embeddings ... 35
5.3 Abstract coordinate systems ... 37
5.3.1 Overview ... 37
5.3.2 Definition ... 37
5.3.3 Coordinate system types ... 38
5.3.4 Coordinate-component surfaces and curves ... 41
5.3.4.1 Overview ... 41
5.3.4.2 Coordinate-component surfaces and induced surface CSs ... 41
5.3.4.3 Coordinate-component curves ... 42
5.3.5 CS properties ... 43
5.3.5.1 Linearity ... 43

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5.3.5.2 Orthogonality 43
5.3.5.3 Linear CS properties: Cartesian, and orthogonal 43
5.3.5.4 CS right-handedness and coordinate-component ordering 44
5.3.6 CS localization 44
5.3.6.1 Overview 44
5.3.6.2 Localization operators 45
5.3.6.3 Localized frame and local tangent frame at a coordinate 47
5.3.6.4 Vectors, directions, and localized frames 50
5.3.7 Map projection coordinate systems 51
5.3.7.1 Map projections 51
5.3.7.2 Map projection as a surface CS 51
5.3.7.3 Map projection geometry 52
5.3.7.4 Relationship to projection functions 56
5.3.7.5 Map projection CS common parameters 59
5.3.7.6 Augmented map projections 60
5.3.8 CS specifications 61
5.3.8.1 Specification table elements and common functions and parameters 61
5.3.8.2 Euclidean 3D CS specification 64
5.3.8.3 Lococentric Euclidean 3D CS specification 65
5.3.8.4 Equatorial Spherical CS specification 67
5.3.8.5 Lococentric Equatorial Spherical CS specification 68
5.3.8.6 Azimuthal Spherical CS specification 70
5.3.8.7 Lococentric Azimuthal Spherical CS specification 72
5.3.8.8 Geodetic 3D CS specification 73
5.3.8.9 Planetodetic 3D specification 76
5.3.8.10 Cylindrical CS specification 77
5.3.8.11 Lococentric Cylindrical CS specification 79
5.3.8.12 Mercator CS specification 80
5.3.8.13 Oblique Mercator Spherical CS specification 82
5.3.8.14 Transverse Mercator CS specification 85
5.3.8.15 Lambert Conformal Conic CS specification 89
5.3.8.16 Polar Stereographic CS specification 91
5.3.8.17 Equidistant Cylindrical CS specification 93
5.3.8.18 Surface Geodetic CS specification 95
5.3.8.19 Surface Planetodetic CS specification 96
5.3.8.20 Lococentric Surface Euclidean CS specification 98
5.3.8.21 Lococentric Surface Azimuthal CS specification 100
5.3.8.22 Lococentric Surface Polar CS specification 101
5.3.8.23 Euclidean 2D CS specification 103
5.3.8.24 Lococentric Euclidean 2D CS specification 104
5.3.8.25 Azimuthal CS specification 106
5.3.8.26 Lococentric Azimuthal CS specification 107
5.3.8.27 Polar CS specification 109
5.3.8.28 Lococentric Polar CS specification 110
5.3.8.29 Euclidean 1D CS specification 112
5.3.8.30 Azimuthal Cylindrical CS specification 113
5.3.8.31 Lococentric Azimuthal Cylindrical CS specification 114
5.4 Spatial coordinate systems 116
5.4.1 Overview 116
5.4.2 Definition 116
5.5 Temporal coordinate systems 118
5.5.1 Overview 118
5.5.2 Universal time 119
5.5.3 International atomic time 119
5.5.4 Coordinated universal time 119
5.5.5 Specified temporal coordinate systems 119

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Full document details: BS ISO/IEC 18026:2025

6 Orientation – change of basis and rotation 121
6.1 Overview 121
6.2 Change of basis 121
6.2.1 Overview 121
6.2.2 Change of basis operations 121
6.2.3 Direction cosine matrix 124
6.2.4 Consecutive change of basis 124
6.2.5 Equivalence of change of basis and rotation operators 124
6.2.6 Change of basis and orientation 125
6.3 Orientation 125
6.3.1 Overview 125
6.3.2 Orientation defined in terms of a change of basis operator 126
6.3.3 Orientation defined in terms of a rotation operator 126
6.3.4 Orientation contexts 126
6.4 Rotation 126
6.4.1 Overview 126
6.4.2 Coordinate-free rotation 127
6.4.2.1 Origin-fixed rotation 127
6.4.2.2 Rodrigues' rotation formula 128
6.4.2.3 Rotation properties 128
6.4.2.4 Consecutive rotations 129
6.4.3 Frame-based rotation 133
6.4.3.1 Overview 133
6.4.3.2 Rotation of position-vectors 134
6.4.3.3 Rotation of basis vectors and orthonormal frames 135
6.4.3.4 Principal rotations 136
6.4.3.5 Equivalence of rotation and change of basis operators 136
6.4.4 Rotation and orientation 137
6.5 Operator summary 137
6.6 Representing rotations 139
6.6.1 Overview 139
6.6.2 Axis-angle 139
6.6.3 Matrix 139
6.6.4 Euler angles 140
6.6.4.1 Principal rotations 140
6.6.4.2 Euler angle conventions 140
6.6.4.3 The Euler z-x-z convention 141
6.6.4.4 Tait-Bryan angles 142
6.6.4.5 Gimbal lock 143
6.6.5 Quaternions 144
6.6.5.1 Quaternion notations and conventions 144
6.6.5.2 Quaternion algebra 145
6.6.5.3 Quaternion operators on 3D Euclidean space 145
6.6.6 Representation summary 146
6.7 Rotation representation conversions 147
6.7.1 Overview 147
6.7.2 From axis-angle to matrix 147
6.7.3 From matrix to axis-angle 147
6.7.4 From Euler angle z-x-z convention to matrix 147
6.7.5 From matrix to Euler angle z-x-z convention 148
6.7.6 From Tait-Bryan angle x-y-z convention to matrix 149
6.7.7 From matrix to Tait-Bryan angle x-y-z convention 149
6.7.8 From Tait-Bryan angle z-y-x convention to matrix 150
6.7.9 From matrix to Tait-Bryan angle z-y-x convention 150
6.7.10 From axis-angle to quaternion 151
6.7.11 From quaternion to axis-angle 151
6.7.12 From quaternion to matrix 152
6.7.13 From matrix to quaternion 152

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Documents
Document Sharing Hub

Full document details: BS ISO/IEC 18026:2025

6.7.14 From Euler angle z-x-z convention to quaternion 152
6.7.15 From quaternion to Euler angle z-x-z convention 153
6.7.16 From Tait-Bryan angle x-y-z convention to quaternion 153
6.7.17 From quaternion to Tait-Bryan angle x-y-z convention 153
6.7.18 From Tait-Bryan angle z-y-x convention to quaternion 154
6.7.19 From quaternion to Tait-Bryan angle z-y-x convention 154

7 Reference datums, embeddings, and object reference models 155
7.1 Overview 155
7.2 Reference datums 155
7.2.1 Overview 155
7.2.2 Reference datum categories 155
7.2.3 Ellipsoidal RDs 157
7.2.4 RDs associated with physical objects 159
7.2.5 RD binding 160
7.3 Normal embeddings and similarity transformations 162
7.3.1 Normal embeddings 162
7.3.2 Similarity transformations 162
7.3.3 Similarity transformation templates 165
7.3.3.1 Identity transformation 3D 167
7.3.3.2 Identity transformation 2D 167
7.3.3.3 Translation transformation 3D 168
7.3.3.4 Translation transformation 2D 168
7.3.3.5 Simplified Helmert transformation (PVR convention) 169
7.3.3.6 Simplified Helmert transformation (CFR convention) 170
7.3.3.7 Molodensky-Badekas transformation (CFR convention) 171
7.3.3.8 General rotate-scale-translate transformation 3D 172
7.3.3.9 General rotate-scale-translate transformation 2D 173
7.3.3.10 Homogeneous matrix 4x4 transformation 3D 174
7.3.3.11 Homogeneous matrix 3x3 transformation 2D 174
7.3.3.12 Generalized Helmert transformation (PVR convention) 175
7.3.3.13 Generalized Helmert transformation (CFR convention) 176
7.3.3.14 Tait-Bryan z-y-x rotate-translate transformation 177
7.3.3.15 Non-Greenwich prime meridian z rotate-translate transformation 178
7.3.3.16 Geomagnetic z-y rotate transformation 179
7.4 Object reference model 180
7.4.1 Overview 180
7.4.2 Definition 180
7.4.3 Binding constraint 182
7.4.4 ORM template 182
7.4.5 Standardized ORMs 191
7.4.6 Reference ORMs and reference transformations 191
7.4.7 ORM specifications 192
7.5 Object binding rules for ORMT BI_AXIS_ORIGIN_3D realisations 194
7.5.1 Object binding rule set 194
7.5.2 Equatorial inertial 196
7.5.3 Solar ecliptic 198
7.5.4 Solar equatorial 200
7.5.5 Heliocentric Aries ecliptic 201
7.5.6 Heliocentric planet ecliptic 202
7.5.7 Heliocentric planet equatorial 203
7.5.8 Celestiomagnetic 204
7.5.9 Solar magnetic ecliptic 205
7.5.10 Solar magnetic dipole 207

8 Spatial reference frames 209
8.1 Overview 209
8.2 Spatial reference frame structure 209

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AVA Documents Document Sharing Hub
Full document details: BS ISO/IEC 18026:2025

8.3 Spatial reference frame specification ... 210
8.3.1 SRF definition ... 210
8.3.2 SRF specification elements ... 210
8.3.2.1 ORM and CS compatibility ... 210
8.3.2.2 CS parameter binding ... 211
8.3.2.3 Coordinate-component names ... 211
8.3.2.4 Applicable region ... 211
8.4 SRF relationships ... 213
8.4.1 Overview ... 213
8.4.2 Application-based SRF relationships ... 213
8.4.3 Induced surface SRFs ... 215
8.4.4 Lococentric SRFs ... 216
8.4.5 SRFs for vector specification ... 218
8.5 SRF templates ... 219
8.5.1 Overview ... 219
8.5.2 Celestiocentric SRFT ... 222
8.5.3 Local space rectangular 3D SRFT ... 223
8.5.4 Celestiodetic SRFT ... 224
8.5.5 Planetodetic SRFT ... 225
8.5.6 Local tangent space Euclidean SRFT ... 226
8.5.7 Local tangent space azimuthal spherical SRFT ... 228
8.5.8 Local tangent space cylindrical SRFT ... 231
8.5.9 Lococentric Euclidean 3D SRFT ... 233
8.5.10 Celestiomagnetic SRFT ... 234
8.5.11 Equatorial inertial SRFT ... 235
8.5.12 Solar ecliptic SRFT ... 235
8.5.13 Solar equatorial SRFT ... 236
8.5.14 Solar magnetic ecliptic SRFT ... 236
8.5.15 Solar magnetic dipole SRFT ... 237
8.5.16 Heliospheric Aries ecliptic SRFT ... 238
8.5.17 Heliospheric Earth ecliptic SRFT ... 238
8.5.18 Heliospheric Earth equatorial SRFT ... 239
8.5.19 Mercator SRFT ... 239
8.5.20 Oblique Mercator spherical SRFT ... 240
8.5.21 Transverse Mercator SRFT ... 241
8.5.22 Lambert conformal conic SRFT ... 242
8.5.23 Polar stereographic SRFT ... 243
8.5.24 Equidistant cylindrical SRFT ... 244
8.5.25 Local space rectangular 2D SRFT ... 245
8.5.26 Local space azimuthal 2D SRFT ... 246
8.5.27 Local space polar 2D SRFT ... 246
8.6 Standardized SRFs ... 247
8.6.1 Overview ... 247
8.6.2 British national grid ... 248
8.6.3 UK ordnance survey GRS80 grid ... 249
8.6.4 Delaware (US) state plane coordinate system ... 249
8.6.5 Geocentric WGS 1984 ... 250
8.6.6 Geodetic Australia 1984 ... 250
8.6.7 Geodetic WGS 1984 ... 250
8.6.8 Geodetic North American 1983 ... 251
8.6.9 Irish Grid ... 251
8.6.10 Irish transverse Mercator ... 251
8.6.11 Lambert-93 ... 252
8.6.12 Lambert II étendu (Lambert II wide) ... 252
8.6.13 Mars planetocentric ... 253
8.6.14 Mars planetographic ... 253
8.6.15 Maryland (US) state plane coordinate system ... 254
8.7 Standardized SRF sets ... 254

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Documents
Document Sharing Hub
Full document details: BS ISO/IEC 18026:2025

8.7.1 Overview ... 254
8.7.2 Alabama (US) state plane coordinate system ... 256
8.7.3 GTRS global coordinate system (GCS) ... 257
8.7.4 Japan plane coordinate system ... 259
8.7.5 Lambert NTF ... 264
8.7.6 Universal polar stereographic ... 266
8.7.7 Universal transverse Mercator ... 267
8.7.8 Wisconsin (US) state plane coordinate system ... 269

9 Designated spatial surfaces and vertical offsets ... 271
9.1 Overview ... 271
9.2 Designated spatial surface ... 271
9.3 Vertical offset surface ... 272
9.4 Geoidal separation ... 273
9.5 Vertical offset height and elevation ... 273
9.6 Use of vertical offset height in spatial referencing ... 274
9.7 Other vertical measurements ... 274
9.8 Standardized DSS specifications ... 275

