



IEEE Standard for a Framework for Structuring Low-Altitude Airspace for Unmanned Aerial Vehicle (UAV) Operations

IEEE Communications Society

Developed by the
Access and Core Networks Standards Committee

IEEE Std 1939.1™-2021

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Access and Core Networks Standards Committee
of the
IEEE Communications Society

Approved 23 September 2021

IEEE SA Standards Board

Abstract: A structure of low-altitude airspace for efficient unmanned aerial vehicle (UAV) traffic management is defined in this standard. The standard elaborates the structural low altitude based on UAV low-altitude public air routes from five parts: grid technology, remote sensing data, communication and networking, route planning, operation, and management.

Keywords: airspace assessment, communication and networking, geographic data, geographic information technology, gridding, IEEE 1939.1™, low-altitude airspace, low-altitude public air route network, meteorological service, operation and management, path planning, remote sensing, risk assessment, UAV, unmanned aerial vehicle

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

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PDF: ISBN 978-1-5044-7972-1 STD24953
Print: ISBN 978-1-5044-7973-8 STDPD24953

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Introduction

This introduction is not part of IEEE Std 1939.1-2021, IEEE Standard for a Framework for Structuring Low-Altitude Airspace for Unmanned Aerial Vehicle (UAV) Operations.

With the increasingly prominent contradiction between the development demand of Unmanned Aerial Vehicle (UAV) flights and the use of limited low-altitude resources, safe and efficient management of low-altitude operations of UAVs is urgent. Structuring low altitudes is an efficient solution to solve this problem, such as the Metropolis project in Europe, in which four type of airspace structures (full mix, layers, zones, and tubes) were proposed. However, there is no clear consensus yet on how to construct this and which factor(s) is necessary.

This standard defines a low-altitude structure in the form of an air route network for efficient UAV traffic management. It contains five parts: grid technology, remote sensing data, communication and networking, route planning, and operation and management. A summary is as follows:

- Gridding and coding are the basic techniques for constructing structured low altitude.
- Remote sensing and surface object extraction technology are important sources of surface geographic information for low-altitude structural construction (which can meet the demand of high dynamic updating of information).
- Communication and networking technology provides high-quality, reliable communication and data links for low-altitude UAV operations.
- The low-altitude air route is a kind of fine low-altitude airspace structure.
- Operation and management techniques provide macro-policy support for the docking between the route and UAS traffic management (UTM).

The IEEE Std 1939.1 working group consists of teams with backgrounds in the fields of geographic information, remote sensing surveying and mapping, communication, standards produce, air traffic control, etc. The team has a solid research foundation, rich practical experience, and an in-depth understanding of the policies and user needs of UAVs. In addition, it includes UAV applications and load manufacturers and other units.

Acknowledgments

Special thanks are given to the National Key Research and Development Program of China, the National Natural Science Foundation of China, and the Strategic Priority Research Program of Chinese Academy of Sciences for being participants in the development of this standard.

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1. Overview

1.1 Scope

This standard defines a structure for low-altitude airspace for efficient unmanned aerial vehicle (UAV) traffic management.

It defines UAV capabilities and related infrastructure for UAVs to operate in low-altitude air space.

1.2 Purpose

This standard recognizes, but does not intend to restate or replace, applicable laws and regulations related to low-altitude airspace, UAV operations, and air traffic management. Users of this standard are responsible for referring to and observing all such laws and regulations. Compliance with the provisions of this standard does not imply compliance with any such legal or regulatory requirements.

The standard aims to form a low-altitude airspace structure in the form of low-altitude public air routes of UAVs, and elaborates on gridding technology, remote sensing, communication and networking technology, air route planning, operation, and management.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{1,2}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

¹ The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

² The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ISO 21895:2020, Classification of Civil Unmanned Aircraft Systems.³

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.⁴

aerial photography vulnerabilities: In aerial photography, these occur when the overlap of photographs or images is too small or there is no overlap.

airborne LiDAR: An integrated system consisting of a LiDAR system, a Position and Orientation System (POS), a digital camera and a control system on an aeronautical platform. *See also:* **LiDAR**.

Beyond VLOS (BVLOS): A unmanned aerial vehicle (UAV) operating outside the visual line of sight and an operating radio link to the control station.

C2: A command and control data link between the unmanned aerial vehicle (UAV) and the control station for flight management purposes.

canopy height model: A model used to reflect vegetation canopy height, which is the interpolation of a digital surface model (DSM) and a digital elevation model (DEM) in an area with vegetation coverage.

contour plane: The closed surface formed by points of equal geodetic height.

drone-port: The unmanned aerial vehicle (UAV) airport and necessary service facilities associated with legal airspace. Hardware facilities include runways, hangars, assembly and debugging areas, navigation, and communication facilities for UAVs, etc. Software facilities include a flight supervision system, an air traffic control coordination system, etc. The drone-port is a hub for connecting low-altitude airways with ground facilities to contribute to UAV landings and transitions.

Dynamic Cloud Provided Number (D-CPN): The dynamic information interaction service number assigned by the unmanned aerial vehicle (UAV) cloud platform, used for information interaction between the UAV cloud and the UAV system during flight.

³ ISO publications are available from the International Organization for Standardization (<http://www.iso.org/>) and the American National Standards Institute (<http://www.ansi.org/>).

⁴ *IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

enhanced mobile broadband (eMBB): This refers to the enhancement of the user's experience and other performance factors based on the existing mobile broadband service scenarios.

Flight Control Identity (FCID): The unmanned aerial vehicle (UAV) flight control system identification code, which is customized and managed by each manufacturer, and is generally stored in the flight control system as a string.

geodetic height: The distance from the normal direction of the ellipsoid to the point of interest.

global subdivision: The process of dividing the Earth's space into approximate, continuous, and seamless sets of multi-level spatial elements.

grid code: The unique identifier code corresponding to a grid cell according to certain rules.

ground point: A point in a point cloud that reflects the real surface morphology.

ground resolution: The limit of detail clarity in an image of the Earth's surface collected by a remote sensing device, usually measured in meters (m).

horizontal granularity: The length of the equator corresponding to the span of the longitude and latitude.

hyperspectral remote sensing: The spectral resolution is above $10^{-2} \lambda$ or more, and remote sensing technology can obtain continuous and complete spectral data concerning ground objects.

identification code: The code to identify spatial objects based on two-dimensional or three-dimensional spatial information, according to certain rules. In most cases, the grid code is embedded in the identification code for high-efficiency identification. The identification codes are different according to the application scenarios.

instantaneous field of view (IFOV): The solid angle through which a detector is sensitive to radiation.

laser effective distance: The distance that a laser scanner can detect.

laser scanner: The laser ranging system is used to measure the distance between the transmitting point and the reflecting point on the target, by recording the time delay of the laser pulse between the transmitting object and the receiving unit.

layer: The grid count from the Earth's surface in the direction of the geodetic height.

level: The number of geographically located grids recursively dissecting the Earth's surface and the geodetic height.