10 Operations ... 279
10.1 Overview ... 279
10.2 Symbols and terminology ... 279
10.3 ORM operations ... 280
10.3.1 Overview ... 280
10.3.2 Relating different ORMs for the same object ... 280
10.3.3 Relating ORMs for different objects ... 282
10.4 Position operations ... 283
10.4.1 Overview ... 283
10.4.2 General case ... 284
10.4.3 Matched normal embeddings ... 285
10.4.4 Matched normal embeddings and map projection SRFs ... 286
10.4.5 SRFs with Cartesian coordinate systems ... 287
10.4.6 Instantiating abstract object-space SRFs ... 289
10.5 Vector operations ... 292
10.5.1 Overview ... 292
10.5.2 Converting vectors between different vector reference frames ... 293
10.5.3 Instantiating abstract object-space vectors ... 294
10.6 Euclidean distance operation ... 295
10.7 Geodesic operations ... 295
10.7.1 Overview ... 295
10.7.2 Auxiliary functions ... 297
10.7.3 The direct problem ... 298
10.7.4 The indirect problem ... 299

11 Application program interface ... 301
11.1 Overview ... 301
11.2 Data types ... 301
11.2.1 Overview ... 301
11.2.2 SRFT abbreviated forms ... 301
11.2.3 Numbers ... 303
11.2.4 Logicals ... 303
11.2.5 Object_Reference ... 303
11.2.6 Enumerated data types ... 303
11.2.6.1 Overview ... 303
11.2.6.2 Axis_Direction_2D ... 304
11.2.6.3 Axis_Direction_3D ... 304
11.2.6.4 Interval_Type ... 305
11.2.6.5 Polar_Aspect ... 305

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Full document details: BS ISO/IEC 18026:2025

11.2.6.6 SRF_Region_Status 305
11.2.6.7 SRF_Region_Type 306
11.2.7 Selection data types 306
11.2.7.1 Overview 306
11.2.7.2 CS_Code 306
11.2.7.3 DSS_Code 306
11.2.7.4 ORM_Code 307
11.2.7.5 ORMT_Code 307
11.2.7.6 Profile_Code 307
11.2.7.7 RT_Code 307
11.2.7.8 SRF_Code 307
11.2.7.9 SRFS_Code 307
11.2.7.10 SRFS member types 307
11.2.7.11 SRFT_Code 308
11.2.7.12 Status_Code 308
11.2.7.13 STT_Code 311
11.2.8 Array data types 311
11.2.8.1 Overview 311
11.2.8.2 Coordinate2D_Array 311
11.2.8.3 Coordinate3D_Array 311
11.2.8.4 Direction_Array 312
11.2.8.5 DSS_Code_Array 312
11.2.8.6 Matrix_2x2 312
11.2.8.7 Matrix_3x3 312
11.2.8.8 Matrix_4x4 312
11.2.8.9 ORM_Code_Array 312
11.2.8.10 Profile_Code_Array 313
11.2.8.11 RT_Code_Array 313
11.2.8.12 SRF_Code_Array 313
11.2.8.13 SRF_Region_Status_Array 313
11.2.8.14 SRFS_Code_Array 313
11.2.8.15 SRFT_Code_Array 313
11.2.8.16 VectorQuantity3D_Array 314
11.2.8.17 Vector_3D 314
11.2.9 Record data types 314
11.2.9.1 Overview 314
11.2.9.2 Interval 315
11.2.9.3 ORM_Transformation_Parameters 316
11.2.9.4 Rotation and Orientation representation parameters 316
11.2.9.5 SRFT parameter record data types 317
11.2.9.6 STT parameter record data types 321
11.3 Object classes 324
11.3.1 Overview 324
11.3.2 Class specification format 326
11.3.3 LifeCycleObject 327
11.3.4 Coordinate and vector classes 328
11.3.4.1 Overview 328
11.3.4.2 Coordinate2D 329
11.3.4.3 Coordinate3D 329
11.3.4.4 Direction 329
11.3.4.5 SurfaceCoordinate 329
11.3.4.6 VectorQuantity3D 330
11.3.5 Abstract classes 330
11.3.5.1 BaseSRF 330
11.3.5.2 BaseSRF2D 332
11.3.5.3 BaseSRF3D 336
11.3.5.4 BaseSRFMapProjection 354
11.3.5.5 BaseSRFwithEllipsoidalHeight 357

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Full document details: BS ISO/IEC 18026:2025

11.3.5.6 BaseSRFwithTangentPlaneSurface 361
11.3.6 SRF concrete subclasses of BaseSRF2D 364
11.3.6.1 Overview 364
11.3.6.2 LocalSpaceAzimuthal 364
11.3.6.3 LocalSpacePolar 365
11.3.6.4 LocalSpaceRectangular2D 366
11.3.7 SRF concrete subclasses of BaseSRF3D 367
11.3.7.1 Overview 367
11.3.7.2 Celestiocentric 367
11.3.7.3 Celestiomagnetic 368
11.3.7.4 EquatorialInertial 369
11.3.7.5 HeliosphericAriesEcliptic 370
11.3.7.6 HeliosphericEarthEcliptic 371
11.3.7.7 HeliosphericEarthEquatorial 372
11.3.7.8 LocalSpaceRectangular3D 373
11.3.7.9 LococentricEuclidean3D 374
11.3.7.10 SolarEcliptic 375
11.3.7.11 SolarEquatorial 376
11.3.7.12 SolarMagneticDipole 377
11.3.7.13 SolarMagneticEcliptic 378
11.3.8 SRF concrete subclasses of BaseSRFMapProjection 379
11.3.8.1 Overview 379
11.3.8.2 EquidistantCylindrical 379
11.3.8.3 LambertConformalConic 381
11.3.8.4 Mercator 382
11.3.8.5 ObliqueMercatorSpherical 383
11.3.8.6 PolarStereographic 385
11.3.8.7 TransverseMercator 386
11.3.9 SRF concrete subclasses of BaseSRFwithEllipsoidalHeight 387
11.3.9.1 Overview 387
11.3.9.2 Celestiodetic 387
11.3.9.3 Planetodetic 389
11.3.10 SRF concrete subclasses of BaseSRFwithTangentPlaneSurface 390
11.3.10.1 Overview 390
11.3.10.2 LocalTangentSpaceAzimuthalSpherical 390
11.3.10.3 LocalTangentSpaceCylindrical 391
11.3.10.4 LocalTangentSpaceEuclidean 392
11.3.11 Rotation and Orientation classes 394
11.3.11.1 Overview 394
11.3.11.2 Rotation 394
11.3.11.3 Orientation 398
11.4 Functions 402
11.4.1 Function to create instances of standardized SRFs 402
11.4.2 Function to create instances of standardized SRF set members 403
11.4.3 Implementation support query functions 403
11.5 Data storage structures 408
11.5.1 Overview 408
11.5.2 Selection data types 408
11.5.2.1 OBRS_Code 408
11.5.2.2 RD_Code 408
11.5.2.3 Spatial_Coordinate_Code 409
11.5.2.4 SRF_Parameters_Info_Code 409
11.5.3 Record data types 410
11.5.3.1 Coordinate structures 410
11.5.3.2 Coordinate 413
11.5.3.3 SRF_Parameters_Info 414
11.5.3.4 SRF_Reference_Surface_Info 414
11.5.3.5 SRFS_Info 415

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Full document details: BS ISO/IEC 18026:2025

11.5.3.6 SRFT_Parameters 415

12 Profiles 417
12.1 Overview 417
12.2 Profile specification 417
12.3 Default profile 419

13 Registration 423
13.1 Overview 423
13.2 Specification elements for SRM registered items 423
13.2.1 Overview 423
13.2.2 Label 423
13.2.3 Code 425
13.2.4 Description 425
13.2.5 References 426
13.2.5.1 Overview 426
13.2.5.2 Citation format 426
13.3 Guidelines for specific SRM concepts 426
13.3.1 Guidelines for registration of abstract CSs 426
13.3.2 Guideline for registration of temporal CSs 427
13.3.3 Guidelines for registration of RDs 427
13.3.4 Guidelines for registration of STTs 428
13.3.5 Guidelines for registration of ORMTs 429
13.3.6 Guidelines for registration of ORMs 429
13.3.7 Guidelines for registration of RTs 430
13.3.8 Guidelines for registration of OBRSs 430
13.3.9 Guidelines for registration of SRFTs 430
13.3.10 Guidelines for registration of SRFs 432
13.3.11 Guidelines for registration of SRF sets and their members 432
13.3.12 Guidelines for registration of DSSs 434
13.3.13 Guidelines for registration of profiles 434

14 Conformance 437
14.1 Overview 437
14.2 Functional implementation conformance 437
14.2.1 Functional accuracy 437
14.2.2 Functional conformance 438
14.3 Conformance of exchange formats 439
14.4 Conformance of language bindings of the SRM API 439
14.5 Conformance of applications that use the SRM API 439
14.6 Conformance of specifications that reference this document 440

Annex A Mathematical foundations (normative) 441
A.1 Overview 441
A.2 $\mathbb{R}^n$ as a real vector space 441
A.3 The point set topology of $\mathbb{R}^n$ 442
A.4 Smooth functions on $\mathbb{R}^n$ 442
A.5 Functional composition 443
A.6 Smooth surfaces in $\mathbb{R}^3$ 443
A.6.1 Implicit definition 443
A.6.2 Ellipsoid surfaces 444
A.7 Smooth curves in $\mathbb{R}^n$ 445
A.7.1 Parametric definition 445
A.7.1.1 Smooth curve 445
A.7.1.2 Tangent to a smooth curve 445
A.7.1.3 Angle between curves 446
A.7.1.4 Closed curve 446
A.7.1.5 Surface curves, connected and orientable surfaces 446

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Documents
Document Sharing Hub
Full document details: BS ISO/IEC 18026:2025

A.7.2 Implicit definition 447
A.7.3 Arc length 448
A.7.4 Geodesics on an ellipsoid 448
A.8 Special functions 448
A.8.1 Double argument arctangent function 448
A.8.2 Jacobian elliptic functions 449
A.9 Projection function 449
A.9.1 Geometric projection functions into a developable surface 449
A.9.2 Planar projection functions 449
A.9.2.1 Orthographic projection function 449
A.9.2.2 Perspective projection function 450
A.9.2.3 Stereographic projection function 451
A.9.3 Cylindrical projection function 451
A.9.4 Conic projection function 452
A.10 Quaternion algebra 452
A.11 Body-fixed rotations in terms of space-fixed axes 453
A.12 Rotation and change of basis equivalence 455

Annex B Implementation guidelines (informative) 459
B.1 Overview 459
B.2 Error types considered in this document 459
B.2.1 Measurement and modelling error 459
B.2.2 Implementation error 460
B.2.3 Finite precision 460
B.2.4 Approximation error 460
B.3 General observations on implementations 461
B.4 Guidelines for algorithm development for spatial operations 461
B.4.1 Overview 461
B.4.2 The computational environment 461
B.4.3 Domain of application 462
B.4.4 Define a meaningful error measure 463
B.4.5 Avoid excessive computational accuracy 463
B.4.6 Determine the acceptable error before starting 463
B.4.7 Mathematical approaches 463
B.4.8 Good programming and formulation practices 464
B.4.9 Design in context 465
B.4.10 Software verification and computational error testing 465
B.4.11 Singularities and near singularities 466
B.4.12 Performance testing 466
B.5 Practical considerations 467
B.5.1 Distortion considerations 467
B.5.2 Validity checking 467
B.5.3 Spherical ORMs 467

Annex C Hierarchical diagrams for SRM concepts (informative) 469
C.1 Overview 469
C.2 SRM concepts 469
C.3 Reference datum hierarchy 469
C.4 ORM template realisation examples 470

Annex D RDs associated with physical objects (normative) 473
D.1 Overview 473
D.2 RDs 473

Annex E ORM specifications (normative) 489
E.1 Overview 489
E.2 ORMs 489

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AVA Documents Document Sharing Hub
Full document details: BS ISO/IEC 18026:2025

E.2.1 Reference ORMs ... 489
E.2.2 Standardized ORMs ... 493
E.2.2.1 Abstract ORMs ... 494
E.2.2.2 Object-fixed ERMs ... 495
E.2.2.3 Dynamic ERMs ... 593
E.2.2.4 Object-fixed planet (non-Earth) ORMs ... 602
E.2.2.5 Dynamic planet (non-Earth) ORMs ... 609
E.2.2.6 Object-fixed satellite ORMs ... 613
E.2.2.7 Dynamic satellite ORMs ... 632
E.2.2.8 Object-fixed stellar ORMs ... 632
E.2.2.9 Dynamic stellar ORMs ... 633

Annex F Abbreviated forms used in the construction of labels (normative) ... 635
F.1 Overview ... 635
F.2 Table of abbreviated forms ... 635

Annex G Change and deprecation plan (normative) ... 637
G.1 Overview ... 637
G.2 Addition ... 637
G.3 Change ... 637
G.3.1 Overview ... 637
G.3.2 Correction ... 638
G.3.3 Update ... 638
G.4 Deprecation ... 638
G.4.1 Overview ... 638
G.4.2 Deprecation of SRM standardized concept instances ... 638
G.4.3 Deprecation of SRM registered items ... 639
G.5 Reinstatement ... 639
G.5.1 Overview ... 639
G.5.2 Reinstatement of SRM standardized concept instances ... 639
G.5.3 Reinstatement of SRM registered items ... 639