LiDAR: A system that emits a laser beam and receives an echo, to obtain three-dimensional information concerning a target.

LiDAR point cloud: A point cloud obtained by LiDAR scanning.

low altitude: An altitude ground level height that is low enough to be affected by a ground facility and the natural geomorphology; low enough to be covered by ground mobile communication signals; and, low enough to be away from traditional general aviation and civil aviation activities. The actual altitudes qualifying as 'low-altitude' vary from place to place and from time to time and oscillate from around 200 m to 500 m above ground level.

maximum height: The vertical gap between the average altitude within the route and the maximum altitude of the highest point of the surface object.

mobile communication identity (MCID): The unique identifier for a mobile communication terminal, applicable to all mobile communication devices including communication terminals such as satellites, cellular phones, Wi-Fi, etc.

mobile device identity (MDID): Refers to the physical identity of all mobile internet devices that are accessed through wireless communication.

non-ground point: A point in a point cloud that does not represent a ground point.

payload pod service data: Includes image data, live video, sensor data, and other business data collection.

point cloud: A set of points that are distributed in three-dimensional space in a discrete and irregular manner.

point cloud density: The average number of points per unit area, such as points per square meter.

positioning and attitude determination system: The system used to determine the spatial position and attitude of sensors; it is integrated by a Global Navigation Satellite System (GNSS) receiver and an Inertial Measurement Unit (IMU).

public attribution: The commonality of the route is reflected in the fact that it can accommodate multiple fixed-wing and rotary UAVs operating over the same area at the same time. Route turning must therefore be sufficiently smooth. Commonality is also reflected in the existence of multi-channel and emergency channels to allow UAVs to overtake, to be stopped for emergency purposes, and to leave the route.

quality of service (QoS): The ability of a network to make use of various basic technologies to provide better service capability for the designated network communication.

reflectance: The ratio of the radiation energy reflected by an object to the total radiation energy projected onto the object.

remote control station: A control station that provides the facilities for pilot control or automatic UAS flight.

route curvature: The maximum deviation from the main point of each photograph to the main point of the first and last two photographs on a photographic route.

side overlap: This corresponds to images of the same area on adjacent photographs along adjacent routes, usually expressed as a percentage.

spectrum band width: The difference between the upper and lower frequencies in a continuous band of frequencies, measured typically in Hertz.

subdivision grid: A discrete spatial region element composed of geospatial fractals.

tilt angle of a photograph: The angle between the main optical axis of the aerial camera and the plumb line in aerial photography, or the angle between the main optical axis of the aerial camera and the horizontal plane in ground photography.

traffic management data link: A data link for UAV traffic management between unmanned aircraft systems and transportation service systems.

UAS management system: A system responsible for UAS registration, flight permits, application data reception, and management.

UAS Operator Identity (UOID): A UAV operator identification, which identifies the operator that is currently operating the UAV system.

UAV flight information: Includes the flight position, altitude, speed, direction, mission, and other relevant information concerning UAVs.

UAV hyperspectral remote sensing: Remote sensing technology for the data acquisition, processing, and application of hyperspectral images based on aircraft.

UAV low-altitude public air route (LAPAR): This refers to a pre-planned air passage with a certain width, designed for all types of UAVs, the maximum altitude ground level height of which is lower than the flying AGL height of manned aircraft.

unmanned aircraft system (UAS): An aircraft and its associated elements that are operated with no pilot on board.

vertical overlap: The part of an image that shows the same area on adjacent photographs along a route, usually expressed as a percentage.

visual line-of-sight operation (VLOS): An operation mode in which the UAV pilot or the UAV pilot maintains direct visual contact with the UAV. The aircraft is within a range of 500 m in the visual line of sight of the driver or observer, and the relative height is less than 120 m.

3.2 Acronyms and abbreviations

3G/4G/5G	3rd/4th/5th generation
3GPP	3rd Generation Partnership Project
AKA	authentication and key agreement
APDU	application protocol data unit
BVLOS	Beyond VLOS
BWP	bandwidth part
CA	certification authority
DAA	detect and avoid
DEM	digital elevation model
DH	Diffie-Hellman
DIN	UAV Identity Number
E2E	end to end
ECC	elliptic curve cryptography
ECDH	elliptic curve Diffie-Hellman
ECDSA	elliptic curve digital signature algorithm
eMBB	enhanced mobile broadband
eUICC	embedded Universal Integrated Circuit Card
FCID	Flight Control Identity
GNSS	Global Navigation Satellite System
IDPS	Intrusion Detection and Protect System
IFOV	instantaneous field of view
LAPAR	low-altitude public air route
LBS	location-based service
LTE	long term evolution
MAC	message authentication code
MCID	mobile communication identity

MDID	mobile device identity
MEC	Mobile-Edge Computing
mMTC	Massive Machine Type Communication
MTBF	Mean Time Between Failure
NB-IoT	Narrow Band Internet of Things
OTT	over the top
QoS	quality of service
RSA	Rivest-Shamir-Adleman
RSN	remote serial number
RTK	Real-Time Kinematic
SN	serial number
UAS	unmanned aircraft system
UAV	unmanned aerial vehicle
UOID	UAS Operator Identity
URLLC	Ultra Reliable & Low Latency Communication
USP	UAS traffic management service provider
UTC	Coordinated Universal Time
UTM	UAS traffic management
UTMS	UAS traffic management system
VLOS	visual line-of-sight operation

4. Contents

The standard defines a low-altitude airspace structure in the form of low-altitude public air routes for efficient UAV traffic management, which is elaborated in five parts, including grid technology, remote sensing data, communication and networking, air route planning, operation, and management. (See Figure 1.)

Firstly, the relationship among low altitudes, low-altitude airspace structure, and low-altitude air routes should be clarified. Low altitude refers to the space up to several hundred meters on the ground, which is closely related to human activities and has a great impact on UAV activities. Low-altitude airspace structure refers to the classification of various airspace types, the relative space positions of each airspace type, and the provision of necessary conditions and services for aircraft flight in each airspace type. Low-altitude air route is a kind of isolated airspace type exclusive to UAVs. It is also the carrier and expression form of low-altitude airspace structure.