Annex H Templates for registration proposals (normative) ... 641
H.1 Overview ... 641
H.2 Proposal for the registration of a CS ... 641
H.3 Proposal for the registration of a temporal CS ... 642
H.4 Proposal for the registration of an RD ... 642
H.5 Proposal for the registration of an STT ... 643
H.6 Proposal for the registration of an ORMT ... 643
H.7 Proposal for the registration of an ORM ... 644
H.8 Proposal for the registration of a reference transformation ... 644
H.9 Proposal for the registration of an OBRS ... 645
H.10 Proposal for the registration of an SRFT ... 645
H.11 Proposal for the registration of an SRF ... 646
H.12 Proposal for the registration of an SRF set and its members ... 646
H.13 Proposal for the registration of a DSS ... 647
H.14 Proposal for the registration of a profile ... 647
H.15 Proposal for the registration of a reference ... 648

Annex I Conformance testing for SRF operations (informative) ... 649
I.1 Overview ... 649
I.2 Computational error ... 649
I.3 SRF operations baseline ... 649
I.4 Implementations ... 649
I.5 Fundamental measure of conformance ... 650
I.6 Error metrics for SRF operations ... 650
I.7 Computational error evaluated over test data sets ... 652
I.8 Level of conformance ... 652

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Document Sharing Hub
Full document details: BS ISO/IEC 18026:2025

Annex J Deprecated SRM concept instances (normative) 655
J.1 Overview 655
J.2 Deprecated RDs 655
J.3 Deprecated ORMs 661
J.4 Deprecated DSSs 689

Bibliography 691

Index 697

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AVA Documents Document Sharing Hub

Full document details: BS ISO/IEC 18026:2025

Tables

Page

Table 3.1 — Mathematical notation 6
Table 3.2 — Symbols 6
Table 3.3 — Abbreviated terms 9

Table 4.1 — Coordinate system types 18

Table 5.1 — Coordinate system types 38
Table 5.2 — Localization operators 45
Table 5.3 — Localization inverse operators 45
Table 5.4 — Localized CS type relationships 46
Table 5.5 — Coordinate system specification elements 61
Table 5.6 — Common parameters and functions of an oblate ellipsoid 62
Table 5.7 — CS specification directory 63
Table 5.8 — Euclidean 3D CS 64
Table 5.9 — Lococentric Euclidean 3D CS 65
Table 5.10 — Equatorial Spherical CS 67
Table 5.11 — Lococentric Equatorial Spherical CS 68
Table 5.12 — Azimuthal Spherical CS 70
Table 5.13 — Lococentric Azimuthal Spherical CS 72
Table 5.14 — Geodetic 3D CS 73
Table 5.15 — Planetodetic 3D CS 76
Table 5.16 — Cylindrical CS 77
Table 5.17 — Lococentric Cylindrical CS 79
Table 5.18 — Mercator CS 80
Table 5.19 — Oblique Mercator Spherical CS 82
Table 5.20 — Transverse Mercator CS 85
Table 5.21 — Lambert Conformal Conic CS 89
Table 5.22 — Polar Stereographic CS 91
Table 5.23 — Equidistant Cylindrical CS 93
Table 5.24 — Surface Geodetic CS 95
Table 5.25 — Surface Planetodetic CS 96
Table 5.26 — Lococentric Surface Euclidean CS 98
Table 5.27 — Lococentric Surface Azimuthal CS 100
Table 5.28 — Lococentric Surface Polar CS 101
Table 5.29 — Euclidean 2D CS 103
Table 5.30 — Lococentric Euclidean 2D CS 104
Table 5.31 — Azimuthal CS 106
Table 5.32 — Lococentric Azimuthal CS 107
Table 5.33 — Polar CS 109
Table 5.34 — Lococentric Polar CS 110
Table 5.35 — Euclidean 1D CS 112
Table 5.36 — Azimuthal Cylindrical CS 113
Table 5.37 — Lococentric Azimuthal Cylindrical CS 114
Table 5.38 — Temporal coordinate system specification elements 119
Table 5.39 — Temporal coordinate system specifications 120

Table 6.1 — Principal rotation matrices 136
Table 6.2 — Rotation and change-of-basis operators 137
Table 6.3 — Summary of representation attributes 146
Table 6.4 — Principal rotation factors for the Euler angle z-x-z convention 148
Table 6.5 — Equivalence of z-x-z principal rotation factor sequences 149
Table 6.6 — Principal rotation factors for the Tait-Bryan angle x-y-z convention 149
Table 6.7 — Principal rotation factors for the Tait-Bryan angle z-y-x convention 150
Table 6.8 — Equivalence of x-y-z or z-y-x principal rotation factor sequences 151

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Documents
Document Sharing Hub
Full document details: BS ISO/IEC 18026:2025

Table 7.1 — RD categories 156
Table 7.2 — RD specification elements 156
Table 7.3 — RD specification directory 156
Table 7.4 — 2D RDs of category point 157
Table 7.5 — 3D RDs of category point 157
Table 7.6 — 2D RDs of category directed curve 157
Table 7.7 — 3D RDs of category directed curve 157
Table 7.8 — 3D RDs of category oriented surface 157
Table 7.9 — Physical object RD specification elements 159
Table 7.10 — Physical RD specification table locations 160
Table 7.11 — STT specification elements 166
Table 7.12 — Similarity transformation template directory 166
Table 7.13 — Identity 3D STT 167
Table 7.14 — Identity 2D STT 167
Table 7.15 — Translation 3D STT 168
Table 7.16 — Translation 2D STT 168
Table 7.17 — Simplified Helmert STT (PVR convention) 169
Table 7.18 — Simplified Helmert STT (CFR convention) 170
Table 7.19 — Molodensky-Badekas STT (CFR convention) 171
Table 7.20 — General rotate-scale-translate 3D STT 172
Table 7.21 — General rotate-scale-translate 2D STT 173
Table 7.22 — Homogeneous matrix 4x4 3D STT 174
Table 7.23 — Homogeneous matrix 3x3 2D STT 174
Table 7.24 — Generalized Helmert STT (PVR convention) 175
Table 7.25 — Generalized Helmert STT (CFR convention) 176
Table 7.26 — Tait-Bryan z-y-x rotate-translate STT 177
Table 7.27 — Non-Greenwich prime meridian z rotate-translate STT 178
Table 7.28 — Geomagnetic z-y rotate STT 179
Table 7.29 — ORMT specification elements 183
Table 7.30 — ORMT specification directory 183
Table 7.31 — 2D ORMT specifications 184
Table 7.32 — 3D ORMT specifications 185
Table 7.33 — ORM specification elements 192
Table 7.34 — Reference transformation specification elements 193
Table 7.35 — OBRS for ORMT BI_AXIS_ORIGIN_3D specification elements 195
Table 7.36 — OBRS for ORMT BI_AXIS_ORIGIN_3D specification directory 195
Table 7.37 — Equatorial inertial OBRS 196
Table 7.38 — Equatorial inertial ORM directory 198
Table 7.39 — Solar ecliptic OBRS 198
Table 7.40 — Solar ecliptic ORM directory 199
Table 7.41 — Solar equatorial OBRS 200
Table 7.42 — Solar equatorial ORM directory 200
Table 7.43 — Heliocentric Aries ecliptic OBRS 201
Table 7.44 — Heliocentric Aries ecliptic ORM directory 202
Table 7.45 — Heliocentric planet ecliptic OBRS 202
Table 7.46 — Heliocentric planet ecliptic ORM directory 202
Table 7.47 — Heliocentric planet equatorial OBRS 203
Table 7.48 — Heliocentric planet equatorial ORM directory 203
Table 7.49 — Celestiomagnetic OBRS 204
Table 7.50 — Celestiomagnetic ORM directory 205
Table 7.51 — Solar magnetic ecliptic OBRS 205
Table 7.52 — Solar magnetic ecliptic ORM directory 206
Table 7.53 — Solar magnetic dipole OBRS 207
Table 7.54 — Solar magnetic dipole ORM directory 208

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AVA Documents Document Sharing Hub
Full document details: BS ISO/IEC 18026:2025

Table 8.1 — Compatible CS types 210
Table 8.2 — SRFT specification elements 220
Table 8.3 — SRFT directory 221
Table 8.4 — Celestiocentric SRFT 222
Table 8.5 — Local space rectangular 3D SRFT 223
Table 8.6 — Celestiodetic SRFT 224
Table 8.7 — Planetodetic SRFT 225
Table 8.8 — Local tangent space Euclidean SRFT 226
Table 8.9 — Local tangent space azimuthal spherical SRFT 228
Table 8.10 — Local tangent space cylindrical SRFT 231
Table 8.11 — Lococentric Euclidean 3D SRFT 233
Table 8.12 — Celestiomagnetic SRFT 234
Table 8.13 — Equatorial inertial SRFT 235
Table 8.14 — Solar ecliptic SRFT 235
Table 8.15 — Solar equatorial SRFT 236
Table 8.16 — Solar magnetic ecliptic SRFT 236
Table 8.17 — Solar magnetic dipole SRFT 237
Table 8.18 — Heliospheric Aries ecliptic SRFT 238
Table 8.19 — Heliospheric Earth ecliptic SRFT 238
Table 8.20 — Heliospheric Earth equatorial SRFT 239
Table 8.21 — Mercator SRFT 239
Table 8.22 — Oblique Mercator spherical SRFT 240
Table 8.23 — Transverse Mercator SRFT 241
Table 8.24 — Lambert conformal conic SRFT 242
Table 8.25 — Polar stereographic SRFT 243
Table 8.26 — Equidistant cylindrical SRFT 244
Table 8.27 — Local space rectangular 2D SRFT 245
Table 8.28 — Local space azimuthal 2D SRFT 246
Table 8.29 — Local space polar 2D SRFT 247
Table 8.30 — Standardized SRF specification elements 247
Table 8.31 — Directory of standardized SRFs 248
Table 8.32 — British national grid SRF 248
Table 8.33 — UK ordnance survey GRS80 grid SRF 249
Table 8.34 — Delaware (US) state plane coordinate system SRF 249
Table 8.35 — Geocentric WGS 1984 SRF 250
Table 8.36 — Geodetic Australia 1984 SRF 250
Table 8.37 — Geodetic WGS 1984 SRF 250
Table 8.38 — Geodetic North American 1983 SRF 251
Table 8.39 — Irish Grid SRF 251
Table 8.40 — Irish transverse Mercator SRF 251
Table 8.41 — Lambert-93 SRF 252
Table 8.42 — Lambert II étendu (Lambert II wide) SRF 252
Table 8.43 — Mars planetocentric SRF 253
Table 8.44 — Mars planetographic SRF 253
Table 8.45 — Maryland (US) state plane coordinate system SRF 254
Table 8.46 — SRF set specification elements 255
Table 8.47 — SRF set member specification elements 255
Table 8.48 — Directory of SRF sets 256
Table 8.49 — Alabama (US) state plane coordinate system SRF set 256
Table 8.50 — SRF set membership Alabama (US) state plane coordinate system 256
Table 8.51 — GTRS global coordinate system (GCS) SRF set 257
Table 8.52 — SRF set membership GTRS global coordinate system (GCS) 258
Table 8.53 — GTRS natural origin and applicable region by code index 258
Table 8.54 — Japan plane coordinate system SRF set 259
Table 8.55 — SRF set membership Japan plane coordinate system 260
Table 8.56 — Lambert NTF SRF set 264
Table 8.57 — SRF set membership Lambert NTF 265
Table 8.58 — Universal polar stereographic (UPS) SRF set 266

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Document Sharing Hub

Full document details: BS ISO/IEC 18026:2025

Table 8.59 — SRF set membership Universal polar stereographic (UPS) 266
Table 8.60 — Universal transverse Mercator (UTM) SRF set 267
Table 8.61 — SRF set membership Universal transverse Mercator (UTM) 268
Table 8.62 — Wisconsin (US) state plane coordinate system SRF set 269
Table 8.63 — SRF set membership Wisconsin (US) state plane coordinate 269

Table 9.1 — Geoidal and equipotential DSS specification elements 276
Table 9.2 — Geoidal and equipotential DSS specifications 276

Table 10.1 — Symbols 279

Table 11.1 — SRFT abbreviated forms 302
Table 11.2 — Integer data types 303
Table 11.3 — Logical data type 303
Table 11.4 — Array data type notation 311
Table 11.5 — Class specification elements 326
Table 11.6 — LifeCycleObject 327
Table 11.7 — Coordinate2D 329
Table 11.8 — Coordinate3D 329
Table 11.9 — Direction 329
Table 11.10 — SurfaceCoordinate 329
Table 11.11 — VectorQuantity3D 330
Table 11.12 — BaseSRF 332
Table 11.13 — BaseSRF2D 333
Table 11.14 — BaseSRF3D 339
Table 11.15 — BaseSRFMapProjection 355
Table 11.16 — BaseSRFwithEllipsoidalHeight 358
Table 11.17 — BaseSRFwithTangentPlaneSurface 362
Table 11.18 — LocalSpaceAzimuthal 364
Table 11.19 — LocalSpacePolar 365
Table 11.20 — LocalSpaceRectangular2D 366
Table 11.21 — Celestiocentric 367
Table 11.22 — Celestiomagnetic 368
Table 11.23 — EquatorialInertial 369
Table 11.24 — HeliosphericAriesEcliptic 370
Table 11.25 — HeliosphericEarthEcliptic 371
Table 11.26 — HeliosphericEarthEquatorial 372
Table 11.27 — LocalSpaceRectangular3D 373
Table 11.28 — LococentricEuclidean3D 374
Table 11.29 — SolarEcliptic 375
Table 11.30 — SolarEquatorial 376
Table 11.31 — SolarMagneticDipole 377
Table 11.32 — SolarMagneticEcliptic 378
Table 11.33 — EquidistantCylindrical 379
Table 11.34 — LambertConformalConic 381
Table 11.35 — Mercator 382
Table 11.36 — ObliqueMercatorSpherical 383
Table 11.37 — PolarStereographic 385
Table 11.38 — TransverseMercator 386
Table 11.39 — Celestiodetic 387
Table 11.40 — Planetodetic 389
Table 11.41 — LocalTangentSpaceAzimuthalSpherical 390
Table 11.42 — LocalTangentSpaceCylindrical 391
Table 11.43 — LocalTangentSpaceEuclidean 392
Table 11.44 — Rotation 394
Table 11.45 — Orientation 398
Table 11.46 — CreateStandardizedSRF 402
Table 11.47 — CreateStandardizedSRFSetMember 403

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Documents
Document Sharing Hub
Full document details: BS ISO/IEC 18026:2025

Table 11.48 — QueryDSSSupport ... 404
Table 11.49 — QueryDSSSupportList ... 404
Table 11.50 — QueryRTRegionSpecification ... 404
Table 11.51 — QueryORMSupport ... 405
Table 11.52 — QueryORMSupportList ... 405
Table 11.53 — QueryProfileSupport ... 406
Table 11.54 — QueryProfileSupportList ... 406
Table 11.55 — QueryRTSupportList ... 406
Table 11.56 — QuerySRFSetSupport ... 406
Table 11.57 — QuerySRFSetSupportList ... 407
Table 11.58 — QuerySRFSupport ... 407
Table 11.59 — QuerySRFSupportList ... 407
Table 11.60 — QuerySRFTSupport ... 407
Table 11.61 — QuerySRFTSupportList ... 408
Table 11.62 — QueryVersion ... 408

Table 12.1 — SRM profile specification elements ... 417
Table 12.2 — Default profile specification ... 419

Table D.1 — RD specification directory ... 473
Table D.2 — Oblate ellipsoid RD specifications ... 474
Table D.3 — Sphere RD specifications ... 479
Table D.4 — Prolate ellipsoid RD specifications ... 483
Table D.5 — Tri-axial ellipsoid RD specifications ... 483

Table E.1 — Reference ORM directory ... 489
Table E.2 — ORM specification directory ... 493
Table E.3 — Abstract ORM specifications ... 494
Table E.4 — Abstract ORM reference transformation specifications ... 494
Table E.5 — Object-fixed ERM specifications ... 495
Table E.6 — Object-fixed ERM reference transformation specifications ... 521
Table E.7 — Dynamic ERM specifications ... 593
Table E.8 — Time-fixed instances of dynamic ERM specifications ... 594
Table E.9 — Time-fixed instances of dynamic ERM reference transformation specifications ... 599
Table E.10 — Object-fixed planet (non-Earth) ORM specifications ... 602
Table E.11 — Object-fixed planet (non-Earth) ORM reference transformation specifications ... 607
Table E.12 — Dynamic planet (non-Earth) ORM specifications ... 609
Table E.13 — Time-fixed instances of dynamic planet (non-Earth) ORM specifications ... 611
Table E.14 — Time-fixed instances of dynamic planet (non-Earth) ORM reference transformation specifications ... 612
Table E.15 — Object-fixed satellite ORM specifications ... 613
Table E.16 — Object-fixed satellite ORM reference transformation specifications ... 625
Table E.17 — Time-fixed instances of dynamic satellite ORM specifications ... 632
Table E.18 — Time-fixed instances of dynamic satellite ORM reference transformation specifications ... 632
Table E.19 — Object-fixed stellar ORM specifications ... 632
Table E.20 — Object-fixed stellar ORM reference transformation specifications ... 632
Table E.21 — Dynamic stellar ORM specifications ... 633
Table E.22 — Time-fixed instances of dynamic stellar ORM specifications ... 633
Table E.23 — Time-fixed instances of dynamic stellar ORM reference transformation specifications ... 633

Table F.1 — Abbreviated forms used in labels ... 635

Table H.1 — Common registration proposal specification elements ... 641
Table H.2 — Coordinate system registration proposal elements ... 641
Table H.3 — Temporal coordinate system registration proposal elements ... 642
Table H.4 — RD registration proposal elements ... 642
Table H.5 — Similarity transformation template registration proposal elements ... 643
Table H.6 — ORMT registration proposal elements ... 643

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Document Sharing Hub

Full document details: BS ISO/IEC 18026:2025

Table H.7 — ORM registration proposal elements 644
Table H.8 — RT registration proposal elements 644
Table H.9 — OBRS registration proposal elements 645
Table H.10 — SRFT registration proposal elements 645
Table H.11 — SRF registration proposal elements 646
Table H.12 — SRF set registration proposal elements 646
Table H.13 — SRF set member registration proposal elements 647
Table H.14 — DSS registration proposal elements 647
Table H.15 — Profile registration proposal elements 647
Table H.16 — Reference registration proposal elements 648

Table J.1 — Deprecated RD specification directory 655
Table J.2 — Deprecated oblate ellipsoid RDs 656
Table J.3 — Deprecated sphere RDs 656
Table J.4 — Deprecated prolate ellipsoid RDs 657
Table J.5 — Deprecated tri-axial ellipsoid RDs 658
Table J.6 — Deprecated ORM specification directory 661
Table J.7 — Deprecated abstract object ORMs 661
Table J.8 — Deprecated object-fixed ERMs 661
Table J.9 — Deprecated dynamic ERMs 661
Table J.10 — Deprecated time-fixed instances of dynamic ERMs 662
Table J.11 — Deprecated time-fixed instances of dynamic ERM RTs 665
Table J.12 — Deprecated object-fixed planet (non-Earth) ORMs 667
Table J.13 — Deprecated object-fixed planet (non-Earth) RTs 669
Table J.14 — Deprecated dynamic planet (non-Earth) ORMs 671
Table J.15 — Deprecated time-fixed instances of dynamic planet (non-Earth) ORMs 671
Table J.16 — Deprecated object-fixed satellite ORMs 672
Table J.17 — Deprecated object-fixed satellite RTs 682
Table J.18 — Deprecated dynamic satellite ORMs 687
Table J.19 — Deprecated time-fixed instances of dynamic satellite ORMs 687
Table J.20 — Deprecated object-fixed stellar ORMs 688
Table J.21 — Deprecated object-fixed stellar RTs 688
Table J.22 — Deprecated dynamic stellar ORMs 689
Table J.23 — Deprecated time-fixed instances of dynamic stellar ORMs 689
Table J.24 — Deprecated DSSs 689

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Full document details: BS ISO/IEC 18026:2025

Figures

Page

Figure 4.1 — Coordinate-space, position-space, and object-space relationships 14
Figure 4.2 — A coordinate-space (for spherical coordinates) 15
Figure 4.3 — 3D position-space and its canonical Cartesian basis 16
Figure 4.4 — Object-spaces for the Earth and for a CAD model 16
Figure 4.5 — Abstract equatorial spherical coordinate system example 17
Figure 4.6 — A normal embedding of an abstract coordinate system 19
Figure 4.7 — An ellipsoid reference datum 21
Figure 4.8 — Reference datums bound to abstract and physical objects 22
Figure 4.9 — A reference datum binding 23
Figure 4.10 — An object reference model 24
Figure 4.11 — A vertical offset surface for ellipsoidal height 27
Figure 4.12 — Change of spatial reference frame operation applied to a coordinate 28

Figure 5.1 — A coordinate-space (including the domain for spherical coordinate n-tuples) 32
Figure 5.2 — A right-handed orthonormal frame 32
Figure 5.3 — 3D position-space, its orthonormal frame, and its canonical Cartesian basis 33
Figure 5.4 — Object-spaces for the Earth and for a CAD model 34
Figure 5.5 — A normal embedding that maps position-space to an object-space 35
Figure 5.6 — Two distinct normal embeddings that map position-space to an object-space 36
Figure 5.7 — Abstract equatorial spherical coordinate system example 38
Figure 5.8 — Polar CS geometry 39
Figure 5.9 — The Polar CS generating function 39
Figure 5.10 — The geodetic coordinate system geometric and trigonometric relationships 40
Figure 5.11 — Surface geodetic CS geometric and trigonometric relationships 40
Figure 5.12 — Geodetic 3D CS geometry, and coordinate-component surface and curves 43
Figure 5.13 — Induced surface CS with localization 47
Figure 5.14 — Lococentric Euclidean CS on a local tangent plane 49
Figure 5.15 — Lococentric azimuthal spherical CS on a local tangent plane 50
Figure 5.16 — A map projection generating function 52
Figure 5.17 — Geodetic azimuths $\boldsymbol{\alpha_1}$ from $\boldsymbol{p_1}$ to $\boldsymbol{p_2}$ 55
Figure 5.18 — Convergence of the meridian 56
Figure 5.19 — Polar Stereographic map projection 57
Figure 5.20 — Tangent and secant cylindrical map projections 58
Figure 5.21 — Tangent and secant conical map projections 59
Figure 5.22 — Vertical distortion 60
Figure 5.23 — Coordinate-space, position-space, and object-space relationships 116
Figure 5.24 — A spatial CS of type surface 117
Figure 5.25 — Two spatial coordinate systems for the same object-space 117

Figure 6.1 — Change of basis relationships 122
Figure 6.2 — Rotation operator applied to a point, a line segment, and a 3D object 127
Figure 6.3 — Origin-fixed rotation 128
Figure 6.4 — Consecutive rotation operations: axis n followed by axis m 129
Figure 6.5 — Consecutive rotation operations: axis m followed by axis n 130
Figure 6.6 — Space-fixed, body-fixed, and space-fixed equivalent of body-fixed conventions 131
Figure 6.7 — Space-fixed convention 132
Figure 6.8 — Body-fixed convention 132
Figure 6.9 — Space-fixed equivalent of body-fixed convention 133
Figure 6.10 — Rotation of a position-vector within an orthonormal frame 134
Figure 6.11 — Rotation of the basis vectors in the same direction as the position-vector 135
Figure 6.12 — Euler z-x-z convention rotation sequence 142
Figure 6.13 — Tait-Bryan angles 143

Figure 7.1 — Oblate and prolate ellipsoids 158
Figure 7.2 — An ellipsoid reference datum 160

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Full document details: BS ISO/IEC 18026:2025

Figure 7.3 — Two RDs bound to an abstract object and to a physical object 161
Figure 7.4 — A reference datum binding 162
Figure 7.5 — 3D normal embedding relationships 163
Figure 7.6 — Oblate ellipsoid ORMT binding 181

Figure 8.1 — The components of a spatial reference frame 209
Figure 8.2 — Examples of SRF relationships 215
Figure 8.3 — Coordinate-space, position-space, and object-space directions compared 219
Figure 8.4 — Local tangent space Euclidean SRFT 228
Figure 8.5 — Local tangent space azimuthal spherical SRFT 230
Figure 8.6 — Local tangent space cylindrical SRFT 233

Figure 9.1 — Vertical offset surface for ellipsoidal height 272
Figure 9.2 — Vertical offset surface tangent plane 273
Figure 9.3 — Geoidal separation 273
Figure 9.4 — Vertical coordinate-component with respect to a vertical offset surface 274
Figure 9.5 — Orthometric height 275

Figure 10.1 — Composed transformations for a single object 281
Figure 10.2 — Composed transformations for two different objects 282
Figure 10.3 — Change of SRF operation – applied to coordinates 284
Figure 10.4 — Change of SRF operation for Lococentric Euclidean 3D SRFs 288
Figure 10.5 — Abstract object realised in another abstract object-space 291
Figure 10.6 — Abstract object realised using a geodetic reference point 291
Figure 10.7 — Abstract object realised using a geocentric reference point 292
Figure 10.8 — Four examples of geodesic segments 296

Figure 11.1 — Class inheritance hierarchy summary 325
Figure 11.2 — BaseSRF class hierarchy 331
Figure 11.3 — BaseSRF2D class hierarchy 333
Figure 11.4 — BaseSRF3D class hierarchy 338
Figure 11.5 — BaseSRFMapProjection class hierarchy 355
Figure 11.6 — BaseSRFwithEllipsoidalHeight class hierarchy 357
Figure 11.7 — BaseSRFwithTangentPlaneSurface class hierarchy 362

Figure A.1 — Tangent to a curve 445
Figure A.2 — Angle between two curves 446
Figure A.3 — Tangent plane to a surface 447
Figure A.4 — Orthographic projection 450
Figure A.5 — Perspective projection 450
Figure A.6 — Stereographic projection 451
Figure A.7 — Cylindrical projection 452
Figure A.8 — Conic projection 452

Figure C.1 — SRM concepts and their relationships 469
Figure C.2 — Reference datum hierarchy 470
Figure C.3 — Sphere-based ORM template realisation example 471
Figure C.4 — Oblate ellipsoid-based ORM template realisation example 471
Figure C.5 — Object-dynamic ORM template realisation example 472

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Foreword

ISO (the International Organization for Standardization) and IEC (the International Electrotechnical Commission) form the specialized system for worldwide standardization. National bodies that are members of ISO or IEC participate in the development of International Standards through technical committees established by the respective organization to deal with particular fields of technical activity. ISO and IEC technical committees collaborate in fields of mutual interest. Other international organizations, governmental and non-governmental, in liaison with ISO and IEC, also take part in the work.

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This document was prepared by Joint Technical Committee ISO/IEC JTC 1, Information technology, Subcommittee SC 24, Computer graphics, image processing and environmental data representation, in collaboration with The SEDRIS Organization.

This third edition cancels and replaces the second edition (ISO/IEC 18026:2009) which has been technically revised.