Secondly, the role of each part in the low-altitude airspace structure and its relationship with air routes shall be clarified. The gridding and coding technology are basic techniques for constructing structured low altitude. Grid-based airspace and remote sensing image of UAV can express, organize, and store low-altitude information efficiently and uniformly, while the coding technology enables the low-altitude information to be flexibly invoked and indexed to realize the efficient planning and expression of low-altitude air routes. Remote sensing and feature extraction technology are important sources of surface geographic information for low-altitude structural construction and is a solution to the high-dynamic information updating problem. It involves the low-altitude data acquisition, extraction, and production process, which is the main database of air route planning and construction. Communication and networking technology provide high-quality and reliable communication and data link for low-altitude UAV operations by standardizing communication link, communication networking, airborne communication terminal, and network security requirements. It can guide low-altitude structure and air route construction through communication coverage test of target airspace. The low-altitude air route is a kind of fine airspace structure; operation and management technologies provide macro policy support for air route docking with UAS traffic management (UTM) and standardize route planning and construction according to current UAV and airspace policies.

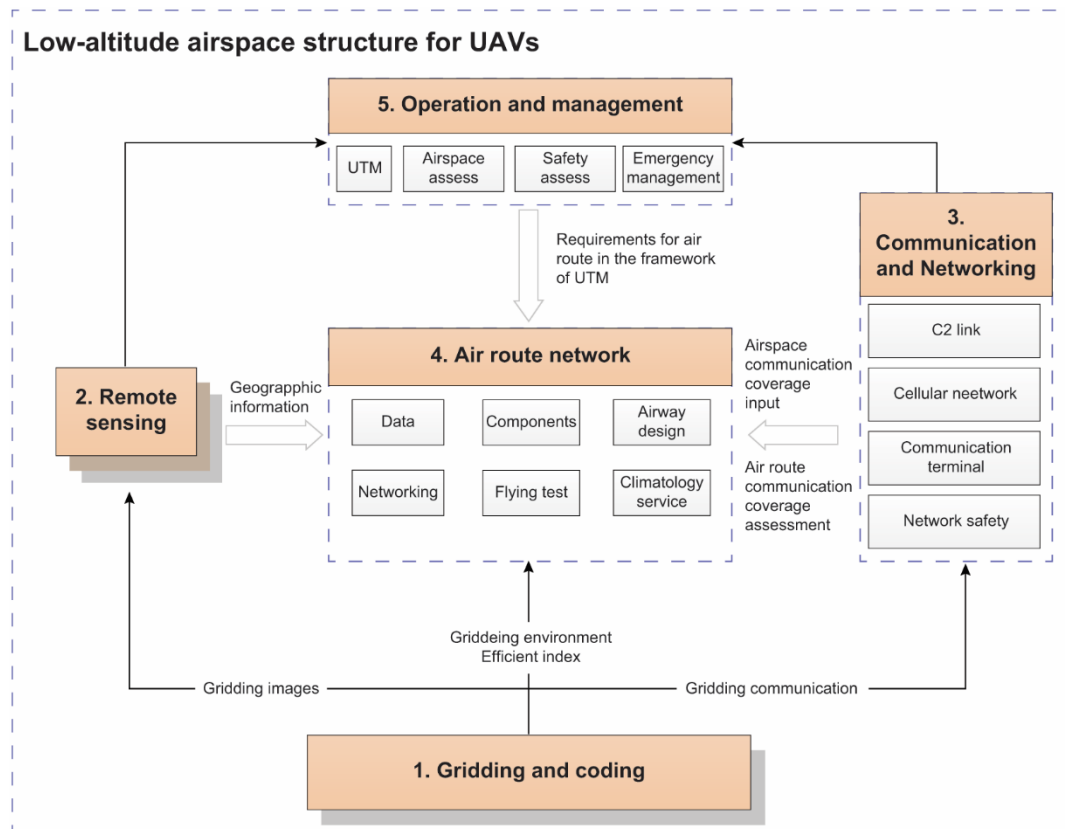


Figure 1 —Structure of the standard

4.1 Gridding

The subdivision grid system is based on longitude, latitude, and geodetic height. The grid system exists in the Earth reference spheroid, forms the Earth's surface subdivision, and is coupled with the geodetic height to form a three-dimensional subdivision. In order to apply to the UAV field, new coding rules have been formulated that were based on the subdivision grid system.

UAV path planning is divided into the following two stages:

- a) Environment modeling
- b) Track searching

For the first stage, the key is to use the above grid coding to divide and encode the mission airspace of the UAV, and build a three-dimensional grid map of the airspace, which is convenient for the next stage of UAV track search. During the execution of UAV path planning, a large amount of spatio-temporal data are required, such as terrain data, aircraft data, building data, flight trajectory data, restricted area data, etc. Using grid code to associate the previous data with the airspace is conducive to unified organization and management. Use grid coding as an index to associate environmental data with UAV track data. It realizes the unified organization and management of a variety of data, which is convenient for query and use in the next stage.

In the track search stage, a three-dimensional grid map of the airspace constructed by environmental modeling is used to reasonably model the constraints and cost functions. Finally, a flight path planning algorithm is used to plan a feasible flight path, which can satisfy the constraint conditions and can minimize the predetermined cost function.

4.1.1 Grid model

The subdivision grid system is based on longitude, latitude, and geodetic height. The grid system exists in the Earth's reference spheroid, forms the Earth's surface subdivision, and is coupled with the geodetic height to form a three-dimensional subdivision.

4.1.1.1 Surface coordination system

The coordinate origin of the subdivision grid system is the intersection of the equator and the primary meridian on the Earth's surface. The global surface space is extended to form a virtual space with the latitude and longitude composed of degrees, minutes, and seconds, each expressed as an integer of the n th power of 2. For example, the degrees are expanded from 180° and 360° to 512° and 512° , then $60'$ of each 1° are expanded to $64'$, and $60''$ of each $1'$ are expanded to $64''$. By such virtual extension, the coordinate degrees, minutes, and seconds can be divided by 2 to give an integer of the n th power of 2, until 1° , $1'$, and $1''$ are reached. This makes it possible to directly convert the divided coordinates into integral codes.