The main changes are as follows:

1) Comprehensive and improved treatment of geodesics
2) Similarity transformation templates (STT)
3) Revisions to *Clause 12 Profiles* and *Clause 14 Conformance*, as well as informative Annex I.6 to cover positional error measurement cases
4) Improved accuracy domains in the Default Profile
5) Incorporation of a new *Clause 6 Orientation – change of basis and rotation*
6) Revision to *Clause 5 Coordinate Systems*, *Clause 8 Spatial Reference Frames*, and *Clause 10 Operations*
7) Other improvements throughout the standard, including editorial and self-consistency improvements, incorporation of new figures, and correction of defects.

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0 Introduction

0.1 Purpose

Spatial information processing requires a robust capability to describe geometric properties such as position, direction, orientation, and distance. Information is sometimes spatially referenced to local structures (Example: interior walls and doorways within a building) or local regions (Example: streets and buildings within a city), or to the Earth as a whole (Example: global weather). Information is sometimes spatially referenced to other celestial bodies (Examples: astronomical, orbital, and geomagnetic observations). Information is also sometimes spatially referenced to objects defined within contexts such as virtual realities (Example: 3D models). In each of these cases, a spatial reference frame is defined, with respect to which the values of geometric properties can be determined.

It is often necessary to represent a position in several different spatial reference frames, simultaneously, according to the context in which the position is to be used. Each spatial reference frame corresponds to a particular way of expressing position. Spatial reference frames are sometimes specified relative to moving objects (Examples: planets and spacecraft), and therefore provide spatial values that are a function of time. It is necessary to specify the time to which the spatial position refers, and the time for which the spatial reference frame is defined.

This document defines the conceptual model and the methodologies that allow the description, and transformation or conversion, of geometric properties within or among spatial reference frames. The Spatial Reference Model (SRM) supports unambiguous specification of the positions, directions, orientations, distances, and times associated with spatial information. It also defines algorithms for precise transformation of positions, directions, orientations, and distances among different spatial reference frames.

0.2 Design criteria

The concepts in this document were developed to fulfil the following requirements:

a) *Unification*: Define a comprehensive set of general principles and specific concepts that allow spatial information to be shared among different communities.

b) *Unambiguity*: Provide for the unambiguous specification of spatial concepts and the spatial relationships among geometric objects.

c) *Extensibility*: Provide a framework under which future spatial concepts can be accommodated through registration of new concepts.

d) *Completeness*: Specify a broad set of well-defined spatial reference frames, their parameter sets, and spatial operations.

e) *Implementability*: Define an application program interface supporting spatial reference frames and spatial operations.

f) *Mathematical formulation explicitness:* Provide mathematical formulations to support conformance testing.

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Information technology — Spatial Reference Model (SRM)

1 Scope

This document specifies the Spatial Reference Model (SRM) defining relevant aspects of spatial positioning and related information processing. The SRM allows precise and unambiguous specification of geometric properties such as position, direction, orientation, and distance. The SRM addresses the needs of a broad community of users, who have a range of accuracy and performance requirements in computationally intensive applications.

Aspects of this document apply to, but are not limited to:

a) mapping, charting, geodesy, and imagery;

b) topography;

c) location-based services;

d) oceanography;

e) meteorology and climatology;

f) interplanetary and planetary sciences;

g) embedded systems; and

h) modelling and simulation.

The SRM specifies an application program interface (API) that supports the representations, conversion, and transformation of position and orientation information in a variety of forms. To ensure that spatial operations are performed consistently, the application program interface specifies conversion operations between alternative representations of geometric properties.

This document is not intended to replace the standards and specifications developed by ISO/TC 211, ISO/TC 184, the International Astronomical Union (IAU), and the International Association of Geodesy (IAG). It is applicable to applications whose spatial information requirements overlap two or more of the application areas that are the scope of the work of ISO/TC 211, ISO/TC 184, the IAU, and the IAG.

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2 Normative references

The following documents are referred to in the text in such a way that some or all their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE Because citations to International Standards are made by giving the number of the standard followed by the year (if applicable) and any other specific information identifying the portion of the standard cited, identifiers are not needed for this purpose. Therefore, the identifier element is grey when a reference is an International Standard.

Identifier	Reference
	ISO 8601, *Data elements and interchange formats — Information interchange — Representation of dates and times*.
	ISO/IEC 9973, *Information technology — Computer graphics, image processing and environmental data representation — Procedures for registration of items.*
	ISO/IEC/IEEE 60559, *Information technology — Microprocessor Systems — Floating-Point arithmetic.*
	ISO 80000-2, *Quantities and units — Part 2: Mathematical signs and symbols to be used in the natural sciences and technology.*
	ISO 80000-3, *Quantities and units — Part 3: Space and time.*
I460	International Telecommunication Union (ITU). *Standard-Frequency and Time-Signal Emissions*. Online. ITU document ITU-R TF.460-6:2002. Geneva: ITU, 2002. Available from: https://www.itu.int/rec/R-REC-TF.460-6-200202-I/en [viewed 2022-08-25].
83502T	US National Geospatial-Intelligence Agency (NGA). *Department of Defense World Geodetic System 1984 - Its Definition and Relationships with Local Geodetic Systems*. Online. Third Ed. Technical report TR 8350.2. Washington: NGA, 2000. Available from: https://apps.dtic.mil/sti/citations/ADA280358 [viewed 2023-05-07].
NGA36	US National Geospatial-Intelligence Agency (NGA). *Department of Defense World Geodetic System 1984 - Its Definition and Relationships with Local Geodetic Systems*. Online. Version 1.0.0. Available from: https://nsgreg.nga.mil/doc [viewed 2022-08-25].

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3 Terms, definitions, symbols, and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at https://www.iso.org/obp
- IEC Electropedia: available at https://www.electropedia.org

3.1.1
Earth gravitational model
spherical harmonic expansion of the gravitational field potential

Note 1 to entry: Gravity includes rotational effects; however, such rotational effects are not included in this model.

3.1.2
ecliptic plane
plane defined by the orbit of a planet at a point in time

3.1.3
equatorial plane
plane through a designated centre of an object and perpendicular to the rotational axis of the object

3.1.4
geodetic datum
datum (or reference frame) describing the relationship of a 2- or 3-dimensional coordinate system to the Earth

Note 1 to entry: ISO 19111:2019 uses the term *geodetic reference frame*.

Note 2 to entry: In most cases, the geodetic datum includes an ellipsoid definition.

[SOURCE: ISO 19111:2019, 3.1.34]

3.1.5
north pole
that pole of rotation that lies on the north side of the invariable plane of the solar system

Note 1 to entry: Some planets have retrograde rotation with respect to this definition.

Note 2 to entry: Map north (see 5.3.7.1) may be unrelated to this direction.

Note 3 to entry: The north side of the invariable plane of the solar system is the side facing in the direction of Polaris.

[SOURCE: RIIC15]

3.1.6
replete set
connected subset of a Euclidean space with non-empty interior such that all its points belong to either its interior or to the topological closure of its interior

Note 1 to entry: A replete set is a generalization of an open set that allows the inclusion of boundary points. Boundary points are important in the definitions of certain coordinate systems.

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3.1.7
spatial object
physical or virtual object to which spatial information applies

3.1.8
spatial operation
mathematical function that re-expresses coordinates, directions, and/or orientations expressed in one spatial reference frame in terms of a different spatial reference frame; or mathematical function for distance or other geometric quantities within a single spatial reference frame

3.2 Notation, symbols, and abbreviated terms

In this document, dates that are included in an element of a concept instance specification shall conform to the notation and formats of ISO 8601.

Table 3.1 lists mathematical notation conventions commonly used in this document.

Table 3.1 — Mathematical notation

Style	Use	Examples
lower case, bold, italic	points, vectors	$\boldsymbol{x}, \boldsymbol{p}$
lower case, italic	variables, scalars, scalar-valued functions, axes of a linear coordinate system	a, b, f, x-axis
upper case, bold, italic	vector-valued functions, matrices, orthogonal frames	$\boldsymbol{F}, \boldsymbol{G}, \boldsymbol{M}$
upper case, italic	sets	S, T

Upper case italic letter symbols are also used for scalar-valued functions that are customarily capitalized.

Table 3.2 lists the symbols used in this document.

Table 3.2 — Symbols

Symbol	Definition
CS_S	spatial coordinate system of SRF_S
ORM_S	object reference model of SRF_S
ORM_R	reference ORM for a given spatial object
SRF_S	source spatial reference frame
SRF_T	target spatial reference frame
$\mathbf{0}$	origin of an orthonormal frame
a	major semi-axis length of an oblate ellipsoid
b	minor semi-axis length of an oblate ellipsoid
$\boldsymbol{C}_i[\boldsymbol{G}]( )$	i^{th} coordinate-component curve at a point
$\boldsymbol{c}_S$	coordinate of a position in SRF_S
$d_E( )$	Euclidean distance function
$d_G( )$	geodesic distance function

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Symbol	Definition
E	computational error
$\boldsymbol{E}$	embedded orthonormal frame; normal embedding
E_{S}	extended region of SRFs
$\boldsymbol{E}_{\mathrm{S}}$	embedded frame of SRFs
$\boldsymbol{E}(\,)$	embedding function
$(\boldsymbol{e_1}, \boldsymbol{e_2}, \boldsymbol{e_3})$	set of Cartesian basis vectors of an orthonormal frame
(e_0, e_1, e_2, e_3)	quaternion in 4-tuple form
$(e_0, \boldsymbol{e})$	quaternion in scalar vector form
f	flattening of an oblate ellipsoid
$\boldsymbol{G}$	generating function of a coordinate system
$\boldsymbol{G}_L$	generating function of a localized coordinate system
$\boldsymbol{G}_{\mathrm{S}}$	spatial generating function of CSs
$Dom(\boldsymbol{G}_{\mathrm{S}})$	domain of the generating function $\boldsymbol{G}_{\mathrm{S}}$
$Rng(\boldsymbol{G}_{\mathrm{S}})$	range of the generating function $\boldsymbol{G}_{\mathrm{S}}$
$\boldsymbol{H}_{F\leftarrow E}$	similarity transformation from frame $\boldsymbol{E}$ to frame $\boldsymbol{F}$
h	ellipsoidal height
h_0	ellipsoidal height at the CS origin
h_e	elevation with respect to the geoid
h_o	orthometric height
$\boldsymbol{I}$	identity matrix (or operator)
$\boldsymbol{I}_{F\leftarrow E}$	identity transformation from frame $\boldsymbol{E}$ to frame $\boldsymbol{F}$
k_0	central scale
k_{scaled}	point scale
k, m, n	number of dimensions, $1 \leq k, m, n \leq 3$
$k(\,)$	point distortion function
$\boldsymbol{L}$	localized orthonormal frame
$\boldsymbol{L}_{3\mathrm{D}}$	localization operator (3D)
$\boldsymbol{M}_{F\leftarrow E}$	rotation matrix from frame $\boldsymbol{E}$ to frame $\boldsymbol{F}$
$\mathcal{M}(\varphi)$	radius of curvature in the meridian at latitude φ
$\mathcal{N}(\varphi)$	radius of curvature in the prime vertical at latitude φ
$\boldsymbol{n}_{\mathrm{S}}$	direction vector in SRFs
(n_1, n_2, n_3, θ)	rotation representation in terms of axis unit vector components and rotation angle
$\boldsymbol{O}_{\mathbf{E}}$	origin of the embedded orthonormal frame $\boldsymbol{E}$
$\overrightarrow{\boldsymbol{O}_{\boldsymbol{E}}\boldsymbol{O}_{\boldsymbol{F}}}$	vector from the origin of frame $\boldsymbol{E}$ to the origin of frame $\boldsymbol{F}$
$\overrightarrow{\boldsymbol{O}_{\boldsymbol{E}}\boldsymbol{p}}$	vector from the origin of frame $\boldsymbol{E}$ to the position $\boldsymbol{p}$

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Symbol	Definition
$\boldsymbol{P}$	generating projection
$\boldsymbol{P}_{\mathrm{S}}$	mapping equations for SRFs
$\boldsymbol{p}, \widetilde{\boldsymbol{p}}$	position vector
$\boldsymbol{p}_{\boldsymbol{E}}$	coordinate of position $\boldsymbol{p}$ expressed in terms of frame $\boldsymbol{E}$
$\left(p_x, p_y, p_z\right)_{\boldsymbol{E}}$	coordinate-components of position $\boldsymbol{p}$ in terms of frame $\boldsymbol{E}$
$\boldsymbol{Q}$	inverse generating projection
$\boldsymbol{Q}_{\mathrm{S}}$	inverse mapping equations for SRFs
$\boldsymbol{q}, \boldsymbol{r}, \boldsymbol{s}, \boldsymbol{t}$	localization parameters
$\boldsymbol{R}$	rotation operator
$\mathbb{R}^{\boldsymbol{m}}$	vector space of m-tuples
$\boldsymbol{R}_{\boldsymbol{n}}\langle\theta\rangle$	rotation through angle θ about the axis $\boldsymbol{n}$
$\boldsymbol{R}_{\boldsymbol{n},\boldsymbol{t}}\langle\theta\rangle$	non-origin-fixed rotation through angle θ about the directed axis $\{\boldsymbol{t}+\alpha\boldsymbol{n} \mid \alpha \in \mathbb{R}\}$ passing through the position vector $\boldsymbol{t}$ and parallel to the unit vector $\boldsymbol{n}$
$\boldsymbol{R}_{\boldsymbol{E}\rightarrow\boldsymbol{F}}$	orientation of frame $\boldsymbol{F}$ with respect to frame $\boldsymbol{E}$
$\boldsymbol{S}_i[\boldsymbol{G}]( )$	i[th] coordinate-component surface at a point
$\boldsymbol{\mathcal{S}}(\varphi)$	meridional distance from latitude φ to the equator
u_{F}	false easting
$[u, v]^{\mathsf{T}}$	2D position vector components
$[u, v, w]^{\mathsf{T}}$	3D position vector components
V_{S}	applicable region of SRFs
v_{F}	false northing
$\boldsymbol{v}_{\mathrm{S}}$	vector quantity in SRFs
$v( )$	vertical offset at a position
$\boldsymbol{W}$	world 3x3 transformation matrix
$[x, y]^{\mathsf{T}}$	2D position vector components
(x, y, z)	Cartesian coordinate tuple
$[x, y, z]^{\mathsf{T}}$	3D position vector components
$[\Delta x, \Delta y, \Delta z]_{\mathrm{S}}^{\mathsf{T}}$	3D position vector components in SRFs
$[x, y, z]_{\boldsymbol{E}}^{\mathsf{T}}$	3D position vector components with respect to the basis of frame $\boldsymbol{E}$
$\boldsymbol{x}$-$\boldsymbol{y}$-$\boldsymbol{z}$	Euler angle convention for sequence of body-fixed principal axis rotations
α	geodetic azimuth
α_0	geodetic azimuth of the secondary axis relative to local north
(α, ρ)	azimuthal coordinate tuple
(α, ρ, h)	azimuthal cylindrical coordinate tuple
(α, ρ, θ)	azimuthal spherical coordinate tuple