4.1.1.2 Horizontal subdivision

The global surface is divided recursively by 4 into the following 32-level quad tree:

- The degree-level grids include 10 levels of grids from level 0 (Figure 2) to level 9.
- The minute-level grids include 6 levels of grids from level 10 to level 15.
- The second-level grids include 6 levels of grids from level 16 to level 21.
- The grids below the second-level include 11 levels of grids from level 22 to level 32.

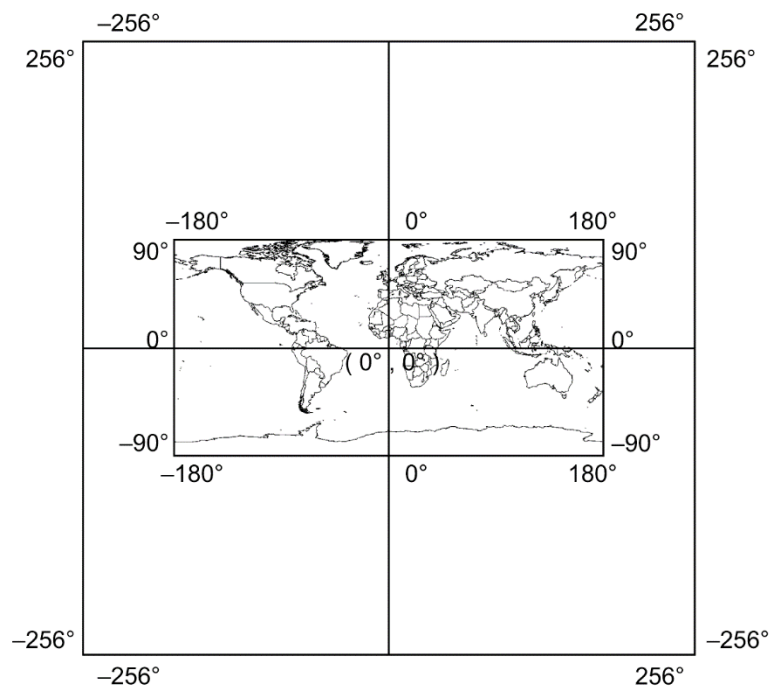


Figure 2 —Level 0 grid example

Each grid with a longitude and latitude of $1^\circ \times 1^\circ$ ($60' \times 60'$, 9-level grid) is expanded to $64' \times 64'$. The direction of grid expansion is determined by the location of the grid, and is shown in Figure 3 through Figure 6 for the situations where the grid is located in the northeast, northwest, southeast, and southwest hemispheres.

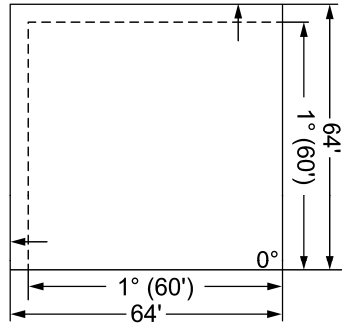


Figure 3 —Direction of northeast hemisphere expansion

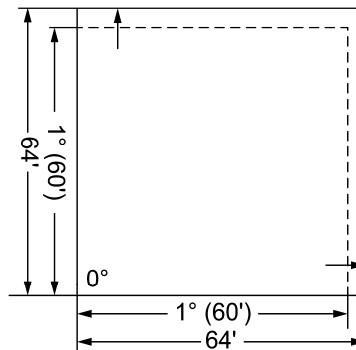


Figure 4—Direction of northwest hemisphere expansion

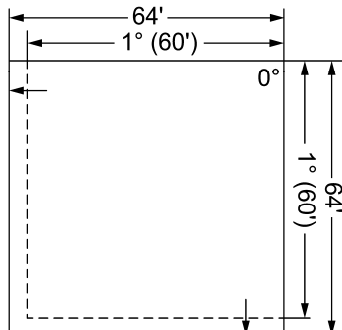


Figure 5 —Direction of southwest hemisphere expansion

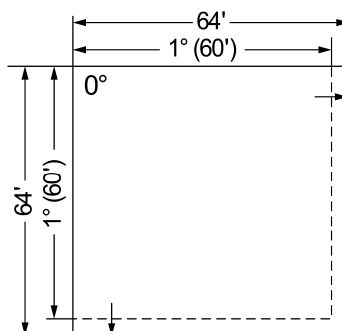


Figure 6 —Direction of southeast hemisphere expansion

Table 1—GeoSOT gridding system

Level	Space extension	Types of subdivided grids
G	512°	180°×360°
1	256°	90°×180°
2	128°	90°×128°, 90°×52°
3	64°	64°×64°, 26°×64°, 64°×52°, 26°×52°
4	32°	32°×32°, 26°×32°, 32°×20°, 26°×20°
5	16°	16°×16°, 10°×16°, 16°×4°, 10°×4°
6	8°	8°×8°, 8°×4°
7	4°	4°×4°
8	2°	2°×2°
9	1°	1°×1°
10	32'	32'×32', 28'×32', 32'×28', 28'×28'
11	16'	16'×16', 12'×16', 16'×12', 12'×12'
12	8'	8'×8', 8'×4', 4'×8', 4'×4'
13	4'	4'×4'
14	2'	2'×2'
15	1'	1'×1'
16	32"	32"×32", 28"×32", 32"×28", 28"×28"
17	16"	16"×16", 12"×16", 16"×12", 12"×12"
18	8"	8"×8", 4"×8", 8"×4", 4"×4"
19	4"	4"×4"
20	2"	2"×2"
21	1"	1"×1"
22	1/2"	1/2"×1/2"
23	1/4"	1/4"×1/4"
24	1/8"	1/8"×1/8"
25	1/16"	1/16"×1/16"
26	1/32"	1/32"×1/32"
27	1/64"	1/64"×1/64"
28	1/128"	1/128"×1/128"
29	1/256"	1/256"×1/256"
30	1/512"	1/512"×1/512"
31	1/1024"	1/1024"×1/1024"
32	1/2048"	1/2048"×1/2048"

4.1.1.3 Subdivision for polar areas

Between 88° to 90° in Antarctica and 88° to 90° in the Arctic, grid levels 8 and below need to be merged. The merging rules are as follows:

- 8-level grids: 180 2°×2° grids in the 88° to 90° latitude range in the South (North) are merged into one grid. An example is shown in Figure 6.
- 9-level grids: 360 1°×1° grids in the 89° to 90° latitude range in the South (North) are merged into one grid; 360 1°×1° grids in the 88° to 89° latitude range in the South (North) are merged into three grids. An example is shown in Figure 7.
- 10-level grids: The grids in the 89°32' to 90° latitude range in the North and South are merged into one grid, and the grids in the 89° to 89°32' latitude range are merged into three grids. The grid within the 88° to 89° latitude range is divided into quad trees based on the merging of nine-layer grids. An example is shown in Figure 8. The longitude and latitude of the merged grids are as follows:
 - The meshes of P0 are: P00(360°×28'), P01(128°×32'), P02(104°×32'), P03(128°×32').
 - The meshes of P1 are: P10(64°×32'), P11(64°×32'), P12(64°×28'), P13(64°×28').
 - The meshes of P2 are: P20(52°×32'), P21(52°×32'), P22(52°×28'), P23(52°×28').
 - The meshes of P3 are: P30(64°×32'), P31(64°×32'), P32(64°×28'), P33(64°×28').

- d) The grid below level 10: The expansion rule is consistent with the low latitude region, and the merging rule is consistent with the merging rule of level 9. It is formed by successive quad tree subdivision in the South (North).

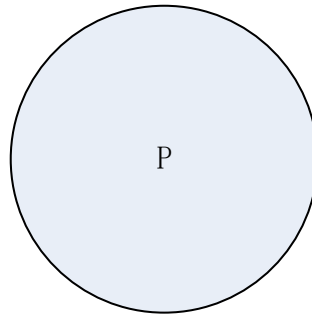


Figure 7 —8-level grid in the Antarctic and Arctic regions

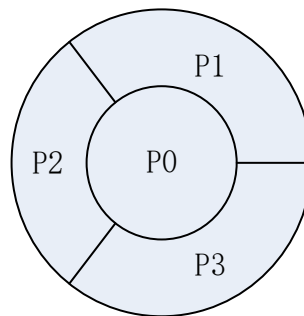


Figure 8 —9-level grid in the Antarctic and Arctic regions

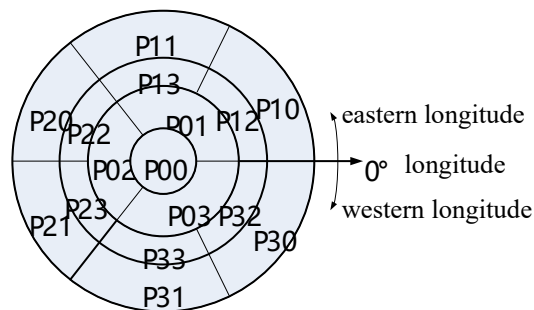


Figure 9 —10-level grid in the Antarctic and Arctic regions

4.1.1.4 Vertical subdivision

The series of height domain subdivisions is consistent with the series of Earth reference ellipsoid subdivisions. For an arbitrary subdivision number m , the height domain is divided into $2m$ layers, and the ground is the $2m-1$ layer. The height of each grid at the same level shall be equal and shall be consistent with the latitude of the equator on the corresponding level.

According to the motion range of UAVs, the coding height range is limited to -500 m to 2000 m, which is a simple mark beyond the range.

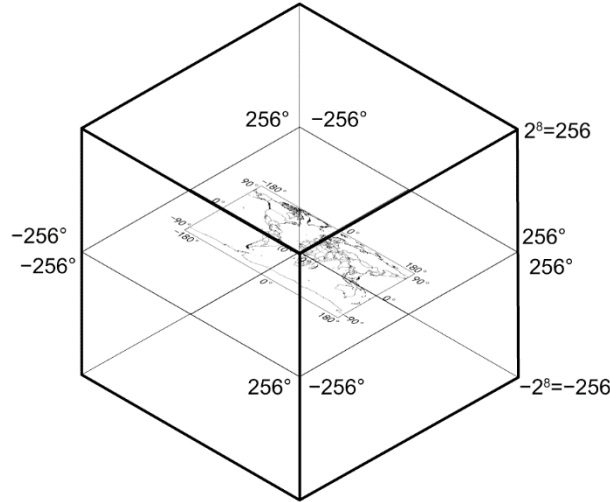


Figure 10—Schematic diagram of the global subdivision area

The relationship between the grid height at the same level and the length of the grid latitude at the equator of the corresponding contour plane is shown in Figure 11.

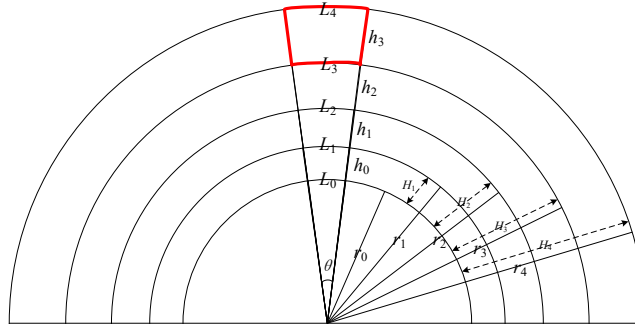


Figure 11— Relationship between the height of the equatorial grid of the same level and the length of the equatorial grid of the corresponding contour

The equations for calculating the grid parameters of a layer N above the Earth's surface are as follows:

- a) Calculation of the grid geodetic height H_n :

$$H_n = (1 + \theta_0)^{n \cdot \left(\frac{\theta}{\theta_0}\right)} r_0 - r_0 \quad (1)$$

where θ_0 is the longitude (latitude) span corresponding to the basic grid defined by the initial partition range, $\pi/180$ rad. In order to remain consistent with the grid expansion mode of longitude and latitude on the Earth's surface,

$$\text{when } \theta \geq 1^\circ, \theta_0 = 1^\circ \left(\frac{\pi}{180} \text{ rad} \right)$$

$$\text{when } 1^\circ > \theta \geq 1', \theta_0 = 64' \left(\frac{16}{15} \times \frac{\pi}{180} \text{ rad} \right)$$

$$\text{and when } \theta < 1', \theta_0 = 64'' \left(\frac{16^2}{15^2} \times \frac{\pi}{180} \text{ rad} \right)$$

where θ is the longitude (latitude) span corresponding to the grid (unit: rad) and n is the n -layer solid grid from the ground to the top (or down). n is an integer as follows: when above the ground $n > 0$, when below the ground $n < 0$. r_0 is the average radius of the Earth (6,371,008.77138 m).