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Symbol	Definition
γ	convergence of the meridian
Δs	scale difference from unity
$[\Delta x, \Delta y, \Delta z]^{\mathsf{T}}$	origin displacement vector components
$[\Delta x, \Delta y, \Delta z]_{\mathrm{S}}^{\mathsf{T}}$	origin displacement vector components in $\mathrm{SRF_S}$
$\vec{\Delta}_{F \leftarrow E}$	origin displacement vector from the origin of frame $\boldsymbol{E}$ to the origin of frame $\boldsymbol{F}$
ε	(first) eccentricity of an oblate ellipsoid
ε'	second eccentricity of an oblate ellipsoid
ε_{D}	directional error bound
ε_{P}	positional error bound
ε_{R}	ratio error bound
θ	spherical latitude, depression/elevation, cylindrical, polar, or rotation angle
$\Lambda_C(\lambda, \lambda_C)$	longitudinal centring function
λ	geodetic or planetodetic longitude
$\lambda_{\mathrm{origin}}$	origin longitude
(λ, φ)	surface geodetic coordinate tuple
(λ, θ, ρ)	equatorial spherical coordinate tuple
(λ, φ, h)	geodetic coordinate tuple
$(\lambda_{\mathrm{S}}, \varphi_{\mathrm{S}}, h_{\mathrm{S}})$	geodetic coordinate tuple for a position in $\mathrm{SRF_S}$
ρ	radius or range
(ρ, θ)	polar coordinate tuple
(ρ, θ, h)	cylindrical coordinate tuple
φ	geodetic latitude
$\varphi_{\mathrm{origin}}$	origin latitude
(φ, λ)	surface planetodetic coordinate tuple
(φ, λ, h)	planetodetic coordinate tuple
σ	scale factor, map scale
$\sigma_{F \leftarrow E}$	scale factor from frame $\boldsymbol{E}$ to frame $\boldsymbol{F}$
$\boldsymbol{\Omega}_{F \leftarrow E}$	change of basis operator from frame $\boldsymbol{E}$ to frame $\boldsymbol{F}$
ω_i	$\mathrm{i^{th}}$ principal axis angle of rotation

Table 3.3 lists the abbreviated terms used in this document.

Table 3.3 — Abbreviated terms

Abbreviated form	Abbreviated term
1D	one-dimensional
2D	two-dimensional

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Abbreviated form	Abbreviated term
3D	three-dimensional
AFWA	Air Force Weather Agency
API	application program interface
BIPM	Bureau International des Poids et Mesures (International Bureau of Weights and Measures)
CAD/CAM	computer-aided design/computer-aided manufacturing
CFR	coordinate frame rotation
CH1903	CH 1903 ("CH" is the ISO 3166-1 country code for Switzerland)
CS	coordinate system
COAMPS	Coupled Ocean/Atmospheric Mesoscale Prediction System
COM	convergence of the meridian
D73	Datum 1973
DCS	Directorate of Colonial Surveys
DGRF	Definitive Geomagnetic Reference Field
DHDN	Deutschen Hauptdreiecksnetzes (Germany)
DOS	Directorate of Overseas Surveys
DRAM	dynamic random access memory
DSS	designated spatial surface
E	east
EGM	Earth gravitational model
ENU	east-north-up
ERM	Earth reference model
ESA	European Space Agency
ETRF	European Terrestrial Reference Frame
ETRS89	European Terrestrial Reference System 1989
FRG	Federal Republic of Germany
GCS	global coordinate system
GDA	Geocentric Datum of Australia
GGRS	Greek Geodetic Reference System
GPS	Global Positioning System
GRS	geodetic reference system
GTRS	Geo Tile Reference System
IAG	International Association of Geodesy
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers

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Abbreviated form	Abbreviated term
IERS	International Earth Rotation and Reference Systems Service
IGLD	International Great Lakes Datum
IGN	Institut Géographique National (France)
IGRF	International Geomagnetic Reference Field
ISO	International Organization for Standardization
ISTS	International Satellite Triangulation Station
ITRF	International Terrestrial Reference Frame
JGD	Japan Geodetic Datum
JTC	Joint Technical Committee
KKJ	Kartastokoordinaattijarjestelma
LKS	Lietuvos Koordinaciu Sistema (Lithuania)
MGI	Militärgeographisches Institut
MM5	Mesoscale (weather) Model 5
MODTRAN	moderate resolution transmittance (atmospheric radiation transfer)
MP	map projection
MSL	mean sea level
N	north
NASA	National Aeronautics and Space Administration
NAVD	North American Vertical Datum
NED	north-east-down
NGO	Norges Geografiske Oppmåling
NOGAPS	Navy Operational Global Atmospheric Prediction System (United States)
NT	Nouvelle Triangulation (Luxembourg)
NTF	Nouvelle Triangulation Français (France)
OBRS	object binding rule set
ORM	object reference model
ORMT	object reference model template
OSGB	Ordnance Survey of Great Britain
OSGM	Ordinance Survey Geoid Model
PVR	position vector rotation
PZ90	Parametry Zemli 1990 (Russia)
RD	reference datum
RGF	Reseau Géodésique Français (France)
RT	reference transformation
RT90	Rikets Triangelnät 1990 (Sweden)

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Abbreviated form	Abbreviated term
S	south
S-JTSK	System - Jednotné Trigonometrické Síti Katastrální (Czechoslovakia)
SI	Système International d'unités (International System of Units)
SIRGAS	Sistema de Referencia Geocéntrico para las Américas (The Americas)
SO(3)	special orthogonal group of degree 3
SPCS	State Plane Coordinate System (United States)
SRF	spatial reference frame
SRFT	spatial reference frame template
SRM	Spatial Reference Model
SSM	SRF set member
STT	similarity transformation template
TAI	Temps Atomique International (International Atomic Time)
UK	United Kingdom
UPS	Universal Polar Stereographic
US	United States
USGS	United States Geological Survey
UT0	universal time observed
UT1	universal time polar motion corrected
UT2	universal time Earth rotation corrected
UTC	coordinated universal time
UTM	Universal Transverse Mercator
VOS	vertical offset surface
W	west
WGS	World Geodetic System
WMM	World Magnetic Model

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4 Concepts

4.1 Overview

The SRM provides an integrated framework and precise terminology for describing spatial concepts and operations on spatial information. The SRM includes the following features:

a) precise and uniform definitions of commonly used spatial coordinate systems, including those based on map projections,

b) spatial referencing of positions, directions, vector quantities, and orientations for physical and abstract objects,

c) spatial operations and transformations on positions, directions, vector quantities, and orientations, including coordinate conversions and transformations, and calculations of distances and other geometric quantities,

d) an application program interface for performing the defined spatial operations,

e) codes and labels to support the encoding and exchange of spatial data,

f) an extensible framework that supports the registration of additional instances of SRM concepts, and

g) profiles to allow subsets of the SRM to be defined to conform to the specific requirements of an application or an application domain.

This document is based on the following set of foundational and unifying core concepts, which are addressed in greater detail in the remainder of this clause and subsequent clauses:

a) Spatial points are identified by coordinates in a *spatial reference frame* associated with a spatial object of interest, such as the Earth or an engineering model. An *object-space* is the collection of points associated with a spatial object of interest (see 4.2.3).

b) *Position-space* is the Euclidean vector space of dimension $n = 1$, 2 or 3 that serves as a mathematical abstraction of object-space of matching dimension. In both position-space and object-spaces, *orthonormal frames* are defined by the selection of an origin point and a set of mutually perpendicular basis vectors. A *normal embedding* is a length-preserving function that maps positions in position-space to points in an object-space of the same dimension. There are infinitely many possible normal embeddings of an n-dimensional position-space for a given object-space (see 4.2.2).

c) An *abstract coordinate system* assigns a unique coordinate n-tuple defined in a *coordinate-space* to each point in a subset of position-space of dimension n or greater. An abstract coordinate system has a *generating function* that assigns a coordinate in coordinate-space to a corresponding point in position-space (see 4.3.1).

d) A *spatial coordinate system* assigns a unique coordinate in coordinate-space to each point in a region of object-space. A spatial coordinate system assigns a coordinate in coordinate-space to a unique point in object-space using a spatial generating function that is the functional composition of an abstract coordinate system generating function with a normal embedding. Different normal embeddings produce different spatial coordinate systems (see 4.3.2).

e) A *temporal coordinate system* is a Euclidean 1D coordinate system that assigns a one-to-one relationship between temporal coordinate values and instants in time. Temporal coordinate systems are used when spatial coordinate values are time-dependent to associate unique instants in time with events or references (see 4.3.3).

f) *Orientation* is the rotational relationship between a rigid object of interest and a reference. Orientation is specified in terms of the angular displacement, or attitude, of the object's orthonormal frame with respect to an orthonormal reference frame (see 4.4).

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g) A *reference datum* is a geometric primitive, such as a point, directed curve, or oriented surface in position-space, whose determining characteristics are bound to a measured or conceptual geometric aspect of a spatial object in an object-space (see 4.5).

h) An *object reference model* is a set of bound reference datums that implicitly defines a unique normal embedding of position-space into object-space. An object reference model is a generalised abstraction of the geodesy notion of a datum (see 4.6).

i) A *spatial reference frame* is a means of specifying a spatial coordinate system for an object-space. A spatial reference frame specification includes (1) an object reference model, (2) a compatible abstract coordinate system, and (3) the binding of object reference model parameters to corresponding abstract coordinate system parameters (if any). The normal embedding implicitly defined by the object reference model is then functionally composed with the abstract coordinate system to produce a spatial coordinate system for the object-space (see 4.7).

j) *Vertical offset surfaces* are introduced to define heights with respect to equipotential or other complex surfaces (see 4.8).

Diagrams that illustrate SRM concepts and their relationships can be found in Annex C.

The relationships among some of these concepts are depicted in Figure 4.1. In this figure, spherical coordinate tuples are defined in a coordinate-space. An abstract spherical coordinate system is then defined by its generating function, which uniquely assigns spherical coordinate tuples to each point in 3D position-space, based on its canonical orthonormal frame. A normal embedding implicitly defined by an object reference model of the Earth is used to map the position-space orthonormal frame to a corresponding orthonormal frame embedded in the Earth's object-space. A spatial coordinate system based on this embedded frame allows points in the Earth's object-space to be located, and various spatial operations to be performed.

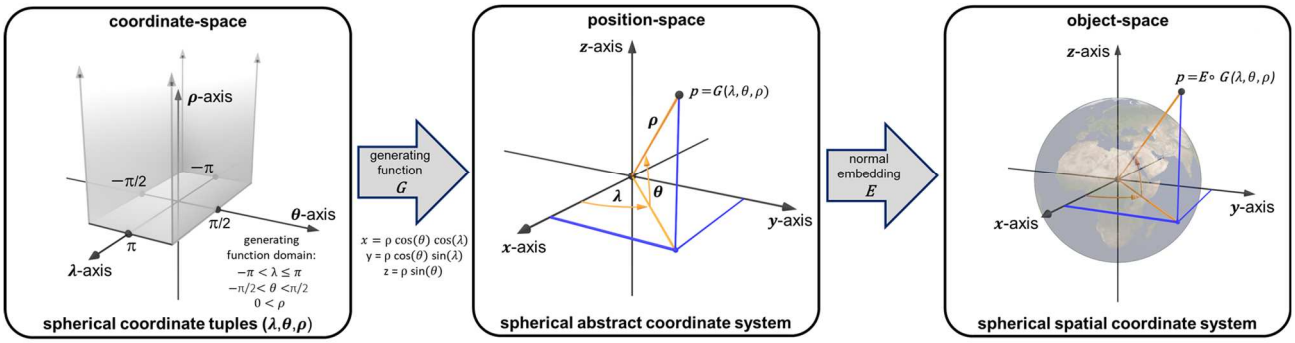


Figure 4.1 — Coordinate-space, position-space, and object-space relationships

The concepts introduced in this subclause are discussed in greater detail in the remainder of this clause. This document takes a functional approach to the definition of these concepts. Basic geometric concepts, including the concepts of point, line, and plane, are assumed. Annex A provides a concise summary of mathematical concepts, including specialized concepts, and notational conventions used in this document.

In this document, the unit of length is the metre and the unit of angular measure is the radian (see ISO 80000-3) unless explicitly identified otherwise. Some angular values are specified in the units of either arc degree or arc second, to support common usage or to prevent loss of precision in data specification.

An application or an exchange format using the data storage structures specified in this document (see 11.5) may use equivalent units of measure, provided those units are identified. For a unit not defined in ISO 80000-3, the conversion factor to metre or radian, as appropriate, shall be explicitly stated. One suitable mechanism for accomplishing the identification of a unit is to use unit and unit scale identifiers as specified in Clause 7 of ISO/IEC 18025.

When interfacing with the methods and/or functions of the SRM (see 4.10), applications shall use the units of metre and radian, as appropriate. All length and angular data shall be converted to the units of metre or radian, as appropriate, before the data is provided as input to an SRM method or function.

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When measures of computational accuracy are being determined, such measurements shall be expressed in the units of metre and radian, where applicable.

4.2 Coordinate-space, position-space, and object-space

4.2.1 Coordinate-space

A *coordinate* is an ordered n-tuple $(1 \leq n \leq 3)$. A *coordinate-component* is an individual component of a coordinate n-tuple. A *coordinate-space* specifies a set of coordinate n-tuples that forms a Euclidean vector space (see A.2). The domain of a coordinate system is a replete subset of coordinate space. Such coordinate n-tuples include, but are not restricted to, Cartesian (x, y, z), polar (ρ, θ), cylindrical (ρ, θ, h), and geodetic (λ, φ, h).

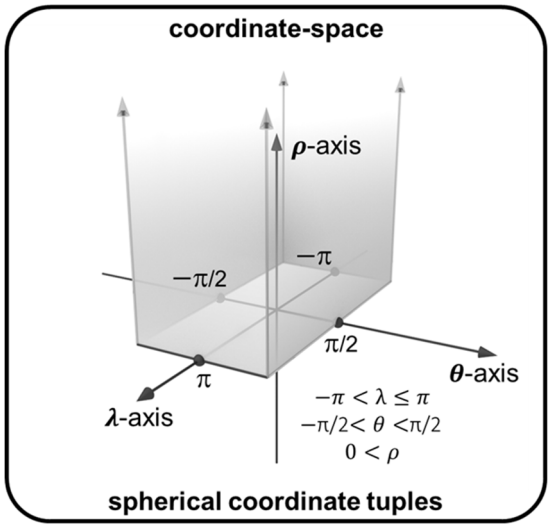


Figure 4.2 — A coordinate-space (for spherical coordinates)

Figure 4.2 illustrates the structure of a coordinate-space for 3D spherical coordinate tuples of the form (λ, θ, ρ). The coordinate-components of these tuples are:

λ: longitude in radians, such that $-\pi < \lambda \leq \pi$,
θ: spherical latitude in radians, such that $-{}^{\pi}/_{2} < \theta < {}^{\pi}/_{2}$, and
ρ: radius in metres, such that $0 < \rho$.

Coordinate-space is further defined in 5.2.1.

4.2.2 Position-space and orthonormal frames

Position-space of dimension m, $(1 \leq n \leq m \leq 3)$, is the Cartesian vector space $\mathbb{R}^m$ (see A.2), which serves as a mathematical abstraction of an object-space. Position-space allows abstract coordinate systems to be applied to object-spaces for many different types of spatial objects of interest.

An ordered set of m mutually perpendicular unit position vectors forms a canonical Cartesian basis for position-space, which allows positions, directions, vector quantities, and distance measurements in position-space to be quantified.

The origin and Cartesian basis vectors together define an *orthonormal frame*. Every point in position-space is uniquely represented by a linear combination of the orthonormal frame's basis vectors represented by a corresponding n-tuple of scalars in the basis order. An orthonormal frame is *right-handed* if the vertices of the triangle formed by its basis unit vectors are in clockwise order when viewed from the origin, as defined in ISO 80000-2.

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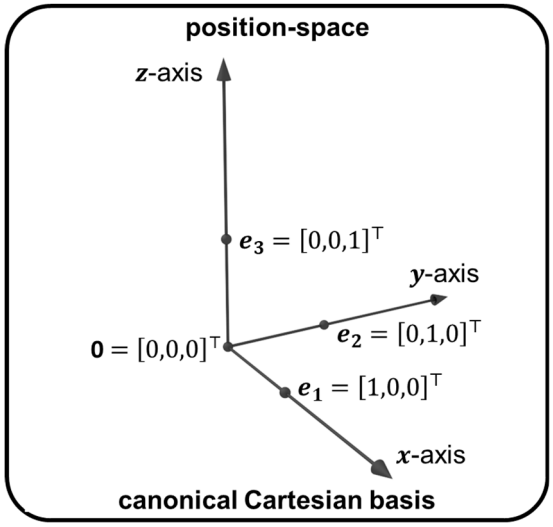


Figure 4.3 — 3D position-space and its canonical Cartesian basis

Figure 4.3 illustrates 3D position-space, showing its origin, and the unit vectors that form its canonical Cartesian basis.

Orthonormal frames and position-space are further defined in 5.2.2 and 5.2.3, respectively.

The *position* of a point is the directional displacement of that point with respect to a designated point, called the origin. The position of a point is represented in terms of a position vector. The position of an object is typically expressed in terms of the position of a representative point within the object.

A *direction* is represented by a unit vector with respect to an orthonormal frame. *Vector quantities*, such as velocity and acceleration, combine a direction vector with a magnitude.

4.2.3 Object-space and normal embeddings

An *object-space* is the collection of points that is fixed to a designated spatial object of interest. Object-space provides the application domain context for spatial concepts including positions, directions, vector quantities, and orientations.

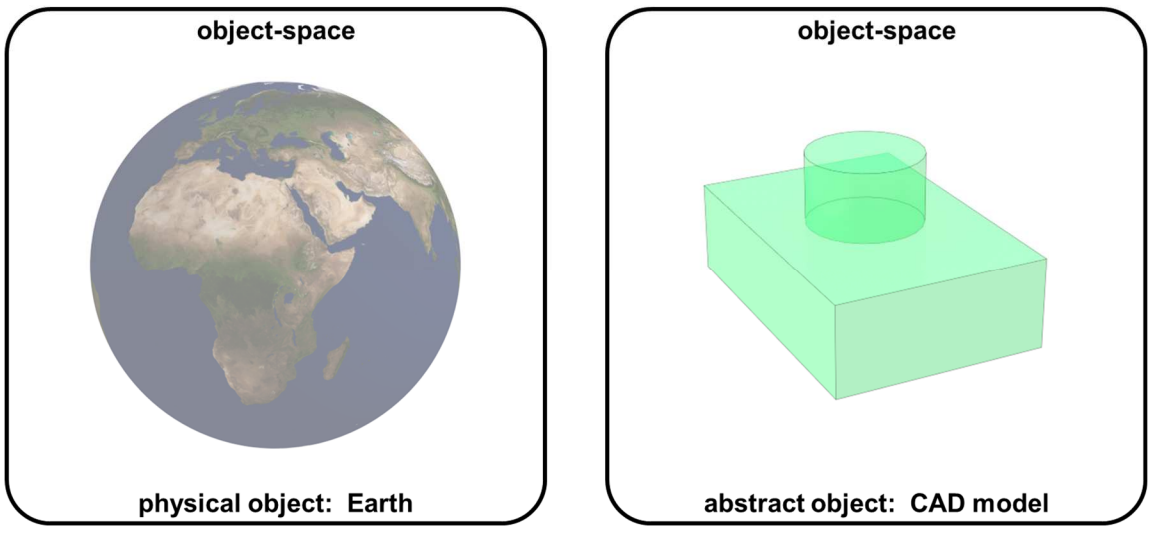


Figure 4.4 — Object-spaces for the Earth and for a CAD model

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The spatial objects of interest in this document include physical and abstract objects. *Physical objects* are real-world objects, such as Earth or a building. *Abstract objects* are conceptual objects including engineering, mathematical, and virtual models. Figure 4.4 illustrates two object-spaces: one for a physical object (i.e., the Earth), and one for an abstract object (i.e., a CAD model).

A *normal embedding* is a distance-preserving function mapping vectors in position-space to points in an object-space of the same dimension. Position-space together with a normal embedding provides a specific algebraic model of an object-space by determining an orthonormal frame embedded in the object space. There are infinitely many normal embeddings of an n-dimensional position-space for a given object-space, depending on the placement of the origin and direction of the axes. The method of specifying a normal embedding varies across disciplines and application domains. This document encapsulates these methods within the concepts of reference datum (see 4.5) and object reference model (see 4.6).

Object-space and normal embeddings are further defined in 5.2.4 and 5.2.5, respectively.

4.3 Coordinate systems

4.3.1 Abstract coordinate systems

An *abstract coordinate system* assigns a unique coordinate n-tuple to each point in a subset of m-dimensional position-space $(1 \leq n \leq m \leq 3)$. An abstract coordinate system is comprised of a domain, a range, and a generating function. The *generating function* is a *smooth*, one-to-one function from the domain in n-dimensional coordinate-space onto the range that is a set of positions in m-dimensional position-space. The generating function may be parameterized by coordinate system parameters. The domain can be a proper subset of coordinate-space.

Figure 4.5 illustrates these components for the Equatorial Spherical abstract coordinate system.

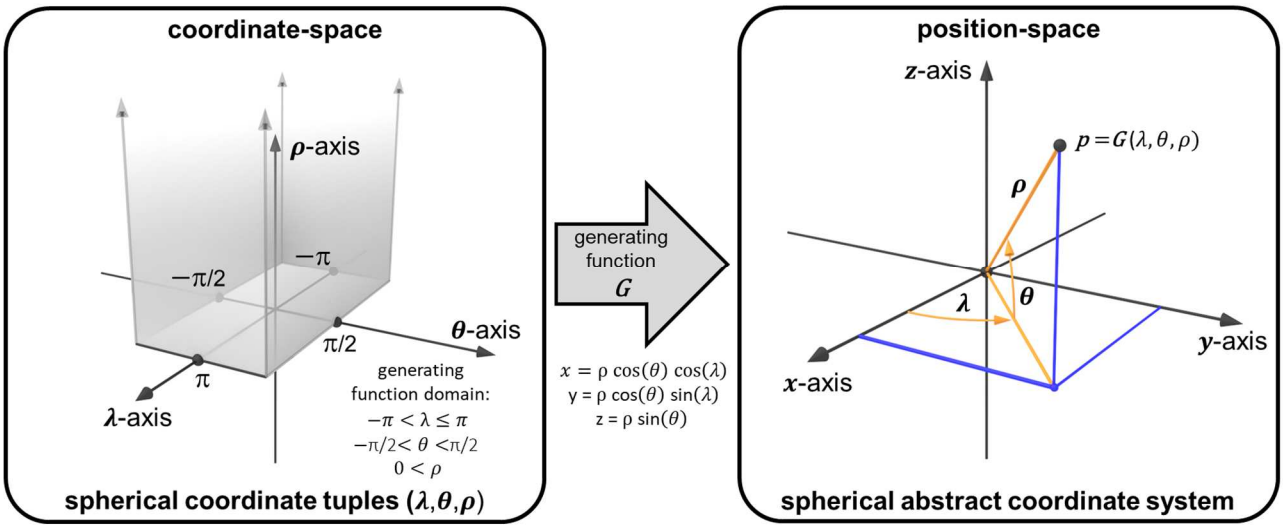


Figure 4.5 — Abstract equatorial spherical coordinate system example

In this document, the term “coordinate system”, if not otherwise qualified, means “abstract coordinate system.”

A coordinate system is *linear* if its generating function is an *affine* function. Otherwise, it is curvilinear. The Geodetic 3D coordinate system and all map projection coordinate systems are curvilinear. A linear coordinate system is orthogonal if its axes are pairwise perpendicular. A Cartesian coordinate system is a linear coordinate system that is also orthogonal. A three-dimensional coordinate system is *right-handed* if the vertices of the triangle formed by its basis unit vectors are in clockwise order when viewed from the origin, as defined in ISO 80000-2.

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The coordinate-space and position-space dimensions characterize a *coordinate system type* as in Table 4.1.

Table 4.1 — Coordinate system types

Coordinate system type	Dimension of coordinate-space	Dimension of position-space
3D	3	3
surface	2	3
curve	1	3
2D	2	2
plane curve	1	2
1D	1	1

Many applications need to perform operations involving multiple related coordinate systems. The relationships between coordinate systems used in an application often reflect corresponding relationships among the objects of interest within the application context. Such abstract coordinate system relationships are the foundation for corresponding spatial coordinate system and spatial reference frame relationships in object-space. This document provides a set of parameterized localization operators for defining local coordinate systems relative to base coordinate systems and specifies several standard localized coordinate systems.

It is also useful in some applications to reduce the dimensionality of a coordinate system by fixing the values of one or more of its coordinate-components. The resulting *coordinate-component surfaces* and *curves* are particularly useful when dealing with curvilinear coordinate systems. Thus, fixing the ellipsoidal height coordinate-component (h) of a 3D geodetic coordinate system to zero results in an induced surface geodetic coordinate system that represents positions on the surface of the ellipsoid modelling the Earth. This document provides functions for creating coordinate-component surfaces and curves and specifies several standard induced surface coordinate systems.

The two coordinate-component curves at a point on a curvilinear surface, such as an ellipsoid-based model of the Earth, can be used to define a plane that is tangent to the curves at the point. This tangent plane can be used to define a localized 2D or 3D coordinate system. These *localized coordinate systems* are used in modelling the position and orientation of objects, such as vehicles and sensors, located on or near the Earth or other celestial bodies. Such localized coordinate systems also provide Euclidean vector spaces for denoting directions in curvilinear coordinate systems.