- b) Calculation of the grid height (longitudinal granularity) h_n :

$$h_n = (1 + \theta_0)^{(n-1)(\frac{\theta}{\theta_0})} r_0 \left[(1 + \theta_0)^{\frac{\theta}{\theta_0}} - 1 \right] \quad (2)$$

where θ_0 is the longitude (latitude) span corresponding to the basic grid defined by the initial partition range, $\pi/180$ rad. In order to remain consistent with the grid expansion mode of longitude and latitude on the Earth's surface,

$$\text{when } \theta \geq 1^\circ, \theta_0 = 1^\circ \left(\frac{\pi}{180} \text{ rad} \right)$$

$$\text{when } 1^\circ > \theta \geq 1', \theta_0 = 64' \left(\frac{16}{15} \times \frac{\pi}{180} \text{ rad} \right)$$

$$\text{and when } \theta < 1', \theta_0 = 64'' \left(\frac{16^2}{15^2} \times \frac{\pi}{180} \text{ rad} \right)$$

where θ is the longitude (latitude) span corresponding to the grid (unit: rad) and n is the n -layer solid grid from the ground to the top (or down). n is an integer as follows: when above the ground $n > 0$, when below the ground $n < 0$. r_0 is the average radius of the Earth (6,371,008.77138 m).

- c) Calculation of the length (transverse granularity) of the grid on the contour plane L_n :

$$L_n = (1 + \theta_0)^{n(\frac{\theta}{\theta_0})} r_0 \times \theta \quad (3)$$

where θ_0 is the longitude (latitude) span corresponding to the basic grid defined by the initial partition range, $\pi/180$ rad. In order to remain consistent with the grid expansion mode of longitude and latitude on the Earth's surface,

$$\text{when } \theta \geq 1^\circ, \theta_0 = 1^\circ \left(\frac{\pi}{180} \text{ rad} \right);$$

$$\text{when } 1^\circ > \theta \geq 1', \theta_0 = 64' \left(\frac{16}{15} \times \frac{\pi}{180} \text{ rad} \right);$$

$$\text{and when } \theta < 1', \theta_0 = 64'' \left(\frac{16^2}{15^2} \times \frac{\pi}{180} \text{ rad} \right);$$

where θ is the longitude (latitude) span corresponding to the grid (unit: rad) and n is the n -layer solid grid from the ground to the top (or down). n is an integer when above the ground $n > 0$ and when below the ground $n < 0$. r_0 is the average radius of the Earth (6,371,008.77138 m).

4.1.1.5 Grid location and boundary surface attribution

4.1.1.5.1 Grid location

The geographical position grid is formed by geospatial partition, and the locating point is at the corner. The locating points of each grid shall be located at the position closest to the origin (the starting position O) of all corners of the grid. Let the intersection points of the contour, equatorial and primary meridian planes of different levels be O_n . The locating corner points of the grid on the contour plane are the grid corners that are horizontally close to O_n and vertically close to the surface. The specific locations are as follows:

- a) The locating points of the underground series of grids in the northeastern hemisphere shall be located at the southwest corner near the surface grids of the Earth, and those corresponding to the series of grids above the Earth's surface in the northeastern hemisphere shall be located at the southwest corner.
- b) The locating points of the underground series of grids in the southeastern hemisphere shall be located at the northwest corner near the surface grids of the Earth, and those corresponding to the series of grids above the Earth's surface in the southeastern hemisphere shall be located at the northwest corner.
- c) The locating points of the underground series of grids in the northwestern hemisphere shall be located at the southeast corner near the surface grids of the Earth, and those corresponding to the series of grids above the Earth's surface in the northwestern hemisphere shall be located at the southeast corner.
- d) The locating points of the underground series of grids in the southwestern hemisphere shall be located at the northeast corner near the surface grids of the Earth, and those corresponding to the series of grids above the Earth's surface in the southwestern hemisphere shall be located at the northeast corner.

The geographical position grid showing locating point positions is illustrated in Figure 12.

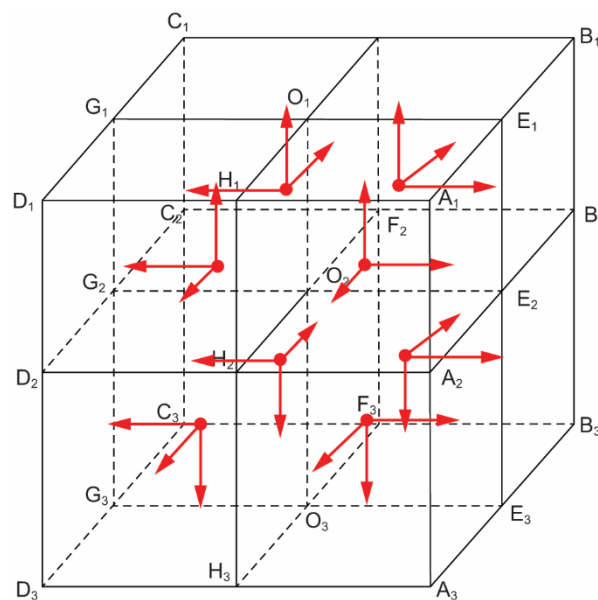


Figure 12—Geographical position grid showing the locating point locations

4.1.1.6 Merged grid positioning in the Antarctic and Arctic regions

The location rules of the combined grid in the Antarctic and Arctic regions in the 88°–90° latitude range in the South and North are as follows:

- 8-layer grid positioning: The South (North) polar region grid takes as the positioning point the intersection point of the meridian and the latitude of ± 88 degrees, and the direction of the geodetic height remains unchanged. For example, the positioning points of the 8-level grid of the Earth's reference ellipsoid in the Antarctic region are $(0^\circ, -88^\circ, 0)$, and those of the 8-level grid of the Earth's reference ellipsoid in the Arctic region are $(0^\circ, 88^\circ, 0)$.
- 9-layer grid positioning: The positioning points of P0, P1, P2 and P3 in the Arctic region are $(0^\circ, 89^\circ, 0)$, $(0^\circ, 88^\circ, 0)$, $(128^\circ, 88^\circ, 0)$, $(0^\circ, 88^\circ, 0)$, and the positioning points of P0, P1, P2, and P3 in the Antarctic region are $(0^\circ, -89^\circ, 0)$, $(0^\circ, -88^\circ, 0)$, $(128^\circ, -88^\circ, 0)$, $(0^\circ, -88^\circ, 0)$.

4.1.1.6.1 Boundary surface attribution of grid

The three boundary surfaces of the geographical location grid include the locating points belonging to the local grid but exclude the locating points that do not belong to the local grid (Figure 13).

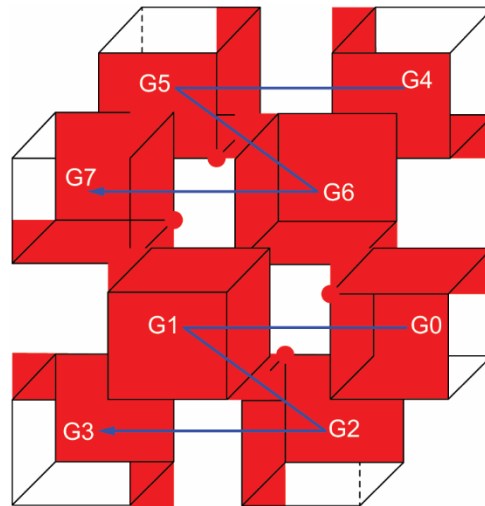


Figure 13—Boundary surface attribution of the geographical location grid

4.1.2 Grid identification

The mesh size of the first-level mesh generation is $6^\circ \times 4^\circ$. The first-level trellis coding rule specifies to take N (northern hemisphere) and S (southern hemisphere) as the identification codes. The longitude direction is coded as 1–60, and the latitude direction is coded as A–V in the northern and southern hemispheres. The coding direction is shown in Figure 14.

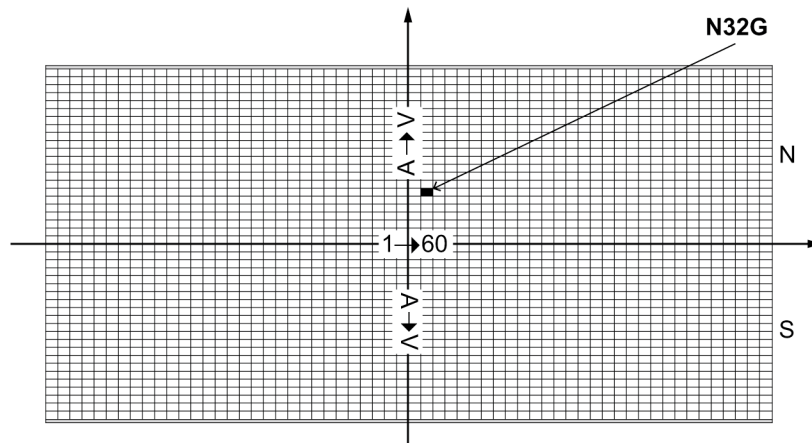


Figure 14—First-level meshing and coding method

4.1.2.1 First-level meshing and coding rules

The first-level trellis code is four units in length and consists of the northern or southern hemisphere identification code, the first-level longitude identification code, and the first-level latitude identification code.

4.1.2.2 Second-level meshing and coding rules

The first 6×4 grid specified in 4.1.2.1 is divided into 12×8 second-level grids, corresponding to a 30×30 grid, which is equivalent to a $55.66 \text{ km} \times 55.66 \text{ km}$ grid at the equator of the Earth.

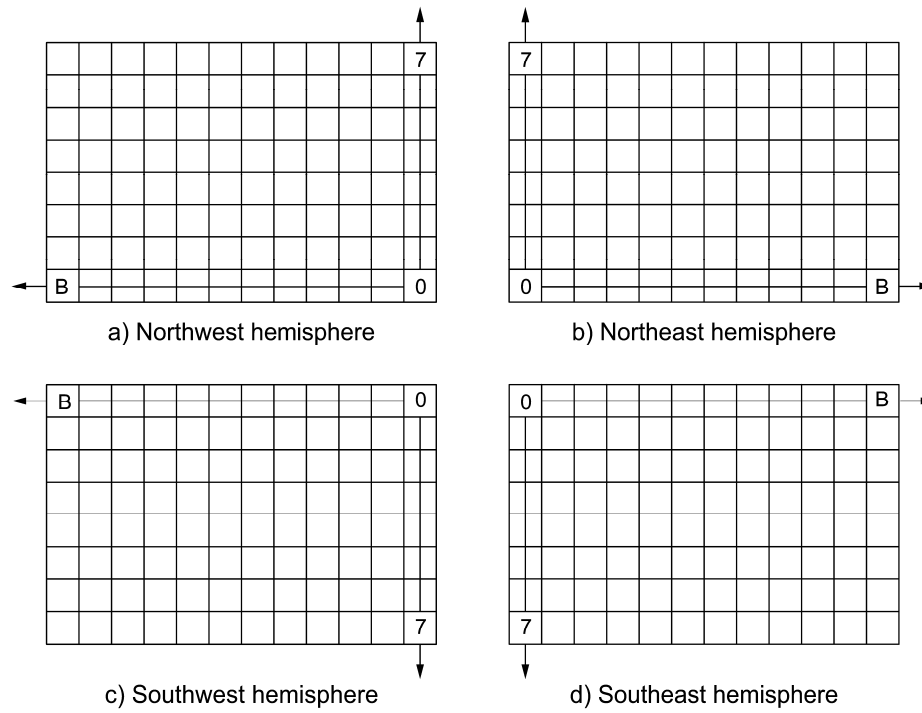


Figure 15—Second-level meshing and coding method

The second-level trellis code is six units in length and consists of the first-level trellis code, and the second-level longitude and the latitude identification code. The encoding structure is shown in Figure 14. The first-level trellis code is described in 4.1.2.1. The second-level longitude trellis code is represented by 0–B and the second-level latitude trellis code is represented by 0–7. The direction of encoding is related to the hemisphere where the trellis is located (see Figure 15).

4.1.2.3 Third-level mesh generation and coding rules

The second-level grid specified in 4.1.2.2 is divided into 2×3 third-level grids, corresponding to $15' \times 10'$ grids of 1:50 000 maps, equivalent to $27.83 \text{ km} \times 18.55 \text{ km}$ grids at the equator of the Earth.

The third-level trellis coding is seven units in length and consists of the second-level trellis code and the third-level identification code. The encoding structure is shown in Figure 16. The second-level of trellis coding is described in 4.1.2.2. The third-level of trellis coding is 0–5 in Z order. The direction of Z sequence coding is related to the hemisphere where the trellis is located.