Maps are traditionally created by functionally projecting a region of the surface of an oblate ellipsoid (or sphere) onto a flat 2D surface for presentation and other user purposes. These and similar functions are termed *mapping equations* and are defined in terms of surface geodetic coordinates on the ellipsoid. When inverse mapping equations are composed with the generating function of the surface geodetic coordinate system, the resulting function is the generating function for a surface coordinate system. In this way, coordinate systems based on traditional map projections may be treated as a special case of abstract coordinate systems of coordinate system type surface. This special case is termed a *map projection coordinate system*.

NOTE In other contexts, map projection coordinate systems are sometimes described as rectilinear or Cartesian because of the vector space structure of coordinate-space. That description does not imply that a map projection coordinate system is a linear coordinate system. Map projection coordinate systems are not linear because the associated generating functions are not affine. With respect to a linear coordinate system for the same position-space, map projection coordinate systems exhibit various types of distortion (see 5.3.7.3). In applications the effect of distortion is often mitigated by restricting the coordinate system domain of the map projection to a smaller sub-set.

Abstract coordinate systems are addressed in greater detail in 5.3. This document specifies a standardized set of abstract coordinate systems (see 5.3.8).

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4.3.2 Spatial coordinate systems

A *spatial coordinate system* assigns a unique coordinate to each point in a region of object-space. Abstract coordinate systems are defined (see 4.3.1) for position-space. Position-space can serve as a model of an object-space by specifying a normal embedding that maps the position-space orthonormal frame to a corresponding orthonormal frame embedded in object-space. Using this concept, a spatial coordinate system is defined as the functional composition of an abstract coordinate system generating function and a normal embedding. The abstract coordinate system generating function $\boldsymbol{G}$ associates coordinates in coordinate-space to positions in position-space. A normal embedding $\boldsymbol{E}$ maps those positions in position-space to points in object-space. Different normal embeddings produce different spatial coordinate systems. If $\boldsymbol{c}$ is a coordinate for the coordinate system, then $\boldsymbol{c}$ identifies the object-space point $\boldsymbol{p} = \boldsymbol{E} \circ \boldsymbol{G}(\boldsymbol{c})$.

Figure 4.6 illustrates a spatial surface coordinate system bound with a normal embedding of 3D position-space to the 3D object-space. In this illustration, a surface coordinate (u, v) in coordinate-space is associated to a position vector (x, y, z) in position-space. That position then identifies a location in the space of an object via the normal embedding of position-space. In this example, the normal embedding is determined by the selection of an origin and three unit points.

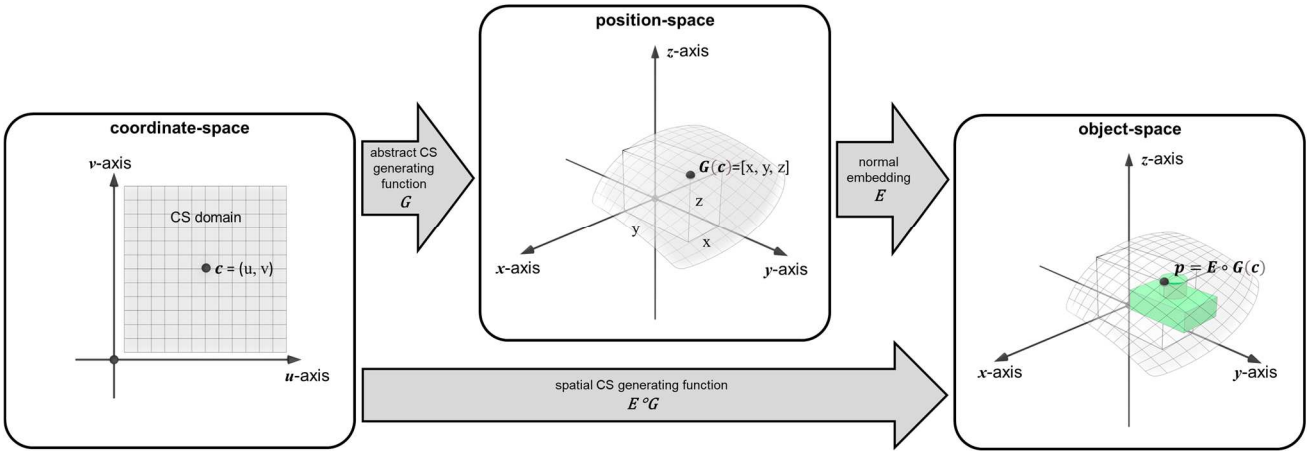


Figure 4.6 — A normal embedding of an abstract coordinate system

In applications where a one spatial coordinate system is defined in terms of another spatial coordinate system, the relationships between them build upon the corresponding relationships between their respective abstract coordinate systems (see 4.3.1).

The details of spatial coordinate systems are addressed in 5.4.

4.3.3 Temporal coordinate systems

A *temporal coordinate system* is a realisation of an abstract Euclidean 1D coordinate system that assigns a one-to-one monotonically increasing relationship between temporal coordinate values and instants in time, such that larger coordinate values are assigned to later instants in time. A temporal coordinate system is used to associate a unique instant in time with an event or reference.

There is a requirement to identify time as well as position in environmental representation. Time and position are often used together by an application to describe when a given condition exists or when an object was present at a given location. Furthermore, in dynamic physical systems, the normal embedding that maps position-space to an object-space may change over time. As a result, the relationship between coordinates and positions is time-dependent. In such systems, time and time differences have to be considered in order to accurately determine positions and position differences.

This document uses the concept of time in several ways. An object reference model (see 4.6) has either a static or dynamic binding to a spatial object. In the latter case, time is a parameter of the reference transformation that

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specifies the binding (see 7.5). Spatial reference frames (see 4.7) that are based on dynamic object reference models also depend on a time parameter. However, these dynamic cases reduce to the corresponding static cases by fixing a value for the time parameter.

Time is also a factor for static object reference model bindings that are based on physical measurements of objects or systems that change with time. Time is used to identify the epoch for which these measurements are applicable.

The details of temporal coordinate systems are specified in 5.5.

4.4 Orientation

The *orientation* of a rigid object describes its angular displacement, or attitude, with respect to a reference. When the object is represented by an orthonormal frame attached to the object, the orientation of the object is represented by the angular displacement of the object's frame with respect to a reference frame. Orientation can be specified in terms of either: 1) a change of basis operation that would convert a coordinate from the object's frame to the reference frame (see 6.2), or 2) a rotation operation that would move the object's frame away from alignment with the reference frame (see 6.4).

Several representations of orientation and rotations are in wide use in different application domains. Consistent definitions of orientations and rotations are required to support interoperability of systems and applications. This document supports several common representations of orientations and rotations (see 6.6), as well as inter-conversion operations between these representations (see 6.7). The supported representations defined include:

a) 3x3 matrix,

b) axis-angle,

c) Euler angles, including proper Euler angles and Tait-Bryan angles, and

d) quaternions.

4.5 Reference datums

A *reference datum* is a geometric primitive in position-space. In 2D position-space, reference datums are points or directed curves. In 3D position-space, reference datums are points, directed curves, or oriented surfaces. Oblate ellipsoid surfaces are commonly used to model the Earth and other celestial bodies.

EXAMPLE 1 An ellipsoid reference datum with major semi-axis a and minor semi-axis b is the surface implicitly defined by:

$$f(x,y,z) = \frac{x^2}{a^2} + \frac{y^2}{a^2} + \frac{z^2}{b^2} - 1 = 0$$

and is illustrated in Figure 4.7. The WGS 1984 ellipsoid reference datum has major semi-axis $a = 6\ 378\ 137$ metres and flattening $f = 1/298{,}257\ 223\ 563$, resulting in a minor semi-axis $b = a - af = 6\ 356\ 752$ metres.

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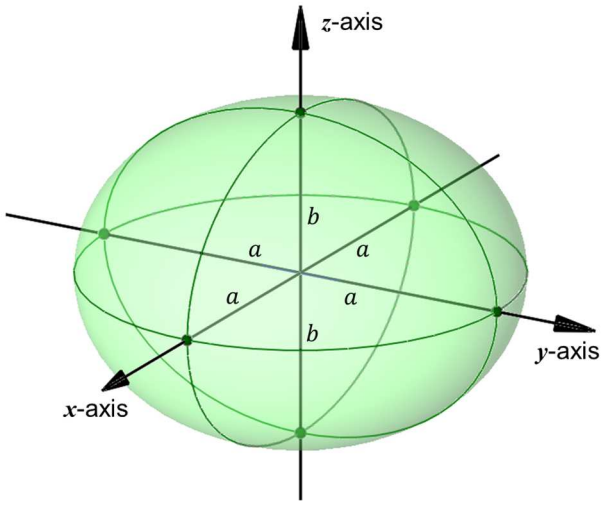


Figure 4.7 — An ellipsoid reference datum

A reference datum is *bound* when the reference datum in position-space is identified with a corresponding constructed entity (i.e., a measured or conceptual geometric aspect of a spatial object) in object-space. The term “corresponding” in this context means that each position-space reference datum is bound to a constructed entity of the same geometric primitive type. That is, position-space points are bound to object-space points, position-space curves to object-space curves, and position-space surfaces to object-space surfaces.

Figure 4.8 illustrates two distinct bindings of a point reference datum. On the upper right, the point reference datum is bound to a specific point in the object-space of a CAD/CAM model. On the lower right, the point reference datum is bound to a corresponding point in the object-space of a physical object that has been manufactured in accordance with that CAD/CAM model. Similarly, the yz-plane reference datum is bound to corresponding planes in the two object-spaces.

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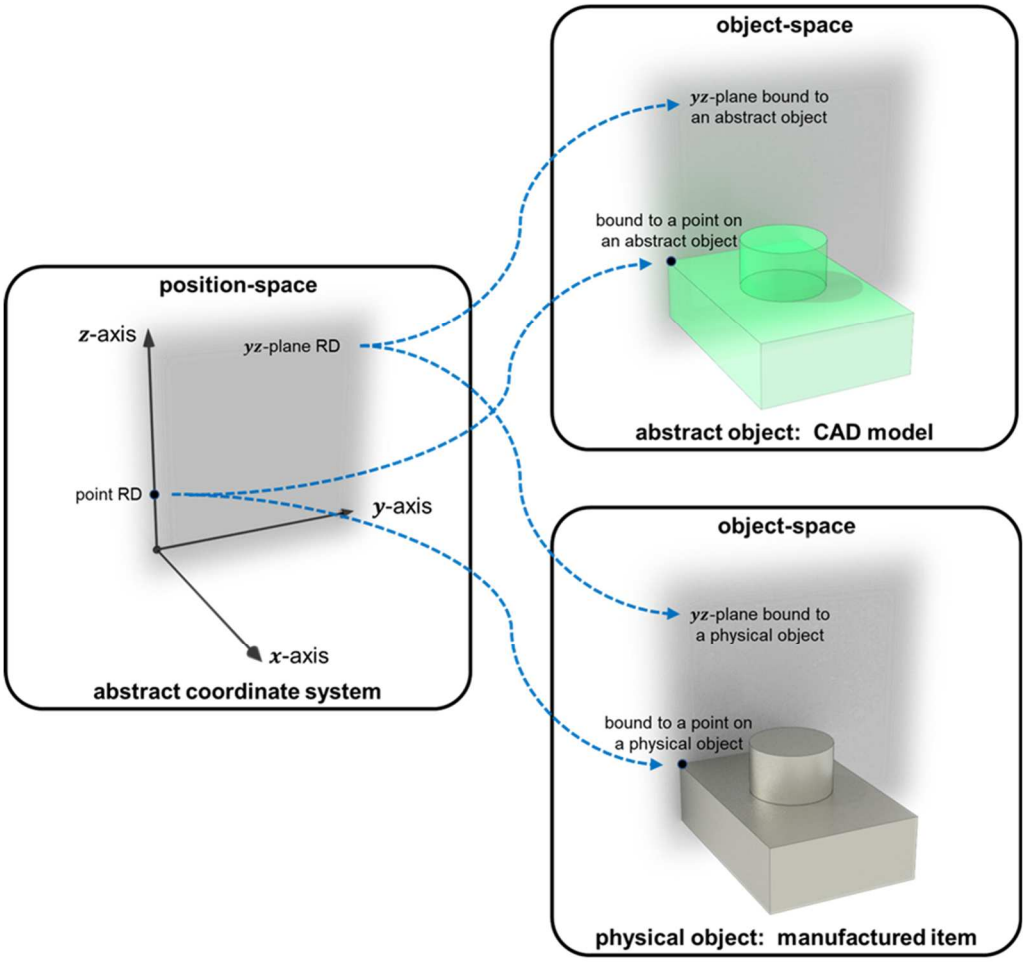


Figure 4.8 — Reference datums bound to abstract and physical objects

In some application domains, bound reference datums are used to model a significant aspect of the problem domain. In geodesy, oblate ellipsoids are used to model the figure of the Earth or a subset thereof.

EXAMPLE 2 Semi-axis values a and b, $a \geq b$, are selected to specify an oblate ellipsoid reference datum. The following steps (see Figure 4.9) illustrate one way to bind an ellipsoid reference datum specified by semi-axis values a and b to a conceptual ellipsoid that represents the figure of the Earth in a region as approximated by a geodetic survey control network:

a) A point on the surface of the reference datum is specified. This point has a computable geodetic latitude φ.

b) The specified position-space point is identified with a specific point in object-space.

c) The direction of the oblate ellipsoid rotational axis is constructed in object-space.

d) The direction of the outward surface normal at the point is constructed in object-space so that the angle it makes with respect to the oblate ellipsoid rotational axis direction is $(\pi/2 - \varphi)$.

This binding requires the specification of a point and two directions in object-space.

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