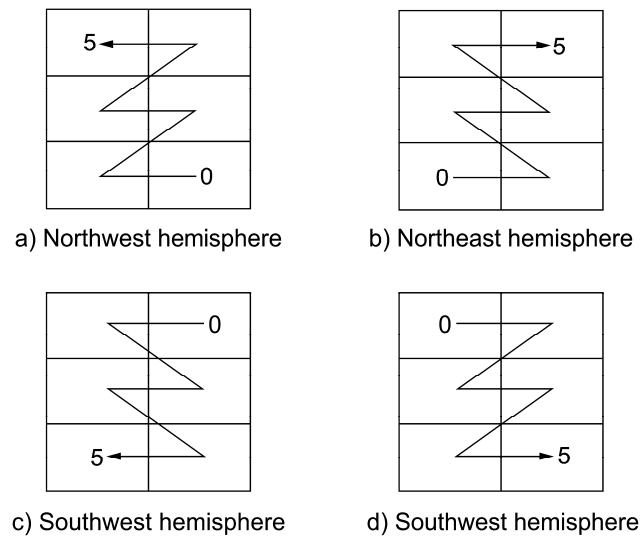


Figure 16—Third-level meshing and coding method

4.1.2.4 Fourth-level meshing and coding rules

The third-level grid described in 4.1.2.3 is divided into 15×10 fourth-level grids, corresponding to a fifteenth level $1' \times 1'$ grid, equivalent to a $1.85 \text{ km} \times 1.85 \text{ km}$ grid at the equator of the Earth.

The encoding structure is shown in Figure 17. See 4.1.2.3 for the third-level trellis code, 0–E for the fourth-level longitude trellis code and 0–9 for the fourth-level latitude trellis code. The encoding direction is related to the hemisphere where the trellis is located.

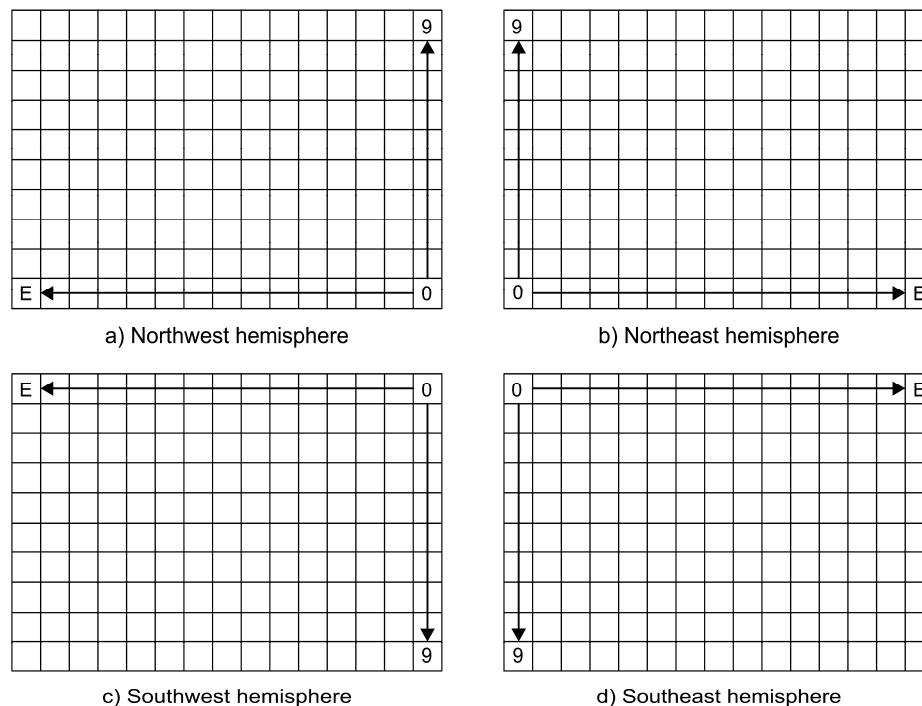


Figure 17—Fourth-level meshing and coding method

The three-dimensional coding uses the same partition as the equator's 1' length, and the coding mark is 0–2, with each partition representing around 2 km.

The fourth-level trellis code is ten units in length, which includes the third-level trellis code.

4.1.2.5 Fifth-level meshing and coding rules

The fourth-level grid is divided into 8×8 fifth-level grids (see Figure 18), which correspond to the eighteenth level 8"×8" grids in the global three-dimensional subdivision, equivalent to 231 m × 231 m grids at the equator of the Earth.

The fourth-level trellis code is described in 4.1.2.4. The fifth-level longitude trellis code is represented by 0–7, and the fifth-level latitude trellis code is also represented by 0–7. The direction of encoding is related to the hemisphere where the trellis is located.

The three-dimensional coding uses the same partition as the length of equator 8 and the coding mark is 0–7, with each partition representing around 256 m. The fifth-level trellis code is thirteen units in length, which includes the fourth-level trellis code.

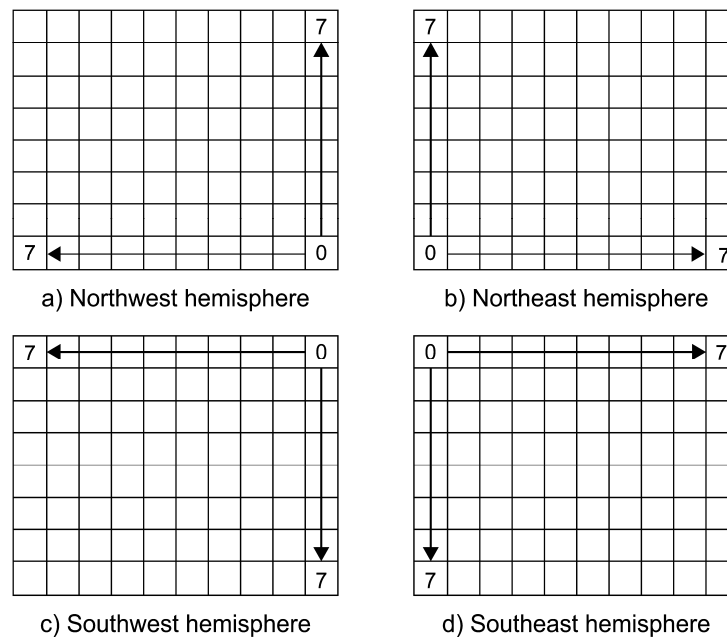


Figure 18—Fifth-level meshing and coding method

4.1.2.6 Sixth-level meshing and coding rules

The fifth-level grid is divided into 8×8 fourth-level grids (see Figure 19), which correspond to the eighteenth level 1"×1" grids in the global three-dimensional subdivision, equivalent to 28.9 m × 28.9 m grids at the equator of the Earth.

The fifth-level trellis code is described in 4.1.2.5. The sixth-level longitude trellis code is represented by 0–7, and the sixth-level latitude trellis code is also represented by 0–7. The direction of encoding is related to the hemisphere where the trellis is located.